Nature-Based Solutions (NBS) to Urban Regenerative Design:
the role of green infrastructure in promoting the development of low-carbon city

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ABSTRACT

As a further evolution of the sustainable concept, restorative and regenerative urban design aims to remediate the harms that previous practices have caused on the urban environment. Nature-Based Solutions is regarded as a significant measure of stimulating the development of restorative and regenerative urban design. In the context of climate change, reducing building energy demand has become a global consensus as it takes up 8% of direct carbon emissions. As an important component of Nature-Based Solutions, green infrastructure has been confirmed to play a positive role in eco-environmental management. However, it is unclear whether it can provide a reliable incremental path for the development of low-carbon cities. This Ph.D. research focuses on exploring the potential of Nature-Based Solutions in promoting urban regenerative design. Specifically, it aims to demonstrate, through qualitative and quantitative comparation analysis, whether green infrastructure can effectively contribute to the reduction of building carbon emissions. The research employed a comprehensive approach to achieving this purpose, including (1) a systematic review of restorative and regenerative urban design, (2) climatic specific meta-analysis on different Nature-Based Solutions types on building energy needs in various climates, (3) and Building Energy Modeling on three residential building types and climate zones. The systematic review shows that there is a significant difference between restorative and regenerative urban design; however, these two terms were developed independently. Both terms have a strong relationship with the United Nations Sustainable Development Goals. In addition, seven Nature-Based Solutions types were evaluated in the meta-analysis. Research found that these seven types assessed all have a net positive influence on cooling energy reduction; however, the result on heating energy reduction is inconsistent. The proportion of reduced cooling or heating energy depends on the types and climate zones. Furthermore, by conducting building energy simulation, the study confirmed that green roofs, green walls, and a combination of both positively impact reducing cooling and heating energy demand on slab building, clustered low-rise building and detached house in temperate oceanic climate, humid continental climate and Mediterranean climate.

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1. He, Q., & Reith, A. (2022). (Re) Defining Restorative and Regenerative Urban Design and Their Relation to UNSDGs—A Systematic Review. *Sustainability*, *14*(24), 16715. https://doi.org/10.3390/su142416715
2. He, Q., & Reith, A. (2022). A study on the impact of green infrastructure on microclimate and thermal comfort. *Pollack Periodica*.
3. He, Q., & Reith, A. (2022). Using nature-based solutions to support urban regeneration: A conceptual study. *Pollack Periodica*, *17*(2), 139-144. https://doi.org/10.1556/606.2022.00514
4. He, Q., & Reith, A. (2021). Potentiality of a residential area: Practical design at Brigittaplatz. *Pollack Periodica*, *16*(3), 158-163. https://doi.org/10.1556/606.2021.00332
5. He, Q., & Reith, A. (2021). Urban Regenerative Design: A Comprehensive Analysis of the Relationship Between Urban Greenspace and Child obesity . *UBT International Conference*. 15. DOI: 10.33107/ubt-ic.2021.12
6. He, Q., & Reith, A. (2022). Evaluation of green elements arrangement and high albedo materials on the outdoor microclimate and thermal comfort. *UBT International Conference*. 2022. 10

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Chapter 1: Introduction and Key Definitions

This study concerns the impact of Nature-Based Solutions (NBS) on urban regenerative design, with a particular attention focus on examining the role of green infrastructure in promoting the creation of low-carbon cities. Nowadays, urban residents are witnessing an unsustainable and un-resilient cycle of urban environment. Specifically, urban environmental issues (e.g., extreme heat waves) are becoming increasingly prominent due to the combined effect of climate change and anthropogenic activities. Those phenomena not only bring a negative impact on public health but also put significant pressure on urban energy demand. As urban warming and climate change have become more and more prominent, the demand for urban cooling energy is significantly increasing. This will undoubtedly exacerbate the above issues as increased demand for cooling energy will increase carbon dioxide emissions. Therefore, it is time to break this “unusual” cycle and turn the cities into a sustainable and regenerative way.

It has long been confirmed that green infrastructure could deliver a wide range of functions and services in ecological, economic and social aspects; also, maintain and protect ecosystem diversity in urban and rural settings. In particular, it plays a crucial role in the development of sustainable and low-carbon cities, as their bio functions (e.g., transpiration and photosynthesis) could reduce carbon emissions and store carbon to a certain extent; thereby, compensating for the negative impact of urban or global warming with low maintenance and operational costs.

However, previous studies on green infrastructure have mostly emphasized environmental aspects, such as biodiversity, urban flooding, ecological restoration, etc. Less attention is being paid to their influence on energy use.

This chapter provides an outline of the study. It starts with a general context on the importance of the research. After that, it introduces the purposes and objectives of the research, then concludes with some concepts that are relevant to this research.

1.1 Background to the research

Urbanization is defined as the transfer of the population from rural areas with agriculture as the main economic activity to urban areas dominated by industry and services, which is an unstoppable phenomenon that pushes the cities to the heart of the future of human development (Hes & Du Plessis, 2014). Undoubtedly, urbanization brings efficient services, convenient transportation and a stronger economy, while it also carries unforeseen risks. A series of complex problems have continued to emerge over the past few decades, such as environmental degradation, biodiversity degradation, social dysfunction, urban warming and climate change (Du Plessis, 2012). One of the assessments found that the global temperatures are 0.8°C warmer than that of the past 100 years. Intergovernmental Panel on Climate Change (IPCC) predicted that global surface temperatures would continue to rise to at least 1.5°C to 2°C unless carbon dioxide and other greenhouse gas emissions are significantly reduced in the coming decades (Aldhshan, 2021). Study by Hes & Du Plessis (2014) supported that if the carbon emissions continue to grow, this figure will increase to 2°C in 2040, with a devastating impact on the global economy and biodiversity. At the same time, the phenomena of urban warming and climate changes will, in turn, further increase the energy demand, especially the cooling energy consumption in buildings.

The concept of sustainability was put forward in the second half of the 20th century. It appears as if the concept of the sustainable city is merely a mechanism of equilibrium, which attempts to maintain a balance of input and output between energy, material and capital (Brown et al., 2018). This is insufficient to accomplish long-term urban development. As a result, the terminology of urban regeneration has been proposed, which goes beyond sustainability. The term regeneration refers to the process of restoring, repairing, or recovering the resource supply capacity of energy, water, air, or any other substance (Attia, 2018). Unlike urban restoration, which is primarily dedicated to addressing environmental issues, urban regeneration is defined as a holistic and comprehensive approach with flexibility at the scale of implementation. According to Steiner (2014), urban regenerative design seeks solutions to existing urban problems, addressing not only environmental issues but also energy, social and economic aspects; etc. Additionally, as the further evolution of the sustainable concept, urban regeneration has a significant relationship with the United Nations Sustainable Development Goals. Urban regeneration has also been considered a process of replacing the present linear system with a cyclical system that dedicates to the rebirth of life itself, providing hope for the future (Thomson & Newman, 2018). But the transition to urban regeneration could not be a gradual improvement process. It requires fundamentally rethinking the relationship between architecture, built environment and nature (Zari et al., 2009). As explained by Cole (2012), urban regenerative design represents not only an intention of restoring and regenerating sociocultural and ecosystems but also suggests a change in the perception of the role of the built environment itself, from being a subject of interest to being seen as a system that could facilitate the relationship between humans and nature.

NBS urban design ideas include examples that are inspired, learned, or copied from nature. The concept of NBS was initially proposed at the beginning of the 21st century. Then, it has been widely adopted to promote synergy between nature, society and economy from a systematic perspective. NBS is an umbrella terminology containing many categories and approaches; for instance, issues-specific ecosystem-related approaches involve climate adaptation services, and infrastructure-related approaches include natural and green infrastructure (Cohen-Shacham et al., 2016). However, in the context of urban warming and climate change, NBS should not only play a positive role in improving the living environments but also in living in a green and energy-efficient way. According to Estache & Kaufmann (2011), the European Commission intends to reduce more than 20% of carbon emissions by employing NBS and sustainable green space management. Specifically, the EU‘s Commission Document 249 of 2013 and Directive 2018/844 highlight the requirement to improve energy efficiency by enhancing Europe's natural capital; in particular reducing energy consumption in building sectors through green infrastructure (Campiotti et al., 2022).

Currently, buildings have already become the world’s largest energy consumer (Cao et al., 2016). It is reported that nearly 70% of all greenhouse gas emissions come from urban areas, of which building sectors globally occupied 30% of total energy use and emitted 27% of energy-related carbon dioxide, compared to 26% of transportation (Estache & Kaufmann,2011). This figure has the potential to rise to 50% by 2030 without taking effective measures (Aldhshan et al., 2021). Research by Estache & Kaufmann (2011) supported that building energy efficiency improvement is the cheapest and most efficient way to reduce carbon emissions.

Improving the efficiency of building energy utilization and minimizing carbon emissions are of great significance for achieving the establishment of low-carbon cities. Low-carbon city refers to taking effective actions and measures to decrease their environmental impacts and carbon dioxide emissions. From the urban development perspective, low-carbon-related actions need to be more integrated into urban planning and urban design processes to effectively implement low-carbon development (Laine et al., 2020). As an urban multifunctional ecological system and the important approach of NBS, green infrastructure could produce multi-dimensional co-benefits in land use, buildings and the environment. It could also form advantages in energy and climate change-related actions in improving microclimate conditions, carbon sequestration, building cooling consumption reduction; etc. (Coletta et al., 2021; Laine et al., 2020). Green infrastructure is termed as an interconnected network of natural, semi-natural and artificial ecological systems, supplying a wide range of ecological, economic and social benefits as well as ecosystem services, which could sustain natural processes and protect the biodiversity of urban and rural environments (Pakzad et al., 2015). A significant number of researches have proved that the categories of green infrastructure (e.g., nature reserves and green belts) could slow down the urban heat island effect, improving indoor and outdoor microclimate conditions (Ying et al., 2021; Priya & Senthil, 2021). At the same time, it could directly absorb and sequestrate carbon dioxide from the atmosphere through photosynthesis; thereby, decreasing the atmospheric concentration of carbon (WMO, 1996). Many studies revealed that a tree could absorb an average of 10 to 30 kilograms of carbon annually (Beecham, 2020; Akbari, 2002). Research by Nowak calculated that urban trees provide 700 million tons of carbon storage in the United States by using data and urban tree cover estimates from 10 cities (Nowak & Crane, 2002). In addition, forest biomass in 27 EU countries is estimated to store 9.8 billion tons of carbon (UNECE, 2022). As such, green infrastructure might offer a credible and incremental path toward the realization of low-carbon city.

At present, the research on exploring the impact of green infrastructure on the energy use of buildings is evolving. Although there is current evidence of positive cooling benefits of green infrastructure, it is influenced by the biophysical, morphological and spatial arrangement of green infrastructure as well as the local climatic background and the surrounding built environment (Zupancic et al., 2015; Priya & Senthil, 2021). Therefore, it requires more in-depth studies.

1.2 Research purposes, processes and questions

The primary purpose of this research is to explore the potential of NBS in promoting urban regenerative design. Specifically, the study aims to demonstrate, through qualitative and quantitative comparison analysis, whether green infrastructure can effectively contribute to the reduction and avoidance of building carbon emissions. In simple terms, the influence of green infrastructure on building energy demand. Although this study is framed as the quantitative and qualitative research, the higher goal is to better support and guide the practice of future urban design. To achieve this aim, the study divided the research process into three parts.

- Firstly, a systematic review research on restorative and regenerative urban design is conducted, aiming to explore “What are the differences and interrelationships between restorative and regenerative urban design?”; and also attempts to assess “Is the existing definition of restorative and regenerative urban design applicable?”.

Although studies on restorative and regenerative urban design have been conducted for many years, many uncertainties remained. For example, in some cases, these two terms are often mix used. Therefore, research needs to clarify these uncertainties to provide the foundation for this research.

- Secondly, a climate-specific meta-analysis review was performed, which tends to quantify "How far are NBS reducing heating and cooling building energy demands in different climate zones?”.

- The last part refers to building energy modeling. In this part, a series of building energy simulations were conducted, and the related research question is: "How high is the dependency of heating and cooling energy demand on specific building types and climate zones energy?"

1.3 Thesis structure

This chapter outlined the general research background and research purpose of this dissertation. After that, it listed the key research questions. Then, it described several definitions and concepts related to the research. In the following chapters, the study will depict, evaluate and discuss each of the research components in greater depth.

Chapter 2 describes the methodologies of systematic review on restorative and regenerative urban design, as well as the findings of this systematic review.

Chapter 3 depicts the methodologies of climatic specific meta-analysis for NBS typologies and building energy demand in different climate zones, as well as presents the current status of this research field.

Chapter 4 is designated to introduces the methodology of Building Energy Modeling, as well as provides the corresponding results of building energy simulations.

Chapter 5 aims to discuss the findings derived from the analysis conducted in Chapters 2 to 4.

Chapter 6 and chapter 7 describes the limitations and conclusions of this research, respectively.

1.4 Key definitions and related concepts

1.4.1 NBS and its related goals, principles, and conceptual framework

The concept of NBS emerges in the context of environmental sciences and nature protection.

Ecosystem service has long been reflected in traditional knowledge systems, but it has not attracted much attention from scholars (Cohen-Shacham et al., 2016). It began to build itself in modern scientific research in the 1970s. The research on ecosystem services accessed a stage of rapid development at the end of the 20th century. Because there is a widespread recognition that ecosystems need constant protection, restoration and sustainable management to meet the growing demand. As a result, the terminology “NBS” was proposed in the early 2000s, which indicated a subtle and important shift in perspective. That is, the role of humans extends from the pure beneficiaries of ecosystem services to the protectors and managers of nature systems (Cohen-Shacham et al., 2016).

NBS has been widely adopted since 2013 (Somarakis et al., 2019). Although limited studies on the concept to date, the terms have already diversified and therefore lack widely agreed definitions (Eggermont et al., 2015). In the United States, "nature-based infrastructure" and "nature-based engineering" tend to describe actions that support resilience and reduce flood risk (Nesshöver et al., 2017). The emerging academic literature largely considers NBS as an umbrella concept containing disaster risk reduction approaches, ecosystem-based adaption and mitigation approaches; etc. However, many scholars point out that some of these definitions seem impractical due to the lack of precise criteria for identifying NBS (Albert et al., 2017).

The International Union for Conservation of Nature (IUCN) termed NBS as ‘actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g., climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits’ (Cohen-Shacham et al., 2016, p. 5). Similarly, the NBS understood by European Commissions (EC) as living actions that were supported, learned and copied from nature, aiming to resolve various social challenges in a resource-efficient and adaptive way while providing environmental, social and economic benefits. These two definitions both highlight nature's potential power in addressing complex social challenges while sharing a common goal of bringing social, economic, and environmental benefits through the effective utilization of ecosystems. Compared to the description from ICUN, the definition from EC is broader, emphasizing applications that utilize nature and are inspired and supported by nature. However, nature-inspired designs and imitations (biomimicry) are not regarded as an NBS by EC because it is not associated with natural ecosystems (Cohen-Shacham et al., 2019). Furthermore, the definition from IUCN has a global perspective and focuses on managing and protecting natural ecosystems. On the contrary, due to the high proportion of the European urban population, EC is more concentrated on urban ecosystems, which require coordinating the relationship between human wellbeing, climate change and urban development. This has led to many disputes between these two definitions, for instance, the relationship to innovation and ecosystem-based approaches (Cohen-Shacham et al., 2019; Calliari et al., 2019).

At present, most of the conceptualizations still are built on or related to the concepts elaborated by the IUCN and EC; for example, Oxford University interprets the NBS as actions that support biodiversity, address societal challenges, bring benefits to human well-being through the protection, restoration, or management of natural or semi-natural ecosystems; also, designed and implemented with the full participation and consent of local communities and indigenous people. In the study of NBS for European sustainable development, Maes & Jacobs (2017) depicted the NBS as any transition to using ecosystem services while reducing investment in non-renewable natural capital and increasing investment in renewable natural processes.

With respect to the goals of NBS, NBS has a multifunctional role and is considered a way of working with nature to innovate and address social challenges (Somarakis et al. (2019). This idea has been translated into several goals and embedded into action plans and reports; e.g., the Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-naturing Cities.' This report highlights the four goals of NBS, including:

- *Sustainable urbanization* - cities attract most of the world's population and face various challenges; e.g., freshwater shortage and human wellbeing.
- *Degraded ecosystems restoration* – Due to anthropic activities, nature and ecosystems has been damaged significantly.
- *Adaption and mitigation of climate change* - Climate change is one of the most serious challenges in the 21st century, affecting the environmental, social and economic aspects.

- *Risk management and resilience* – The preparation needs to face multiple hazards avoiding significant losses of natural and social resources.

Furthermore, another main goal of NBS is to address the global challenges directly related to the United Nations Sustainable Development Goals (SDGs) (Somarakis et al., 2019). In simple terms, NBS should not only focus on improving ecosystems and biodiversity but also contribute to achieving SDGs. To date, many initiatives use NBS to correspond to SDGs (Somarakis et al., 2019). For example, the initiative of natural coastal protection is related to Goal 14, sustainable management of marine resources. Urban agriculture is relevant to Goal 2 for ensuring food provision and security. The initiatives of green roofs and vertical greenery systems are linked to Goal 11 and Goal 13 for sustainable cities and communities as well as climate action.

Regarding the conceptual framework of NBS and its related principles. NBS comprises natural capital or actions to support and strengthen the flow of ecosystem services. It was categorized into three types based on the level of intervention. They are:

- Better use of natural ecosystems;
- Sustainable and multifunctional management of ecosystems;
- Design and management of new ecosystems.

The above classification of NBS indicates the open nature of this term, which contributes the wider adoption. Furthermore, NBS recognizes and builds upon the earlier concepts, such as ecological engineering, green and blue infrastructure, etc. Therefore, NBS is an umbrella terminology containing a wider range of ecosystem-based approaches. These approaches could be divided into five categories, each with appropriate approaches (Table 1.1) to address societal challenges; while providing human wellbeing and biodiversity benefits (Figure 1.1).

Table 1.1 Categories and examples of NBS methods as well as resolved challenges

Category of NBS approach	**Examples**	**Challenges to be resolved**

Ecosystem restoration approaches	Ecological restoration; forest restoration; ecological engineering	·Air quality ·Coastal resilience ·Climate mitigation and adaption ·Flood protection ·Erosion prevention ·Water purification ·Carbon sequestration ·Greenspace management ·Public well-being
Issue-specific ecosystem-related approaches	Ecosystem-based adaption and mitigation; climate adaption services; ecosystem-based disaster risks reduction	
Infrastructure-related approaches	Green and natural infrastructure	
Ecosystem-based management approaches	Integrated water resources management; integrated coastal zone management	
Ecosystem protection approaches	Area-based conservation approaches	

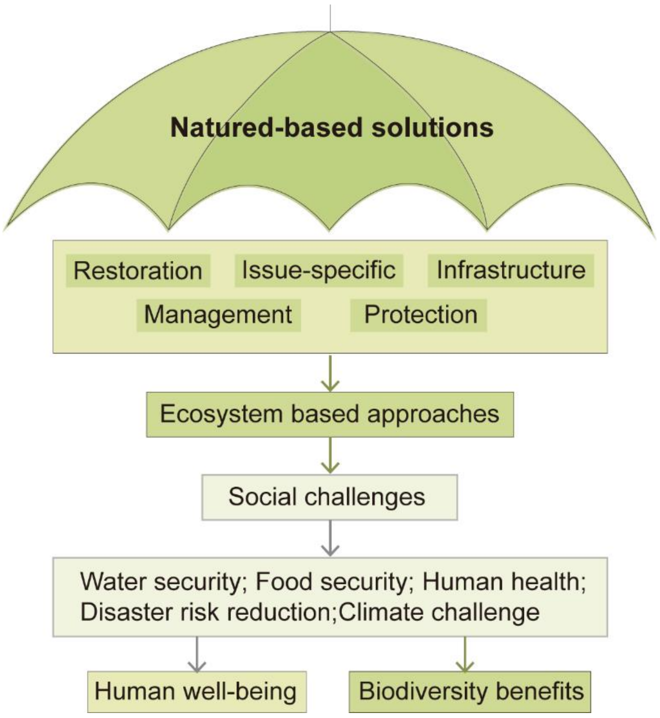


Figure 1.1 The conceptual framework for addressing social challenges by NBS-related approaches (*Author's plot*)

Besides, NBS has eight principles, many of which are interrelated and, in some cases, interdependent (Cohen-Shacham et al. 2019). They are as follows (Cohen-Shacham et al. 2019):

1. embracing nature conservation rules (and principles);
2. NBS could be conducted individually or in a combined way with other approaches to social challenges (e.g., engineering solutions);
3. NBS is an evidence-based method grounded on a thorough understanding of the various context of the site; e.g., culture and nature ;
4. NBS produces social profits in a fair and equitable approach in a manner that improves transparency and broad participation;
5. NBS maintains biological and cultural diversity and supports the temporal dynamics of ecosystems to accommodate future environmental changes;
6. The application of NBS could integrate multiple ecosystems but needs to be implemented at large spatial scales (landscape scale);
7. NBS recognizes and addresses the trade-offs between the production of a few immediate economic benefits for development and future options for the production of the full range of ecosystems services;
8. NBS is incorporated into policies or related actions to support and address challenges.

To sum up, the concept of NBS derives from a vision to promote a close association between biodiversity and human well-being. It is learned, copied and inspirited from nature and based upon many early natural approaches. As a result, it contains many categories, approaches, and principles. Although there has yet to be a consensus on the definition of NBS, it has been recognized as a sustainable approach to coordinating social, economic development and nature conservation through natural means. More importantly, NBS not only focuses on the improvement of ecosystems and biodiversity but also contributes to the achievement of SDGs.

1.4.2 Urban regeneration and its related characteristics

Urban regeneration development has experienced a long period and could be divided into several stages. The term urban regeneration was initially designed to inhibit the severity of urban problems and attempt to revitalize the recession in urban areas with a comprehensive perspective (Mehan, 2016). The significant development period of urban regeneration was after the middle of the 20th century. The nature of this term has undergone several changes in direction during the past few decades. The sequence of the following terms summarizes the evolution of urban regeneration and could be used to represent each development stage (Mehan, 2016). The evolution of urban regeneration is shown in Figure 1.2.

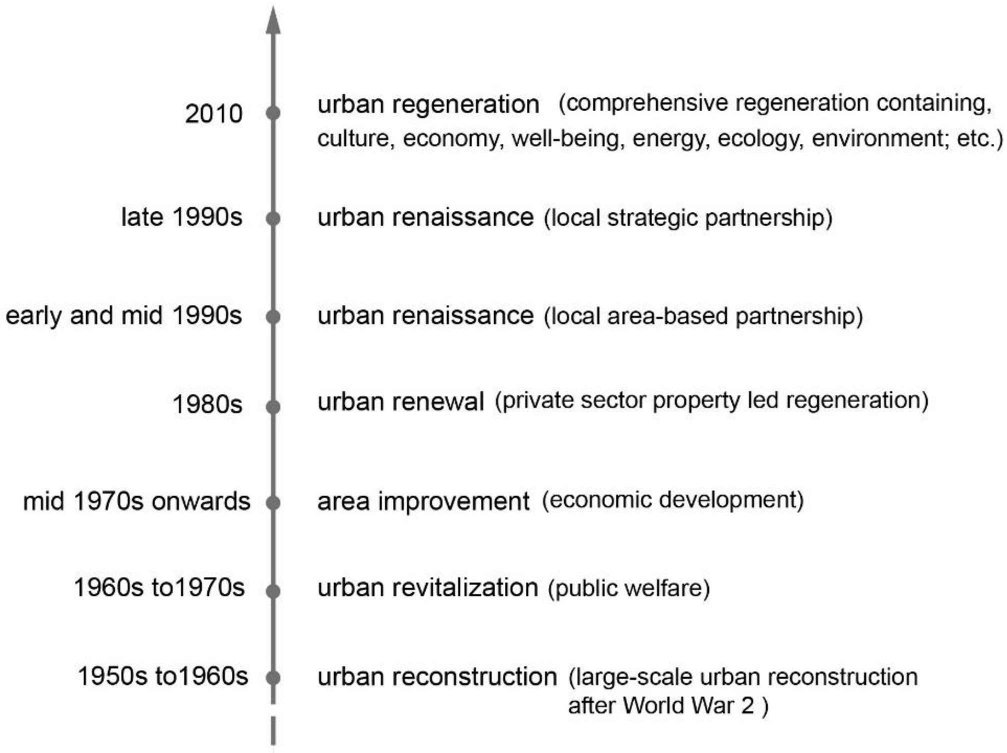


Figure 1.2 The evolution of the term urban regeneration and its related polices (*Redrawn based on Mehan, 2016*)

(1) The first stage is urban reconstruction which occurred after world war two from 1950 to 1960 based on the modernist approach. (2) After that, the period of urban revitalization enhances the development of public welfare despite the deprivation still existing in the city's core area (McDonald et al., 2009). (3) In the 1970s, urban development prevailed in the policies because the changes in the structural economy brought various urban issues resulting in area restoration needed to cooperate with economic development (Mehan, 2016). (4) Later, urban renewal was dominated by the regeneration of private-sector property (Mehan, 2016). In the

strict sense, it only focuses on an area with structural and functional deficits rather than the whole space (Ruming, 2018). As such, urban renewal has been criticized for emphasizing the purposes and means of physical change (Tang, 2016). (5) Urban Renaissance tended to establish local area-based partnerships (Cameron & Doling, 1994). (6) In the 21st century, this term has evolved into a holistic approach to dealing with urban problems, stimulating policy changes (Roberts & Skyes, 2000).

The conceptualization of urban regeneration has gradually shifted from the simple enhancement of the physical environment to holistically restoring and regenerating the social, economic and physical environment (Tang, 2016). In this sense, urban regeneration goes beyond the purposes and achievements of urban revitalization, development, and renewal.

Regenerative development has been considered as a further development of sustainable development (Girardet, 2017). The concept of sustainable development focuses on emphasizing the contemporary use of resources in ways that do not negatively influence the ability of descendants to meet their needs (Curwell S & Cooper, 1998). In simple terms, it is merely an equilibrium point that cannot meet the long-term development of the city. Correspondingly, the sustainable built environment aims to remain neutral or reduce environmental impact in energy, carbon, waste, or water (Mang & Reed, 2020). Nevertheless, rapid urbanization urges the built environment to go beyond this goal to bring net positive environmental benefits to the cities (Jenkin & Zari, 2015). As a result, the terms cradle-to-cradle, restorative and regenerative development have been proposed. These are the new ways of thinking and designing to provide net-positive environmental outcomes while treating development as a way to improve the health of the ecosystem (Jenkin & Zari, 2015). This interpretation is visualized in Figure 1.3.

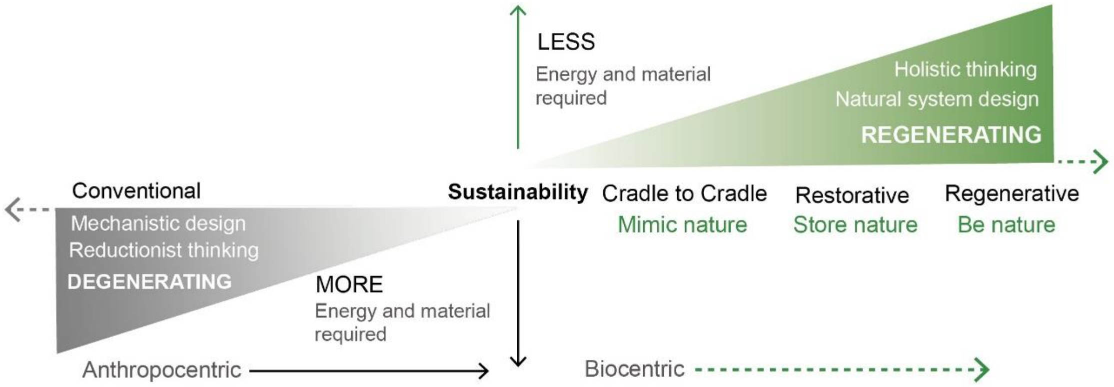


Figure 1.3 Schematic illustration of the relationship between sustainability, cradle-to-cradle, restoration and regeneration (*Author's plot*).

Although these three terms are designed to deliver net positive benefits to the built environment, they have distinct differences. Cradle-to-cradle mimics the cycle of nature, depicting a closed-loop system of materials. Wherein all types of products could be recycled and reused or become raw materials of another product at the end of their life. In this sense, the cyclic pattern of cradle-to-cradle optimizes the sustainability of materials by using technical and biological components, which is equivalent to true sustainability (McDonough & Braungart, 2010). In addition, urban restoration is committed to restoring the current damaged ecosystem to its original state through active human management. On the contrary, urban regeneration has been considered a comprehensive and holistic approach (Girardet, 2017). It seeks to restore the ability of ecosystems to function at an optimal level without constant human involvement that allows the health system to flourish (Reed, 2007; Luca, 2018). It also acknowledges human development, social structure and cultural concerns as an inherent and essential part of the ecosystems. Study by Steiner (2014) revealed that the main principles of regenerative design are to maintain the co-evolutionary and cooperative relationship between sociocultural and ecological systems. This means that regenerative design is a fundamental rethinking of the role of buildings and the built environment itself, moving from a primary theme of interest to an approach that has the potential to contribute to the mutual prosperity of human and natural systems through collaboration (Cole, 2012).

Urban regeneration is defined as an integrated method involving three purposes (economy, equity, and environment). It aims to improve economic competitiveness, decrease inequality, protect the environment, and advise policies for government and private organizations and other institutions (Gibson, 2001). In addition, urban regeneration highlights the co-evolution of the entire system in which we are involved (Reed, 2007; Steiner, 2014). Study by Mang & Reed (2020) pointed out that regenerative design includes three phases, comprehending the association with the site, providing harmonious design to the place, and designing for co-evolution. This means that regenerative design is an approach that produces mutual benefits and seeks to co-evolve with natural systems. As such, the transition from sustainability to regeneration ensures that cities not only become resource-efficient and low-carbon emitting but also actively improve instead of undermining the ability of the ecosystem services they obtain beyond their boundaries (Figure 1.4).

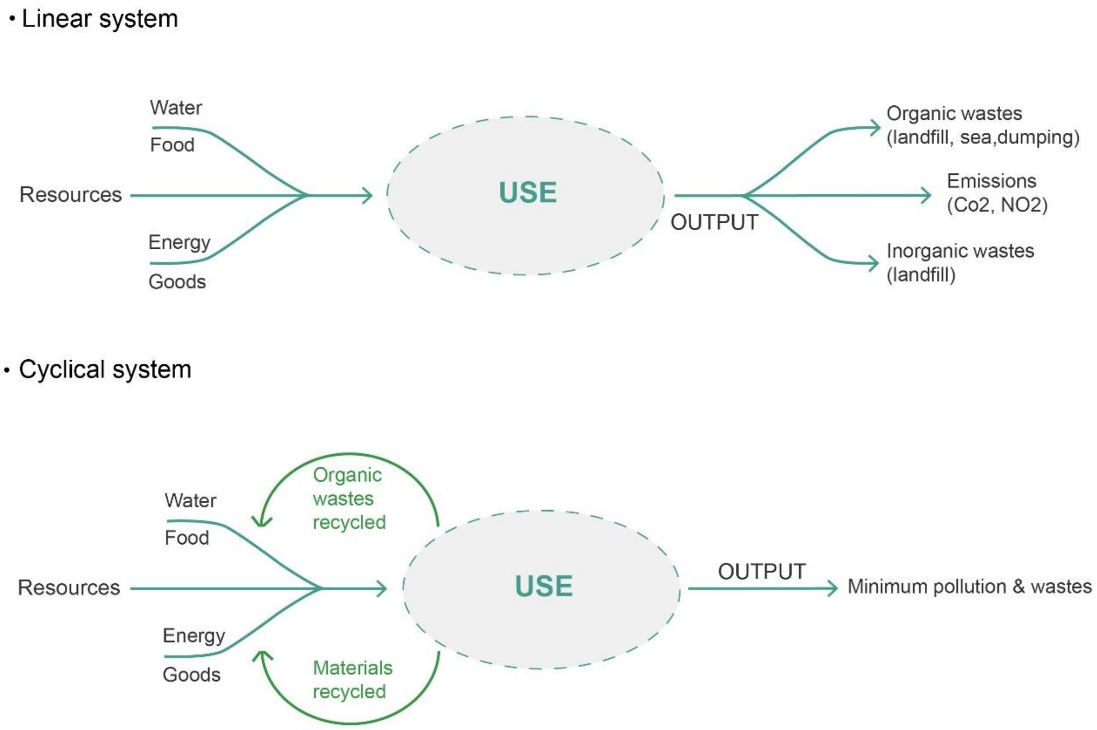


Figure 1.4 The difference between conventional and regenerative urban development (*Author's plot*)

In short, urban regeneration is a comprehensive and integrated vision and action aiming at addressing urban problems and lasting improvement of a region's economic, material, social and environmental conditions that have declined or provided opportunities for improvement. It can not only positively impact human communities, culture, ecosystem, and built environment but also help offset the continuous undesirable environmental impact of the existing building stock and decrease the proportion of energy-dependent new buildings (Jenkin & Zari, 2015).

