The University of Pecs

Faculty of Engineering and Information Technology

Breuer Marcel Doctoral School of Architecture

Ph.D. Thesis Statement

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degree of PhD in Architecture Engineering

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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1. Introduction

'A natural system consists of highly productive and interconnected subsystems producing and recycling goods in a highly effective way. These "ecosystems" evolve to diverse but locally optimal equilibriums between productivity, adaptability, and resilience' (Maes & Jacobs, 2017, p. 122).

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 (Ferreira, 2008). In contrast to urban restorative design, urban regenerative design further seeks net-positive environmental benefits (Pedersen Zari, 2012). In other words, it aims to promote the co-evolution of humans and natural systems in a mutually beneficial way (Mang & Reed, 2020). As part of the restorative and regenerative design, Nature-Based Solutions (NBS) play a crucial role in promoting the low-carbon city concept. NBS was accepted by scholars in 2013, and then it has been regarded as an important means to support urban regenerative design (Enzi et al., 2017). NBS was defined by the International Union for Conservation of Nature (IUCN) 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). Against the background of climate neutrality initiatives, many organizations also believe that NBS should play a key role in promoting environmentally friendly and energy-efficient living. For example, the European Commission's Document 249 of 2013 and Directive 2018/844 on energy efficiency highlight the potential of NBS as a natural tool to decrease energy demand in buildings (Campiotti et al., 2022). Currently, urban areas are responsible for nearly 70% of all greenhouse gas emissions, with buildings alone contributing over 8% of direct energy consumption in cities (International Energy Agency, 2022). Improving building energy efficiency and reducing building energy consumption has become one of the keys to achieving climate neutrality initiatives. From the perspective of urban development, it is necessary to integrate NBS more effectively into the process of urban design and planning to promote the development and realization of low-carbon cities. Green infrastructure, as a significant component of NBS, is a flexible and multifunctional ecological network in urban areas (Coletta et al., 2021; Laine et al., 2020). Although the positive role of green infrastructure in eco-environmental management has been confirmed, it is unclear whether it can provide a reliable incremental path for the development of low-carbon cities.

This thesis statement briefly presents the results of my past four years of work on the exploration and evaluation of the role of green infrastructure as part of restorative and regenerative urban design approach in promoting the development of low-carbon cities.

After careful review of the research field, it can be stated that some of the high-level terms; e.g., restorative and regenerative urban design, are often misunderstood. Therefore, research also needs to clarify some of the basics of my investigation (He & Reith, 2022). Furthermore, this research built on the recognition that although NBS, literally is a specific application framed to address ecosystem issues, the management or restoration of ecosystem functions can play an important role in promoting the achievement of low carbon-related urban regeneration. The systematic review of research in this field indicates that the field is currently evolving. Many studies verified the effectiveness of various exploratory approaches, such as empirical studies, building energy modeling, or the combination of both methods. Moreover, a wide range of tools and techniques that are now available in this field has been extensively developed. This provides significant support for exploring and evaluating the research perspectives on avoiding and reducing emissions proposed in the 'Climate Action' work of Gray et al. (2021).

2. Aim of the research

The primary purpose of this study is to explore the potential of NBS in promoting urban regenerative design. Specifically, the study aims to demonstrate, through qualitative and quantitative comparative analysis, whether green infrastructure can effectively contribute to the reduction of building carbon emissions and the avoidance of building carbon emissions. To achieve this aim, the research process was divided into three parts, and the general research questions are:

- Firstly, 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 “Is the existing definition of restorative and regenerative urban design applicable?”.
- 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?”.
- Thirdly, building energy simulations were conducted to answer the question: "How high is the dependency of heating and cooling energy demand on specific building types and climate zones energy?". Therefore, three different housing types and three different climate zones were selected for cross-evaluation.

3. Research Methodology

To achieve the aim, the study employed a comprehensive research approach that combined the theoretical part and empirical part.

- The first part is the theoretical section, which refers to conducting literature studies that respectively correspond to the field of restorative and regenerative urban design, as well as the field of NBS and building energy demand. The former review aims to explore the difference between restorative and regenerative urban design as well as their association with United Nations Sustainable Development Goals (SDGs). For example, *figure* 1 shows the Key Performance Indicator (KPI) analysis used to analyze the differences between these two terms. The later specific climate review was designated to assess the energy performance of NBS typologies on buildings under different climate conditions, as well as explore the research methods, technique tools; etc. For instance, *figure* 2 shows the distribution of studies in different climatic zones in geographic distribution analysis.

