Politecnico di Torino

EXPLORING ADAPTIVE FAÇADE AS MITIGATION STRATEGY THOUGH GIS-BASED URBAN MICROCLIMATE ANALYSIS

POLITECNICO DI TORINO
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ABSTRACT

This research examines the increasing challenges faced by urban areas due to climate change, specifically focusing on the Urban Heat Island (UHI) effect, which intensifies environmental issues and contributes to the urban climate crisis. As cities grow and become denser, adopting adaptive strategies is critical for reducing the adverse impacts of UHI and improving overall urban resilience. The study explores the relationship between urban adaptation strategies, UHI phenomena, and the role of adaptive facades in creating sustainable, climate-responsive urban environments.

A central aspect of this research is the application of Geographic Information Systems (GIS), which provide advanced tools for spatial analysis and the simulation of microclimatic conditions. GIS technology enables urban planners, architects, and environmental engineers to model the thermal behaviour of cities, helping to define the best facade solutions based on key environmental parameters. These parameters can adjust in real time to changing climate conditions. By using GIS to analyse specific location, the research identifies which adaptive facade technologies are most effective in improving the urban microclimate.

Adaptive facades, utilizing innovative materials and dynamic design features, have the potential to control temperature, enhance energy efficiency, and reduce the negative impacts of UHI. These facades can also improve outdoor thermal comfort by lowering cooling demands, reducing carbon emissions, and enhancing air quality. By integrating GIS-based modelling and analysis with adaptive facade technologies the research offers a more comprehensive, data-driven approach to addressing UHI challenges. The findings of this study provide valuable insights for urban designers, offering an effective way to enhance urban climate adaptation and contribute to the development of energy-efficient, resilient, and sustainable cities. Ultimately, this research serves as a foundation for informed decision-making on the implementation of adaptive facades, improving the quality of life for urban residents while mitigating climate change impacts.

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Sincerely,

Ana Kartvelishvili

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ABBREVIATIONS

ALUHI	Atmospheric Layer Urban Heat Islands
ARPA	Agenzia Regionale per la Protezione Ambientale/Regional Environmental Protection Agency
ASVF	Boundary Layer Urban Heat Islands
BDTRE	La Base Dati Territoriale di Riferimento degli Enti Piemontesi
BLUHI	Committee for Economic Planning
CFD	Canopy Layer Urban Heat Islands
CIPE	City Water Circle
CLUHI	European Union
CVR	Canyon Verticality Ratio
CVS	Comma-Separated Values
CWC	United Nations
DRR	Disaster Risk Reduction
EC	Istituto per le Piante da Legno e l'Ambiente
ECG	Electrochromic Glazing
EEA	Outdoor Standard Effective Temperature
ERA5	European Climate Assessment & Dataset
EU	Sustainable Energy and Climate Action Plan
FSR	Physiological Equivalent Temperature
GIS	Predicted Mean Vote
IPLA	National Climate Change Adaptation Plan
NDVI	Normalized Difference Vegetation Index
OUTSET	Regional Strategy for Climate Change
PAESC	Roughness Sub-Layer
PET	Sustainable Development Goals
PM	Matter
PMV	Surface Layer
PNACC	Surface Layer Urban Heat Islands
RSCC	National Strategy for Adaptation to Climate Change
RSL	Sustainable Energy Action Plan
SCR	Urban Boundary Layer
SDG	Urban Canopy Layer
SHGC	Solar Heat Gain Coefficient
SL	Urban Heat Islands
SLUHI	European Commission
SNACC	Universal Thermal Comfort
SVF	Volatile Organic Compound
TAPE	Area Sky View Factor
UBL	Sky View Factor
UCL	Façade to Site Ratio
UHI	Site Coverage Ratio
UN	European Environment Agency
UTCI	Urban Weather Generator
UWG	Geographic Information System
VOC	Computational Fluid Dynamics
VT	Visible Transmittance

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01 INTRODUCTION

1.INTRODUCTION

In recent years, the urgent need to strengthen Europe's resilience to large-scale, uncontrolled events has become increasingly noticeable. With its escalating and complex impacts, climate change presents a threat of greater magnitude than many other crises, as extreme weather events grow both more frequent and severe. While it is a global issue that demands international cooperation for mitigation, its effects are intensely localized and must be addressed within specific regional and urban contexts. In this regard, European cities and towns, as local centers of population and economic activity, play a critical role in adapting to these challenges. Starting from local scales as interventions, particularly in areas such as land-use planning and emergency management, are crucial to effective climate adaptation.

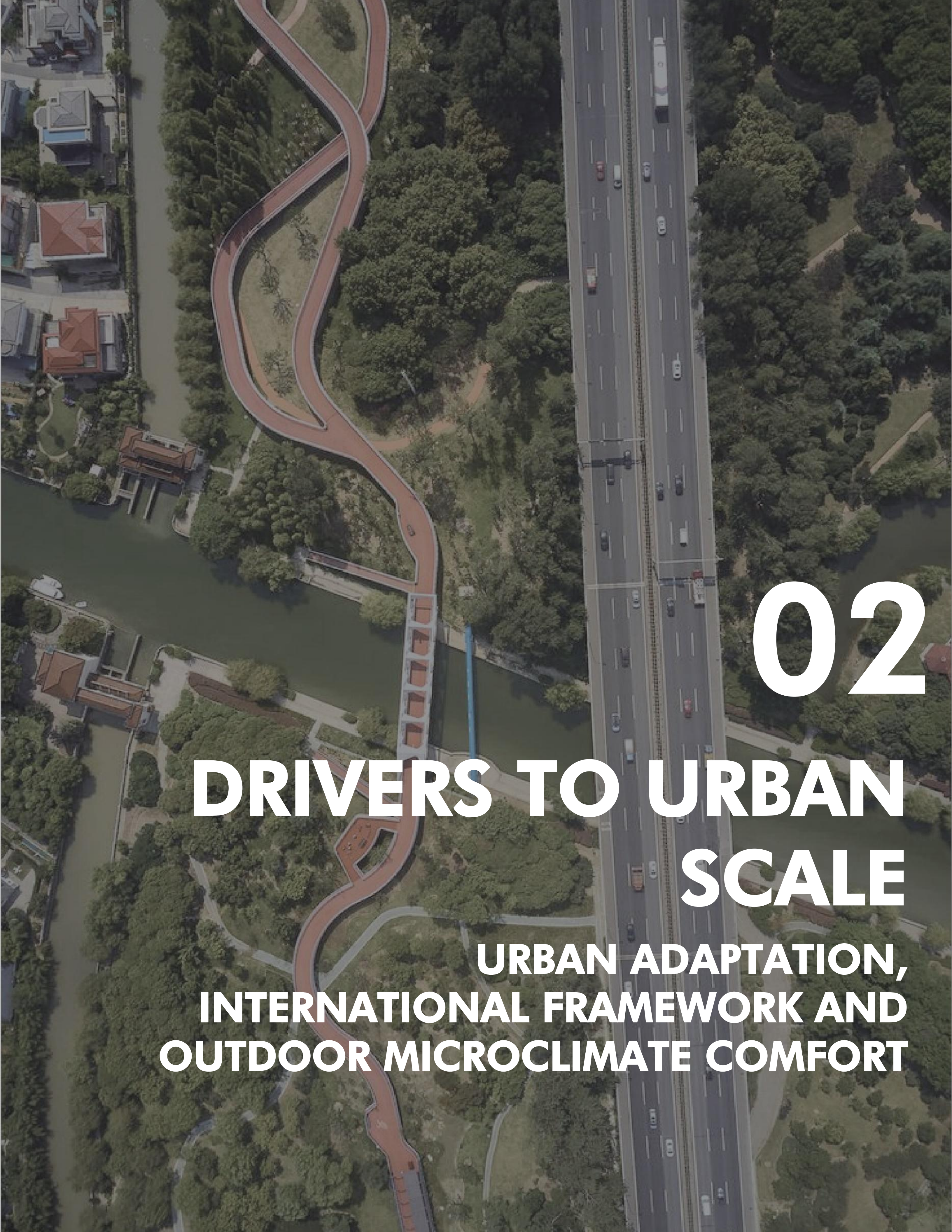
Everything can starts from city scale, build environment, which can also have influential effects on local climate, such as microclimate. The impacts of climate change on cities are varied and wide-ranging, with heatwaves, heavy rainfall, floods, and droughts being some of the most pressing challenges. To address these threats, everything should be started from a small picture, local climate, and its risk or vulnerability assessments are essential for understanding both current and future risks. These assessments provide the foundation for developing effective adaptation strategies and lead towards decision-making processes, helping to determine how best to mitigate and adapt to these risks, but before all of these we need to define all the inclueences that can possible affect on outdoor microclimate.

Morphology of a city is one of the main influental parameter of microclimate. To be more specific, urban geometry which itself forms thermal properties, it has an impact on enivronmental factors: direct and indirect solar radiation effects, mean radiant temperature, air temperature, humidity and wind. By definition of urban geometry it does not only considers three dimensional volumes, it also includes their orientation, canyon surfaces, the ratio's between building heights and distances, sky view factor, solar radiation and its reflectance or absorbanse characteristics. All of the parameters mentioned above, can be united in one explication which can improve directly or indirectly all the aspects listed down and overall to improve outdoor thermal comfort, this solution can be - Adaptive Facade Technologies.

Adaptation measures must encompass both soft strategies, such as awareness campaigns and early warning systems, and more tangible physical solutions, such as nature-based and innovative approaches, which offer a range of benefits. Concept of building resilience is not only about upgrading physical infrastructure but also about strengthening health and social care systems, ensuring that cities are inclusive and liveable for all residents, and guaranteeing as well as internal also external thermal comfort and well-being for diverse populations, which can be taken into account from the beginning, on early stages of each project development phase.

Adressing outdoor thermal comfort and make the design choices with their possible impact on are one of the most important among the various physical measures available, one promising solution is the implementation and development of adaptive facade designs. Facades-the exterior envelopes of buildings-serve as a critical interface between indoor environments and external climatic conditions. In the context of climate resilience, adaptive facades offer dynamic solutions that improve energy efficiency, enhance thermal comfort, and protect buildings from extreme weather events, and all of these due to study of the albedo of the surfaces and overall technologies, that can possible change urban fabric configuration for better.

Adaptive facades thus play one of vital role in urban adaptation, offering significant benefits to cities confronting the challenges of a changing climate. This study aims to define all the possible options, material or adaptive technological solutions of building surfaces in urban canyons, to have optimized local response, monitor the behavioural changes in parameters of outdoor thermal comfort and descirbe all the processes in quantitative and graphical way, within all climate change strategies, particulary regarding the urban contexts on a local microclimate scale.