1.4.3 Low-carbon city and its association with NBS

The term "low-carbon city" derives from the requirement to mitigate climate change and achieve cities' carbon reduction targets (Tan et al., 2017). Nowadays, low-carbon practices have been widely carried out around the world; for example, more than a thousand cities in the US have set low-carbon development goals in their urban development blueprint. However, the low-carbon actions and development forms are diverse, as the low-carbon development goals of each country are inconsistent. In Copenhagen, the low-carbon development form focuses on the promotion of sustainable renewable energy, while London emphasizes energy efficiency projects. Additionally, New York focuses on improving building energy efficiency (Tan et al., 2017).

To date, there is no unified definition of the low-carbon city because the theoretical development of the low-carbon city is still in its infancy. However, the concept of it aims not only to reduce carbon emissions but also emphasizes the co-development of the economic, environmental and social aspects. As stated by Shi et al. (2021), low-carbon related actions could not only continuously decrease carbon emissions, reduce air pollution concentration and improve air quality but also promote the better integration of energy planning into the long-term urban development process. In addition, the concept of low-carbon city is built within the framework of sustainable development and is always relevant to the ultimate goal of sustainability (Tan et al., 2017). Therefore, it is the extension and practice of sustainable development theory. Moreover, Cheshmehzangi et al. (2018) pointed out that the low-carbon city concept also has a significant association with the idea of "circular economy." Roseland (1997) suggested that the concept of low-carbon cities should be defined from a local perspective but consistent with the framework of global sustainability. Zhang et al. (2008)

stressed that low-carbon cities should maintain low-carbon manufacturing and consumption and achieve a sustainable energy ecosystem. Similarly, Dai (2009) noted that low-carbon cities should focus on reducing carbon emissions and encourage citizen behavior to shift towards low-carbon emissions. Moreover, Wei (2011) proposed that low-carbon cities need multi-scale coordination actions, from individual to community and then citywide. More importantly, the Chinese research Academy of Environmental Sciences concluded that the concept of low-carbon city has two aspects: low carbon economy and low carbon consumption (Kenaga, 2011).

- Low carbon economy refers to reducing carbon emissions by improving resource utilization efficiency and green technology.
- Low carbon consumption indicates reducing the carbon emissions in all aspects of the city while improving the low-carbon awareness of urban residents and increasing carbon sink.

As such, it could be inferred that low-carbon cities are essentially cities that take effective actions and measures to decrease their environmental impacts and carbon dioxide emissions.

Furthermore, there are several terms (Table 1.2) that share a similarity to low-carbon cities. To some extent, they could be considered synonymous with low-carbon cities or the individual terms overlap in meaning, but they are also different in vision and governance (Tan et al., 2017). For example, the terms carbon-neutral and net-zero carbon may seem interchangeable, but they have obvious differences. Carbon neutrality aims at maintaining a balance between carbon emissions and absorption. In comparison, net-zero carbon refers to decreasing the carbon emission to the lowest volume and offsetting as the last resort. Moreover, carbon neutrality is more flexible than net-zero carbon because it allows offsetting emissions by buying carbon compensation from third parties outside city boundaries. Instead, net-zero carbon emphasizes the elimination of all carbon emissions (Damsø et al., 2017).

Table 1.2 The concepts similar to low-carbon city

Terms	**Definitions**
Carbon neutral city	- carbon emissions are equivalent to the amount of local carbon

	sinks' absorption (Huovila et al., 2022).
Net-zero carbon city	- cities that do not produce greenhouse gases and rely entirely on renewable energy (Tan et al., 2017).
Eco-city	- it refers to an ecologically healthy city where people can live in harmony with nature, thereby significantly decreasing their ecological footprint (Suzuki et al., 2010)

Regarding the association with NBS, the creation and development of low-carbon cities need extensive implementation of NBS. In other words, NBS provides a practical pathway to promote the development of low-carbon cities. Several studies proposed many approaches from the perspectives of energy, technology, society, and low-carbon operation management (Wu et al., 2022; Selman, 2010). These approaches and advice could be summarized and categorized as reducing emissions, avoiding emissions, and carbon absorption (Figure 1.5).

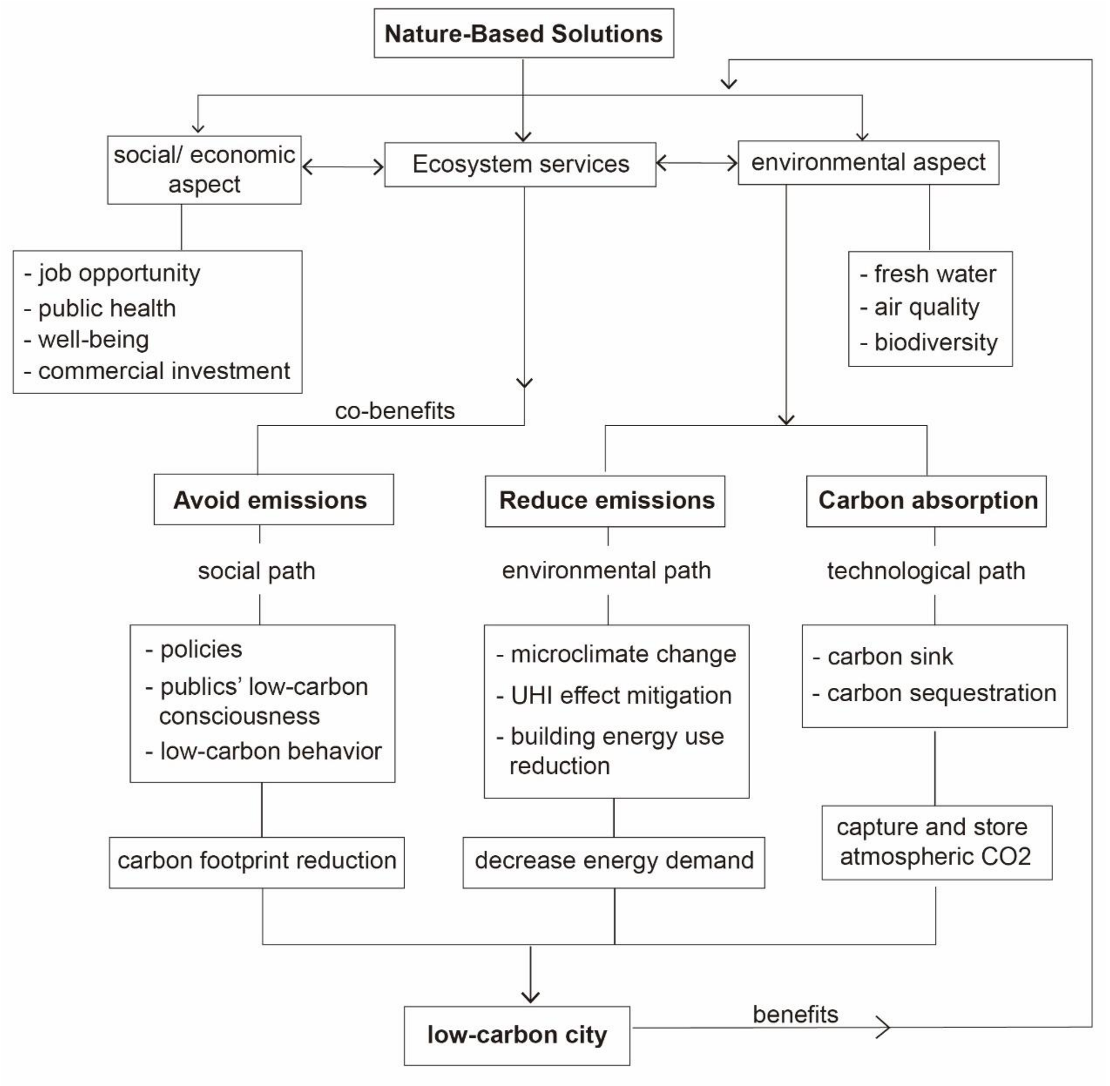


Figure 1.5 The conceptual framework between NBS and low-carbon city (*Author's plot*)

Among them, carbon absorption is closely associated with carbon sink technology. Carbon sink refers to the absorption and accumulation of carbon dioxide indefinitely through afforestation and vegetation restoration measures; thereby reducing the concentration of carbon dioxide in the atmosphere. It usually comprises terrestrial and ocean carbon sinks (Wu et al., 2022). The terrestrial carbon sink contains agricultural, forest, soil; etc. However, no artificial carbon sink at present is able to remove carbon from the atmosphere at the necessary scale to cope with global warming (Becker et al., 2020). The most common carbon sink in the cities is the tree or urban forest, which could fix the carbon during photosynthesis and store it as biomass in its life cycle (UNECE, 2020). In the case of carbon sequestration popularizing (trees have a negative net equilibrium of carbon emission), trees play a significant role as a carbon reservoir and sequestration tool (UNECE, 2020). Therefore, they could greatly contribute to reducing carbon emissions and alleviating climate change. For example, using data from urban tree cover estimates from 10 cities, research by Nowak calculated that urban trees provide 700 million tons of carbon storage in the United States (Nowak & Crane, 2002). Similarly, forest biomass in 27 EU countries is estimated to store 9.8 billion tons of carbon (UNECE, 2022).

Regarding reducing emissions, the role of NBS and related types provide a pathway for modifying the local microclimate (e.g., wind speed, humidity, air temperature) and alleviating the phenomenon of the urban heat island effect, thereby reducing the energy consumption for cooling and heating (Castaldo et al., 2018; Bush & Doyon, 2019). In other words, except for allowing maximum carbon sequestration, NBS could improve the urban thermal environment, balance the albedo effect and promote indoor and outdoor thermal comfort, thus indirectly decreasing building energy demand.

In terms of avoiding emissions, this apart is significantly related to low-carbon behavior and consciousness from the dimension of society to the individual. Low-carbon behavior is termed as the behaviors that have the potential to positively affect the effectiveness of substance and energy; also, it is divided into private and public domain behaviors (Stern, 2000). Wherein public domain behavior refers to indirectly affecting the environment by influencing public policies (Chen & Li, 2019). Private behaviors are mainly related to the actions of low-carbon consumption (Barr et al., 2005). As revealed by Somarakis et al. (2019), due to the multiple benefits of NBS, it will inevitably attract the attention of authorities to encourage the introduction and promulgation of relevant policies. These policies and initiatives disseminate the concept and importance of NBS and low-carbon activities at a macro level to encourage and guide urban residents to develop low-carbon living and consumption patterns, such as the encouragement of installing green roofs and vertical greening systems (Wu et al., 2022).

In short, as a long-term development trend and the practice of sustainable development concept, low-carbon city not only dedicates to alleviating climate change but also helps to coordinate and promote sustainable development in the economy, society, and environment. Although there is no unified definition of low-carbon city, many scholars and organizations pointed out its main characteristics. NBS and its related types or actions could contribute to the development of low-carbon cities from the aspects of avoiding emissions, reducing emissions, and carbon absorption.

1.4.4 Definitions, principles, typologies, and importance of green infrastructure

As a relatively new term, the development of green infrastructure theories is rooted in long-term thinking because it provides a contemporary and sustainable way to plan, design, and manage natural and built resources (Mell, 2010; Youngquist, 2009). The concept of green infrastructure was first proposed in the United States in the 1990s and developed rapidly in Europe as it provides chances to develop, preserve and improve environments for spatial and landscape planning (Mell, 2010). The conceptualization of this term is affected by the scope of research, interest, and specific methods; also, the multidimensional features of green infrastructure in terms of time, space, and perception leads to variability and subjectivity in its application (Pauleit et al., 2011). To some extent, this restricts a common understanding of its significance at the local and global levels (Pauleit et al., 2011). Green infrastructure was initially used to delineate ecological and conservation purposes and its role in landscape and biodiversity management (Benedict & McMahon, 2012). As this term continues to develop, green infrastructure has encompassed the disciplines of landscape ecology, urban planning, and geography (Sinnett, 2015). Its related approaches have been widely used in various fields, such as protecting natural resources and biodiversity (Sinnett, 2015), improving public health and well-being (Nieuwenhuijsen, 2021; Coutts, 2016; Tzoulas et al., 2007), promoting water management and runoff control (Liu & Jensen, 2018; Ellis, 2013), maintain the multi-functional of green resources (Davies et al., 2015; Lovell & Taylor, 2013).

Green infrastructure has no uniform definition, as it is influenced by academics, policies, and practical context (Wright, 2011). This is shown in Table 1.3. However, many researchers have considered green infrastructure as an interconnected network of natural, semi-natural, and artificial ecological systems, supplying a wide range of ecological, economic and social benefits as well as ecosystem services, which could sustain the natural processes and protect the biodiversity of urban and rural environments (Pakzad et al., 2015). In England, the government guidance states that "*Green infrastructure is a network of multi-functional green space, both new and existing, both rural and urban, which supports the natural and ecological processes and is integral to the health and quality of life of sustainable communities*" (Anggraeni, 2019, p. 4). As a result, this official definition has been widely utilized in many studies across countries (Jerome et al., 2019).

Table 1.3 The definitions of green infrastructure in different ways

Green infrastructure defined by policy documents	
The national planning policy framework (2012)	Green infrastructure is a multifunctional greenspace network that provides a range of environmental and quality of life profits to the local community.
Landscape institution, (2022)	Green infrastructure is a network that links greenspaces scattered across rural and urban areas. It has potential to bring many benefits.
Definition of green infrastructure defined by academics	
Weber, Sloan and Wolf (2006)	Green infrastructure is a terminology utilized for depicting the rich and distributed natural characters, such as wetlands and forests.
Davies, MacFarlane, McGloin, Roe (2006)	It is a multifunctional network of various natural resources, which could make a great contribution to sustainable natural resources management.
Benedict & McMahon (2012)	Green infrastructure refers to an interconnected greenspace network containing private gardens, public greenspaces; etc.
Definition of green infrastructure defined by practices	
Town and Country Planning Association (2012)	Green infrastructure must deliver ecosystem services and other functional services; like, microclimate modification and floodwater management. It should also have the flexibility in

implementation on the scale

Green infrastructure is the ecological collection of natural and artificial elements, usually made up of “hubs.” These hubs are interconnected and merged spatially through the corridor, promoting the interrelationship between species. Although the morphological composition and spatial configuration of natural systems determine the degree of such interconnection, these linkages effectively enhance the resilience of ecological networks and prevent habitat fragmentation (Pickett et al., 2017).

There are three basic principles of green infrastructure and it is necessary to understand them from a multi-scale perspective. (1) multi-functionality principle (Pauleit et al., 2011), (2) spatial interconnection or integration principle (gray-green spatial continuity) (Pauleit et al., 2011), (3) dynamic spatial and temporal heterogeneity principle (Pickett et al., 2017). Furthermore, green infrastructure could also be regarded as a phenomenon of spatial heterogeneity and temporal dynamics due to the composition of natural, semi-natural and artificial elements (Cadenasso et al., 2013). The heterogeneity has flexibility on the spatial scale. Nevertheless, the fine scales show highly heterogeneous conditions compared to the coarse scales (Koc, 2018). Therefore, urban design interferes with the heterogeneity level by influencing the number and configuration of these elements, such as the integration of street landscapes (Cadenasso et al., 2013).

Improving and maintaining the connectivity of the ecology is an important purpose of green infrastructure that can preserve the functions of the ecosystem and promote the prosperity of biodiversity (Koc, 2018). This connectivity consists of two aspects: (1) physical connectivity, that is, the structural interconnection between different natural elements in an ecological network; (2) functional connectivity, which refers to the interactions between different species and the landscape structure (Mazza et al., 2011). The interrelationship between structures and functions could preserve the ecological balance between natural and built environments (Lehmann et al., 2014). To some extent, this also promotes the multi-functionality of green infrastructure (Koc, 2018).

Green infrastructure can bring a wide range of environmental and human services from the natural ecosystem, known as "ecosystem services" (Pakzad et al., 2015). Ecosystem services can be classified as follows (Ely & Pitman, 2014):

- Provisioning services which refer to providing food, drinking water, raw materials, genetic resources, natural medicines; etc.;
- Regulating services containing climate modification, air quality regulation, diseases regulation, and water purification;
- Cultural services related to aesthetic and psychological profits, such as education and inspiration, spiritual and religious services, and sense of place;
- Supporting services which refer to offering habitats for plants and animals; e.g., nutrient and water cycling, soil formation and retention.

It is widely acknowledged that ecosystem services are closely associated with the quality of life of human beings, such as security, health, and social identity (De Groot et al., 2010). As such, many scholars consider ecosystem services as a crucial indicator of measuring the impact and effectiveness of green infrastructure because their contribution to the aspects of economy, society, and environment is numerous; for instance, improving urban resilience, absorbing atmospheric carbon, mitigating the UHI effect and alleviating climate change; etc. (Pakzad & Osmond, 2016). However, the assessment of green infrastructure is based on the typology (Shi, 2013). Study by Pitman et al. (2015) categorized green infrastructure into spaces; e.g., parks, gardens, wetlands, farms, squares, plazas, sport fields, green roofs, greenways, cemeteries, streets, and transport corridors. Moreover, Nature England proposed the typology of green infrastructure in 2009, which classified green infrastructure into five categories (Table 1.4).

Table 1.4 The categories of green infrastructure (Nature England, 2009.P. 7)

Parks and Gardens	urban parks, Country and Regional Parks, formal gardens
Amenity Greenspace	informal recreation spaces, housing green spaces, domestic gardens, village greens, urban commons, other incidental

	spaces, green roofs
Natural and semi-natural urban greenspaces	woodland and scrub, grassland (e.g. downland and meadow), heath or moor, wetlands, open and running water, wastelands and disturbed ground), bare rock habitats (e.g. cliffs and quarries)
Green corridors	rivers and canals including their banks, road and rail corridors, cycling routes, pedestrian paths, and rights of way
Other	allotments, community gardens, city farms, cemeteries and churchyards

In addition, the landscape institute of the UK also considers the different assets of green infrastructure at different scales, from a single factor to wider ranges (Table 1.5). Because the functionality and effectiveness of green infrastructure may also vary by scale, such as some profits will appear regionally; while others may locally (Shi, 2013). As such, the debate on the different benefits and values of green infrastructure requires planners to have a clear understanding of the components and scales of green infrastructure.

Table 1.5 Typical assets of green infrastructure and its associated scales (landscape institute, 2009, P. 6)

Local, neighborhood and village scale	**Town, city and district scale**	**City-region, regional and national scale**
Street trees, verges and hedges	Business settings	Regional parks
Green roofs and walls	City/district parks	Rivers and floodplains
Pocket parks	Urban canals	Shoreline
Private gardens	Urban commons	Strategic and long-distance trails
Urban plazas	Forest parks	Forests, woodlands and community forests

Town and village greens and commons	Country parks	Reservoirs
Local rights of way	Continuous waterfront	Road and railway networks
Pedestrian and cycle routes	Municipal plazas	Designated greenbelt and Strategic Gaps
Cemeteries, burial grounds and churchyards	Lakes	Agricultural land
Institutional open spaces	Major recreational spaces	National Parks
Ponds and streams	Rivers and floodplains	National, regional or local landscape designations (e.g. AONBs, NSAs and AGLVs) Canals
Small woodlands	Brownfield land	Common lands
Play areas	Community woodlands	Open countryside
Local nature reserves	(Former) mineral extraction sites	
School grounds	Agricultural land	
Sports pitches	Landfill	
Swales, ditches		
Allotments		
Vacant and derelict land		

1.4.5 The mechanism between green infrastructure and building energy demand

Microclimate and thermal comfort are the internal mechanisms behind the association between green infrastructure and building energy use (Figure 1.6). Microclimate has been accepted as an important element affecting building energy use. However, in the design process, scholars often ignore the parameter of urban microclimate when using computational models for predicting building energy performance (Mosteiro-Romero et al., 2020). As a passive cooling system, green infrastructure contributes greatly to building energy saving through microclimate modification and shading effects on the building envelope (Pérez et al., 2014).

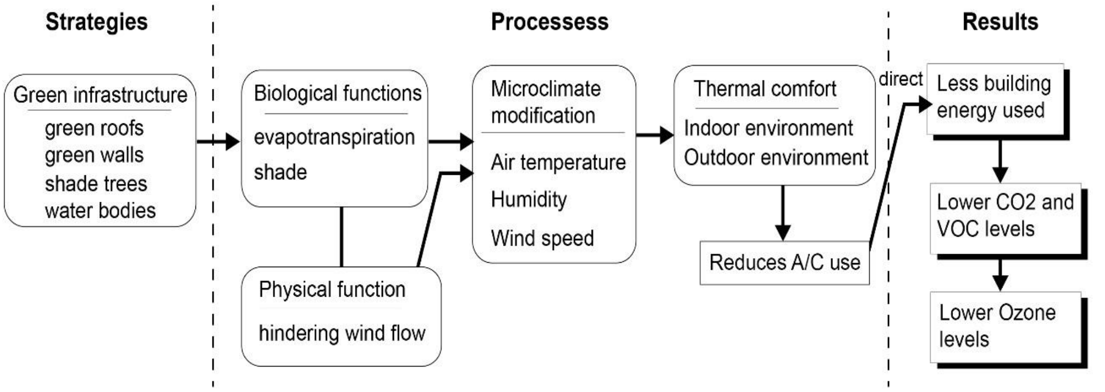


Figure 1.6 The mechanism between green infrastructure and low-carbon cities. (*redrawn based on the Akbari et al. 2001*)

Green roofs, vertical greenery systems and street trees are common types of green infrastructure and are often used to discuss building energy consumption. As stated by Koch et al. (2020), green roofs and vertical greenery systems have higher popularity than other types of urban green infrastructure, as they do not inhibit the natural ventilation of street canyons or occupy larger spaces. A significant number of scholars believe that the impact of the roof on building energy efficiency is more significant than any other building envelope component, as it usually receives more than 60% of heat transfer (Suman & Srivastava, 2009). According to Mohapatra et al. (2021), the roof covers more than 20% of the urban surface without any insulation, which results in the absorption of most solar radiation from the bare roof surface, causing indoor discomfort and increasing building energy consumption. However, the surface area of the building wall is larger than that of the rooftop. Therefore, many scholars stated that vertical greenery systems significantly impact the building environment (Pérez et al., 2014). Green roofs and vertical plants have different radiation and thermal properties compared to building materials. They also reduce the heat absorbed by the roof and the envelope through photosynthesis and transpiration. As explained by Akbari et al. (2001), buildings integrated with green roofs and vertical greenery systems are able to improve evaporative cooling, inhibit solar radiation, insulate heat gains, and stable interior temperatures. This is because the process of heat transfer to vegetated roofs or walls is significantly different compared with bared roofs and walls. Vegetations could absorb a great amount of solar radiation through their biological functions, causing the meteorological parameters (air temperature, humidity) reduction when they pass through the leaves. The rest of the solar radiation will change the thermal loads, reducing the impact on the internal climate (Kruche et al., 1982). As a result, in an enclosed space, the air temperature above the plants is significantly higher than that of air below (Niachou et al., 2001).

In the field of building energy use, microclimate phenomena are usually related to the parameters of wind speed, air temperature, solar radiation and humidity, which can seriously influence the heat perception of humans and thus affect the cooling and heating energy demand of buildings (Li et al., 2021). Among these parameters, "temperature" and "ventilation" are the two main study subjects. Many scholars believe that temperature has the most direct and significant relationship with thermal comfort compared with other parameters (Li et al., 2021). Because “comfort” is the fundamental principle of building energy-saving and consumption reduction. Thermal comfort refers to a person’s subjective perception of the indoor and outdoor temperature; that is, whether the person feels too cold or too hot. Many studies confirmed that temperature changes would directly increase building energy consumption, such as Szkordilisz & Kiss (2016); Alcazar et al. (2016). Besides, many scholars ascribed natural ventilation to “temperature,” which indirectly influences the building temperature by changing over time, affecting building energy consumption (Li et al., 2021). For instance, in high-density cities, nature ventilation brings a strong sense of indoor comfort, reducing the desire for cooling buildings (Sjöman & Johansson, 2020). Study by Anđelković et al. (2015) analyzed multi-story buildings with naturally ventilated double facades and showed that optimized nighttime natural ventilation systems and airflow can help reduce overall energy consumption by preventing overheating in summer. However, the cooling effectiveness of ventilation is significantly influenced by the thermal characteristics of buildings and climatic boundary conditions, such as wind direction and wind speed (Li et al., 2021).

In general, building energy demand will be affected by the superposition of multiple elements. It is necessary to comprehensively compare the influence of these meteorological parameters on building energy consumption to determine the impact on the overall energy consumption. At present, most studies believe that temperature is the major element affecting building energy consumption; followed by humidity and solar radiation. However, this claim is ambiguous and has not been unanimously recognized by the academic organization. For example, Li et al. (2021) revealed that building energy use is mainly affected by humidity and temperature in summer and winter, respectively. However, Liu et al. (2017) revealed that relative humidity has no impact on building energy consumption; however, it significantly affects the energy use of air conditioning. Meanwhile, regardless of the season, solar radiation is not the main parameter influencing building energy consumption. Research by Shen (2010) found that outdoor temperature is the main factor in building energy consumption; followed by solar radiation.

Overall, the mechanisms for how green infrastructure affects building energy consumption have been confirmed and recognized. There is no consensus on which meteorological parameters will have the greatest impact on building energy consumption.

1.5 Conclusion

This chapter describes the research background, aims, objectives, and related definitions and concepts. It attempted to set up a theoretical framework for this research topic from the urban planning and design perspective. In general, the development of NBS and urban regeneration is in its infancy and their definitions are still somewhat controversial.

Briefly, NBS could be considered an effective and sustainable way to achieve urban regeneration because its related approaches or actions could contribute to the development of low-carbon cities, especially the aspects of avoiding emissions, reducing emissions and carbon absorption.

Furthermore, this chapter has provided an overview of the principles, typologies and importance of green infrastructure. As an important component of NBS, green infrastructure is defined as an interconnected network of natural, semi-natural and artificial ecological systems from rural to urban, supplying a wide range of ecological, economic and social benefits. Moreover, it also contains three fundamental principles: the multi-functionality principle, spatial interconnection or integration principle, and dynamic spatial and temporal heterogeneity principle. In addition, the causality between green infrastructure and building energy use has also been explained, which makes a significant contribution to the further implementation of the study.

Chapter 2: Systematic Review of Restorative and Regenerative Urban Design

2.1 Introduction

As the further evolution of sustainable concept, publications on restorative and regenerative urban design first appeared in the mid-1990s, and both disciplines have developed rapidly up to the present time. However, due to the complexity of balancing multiple goals in the built environment, both research fields are multidisciplinary in nature, which leads to integrative research. Meanwhile, there is currently a tendency to confuse regenerative design methods with the design scope that emerged in the 1990s in pursuit of ecosystem sustainability. This confusion may arise because these two terms only roughly describe their respective characteristics and do not involve specific design parameters or indicators (Morseletto, 2020). As such, it is necessary to clarify the uncertainty between these two terms so as to provide significant foundation for the further in-depth exploration in this research. For instance, the interrelationships and differences between restorative and regenerative urban design, and their association with the United Nations Sustainable Development Goals. Most appropriately, this could be achieved by executing a systematic literature study focusing on these aspects in the current research field. According to Petticrew & Roberts, (2008), literature study as a means of collecting comprehensive evidence on specific questions provides an important source of evidence-based information to support and develop practice. As such, this stage involves a review of articles, books, and other resources, based on a series of review criteria. The study of professional literature helps researchers to understand the current condition in the research field and also helps to further determine the methodological framework for this research (Koc, 2018).

2.2 The methodology of systematic review

The description of the methodology of systematic review consists of two parts. The first is the approach of publication collection. The second part is the approaches to analyze the collected data.

- **Publication collection approach**

Restorative and regenerative urban design have attracted widespread attention from government sectors and urban designers for many years. In order to identify relevant publications, the study conducted a search via the Web of Science database using the time span of 1960 to 2021. There were no restrictions on document type, data category, document year and country, but inclusions were limited to English language. The following search terms were used to collect publications:

‘Restorative urban’ AND ‘design’
‘Regenerative urban’ AND ‘design’
‘Restorative urban’ AND ‘planning’
‘Regenerative urban’ AND ‘planning’
‘Restorative urban’ AND ‘study’
‘Regenerative urban’ AND ‘study’

The publications obtained using the above search terms in the Web of Science database were not all entirely within the scope of this study. As such, the obtained publications were first screened by interpreting the titles and abstracts. Then, the remaining publications were further refined by reviewing their content. Finally, the results of the search were downloaded in the form of a citation report, which contained key information about the publications, such as title, citations, abstract and authors, publication year, etc. To systematically and holistically analyze the relationship between the publications, the downloaded data was analyzed with the help of *VOSviewer* and *Rstudio*. Two functions from the software were used to generate bibliographical maps of the scientific realm: (1) extracted the number of annual scientific productions, document types and relevant sources; (2) extracted citation relationships between the publications.

- **The approaches of data analysis**

In order to achieve the purpose of this review, the study employed a comprehensive approach, including the scientific publication analysis, key performance indicators (KPI), detailed analysis, and citation network analysis.

(1) Scientific publication analysis

Scientific publication analysis was used to explore the historical development of these two disciplines. Based on the downloaded details of selected publications, such as publication year, source abbreviation and document type, a line chart was generated by *Rstudio* to visualize the annual scientific publications and to count the main document types and most relevant sources.

(2) Key Performance Indicators (KPI)

The KPI analysis was used as an initial qualitative assessment to confirm the relationship between restorative and regenerative urban design and the SDGs, and to identify differences between the two disciplines. The KPI analysis serves as a tool for assessing the actions corresponding to the goals previously established for the city (Boulanger, 2017). To collect the relevant KPIs, this study reviewed many publications that focused on assessing sustainability, urban restorative design, and urban regenerative design; such as, Toros, (2015); Zhang, (2015); Castanheira et al. (2013); Ülker et al. (2021); Global BRE, (2011); United 4 Smart Sustainable Cities, (2017); Hemphill et al. (2004); Tanguay et al. (2010); Balsas, (2004). The overlapping indicators from these publications were identified and employed in this analysis. In this study, the structure of KPIs have three dimensions, namely, dimensions, sub-dimensions, and indicators (Appendix A). In the dimension level, there are five indexes, including economy, environment, society, scale, and the SDGs. Each index has related sub-dimensions, except for SDGs.

During the process of analysis, the sub-dimensions of KPIs involved in each paper were marked and counted (see Appendix B). Then, the cumulative marks of each sub-dimension of KPIs were calculated and visualized in a diagram; for example, if the KPI marks in the productivity sub-category affiliated to the economic dimension were 10, this means that 10 articles mentioned the indicators in the sub-dimension of productivity. However, one publication may involve multiple sub-categories. Hence, these marks cannot match the total number of publications. This analysis helped to categorize and reorganize the collected publications. Therefore, the fields mentioned in the papers of restorative or regenerative urban design could be identified and the differences between them could be noted. Moreover, it also facilitated counting the number and types of SDGs mentioned in the downloaded data, which in turn allowed verification of the relationship between these two terms and SDGs.

(3) Detailed analysis

Detailed analysis aims to explore the emerging principles, methods, assessment tools, and current barriers to these two fields. Strictly speaking, the text mining and KPI analysis were insufficient for deeply exploring the current internal development status of restorative and regenerative urban design. As such, conducting detailed review was necessary. The data collection identified papers spanning from 1960 to 2021. While earlier studies undoubtedly stimulated the development of later urban restorative and regenerative studies, they could not shed light on the current hot topics, obstacles and new tools, or make predictions for future research trends. As such, the detailed analysis concentrated on the literature published within the last 6 years (after 2015). To systematically review these publications, this study divides the collected data on restorative and regenerative urban design into five themes: (1) documenting and describing the theoretical development of these two disciplines, as well as the emerging principles and methods; (2) determining how to support, monitor and evaluate them (mainly referring to assessment tools and approaches); (3) identifying cases of current practice; (4)

identifying barriers and enablers that need to be understood and addressed to make faster progress in implementing restoration and regeneration in the urban built environment; and (5) other themes. A table is generated to show each category of the themes and the papers involved. In addition, some research may use case studies to test their proposed theories or methods; therefore, one article may involve two themes.