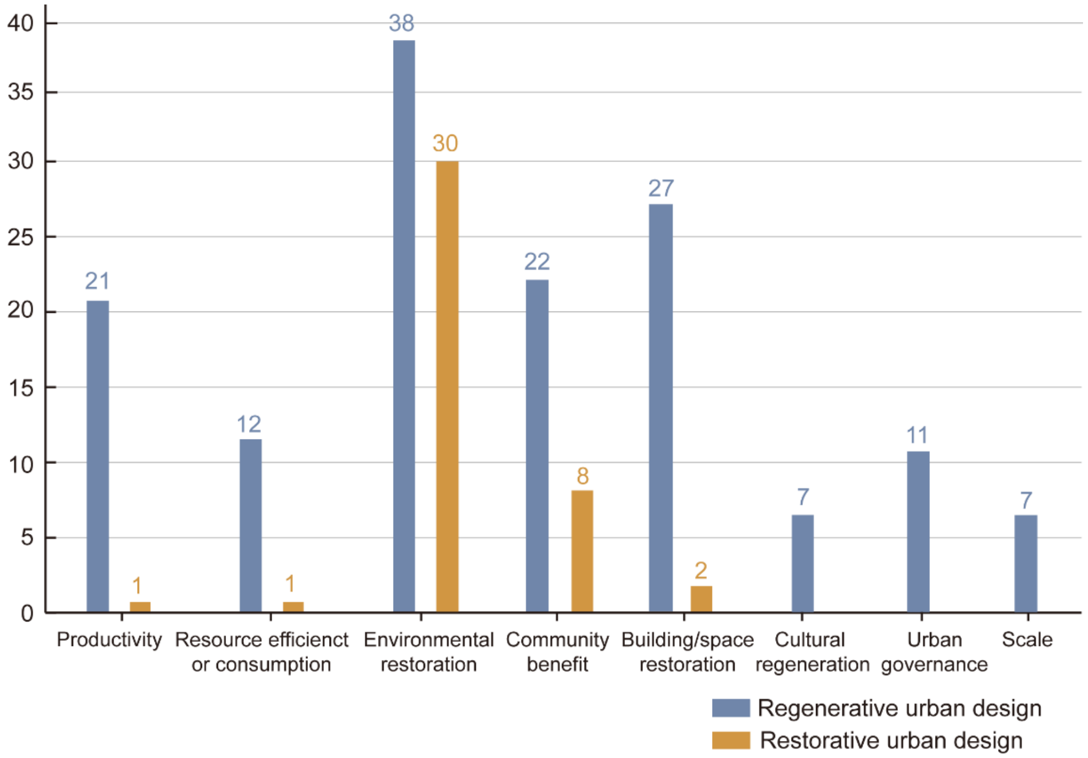


Figure 1. *The differences between restorative and regenerative urban design by KPI analysis*

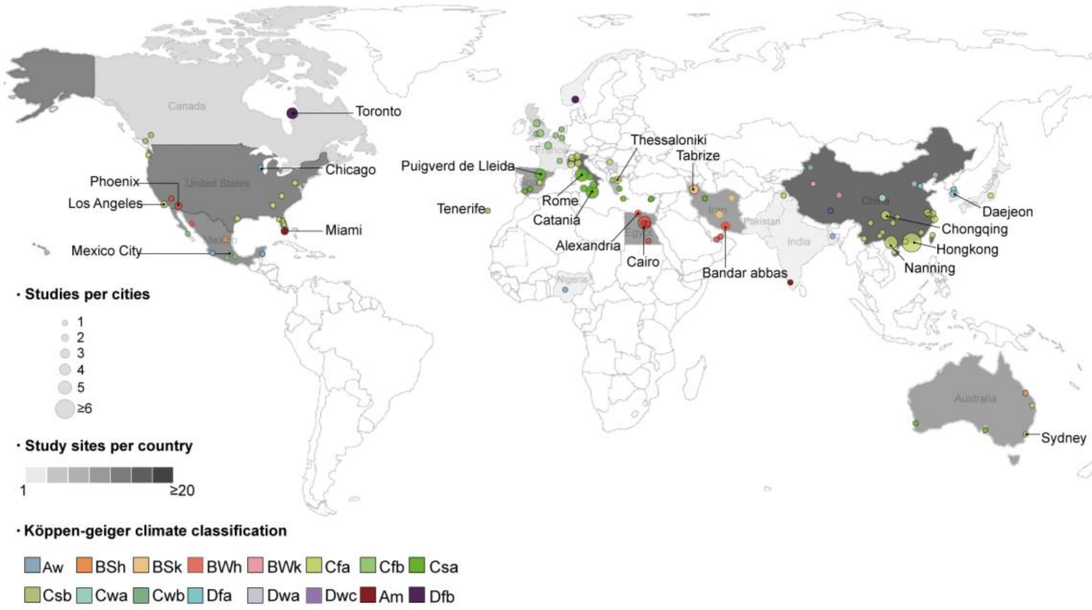


Figure 2. *Distribution of studies in different climatic zones in geographic distribution analysis*

· The second part refers to the direct verification of the impact of different green infrastructure categories on the energy demand of residential building types in different climate zones through Building Energy Modeling (*Figure* 3). Specifically, study selected three European cities for building energy simulations, including Rome (Italy), Szombathely (Hungary), and Oslo (Norway), which respectively represent the hot-summer Mediterranean climate, temperate oceanic climate, and warm-summer humid continental climate. Unlike most studies that straightly rely on open-source weather data collected by rural weather stations or airports, this study generated urban weather data based on the characteristics of the urban built environment of each city by using the *Urban Weather Generator (UWG)* tool. Furthermore, the study selected three commonly owned residential building types in these three countries by using the Typology Approach for Building Stock Energy Assessment (TABULA); that is, slab building, detached house, and clustered low-rise building. It is worth mentioning that TABULA is one of the important components of the European Smart Energy Program that supported by the European Commission. Therefore, it is widely accepted by scholars and used in academic research. Based on the above steps, the study evaluated the influence of green roofs, green walls, or a combination of both on the annual cooling and heating energy demand of three residential building types in three different climatic zones.