02

DRIVERS TO URBAN SCALE

URBAN ADAPTATION, INTERNATIONAL FRAMEWORK AND OUTDOOR MICROCLIMATE COMFORT

2. DRIVERS TO URBAN SCALE

The global trend of urban expansion has significantly transformed both natural and built environments. This growth is driven by a range of economic, social, environmental, and political factors that work together to accelerate the development of cities on an unprecedented scale.

Understanding the factors behind urban expansion is crucial for addressing the challenges of modern city life, particularly as cities face increasing pressures from climate change, population growth, and social inequalities. This section explores the main forces shaping urban growth and change, including technological advancements, changing migration patterns, economic policies, and environmental concerns. It also examines the connections between these factors, highlighting their impact on urban areas, infrastructure, and governance systems.

By analyzing these factors, we can gain valuable insights into how cities evolve, the forces driving future growth, and the strategies needed to promote sustainable and resilient urban development. This chapter aims to provide a comprehensive understanding of the dynamics behind urban growth, laying the foundation for further discussions on how cities can adapt and thrive amid ongoing global challenges.

2.1 URBAN ADAPTATION

To resist global climate changes, socio-economic challenges and environmental issues, cities employ urban adaptation strategies, aiming to decrease vulnerability and boost resilience. These impacts have a wide range for urban areas, they anticipate changes in temperature, precipitation, natural hazards and perception of outdoor comfort, mostly stresses as outcomes of these effects are on infrastructure, public and private buildings, historical buildings, quality on environment and in general on ecosystems. Minimizing all the impacts and plan mitigation processes involves adjusting urban infrastructure, policies, and practices to handle both present and future impacts, including severe weather events, coastal flooding, and increased urban temperatures. Essential components of urban adaptation encompass upgrading infrastructure to endure extreme weather conditions, such as floods and heat waves, by utilizing water-resistant materials and enhancing drainage networks[1]. It also includes expanding green spaces, like urban parks and vegetated rooftops, to capture carbon, enhance air quality, and mitigate heat effects.

Adaptation has potential not only for an existing activity that takes place on an urban scale but also for the future approaches. As an example, risk assessment or regional and local data analysis for future scenario generations. In general, no matter what type of approach will be taken, even from characteristics of climate change, adaptation planning can be considered as a public process. As much as it depends on public-sectors involvement as stakeholders, on the other hand engaging the community is crucial, providing education

[1] *Urban adaptation in Europe: how cities and towns respond to climate change, EEA Report, 2020*

about climate risks and promoting sustainable habits like water conservation and energy efficiency. Additionally, urban adaptation addresses social and economic inequalities by supporting at-risk populations, enhancing public health, ensuring access to affordable housing, and establishing social support systems. The aim of urban adaptation is to improve the livability, sustainability, and resilience of urban areas, enhancing residents' quality of life while preparing for upcoming climate challenges[2].

Approaches for an urban adaptation are different depending on the country or a region, due to their distinct priorities, from strategic to sector plans. This process itself demands the involvement of different parties, which gives us a variety of activities that need to take place. Although some trends are emerging. Based on research, what types of activities different cities are included in their urban adaptation planning are given in Figure 1.

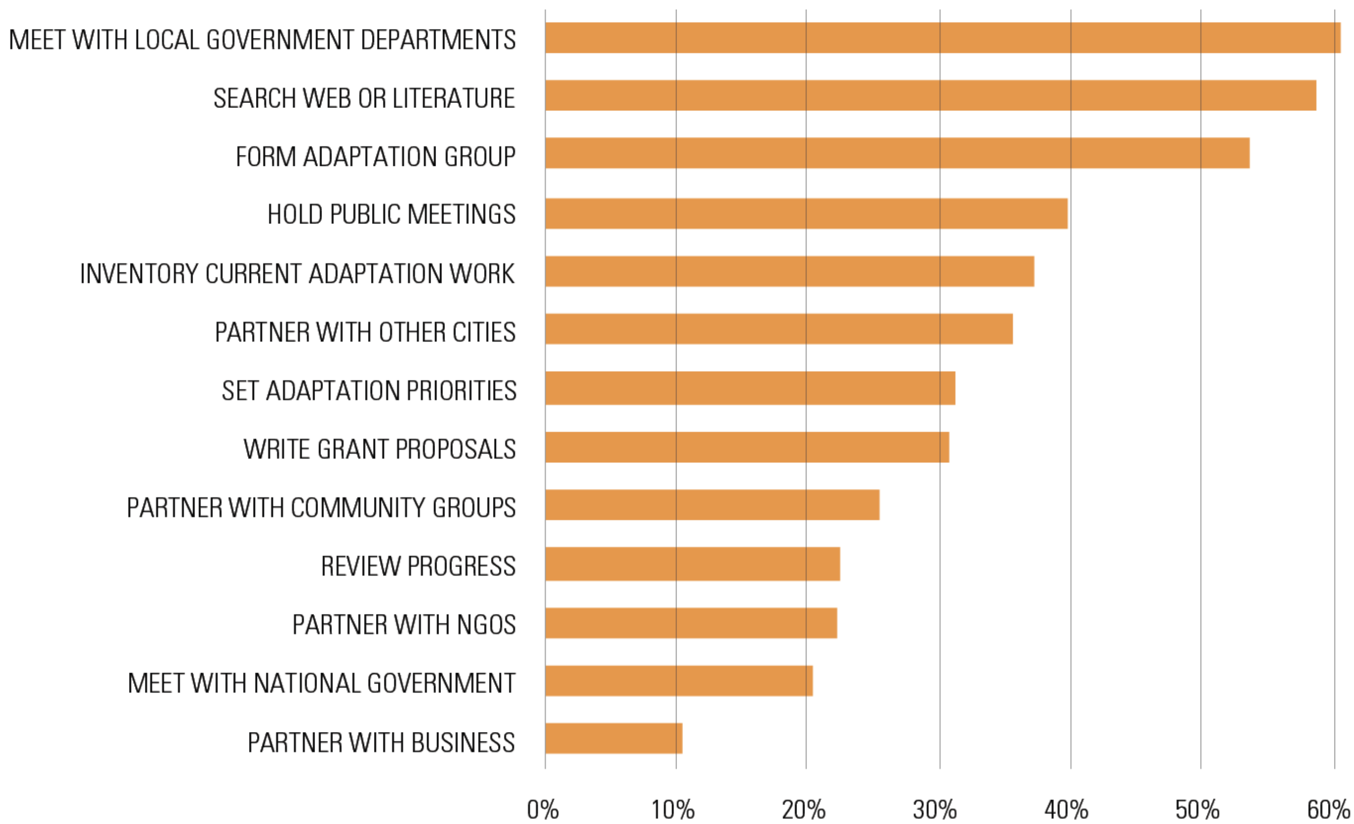


Figure 1. *Activities to support urban climate adaptation planning.*
Source: Progress and Challenges in Urban Climate Adaptation Planning – Results of Global Survey, 2018

If we need to ask why there is need to adapt our cities, answer can be very simple – our climate is changing and can't be ignored. Which means that also urban development needs to have the same speed as the changes in our environment, that effects on our quality of life, with wide range impacts, from the local assets, natural systems, to the end of environmental quality (Figure 2). Nowadays, these accelerated changes are compounded

[2] *UN-Habitat - The New Urban Agenda. United Nations Human Settlements Programme, 2018.*

by trends like: Urbanisation, losses of biodiversity, pollution, unsustainability, high densities with increased mobility issues and less energy consumption.

Today, most cities have recognized the importance of urban adaptation and have started planning the steps needed for the process. These approaches vary in how they are carried out, but the most common methods include creating adaptation communities, holding public meetings, and organizing discussions with local government departments. Despite the strong desire to address climate-related issues and promote adaptation, cities around the world face several challenges, such as a lack of resources. Financial resources are essential for making infrastructure more resilient. However, some cities are integrating new sustainable goals and adaptation activities into ongoing development projects, where budgets are already set, and additional funding is not required.

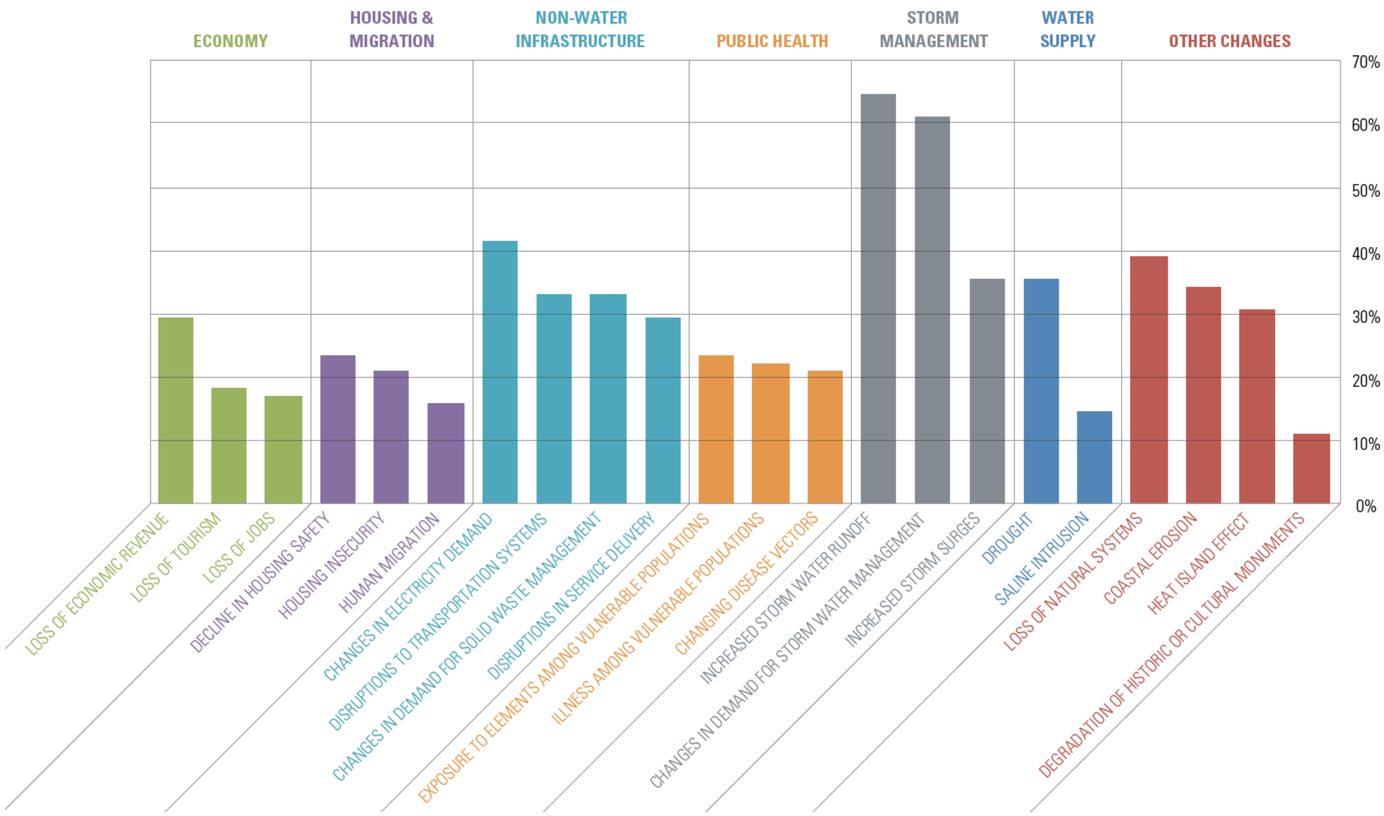


Figure 2. Impacts anticipated as a result of Climate Change.
Source: Progress and Challenges in Urban Climate Adaptation Planning – Results of Global Survey, 2018