(4) Citation network analysis

The citation network analysis was used to identify the interaction between urban restorative and urban regenerative design. The study investigated the citations of all publications with the help of *VOSviewer*. Specifically, the cited information of each collected publication was run in the *VOSviewer* to visualize the citation network in a diagram. Of special attention are papers that appeared in both restorative urban design and regenerative urban design, as they were the best candidates to understand the interaction between the fields. In addition, the study explored the reasons why these publications appeared in both disciplines.

2.3 The result of systematic review

2.3.1 Publication collection overview

A total of 1637 publications were initially identified by using the search terms described in Section 2.2. However, only 86 publications remained after eliminating a significant number of overlapping and irrelevant documents (e.g., landscape or medicine restoration, wetland and riverfront regeneration as well as mental health restoration, etc.). Meanwhile, 31 additional papers were found by searching the references of these 86 papers. However, since they are not included in the database of Web of Science, their details could not be downloaded. To generate the required diagrams, the detailed information of these 31 papers was manually inputted in the software. However, the software of *VOSviewer* was unable to recognize and read the manually added references cited by these 31 papers. As a result, these 31 articles feature in all the analyses except for the citation network analysis.

In short, a total of 117 documents were studied in this research, of which 37 publications related to urban restorative design and 80 related to urban regenerative design.

2.3.2 The result of scientific publication analysis

The annual publications from 1960 to 2021 are shown in Figure 2.1. Generally speaking, the number of publications on restorative and regenerative urban design has been increasing but fluctuating. The publications of urban regenerative design have increased much faster than those of urban restorative design, particularly in the last decade. During this time, publications in these two research fields accounted for 68% of total publications. The number of articles on urban regenerative design reached its highest level in 2012. This might relate to the 2012 Rio + 20 conference, which stimulated the establishment of the United Nations Environment Assembly and emphasized the need for a set of sustainable development goals. However, papers on restorative urban design started to decline after peaking in 2015. The first publications on regenerative and restorative urban design appeared in 1996 and 1998, respectively.

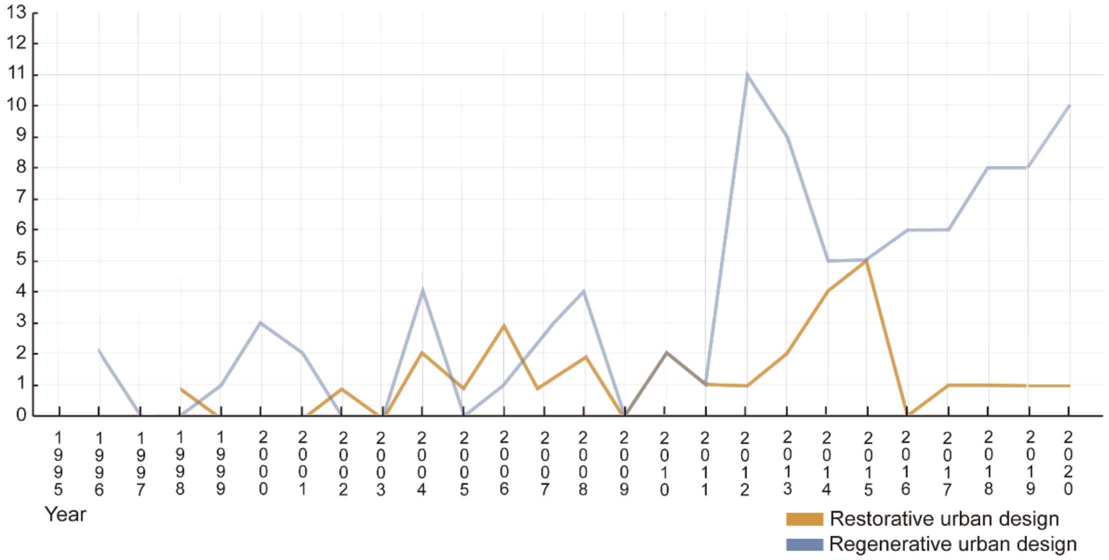


Figure 2.1 The annual scientific publications from 1960 to 2021 (*Author's plot*)

- **Document types**

ARTICLE	62
ARTICLE, BOOK CHAPTER	2
ARTICLE, PROCEEDING PAPER	3
BOOK	8
BOOK REVIEW	7
EDITORIAL MATERIAL	4
PROCEEDINGS PAPER	16
REVIEW, BOOK CHAPTER	8
DISSERTATION/THESIS	7

- **Most relevant sources**

(Sources)	(Articles)
1. SUSTAINABILITY	9
2. BUILDING RESEARCH AND INFORMATION	8
3. LANDSCAPE AND URBAN PLANNING	4
4. URBAN STUDIES	5
5. EUROPEAN PLANNING STUDIES	3

Figure 2.2 The document types and most relevant sources of publication on restorative and regenerative urban design (*Author's plot*).

Figure 2.2 shows the document types and the top five most relevant sources of publication. More than half of the publication types are articles. Proceedings papers rank second with 16 papers. The number of publications in the remaining document types is under 10. Articles in book chapters are the lowest number. In terms of the most relevant sources of publication, the dominant publication source is Sustainability with nine papers, followed by Building Research and Information with eight papers. Landscape and Urban Planning and Urban Studies have four and five publications, respectively. European Planning Studies rank last.

2.3.3 The KPI fields involved in restorative and regenerative urban design

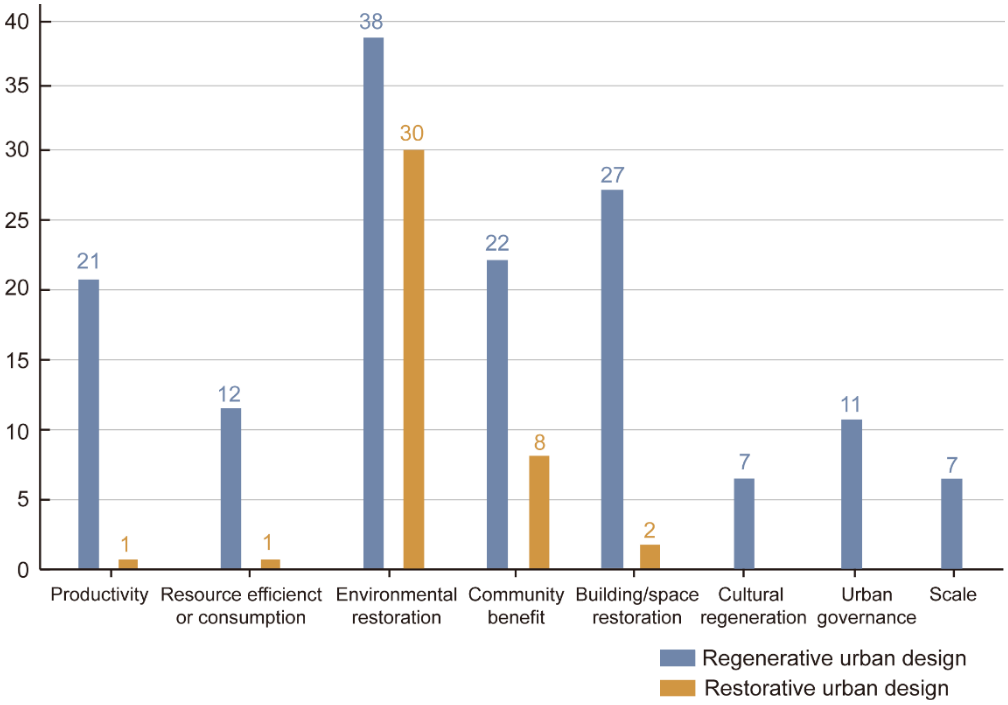


Figure 2.3 The marks of different sub-dimension of KPIs in restorative and regenerative urban design (*Author's plot*).

In Figure 2.3, there is an exceptionally clear difference in research fields between restorative and regenerative urban design. Regenerative urban design involves all the sub-dimensions of KPIs. In contrast, restorative urban design is mainly concentrated on environmental restoration and community benefit. In addition, the sub-category of environmental restoration was dominant in both research fields, and the indicator of enriching biodiversity was significantly emphasized. Apparently, addressing the existing environmental problems is the mutual objective of restorative and regenerative urban design. In the community benefit sub-category, restorative and regenerative urban design have 22 and 8 papers, respectively. In this sub-category, the indicator of mental and physical health attracted significant attention in both disciplines. Additionally, the indicators of housing and citizen participation were frequently mentioned in urban regenerative design studies. This indicates that the process of regenerative design requires active participation from the public and the community. Building or space restoration, and productivity were the prevalent research topics in urban regenerative design studies, especially relating to resource efficient building and employment improvement. On the contrary, only three publications on urban restorative design concentrated on these two sub-categories. Further, resource-efficient or consumption and urban governance correspond to 12 and 11 publications, respectively. Among them, the indicators of renewable energy supply and consumption, and policy guidance and support were frequently mentioned. Only seven publications involved both cultural regeneration and scale.

2.3.4 The SDGs involved in the KPIs of restorative and regenerative urban design

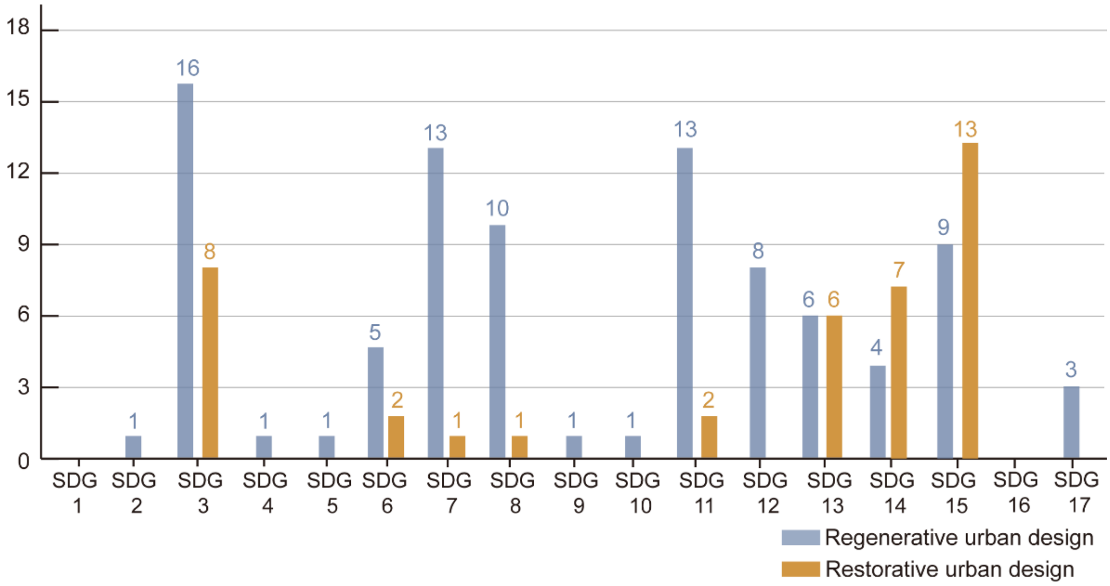


Figure 2.4 The KPIs of regenerative and restorative urban design involving SDGs (*Author's plot*).

Figure 2.4 and Table 2.1 show the SDGs involved in restorative and regenerative urban design as well as detailed description of SDGs, respectively. Eighty papers directly referenced or were related to the SDGs, representing 68% of the total number of publications, while restorative and regenerative urban design relate to 8 and 15 sustainable development goals, respectively. In terms of urban regenerative design, SDG3 was associated with the largest number of publications, compared with other SDGs. This might relate to the indicator of mental and physical health as it was frequently mentioned in the publications. SDG7 and SDG11 were both referenced by 13 articles. According to the explanations of the United Nations (Brown et al. 2018), SDG 11 contains several specific targets, such as providing affordable housing, protecting cultural and natural heritage, expanding public transport, improving air quality and waste management, etc. Therefore, it corresponds to more indicators of KPIs than the other SDGs. Providing decent work and economic growth (SDG 8) ranks third with ten papers. To some extent, the indicators in the productivity sub-category of KPIs made a significant contribution to SDG 8, such as the indictors of increasing the percentage of the GDP of the knowledge economy, and new capital investment. Notably, SDGs 2, 4, 5, 9, and 10 were only mentioned in one related paper. As for urban restorative design, only SDG 15 was referenced in more than 10 articles, while 7 papers mentioned SDG 14. The indicator of enriching biodiversity has a significant association with both SDGs 14 and 15. Moreover, SDG 3 and SDG 13 were mentioned by 8 and 6 articles, respectively. The high involvement of SDG 13 in the publications is related to its association with multiple indicators. The number of papers related to SDGs 6, 7, 8, 11 was less than two. In addition, for SDGs 3, 6, 7, 8, 11, 13, 14, and 15, there is overlap between restorative and regenerative design.

Table 2.1 The corresponding information of 17 SDGs

SDG 1 No Poverty	SDG 10 Reduced Inequalities
SDG 2 Zero hunger	SDG 11 Sustainable cities and communities
SDG 3 Good health and well-being	SDG 12 Responsible consumption and production
SDG 4 Quality education	SDG 13 Climate action
SDG 5 Gender equality	SDG 14 Life below water
SDG 6 Clean water and sanitation	SDG 15 Life on land
SDG 7 Affordable and clean energy	SDG 16 Peace, justice and strong institutions
SDG 8 Decent work and economic growth	SDG 17 Partnerships for the goals
SDG 9 Industry, innovation and infrastructure	

Overall, this analysis confirmed that restorative and regenerative urban design have a significant relationship with the SDGs, especially regenerative urban design. Restorative urban design is very limited in terms of addressing SDGs as it mainly focuses on four SDGs. Therefore, it is necessary for this discipline to take more comprehensive approaches and integrate sustainable thinking in order to add significant value to the field. In addition, both terms are closely associated with SDG 3 and SDG 15.

2.3.5 The result of detailed analysis

Fifty-two papers were published after 2015, of which only nine papers related to urban restorative design. Table 2.2 shows the themes included in each article.

Table 2.2 The type of themes and articles involved.

The Type of Themes	Related Papers
1. Describing the theoretical development or proposing principles and methods	Girardet, (2017); Brown et al. (2018); Ferreira, (2008); Van Timmeren (2012); Hemphill et al. (2004); Reed, (2007); Zhang, (2014); Cole, (2012); Choi, (2007); Cole, (2012); Steiner, (2014); Stouten, (2016); Yüksek, (2015); Thomson, (2006); Couch & Dennemann, (2000); Hubbard (1996)
2. Evaluating these two terms or providing new assessment tools and approaches	Toros, (2015); Guan et al. (2019); Axinte et al. (2019); Pedersen, (2012); Cole et al. (2012); Plaut et al. (2012); Cole, et al. (2013); Kamrowska-Zaluska & Obracht-Prondzyńska, (2018); Rovai et al. (2014); Balaban & Puppim, (2014)
3. Cases of current practice	Zuo et al. (2018); Guan et al. (2019); Cole et al. (2012); Choi, (2007); Weingaertner & Barber (2010); Gibbons et al. (2020); Cartlidge et al. (2021); Afacan, (2015); Chan et al. (2019); Alsubeh (2017); Ferguson, (2004); Thomson, (2006); Toros, (2011); Balaban & Puppim, (2014); Roberts & Sykes, (1999); Hubbard (1996); Syms, (2000); Palamar (2010); Yu et al. (2012)
4. Current barriers and enablers	Choi, (2004); Weingaertner & Barber, (2010); Boussaa, (2017); Tallon, (2010)
5. Others	Criado et al. (2018); Gibbons et al. (2020); Kennedy et al. (2012); Shi et al. (2020); Kennedy et al. (2012); MacGregor, (2010); Thwaites & Simkins, (2008); Douvlou & Ryder (2007); Dargan, (2009); Syms, (2000); Palamar (2010); Zari & Storey (2007); Yu et al. (2012)

As shown in Table 2.2, many articles describe the theoretical development of these two terms or propose some new research methods or conceptual theories. One study stated that urban regenerative design requires transforming traditional urban planning and design into sustainable practices and then into more regenerative ones, and additionally requires changes to the urban fabric at three scales including urban, neighborhood, and individual plots (Reed, 2007). Similarly, several researchers suggest incorporating ecosystem services analysis (ESA) into the process of urban regenerative design, avoiding the human-centric goals and useless design metaphors that are hard to quantify (Zhang, 2014; Cole, 2012; Ferreira, 2008). Other studies proposed a new decision support tool to aid urban regeneration (Pedersen Zari, 2012; Cole et al. 2012; Plaut et al. 2012). Several articles discussed urban regeneration in terms of social sustainability and institutions (Cole, 2012; Choi, 2007). Only three articles depicted the general characteristics of restorative and regenerative design, of which two were related to regenerative design (Hemphill et al. 2004; Steiner, 2014; Brown, 2018). Although these papers belong to the same theme, they are involved different research topics.

In terms of Theme 2, it can be divided into two categories based on the type of data: first, evaluating the output of restorative and regenerative design (e.g., health assessment); second, proposing new models or indicators to guide the process of restorative and regenerative urban design. As a result, five papers belong to the second type, of which four are related to urban regenerative design (Toros, 2015; Axinte, 2019; Pedersen Zari, 2012; Cole et al. 2013; Kamrowska-Zaluska & Obracht-Prondzyńska, 2018). The remaining articles are devoted to evaluating the results of restorative and regenerative design, such as resident satisfaction, health and cultural identity.

As for Theme 3, strictly speaking, it cannot be treated in isolation because most of the articles, to some extent, are related to the other themes. In other words, many scholars have used former urban design cases to reflect on the results in order to identify current barriers or propose new strategies, and sometimes to directly verify their theories or models through case studies at an appropriate scale. Furthermore, four papers discussed the current barriers and enablers. One of these articles proposed three strategies based on the current barriers to urban regeneration including public action, certification standards, and corporate responsibility (Choi, 2004). The rest of the papers mentioned the topics of gentrification, private and public collaboration, public attitudes and ecosystem health. In addition, many articles do not belong to the above four research themes. Their research themes are diverse, including rain gardens, industrial landscape restoration, urban greenery, etc.

Overall, the time span of data in this analysis is the last six years, but only a few studies have explored and described the concepts of these two terms in detail. Most studies aim to present new insights into urban regenerative design or explore the models and frameworks that support and evaluate these two approaches. Thus, it could be inferred that restorative and regenerative urban design have evolved from internal conceptual development to the stage of exploring external relationships and frameworks as well as mechanisms.

2.3.6 The result of citation network analysis

The citation network analysis was conducted on the 86 collected papers by using the *VOSviewer* software.

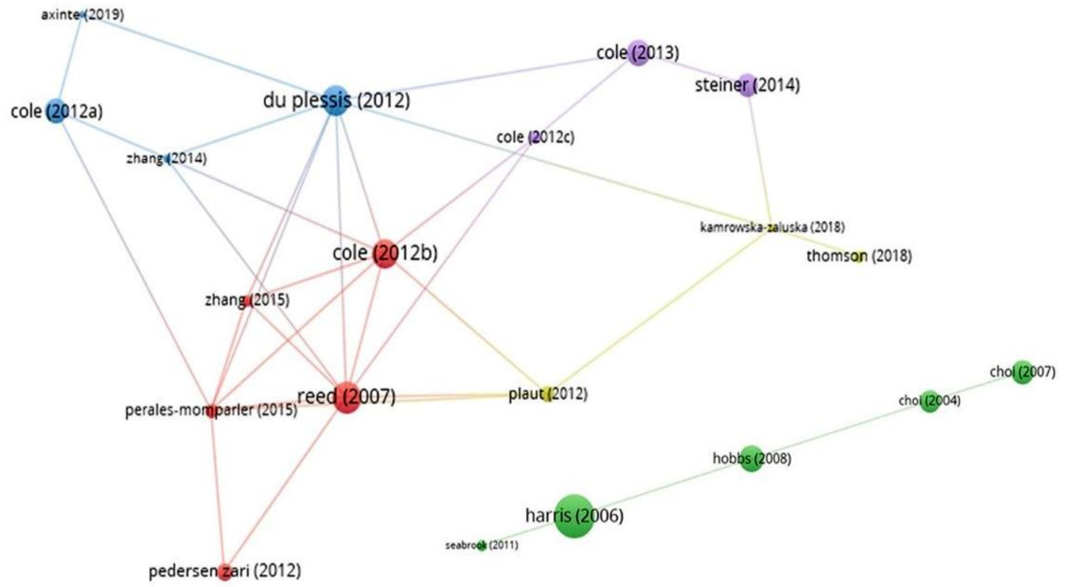


Figure 2.5 The citation network between restorative and regenerative urban design (*Author's plot*).

Figure 2.5 illustrates the citation network between restorative and regenerative urban design. Twenty citation relationships could be found, which means 66 papers were not cited by any other publications. Furthermore, these citation relationships were divided into two groups, with one group having 15 papers and the remaining 5 papers belonging to the other group. These groups of 15 papers and 5 papers will be referred to as Groups 1 and 2 in the following description.

Concerning the cited urban regenerative design publications, 14 citation relationships were identified, all of which were in Group 1. The citation relationships of urban restorative design were identified in six papers, mainly belonging to Group 2, except for one article. More importantly, there is no direct citation link between these two groups. This implies that the citation interrelationship between restorative and regenerative urban design was not present in Group 2. In terms of Group 1, with the exception of one paper, the rest of the citation interrelationships occurred after 2010, revealing that studies in urban regenerative design have developed significantly over the last decade. In contrast, all citation interrelationships of restorative urban design in Group 2 occurred before 2011, implying that the rapid development stage of restorative urban design theory began earlier than that of regenerative urban design.

2.4 Conclusion

The disciplines of restorative and regenerative urban design are in their infancy but are growing rapidly. There are still ambiguities in terms of the tangible differences and internal relationships. To clarify these uncertainties, Study employed a comprehensive approach, including KPI analysis, and citation relationship analysis. A total of 117 papers were studied with the help of VOS viewer and R studio, based on the Web of Science database. KPI analysis showed that there are significant differences between restorative and regenerative urban design; also, both disciplines are closely related to the SDGs, especially urban regenerative design. In addition, the citation analysis showed that there is no significant association between these two disciplines. In the Chapter 5.2, the study provides an in-depth discussion of restorative and regenerative urban design based on the results generated in this chapter.

Chapter 3: Climatic-Specific Review on NBS Typologies and Building Energy Needs

3.1 Introduction

As mentioned in Chapter 1, green infrastructure could affect the surrounding airflow and heat exchange by shading, reducing wind speed and evaporative cooling, then indirectly affecting building energy demand. However, different types of green infrastructure may have different cooling impacts on energy demand in different conditions, such as climate zones, building properties and characteristics; etc. (Morakinyo et al., 2017). Moreover, different research methods may also lead to different research outcomes. Hence, conducting a review of this research field is necessary.

3.2 The methodology of this review

Unlike typical critical reviews, this review integrates much of the literature by systematically extracting specific data from representative studies over a given period. The approach incorporates information into a single study for quantitative and qualitative analysis. This approach also has been used in similar studies, such as Pickering & Byrne (2014); Koc (2018).

There are fifth phases in this climatic-specific review. In the first stage, some specific review questions were defined based on the research objectives and the aim of this chapter. These questions help to determine the data to be extracted from the collected articles and facilitate the establishment of the screening criteria. The main research questions raised in this review were:

- What is the geographical distribution of the collected publications, or which countries are more actively studied in this research field?
- Which NBS categories received the most attention?
- Which geographical locations or climate zones are more actively studied in the publications?
- What are the main research methods or tools used in the studies?
- How much cooling and heating energy could be reduced by applying different types of

NBS in different climate zones?

The second phase establishes the quality selection criteria based on the above questions. As one of the important criteria, the classification of the NBS category is based on the research of Langergraber et al. (2021). That study categorized the NBS into several units, in which the spatial and technological units are significantly relevant to the types of NBS on building scales, such as green belts, street trees, urban parks, gardens, urban meadows and green corridors. Thus, the specific research criteria are as follows:

- Publications must be peer-reviewed and published in English (to some extent, using only English research may cause bias in interpreting outcomes).
- Studies should evaluate any of the following types of NBS: (1) water body; (2) street trees or tree canopy; (3) green roofs; (4) vertical greenery systems and green facades; (5) gardens; (6) green belt; (7) park.
- Publications without the specific geographic location or climate zone for assessment or comparative experiments were excluded (this is important for examining the energy performance of NBS in different climate zones).
- The research theme of studies should closely relate to building energy consumption.

The third phase was used to collect literature. Study collected relevant data through the Web of Science and Scopus databases using the combined search terms. There is a restriction on the time of the literature collection. This could be explained for two reasons. First, studies on NBS and energy demand have been conducted for many years, and the results have been extensively documented in the literature. However, it is necessary to ensure the data is relatively updated. Secondly, although the NBS term was proposed in the early 2000s, it was widely recognized and accepted by 2013. The earlier studies on the NBS could not be the data for this research as they mainly focus on agricultural fields, such as pest management (Somarakis et al., 2019). As such, the time of the literature collection was restricted to the last ten years, namely, from January 2013 to July 2022. Further, the combined search terms used for the initial search are arranged in Table 3.1

Table 3.1 The combined research terms for the literature collection

‘Nature-Based Solutions’	AND ‘building energy demand’
‘Green Infrastructure’	AND ‘building energy consumption’
‘Vertical Greenery System’	
‘Street Trees’	
‘Green Roofs’	
‘Gardens’	
‘Water Bodies’	
‘Urban Parks’	
‘Urban Farms’	
‘Urban Orchards’	

The next stage was used to assess, screen and select relevant articles. The publications obtained using the above search terms were not all entirely relevant to this research field. Thus, literature filtering was first used to exclude irrelevant publications in this research field by directly reviewing the title and abstract of each article. Then, the remaining papers were further screened by checking their text. After that, the selected publications were directly evaluated in the meta-analysis.

The final phase was employed to extract useful information and conduct qualitative and quantitative analysis through basic statistical methods.

3.3 The result of literature study

3.3.1 Overview of the collected literature

A total of 3188 publications were initially found by using the search terms described in the last Section. Study first carefully reviewed the abstracts of these publications and excluded a large number of overlapping and irrelevant publications, such as microclimate modification, heating ventilation and air conditioning (HVAC) systems and energy use, water supply and treatment, noise reduction, ecosystem services, UHI mitigation; etc.

Finally, only 101 publications were identified as eligible for this review. The annual publications from 2013 to 2022 is illustrated in Figure 3.1.

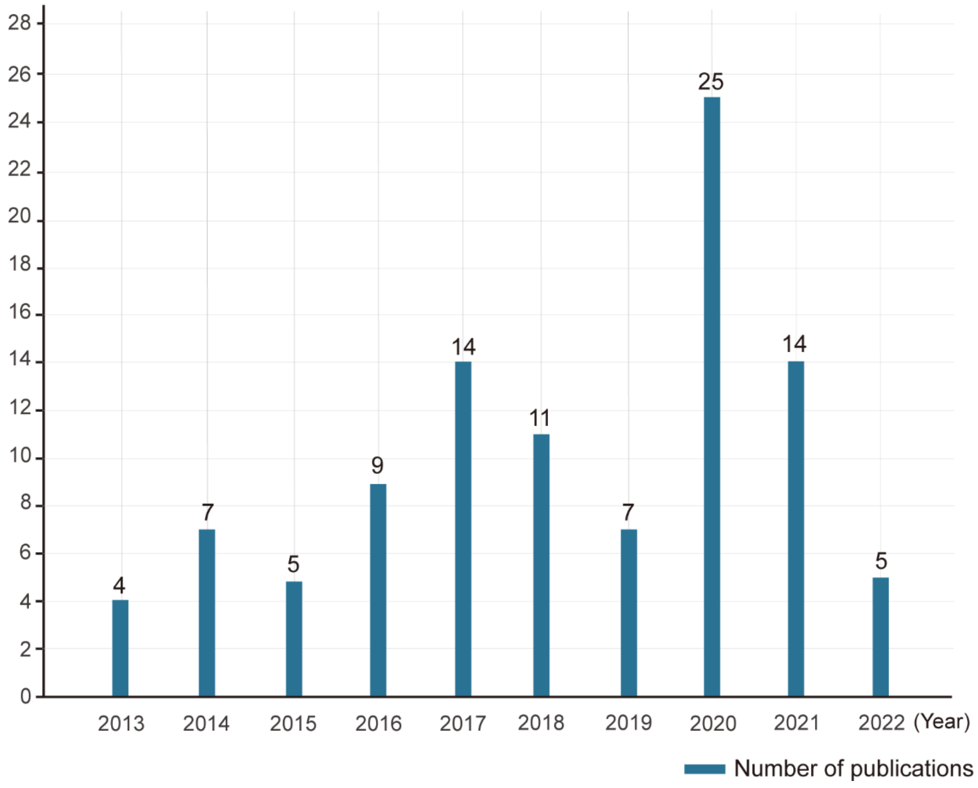
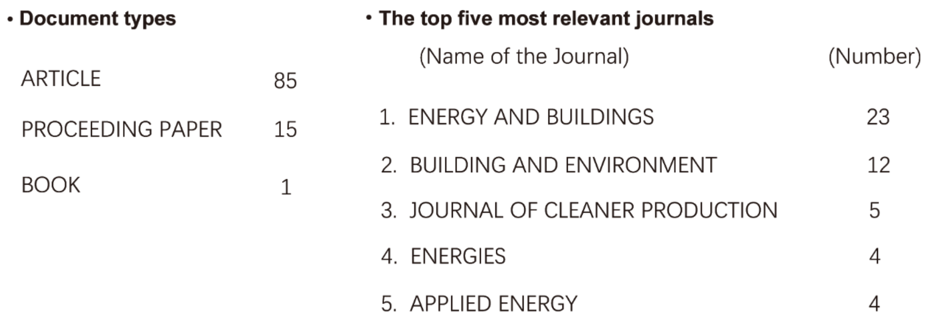


Figure 3.1 Annual publications from 2013 to 2022 (*Author's plot*)

In Figure 3.1, it is clear that the number of publications fluctuated from 2013 to 2022. The largest number of publications appeared in 2020, with 25 papers accounting for a quarter of the total number of publications. In addition, the number of publications published in 2017 and 2021 ranked second, with 14 papers. 11 papers were published in 2018. The number of publications in the rest of the years was less than 10.



- **Document types**

ARTICLE	85
PROCEEDING PAPER	15
BOOK	1

- **The top five most relevant journals**

(Name of the Journal)	(Number)
1. ENERGY AND BUILDINGS	23
2. BUILDING AND ENVIRONMENT	12
3. JOURNAL OF CLEANER PRODUCTION	5
4. ENERGIES	4
5. APPLIED ENERGY	4

Figure 3.2 Document types and the top five most relevant resources (*Author's plot*)

As shown in Figure 3.2, there are three document types among the collected publications, in which the majority of publications belong to article, accounting for 84% of the total number of publications. As for the top five most relevant journals of literature, the dominant source is Energy and Buildings, with 23 publications, followed by Building and Environment (12 papers). The rest of them are less than five publications.