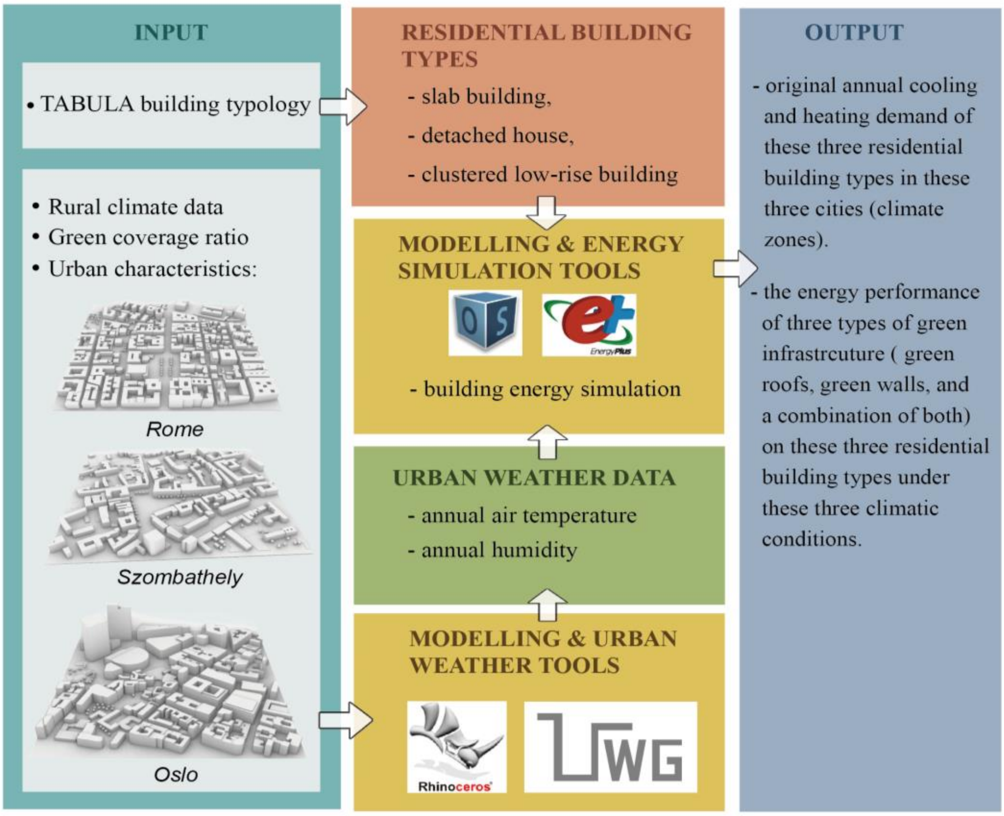


***Figure 3**. Building energy simulation framework*

4. Principal findings

· Finding 1

He & Reith, (2022), [1]

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, in some cases, the definitions of restorative and regenerative urban design are often mixed up, as they only roughly describe their respective characteristics and do not involve specific design parameters or indicators. To clarify the uncertainties, I employed a comprehensive method to explore the interrelationships and differences between restorative and regenerative urban design as well as their association with the United Nations Sustainable Development Goals (SDGs)

1.1 By using Key Performance Indicator (KPI) analysis, I found that urban restorative design involves 5 out of 8 sub-dimensions. In contrast, urban regenerative design involved all the sub-dimensions. Based on the significant differences between these two terms, I redefined restorative and regenerative urban design. Urban restorative design is not as defined as most studies of maximizing certain ecological goals. Instead, it attempts to restore the relationship between humans and nature as well as integrate nature into life, creating a built environment that thrives 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.

1.2 Based on the detailed KPI analysis, I further found that restorative and regenerative urban design is related to 8 and 15 of the 17 SDGs, respectively. This means that both terms have a significant relationship with SDGs; especially urban regenerative design. This proves that restorative and regenerative urban design will provide significant support for the practice of sustainable development.

1.3 By investigating the citations of all publications with the help of *VOSviewer* tool (*Figure* 4), I discovered that there is no significant internal relationship between restorative and regenerative urban design. In other words, these two terms are developing independently.