Several factors are key to successfully carrying out adaptation actions. These include long-term political support, with resilience being recognized by government bodies. Good governance helps ensure clear communication and coordination among all sectors and stakeholders. Sharing successful practices allows for faster actions and broader implementation. Citizen involvement is essential, as they play a central role in adaptation efforts. Proper use of knowledge and data is important to make sure actions are effective. Finally, ongoing funding and the ability to access and use financial resources are crucial for the long-term success of adaptation plans. These factors make adaptation efforts more efficient and widespread.

In addition to these local factors, international and EU policy frameworks play a significant role in shaping urban adaptation. Policies from global organizations and the European Union provide guidance and resources for cities to implement climate adaptation strategies. These frameworks support the exchange of best practices, promote funding opportunities, and set common goals to ensure that cities worldwide are prepared for future climate challenges. By aligning local actions with international and EU standards, cities can strengthen their adaptation plans and create more resilient urban environments.

2.2 INTERNATIONAL AND EU POLICY FRAMEWORK FOR URBAN ADAPTATION

Local climate change adaptation operates within a broader governance framework, where cities are influenced by higher levels of governance while simultaneously acting as key agents of change. International agreements such as the Paris Agreement, Agenda 2030, the New Urban Agenda, and the Sendai Framework highlight the critical importance of addressing climate adaptation at the local level, with a specific focus on urban areas.

The European Union (EU) provides substantial support for urban adaptation through its EU Adaptation Strategy and its subsequent updates. In addition, complementary instruments such as the Floods Directive, the green infrastructure strategy, and the EU Urban Agenda play a vital role in supporting and guiding adaptation efforts. These frameworks and policies collectively strengthen the capacity of cities to plan and implement effective climate adaptation measures.

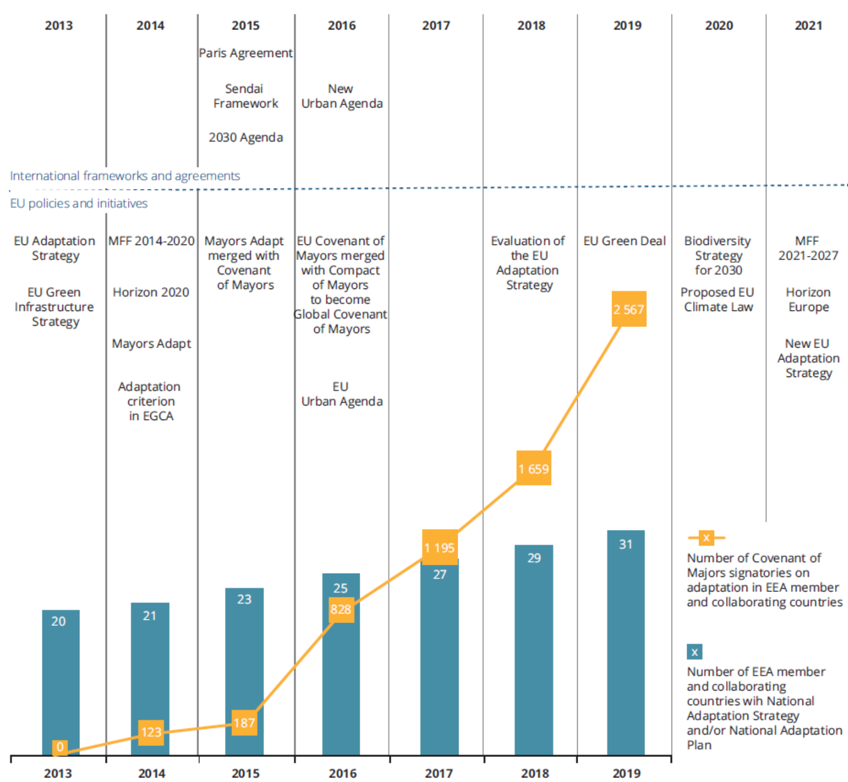


***Figure 3**. Timeline of policies, activities and milestones relevant to urban adaptation*
Source: Lea Kleinenkuhnen, Covenant of Mayors for Climate and Energy, 2020.

EU funding for climate adaptation at the local level is part of several sector-based policies, with many cities receiving financial support for activities like research, knowledge sharing, planning, and implementing adaptation measures. Many EU Member States understand the importance of urban adaptation and see local governments as key players in carrying out adaptation strategies. In some countries, local-level adaptation planning and climate risk assessments are required by law.

National governments assist local authorities by offering financial help, capacity-building programs, and sharing knowledge. However, the level and type of support vary between different European countries. At the regional level, governance structures are important for coordinating and helping local adaptation efforts, especially for smaller municipalities that may not have enough resources or expertise to deal with climate change impacts on their own. These issues will be further discussed in the upcoming chapters on national frameworks.

2.2.1 International Frameworks

The international policy landscape for urban climate change adaptation underwent significant transformation in 2015-2016 with the adoption of key United Nations (UN) agreements, designed to reinforce one another and promote synergies across policies. These frameworks collectively emphasize the critical role of local authorities in climate adaptation efforts.

The Paris Agreement, adopted in December 2015, marked a milestone by establishing the first global goal on climate adaptation, underscoring its local dimension. Adaptation was recognized as essential to addressing climate change, alongside mitigation efforts, highlighting its equal importance in the global response to climate impacts[3].

The 2030 Agenda for Sustainable Development, adopted earlier in 2015, introduced Goal 11, focused on making cities resilient and sustainable. It set a target for cities to adopt and implement climate adaptation and disaster resilience policies by 2020[4]. Additionally, Goal 13 emphasized the need for urgent climate action, including enhancing resilience and integrating adaptation into national policies. The New Urban Agenda, ratified in 2016, further supported local climate action by urging states to assist cities in adaptation planning and climate vulnerability assessments.

The Sendai Framework for Disaster Risk Reduction (2015-2030) recognized climate change as a key driver of disaster risk and called for full engagement from national and local governments in disaster risk reduction (DRR). It set a target to increase the adoption of local DRR strategies, with progress being made in several countries.

While these international frameworks influence local adaptation indirectly—through national regulations, funding, and policies—direct action by cities remains dependent on

[3] *Magnan, A.K., & Ribera, T. The Paris Agreement and the role of adaptation. Environmental Science & Policy, 2016*
[4] *United Nations (UN). (2015b). Paris Agreement. United Nations Framework Convention on Climate Change (UNFCCC).*

national governments, as evidenced by the limited impact of UN agreements on local adaptation plans in Europe[5].

2.2.2 European Key Policies and Frameworks

European Green Deal

In December 2019, the European Commission introduced the European Green Deal as a strategic initiative to transform Europe's economy, aiming to prevent further climate change and environmental degradation. The Deal outlines a pathway to a modern, resource-efficient economy with zero net greenhouse gas emissions by 2050 and sustainable resource management. It emphasizes a just and inclusive transition, focusing on enhancing resource efficiency, restoring biodiversity, and reducing pollution. The Deal also identifies necessary investments and financial instruments to support this transformation, with all EU policies and actions required to align with its objectives.

As part of the Green Deal, the European Commission planned to adopt a more ambitious EU adaptation strategy by 2021. This strategy will focus on strengthening adaptation efforts, driving both public and private investments, and ensuring that a broad range of stakeholders, including cities, have access to the necessary data and tools to integrate climate change into risk management practices[6].

The Green Deal also presents opportunities for improving urban climate resilience. The 'Renovation Wave' initiative aims to decarbonize existing buildings, enhancing their safety and health standards, while addressing climate challenges like heatwaves and flooding. Furthermore, the Green Deal promotes actions to support biodiversity, accelerating the adoption of nature-based solutions, such as afforestation and tree planting, to strengthen urban adaptation to climate impacts.

EU Adaptation Strategy for Climate Changes

The 2013 EU Strategy on Adaptation to Climate Change serves as the cornerstone of Europe's adaptation policy framework[7]. Recognizing the importance of action at all levels, including local governments, the strategy introduced initiatives such as Mayors Adapt (2014), later merged with the Covenant of Mayors for Climate and Energy in 2015. The strategy also provided guidance for mainstreaming climate action across EU policies, including cohesion policy, and supported the climate action subprogramme of the LIFE initiative. These initiatives have enabled local authorities to develop adaptation plans and implement specific actions with EU funding.

The EU adaptation strategy underwent an evaluation in 2017-2018, which confirmed its effectiveness despite the increasing and diversifying adaptation needs. The evaluation report stated that the strategy met its objectives, fostering action across various levels of

[5] Aguiar, A. F., Silva, R. M., & Santos, M. Climate adaptation in urban areas: a review of policies and practices. Environmental Policy and Governance, 2018

[6] European Commission (EC). (2019c). The European Green Deal. COM/2019/640 final.

[7] European Commission (EC). (2013a). White Paper: Adapting to climate change: Towards a European framework for action. COM/2013/216 final.

government[8]. However, progress at the local level has been uneven, with the original target for cities with over 150,000 inhabitants to adopt adaptation strategies by 2020 only partially met, with approximately 40% of the target achieved by 2018. To address this, the European Commission advocates for increased awareness and enhanced technical and financial support for local authorities through initiatives like the Covenant of Mayors and encourages Member States to integrate adaptation into national and regional frameworks.