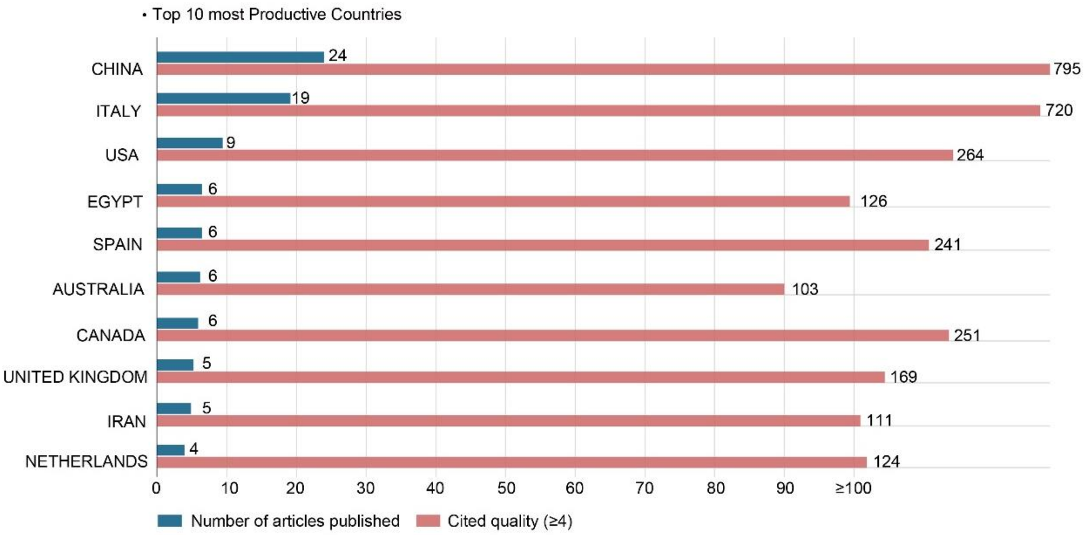


Figure 3.3 Top 10 most productive countries and total citation per country (*Author's plot*)

Figure 3.3 shows the top 10 most productive countries of publication and total citations per country. China had the largest number of papers in this research field, accounting for 24% of all related publications, followed by Italy with 19 papers (19%). The number of publications in the rest of the countries was less than 10. In addition, it is clear that although Canada published a few papers in this time period, the total citations are higher than in most countries.

3.3.2 Publication distributions on different types of NBS

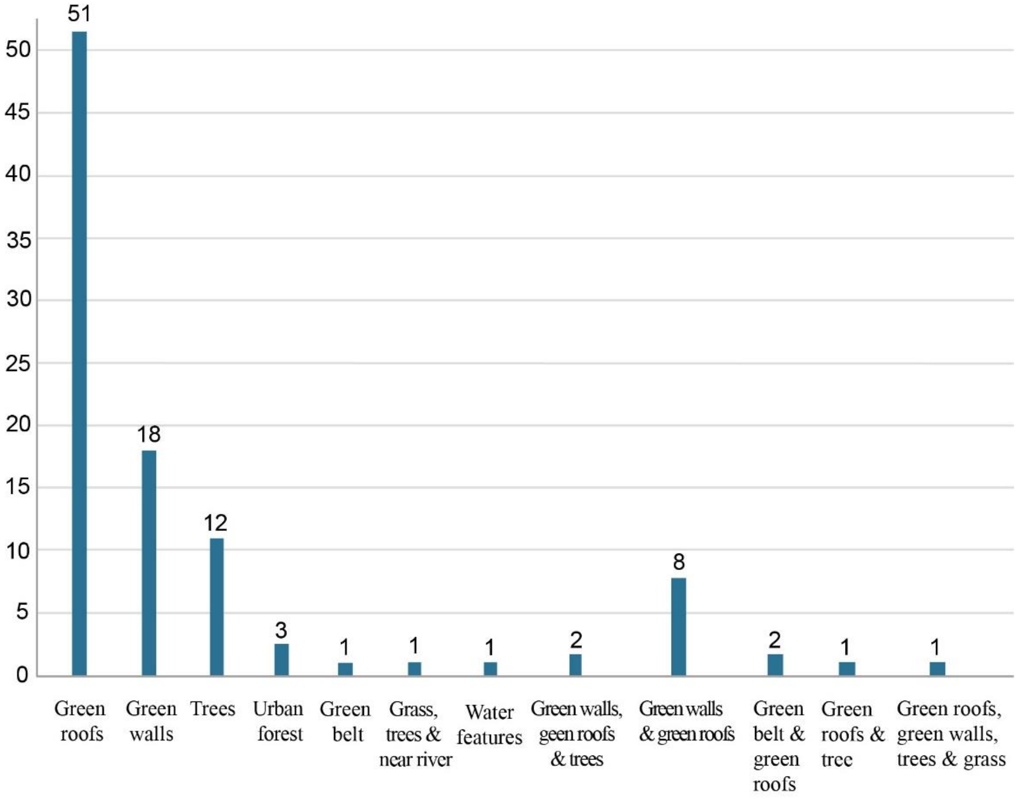


Figure 3.4 The number of publications in different types of green infrastructure and their combinations (*Author's plot*)

As shown in Figure 3.4, it is evident that there are two research types, including single-type analysis and different types of combination analysis. In the single-type analysis, green roofs had the largest number of publications, with 51 papers occupying 50.5% of the total number of publications. Green wall had 18 papers (17.8%), followed by the type of tree, with 12 articles (11.9%). Three papers have assessed the association between urban forests and building energy demand. Notably, the types of green belt, and grass, trees and near the river were only mentioned in one related paper. Regarding different types of combination analysis, the integration of green roofs and green walls had evaluated eight times. The mixture of green walls, green roofs, trees, and the combination of green belt and green roof have the same number of publications, with two papers. Each of the remaining two combination analyses had only one article.

In addition, study further classified green roofs, water features, and green walls into several specific types, as the majority of data was used the specific types in the related analysis, for example, assessing indirect green façades on energy use, and extensive green roofs on cooling energy saving. As such, green roof was divided into extensive green roof, semi-intensive green roof, and intensive green roof. Similarly, green wall was classified into indirect green façade, direct green façade, living wall, movable green window system, and perimeter flowerpots. Water features were classified into bioswale, lake, stream, wetland, river, and water fountain. The specific types in single-type analysis and combination analysis are shown in Figure 3.5 and Figure 3.6, respectively.

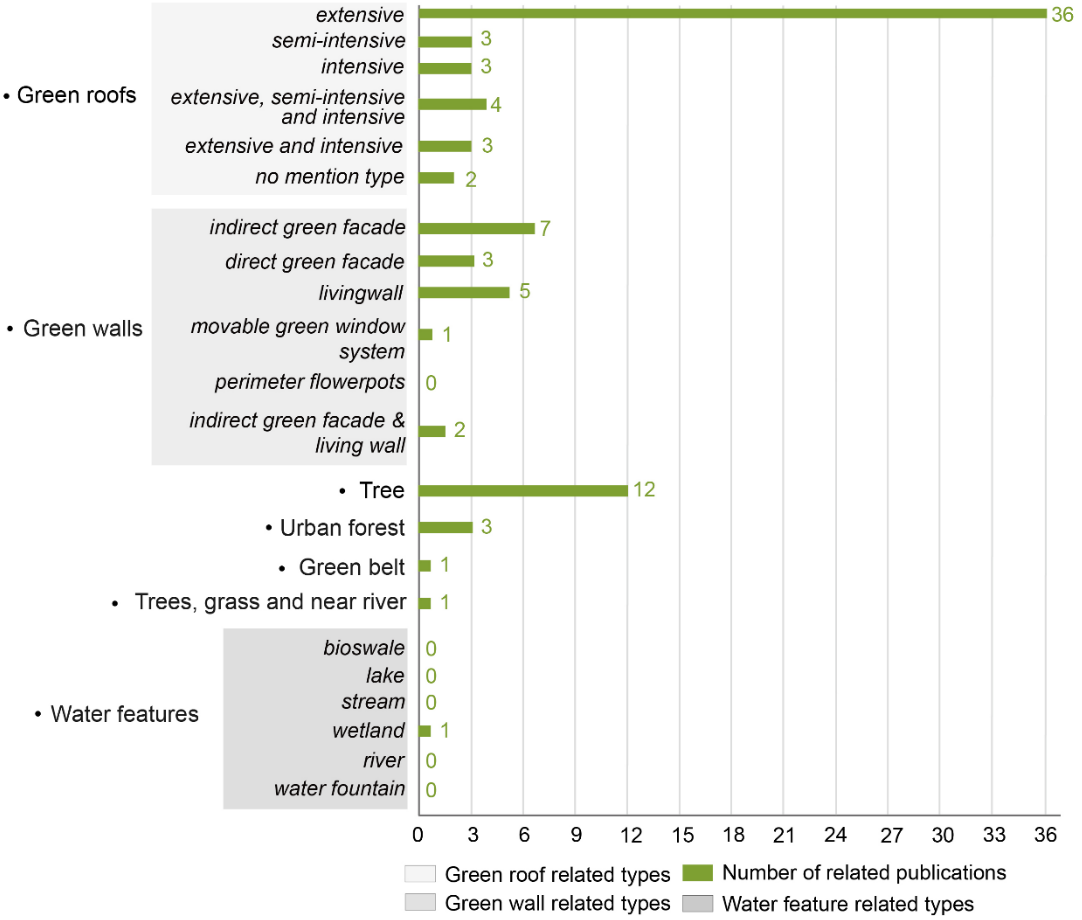
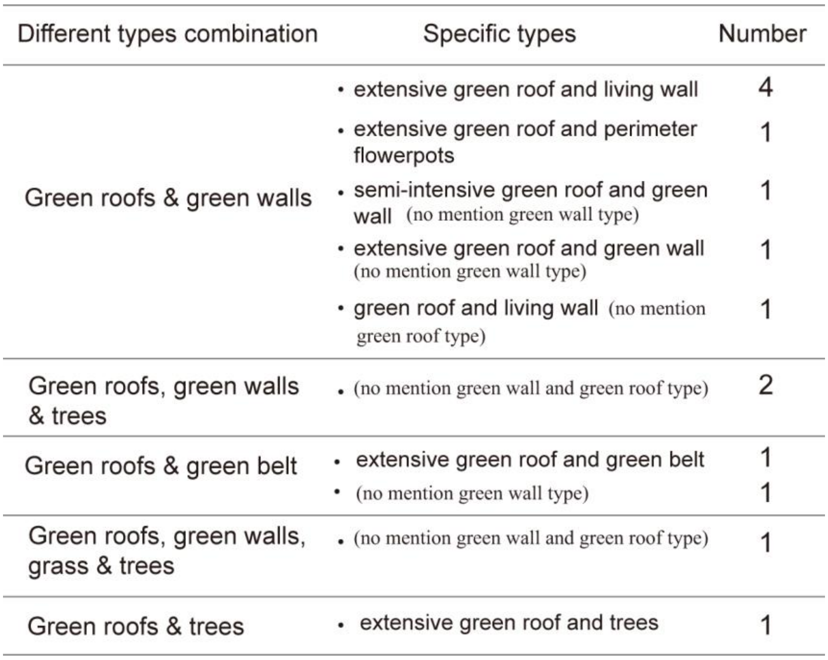


Figure 3.5 The number of publications on the specific types of green roofs and green walls (*Author's plot*)

Figure 3.5 clearly indicates that a significant portion (70.1%) of green roof publications focuses on extensive green roofs, likely due to their low structural support requirements, low maintenance needs, and comparatively lower investment costs (Cascone et al., 2019). Indirect green façade had seven publications, ranking first in the specific types of green walls; followed by living walls, with five papers. Notably, only one publication related to the specific types of water features.

In Figure 3.6, there are 14 publications belonging to the combined analysis. Extensive green roofs are involved in 8 studies. The types of perimeter flowerpots and semi-intensive green roofs only appeared once in the combined analysis. In addition, seven papers did not mention the specific types of green roofs or green walls.



Different types combination	Specific types	Number
Green roofs & green walls	• extensive green roof and living wall • extensive green roof and perimeter flowerpots • semi-intensive green roof and green wall (no mention green wall type) • extensive green roof and green wall (no mention green wall type) • green roof and living wall (no mention green roof type)	4 1 1 1 1
Green roofs, green walls & trees	• (no mention green wall and green roof type)	2
Green roofs & green belt	• extensive green roof and green belt • (no mention green wall type)	1 1
Green roofs, green walls, grass & trees	• (no mention green wall and green roof type)	1
Green roofs & trees	• extensive green roof and trees	1

Figure 3.6 The specific types of green roofs and green walls in the combination analysis (*Author's plot*)

Further, 40 studies out of these 101 publications involved the comparison analysis between different parameters, of which 17 papers associated with green roofs. Green walls and trees have 6 and 10 articles, respectively. In addition, five papers compared the different parameters on building energy demand in the different types of combination analysis. This study summarized these parameters in Table 3.2 based on the different types of NBS. In this review, the parameters analyzed in these publications were divided into four groups corresponding to

(1) morphological of vegetation (e.g., height, size, species); (2) structural factors; (3) spatial distribution; (4) others.

Table 3.2 The parameters involved in different types of NBS analysis.

Types	Parameters	Key parameters
Green roofs	morphological	- Leaf Area Index (LAI)
		- irrigation state
		- plant species
		- thermal mass
		- soil thickness
		- green coverage ratio
	structural	- insulation or non-insulation
		- drainage layers
	others	- weather state (sunny, cloudy, or rainy)
		- building types and height
Trees	spatial	- distance to buildings
		- planting orientation
		- number of trees
		- planting configuration
	morphological	- Leaf Area Density (LAD)
		- tree species
		- green coverage ratio
	others	- building orientation
Green walls	morphological	- LAI
		- plant species
	spatial	- plating orientation
	others	- building types
		- internal load

In Table 3.2, regarding the green roof, most evaluated parameters focused on vegetation morphology and green roof structure. For instance, several studies have demonstrated that the soil thickness of green roofs has a significant relationship with building energy use. They also revealed that the more substrate depth, the less building cooling energy consumption (Zhang et al., 2022; Berardi, 2016). Moreover, the irrigation state has also been deeply analyzed. Research by De Munck (2018) compared the cooling energy saving between irrigation and non-irrigation green roof and found that the irrigated green roof could save 8% more energy than those without irrigation. Similarly, Bevacqua et al. (2018) detected that a well-irrigated green roof could reduce cooling load by up to 60% in the Mediterranean climate. More importantly, it has been confirmed that different green roof species can also result in different cooling energy savings. The tall gramineous vegetation saves more cooling energy than short-sedum vegetation (Stamenković et al., 2018). The influence of building type parameters on green roofs is reflected in whether the building has an insulation layer. Studies have confirmed that applying green roofs in non-insulated buildings saves more energy than insulated buildings. Notably, no parameters were related to spatial distribution (Kokogiannakis et al., 2014; Bevilacqua et al., 2018). For the green walls, parameters of LAD, planting orientation, and vegetation species were most frequently involved in the comparison analysis. For instance, Poddar et al. (2017) conducted an analysis in South Korea. They found that the north-facing green wall is more efficient in heating energy saving, while the east-facing green wall could save more cooling energy than in other directions. In addition, in a warm temperate climate, the higher the LAI, the more cooling energy is saved during the summer (Perez et al., 2022).

Furthermore, although the study on the influence of trees on building energy consumption involves three parameter categories (spatial, morphological, and other factors), most researchers have focused on the spatial parameters, especially the planting orientation, and configuration. For example, trees plant 5 meters away from the building and in a row on the south, east and west can effectively reduce energy consumption, especially in the west (Palme et al., 2019). Under the same climate zone, Rouhollahi et al. (2022) compared the influence of trees planted 3 and 5 meters away from the building on energy demand. They detected that planting 3 meters can save 8% more energy consumption than that planted 5 meters.

3.3.3 Geographic distribution patterns of the studies

Figure 3.7 to 3.10 shows the geographic distribution pattern of the collected literature.

Figure 3.7 shows the number of study sites on six continents. There were 112 study sites, of which 43 were Asian cities, representing 38.4% of the total number of study cities. There were 31 (27.7%) and 26 (23.2%) study sites in Europe and North America, respectively. Few sites relate to Africa and Oceania, with 7 (6.3%) and 6 (5.4%) cities. In addition, a clear and heavy geographic bias could be found in the country-based analysis (Figure 3.8). China had 28 study sites, occupying 25%; followed by the USA with 15 study cities (13.4%). 11 study cities (9.8%) were in Italy.

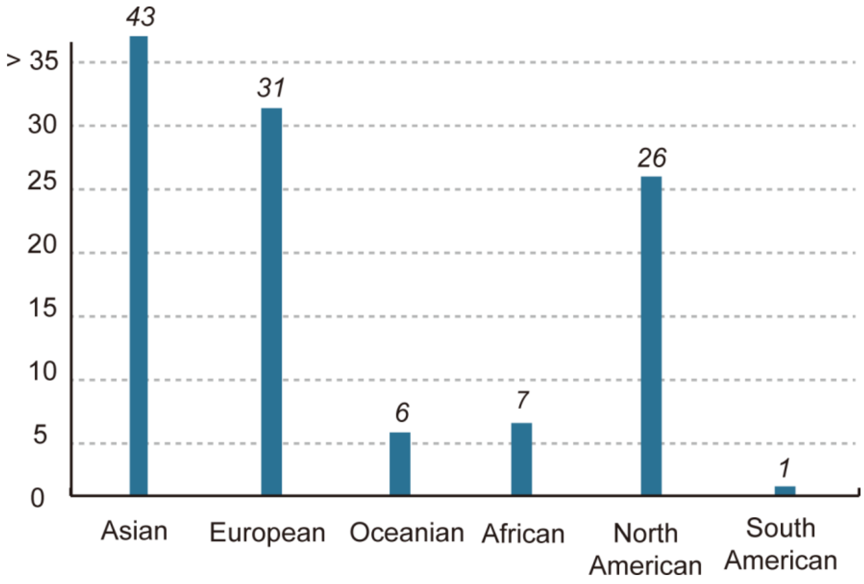


Figure 3.7 The number of study sites in six continents (*Author's plot*)

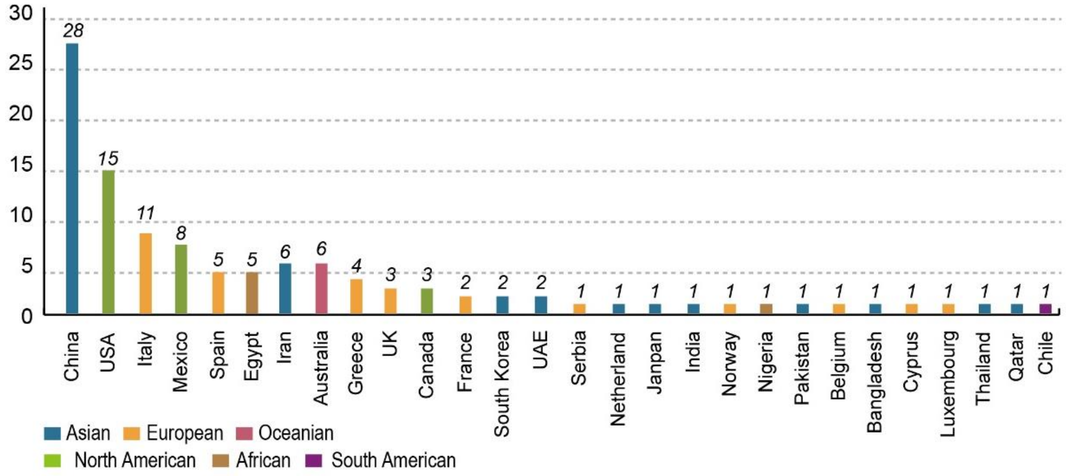


Figure 3.8 The number of study sites in the relevant countries (*Author's plot*)

As shown in Figure 3.9, the majority of studies correspond to the North Hemisphere; particularly along the Mediterranean Sea and the Asian Pacific coast. In terms of city-based analysis, it was obvious that the cities of Hongkong (6 times), Nanjing (5 times), Cairo (5 times), Catania (6 times), Rome (6 times) and Toronto (4 times) were the most investigated.

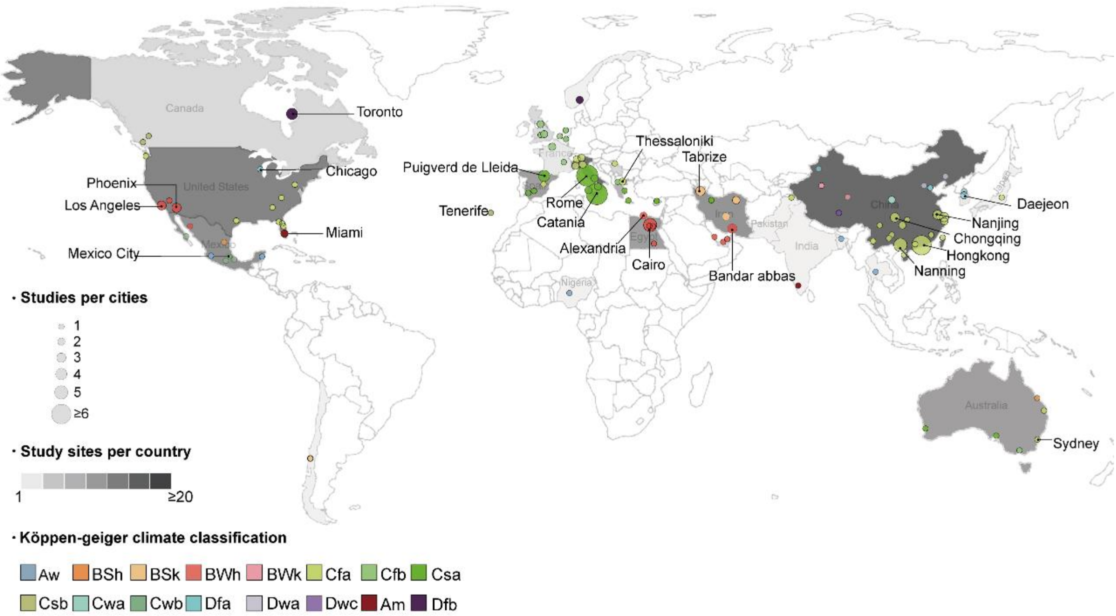


Figure 3.9 Geographic distributions of study sites (*Author's plot*)

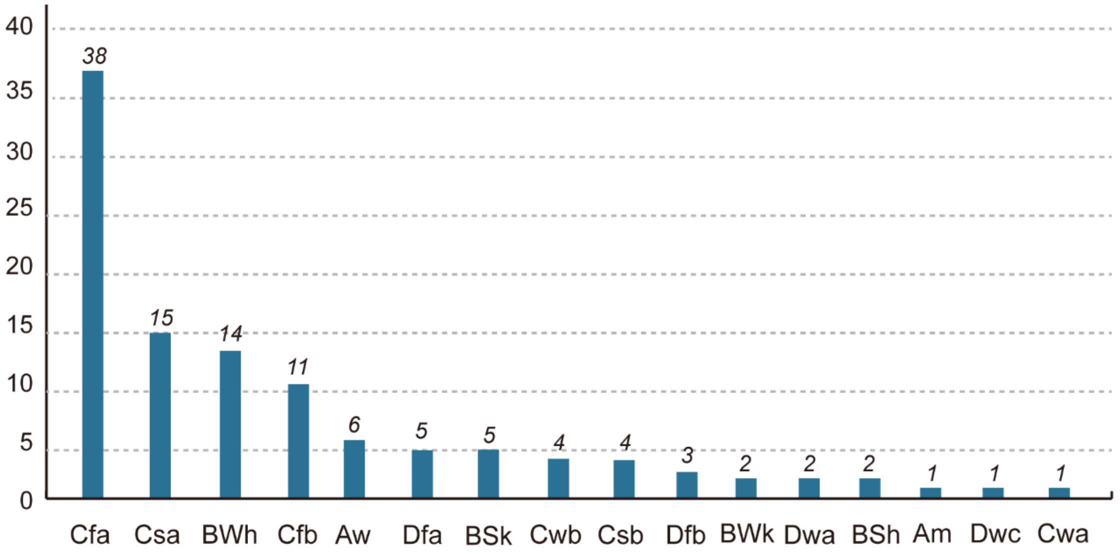


Figure 3.10 The number of publications in different climate zones based on the

KÖPPEN-GEIGER climate classification (*Author's plot*)

According to the KÖPPEN-GEIGER climate classification Figure 3.10, studies show a strong bias toward the climate zone Cfa (33.3%), which has the characteristic of warm temperate, fully humid and hot summer. Researchers also concentrated on the *hot summer Mediterranean climate* Csa (13.2%), *arid hot desert climate* BWh (12.3%) and *temperate oceanic climate* Cfb (9.6%). In addition, *warm humid tropical climate* Aw and *Hot Summer Continental Climate* Dfa occupied 5.2% and 4.4%, respectively. Very few researches focus on *tropical monsoon climate* Am*, temperate continental climate* Cwa and *cold semi-arid climate* Dwc.

3.3.4 Research methods and assessment tools

Three main research methodologies were identified in this review (Figure 3.11), including (1) empirical approach, (2) numerical modeling and simulation, (3) experiment and simulation. As shown in Figure 3.12, the method of numerical modeling and simulation was widely used in this research field, with 71 papers taking up 70.3% of the total number of publications. Eighteen papers employed the empirical approach. Twelve publications utilized the approach of integrating experiment and simulation.

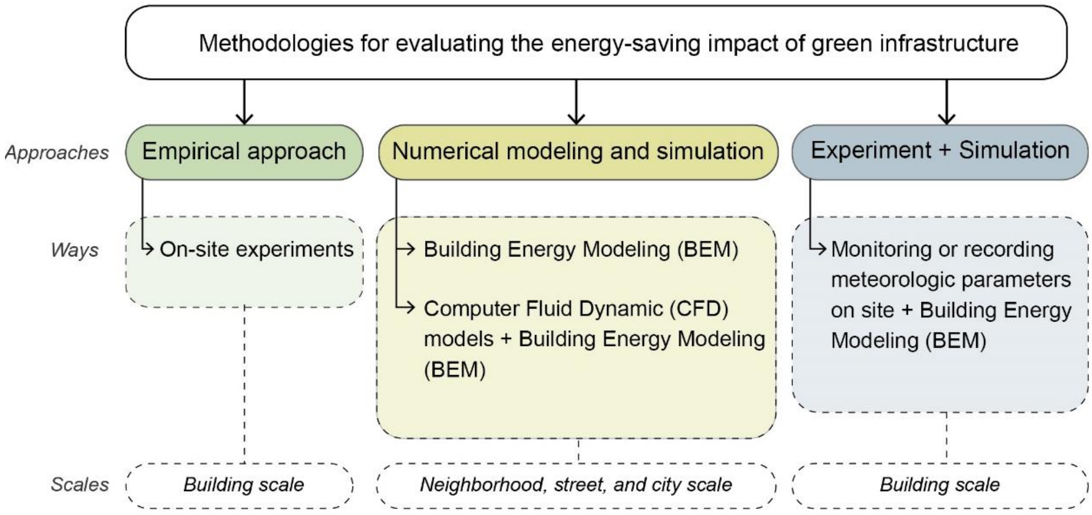


Figure 3.11 The methodologies for evaluating the energy-saving potential of NBS on buildings (*Author's plot*)

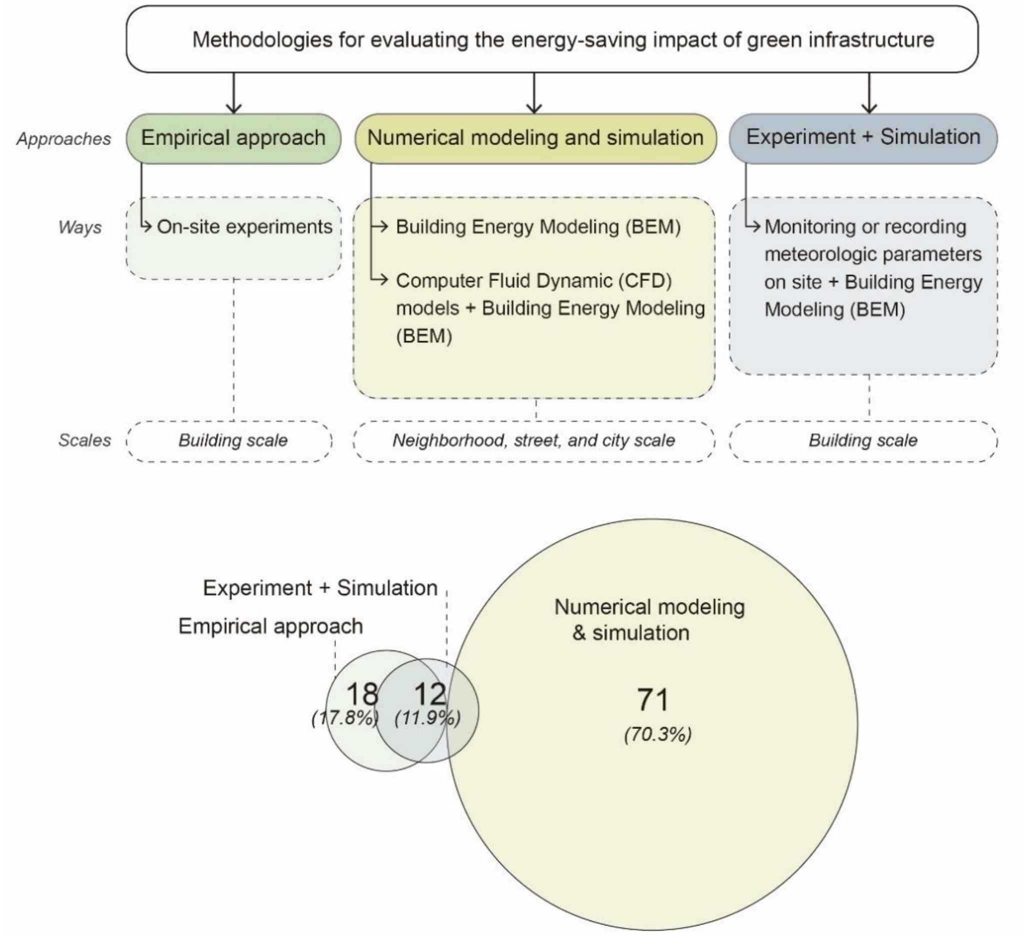


Figure 3.12 The number of publications involved in each research methodology (*Author's plot*)

In terms of numerical modeling and simulation approach, it contained two popular ways. First, 17 studies integrated Computer Fluid Dynamic *(CFD)* models with Building Energy Modeling *(BEM)*. In simple terms, scholars tended to use *CFD* to generate meteorological parameters (e.g., air temperature, humidity, wind speed; etc.) on typical days. Then, these parameters were used as an important input of *BEM* software to calculate the current and proposed scenarios' cooling and heating energy consumption. This method could decrease the errors in the simulation process as the meteorological parameters were generated based on the actual conditions around the site (Mosteiro-Romero et al., 2020). Alternatively, another method is to set different vegetation parameters directly in the *BEM* software and combine them with publicly available meteorological data to calculate energy consumption. This review found that

53 papers employed this method in their research, accounting for 75% of the total papers on numerical modeling and simulation. In contrast to the former method, this method allows the analysis of annual cooling and heating energy consumption. However, it relies heavily on public weather data, which could cause the simulation results in some areas with high building density or low vegetation coverage to not accurately reflect the actual energy demand of buildings, as this weather data is mostly collected by the rural weather stations or airports.

As for the experiment and simulation approach, to some extent, it is similar to the method of integration of *CFD* and *BEM*. In this approach, the local meteorological parameters were monitored and recorded by various environmental sensors. After that, they were employed in the *BEM* software for energy calculation.

The empirical approach refers to observing and recording the practical application of various types of NBS on the experimental scale for a certain period, for example, installing direct green façade and extensive green roofs on buildings or small cubes. During the experiment, the researchers need to regularly record the values on the sensors; then summarize and analyze them at the end of the experiment. The results generated by this method have high accuracy, but the experimental cost is high.

Regarding assessment tools, according to Koc (2018), the development on simulation tools have been developed rapidly in recent years, ranging from research-grade soft to commercial software. This review found that the tools used to assess building energy use are diverse. However, it is impossible to describe all the software involved. Thus, this review only focuses on several tools that are frequently employed in the studies.

One of the tools widely used in the investigations was *EnergyPlus*, involving 47 papers, occupying 46.5% of the total number of publications. It is developed and supported by the US Department of Energy. *EnergyPlus* is a program for simulating energy consumption and thermal load (US Department of Energy, 2020). In this tool, users could describe the building from the perspective of its physical composition, internal load, building use type, building age, local meteorological data, etc. Based on this, *EnergyPlus* will consider the entire secondary Heating, Ventilation, and Air Conditioning (HVAC) system and other simulation details to calculate the heating and cooling loads required to maintain the thermal control setpoint (US Department of Energy, 2020). Moreover, *EnergyPlus* uses text as input resulting in it can work with "Graphic User Interface," such as *Sketch-up* and *Design-Builder*, to provide a visual interface for the models of the building (Vadiee et al., 2018). However, this simulation tool cannot apply on a large scale because the simulation capacity is limited to a single building (Mosteiro-Romero et al., 2020).