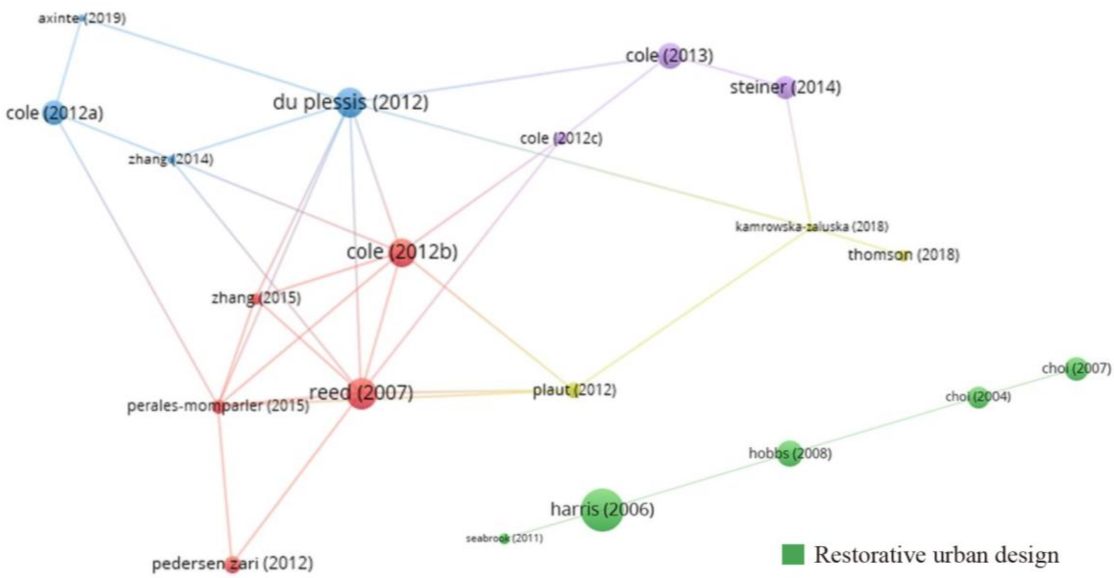


Figure 4*. Citation network analysis between restorative and regenerative urban design*

· Finding 2

I conducted a climate-specific review on how much NBS influences building cooling and heating energy consumption based on previous studies in this field by using the Köppen-Geiger (*Table* 1) climate classification. Seven NBS categories were evaluated for their influence on energy performance in different climatic characteristics at the building scale, including green roofs, green walls, trees, urban forests, green belts, water features (bioswale, wetland, water fountain, river, lake, stream), and the combination of trees, grass and near the river.

Table 1. The description of each related climate (Köppen Climate Classification. 2022)

Code of each climate	**Descriptions**	**Main character**

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

- I detected that the studies in this research field show an obvious characteristic of narrow focus. Specifically, most of the studies concentrated on a few particular NBS categories and climate zones; especially on the extensive green roofs and the humid subtropical climate, and the hot summer Mediterranean climate. In addition, study on the impact of blue infrastructure on building energy performance has not attracted the attention of scholars.
- Scholars and practitioners commonly accept the positive effect of NBS on the energy demand of buildings. Based on a critical review of the literature, I found that the impact of NBS significantly depends on the specific NBS types used and the climate zone where it is applied.

2.1 By conducting the evaluation analysis of the energy performance of different NBS types on buildings, I discovered that the seven NBS categories evaluated all had an absolute effect on building cooling energy reduction. The proportion of cooling energy saved depended on the NBS types and climate zones. *Figures* 5 to 8 show the energy performance of different NBS types on buildings in this analysis. In addition, I observed that green roofs can reduce annual cooling energy demand by nearly 50% in climates with long and hot summers or year-round heat. However, the effect of NBS on building heating energy reduction among these seven NBS types was inconsistent, especially on green roofs and green walls. These two types have the possibility of increasing heating energy demand in the climate zones characterized by year-round hot temperatures or those with long hot summers and short mild winters. In year-round hot climates, green roofs could increase heating energy demand by around 25%. However, the proportion of increased demand for heating energy is offset by the cooling energy saved during the summer. Thus, I suggest 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 the summer months. In addition, in the climate of hot throughout the year, river reduced the building cooling energy needs by 8.2%. In contrast, the combination of trees and grassland is only 4.8%. Even by increasing the canopy coverage ratio, river still can save more cooling energy than the combination of trees and grassland. As such, I recommend that it is necessary to reasonably plan blue infrastructure and properly design water features in existing urban areas.