The forthcoming update to the EU adaptation strategy, outlined in the 2020 blueprint[9], builds on these recommendations, focusing on improving climate impact knowledge, strengthening planning and risk management, and accelerating resilience-building efforts. It highlights the need for cities to access better data for resilience investments and promises that adaptation and disaster risk management will be prioritized in the European Regional Development Fund and the Cohesion Fund for the 2021-2027 period, using a place-based approach to enhance urban and regional resilience.

Urban Agenda for the EU

In addition to the EU Adaptation Strategy, climate adaptation has been recognized as a key priority within the EU Urban Agenda, launched in 2016 through the Pact of Amsterdam by European ministers responsible for urban affairs[10]. The Urban Agenda aims to enhance the involvement of urban authorities in EU policymaking to improve the implementation of the Union's strategic objectives for 2020. This reflects the significant role urban areas play in the enactment of EU legislation, underscoring the importance of addressing local-level implementation challenges. The Urban Agenda also seeks to contribute to the UN 2030 Agenda for Sustainable Development, particularly Goal 11, which focuses on making cities inclusive, safe, resilient, and sustainable, alongside the New Urban Agenda[11].

As one of the 12 priority themes, climate adaptation in urban areas is addressed through a dedicated partnership within the Urban Agenda. This partnership involves stakeholders from various governance levels and aims to act as a key mechanism for delivering the agenda's objectives. The adaptation partnership's actions are based on an analysis of existing EU policies and insights from surveys identifying barriers to urban adaptation. Initially scheduled for completion by mid-2020, these actions are designed to address gaps, enhance the impact of current EU initiatives, and better target existing policies, tools, and strategies related to urban climate adaptation[12].

EU's Territorial Agenda

Initially adopted in 2011 by ministers responsible for spatial planning, aims to foster territorial cohesion across the Union, engaging policymakers at all levels of governance. Its renewed

[8] *European Commission (EC). (2018b). The 2030 Climate and Energy Framework. COM/2018/773 final.*
[9] *European Commission (EC). (2020c). EU Biodiversity Strategy for 2030: Bringing nature back into our lives. COM/2020/380 final.*
[10] *European Commission (EC). (2016b). The Clean Energy for All Europeans package. COM/2016/860 final.*
[11] *United Nations (UN). (2017). New Urban Agenda. UN-Habitat.*
[12] *Purkarthofer, D. Urban Climate Adaptation in European Cities: Trends, Challenges, and Opportunities. Environmental Policy and Governance, 2019*

version, set for adoption in December 2020, introduces a priority axis on a healthy environment, emphasizing the resilience of all regions to climate change impacts[13].

EU Biodiversity Strategy

For 2030[14] underscores the importance of nature-based solutions for both emission reduction and climate adaptation. It highlights ecosystem restoration as a key strategy, with legally binding targets to restore degraded ecosystems, particularly those with high carbon capture potential. In urban areas, the strategy advocates for tree planting and green infrastructure to mitigate climate impacts, such as cooling urban spaces and reducing the effects of natural disasters.

EU's Green Infrastructure Strategy

The strategy promotes the development of new ecosystems and the restoration of degraded ones, focusing on green infrastructure as a critical tool for disaster risk management and climate adaptation. Recognizing that cities and local authorities are at the forefront of addressing climate-related hazards, the strategy emphasizes their vital role in implementing preventive measures like green infrastructure to enhance urban resilience.

European key policies and frameworks, such as the EU Adaptation Strategy, the Paris Agreement, and the EU Green Deal, guide member states in developing climate adaptation plans, with a focus on reducing emissions, enhancing resilience, and promoting sustainable urban growth. These frameworks set the stage for national and local governments to implement climate resilience measures, which is particularly important in Italy, where regional and local actions are essential for addressing the diverse climate risks faced across the country. This leads to the next chapter, where it will be defined how Italy is responding to these EU policies and the specific climate resilience strategies adopted at both national and local levels.

2.3 CLIMATE RESILIENCE ON NATIONAL AND LOCAL LEVELS IN ITALY

Nowadays Italy faces a variety of climate change impacts, from rising temperatures and sea levels to extreme weather events, which have prompted the country to develop targeted climate resilience strategies. This chapter examines how Italy is addressing climate resilience through national policies and local initiatives, emphasizing the role of regional governance in adapting to and mitigating climate risks.

2.3.1 National Framework

Italy approved the National Strategy for Adaptation to Climate Change (SNACC) in 2015, through Executive Decree No. 86, aiming to reduce climate change risks and protect public health, assets, and the environment. In September 2016, the National Climate Change

[13] *European Commission (EC). (2019g). EU Climate Action Progress Report. COM/2019/288 final.*
[14] *European Commission (EC). (2020d). EU Biodiversity Strategy for 2030: Bringing nature back into our lives. COM/2020/380 final.*

Adaptation Plan (PNACC) was developed to carry out the SNACC. The PNACC, currently being reviewed through a Strategic Environmental Assessment, consists of three main parts:

- **Part I** - examines current climate conditions, forecasts future scenarios, and studies the vulnerabilities of various sectors across Italy.
- **Part II** - focuses on identifying key adaptation actions, finding synergies, and setting priorities for different sectors, while also defining tools for implementation and funding.
- **Part III** - The third part includes methods for tracking and evaluating the success of adaptation measures and guidelines for involving stakeholders in planning and execution.

As the national framework provides a common foundation, adaptation measures evolve region by region, considering the unique environmental, social, and economic conditions. This transition allows each chapter to tailor its approach, ensuring alignment with local realities while maintaining the overarching goals of the national framework.

2.3.2 Regional Framework

The development of the Regional Strategy for Climate Change (SRCC) is ongoing at the regional level, and it will play a crucial role in applying the National Strategy for Sustainable Development, as approved by the Inter-ministerial Committee for Economic Planning (CIPE) Resolution no. 108/2017. The region recognizes that mitigation and adaptation are not separate approaches but should be integrated into a single strategy due to their interconnected nature. As part of this, the SRCC focuses on measures to reduce vulnerability and strengthen the region's resilience to the ongoing effects of climate change, while also adopting actions to reduce greenhouse gas emissions. This strategy also supports the region's commitment to the "UNDER 2 MOU" signed in November 2015, which brings together sub-national governments in a Coalition to implement major mitigation actions[15].

The future research, which will be applied in the subsequent chapters, focuses on the northern part of Italy, specifically the Piemonte region. To gain a deeper understanding, the region's climate action strategies have been examined.

The Regional Strategy for Climate Change serves as a guide and a means to assess and align various regional policies that address both mitigation and adaptation to climate change. The region is developing the strategy through an intersectoral working group, which has undergone specialized training to ensure the document is comprehensive and raises awareness of climate change impacts on the environment, economy, and society. Initial efforts focused on understanding climate trends in Piedmont, not only to confirm historical changes but also to forecast future trends across different sectors. Additionally, the region, in collaboration with ARPA[16] Piemonte and IPLA[17], is working on a greenhouse

[15] *Climate Resilience Plan - Città di Torino, 2022*
[16] *Agenzia regionale per la protezione ambientale*
[17] *Istituto per le piante da legno e l'ambiente*

gas emissions inventory to track progress in reducing emissions. In particular, their plan has three main focus areas:

- Regional Environmental Energy Plan
- Regional Air Quality Plan
- Projects to Revise the Water Protection Plan

For detailed analysis even regional framework and its application areas are wide, due to this, research needs to shift focus to the more specific and localized approach of a city resilience plan. While the regional framework provides essential guidelines and objectives for climate action and sustainable development, the city resilience plan narrows in on the unique challenges and opportunities faced by individual urban areas, more specifically city of Turin. Following chapter will explore how the general strategies outlined at the regional level can be adapted and implemented to strengthen the resilience of cities, focusing on their infrastructure, community dynamics, and specific vulnerabilities.

2.3.3 Climate Resilience Plan – City of Turin

City of Turin as many other European cities or regions has joined to the initiative by European Environment Agency – "Climate change, impacts and vulnerability in Europe 2012" which demonstrates existence of global warming risks and points out that actions must be taken as well as independently also together by different cities against a common treat. The adaptation of the measures against climate change and its consequences is also one of the agenda 2030 Sustainable Development Goals, and now Agenda for 2050 which suggest the strategic long-term vision how to become climate neutral.

Figure 4. *Communic Animation - Resilienza Climatica*
Source: Comune di Torino

Turin has taken significant steps to combat climate change through a series of proactive policies. Initially focusing on mitigation strategies such as energy efficiency and renewable energy production, the city joined the Covenant of Mayors in 2009 and adopted the Sustainable Energy Action Plan (TAPE) in 2010, aiming for a 30% reduction in CO2 emissions by 2020 compared to 1991 levels. By 2017, Turin had surpassed this target with a 33% reduction, thanks to initiatives like expanding the district heating network and upgrading public lighting to LED systems. In 2015, the city joined the Mayors Adapt initiative to address climate adaptation, and by early 2019, it committed to the Covenant of Mayors for Climate and Energy, pledging to cut CO2 emissions by 40% by 2030 while integrating both mitigation and adaptation strategies for comprehensive urban resilience[18].

Like many urban cities, Turin and all the cities included in its municipality faces significant challenges due to changing climate conditions primarily driven by greenhouse gas emissions from human activities. Analysing climate data reveals notable shifts in meteorological variables, highlighting both long-term trends and variations from year to year, as well as an increase in extreme weather events. Overall, there is a discernible rise in temperatures, intensified rainfall patterns, a decrease in the number of rainy days, and irregular seasonal shifts between wet and dry periods.

Climate Change in Municipality of Turin

Temperature Trends in Turin

Figure 5. *Communic Animation - Resilienza Climatica*
Source: Comune di Torino

According to data provided in Resilience Plan, Turin has experienced a significant increase in both maximum and average temperatures since 1951, with maximum temperatures rising by approximately 0.6°C per decade. The past 30 years have been particularly notable, with a rise of around 0.8°C every ten years. Over the last fifteen years, average temperatures have consistently exceeded the norm established during the 1971-2000 reference period, resulting in a cumulative increase of roughly 1°C over the past 50 years. Maximum temperature anomalies have remained positive since 1988, indicating a substantial upward

[18] *Climate Resilience Plan - Città di Torino, 2022*

trend of approximately 2.2°C over the past six decades. In contrast, minimum temperatures have shown a slight downward trend, though this change is not statistically significant.