Furthermore, some studies combined the *EnergyPlus* tool with climate analysis software. This is a coupling approach; namely, using the microclimate parameters generated by microclimate analysis software as the boundary conditions for building energy simulation. As explained by Aldhshan et al. (2021), the computational models used to support and understand building energy performance cannot ignore urban microclimate characteristics because the impact of microclimate on building energy consumption has been confirmed. In those publications, the software of *Envi_met* is widely employed to work with *EnergyPlus*. *Envi_met* is a three-dimension predictive model engaged in the microclimate simulation process based on Reynolds-Averaged Navier–Stokes equations used to address the heat transfer and fluid flow in the urban built environment (Pei et al., 2021). Compared with the large eddy simulation, *Envi_met* improves the accuracy of the model and enhances the efficiency of the computational fluid dynamics (*CFD*) model. It consists of four models, including atmosphere, buildings, vegetation and soil. This means that *Envi_met* could simulate the interactions between these four models, in which different models are responsible for calculating different heat fluxes. For example, plant models focus on calculating evaporation rates and heat flux exchange between vegetation and the atmosphere (Mosteiro-Romero et al., 2020). In addition, the heat, airflow, evaporation and transpiration procedures affected by the buildings, vegetation and surfaces could be simulated at a typical spatial resolution between 0.5m to 10m (Pei et al., 2021). Moreover, the typical simulation times for *Envi_met* range from 24 to 48 hours. As a result, it could export hourly values of various climate parameters in different formats; e.g., wind speed, humidity, mean radiant temperature, air temperature; etc. (Mosteiro-Romero et al., 2020).

Therefore, a significant number of studies have used the meteorological parameters generated by *Envi_met* as the local weather data for *EnergyPlus*. However, the weather data is only restricted to specific days, causing it impossible to analyze the annual energy consumption.

In addition, another relatively popular simulation software is *DesignBuilder*, which was used in 27 publications. The functions of this tool are quite similar to *EnergyPlus*, such as building energy modeling, detailed HVAC modeling, thermal comfort prediction; etc. This tool also only can be used for building scale assessments.

Besides, the software *IES-VE* also was used in many studies. This software was recognized as the world's leading three-dimensional building performance analysis software that supports the model and simulation of existing and proposed buildings of any size and complexity. IES-VE produces a detailed output of internal air and thermal conditions and large amounts of energy usage data by using weather data, macro and micro airflow, and shading inputs (Laparé, 2013). It also allows direct comparison of building models with different designs and properties. In addition, IES-VE allows the direct creation of building models and specifies the physical characteristics and properties of materials and mechanical systems, but buildings are often defined by simple lines. In other words, it simply subdivides and assembles all rooms to complete the building modeling by using basic information (e.g., the perimeter of the building) rather than allowing the creation of buildings based on the three-dimensional assembly of materials (Laparé, 2013). Moreover, this software does not provide specific models for setting different vegetation parameters (e.g., green roofs) as compared to *EnergyPlus.*

Overall, in this part, the study described three main research methodologies, containing empirical approach, numerical modeling and simulation, as well as experiment and simulation. In addition, although the collected articles used a variety of *BEM* tools, the tool of *EnergyPlus* was widely used in those publications as it enables annual energy consumption analysis and provides a special module to set the vegetation parameters.

3.3.5 Energy performance of different NBS types in different climate zones

This part explores how much energy could be reduced in different climates by applying different NBS types. Each collected publication usually describes a “percentage,”; namely, how much energy consumption, the sum of the heat fluxes, electricity intensity, or energy loads is reduced or increased. The changes above these parameters reflected the influence of different NBS categories on building energy performance. Besides, the experimental or simulation time and period are different in each study; for instance, most publications tended to assess the impact of tree on building energy performance based on the daily energy reduction analysis on a typical summer day. Instead, the annual energy consumption is often used by extensive green roofs. So that, this review differentiated the energy performance according to the experimental and simulation times used for each NBS type. The trees and green belts use daily cooling or heating energy demand. Urban forest uses monthly cooling or heating energy demand. The rest of the types utilized annual cooling or heating needs. Based on the above step, the saved or increased percentage of energy mentioned in each paper was collected (Appendix C). Then, they were categorized and integrated based on the different climate zone and NBS types (Figure 3.13 to 3.16). In addition, the study listed the description of each relevant climate zone for readers to better understand (Table 3.3).

Table 3.3 The description of characteristics of each related climate (The Köppen Climate Classification)

Code of each climate	Descriptions	Characteristics
Cfa	Humid subtropical climates	Hot summer
Csa	Hot-summer Mediterranean climate	Hot summer
BWh	Hot deserts climate	Hot throughout the year
Cfb	Temperate oceanic climate	Warm summer
Dfa	Humid continental climate	Hot summer
Aw	Tropical savanna	
Cwb	Subtropical highland climate	Warm summer
Csb	Warm-summer Mediterranean climate	
BSk	Cold semi-arid climate	Cold throughout the

		year
Dfb	Warm-summer humid continental climate	Warm summer
BWk	Cold desert climate	Cold throughout the year
Dwa	Monsoon-influenced hot-summer humid continental climate	Hot summer
BSh	Hot semi-arid climate	Hot throughout the year
Am	Tropical monsoon climate	
Dwc	Monsoon-influenced subarctic climate	Cold summer
Cwa	Monsoon-influenced humid subtropical climate	Hot summer

Figure 3.13 shows the energy performance of green roofs in different climate zones. Extensive green roofs show a positive impact on decreasing building cooling energy consumption in the majority of climate zones. Although they also have potential to increase cooling energy demand in three climate zones, the proportion is tiny, around 1%. The largest annual cooling saving appeared in subtropical highland climate (Cwb), up to 90%; followed by Cfa (humid subtropical climate), with a maximum reduction of 57.6%. The notable cooling energy reduction in the former climate far exceeds reductions in the other climate zones. In addition, extensive green roofs also performed a significant cooling energy reduction in the climate zones of Csa (50%) and Cfb (57%). In the hot desert climate (BWh) and tropic climate (Aw), extensive green roofs were associated with a reduction of 45% in cooling energy demand. These two climate zones are hot year-round, and buildings mainly need cooling energy. Extensive green roofs acting as an additional insulation layer have potential to reduce indoor and outdoor heat transfer and maintain indoor thermal comfort. In contrast, extensive green roofs were associated with 10% and 2.7% in cooling energy reduction in the Dfb and Dfa climate zones, respectively. In the climate zones of temperate oceanic climate (Cfb), extensive green roofs reduced 57.3% of cooling energy demand. As for heating energy consumption, it is obvious that extensive green roofs had an unsatisfactory performance in reducing heating energy saving. Five climate zones revealed that extensive green roofs had a negative impact on reducing heating energy consumption, especially in the arid (BWh) and semi-arid (BSh) climates. Extensive green roofs

could increase heating energy use by up to 25% in these two climate zones. This feature also appeared in the Cwb climate. In addition, the maximum reduction of heating energy use, up to 46.2%, occurred in climate zone Cfa. In contrast, it could only decrease heating energy demand by 0.56% in warm-summer Mediterranean climate (Csb). Extensive green roofs had similar heating energy-saving performance in the climate zones of Dfb and Dfa, around 6%.

In addition, several studies combined cooling and heating energy performance together to describe the impact of extensive green roofs on annual building energy demand. In the monsoon-influenced subarctic climate (Dwc), extensive green roofs may reduce annual energy use by 26.4%. Similarly, applying extensive green roofs in cold desert climate (BWk) also has a significant influence on annual energy savings of up to 18.1%. Moreover, it can decrease annual energy use by 6.4% and 5.1% in climate zones of monsoon-influenced humid subtropical climate (Cwa) and monsoon-influenced hot-summer humid continental climate (DWa), respectively.

Regarding semi-intensive green roofs, it is only involved in three climate zones. Semi-intensive green roofs have outstanding cooling and heating energy-saving performances in the Csa, Cfb and Cfa climate zones. The percentage of reduced cooling energy is all over 43%. In addition, it also can reduce 53% of heating energy needs in climate zone Cfa. The heating energy-saving performance in climate zones Csa and Cfb is quite similar (around 35%).

Furthermore, intensive green roofs have shown a significant impact on cooling and heating energy saving in climate zones of Cfa and Cfb. Notably, in climate zone Csa, it can decrease 81% of cooling energy demand; however, only 15% for heating energy reduction. In addition, 4.1% of cooling energy and 8.6% of heating energy can be saved by applying intensive green roofs in warm summer-humid continental climate (Dfb). Moreover, the cooling energy reduction is up to 37% in the tropical savanna climate (Aw).

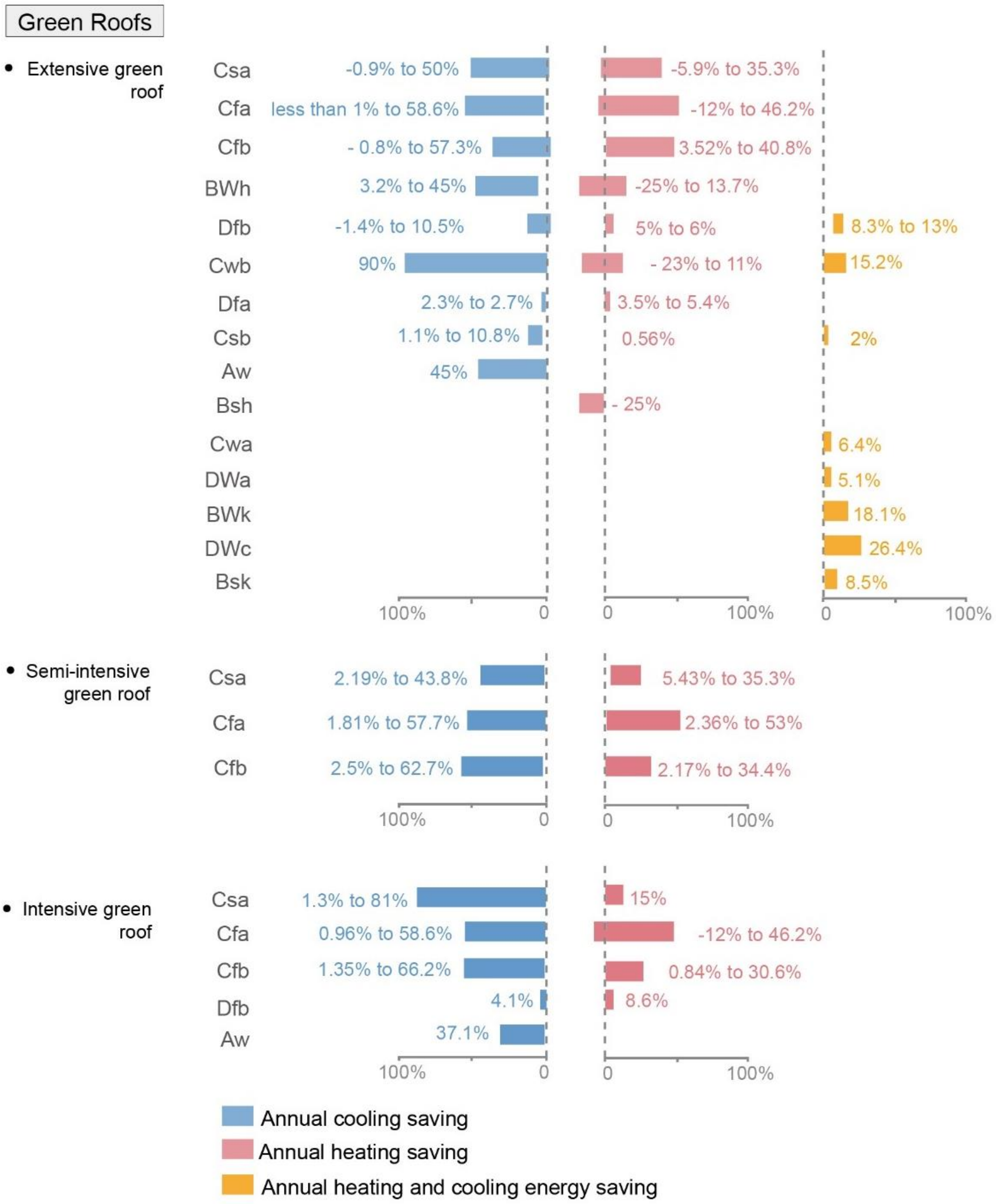


Figure 3.13 The energy performance of green roofs in different climate zones (*Author's plot*)

As shown in Figure 3.14, it is clear that green walls involve a limited number of climate zones compared to green roofs. Studies on direct green façades are only associated with temperate oceanic climate (Cfb) and were focused on heating energy consumption. They could reduce heating energy demand by 21% to 37% in that climate. Furthermore, in the climate zone hot-summer Mediterranean climate (Csa), indirect green façades and living walls showed similar cooling and heating energy-saving performance. They can save over 50% on cooling energy demand but also can increase heating energy demand by around 9%. In the climate zone Cfa, indirect green façades saved more cooling energy (76%) than living walls (3%). In the continental climate (Dfa), where heating energy is required much more than cooling energy, living walls reduce more heating energy demand (60%) than that cooling (17%). Further, in temperate climate zones of Cfb and Csb, living walls reduced cooling energy consumption by 26% and 7.3%, respectively.

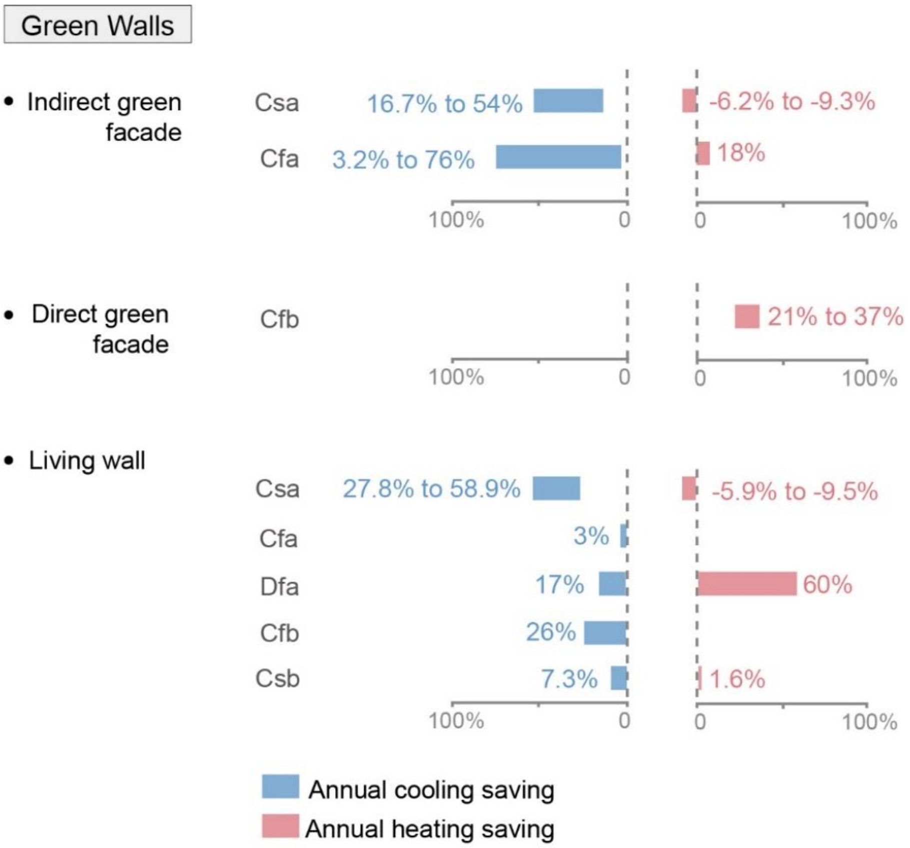


Figure 3.14 The energy performance of green walls in different climate zones (*Author's plot*)

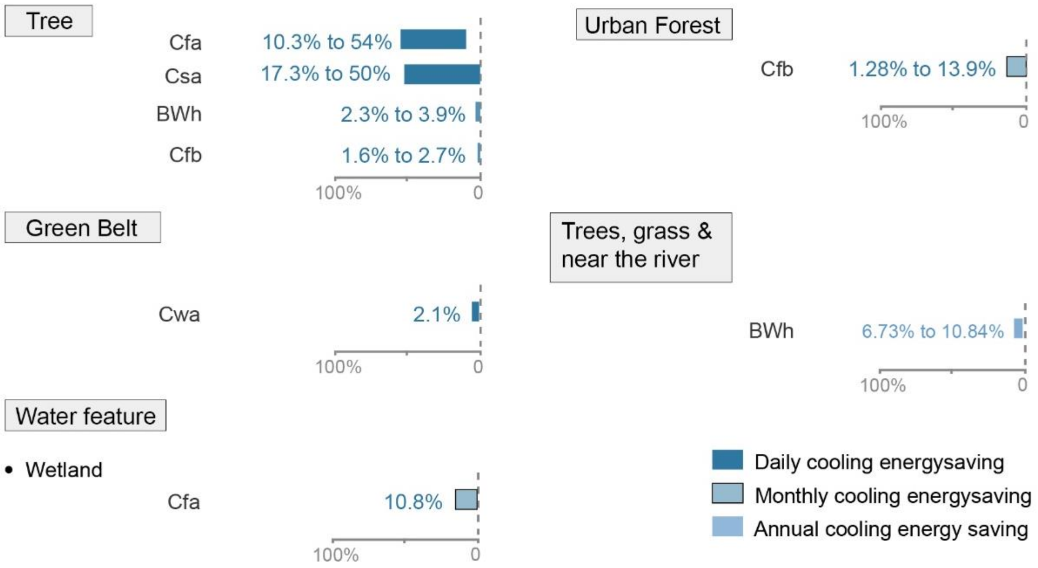


Figure 3.15 The energy performance of trees, urban forests, water features, green belts, and the mixture of trees, grass and near the river in different climate zones (*Author's plot*)

Figure 3.15 shows the energy performance of five NBS types on buildings in climate zones. Trees were involved in four climate zones, where they performed unimpressive energy savings in hot, arid desert climates (BWh) compared to humid subtropical climates (Cfa) and Mediterranean climate (Csa). The daily cooling energy savings in climate Cfa (54%) were 13 times more significant than in climate BWh (3.9%). In addition, buildings near a green belt can decrease daily cooling energy demand by 2.1% in the subtropical monsoon climate with hot summers (Cwa). Similarly, buildings near the urban forest had potential monthly cooling energy savings of up to 13.9%. Wetlands also can reduce 10.8% cooling energy demand in the climate zone Cfa. As for the type of the mixture of trees, grass and near the near, it decreased annual cooling energy consumption by 6.7 to 10.8% in the hot desert climate (BWh). Notably, the proportion of reduced cooling energy demand by river (8.12%) is more than that of the combination of trees and grass (4.78).

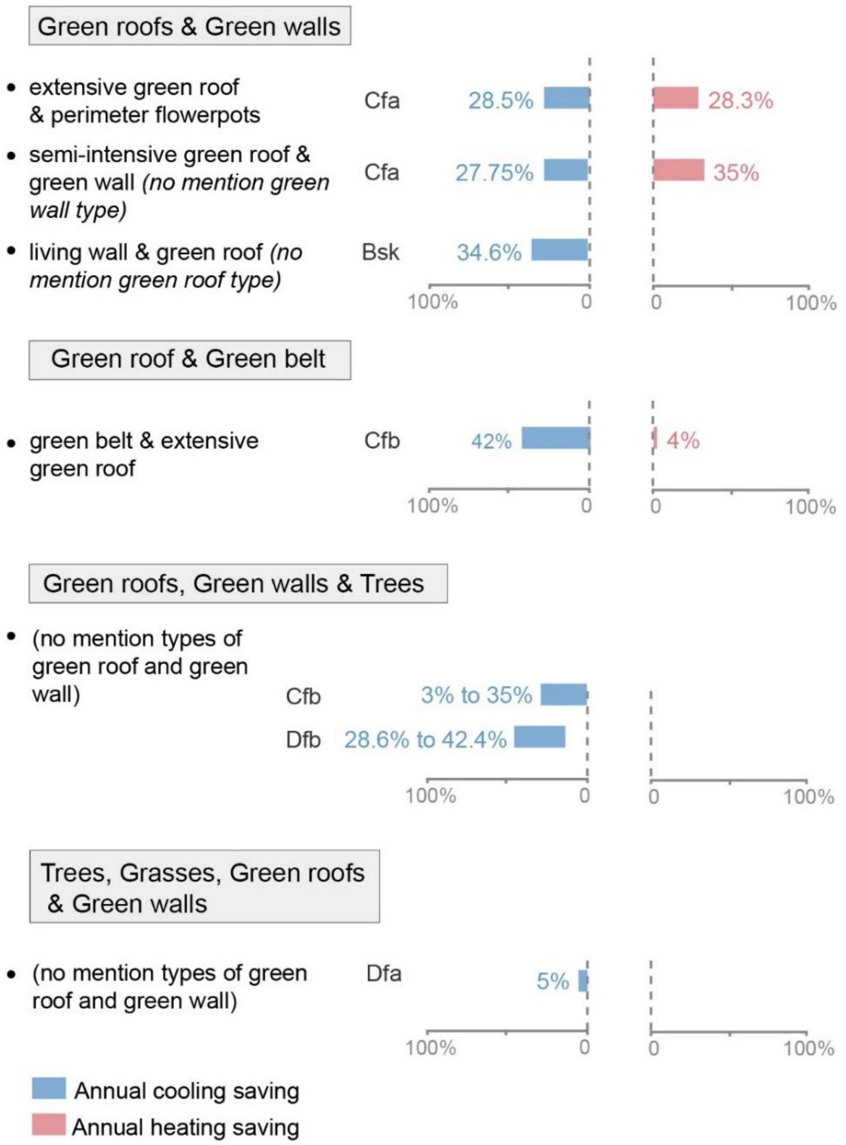
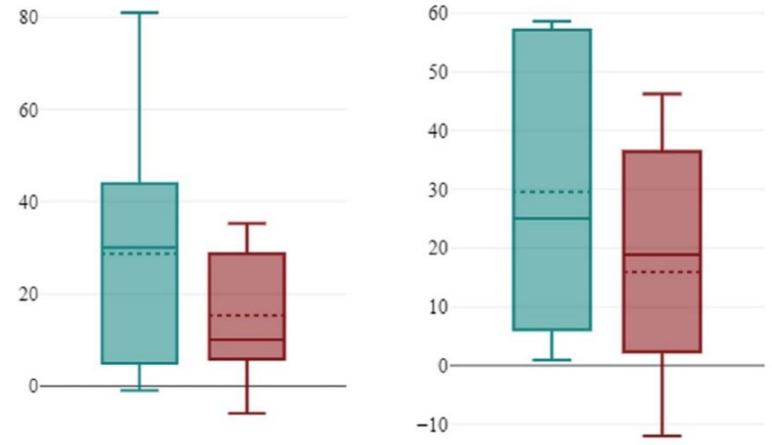


Figure 3.16 The combination of different green infrastructure types on building energy performance in climate zones (*Author's plot*)

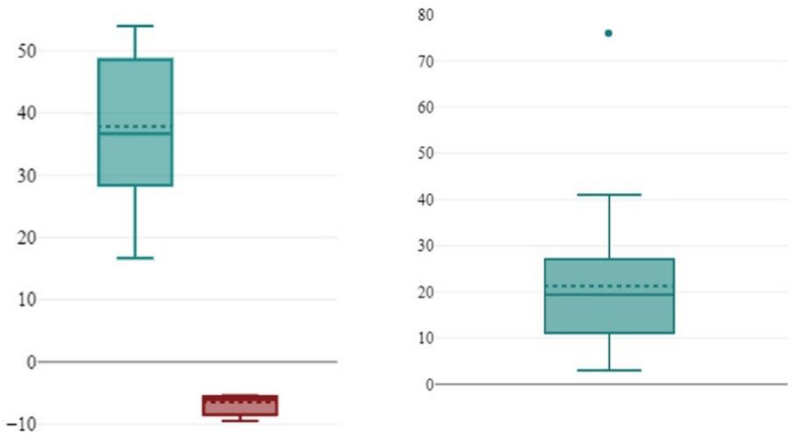
Figure 3.16 shows the energy performance of different NBS types combinations on building. It is evident that all the integrated analyses involved the types of green walls or green roofs. However, most analyses did not mention their related specific types. In the integration analysis of green roofs and green walls, most corresponding assessments were in the humid subtropical climate (Cfa). The integration analysis of extensive green roofs and perimeter flowerpots had a similar cooling reduction performance with the combination of semi-intensive green roofs and green walls of around 28%. However, the latter (35%) had better heating energy savings than the former (28%). Living wall combined with green roofs can reduce 34.6% cooling energy needs in the cold semi-arid climate (Bsk). Furthermore, in the temperate oceanic climate (Cfb), extensive green roofs combined with green belts can maximum decrease 42% cooling energy consumption. Green roofs integrated with green walls and trees had a significant impact on reducing cooling energy in climate zones of Cfb (3% to 35%) and Dfb (28% to 42%). Notably, the combination of trees, green walls, green roofs and grasses only can decrease 5% cooling energy consumption in continental climate (Dfa).

Although the above figures show the influence of the seven NBS categories evaluated on building cooling and heating energy demand in percentage, they only show the maximum and minimum values. To display the range of distribution of numerical values, boxplots were used in the study. Notably, the study is restricted to generating boxplots on green roofs and green walls in the climate zones of Cfa and Csa, as there is insufficient data available for other categories and climate zones. The corresponding boxplots are shown in Figure 3.17.

In Figure 3.17, the solid line and dashed line in the box of boxplots indicate the median and mean values, respectively. It is clear that the interquartile range (IQR) of cooling and heating energy reduction of green roofs in the climate zone Cfa is relatively broad compared with other types and climate zones. This indicates a wider spread of data within the middle 50% of the distribution. The median and mean values for reduced cooling energy of green roofs in climate zone Cfa are 25 and 29.29, respectively. Corresponding, 18.9 and 17.17 for median and mean values of heating energy reduction. As for green roofs in climate zone Csa, the IQR of cooling energy reduction ranges from 4.94 to 43.95. In contrast, the IQR of decreased heating energy ranges between 5.85 to 28.75. Notably, the IQR of heating energy reduction of green walls in the Csa climate zone is below zero, indicating a concentration of data towards to lower values. To some extent, this reveals that there is little impact of green walls on heating energy reduction in the climate zone Csa. In contrast, the IQR of reduced cooling energy ranges between 28.35 to 48.58. Notably, the mean (37.03) and median (36.7) values of reduced cooling energy of green walls in the Csa climate are high than that of green roofs. It could be inferred that green walls have better cooling energy saving performance than green roofs in this climate. Further, the study only generated a boxplot for the cooling energy performance of green walls in climate zone Cfa, as only two data were associated with heating energy performance. It is evident that the IQR is relatively narrow, ranging between 11.13 to 27.06. This tells a relatively small spread of data within the middle 50% of the distribution.



- Energy saving performance of green roofs in the climate zone Csa
- Energy saving performance of green roofs in the climate zone Cfa



- Energy saving performance of green walls in the climate zone Csa
- Energy saving performance of green walls in the climate zone Cfa

🟩 cooling energy reduction 🟥 heating energy reduction

Figure 3.17 The boxplots for green roofs and green walls in Csa and Cfa climate zones (*Author's plot*)

3.4 Conclusion

This chapter aims to describe the findings of the climatic-specific review.

101 publications were collected in the review based on the databases of the Web of Science and

Scopus. The study first provided an overview of the collected data, such as the annual scientific publications, main document types, the top five most relevant journals, and the most productive countries. After that, the study shows the number of publications involved in each NBS type. Then, the review analyzed the geographic patterns among the collected data. The review also explored the main research methodologies and technique tools. Finally, this review evaluated the influence of different NBS types on building energy demand in different climate zones.

The review found that study is this research field is evolving; however, have a feature of narrow focus. Specifically, the majority of studies focus on certain NBS types and climate zones, such as extensive green roofs and Mediterranean climate. In addition, most studies correspond to the North Hemisphere; particularly along the Mediterranean Sea and the Asian Pacific coast. There are three main research methodologies, including (1) empirical approach, (2) numerical modeling and simulation, and (3) experiment and simulation. Among them, the numerical modeling and simulation method is widely used in this research field. Last but not least, the seven NBS types evaluated all have a net positive impact on building cooling energy reduction. The proportion of cooling energy savings depends on the NBS types and climate zones. However, the results of heating energy consumption reduction are inconsistent. Specifically, green roofs and green walls have a high potential to increase building heating energy demand in the climate zones chartered by long hot summers and short mild winters or hot all year around.

Chapter 4. Building Energy Simulation

4.1 Introduction

This chapter concentrates on assessing the influence of some of the green infrastructure types on building energy demand with the help of energy simulation tools. It consists of three parts. The first part outlines the methodological approaches used in this research. After that, it dedicates to providing a detailed description of the method (methodological components). The last part is designated to illustrate the results of building energy simulations.

4.2 Methodological approach

As described in Chapter 1, the main aim of building energy simulation is to answer the question, "how high is the dependence of heating and cooling building energy demand on specific building types and climate zones." To achieve this aim, this study will compare the energy demand status of different building types under different climate conditions by applying different green infrastructure categories. This step has several purposes, including

1. verifying the impact of different green infrastructure categories on energy demand under the same building type in different climate zones;
2. assessing the energy efficiency performance of the same green infrastructure category on different building types in different climate zones;
3. evaluating the effect of energy-saving performance of different green infrastructure types on different building types in the same climate characteristics.

The comparative studies of different green infrastructure categories and building types, as well as different climate zones, can help to explore the actual impact of green infrastructure on building energy use and the potential prospects under different background conditions. As supported by Johansson (2003), comparative studies have the potential to strengthen the findings from different cases.

This study utilized three European cities, representing three different climate zones and urban characteristics, as important input parameters to compare and evaluate the actual performance of green infrastructure on building energy needs. In order to quantify the association, *BEM* was used in the process of this study.

BEM refers to the computer-based simulation software used in the design and thermal analysis of the buildings in the course of case studies (Ávila-Hernández et al., 2020). The basic information of the building is used as input to *BEM* programs, such as geometry, building materials, cooling, water heating; etc. Additionally, these inputs require to be combined with local weather information to calculate the building-related thermal loads, occupant comfort, and energy use through physical equations.

4.3 The method of building energy consumption simulation

4.3.1 Methodological components

Building energy consumption simulation contains two parts. First, finding the appropriate regions representing the different climate characteristics is vital for building energy performance analysis in this research. Second, conducting simulation, analysis, and evaluation of building energy consumption through multiple software combinations.

Regarding the first part, there are many ways to define climate zones. The Köppen-Geiger climate classification is the most popular worldwide climatic classification (Pernigotto & Gasparella, 2018). It categorizes the world climate into five main groups: tropical, dry, temperate, continental, and polar. Moreover, this classification further separated each group into two levels based on seasonal precipitations and seasonal temperature. Study by Pernigotto & Gasparella (2018) conducted a detailed exploration of the climate across European based on the Köppen-Geiger system. They divided the whole of Europe into eight major climatic zones. In that study, the hot summer Mediterranean climate and humid subtropical climate are mainly located in southern Europe, such as Italy and Greece. In central and western Europe, it is occupied by the temperate oceanic climate; such as the cities of Paris, London, Amsterdam; etc. Similarly, the warm-summer humid continental climate and subarctic climate are mainly distributed in northern Europe. The European climates and their specific descriptions are illustrated in Table 4.1.

Table 4.1 European climates and the typical cities based on the Köppen-Geiger climate classification

Climate	Descriptions	Typical cities

Csa	Hot-summer Mediterranean climate	Rome, Athens, Lisbon, Barcelona
Cfb	Temperate oceanic climate	Paris, Frankfurt, Amsterdam,
Dfb	Warm-summer humid continental climate	Oslo, Helsinki
Cfa	Humid subtropical climates	Bologna, Milan
Dsb	Warm, dry-summer continental climate	Ankara,
Dfa	Humid continental climate	Belgrade, Bucharest
Dfc	Subarctic climate	Kiruna, Ostersund
BSk	Cold semi-arid climate	Madrid, Teruel

Based on the above description, the study selected three cities in the south, middle, and north of Europe as the main simulation zones to quantify the building energy consumption performance of green infrastructure in different climate zones. The selected three comparative cities are Rome (Italy), Szombathely (Hungary) and Oslo (Norway). They respectively represent the widespread hot-summer Mediterranean climate, Temperate oceanic climate and warm-summer humid continental climate in Europe. The specific location of these three cities is shown in Figure 4.1.