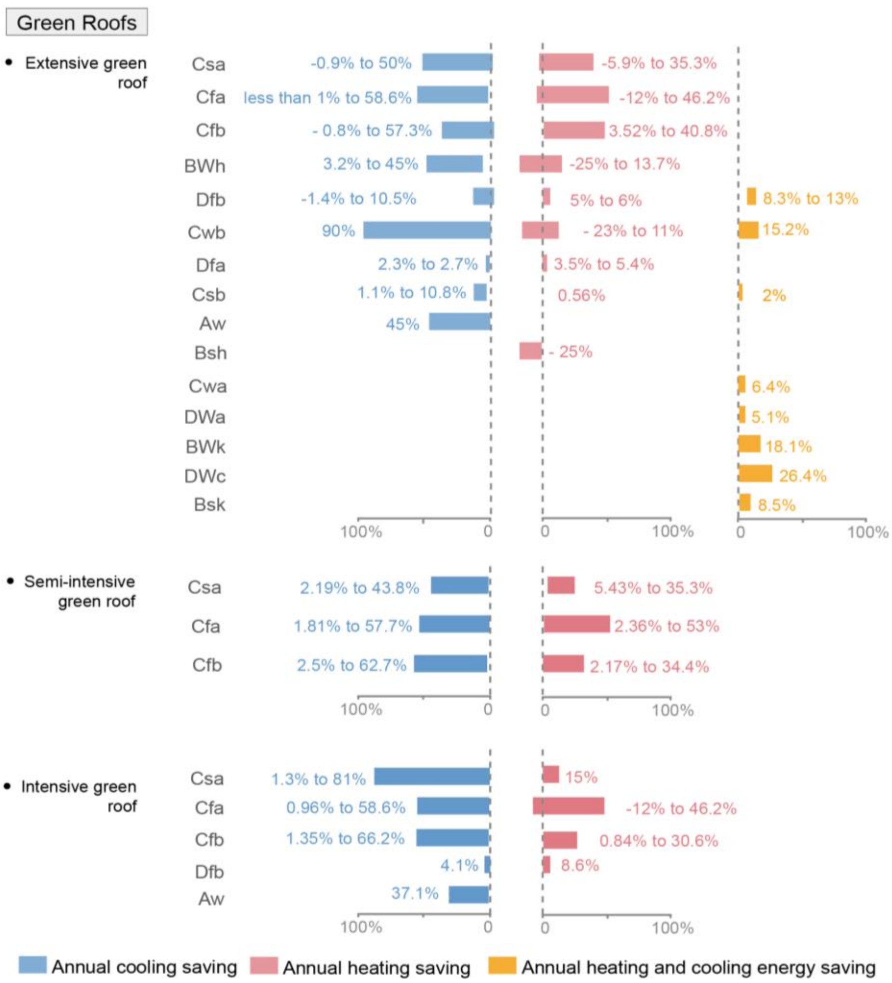


Figure 5*. The energy performance of green roofs in different climates*

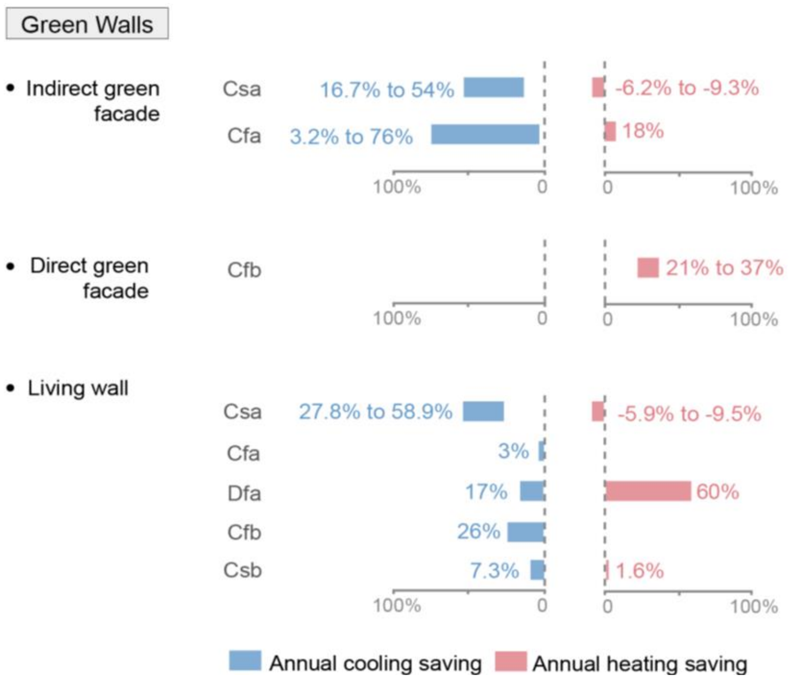


Figure 6*. The energy performance of green walls in different climates*

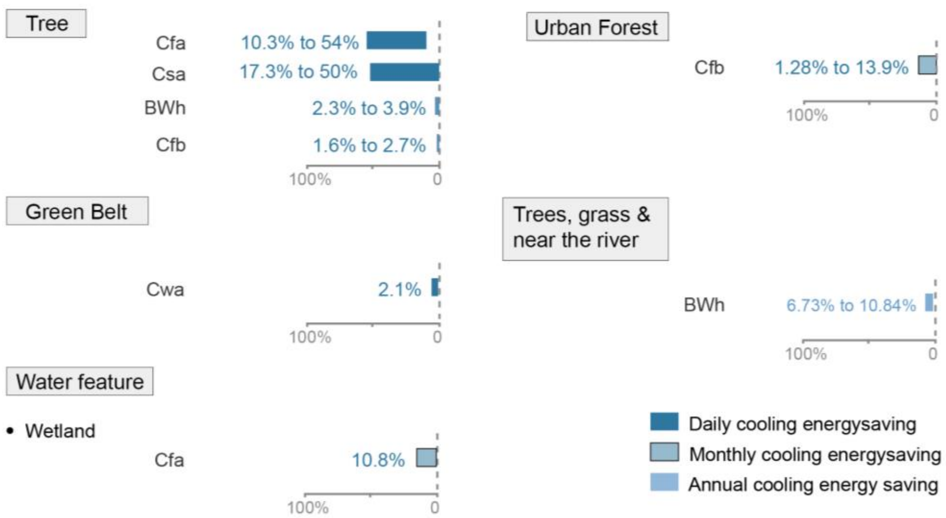


Figure 7*. The energy performance of trees, urban forests, green belts, water features, and the combination of trees, grass and near the river in different climates*