Rainfall Patterns and Variability

Figure 6. *Communic Animation - Resilienza Climatica*
Source: Comune di Torino

The analysis of rainfall in Turin over the past 60 years reveals no clear or statistically significant trend in annual cumulative rainfall anomalies when compared to the 1971-2000 reference period. Since 2000, drier years have been more frequent, although positive rainfall anomalies are more common during the autumn months. In recent years, the rainiest months have shifted to May and November, in contrast to historical patterns where April and June were typically wetter. Furthermore, while there is a slight decrease in the number of rainy days for lower thresholds (1 mm and 5 mm), there has been an increase in more intense rainfall events exceeding 10 mm and 20 mm.

Hydrological Regime Changes

Figure 7*. Communic Animation - Resilienza Climatica*
Source: Comune di Torino

The hydrological regime in Turin has displayed varying flow rates, with lower rates observed during the summer and winter months, and higher rates during autumn and spring. Summer flow is primarily influenced by rainfall and is further reduced by withdrawals during dry periods, while winter flow is mainly derived from liquid precipitation, as snowmelt is limited. In spring, snowmelt plays a significant role in contributing to flow rates, whereas in autumn, precipitation is the dominant factor driving flow increases. Although there are fluctuations in extreme short-term rainfall events, a definitive trend towards an increase cannot be confirmed. However, the data suggest that both summer and autumn seasons show a tendency toward rising intensity, which may reflect broader climatic shifts. These changing patterns may have important implications for water management and flood risk in the region.

Risks and Actions

Climate scenarios in Turin indicates that rising temperatures will lead to an increased risk of heat waves and urban heat islands in the coming years. Heat waves, defined as prolonged periods of excessively high temperatures, can last from a few days to weeks and are particularly dangerous due to their potential health impacts, especially in urban areas like Turin, where humid conditions exacerbate discomfort. These extreme weather events, often referred to as "Silent Killers," do not leave visible destruction but can result in significant fatalities, making them one of the deadliest meteorological phenomena. The characteristics of heat waves include intensity, duration, and humidity levels, all of which influence their severity and impact on public health.

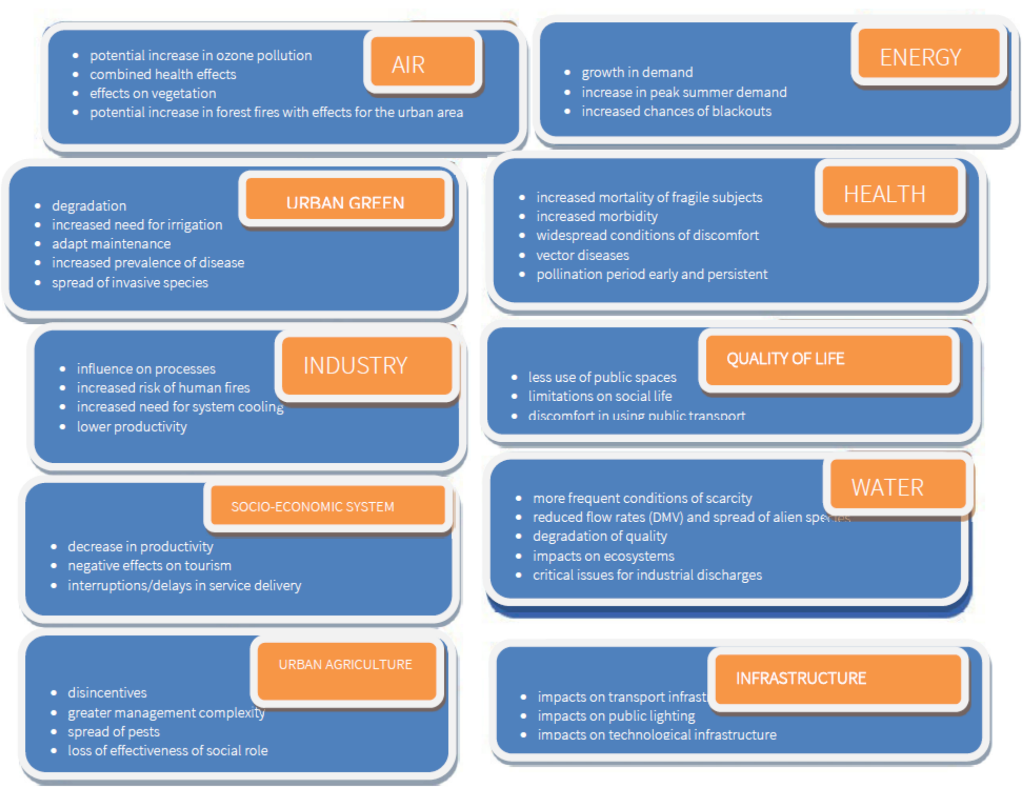


Figure 8. *Impacts of heat waves on the city of Turin*
Source: ARPA Piedmont, City of Turin

To evaluate the effects of more frequent heat waves and the urban heat island phenomenon, a cross-sector working group teamed up with important external stakeholders to explore a variety of consequences for the city's systems. These include increased demand for cooling, which could lead to power outages, problems for public transportation, disruptions in manufacturing processes, heightened risks to public safety, such as fires and service breakdowns, lower water quality and flow, and the degradation of urban green spaces. There are also subtler, yet crucial, long-term impacts on the urban environment, such as reduced use of public areas and transport, restrictions on social interactions, increased discomfort in everyday life, lower work productivity, and negative consequences for tourism. A diagram suggested by ARPA outlining these impacts by sector is provided in Figure 8.

In response to the identified threats related to Urban Heat Islands in the Municipality of Turin, a total of 40 actions have been proposed by Climate Resilience Plan report to improve the urban microclimate, with the primary goal of creating a more resilient city. To summarize the steps necessary for preparing the city's urban morphology for these actions, the measures have been categorized into different groups:

1. ***"Resilient administration" -*** The concept encompasses a series of actions aimed at enabling the city to swiftly and innovatively respond to and adapt to extreme climate-induced events. Key actions include updating urban planning regulations, such as revisions to the General Regulatory Plan and the Energy-Environmental Annex of Building Regulations, to integrate climate-resilient standards in both new constructions and, more critically, renovations in densely urbanized areas. This initiative also fosters collaboration among relevant stakeholders, particularly the working group that developed the plan, ensuring ongoing communication and coordination throughout implementation and monitoring. Additionally, specialized training programs will be introduced to promote the development of innovative solutions for mitigating heat discomfort in buildings, supported by local universities, professional organizations, and the creation of design manuals for practitioners. Finally, the city will monitor the progression of climate-related phenomena and their impacts, potentially revising risk hazard maps as needed.
2. ***"An administration that handles emergencies" -*** This set of actions focuses on ensuring effective communication during abnormal events and implementing measures for managing emergencies. Specifically, it includes issuing heatwave warnings, educating the public on necessary precautions during extreme events, and encouraging local communities to support vulnerable populations. Additionally, it involves executing a heat emergency plan aimed at protecting vulnerable individuals during the summer and providing air-conditioned public spaces to alleviate discomfort on exceptionally hot days.

And after how to adapt:

1. ***"A cooler city" -*** This set of actions aims to mitigate the impacts of heatwaves and the urban heat island effect by reducing the amount of solar radiation absorbed by

urban surfaces. This is achieved through the use of high-albedo materials and an increase in shaded areas. As part of the strategic green infrastructure plan, the city will enhance tree coverage, particularly in heat-vulnerable areas, by planting climate-resilient species that contribute to cooling through shading and evapotranspiration. Additionally, the plan emphasizes the use of reflective, high-solar-reflectance materials, such as light-coloured or permeable road surfaces and roofing, to reduce temperature increases in urban environments.

2. ***"A more liveable city "-*** This set of actions aims to ensure comfort during all daily activities - work, leisure, travel, and home life - even during heatwaves. It includes redesigning public transport stops to reduce waiting times and incorporating shading systems, both natural and artificial, to improve comfort on hot days. Efforts will also focus on enhancing the accessibility and amenities of green spaces, particularly hillside forests, transforming them into "climate refuges" by adding rest areas and improving services and pathways. Additionally, the thermal insulation of schools and public buildings will be improved to increase summer comfort and reduce cooling energy consumption, including the installation of green roofs, walls, and shading systems.

In report actions have been categorized into three types: soft, green, and grey, in line with the European Environment Agency's classification given in Figure 9:

- **Soft Actions -** These interventions involve non-structural measures aimed at strengthening adaptive capacity through management, legal, and political strategies, including training programs, awareness campaigns, and improvements in governance.
- **Green Actions -** These solutions incorporate natural elements into urban environments to mitigate the effects of climate change, while also offering environmental and social benefits.
- **Grey Actions -** These interventions involve technological, and engineering solutions designed to adapt infrastructure and facilities to the impacts of a changing climate.

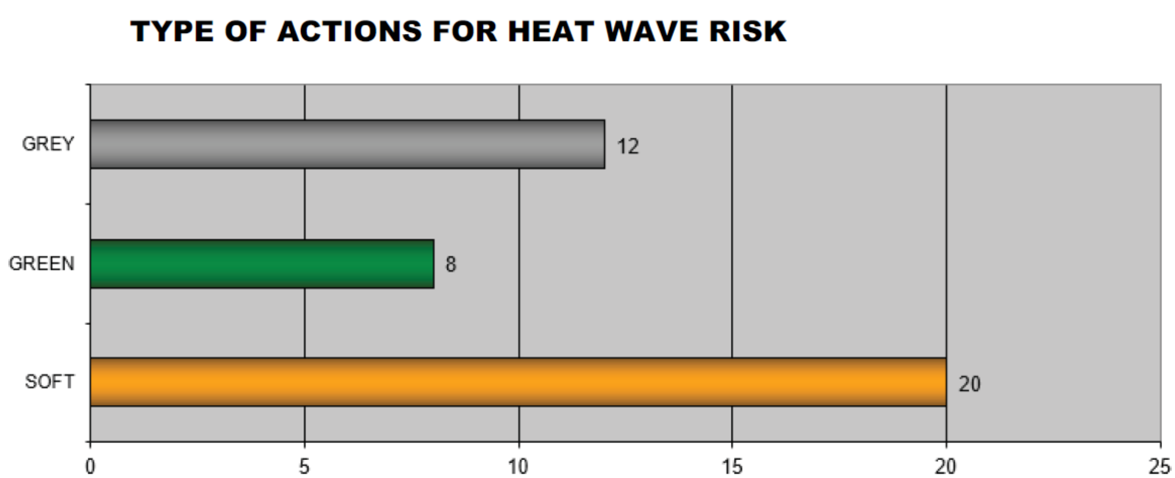


Figure 9. *Classification of the 42 actions identified according to the categorisation by the EEA. Source: ARPA Piedmont, City of Turin*

Adaptation Plan and Recommendations

Following the analysis of climate-related risks, it is essential to present Turin's comprehensive Adaptation Plan, which serves as a dynamic framework for addressing climate change, designed as an ongoing process with continuous evaluation and adaptation based on evolving knowledge and scientific advancements. The plan's success relies on the integration of new insights, future risk assessments, and collaboration with other cities. It aligns with the Sustainable Energy and Climate Action Plan (PAESC), combining efforts to mitigate and adapt to climate change.