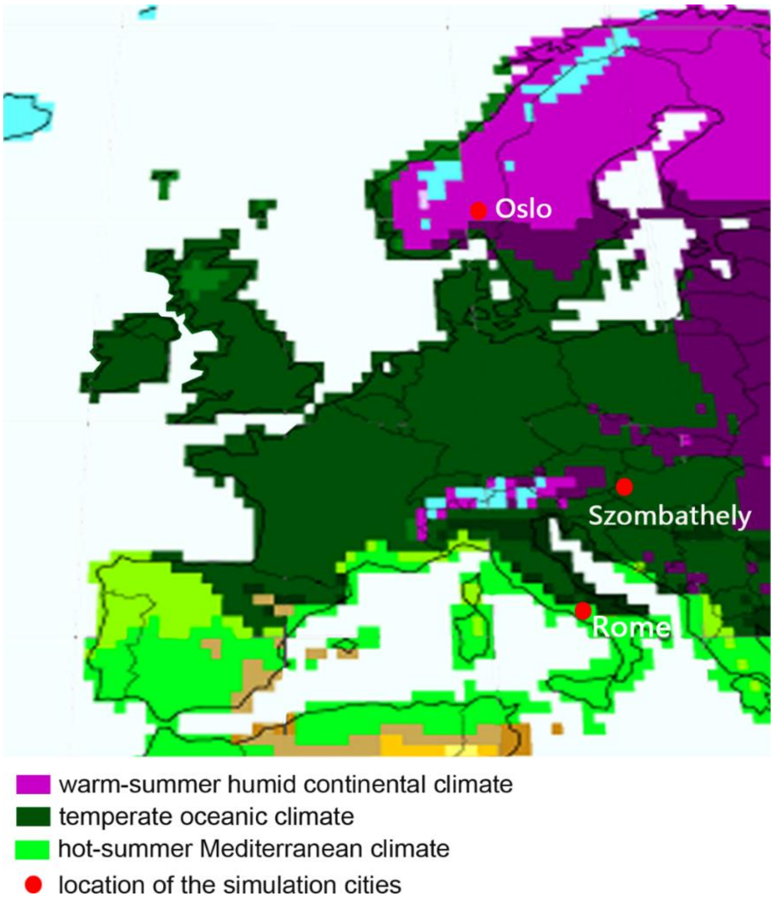


Figure 4.1 The location and climate zone of the comparative cities based on the Köppen-Geiger climate classification (*Redrawn based on Peel et al., 2007*)

Over the past few decades, many tools have been developed for building energy use simulations, such as *EnergyPlus and IES-VE*. According to the climate-specific review findings, the *EnergyPlus* and *IES-VE* software incorporate thermal physical properties into the program and can easily modify the building geometry and obtain the results in a short time (Ávila-Hernández et al., 2020). Although both two software can simulate building energy consumption, there are still significant differences between each other. In other words, each *BEM* tool has its advantage. For example, *IES-VE* provides a range of parameters for building materials (e.g., conductivity, thickness, specific heat capacity, resistance) and a module for solar shading performance analysis, which can determine the shading effect caused by the elements on or around the building (Skelhorn et al., 2016). However, it does not provide a specific module to analyze the impact of green elements (e.g., green roofs and vertical greenery systems) on building energy consumption. This leads to some key parameters, such as Leaf Area Index (LAI) or soil conditions, which cannot be input into *IES-VE*. On the contrary, the *BEM* tool of *EnergyPlus* allows inputting some physical characteristics of vegetation into the analysis process, such as height, LAI, reflectivity, and leaves emissions, resulting in more accurate results. Therefore, the tool of *EnergyPlus* was used in this study for building energy use analysis. Notably, weather data in the *EPW* format are currently widely used in architecture, landscape and urban planning disciplines. This weather data is open to the public and could be utilized in many *BEM* tools, such as *Grasshopper* and *EnergyPlus.* However, this data is collected based on rural weather stations or airports. To some extent, it cannot represent the actual weather characteristics of the urban area, as the UHI effect may affect the urban climate. Thus, it is important to obtain urban weather data.

Urban Weather Generator (UWG) is an efficient tool for estimating hourly urban canopy air temperature and humidity. This tool is based on weather data (*EPW* weather file) collected by rural meteorological stations. It can generate urban weather data by rewriting the used rural weather data through the input parameters of urban form, geometry, and surface materials. The generated urban weather data can be compatible with popular building energy simulation programs. In the study, this tool was utilized to generate the urban weather data for three cities. The building energy consumption simulation process is divided into three steps (Figure 4.2). The specific steps of the simulation are detailed in the following sections.

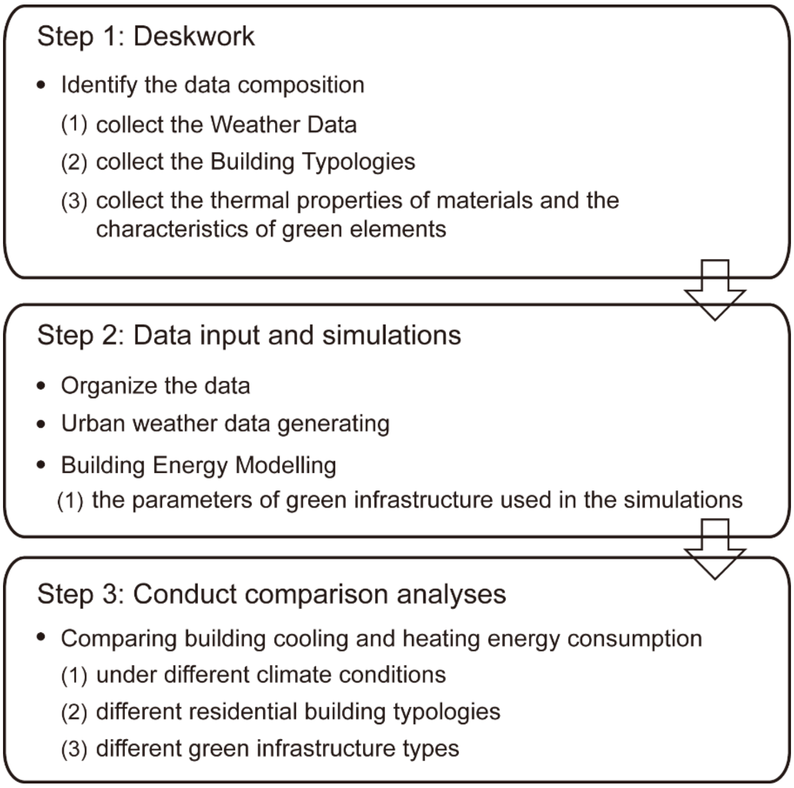


Figure 4.2 The simulation and evaluation method (*Author's plot*)

Step 1: Deskwork

- **Identify the data composition**

The core of deskwork is to consider what kind of data needs to be collected. In light of energy simulation aims and methods, the data to be collected mainly included the weather data, building typologies and materials' thermal properties, and green elements' characteristics. The former can be completed by downloading the weather data files of the study region from the specific website. As for building typology, each country and region have its architectural characteristics. As such, many organizations divide the building typologies according to the building characteristics of different regions. For example, the U.S. Department of Energy (DOE) divided commercial buildings into 16 types. In European, the Typology Approach for Building Stock Energy Assessment (TABULA) is one of the important components of the European Smart Energy Program (IEE). This program aims to establish a uniform structure for the "European building type" to evaluate the energy needs of the residential building stock at the national level. Therefore, that project divided the European residential building types by country, such as single-family houses, apartment houses, terraced houses, etc. Due to the official, authoritative organization involved in the evaluation process, scholars and academic organizations have widely accepted the TABULA building typologies. As mentioned before, there are differences in building types in each country. Thus, three residential building types commonly owned in Rome, Szombathely and Oslo were selected to simulate building energy demand, including slab building, detached house and clustered low-rise building (Figure 4.3). The geometry of these three residential building types is shown in Appendix D.

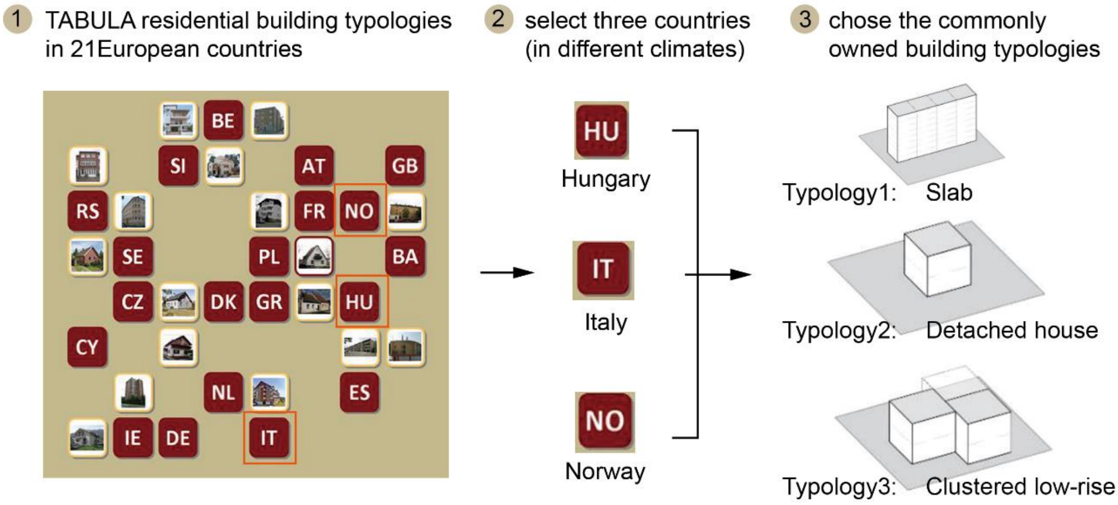


Figure 4.3 The process of selecting residential building types (*Author's plot*)

Regarding the thermal properties of materials and the characteristics of green elements, the tool of *EnergyPlus* requires defining the thermophysical properties of building materials and vegetation; then inputting them into the procedure of energy consumption calculations. However, the tool does not provide parameters for building materials and vegetation (e.g., green roofs). Therefore, this study combined the building materials parameters provided in *IES-VE* with the former findings of the climate-specific review. Specifically, in the process of climate-specific review (Chapter 3), articles describing the thermal properties or specific parameters of building materials and green elements will be marked. Then, these parameters extracted from those articles will be combined with the thermophysical parameters provided by the *IES-VE* as a reference for this study because the " Building Template Manager" module of *IES-VE* provides a series of parameters for building materials.

Step 2: Data input and simulations

- **Organizing the data**

Classifying and organizing the data collected in step 1.

- **Urban weather data generating**

As mentioned before, the *UWG* tool can generate urban weather files. Specifically, it is able to rewrite the dry bulb temperature and humidity of the original weather file (*EPW* format), which was collected in the rural weather station. The changes in these two parameter values represent the microclimatic modification in urban areas. Therefore, it can accurately reflect the meteorological conditions of the city. The workflow of generating urban weather documents is shown in Figure 4.4. As illustrated in Figure 4.4, the core step of this process is to input the urban characteristics of Rome, Szombathely and Oslo into the *UWG* tool, along with the downloaded rural weather document. The urban characteristics that need to be input include the height of the building, the vegetation coverage (the parameter values are between 0 and 1), etc. This step is completed with the help of the software *Rhino* and *Grasshopper*. Notably, the cities of Rome, Szombathely and Oslo represent three different urban characteristics, respectively. In simple terms, Rome represents a uniform, ordered urban form where the buildings have a similar height. Szombathely signifies a spacious, relatively disordered urban form and low building height. On the contrary, the urban characteristics of Oslo are relatively ordered, dense and intertwined buildings of different heights.

To compare the difference between the urban meteorological parameters generated by *UWG* and the original meteorological parameters collected by the rural weather station, this study visualized the annual dry bulb temperature and humidity of Szombathely (Hungary) by the *Grasshopper* related *ladybug* tool (Figure 4.5).

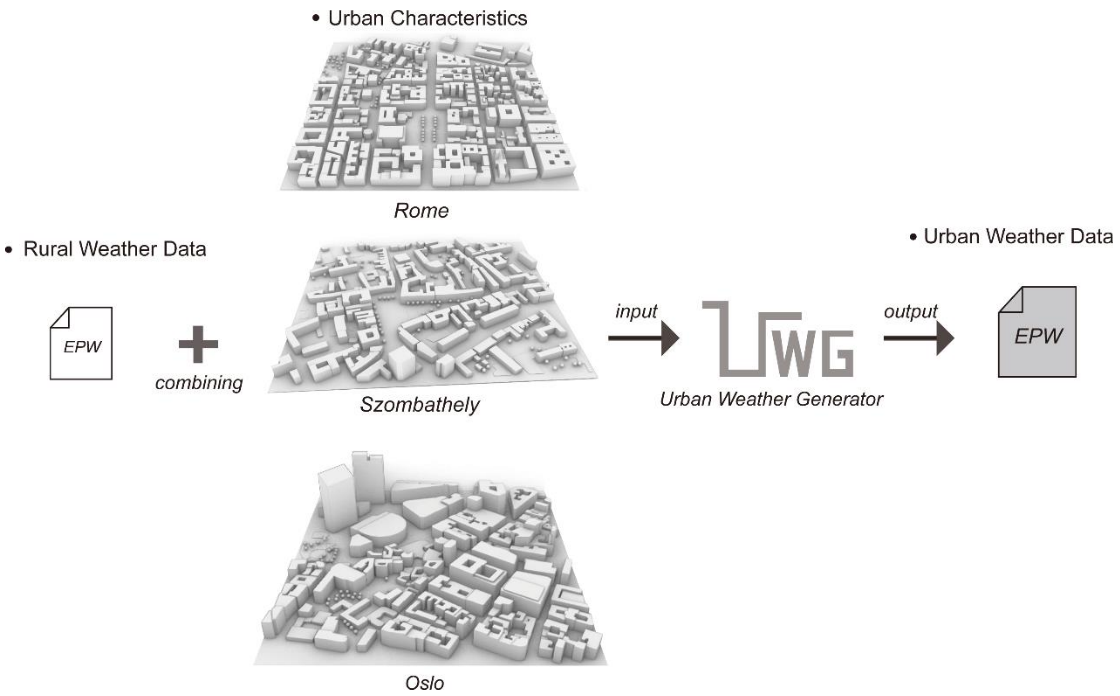


Figure 4.4 The workflow of generating urban weather documents (*Author's plot*).

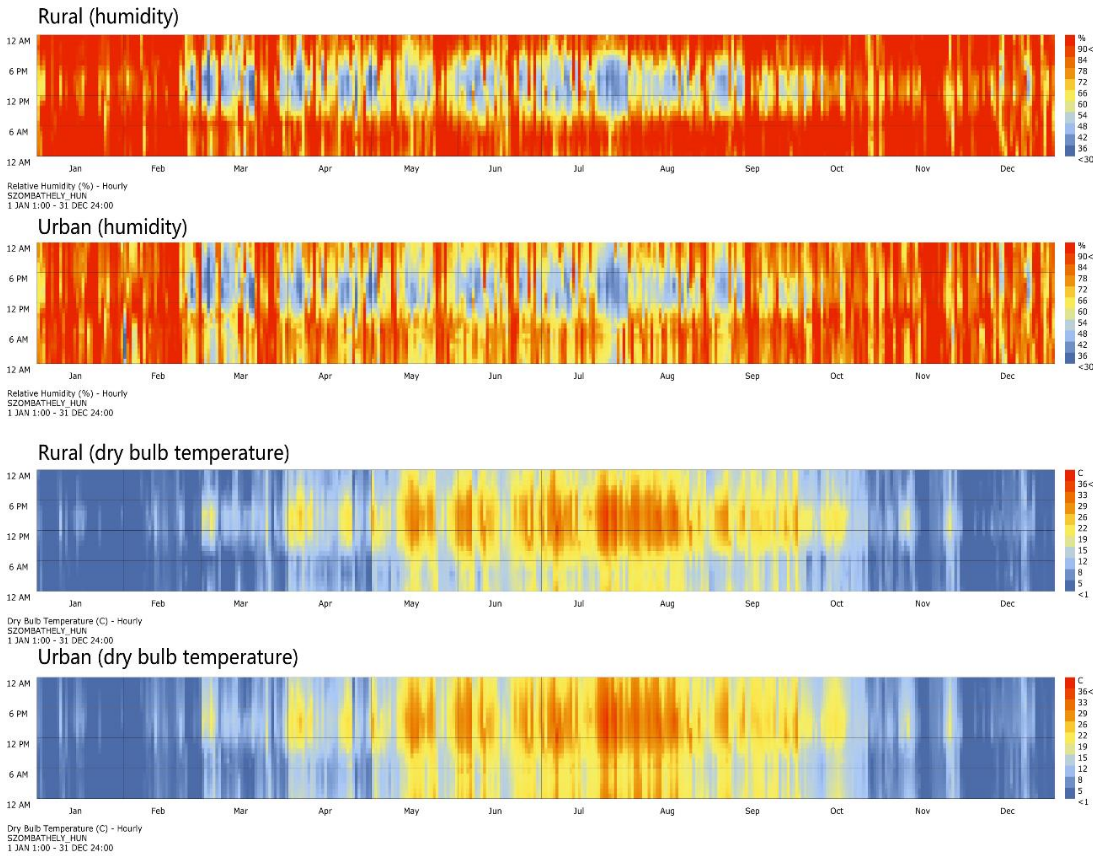


Figure 4.5 The difference between dry bulb temperature and humidity between urban (general by *UWG*) and rural areas (collected by rural weather station) in Szombathely,

Hungary (*Author's plot*)

It can be seen from Figure 4.5 the meteorological data collected by rural meteorological collection stations have significant differences from the data generated by *the UWG* tool, especially humidity. This may be related to the higher vegetation coverage in rural areas. Moreover, the dry bulb temperatures vary significantly during the summer, particularly in late July and early August.

- **Building Energy Modelling**

Building energy modeling refers to conducting building cooling and heating energy simulations. The data collected in previous steps are used as basic input to the simulation. All the building energy consumption simulations are performed by the software *EnergyPlus.* In order to achieve the aims of this research, the study used a series of comparative analyses, including the original scenario and proposed scenarios that contain green roof scenario, green wall scenario, or the scenario of combing green roof and green wall. Since *EnergyPlus* can only present the simulation results for a single residential building type and green infrastructure type, it is difficult to compare the differences in energy demand between different scenarios directly. Therefore, the study converted the result of each simulation into figures. In addition, as reported by European Commission (2022), the average heating temperature in European countries is over 22°C. Moreover, according to the heat stress level of the Universal Thermal Climate Index (UTCI), the temperature between 9°C to 26°C represents not thermal stress. As such, this study's cooling and heating temperature set points are 26°C and 22°C, respectively.

Further, the study set the humidity control set point at 30% minimum and 60% maximum and no thermal regulation for stairs and public areas. For the internal gains, the study assumes one person per 45 square meters, and the occupancy density decreases by 50% between 8 am and 5 pm. Moreover, Tom's survey of internal heat gain in European residential buildings illustrated that the average constant load range is between 3.8 W/m² and 6.6 W/m² when human heat gain is included (Elsland et al., 2014). As such, the value of internal heat gain is taken from the middle of this range, namely 5.0 W/m².

(1) The parameters of green infrastructure used in the simulations

In the proposed scenarios, the *EnergyPlus* requires inputting thermophysical properties of the foliage and substrate (e.g., plant height, leaf area index, soil thickness), especially the types of green roofs. Although the *IES-VE* database contains some parameters that can be used as a reference in the *EnergyPlus*, the number of categories is limited. As mentioned earlier, during the process of climate-specific review, the publications mentioned the above parameters were highlighted, and the relevant thermal parameters were collected. Then, they were used for this analysis (Yaghoobian & Srebric, 2015; Cody et al., 2018; Toparlar et al., 2018; Ávila-Hernández et al., 2020; Ascione et al., 2013; Koroxenidis & Theodosiou, 2021). It is worth noting that in the analysis of climate-specific review, it was found that different values of simulation parameters (e.g., LAI and LAD) have a significant impact on the research outcomes. As such, to avoid confusion in the research results due to the use of different parameter values, the same values were employed for the parameters of three simulated building types and green infrastructure categories in this analysis. The parameters used for simulations are illustrated from Table 4.2 to Table 4.4.

Table 4.2 Extensive green roof parameters for energy simulation

Layers	Types	Value
Vegetation	Height of plants	8 cm
	Leaf area index	5
	Leaf reflectivity	0.28
	Leaf emissivity	0.9
Soil	Thickness	6 cm
	Conductivity	0.20 W/(mK)
	Density	1360 kg/m^3
	Specific heat	800 J/(kgK)
	Thermal absorptance	0.95
	Solar absorptance	0.8
	Visible absorptance	0.7

Table 4.3 The parameter of building materials for energy simulation

Types	**Materials**	**Thickness (m)**	**Conductivity** W/m·K	**Density** kg/m³
External wall: (from outside to inside)	Plaster	0.05	0.6918	1858
	Concrete block	0.1	0.53	1280
	Plaster	0.05	0.6918	1858
Interior wall:	Plasterboard	0.025	0.2	
	Brick	0.08	0.81	1600
	Plasterboard	0.025	0.2	
Roof	Reinforced concrete	0.2	1.7296	2200

Table 4.4 The parameter of green wall for energy simulation

Types	**Greening Height (mm)**	**Plant Species**	**Leaf area index**	**Leaf reflectivity**	**Leaf emissivity**
Green wall:	30	Climbing plants	5	0.22	0.95

Step 3: Comparison analyses

- **Comparing the cooling and heating energy consumption**

Based on the previous steps, the changes in cooling and heating energy demand of different residential building types under different climate characteristics are compared before and after applying green infrastructure. The comparison analyses are divided into three parts:

(1) Exploring the impact of different green infrastructure types on building energy use under different climate characteristics in the same residential building type.

(2) Evaluating the impact of the same green infrastructure type on building energy use in

different residential building types under different climate characteristics.

(3) Assessing the impact of different green infrastructure types on building energy use in the same residential building type under the same climate characteristic.

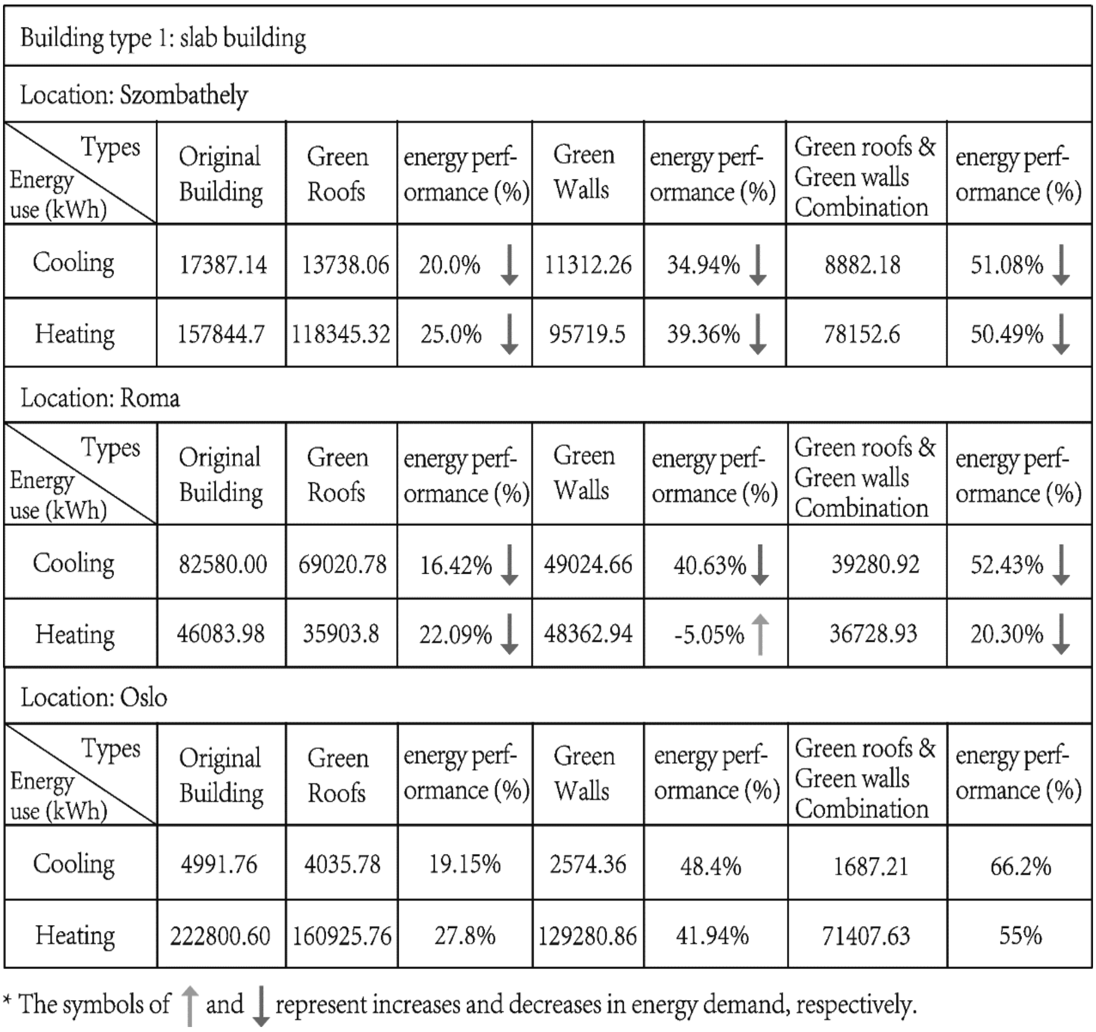
4.4 The result of building energy simulation

This section presents the energy performance of green roofs, green walls and a combination of both on three residential building types (slab building, detached house, and clustered low-rise building) under different climate conditions. The study first introduced the results of the energy demand of slab building; followed by detached house and clustered low-rise building. The corresponding results are illustrated in Figures 4.6 to 4.8.

- **The impact of green infrastructure on the energy needs of slab building in three climates**

According to Figures 4.6, green roofs, green walls, and their combination, all show a significant energy-saving performance under three different climatic conditions, except for the energy performance of green walls in the Roma. In addition, it is clear that the combination of green walls and green roofs has a better energy-saving performance than the use of green walls and green roofs alone applied on the slab building in these three climate zones.

In the Szombathely (temperate oceanic climate), where summer and winter have similar time lengths, green walls save more cooling and heating energy than green roofs. The cooling and heating energy reduced by green walls was more than 30%, compared to only about 20% for green roofs. Similarly, in Roma (hot-summer Mediterranean climate), green walls also saved significant cooling energy than green roofs. However, applying green walls increased annual heating energy demand by 5%. Although the proportion of increased heating energy consumption was offset by the saved cooling energy demand in summer, exploring the causes behind this phenomenon is necessary. This part is discussed in Section 5.4. In addition, winter's short and mild features of the Mediterranean climate also make the combination of green walls and green roofs reduce cooling energy use more than heating energy utilization. Furthermore, in Oslo (warm-summer humid continental climate), the energy performance of green walls is much better than the green roofs, in which the cooling energy reduction of green walls is over two times than that of green roofs. Moreover, green walls (41.94%) decreased heating energy demand more than green roofs (27.8%). Notably, the annual cooling and heating energy reduction of the combination of green roofs and walls are over 50%. This proportion is more significant than that of green roofs and green walls.



Building type 1: slab building

Location: Szombathely

Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	17387.14	13738.06	20.0% ↓	11312.26	34.94% ↓	8882.18	51.08% ↓
Heating	157844.7	118345.32	25.0% ↓	95719.5	39.36% ↓	78152.6	50.49% ↓

Location: Roma

Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	82580.00	69020.78	16.42% ↓	49024.66	40.63% ↓	39280.92	52.43% ↓
Heating	46083.98	35903.8	22.09% ↓	48362.94	-5.05% ↑	36728.93	20.30% ↓

Location: Oslo

Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	4991.76	4035.78	19.15%	2574.36	48.4%	1687.21	66.2%
Heating	222800.60	160925.76	27.8%	129280.86	41.94%	71407.63	55%

* The symbols of ↑ and ↓ represent increases and decreases in energy demand, respectively.

Figure 4.6 The energy performance of green infrastructure on slab building (*Author's plot*)

- **The impact of green infrastructure on the energy needs of detached house in three climates**

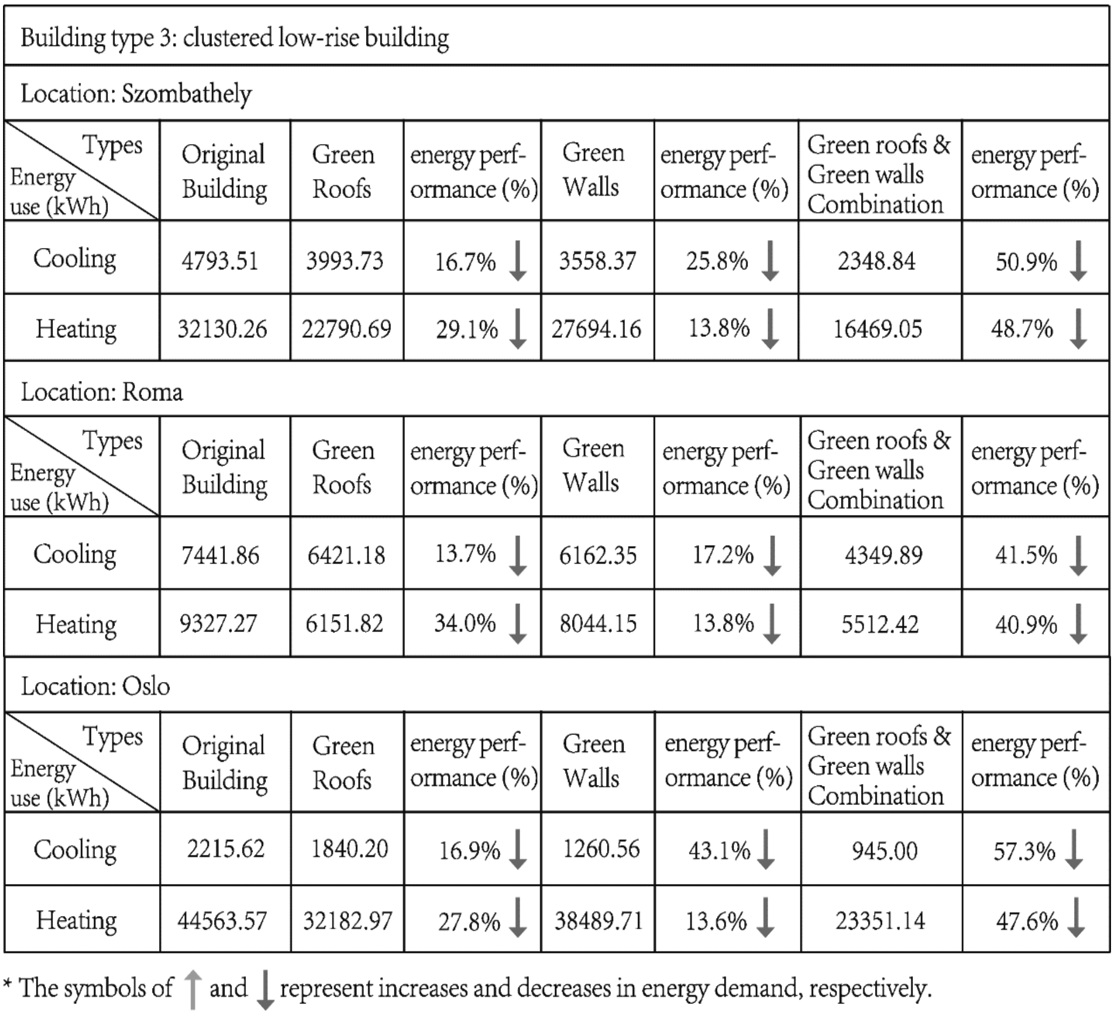
Building type 2: detached house							
Location: Szombathely							
Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	4763.98	4116.81	13.58% ↓	3713.53	22.05% ↓	2818.20	40.84% ↓
Heating	23435.06	15443.08	34.11% ↓	20026.91	14.54% ↓	9340.59	60.14% ↓
Location: Roma							
Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	7363.46	6507.55	11.62% ↓	6248.49	15.14% ↓	5114.59	30.54% ↓
Heating	5896.11	3427.86	41.86% ↓	4962.12	15.84% ↓	1827.60	69% ↓
Location: Oslo							
Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	1505.38	1379.88	8.34% ↓	948.71	36.98% ↓	840.94	44.14% ↓
Heating	33627.41	22747.69	32.35% ↓	28927.52	13.98% ↓	14224.21	57.70% ↓

* The symbols of ↑ and ↓ represent increases and decreases in energy demand, respectively.