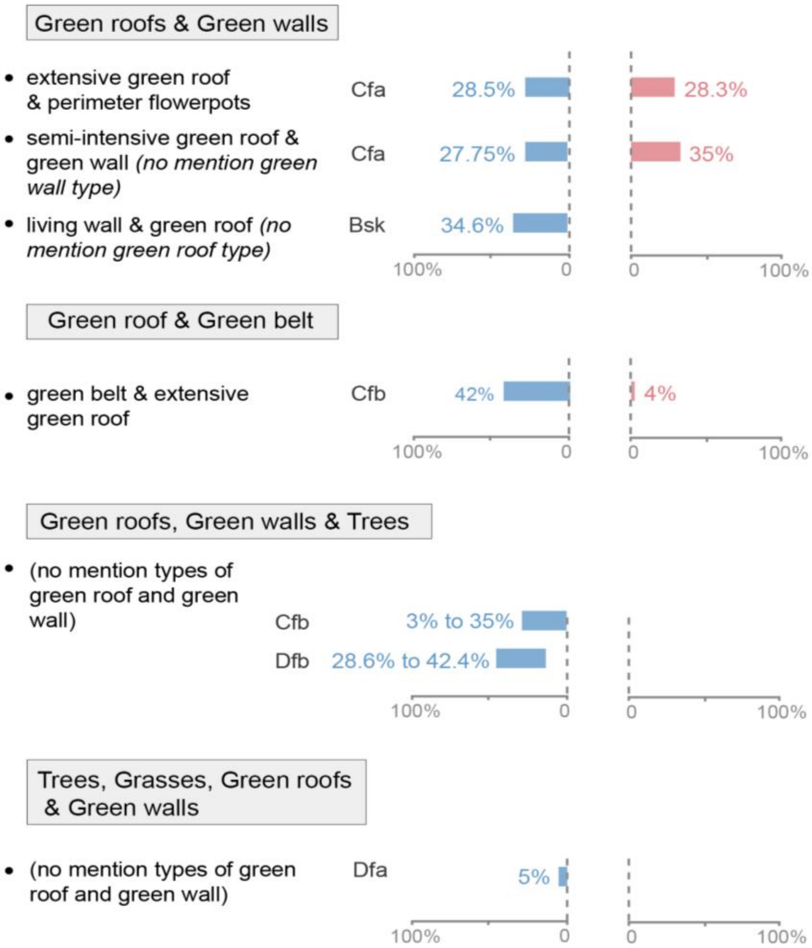


Figure 8. *The energy performance of different NBS types combinations in different climates*

2.2 I compared the range of distribution for numerical values of green roofs and green walls in the current widely examined climate zones of Csa and Cfa (*Figur*e 9). I found 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. As for green roofs in climate zone Csa, the IQR of reduced cooling energy 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 (mean: 28.63; median: 30.12). As such, I deduced that green walls can perform better cooling energy saving performance than green roofs in this climate. Further, I 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. I detected that the IQR of green walls in this climate zone 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.