To monitor progress, 78 actions outlined in the strategy are tracked using a set of indicators that assess resilience over time. These indicators are complemented by qualitative surveys and quantitative data, engaging citizens and measuring the effectiveness of specific actions. The University of Turin and the REEST research group play a pivotal role in supporting these efforts.

A focus of the plan is the preservation and enhancement of ecosystem services during urban development. By integrating these services into a strategic green infrastructure plan, Turin aims to reduce climate risks, targeting areas vulnerable to temperature fluctuations, flooding, and erosion. Green infrastructure solutions, particularly nature-based ones, will help alleviate pressures on existing infrastructure and improve resilience to extreme weather. Additionally, Turin has strengthened partnerships with Genoa and Milan to develop a coordinated climate resilience strategy. The city also plans to use advanced technologies like drones and monitoring systems to track climate events and issue early warnings. To further climate resilience, Turin promotes water conservation and explores alternative resources such as rainwater and grey water through the European City Water Circle (CWC) Project.

Finally, Turin's commitment to climate adaptation is supported by an agreement with the European Investment Bank, which will fund green infrastructure and sustainable urban redevelopment efforts, contributing to long-term resilience.

Building upon the strategies outlined in the urban adaptation plan, it is crucial to address one of the most prominent challenges cities face in the context of climate change: Urban Heat Islands (UHIs). As cities continue to grow and develop, the intensity of UHI effects has become increasingly evident, exacerbating local climate risks such as temperature extremes, energy demand, and public health concerns. UHI's occur when urban areas experience significantly higher temperatures than their rural surroundings due to human activities, land use changes, and the built environment. The impact of UHIs not only contributes to heightened energy consumption and environmental degradation but also underscores the need for targeted mitigation strategies, including the enhancement of green infrastructure, urban planning, and the integration of nature-based solutions. Understanding and addressing UHIs is therefore a critical component of a comprehensive urban climate adaptation framework.

03

URBAN HEAT ISLANDS

FORMATION AND MITIGATION

3. URBAN HEAT ISLANDS

Cities are experiencing extreme speed of growing, which leads to higher densities and narrow down of urban canyon profiles with huge amounts of structural and building masses. Because of mentioned reason above, cities are characterized by temperature differences compared to rural and suburban areas, and significantly high differences during day and night. All these processes created a phenomenon of Urban Heat Islands (UHI).

Between 1800-1830, British chemist and meteorologist, Luke Howard, many years before any other researchers, developed concept of Urban Heat Islands, an effect of urban areas having on local climate in London[19]. Regarding to his studies, difference between temperatures in London and its surrounding areas during the night was 2°C (3.7°F) warmer and cooler during the day. After Howard's first contribution many other researchers have started to study following concept but also need to be highlighted that phenomenon differs across the world due to geographical variations. But the average numbers suggested based on historical observations were that annual mean air temperature of a city with a million or even more inhabitants can be 1-3°C (1.8-5.4°F) warmer than its surroundings, but with clear and calm night, temperature difference can even reach to 12°C (22°F).

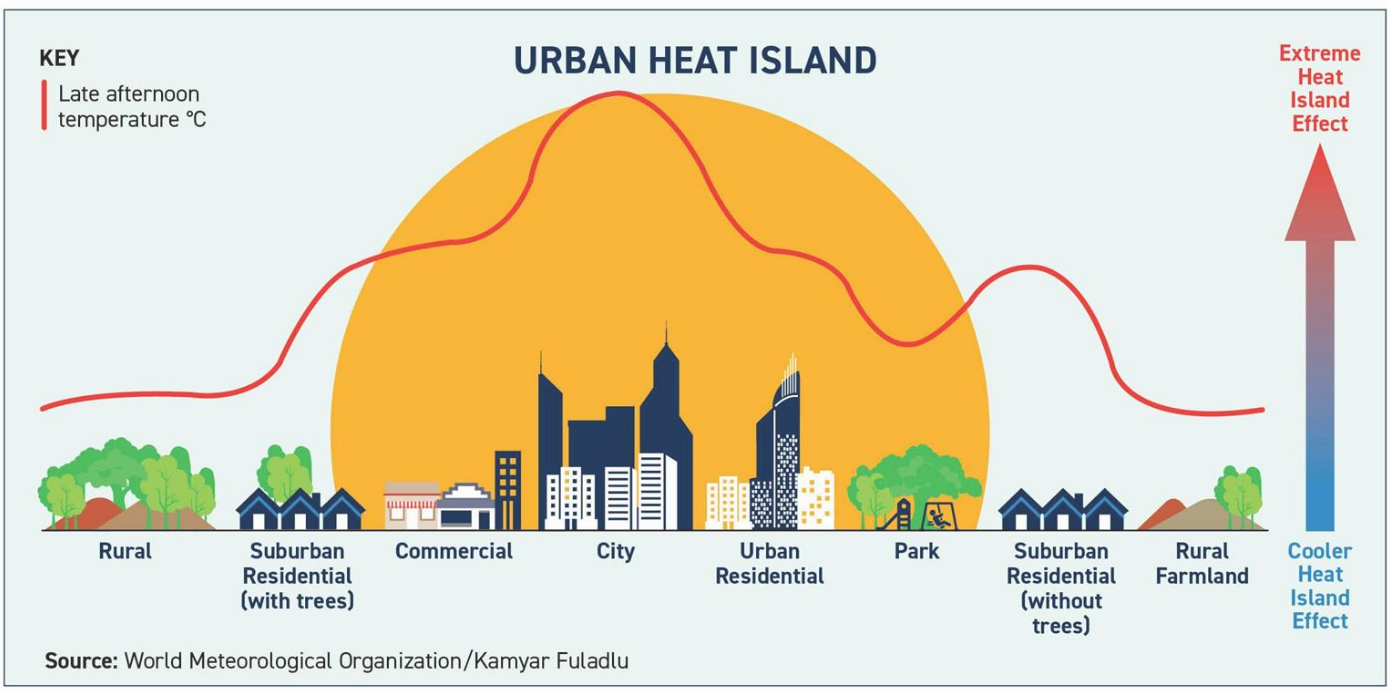


Figure 10. *Urban heat islands impact areas.*
Source: World Meteorological Organization, Kanyar Fuladlu

List of the areas that can possible be affected by UHI is wide, such as worsening air and water qualities, these changes also affect balance of ecosystems and health and well-being of inhabitants. For example, between many estimations, for every 0.6°C rise in

[19] *Urban Planning Characteristics to Mitigate Climate Change in context of Urban Heat Island Effect - The Energy and Resource Institute, 2017*

temperature can cause increase of electricity consumption and demand about 2%, which also increases emissions of greenhouse gasses. When at the end all the issues go to the same path of impacts on Climate Change[20].

The Urban Heat Island (UHI) effect contributes to climate change in two significant ways. Firstly, the accumulation of heat in urban areas exacerbates the impacts of global warming, making these regions more susceptible to extreme heatwaves and excessively high daytime summer temperatures. Secondly, the rise in indoor temperatures due to the UHI effect increases the demand for cooling in buildings. In many developing nations, which rely heavily on traditional energy sources, this heightened electricity consumption further accelerates the emission of greenhouse gases as was already mentioned before. Moreover, for countries with limited natural resources and emerging economies, the surge in energy demand can lead to considerable economic strain. Therefore, the most research agrees about adopting strategies to reduce UHI could play a crucial to avoid results such as:

- Thermal discomfort in indoor and outdoor environments
- Increase of rainfall intensities in urban areas
- Increase of greenhouse gasses
- Risks of fire breakouts
- Increase of heating and cooling demands, which leads to electricity consumption

Having introduced the concept of Urban Heat Islands (UHI), it becomes essential to explore not just the presence of these phenomena, but also their profound impact on the environment, public health, and urban infrastructure. The heat retained in cities does not merely affect temperatures but brings about a series of cascading effects that can influence the quality of life for millions. Understanding the importance of UHI is crucial for urban planning, climate adaptation, and policy formulation.

As cities continue to grow, the intensity and extent of UHIs are expected to escalate, making it increasingly urgent to address their consequences. In following chapter, we will examine why UHI matters – from its environmental impacts to its potential public health area – and highlight the long-term implications for sustainability in urban areas.

3.1 WHY URBAN HEAT ISLANDS ARE SO IMPORTANT?

Urban heat islands (UHIs) have significant impacts on urban areas, particularly during the summer months when temperatures soar, affecting the quality of life. These temperature increases can lead to discomfort, higher energy consumption, and poor air quality. However, UHIs may also have some positive effects, particularly in the winter. The warming effect of UHIs during colder months can reduce the demand for heating, leading to lower energy consumption and potentially lower heating costs. This is a notable contrast to the

[20] *Urban Planning Characteristics to Mitigate Climate Change in context of Urban Heat Island Effect - The Energy and Resource Institute, 2017*

summer months, where the increased temperatures drive up the demand for cooling systems, leading to higher energy consumption.

While UHIs can provide some energy savings in winter, their overall impact on urban microclimates is largely negative. They contribute to reduced air quality, elevated air pollution, and increased greenhouse gas emissions, all of which contribute to climate change. Additionally, UHIs can lead to the deterioration of water quality and negatively affect human health and well-being, exacerbating issues such as respiratory illnesses and heat-related stress. These challenges are directly linked to several of the Sustainable Development Goals (SDGs), particularly those focusing on health, clean energy, and climate action. Addressing urban heat islands is crucial for creating sustainable, resilient cities and improving quality of life for urban residents.

3.1.1 Energy Demand and Consumption

As an opposite of Sustainable Development Goal 7, which promotes affordable and clean energy processes, Urban heat islands can be considered as an impeding factor. During the summertime people massively starts to use air conditioning systems due to increased temperature and to keep indoor spaces cool, while all absorbed masses of heat are released into the atmosphere. But it's not all, pressure is also adding to the electrical grid during the peak periods of demand, when all the inhabitants are running conditioning, lighting and appliances systems, usually this period of a day is the summer weekends, especially during the afternoon (Figure 11).