Figure 4.7 The energy performance of green infrastructure on detached house (*Author's plot*)

As shown in Figure 4.7, it is clear that green roofs, green walls, and a combination of both all have a net positive impact on the cooling and heating energy reduction of detached house. In the temperate oceanic climate, the most significant cooling energy reduction attributed to the utilization of the combination of green roofs and green walls, with around 41%, followed by green walls (22%) and green roofs (13.58%). At the same time, integrating green roofs and green walls saved 60% of heating energy, compared to green walls (15%) and green roofs (34%). Furthermore, combining green roofs and walls reduced the most considerable cooling and heating energy demand in the Mediterranean climate. In contrast, green walls only decreased 15.14% and 15.84% of cooling and heating energy needs, respectively. Notably, green roofs' heating energy saving (41.86%) performance is much better than that of cooling (11.62%) in the Mediterranean climate. In the heating energy use-dominated humid continental climate, green roofs combined with green walls still have the satisfied annual cooling and heating energy reduction performance. Specifically, it decreased 44% and 57.7% of cooling and heating energy demand, respectively. In contrast, green roofs reduced 8.3% and 32.35% of cooling and heating energy demand, respectively. In comparison, green walls decreased by 36.98% and 13.98% in cooling and heating energy demand, respectively. Besides, it is worth noting that green walls' cooling energy reduction performance is much better than green roofs. However, green roofs can save more heating energy than green walls in detached house.

- **The impact of green infrastructure on the energy needs of detached house in three climates**



Building type 3: clustered low-rise building

Location: Szombathely

Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	4793.51	3993.73	16.7% ↓	3558.37	25.8% ↓	2348.84	50.9% ↓
Heating	32130.26	22790.69	29.1% ↓	27694.16	13.8% ↓	16469.05	48.7% ↓

Location: Roma

Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	7441.86	6421.18	13.7% ↓	6162.35	17.2% ↓	4349.89	41.5% ↓
Heating	9327.27	6151.82	34.0% ↓	8044.15	13.8% ↓	5512.42	40.9% ↓

Location: Oslo

Types / Energy use (kWh)	Original Building	Green Roofs	energy performance (%)	Green Walls	energy performance (%)	Green roofs & Green walls Combination	energy performance (%)
Cooling	2215.62	1840.20	16.9% ↓	1260.56	43.1% ↓	945.00	57.3% ↓
Heating	44563.57	32182.97	27.8% ↓	38489.71	13.6% ↓	23351.14	47.6% ↓

* The symbols of ↑ and ↓ represent increases and decreases in energy demand, respectively.

Figure 4.8 The energy performance of green infrastructure on cluster low-rise building

(*Author's plot*)

Figure 4.8 shows the energy demand of the clustered low-rise building after applying green roofs, green walls, and a combination of both. It is clear that these three types of green infrastructure all have a positive effect on cooling and heating energy reduction in these three climate zones. The most significant cooling energy savings appeared in Oslo (warm-summer humid continental climate), up to 57.3%, using the combination of green roofs and walls. Further, green roofs in these three cities have better heating energy savings performance than green walls. On the contrary, green walls can save more cooling energy than green roofs. This phenomenon also occurred in the detached house. However, this phenomenon was only observed in the slab building with green roofs in the Mediterranean climate. This phenomenon is discussed in Section 5.4.

Furthermore, the study detected that the proportion of cooling energy reduction of these three green infrastructure categories is related to the residential building type. For example, in the temperate oceanic climate, green roofs reduced the cooling energy demand of slab building, clustered low-rise building, and detached house by 20%, 16.7% and 13.58%, respectively. Green walls decreased 34.94%, 25.8% and 22.05% cooling energy demand for slab building, clustered low-rise building and detached house, respectively. Similarly, this feature is also observed in the other two climatic zones.

To sum up, the study observed that the energy performance of the combination of green roofs and green walls is better than the types of green roofs and green walls alone applied on these three residential building types. In the climate-based analysis, the study found that green roofs, green walls, and a combination of both have a net positive impact on building cooling and heating energy reduction in humid continental and temperate oceanic climates. The proportion of cooling and heating energy saved depended on the green infrastructure types and climate zones. However, green walls can increase heating energy demand in the Mediterranean climate. However, the proportion of increased heating energy demand is offset by the cooling energy saved in the summer. This indicates that green walls still achieve net energy reduction. Thus, there is considerable potential for using green infrastructure to decrease building energy demand for these three residential building types.

4.5 Conclusion

This chapter described the methodology and results of building energy simulation.

In order to answer the research question of "how much cooling and heating energy was reduced by different green infrastructures on buildings under different climatic conditions," the study employed a comparative analysis. Specifically, a comparative analysis was conducted between three cities, three residential building types, and three green infrastructure types. The TABULA building typologies were employed to identify the residential building types commonly owned in these three cities. The tool *UWG* was responsible for generating urban weather data files. The software *EnergyPlus* was used to conduct building energy simulations.

The results show that green roofs, green walls, and a combination of both all have a net positive impact on cooling energy savings in three residential types and three climate zones. However, the results on heating energy savings are inconsistent. Specifically, green walls increased 5% of heating energy demand in the Mediterranean climate; but the proportion of heating energy increased is offset by cooling energy saved in the summer. In other words, green walls achieve net energy savings in this climate. Notably, the energy-saving performance of the combination of green roofs and green walls is much better than that of the types of green roofs and green walls alone applied on slab building, detached house, and clustered lower rise building in Roma, Oslo and Szombathely.

Chapter 5: Discussion

5.1 Introduction

This chapter designates to discuss the research findings in relation to the aims of this thesis outlined in Section 1.2. Section 5.2 focuses on discussing the differences, and interrelationships between restorative and regenerative urban design. The discussion of the building energy performance of different NBS types is presented in Section 5.3. Subsequently, the research result of BEM for different climate zones, green infrastructure categories and residential building types are discussed in Section 5.4.

5.2 Differences, and interrelationships between restorative and regenerative urban design

- **The differences between restorative and regenerative urban design**

Based on the KPI analysis in Chapter 2, the study observed that there is a clear difference in research fields between restorative and regenerative urban design. Urban regenerative design involved all the subdimensions of KPIs. In contrast, the marks of environmental restoration in the subcategory of urban restorative design account for 70% of all KPI marks. Furthermore, the rest of the KPI marks of urban restorative design mainly concentrate on the subcategory of community benefits, the majority of which are associated with the indicator of mental and physical health. This means that urban restorative design is closely linked to community benefits rather than the previously described definition of merely focusing on environmental restoration. In other words, in practice, urban restorative design is not focused on maximizing certain ecological goals. This significant association may be related to biophilic design. Urban restorative design has a strong association with biophilic design, which seeks to systematically integrate nature into the urban fabric in a way that improves the connection between man and nature (Mehan, 2016). The health benefits of contact with nature, such as stress reduction and decreasing cardiovascular disease, are increasingly accepted by the public. This deliberate behavior of bringing natural elements into urban landscapes and building interiors while mimicking natural geometry or forms could enhance the healing effect of the built environment. From this perspective, urban restorative design is committed to building a close relationship between man and nature, thereby placing physical and mental health alongside ecological restoration at the core of urban design.

In terms of urban regenerative design, many papers define it as an integrated approach that seeks to have a long-term impact on living systems. However, this is a relatively abstract concept. In this study, urban regenerative design included 33 out of 51 indicators, which covered the economic, environmental, and social fields. In the economic dimension, the most frequently mentioned indicators were employment growth and new capital investment. Many papers also mentioned increasing the proportion of the knowledge-based economy in the local economic structure. In the environmental dimension, enriching biodiversity had the highest score. In addition, renewable energy supply and waste recycling indicators have also attracted widespread attention. This may be related to the fact that regenerative design is considered as a transition from the current linear system to a cyclic system in which the life cycles of all materials are carefully considered. Regarding the social dimension, the indicators of resource efficiency of buildings, policy guidance and support, and housing were all frequently mentioned in the literature. In addition, the indicators of recreational facilities, physical health, and mental health also attracted attention. The additional indicators of making sense of space and improving bicycle and pedestrian infrastructure were frequently mentioned. The high scores for the parameter of bicycle and pedestrian infrastructure reflect the return of human-scale urban design. This requires the spatial connectivity of different activity spaces and the accessibility of different services, which is a fundamental principle in sustainable urban design (Serrano-Jiménez et al. 2019).

In short, urban regenerative design has not only frequently mentioned many conventional indicators, but also has included some indicators that emphasize the long-term nature of self-regeneration, such as increasing the percentage of knowledge economy of the GDP, solid waste reuse and recycling, renewable energy supply and consumption, developing a sense of place, etc. It could be inferred that urban regenerative design supports and facilitates the formation of an ability to fulfill the long-term needs of urban development.

Based on this analysis, the most appropriate definitions of restorative and regenerative urban design could be:

Urban restorative design *not only restores the polluted and damaged ecosystems to a healthy* *state, but also integrates nature into life through appropriate design patterns while ensuring consistent interaction and contact with nature to create a built environment that allows its users to thrive both physically and mentally.*

Urban regenerative design *resolves urban problems from an integrated perspective of economy, society and environment, while not only seeking the growth of conventional indicators (e. g. increased employment, enriching biodiversity), but also attempting to restore and establish an "ability" to adapt and meet long-term or future development requirements.*

- **The interrelationships between restorative and regenerative urban design**

The study found that only one urban restoration publication had a citation interrelationship with urban regenerative design. Two papers on urban regenerative design were cited by this publication, which concentrates on studying how to apply the analysis of ecosystem services to the urban built environment and analyzes the starting point of regenerative design. However, one of the articles it cited was published in 2015 and deals with urban stormwater management. This cited relationship seems unusual. However, this cited paper proposed a new conceptual framework and recommends approaching the regenerate urban built environment paradigm with a holistic view by integrating urban sustainable drainage systems with resource management and climate mitigation and adaption. Regarding another cited publication, this cited paper calls for whole system thinking and living systems thinking, which is a holistic way of linking the natural environment with the built environment (Mang & Reed, 2020). It recommends using this approach in sustainable practices to promote urban regeneration. As such, the description and analysis of the "natural environment" and "built environment" sections may bring an interconnection between these three articles. Moreover, although the paper of urban restorative design focuses only on the feasibility of urban regeneration from an ecological perspective, the cited article provides it with an entirely theoretical framework for urban regenerative design. This seems an important reason for the citation relationship between them. Furthermore, study found that there is no direct citation link between these two groups. This implies that the citation interrelationship between restorative and regenerative urban design was not present in Group 2.

Besides, as mentioned in Section 2.3.1, since 31 articles are not included in the database of the Web of Science, it is impossible to directly generate such a schematic diagram of the citation relationship by software. As such, the study manually checked the remaining 31 articles, of which 11 papers belong to urban restorative design. Among them, only two dissertations mentioning “regenerative” focus on regenerating natural systems. The rest concentrated on discussing health and ecosystem restoration. In addition, most of the remaining 20 urban regenerative design papers are conceptual articles. Five articles directly mentioned the definitions and purposes of restorative and regenerative design. To some extent, this cannot be used as evidence of an internal relationship between them. Furthermore, two articles may have associations with urban restorative design. One paper mentioned the use of biomimicry theory to drive a paradigm shift in urban regenerative design, however, it relied on an understanding of ecological theory and analysis of ecosystem services. Thus, the health and integrity of ecosystems are highly valued. Similarly, another article suggested incorporating the analysis of ecosystem services into built environment design and using a practical case to demonstrate the benefits. Therefore, “ecosystem services” are the reason for their correlation to urban restorative design.

In general, there are three possible relationships between restorative and regenerative urban design: namely, development independent of each other, a partial overlap between these two disciplines, and one discipline completely including the other (Figure 5.1). Strictly speaking, the citation analysis demonstrated that there is no significant internal relationship between urban regenerative and urban restorative design. Instead, they have developed almost independently of each other, as shown in Figure 5.1a. However, in the KPI analysis, urban regenerative design involves more indicators and dimensions than does urban restorative design, but the former does not fully include the indicators of urban restorative design (Figure 5.1c). The indicators involved in restorative and regenerative urban design overlap with each other (Figure 5.1b). To some extent, this indicates that restorative and regenerative design should be interrelated with each other.

There are two possible reasons to explain why the findings of restorative and regenerative urban design in the citation analysis differ from the KPI analysis. First, for different research fields, the citation relationship will occur only when a common research topic or theme emerges. The results show that urban regenerative design is a broad research field, while in contrast, urban restorative design mainly concerns physical and mental health as well as ecological restoration. In other words, the citation relationship will only emerge when the research on urban regenerative design is focused on or has some connections with the above two aspects. The second reason is lack of data volume. Mining association and correlation between different items is best served by large amounts of data. However, only 117 documents were studied in this research, of which only 37 publications related to urban restorative design. The insufficient data volume and the large differences in the number of publications between these two fields, to some extent, could further reduce the probability of finding citation relationships. As a result, the superimposed influence of the above two reasons may have led to the weak citation relationship between restorative and regenerative urban design in this study.

The citation analysis demonstrated that there is no significant internal relationship between urban regenerative and urban restorative design. Instead, they have developed almost independently of each other. This contradicts the findings of former KPI analysis in this research. It is necessary to reassess this association based on a large quantity of data in the future.

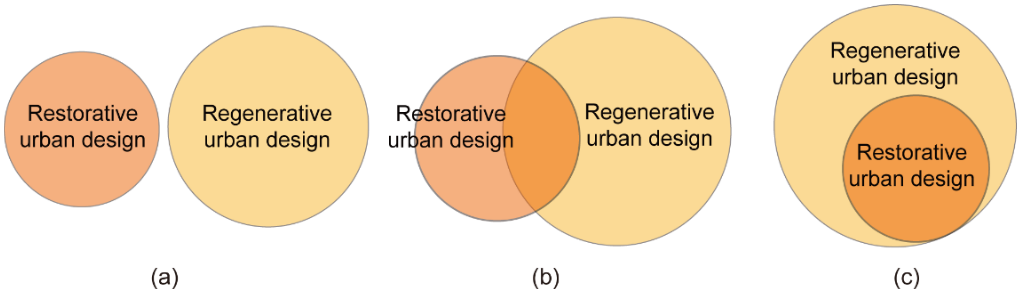


Figure 5.1 The interrelationship between restorative and regenerative urban design: (a) restorative and regenerative urban design develop independently of each other; (b) a partial overlap between restorative and regenerative urban design; (c) one discipline completely

includes the other (*Author's plot*).

Summary, based on the findings of Chapter 2, this chapter discussed the differences and interrelationships between restorative and regenerative urban design. Unlike the descriptions found in many of the identified papers, restorative urban design not only focuses on ecological aspects but also attempts to create a built environment that allows its users to thrive both physically and mentally. Regenerative urban design is more inclined to restore or create an "ability" as it significant associated with many indicators that emphasize the long-term nature of self-regeneration, such as renewable energy supply and consumption, decreasing CO2 emissions from household; etc. Nevertheless, both disciplines are developed independently in the field of urban design. Although there are obvious differences between restorative and regenerative urban design, both disciplines tend to mitigate or minimize the negative impacts of design and development on natural systems, and also use the built environment to promote a closer relationship between man and nature.

Besides, the systematic review of these two disciplines provides a crucial foundation and support for the subsequent research of this study as it clearly defines and differentiate these two disciplines; also, it confirmed that these two disciplines have a significant association with the SDGs; especially regenerative urban design. Further, since NBS emphasize harmony between man and nature and ecological development, representing a comprehensive, human-centered response to climate change, they are considered an important measure to achieve the SDGs. In the next following chapters, the study will focus on discussing how NBS approaches facilitate urban regeneration in terms of low-carbon development.

5.3 The impact of different NBS types on building energy performance in different climate zones

As described in Section 3.3.5, nearly all the studies confirmed that green roofs had a positive impact on decreasing building cooling energy demand in almost all climate zones. Only one study pointed out that extensive green roofs have potential to increase cooling energy demand by a small amount in three different European climates (Csa, Cfb and Dfb) if using short sedum as the roof vegetation (Ascione et al., 2013). Compared with other roof vegetation, the short sedum vegetation used in that study represents a sparse plant type with low values of plant height and LAI. It has been already confirmed that LAI is the key parameter affecting the green roof in building energy efficiency when considering the influence of evaporation rate (Zhou et al., 2018; Ávila-Hernández et al., 2020). In a similar study on energy consumption in an office building, Ferrante et al. (2016) compared six types of plants in the climate zone of Csa, and found that higher LAI could effectively decrease cooling energy consumption. Moreover, the height of plants often acts as additional thermal insulation and mass, which could effectively reduce the heat flux through the roof (Mahmoodzadeh et al., 2019). Therefore, it is suggested that the type of roof vegetation used should be seriously considered when using green roofs in the temperate climate group with hot characteristics in summer. In addition, although the use of extensive green roofs in five climate zones (Cfa, Csa, Cfb, BWh and Aw) with hot summer characteristics may lead to a significant reduction in cooling energy consumption by up to 58%, this percentage is much lower than in the Cwb climate zone. Study by Ávila-Hernández et al. (2020) used simulation approaches and found that extensive green roofs have the potential to reduce cooling energy consumption by up to 90% in one residential building in Tlaxcala (Cwb), Mexico. Compared with the above five climates, the summer temperatures are lower in the Cwb climate. Moreover, the annual average temperature of the simulation site Tlaxcala is around 16.1 °C (Ávila-Hernández et al., 2020). In that publication, the authors explored the optimal combination of parameters affecting indoor temperature by constantly adjusting the vegetation parameters for the extensive green roof. Then, these optimal parameters were used for the energy consumption simulations. In other words, that publication described an optimal or ideal state rather than the actual situation; that is, how much cooling energy could be maximally saved with an optimal state of extensive green roof. To some extent, the 90% reduction in cooling energy consumption obtained by that paper lacks broad representation. In simple terms, it does not represent the actual state of the energy performance of the majority of extensive green roofs in the Cwb climate. Therefore, the study believes that this high energy saving mut be critically observed and need further investigation.

In addition, study detected that green roofs may lead to an increase in heating energy demand in the climates of Cfa, Csa, Cwb, BWh and BSh; also, green walls have the potential to increase energy demand in the climate of Csa. However, further evaluation is needed to assess the impact of green walls on building energy performance in other climate conditions, as it is only associated with limited data and climate zones. Besides, while studies have found an increase in heating energy demand associated with green roofs in the above 5 climate zones, the statistical analysis using boxplots shows that most studies on green roofs tell a reduction in heating energy needs for buildings in the Cfa and Csa climate zones. To date, the impact of green roofs and green walls on building heating energy demand is still controversial in the above-warm temperature climates. Some unusual findings have been reported in some literature. For example, Coma et al. (2020) used experimental approach and observed that indirect green façades and living walls increase heating energy by 9.3% and 9.5% in the climate Csa, respectively. However, study by Chafer et al. (2021) which also used experimental methods, found that green façades and living walls respectively reduced heating energy consumption by 2.65% and 2.47%. Similarly, study by Alexandri & Jones (2008) employed energy modeling approach and found that direct green façades and living walls showed reductions in annual heating energy demand of 1.2% and 4%, respectively. As the above-mentioned studies did not provide key information for simulation or experimentation, the interpretation of these results becomes more challenging. In addition, in the rest of the studies on the types of green roofs and green walls, many studies stress that this phenomenon relates to LAI and the short and mild climatic characteristics of winter (Chafer et al., 2021; Peñalvo-López et al., 2020; Djedjig et al., 2017). The general opinion is that despite vegetation losing its leaves (lower LAI) during winter compared to summer, the scattered branches and the remaining leaves can still function as additional insulation layers, preventing most of the heat flow into the interior. As such, compared with the bare wall, green roofs and green walls will increase part of the heating energy need in the winter. Thus, given that green roofs and green walls may increase heating energy demand in temperate and arid climates which are characterized by short mild winters or year around heat, any effort to improve the energy efficiency of buildings should be concentrated in summer, as summer is hot and much longer than winter.

Furthermore, although green walls were not involved in a large number of climate zone studies compared with green roofs, it is shown in the examined climate zone that it performed better in terms of energy efficiency than green roofs, especially in reducing cooling energy demand. To a large extent, this is because the surface area of building walls is larger than that of the rooftop. Furthermore, among the three specific types of green walls, only in the temperate oceanic climate were living walls discussed with regard to the cooling energy saving performance (Cfb). They were associated with 26% reduction in cooling energy use. However, this proportion is much lower than that of extensive (57.3%), semi-intensive (62.7%) and intensive green roofs (66.2%) in this climate. It is necessary to explore the causes. The significant cooling energy reduction of extensive, semi-intensive and intensive green roofs was found by Pianella in Melbourne (Pianella et al., 2020). The plants used in that study contained multiple types of species. This means that the building roof is well coved by plants. Meanwhile, the vegetation is well irrigated during summer; also, the simulated building had no-insulated layer. In contrast, the study that observed a 26% reduction in cooling energy for green walls showed significant differences in building properties and vegetation maintenance compared to studies on green roofs. Specifically, the simulated building walls had 5cm insulation layer and the irrigation frequency of vegetation was lower than the green roof analysis of the former (Perini et al., 2017). Therefore, the superposition of these two factors may be the reason why the energy saving performance of green walls is lower than that of green roofs in the climate zone Cfb as the irrigation status of vegetation, and insulation layer has been proved by many studies to affect energy saving performance (Koroxenidis, & Theodosiou, 2021; Zhang et al., 2021; Skelhorn et al., 2016; Malys et al., 2016; Silva et al., 2019; Fantozzi et al., 2021). To some extent, this also stressed that optimizing the energy saving performance of buildings through green walls or green roofs requires comprehensively considering the combination of multiple factors.

Additionally, it is worth noting that several current studies on green roofs use a comparative analysis approach on the same rooftop, meaning that one part of roof is transformed to a green roof while another part remains as a traditional roof. Due to the proximity of these two roof types, they may to some extent be influenced by each other (Irga P et al., 2021). Therefore, for this comparative analysis approach, this study suggests that comparing the difference between soil and ground temperature may be a more effective method, as the soil is the heat buffer for green roofs.

As for the remaining five categories, although they have been involved in a small number of studies compared to green roofs and green walls, research in limited climate zones has also shown their positive impact on improving building energy efficiency, especially the energy saving performance of trees in Cfa and Csa climates. Specifically, trees showed a reduction in cooling energy demand by over 50% in both climate zones. This proportion is over 12 times than in the hot, arid desert climate (BWh). The BWh climate has high temperatures throughout the year, whereas the Cfa and Csa are only hot in summer (Pernigotto & Gasparella, 2018). It is necessary to explore the causes behind this phenomenon. Up to the present time, the relationship between trees and building cooling energy demand has been deeply studied, in which the LAD, the height of tree and the distance to building are considered to be important factors affecting building energy consumption (Wang & Akbari, 2016; Rouhollahi et al., 2022; Tsoka et al., 2021; Hsieh et al., 2018). Nevertheless, the studies which mentioned the significant cooling energy reduction of trees in the above Csa and Cfa climate zones benefited not only from the highest value of LAD (dense trees) and the high height of the tree, but also from the unusual arrangement of trees (Tsoka et al., 2021; Palme et al., 2019). Specifically, the trees were arranged into uniform rows, forming a continuous shading canopy with no space between the canopies. This feature allows the trees to form large shaded areas on the walls. Therefore, this planting pattern combined with the high values used in the LAD and tree height may have allowed significant daily cooling energy savings. To some extent, this revealed that reducing building energy consumption through vegetation is a complex process that requires many considerations, which includes not only the characteristics of vegetation itself but also the planting configuration pattern. Moreover, it also recommended that when planting trees in warm or hot climate zones, the vegetation should be arranged in uniform rows when possible to create a continuous shade on the building surface, thereby, further reducing the cooling energy load, especially in the areas where buildings have low height and have large distances between each other.

In addition, green belts also show good energy saving performance in the subtropical monsoon climate with hot summers (Cwa). Although the daily cooling energy reduction was only found to be 2.1%, the energy savings are significant if this percentage is extended to the entire summer period. Green belts are usually small in size but have flexibility in scale and can be applied to a variety of urban spaces (Feng et al., 2022). As such, for the cities with prominent imbalances between people and land, the construction of many small green belts in the dense urban areas could be another option as it is significantly difficult to build new large greenspace in the city centers that have a dense population and urban form.

As for the water feature, wetland performed a significant cooling energy saving performance. This phenomenon also observed in the type of mixture of trees, grass and near the river. Study by Ayad et al. (2019) found that water (8.12%) saved significantly more cooling energy than the combinations of trees and grasses (4.78%) in the hot desert climate. Even by increasing the canopy cover ratio, there are still significant differences in energy saving performance between them. To a large extent, this suggests that in the process of achieving a low-carbon city, it is necessary to reasonably plan blue infrastructure and properly design water features in existing urban areas. For example, when implementing tree planting, combining technologies (e.g., sustainable urban drainage system) can be installed to collect the excess water and return it back to the bioswales or ponds at the neighborhood scale. Further, unlike other types (e.g., green roofs, green walls) that can directly produce shading effect on the buildings, the influence of water features on building energy demand is primarily achieved by modifying the microclimate (Pisello et al., 2015). As such, distance plays a key role in determining the energy saving potential. In simple terms, the closer the distance between building and water feature, the more significant the impact of microclimate on the building. Similarly, distance is also the important factor of urban forests affecting the energy demand of building as it influences the cooling of the outdoor ambient air temperature through transpiration by large areas of plant (Moss et al., 2019; Toparlar et al., 2018). Nevertheless, this study suggests that in the early stage of planning building energy efficiency, priority should be given to considering the size or scale of these two types and then determining their distance from the buildings. Because the influence of smaller scale water features or urban forests on the surrounding microclimate is limited compared to larger scales. Being farther away from buildings will further weaken their impact on the adjacent microclimate of the buildings. Therefore, the size of these two types and the distance to the buildings should be seriously considered to maximize their energy saving potential. Moreover, other measures should be taken to further optimize the energy saving potential of urban forests, such as maximizing their transpiration by selecting the appropriate vegetation type and layout to reduce the outdoor ambient temperature.

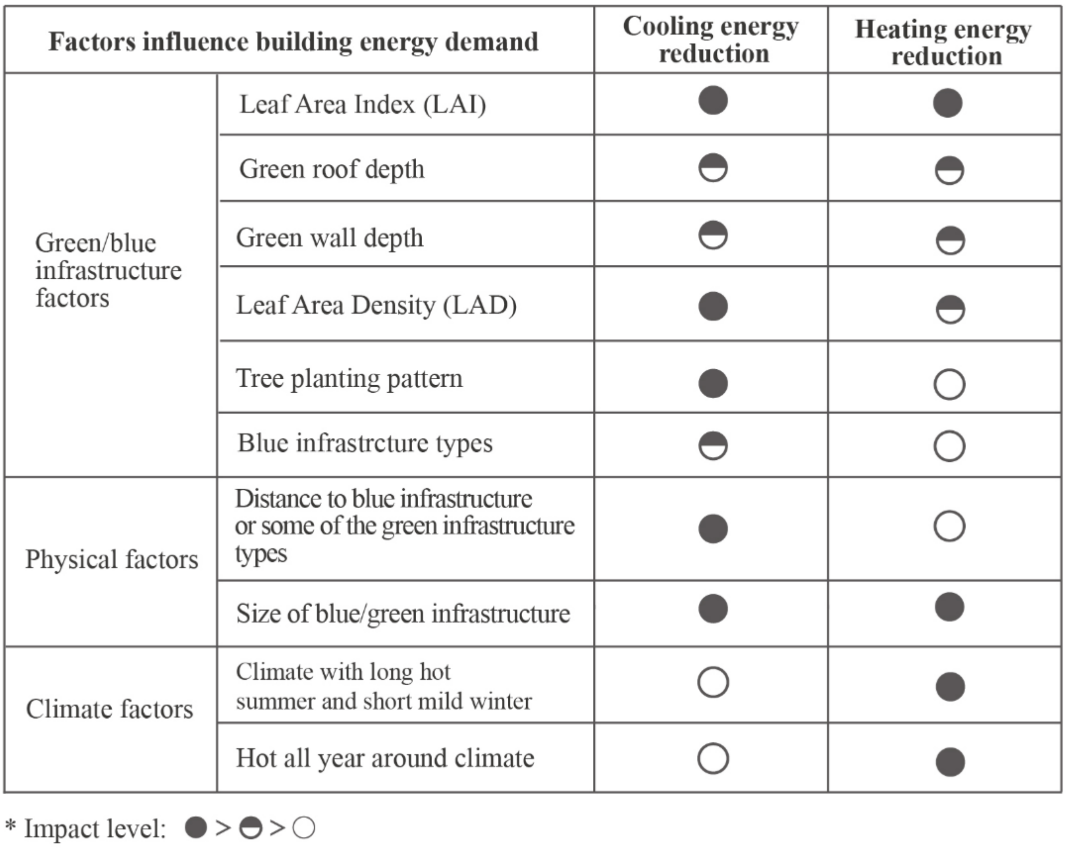
In terms of the combined analysis of different types, as described earlier, most integration studies involve green roofs and green walls. However, few of them mentioned the specific types of these two categories, making it difficult to discuss them in depth. In the subtropical monsoon climate (Cfa) and temperate oceanic climate (Cfb), the combination of different NBS types all showed a significant and positive performance of cooling energy savings. This is consistent with the results of the single type analysis. Notably, extensive green roofs combined with perimeter flowerpots could significantly reduce heating energy demand in the temperate climate. In contrast, indirect green facades and living walls are likely to increase heating energy consumption in such climates. It might be that the perimeter flowerpots cover the building facade to a lesser extent than that of indirect green facades and living walls, thereby the building walls can receive more solar heat in winter. To some extent, this suggests that in climate zones with short and mild winters, using perimeter flowerpots with green roofs could be another option to avoid increasing heating energy use.

Furthermore, the cooling energy savings of the integration of green roofs, green walls, grasses and trees is not significant in the humid continental climate (Dfa), with only 5%. This climate is cold but has hot summers. Green walls, green roofs and trees can all produce a significant shading effect on the experimental building in the summer. Only one study has involved in this combination analysis, in which the façade and roof material of the simulated building all have high albedo properties (Zhang et al., 2017). Moreover, this building is well-insulated. Thus, compared with most of the simulated buildings in the collected publications, this experimental building already has a decent building envelope structure in terms of energy saving. Thus, the

5% cooling energy reduction is the comparison between the combination of green wall, green roof, trees, grass and the current cooling materials of simulated building. In other words, if this experimental building does not use high albedo reflective material on the facades and roof, or has no insulation layer, the combination of green walls, green roofs, trees and grass will save more cooling energy consumption.

To sum up, although the experimental buildings have different characteristics (e.g., with or without insulation, different building materials), the seven NBS types evaluated all have an absolute impact on the saving of building cooling energy. The proportions of cooling savings depend on the NBS types and climate zones; However, the results of reducing heating energy demand are inconsistent. Specifically, green roofs and green walls may increase the heating energy load in the climate zones characterized by short and mild winters or hot year-round temperatures. Notably, the proportion of increased heating energy demand is offset by the saved cooling energy in summer. In this regard, although the energy performance of green walls and green roofs achieve net energy saving over the year, the risk of potentially increased heating energy load in winter still cannot be ignored. As such, it is suggested that when applying green roofs or green walls in these kinds of climates, measures to improve building energy efficiency should be concentrated on solutions for summer months. For the climate zones characterized by hot summers and cold winters, green roofs and green walls can effectively reduce cooling and heating energy demand. As such, it is recommended to widely apply these two NBS types in this kind of climate, which will make contributions to the realization of zero carbon for building sectors.

Based on the above discussion, it can be concluded that reducing building energy demand through NBS is a complicated process that requires considering various factors, such as the factors of climates (Figure 5.2). Importantly, to maximize the energy saving potential of NBS, it is crucial to comprehensively consider the combination of these factors rather than maximizing an individual factor. In other words, exerting the advantages of NBS in reducing building energy demand requires a holistic approach that considers the interactions between different NBS, climatic, and physical components. Moreover, it is important to continue research and development in the NBS to optimize the design and implementation of NBS strategies on building energy reduction.