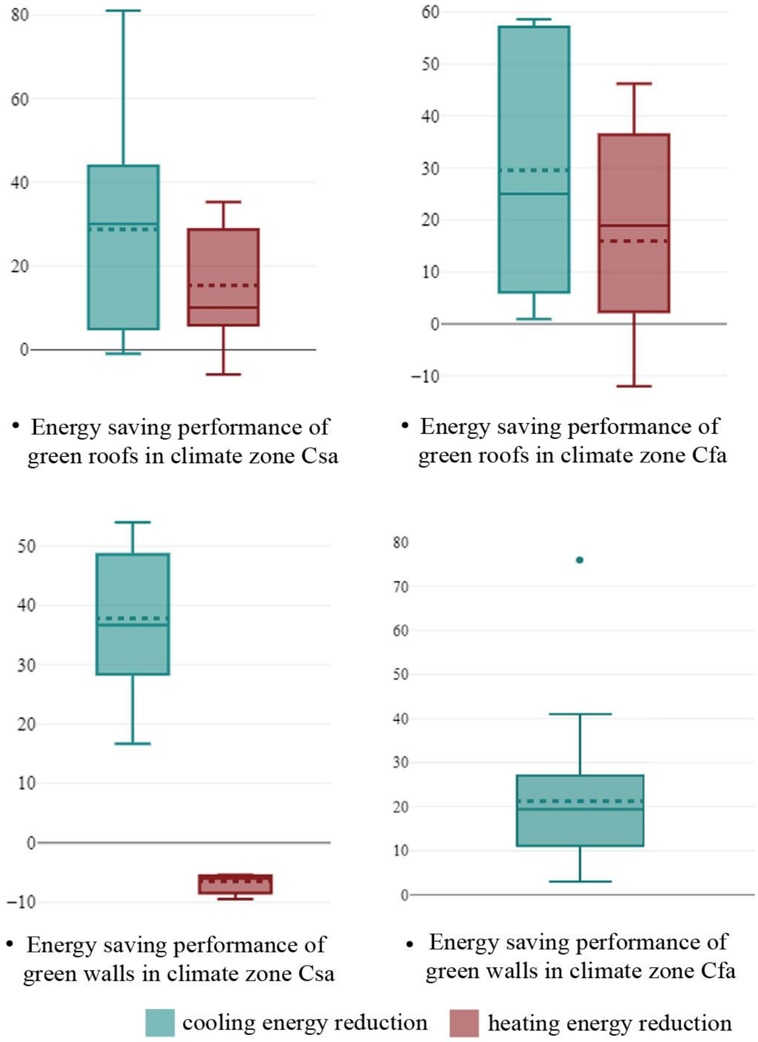


Figure 9. *The energy performance of green roofs and green walls in the climate zones of Cfa and Csa*

2.3 With my review, I confirm that to maximize the energy-saving potential of NBS, it is crucial to comprehensively consider the combination of multiple factors, such as local climate characteristics, vegetation configuration, characteristics of the vegetation itself, and appropriate green infrastructure types, rather than maximizing an individual factor.

- **Finding 3**

Using the urban meteorological data generated by the *UWG* tool, I evaluated the energy performance of green roofs, green walls and their combination on the slab building, detached house, and clustered low-rise building, which is commonly owned in Roma, Szombathely and Oslo. These three cities represent the hot-summer Mediterranean climate, temperate oceanic climate, and warm-summer humid continental climate, representatively.

3.1 I further detected that the applying green roofs on slab building, clustered low-rise building and detached house can reduce 22%, 34% and 42% of heating energy demand in the Mediterranean climate, respectively (*Figure* 10). In contrast, green walls can only decrease 13.8% and 15.8% heating energy demand for clustered low-rise building and detached house; also, it increased the heating energy requirement of slab building by 5%. This indicates that green roofs have better heating energy reduction performance than green walls in the Mediterranean climate. Moreover, I noticed that although green walls can increase heating energy demand in this climate, the cooling energy reduction is significant (over 40%). In other words, green walls still achieved net energy reduction over the year in the Mediterranean climate. In addition, the combination of green roofs and green walls on these three residential building types can reduce at least 31% and 21% of annual cooling and heating energy demand in the Mediterranean climate.

3.2 In warm-summer humid continental climate (*Figure* 11), I found that the combination of green roofs and green walls is able to reduce 55%, 57.7% and 47.6% of heating energy demand on the slab building, detached house and cluster low-rise building, respectively. In contrast, green walls correspondingly reduced 41.9%, 13.98% and 13.6% heating energy requirement. Green roofs decreased 27.8%, 32.3% and 27.8% heating energy demand of slab building, detached house and cluster low-rise building, respectively.

Furthermore, green walls reduced cooling energy demand (36.9%- 48.4%) more than green roofs (8.3%-19.2%) in these three residential building types. Meanwhile, the cooling energy reduction of the combination of green roofs and green walls ranges from 44.1% to 66.2%. As such, I confirmed that the annual cooling and heating energy reduction 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 warm-summer humid continental climate.

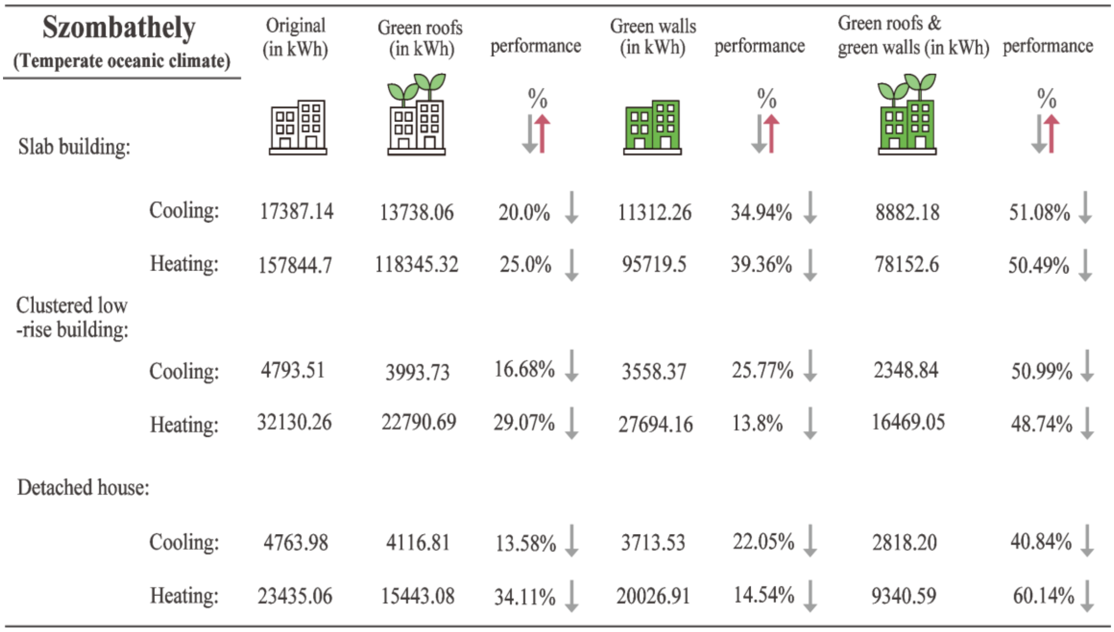
3.3 By undertaking building energy simulation, I observed that green roofs, green walls and a combination of both have net positive cooling and heating energy reductions on these three residential building types in temperate oceanic climate (*Figure* 12). Green roofs respectively decrease cooling energy needs by 13%, 16.7% and 20% for detached house, clustered lower rise building and slab building. The corresponding cooling energy reductions of green walls for these three building types are 22%, 25.8%, and 34.9%, respectively. The combination of green roofs and green walls reduce the cooling energy demand of detached house, clustered lower rise building and slab building by 40.84%, 50.9% and 51.08%, respectively. This means that the cooling energy-saving performance of the combination of green roofs and green walls is far more than that of the green wall and green roof categories applied alone to these three building types. Further, the integration of green roofs and green walls can maximum reduce heating energy demand by 60.14% for detached house. In contrast, green roofs and green walls respectively decreased 34.11% and 14.54% heating energy requirements for detached house.