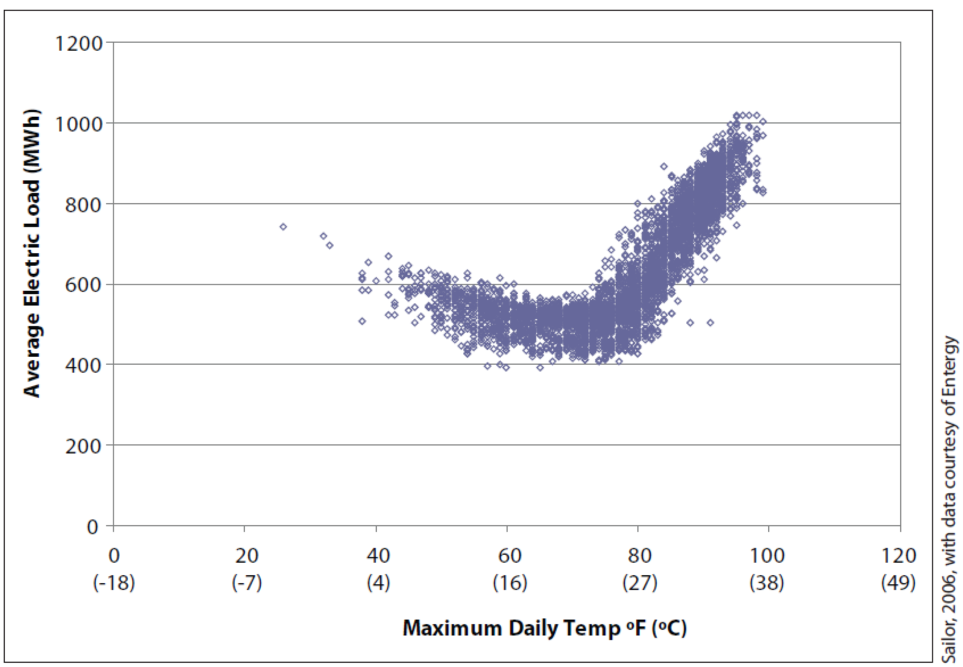


Figure 11. *Increasing Power Loads with Temperature Increases.*
Source: Sailor, 2006, with data courtesy of Entergy

The rising temperatures in downtown areas over the past few decades have led to 5% to 10% of the total electricity demand being used to counteract the heat island effect. During extreme heat events, made worse by urban heat islands, the increased demand for cooling can strain power systems, forcing utilities to implement controlled power outages, such as rolling brownouts or blackouts, to prevent complete power failure.

As energy demand and consumption increase, the environmental impact intensifies, leading to higher levels of air pollution and greenhouse gas emissions. This heightened pollution directly affects air quality and accelerates climate change, creating a need for sustainable energy solutions and cleaner technologies.

3.1.2 Air Quality and Greenhouse Gas Emissions

As highlighted in the previous chapter, rising temperatures lead to an increase in energy demand, which in turn elevates the concentration of pollutants in the atmosphere and exacerbates greenhouse gas emissions. The majority of the electricity we consume is produced through the combustion of fossil fuels. As a result, power plants release pollutants such as sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and mercury (Hg). [21]These pollutants are harmful to people's health and play a major role in causing various air quality problems, such as acid rain. Additionally, fossil fuel-based power plants release greenhouse gases, especially carbon dioxide (CO2), which contribute to climate change.

Along with the rise in air pollution, higher temperatures also speed up the creation of ground-level ozone. This ozone is formed when nitrogen oxides (NOx) and volatile organic compounds (VOCs) react in the sunlight. In simpler terms, when the weather is hotter and sunnier, ozone levels tend to be higher, assuming other factors like the number of emissions or wind patterns stay the same. This is because the heat from the sun helps the chemical reaction that forms ground-level ozone.

Ground-level ozone can cause serious health issues, including respiratory problems and asthma. It also harms the environment by affecting plant life and reducing crop yields. As temperatures continue to rise due to climate change, the formation of ozone and other pollutants may worsen, making air quality even worse. This creates a dangerous cycle where higher temperatures lead to more pollution, and the pollution, in turn, contributes to even higher temperatures, affecting both human health and the environment, which are against Sustainable Development Goals like SDG3: Good Health and Well-being, SDG 11: Sustainable Cities and Communities, SDG 13: Climate Action.

3.1.3 Human Heath

Higher daytime temperatures, reduced cooling at night, and increased air pollution in urban heat islands can negatively impact human health. These conditions can lead to discomfort, breathing problems, heat cramps, exhaustion, non-fatal heat strokes, and even heat-related deaths.

[21] *Reducing Urban Heat Islands: Compendium of Strategies - Urban Heat Island Basics, U.S. Environmental Protection Agency (EPA), 2008*

Urban heat islands can also make heat waves more intense. Heat waves are periods of unusually hot and often humid weather. Certain groups of people, such as young children, the elderly, and those with pre-existing health conditions, are particularly vulnerable during these events. The risk of heat-related health problems is especially concerning in cities, where urban heat islands can significantly raise temperatures, putting more people at risk. It is important to act and promote SDG 3: Good Health and Well-being, to mitigate these effects by reducing heat exposure, improving urban planning, and increasing access to cooling resources, particularly for vulnerable populations.

As we have seen, the impacts of environmental changes on human health are profound, with climate-related factors exacerbating existing health risks. Similarly, these changes also disrupt the water cycle, influencing precipitation patterns, water availability, and quality, which in turn affect ecosystems and communities.

3.1.4 Water Cycle

Surface urban heat islands can significantly impact water quality, primarily through thermal pollution. Urban surfaces like pavements and rooftops can reach temperatures 27 to 50°C higher than the surrounding air, transferring this heat to rainwater. Studies showed that during summer, runoff from urban areas was about 11-17°C warmer than runoff from nearby rural areas when pavement temperatures peaked 11-19°C higher than the air temperature. However, if rainfall occurred before the pavement had time to warm up, the temperature difference between urban and rural runoff was less than 2°C. This heated runoff typically flows into storm drains and raises water temperatures in rivers, streams, ponds, and lakes.

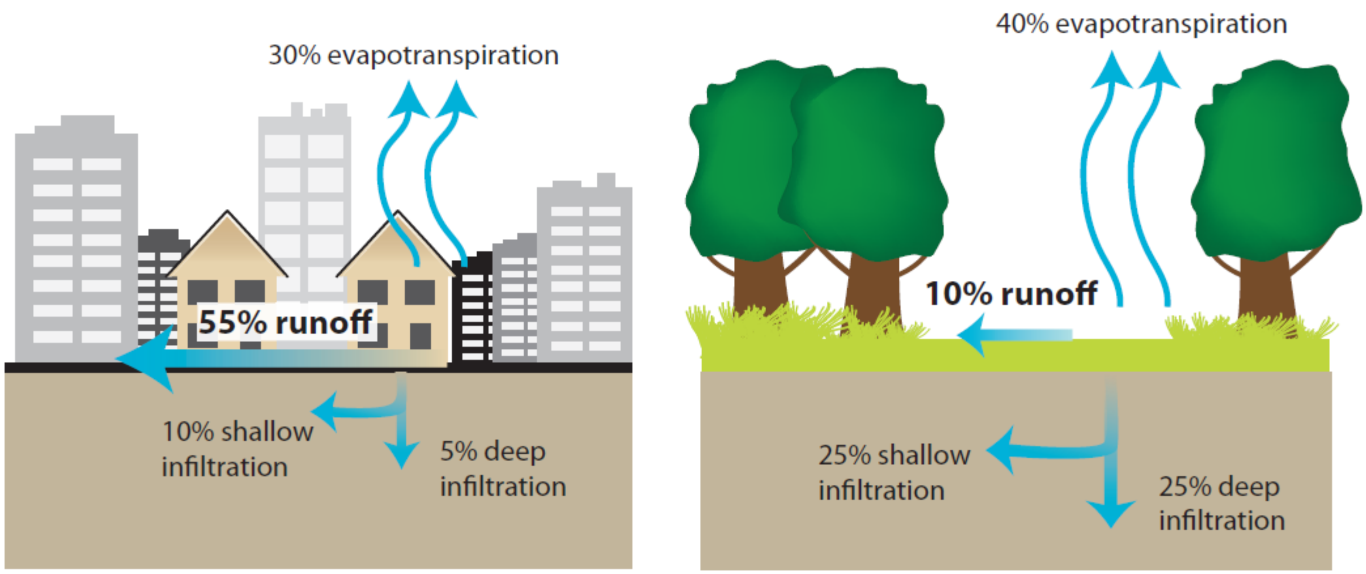


Figure 12. Water cycle - Impervious Surfaces and Reduced Evapotranspiration
Source: Modified from the Federal Interagency Stream Restoration Working Group (FISRWG)

Water temperature is crucial for the health of aquatic ecosystems, as it affects the metabolism and reproduction of many aquatic species. Sudden changes in water temperature, often caused by warm runoff, can be especially stressful for aquatic life. For instance, fishes are sensitive to thermal stress and shock and can suffer if water temperatures change by more than 1-2 °C in just 24 hours. These temperature fluctuations can disrupt their normal biological processes and harm their populations. Therefore, managing urban heat islands and preventing thermal pollution is essential for protecting aquatic ecosystems and ensuring the health of species dependent on these environments, which aims availability and sustainable management of water and sanitation for all as SDG6 about Clean Water and Sanitation.

The significance of Urban Heat Islands in exacerbating temperature extremes has been well established, demonstrating the profound effect of urbanization on local climates. This increased heat not only elevates energy consumption but also directly impacts the well-being of urban populations. In this context, understanding outdoor thermal comfort becomes essential, as it is directly influenced by factors such as UHI, air temperature, and urban planning, all of which determine how individuals experience and adapt to outdoor environments.

3.1.5 OUTDOOR THERMAL COMFORT

In recent decades, rapid urban growth without proper management of public spaces has negatively impacted the local microclimate. This is especially true as temperatures rise, leading to decreased thermal comfort for residents. Today, many cities that aiming to become more resilient and sustainable, are introducing plans to improve outdoor spaces. These plans are focusing on creating thermally neutral and comfortable environments, which are essential for the health and well-being of city dwellers. Thermal comfort of inhabitants and their requitements can be distinguished for internal and external spaces, the range of thermal conditions are comparably wide in case of outdoor environments.