Factors influence building energy demand		Cooling energy reduction	Heating energy reduction
Green/blue infrastructure factors	Leaf Area Index (LAI)	●	●
	Green roof depth	◓	◓
	Green wall depth	◓	◓
	Leaf Area Density (LAD)	●	◓
	Tree planting pattern	●	○
	Blue infrastrcture types	◓	○
Physical factors	Distance to blue infrastructure or some of the green infrastructure types	●	○
	Size of blue/green infrastructure	●	●
Climate factors	Climate with long hot summer and short mild winter	○	●
	Hot all year around climate	○	●

* Impact level: ● > ◓ > ○

Figure 5.2 The factors affect building cooling and heating energy reduction (*Author's plot*)

In conclusion, the climate-specific review found that there is a positive influence of NBS technologies on building energy reduction. The energy reduction potential of NBS for building cooling varies from 3% to 90%, while the potential reduction in heating energy demand ranges from 0.58% to 60%. The extent of the reduction in both cases is significantly dependent on the NBS type and climate. It should be noted that some NBS types may lead to an increase in heating energy demand by between 5.9% and 25%. In other words, the heating energy performance of green roofs and green walls is controversial; especially in climates characterized by year-round hot temperatures or those with long hot summers and short mild winters. However, the increased heating energy demand in these climates is offset by the savings in cooling energy in summers. Besides, it is crucial to note that although this study quantified the building energy demand for different NBS categories, the proportion of reduced energy was not classified according to different building types and designs (substrate thickness, plant type; etc.). While a direct comparison of previous studies based on these factors would be complex and challenging, further classification of energy saving performance based on these factors is necessary in the future. This will provide guidance for different types of NBS to make appropriate decisions in further reducing energy consumption in buildings.

5.4 Building energy performance of three green infrastructure categories applied on three residential building types across three European climates

As mentioned in Section 4.3.1, in order to avoid confusion in the research results due to the use of different parameter values, the same values were employed for the parameters of three simulated building types and green infrastructure categories in *BEM* analysis. The *BEM* analysis shows that green roofs, green walls and a combination of both all have a net positive impact on reducing building cooling and heating energy demand; especially the integration of green roofs and green walls. However, in the Mediterranean climate, the use of green walls in the slab buildings associates with 5% increase in heating energy consumption. This finding is consistent with the research findings of some scholars in climate-specific review. In simple terms, the results of several studies on indirect green roofs and living walls reveal that these two green roofs could lead to an increase in heating energy demand, ranging from 5% to 9.5%. These studies on the potential of green walls to increase heating energy demand were found through comparative experiments with concrete cubicles (Perez et al., 2022; Coma et al., 2020). Although they all use experimental methods, concrete cubicles to some extent cannot imitate the actual conditions of slab buildings, for example, the simulated concrete cubicles usually have no windows; thereby they do not reflect the characteristics of facade (the ratio of windows to walls). Therefore, further experimental investigations on slab buildings are needed. Notably, the *BEM* analysis tells that, unlike slab buildings, both detached houses and clustered low-rise buildings effectively reduced about 15% heating energy demand in the Mediterranean climate. Study by Assimakopoulos also employed simulation approaches and detected that the annual heating energy consumption can be reduced by 10.3% through the use of green walls on the detached house in the Mediterranean climate (Assimakopoulos et al., 2020). Similarly, Carlos's study revealed that the application of living walls increases the energy efficiency of buildings in the winter, resulting in annual heating energy load reduction (Carlos, 2015). To some extent, this indicates that different building categories could also be an important cause for variations in the energy efficiency of green walls. Specifically, compared to clustered low-rise buildings and detached houses, the slab buildings used for simulation have larger values in terms of building height and length. As a result, the facades of slab buildings have a larger surface area compared to the former two building types, leading to a greater coverage of green walls on the building facades. In the Mediterranean climate, characterized by hot, long summers, the application of green walls on slab buildings could result in greater savings in cooling energy demand compared to clustered low-rise buildings and detached houses. This hypothesis was confirmed by the results of the *BEM* analysis. In simple terms, green walls reduced cooling energy demand in slab buildings by 40.63%, in clustered low-rise buildings by 17.2%, and in detached houses by 15.14%. However, the feature of larger coverage area of green walls on slab buildings also reduces the solar radiation exposure of the building façade during the short and mild winter period, thus reducing the heat flux into the interior of the buildings. As such, the energy saving performance of green walls in slab buildings (-5.05%) is far worse than that of clustered low-rise buildings (13.8%) and detached houses (15.84%).

In addition, the results of *BEM* reveal that green walls have better cooling energy saving performance than green roofs, regardless of their application in different building categories and climate zones. This is consistent with the findings of many scholars. On the contrary, green roofs saved heating energy more than that of green walls in clustered-low rise buildings and detached houses. Nevertheless, this feature was not observed on the slab buildings in the climate zones of Cfb (Temperate oceanic climate) and Dfb (Warm-summer humid continental climate). Specifically, green walls reduced more heating energy demand than that of green roofs in these two climate zones. Therefore, it is necessary to explore the causes behind this phenomenon. The occurrence of this phenomenon is not only associated with the larger coverage extent of green walls on slab buildings described earlier, but also related to the climate characteristics of Cfb and Dfb. According to the Köppen Climate Classification (2022), the winters in these two climate zones are long; especially the climate zone Dfb where winters are significantly cold.

Even if green walls lose most of their leaves during the winter, the remaining leaves and scattered branches still provide good insulation for the walls. For instance, study by Cameron et al. (2015) employed empirical surveys and found that in winters of the Cfb climate zone, walls covered by green walls exhibited higher temperatures in comparison to uncovered walls. This indicates that the vegetation acts as an additional insulation layer for the wall and effectively captures the heat behind the leaves; thereby, more heat being retained on the building facade with green walls installed. It is important to note that this study does not advocate the sole utilization of green walls on slab buildings in mild and short-duration winter climates (e.g., Mediterranean climate) as a means to reduce building energy demand. This is due to the fact that, given the climate characteristics, such an approach would result in increased heating consumption during the winter season.

Overall, although this study only investigated the energy performance of three green infrastructure types applied to three residential building types in three European climate zones, the results reveal that the variation in building categories is also a crucial factor contributing to the differences in energy savings performance within the same green infrastructure category. As a significant complement to the climate review in Chapter 3, the study suggests that future research should explore a broader range of building categories to gain a comprehensive understanding of the energy-saving performance of different green infrastructure types applied to various building types. This will provide better guidance for low-carbon practices in urban regeneration.

Chapter 6: Limitations

Several limitations of this research should be noted. First of all, although this research observed a significant correlation between green infrastructure and building energy demand, the energy consumption evaluation was conducted only on the building scale due to the limitations of the current technical tools. In simple terms, current building energy modeling tools only support the input of various detailed parameters (e.g., the height and leaf area index of green roofs) at the building scale to evaluate energy use. Therefore, it is difficult to ensure that the positive influence of green infrastructure on building energy use remains at the upper scale, such as district or city scales. Secondly, even though this study used logically combined search terms to collect the publication for systematic review and climate-specific review, it is impossible to ensure that all the related publications have been collected as some researchers may use other search terms. Moreover, *BEM* analysis was only examined for the energy performance of the three green infrastructure categories applied in the three residential building categories in the three climate zones. Therefore, the corresponding results did not fully reflect the energy saving performance of other green infrastructure types or their application in different building categories.

Chapter 7: Conclusion

Improving energy efficiency and reducing energy demand are widely recognized as the most promising, fastest, lowest-cost, and safest means to mitigate climate change. Given that energy efficiency investment incentives through building materials have weakened, NBS has emerged as an alternative approach for reducing building energy demand. As such, this research has important guiding significance for facilitating cities in transitioning to low-carbon development.

As the evolution of the sustainable concept, urban regeneration is regarded as a process of achieving net-zero carbon emissions. How to promote the transition of cities towards net-zero carbon emissions and achieving urban regeneration through effective ways has become particularly important. At present, the direct carbon emissions of buildings still account for 8%

of total emissions. In the context of climate-neutral initiatives, improving building energy efficiency and achieving net-carbon emissions from buildings has become an unstoppable trend. Against this backdrop, this research aims to explore the influence of green infrastructure on building energy demand through qualitative and quantitative comparison approaches, and then assess whether green infrastructure can play a positive role in the facilitation of urban regeneration in terms of low-carbon development. To achieve this goal, the study divided the research process into three steps. First, a systematic review of research on restorative and regenerative urban design is conducted, aiming to explore "What are the differences and interrelationships between restorative and regenerative urban design?"; and also attempts to assess "Is the existing definition of restorative and regenerative urban design applicable?". The clear definition and distinction of restorative and regenerative urban design in this part will lay a crucial foundation and support for the subsequent research on NBS and building energy demand. The second step is designated to conduct climate-specific meta-analysis, which tends to quantify "How far are NBS reducing heating and cooling building energy demands in different climate zones?". The final step of this research involves conducting a series of building energy simulations to explore the energy performance of different green infrastructure types when implemented in different residential building categories across different climate zones. This part is used to answer, "How high is the dependency of heating and cooling energy demand on specific building types and climate zones energy?"

The systematic review of restorative and regenerative urban design revealed a significant difference between these two terms. The study then redefined them as that urban restorative design not only focuses on ecological aspects but also attempts to create a built environment that allows its users to thrive both physically and mentally. Regenerative urban design is more inclined to restore or create an ability. In addition, both terms are closely related to the SDGs; especially regenerative urban design. But restorative and regenerative urban design have developed independently in the field of urban design.

The results of steps 2 and 3 revealed that there is a positive influence of NBS technologies on building energy reduction. The assessed categories of NBS, including green roofs, green walls, trees, urban forests, green belts, wetlands, and trees, grasses, and near the river, as well as some combination of different types, have varying energy saving potential for building cooling, ranging from 0.58% to 60%. While the potential reduction in heating energy demand ranges from 0.58% to 60%. The extent of the reduction in both cases is significantly dependent on the NBS type and climate. It should be noted that some NBS types may lead to an increase in heating energy demand by between 5% and 25%. Specifically, the heating energy performance of green roofs and green walls is controversial; especially in climates characterized by year-round hot temperatures or those with long hot summers and short mild winters. However, the increased heating energy demand in these climates is offset by the savings in cooling energy in summer. In other words, green roofs and green walls still achieve net energy savings throughout the year. To a larger extent, the results of steps 2 and 3 confirm that NBS can play a positive role in the facilitation of urban regeneration in terms of low-carbon development. As such, this study suggests that NBS can be widely incorporated into regenerative urban design practices as an effective measure to promote low-carbon development. It is worth noting that while the study confirmed the positive role of NBS in reducing building energy demand, it also identified that maximizing the energy saving potential of NBS requires comprehensive consideration of multiple factors, such as vegetation characteristics, local climate characteristics, building types; etc.

Rapid urbanization has tested our ability to develop cities in a sustainable way. Undoubtedly, the majority of interventions compromise, to some extent, the natural environment. As such, urban development must go beyond simply maintaining sustainability. This requires the thinking of urban design to go beyond the logic of co-existence between man and nature. Rather, the logic of co-evolution between man and nature needs to be pursued. As such, urban design practice requires an integrated planning and design perspective that considers the built environment as a system in which humans and nature support and co-evolve with each other, thereby obtaining net positive benefits for social and natural dimensions. This is a crucial and essential shift from sustainable design to regenerative design.

Although green infrastructure is literally a specific application framed to address ecosystem issues, the results of this study confirmed that it is able to provide a reliable incremental path for the development of urban regeneration in terms of low-carbon aspect. As a comprehensive approach, regenerative design not only addresses the challenges of current urban development from a holistic perspective but also emphasizes the repair and establishment of the ability to meet the long-term sustainable development of the city. Improving building energy efficiency and reducing building energy consumption are also important aspects of regenerative design. Incorporating NBS into regenerative design will better promote the evolution of cities towards regenerative and low-carbon development. Because NBS emphasizes the use of natural systems to provide urban infrastructure functions (e.g., stormwater management), fostering a more sustainable and environmentally friendly urban evolution. Urban regenerative design can incorporate these natural infrastructures (e.g., green and blue infrastructure) into the planning and construction process. This not only allows urban areas to benefit from the ecosystem services provided by green infrastructure; such as increasing urban aesthetic value and biodiversity levels, but also improves microclimate conditions through the strategic placement of vegetation, offering increased shading at the pedestrian level and mitigating the urban heat island effect; thereby, indirectly reduces the cooling energy demand for the air conditioning system. In addition, in the process of regenerative design, it is necessary to improve the thermal insulation performance of buildings, optimize the design of ventilation and daylighting systems, and adopt some passive energy-saving technologies. These measures can further enhance the building's energy efficiency.

Furthermore, although this study evaluated and explored the building energy performance of NBS through the literature review and building energy simulation, it is necessary to acknowledge that the study only examined a limited number of NBS types and building categories. As such, future research endeavors should aim to further explore this field, particularly the neglected NBS categories (e.g., blue infrastructure, and various combinations of different NBS categories). Moreover, it is also important to assess the energy efficiency performance of NBS in a wider range of building categories to obtain a more comprehensive understanding of their overall effectiveness in achieving energy savings.

Appendixes

Appendix A. The structure of KPI.

Dimension	Sub-Dimension	Indicators
Economy	Productivity (social economy)	improvement of employment
		traditional industry improvement
		new capital investment
		increase the percentage of knowledge economy in GDP
		patents
		small and medium sized enterprises
Environment	Resource efficiency and consumption	renewable energy supply and consumption
		electricity supply and consumption
		low-carbon emission vehicle
		residential thermal energy supply and consumption
		energy use in transport
		CO2 emissions from household energy
		waste recycled
		building materials
		solid waste reuse and recycle
	Environmental restoration	air quality improvement
		decrease greenhouse gas emission (GHG)
		wastewater collection and reuse
		fresh water supply
		water quality
		urban heat island effect mitigation
		soil treatment
		enrich biodiversity
		stormwater management
		cleaning-up of the polluted deposits
Society	Community benefit	gender income equality
		secure household income
		decrease the poverty rate
		crime rate
		adult literacy
		housing
		education quality
		education enrollment
		local food production
		stability of food supply
		Physical health and mental health
		life expectancy
		human right
		citizen participation
	Building/space restoration	public building sustainability
		resource efficiency building (gas, water, electricity)
		green area accessibility

		quality of green space
		recreational facilities
		land use
		bicycle and pedestrian infrastructure improvement
	Culture regenerative	heritage protection
		cultural infrastructure
		making sense of space
	Urban governance	policy guidance and support
		public and social service
Scale	Urban scale	No category
	Regional scale	
	District scale	
	Neighborhood scale	
UN sustainable Development goals	No category	

Appendix B. The involved sub-dimension in restorative and regenerative urban design (the papers of restorative and regenerative urban design are indicated by à and P, respectively. The presence of these two symbols in the same article represents that this article mentions both disciplines simultaneously).

Reference	**Economy**	**Environment**		**Society**				**Scale**	**UN SDGs**
	productivity	**resource efficiency and consumption**	**environmental restoration**	**community benefit**	**building/space restoration**	**culture regenerative**	**urban governance**	**district/ urban/ regional/neighborhood**	
Zhang, (2014)	**P**	**P**	**P**	**P**	**P**	**P**			SDG 3, 4,6, 5
Elmqvist et al. (2015)			**P**						SDG 13
Perales-Momparler, (2015)					**P**				SDG 3, 17
Sonetti, et al. (2019)			**P**		**P**				SDG 11
Yakovleva et al. (2019)			**à**						SDG 15
Joye et al. (2018)			**à**						SDG 13
Girardet, 2017			**P**						SDG 8,13
Allison, (2017)	**P**	**P**	**P**					**P** urban scale	SDG 7,8, 12,
Alsubeh, (2017)					**P**				SDG 11
Serrano et al. (2016)				**à**	**à**				
Haas & Locke (2018)	**P**				**P**	**P**	**P**	P urban scale	SDG 8,11
Zhang (2014)			**P**						SDG 14, 15
Gioffrè (2019)					**P**				SDG 14, 15
Morash et al. (2019)			**P**						
Houston			**à**					**P**	SDG 6

(2020)								urban scale	
Toros, (2015)			à						SDG 11
Elias & Marsh (2020)	P								SDG 12
Nunes et al. (2013)				P					SDG 3, 10
Cerreta et al. (2020)					P				SDG 11
Hens, (2005)				P					SDG 3
Waldron et al. (2013)			P						
Akturk, (2016)					P				
Cameron (2006)		P	P						
Roberts (2000)			P						
Kong et al. (2022)					P				SDG 11
Lehmann, (2010)			à	à					
Zelenski et al. (2015)			à						SDG 14, 15
Twohig & Jones, (2018)			à						SDG 14, 15
Osman & Jose (2013)					P				
Du, (2012)					P				
Hobbs & Cramer (2008)	P	P	P	P	P		P		SDG 3, 6,7,8,11
Shi et al. (2020)			à	à					
Du et al.(2020)			à	à					SDG 3
Choi, (2004)	P	P	P		P	P	P		SDG 6, 7, 12
Zhang et al. (2015)	P	P	P	P	P				SDG 6, 7, 8, 12
Global BRE (2011)	P	P		P	P				SDG 8, 12
Ahvenniemi et al. (2017)			P						SDG 7, 13
Fang et al. (2021)	P								SDG 7
Thomson & Newman (2020)	P		P	P	P		P		SDG 3, 8,13,17
Chan et al. (2019)						P			
Mehaffy et al. (2019)	P		P	P	P		P		
Standish et al. (2013)			à						SDG 14, 15
Thompson et al. (2020)			à						
Lewin, (2013)			à						SDG 15
United Nations (2022)			à	à					SDG 3, 15
Nunes, et al. (2022)			à P	P		P			SDG 3, 11, 13
Martinez et al. (2008)			à						SDG 3, 13

Espinosa et al. (2016)			**à**						SDG 15
Espinosa et al. (2016)			**à**						SDG 13
Steiner, (2014)	**à**	**à**	**à**	**à**	**à**				SDG 3, 7, 8, 14,15
Ferreira, (2008)			**P**						
Holden et al. (2016)					**P**				SDG 6, 7, 12
Nunes et al. (2014)	**P**		**P**		**P**				
Girardet, (2014)	**P**		**P**	**P**			**P**		SDG 11
Cole et a. (2013)		**P**	**P**	**P**					
Girardet. (2014)	**P**			**P**					SDG 3, 7
Cole et al. (2013)			**P**		**P**	**P**			SDG 3
Kazimee & Bartuska (2004)			**P**					**P** regional scale	
Brown et al. (2018)		**P**	**P**	**P**	**P**			**P** urban scale	SDG 3, 7, 13
Lejano et al. (2015)							**P**		
Hale & Sadler (2012)							**P**	**P** neighborhood scale	SDG 11
Tang et al. (2016)	**P**			**P**	**P**				SDG 11
Hubbard, (1996)	**P**								
Couch et al. (2011)			**P**						SDG 15
Waldron et al. (2013)				**P**					SDG 3
Afacan, (2015)		**P**							SDG 7
Shafray & Kim (2017)			**P**	**P**					
Stouten, (2016)				**P**					SDG 3, 11
Palazzo & Rani (2016)			**P**						SDG 13
Haas & Locke, (2018)							**P**		
Natividade-Jesus et al. (2019)							**P**		SDG 7
Mehan, (2016)	**P**		**P**	**P**					SDG 3, 8
Serrano-Jiménez et al. (2019)				**P**					
Yalazi et al. (2018)	**P**								SDG 9
Rovai et al. (2014)				**P**					
MacGregor & Wathen (2014)	**P**								

Chan et al. (2019)	**P**		**P**	**P**		**P**			SDG 3
Douvlou & Ryder (2007)							**P**		SDG 11
Atkinson et al. (2019)					**P**				SDG 17
Kamrowska-Załuska et al. (2018)			**P**		**P**				SDG 14, 15
Serrano et al. (2016)				**P**					SDG 3
Dargan, (2009)			**P**	**P**				**P** regional scale/urban scale	
Osman & Jose (2013)			**P**			**P**			
Tallon, (2010)									
Morseletto, (2020)		**P**							SDG 7
Hemphill et al. (2004)					**P**				SDG 3, 8, 12
Weingaertner & Barber, (2010)	**P**								SDG 8
Imrie, (2001)			**P**						SDG 15
Syms, (2000)	**P**		**P**						
Cameron, (2006)			**P**						
Palamar, (2010)			**P**						SDG 14, 15
Bleˇci´c et al. (2018)							**P**		
Zari & Storey (2007)					**P**				
Gioffrè, (2019)			**P**						SDG 12
Zhang et al. (2015)					**P**				
Choi, (2004)			**à**						SDG 14, 15
Xia, (2015)			**à**						
Harris et al. (2006)			**à**						SDG 13
Yu et al. (2012)			**à**						SDG 14, 15
Hobbs & Cramer, (2008)			**à**	**à**					SDG 14, 15
Karmanov & Hamel (2008)			**à**						SDG 3
Abkar et al. (2011)			**à**						SDG 3
Seabrook, (2011)			**à**						SDG 13
Cui & Fang (2015)			**à**						
Elmqvist et al. (2015)			**à**	**à**					SDG 3, 15
Morash et al. (2019)			**à**						SDG 15
Thomson & Newman							**P**		

(2020)									
Zuo et al. (2018)			**P**						SDG 15
Houston, (2020)			**P**						
Gibbons et al. (2020)			**P**						
Pedersen & Hecht, (2020)			**P**						SDG 15
Giusti & Samuelsson, (2020)				**P**					SDG 3
Cerreta, (2020)				**P**					SDG 11
Natanian & Auer (2020)	**P**								SDG 7
Elias & Marsh, (2020)			**P**						SDG 2
Thompson, (2020)		**à**							SDG 6
Cattaneo et al. (2020)					**P**				SDG 11

Appendix C. The publications in different NBS types associated with the energy demand related percentage based on the Köppen climate classification.

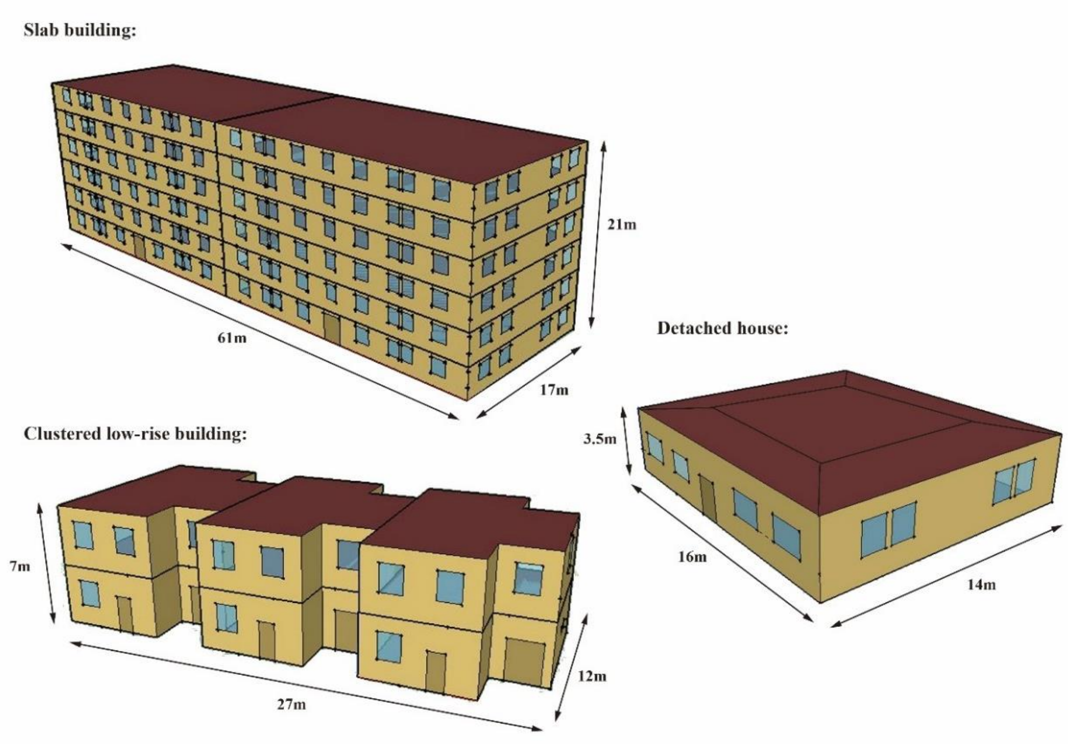
Extensive green roof				
Reference No.	Climate zone	Annual cooling energy use	Annual heating energy use	Annual cooling and heating energy use
Zhang et al. (2022)	Cfa	56.1%	22%	
Abuseif et al. (2021)	Cfa	7% - 8%		
Tsoka et al. (2021)	Csa	2.92%	5.28%	
Tsoka et al. (2021)	Cfa	2.56%	4.45%	
Tsoka et al. (2021)	Cfb	3.5%	3.5%	
Anwar et al. (2021)	Csa	50%	31%	
Ragab & Abdelrady (2020)	Bwh	39.7%		
Ávila et al. (2020)	Bwh	45%	-25%	
Ávila et al. (2020)	Cwb	90%	-23% - -11%	
Ávila et al. (2020)	Bsh		-25%	
Ávila et al. (2020)	Aw	45%		
Ran et al. (2020)	Dfa			2.1%
Ran et al. (2020)	Dwa			5.1%
Ran et al. (2020)	Bwk			18.1%
Ran et al. (2020)	Dwc			26.4%
Ran et al. (2020)	Cwa			6.4%
Ran et al. (2020)	Cwb			15.2%
Ran et al. (2020)	Cfa			6.0%
Porcaro et al. (2019)	Csa			55%
Cascone et al. (2018)	Csa	31.8% - 35.2%	1.8% - 9.5%	

Jahanfar et al. (2018)	Dfb			13%
Stamenković et al.(2018)	Cfa	Less than 1%		
Gao et al. (2017)	Cfa	25%	-9.9%	
Ziogou et al.(2017)	Csa	20%	25%	
Boafo et al.(2017)	Dfa	2.3% - 2.7%	3.5% - 5.4%	
Ran & Tang (2017)	Cfa	26.7%		
Costanzo et al. (2016)	Csa			10%
Costanzo et al. (2016)	Cfa			5%
Refahi et al.(2015)	Bwh	19.4%	-5.6%	
Ascione et al.(2015)	Csa	17%		3.4%
Feng & Hewage (2014)	Csb	3.2%	0.56%	
Moody & Sailor (2013)	Cfa		2%	
Moody & Sailor (2013)	Csb			2%
Mahmoodzadeh et al.(2019)	Dfb			8.3%
Mahmoodzadeh et al.(2019)	Cfb			6.2%
Ascione et al. (2013)	Csb	1.1% - 11%		
Ascione et al. (2013)	Csa	-0.9% - 11%	5.3% - 17.1%	
Ascione et al. (2013)	Cfb	-0.8% - 10%	5.3% - 8.2%	
Ascione et al. (2013)	Dfb	-1.4% - 10.5%	5 - 6%	
Yao et al. (2020)	Cfa	6.1%	26%	
Begum et al. (2021)	Aw	45%		
Aboelata (2021)	Bwh	3.2%		
Evangelisti et al.(2020)	Csa	50%	30%	
Zheng & Weng (2020)	Csb	1.2% - 6.9%		
Gholami et al.(2020)	Cfa		5%	
Ebadati et al. (2020)	Csa	16.3%		
Ebadati et al. (2020)	Bwh	23%		
Zhang et al. (2019)	Cfa	16.7%		
Seyedabadi et al. (2021)	BSk			8.5%
Gagliano et al. (2014)	Csa	44%	34%	
Chen & Lee (2013)	Cfa	48.67%		
Permpituck et al. (2012)	Aw	31.7%		
Algarni et al. (2022)	BWh	7.09%	13.7%	
Lin et al. (2021)	Cfa	9.88%		
Battista et al. (2021)	Csa	10.8%		
Pianella et al (2020)	Cfb	57.3%	40.8%	
Yaghoobian et al.(2015)	BWh	5%		
Semi- intensive green roof				
Zhang et al. (2022)	Cfa	13.3% - 57.7%	36.4% - 53%	
Koroxenidis et al. (2021)	Csa	2.19%	5.43%	
Koroxenidis et al. (2021)	Cfa	1.81%	2.36%	
Koroxenidis et al. (2021)	Cfb	2.5%	2.17%	
Bevilacqua et al. (2020)	Csa	28.4% - 43.8%	7.1% - 35.3%	

He et al. (2018)	Cfa	10.2%	27.5%
Pianella et al. (2020)	Cfb	62.7%	34.4%
Intensive green roof			
Zhang et al. (2022)	Cfa	13.3% - 58.6%	46.2% - 58.9%
Abuseif et al. (2021)	Cfa	22% – 35%	
Koroxenidis et al. (2021)	Csa	1.33%	8.3%
Koroxenidis et al. (2021)	Cfa	0.96%	1.16%
Koroxenidis et al. (2021)	Cfb	1.35%	0.84%
Peñalvo-López et al.(2020)	Cfa	25%	-12%
Berardi (2016)	Dfb	4.1%	8.6%
Kokogiannakis et al.(2017)	Cfa	1.7% - 14.3%	5.4% - 19%
Permpituck et al. (2012)	Aw	37.1%	
He et al. (2021)	Cfa	12.3%	41.6%
Pianella et al. (2020)	Cfb	66.2%	30.6%
Gagliano et al. (2016)	Csa	81%	15%
Indirect green facade			
Bakhshoodeh et al.(2022)	Csa	25% -35%	
Perez et al. (2022)	Csa	30% - 54%	-5.4%
Coma et al. (2022)	Csa	16.7% - 43.4%	-9.3% - -6.2%
Coma et al. (2017)	Csa	33.8%	
Wong et al. (2016)	Cfa	76%	
Pan et al. (2016)	Cfa	16%	
Peng et al. (2020)	Cfa	3.2% - 11%	
Zheng et al. (2020)	Cfa	11.5%	
Varghese et al. (2020)	Cfa	15%	
Tan et al. (2020)	Cfa	25%	18%
Living wall			
Coma et al. (2020)	Csa	27.8% -50.3%	-9.5% - -5.9%
Poddar et al. (2017)	Dfa	17%	60%
Chafer et al. (2021)	Cfb	26%	
Dahanayake et al.(2017)	Cfa	3%	
Coma et al. (2017)	Csa	58.9%	
Feng et al. (2014)	Csb	7.3%	1.6%
Bevacqua et al. (2018)	Csa	41%	
Poddar et al. (2017)	Dfa	3% - 7%	
Direct green facade			
Cameron et al. (2015)	Cfb		21% - 37%
Trees (Daily energy use)			
Tsoka et al. (2021)	Cfa	54%	
Aboelata et al. (2019)	Bwh	2.3% - 3.9%	
Hsieh et al. (2018)	Cfa	10.3% - 15.2%	
Rouhollahi et al. (2022)	Cfa	10%	
Palme et al. (2020)	Csa	17.3%	

Palme et al. (2018)	Csa	50%		
Morakinyo et al. (2018)	Cfa	50%		
Skelhorn et al. (2018)	Cfb	1.6% - 2.7%		
Skelhorn et al. (2016)	Cfb	1.7%		
Calcerano et al. (2016)	Csa	11%		
Green belt (Daily energy use)				
Feng et al. (2022)	Cwa	2.1%		
Urban forest (Monthly energy use)				
Moss et al. (2019)	Cfb	1.28% - 13.4%		
Toparlar et al. (2018)	Cfb	11.4% - 13.9%		
Tree, grass, and the near the river				
Ayad et ai. (2019)	Bwh	6.73% - 10.84%		
Wetland (Monthly energy use)				
Shen et al. (2016)	Cfa	10.8%		
Green roof and Green walls				
Anwar et al. (2021)	Cfa	27.5%	35%	
Hao et al. (2020)	Cfa	7% - 8%		
Li et al. (2019)	Cfa	28.5%	28.3%	
Andric et al. (2020)	BWh			3%
García et al. (2019)	Bsk	34.6%		
Green roof and Green belt				
Santamouris et al. (2018)	Cfa	10%		
De Munck et al. (2018)	Cfb	42%	4%	
Green roof, Green wall and trees				
Dardir et al. (2021)	Dfb	28.6% - 42.4%		
Gros et al. (2016)	Cfb	3% - 35%		
Green roof, Green wall, trees and grass				
Zhang et al. (2017)	Dfa	5%		

Appendix D. The visualization of geometry of the selected three residential building types in the *OpenStudio*.



Slab building:

Detached house:

Clustered low-rise building:

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