Roma (Mediterranean climate)		Original (in kWh)	Green roofs (in kWh)	performance %	Green walls (in kWh)	performance %	Green roofs & green walls (in kWh)	performance %
Slab building:								
	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% ↓
Clustered low -rise building:								
	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% ↓
Detached house:								
	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% ↓

***Figure 10**. The energy performance of green roofs, green walls and a combination of both on three residential building types in the Mediterranean climate.*

Oslo (Humid continental climate)		Original (in kWh)	Green roofs (in kWh)	performance %	Green walls (in kWh)	performance %	Green roofs & green walls (in kWh)	performance %
Slab building:								
	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% ↓
Clustered low -rise building:								
	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% ↓
Detached house:								
	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% ↓

***Figure 11**. The energy performance of green roofs, green walls and a combination of both on three residential building types in the humid continental climate.*



Szombathely (Temperate oceanic climate)		Original (in kWh)	Green roofs (in kWh)	performance % ↓↑	Green walls (in kWh)	performance % ↓↑	Green roofs & green walls (in kWh)	performance % ↓↑
Slab building:								
	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% ↓
Clustered low -rise building:								
	Cooling:	4793.51	3993.73	16.68% ↓	3558.37	25.77% ↓	2348.84	50.99% ↓
	Heating:	32130.26	22790.69	29.07% ↓	27694.16	13.8% ↓	16469.05	48.74% ↓
Detached house:								
	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% ↓

***Figure 12**. The energy performance of green roofs, green walls and a combination of both on three residential building types in the temperate oceanic climate.*

5. List of publications

[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. (2023). A study on the impact of green infrastructure on microclimate and thermal comfort. *Pollack Periodica*. *18*(1), 42-48. https://doi.org/10.1556/606.2022.00668

[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

References

Campiotti, C. A., Gatti, L., Campiotti, A., Consorti, L., De Rossi, P., Bibbiani, C., ... & Latini, A. (2022). Vertical greenery as natural tool for improving energy efficiency of buildings. *Horticulturae*, *8*(6), 526.

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016). Nature-based solutions to address global societal challenges. *IUCN: Gland*, Switzerland, 97, 2016-2036.

Coletta, V. R., Pagano, A., Pluchinotta, I., Fratino, U., Scrieciu, A., Nanu, F., & Giordano, R. (2021). Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment. Journal of Environmental Management, 280, 111668.

Ferreira, S.O. Programa Polis e a Componente Ambiental—Três abordagens de Integração; Parque Expo: Lisbon, Portugal, 2008.

Enzi, V., Cameron, B., Dezsényi, P., Gedge, D., Mann, G., & Pitha, U. (2017). Nature-based solutions and buildings–the power of surfaces to help cities adapt to climate change and to deliver biodiversity. *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice*, 159-183.

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

Gray, K. A. (2021). Climate Action: The Feasibility of Climate Intervention on a Global Scale. In *Climate Geoengineering: Science, Law and Governance* (pp. 33-91). Springer, Cham.

Köppen Climate Classification. (2022). Available online: <

https://www.mindat.org/climate.php >.

Laine, J., Heinonen, J., & Junnila, S. (2020). Pathways to carbon-neutral cities prior to a national policy. *Sustainability*, *12*(6), 2445.

Maes, J., & Jacobs, S. (2017). Nature ‐ based solutions for Europe's sustainable development. *Conservation letters*, 10(1), 121-124.

Mang, P., & Reed, B. (2020). Regenerative development and design. *Sustainable built environments*, 115-141.

International Energy Agency, (2022). Buildings sectorial overview. Available online: < https://www.iea.org/reports/buildings >.

Pedersen Zari, M. (2012). Ecosystem services analysis for the design of regenerative built environments. *Building Research & Information*, *40*(1), 54-64.