Thermal comfort plays a crucial role in the quality of life, especially in urban areas with a high concentration of buildings where it's an outcome of different complex parameters. Achieving a comfortable outdoor environment, however, requires a shift in mindset - a focus on satisfaction with the thermal conditions, known as Outdoor Thermal Comfort. This can be assessed using both subjective and objective measurements.

- Behavioural
- Psychological

Subjective

- T_a - Air Temperature
- V_a - Wind
- RH/ϕ - Relative Humidity
- T_{mr} - Radiation
- M - Metabolic Heat
- I_{cl} - Clothing Insulation

Objective

Thermal comfort is not a universal concept; it varies from person to person and is influenced by the activities being performed. On the other hand, when the human body reaches thermal equilibrium with the surrounding environment, a sense of comfort can be defined.

But how do we measure outdoor thermal comfort if it is not universal? Urban thermal comfort is shaped by many factors, both quantitative and qualitative. While much research has been done to understand comfort and express it through various indices, they currently fall into two main categories: those evaluated as a function of environmental parameters, and those when a homogeneous group of people evaluates their perception of conditions on a sensation scale.

Quantification of Outdoor Thermal Comfort

Predicted Mean Vote – PMV

INDICES/FACTORS	PMV – Predicted Mean Vote
INTRODUCED	Fanger, 1972[22]
DESCRIPTION	A metric used to assess thermal comfort, predicting the average thermal sensation of a group of people based on environmental factors such as air temperature, humidity, clothing, and activity level. It typically ranges from -3 (cold) to +3 (hot), with 0 representing a neutral thermal sensation.
FACTORS CONSIDERED	Air Temperature, Relative Humidity, Wind Speed, Solar Radiation, Metabolic Rate, Clothing Insulation.
LIMITATION	Requires accurate data for all environmental factors, which can be challenging in outdoor conditions due to parametrical fluctuating.
APPLICATION/USE	Mainly used for indoor areas.

One of the most used measurements for thermal comfort is the PMV – Predicted Mean Vote theory. The idea assumes that the thermal comfort of the human body can only be reached and maintained within defined boundary conditions. It is a 6-parameter scale that expresses the perception of the thermal environment (Table 1). PMV is usually used for assessing indoor thermal conditions, as it depends on air temperature, air velocity, clothing insulation, and metabolic rate.

Universal Thermal Climate Index – UTCI

INDICES/FACOTRS	UTCI – Universal Thermal Climate Index
INTRODUCED	International Society of Biometeorology, 2009[23]

[22] *Fanger, P.O. Measurement of Thermal Comfort: Introduction of a Method for Predicting the Thermal Sensation and the Thermal Acceptability of a Room, 1972*

[23] *Jendritzky, G., de Dear, R., & Havenith, G. The Universal Thermal Climate Index (UTCI) for humans and its application to outdoor thermal environments, 2012*

DESCRIPTION	An outdoor thermal comfort index that evaluates the impact of environmental factors, such as air temperature, humidity, wind speed, and radiation, on human thermal comfort. It provides a single numerical value that represents the perceived temperature and is used to assess health risks related to extreme weather conditions across different climates.
FACTORS CONSIDERED	Air Temperature, Wind Speed, Relative Humidity, Solar Radiation, Clothing Insulation, Metabolic Rate.
LIMITATION	Requires detailed meteorological data.
APPLICATION/USE	Conditions from extreme cold to extreme heat. It gives both thermal sensation and physiological stress categories.

Even if PMV can also be applied to estimate how comfortable a person might feel in various weather conditions, additional factors, such as solar radiation, wind speed, and shading, need to be considered. This is the reason for using the Universal Thermal Climate Index (UTCI) for outdoor comfort evaluations, which is based on a physiological response model. UTCI considers solar radiation and radiant temperature, relative humidity, wind speed, and uses human energy balance to measure thermal stress on the human body. In external conditions one of the calculation methods can be following (Blazejczyk, 2011):

$$UTCI = 3.21 + (0.872 \times Ta) + (0.2459 \times Tmr) - (2.5078 \times V) - (0.0176 \times RH) \quad (1)$$ [24]

Where:

- T_a – Temperature of an air [°C]
- T_{mr} – Mean Radiant Temperature [°C]
- V – Wind velocity at 10m above the ground [m/s]
- RH – Relative humidity of air [%]

Physiological Equivalent Temperature – PET

INDICES/FACTORS	**PET – Physiological Equivalent Temperature**
INTRODUCED	Mayer and Hoppe, 1987-1999[25]
DESCRIPTION	An index used to estimate the thermal comfort of a person based on outdoor environmental factors such as air temperature, humidity, wind, and radiation, while accounting for human heat balance. It is expressed in degrees Celsius and helps evaluate the physiological response to various thermal conditions, guiding urban planning and outdoor activities.

[24] *Fiala, D., Havenith, G., Brode, P., Kampmann, B., Jendritzky, G., 2012. UTCI-Fiala multimode model of human heat transfer and temperature regulation*
[25] *Mayer, H., & Höppe, P. (1987). Thermal comfort of man in different urban environments. Experientia,*

FACTORS CONSIDERED	Air Temperature, Relative Humidity, Wind Speed, Solar Radiation.
LIMITATION	PET requires meteorological data and specific human parameters (e.g., metabolic rate, clothing).
APPLICATION/USE	Accurate for extreme outdoor conditions typically. Considers the thermoregulation system of the human body.

Another measurement scale for outdoor conditions was introduced – Physiological Equivalent Temperature (PET), which, for the evaluation assessment, compares the existing situation to a steady indoor state where $T_{mr} = T_a$, wind speed is 0.1 m/s, relative humidity is 50% when air temperature is 20 °C, and the vapor pressure is 12 hPa. This evaluation allows for describing not only the general sensation of a microclimate but also specific ones in urban spaces such as streets, parks, squares, etc.

Outdoor Standard Effective Temperature – OUTSET

INDICES/FACOTRS	**OUTSET – Outdoor Thermal Climate Index**
INTRODUCED	Pickup and De Dear, 1999
DESCRIPTION	The Outdoor Standard Effective Temperature (OUTSET) is an index designed to evaluate outdoor thermal comfort, taking into account environmental factors such as air temperature, humidity, wind speed, and solar radiation. It provides a single value to represent how a person perceives thermal conditions, helping to assess comfort levels in outdoor environments.
FACTORS CONSIDERED	Air Temperature, Relative Humidity, Wind Speed, Solar Radiation, Clothing Insulation.
LIMITATION	Has several limitations, including its reliance on simplified models that may not fully capture the complexity of human perception in diverse environmental conditions. Additionally, OUTSET does not account for individual variations in sensitivity to thermal stress, such as age, health, or clothing, which can affect the accuracy of thermal comfort assessments in specific populations.
APPLICATION/USE	Accurate for extreme outdoor conditions typically. Considers the thermoregulation system of the human body.

Outdoor Standard Effective Temperature (SET) is a metric used to assess human comfort in outdoor environments by considering temperature, humidity, wind speed, and solar radiation. It aims to provide a more accurate representation of how the environment feels to the human body, beyond just air temperature. SET helps in evaluating and designing outdoor spaces for optimal comfort and safety, particularly in extreme weather conditions.

As much as sensation of a temperature is not a universal concept, as well as evaluation and expression of it in quantitative way is not universal (Table 1). It depends on a lot of factors and requirements of each project's design goals.

Outdoor thermal comfort can be achieved through various strategies, such as increasing the amount of vegetation per person by creating green spaces or using a combination of innovative and natural materials in building design. These materials can improve the building envelope, creating more comfortable environments for residents. Each approach offers distinct benefits for the infrastructure, such as better air quality, cooling effects, and aesthetic appeal, while helping reduce heat stress in outdoor spaces. However, it is important to recognize that the perception of thermal comfort is highly subjective, varying from person to person based on individual preferences and physiological differences.

Achieving thermal comfort in outdoor environments is more challenging than in indoor spaces due to the greater influence of external factors like weather, wind, and sunlight. The goal is to reach thermal equilibrium, where the body maintains a balance between heat gain and heat loss. In outdoor settings, heat transfer is influenced by various factors at different scales, such as micro, local, and meso scales. These scales include small, localized areas (micro), specific neighbourhoods or regions (local), and larger urban environments (meso). Understanding these scales is essential for any assessment of outdoor thermal comfort, as the factors influencing heat transfer differ depending on the scale and context. Ultimately, creating outdoor environments that minimize thermal stress requires a comprehensive approach that considers these various factors and the diversity of individual needs.

SENSATION	PMV	PET [°C]	OUTSET [°C]	UTCI [°C]
Very Cold		< +4		<-40
				-40 — - 27
Cold	-3	+4 — +8	+10 — +14.5	-27 — -13
Cool	-2	+8 — +13	+14.5 — +17.5	-13 — 0
Slightly Cool	-1	+13 — +18	+17.5 — +22.2	0 — +9
Comfortable/Neutral	0	+18 — +23	+22.2 — +25.6	+9 — +26
Slightly Warm	1	+23 — +29	+25.6 — +30	+26 — +32
Warm	2	+29 — +35	+30 — +34.5	+32 — +38
Hot	3	+35 — +41	+34.5 — +37.5	+38 — +46

Very Hot		> +41	+37.5 — +44	> +46

Table 1. Comparison of thermal indices

3.2 URBAN LAYERS AND IMPACTS OF URBAN HEAT ISLANDS

Focus of the topic is Microclimate, the relationship between architecture and microclimate is tight, in another words, building envelope has an impact on outdoor thermal comfort and in reverse way, external temperature and urban dense effects on building overall energy use/loads and consumption which forms different Urban Layers into the environment:

- **Urban Canopy Layer (UCL) –** Layer that goes from ground level up the surface of a building roof, trees and urban infrastructure. Compared to surface layer it characterised with high heterogenic essence, the necessity of establishing unique microclimate behaviour, such as: Parameters of site, building technologies and/or systems, construction materials, vegetation etc.
- **Roughness Sub-Layer (RSL) –** if we multiple height of a building in twice, we will stand in roughness sub-layer, which has a strong dependency on different buildings height variations, green and open spaces. We can consider this layer as a transition between vibrant and homogenous parts of an atmosphere.
- **The Urban Boundary Layer (UBL) –** The lowest part of it is known as urban boundary layer (UBL) which is formed by the building technologies and their characteristics. This layer of an atmosphere has itself its own sublayers, according to considering climatic conditions and its fundamentals.
- **Surface Layer (SL) –** goes up to four or five times of average building height in urban areas. It's characterized ground level coverage area and three-dimensional parameters for geometry. Formation of these air is happening when all the air passes over the whole length of the urban infrastructure.

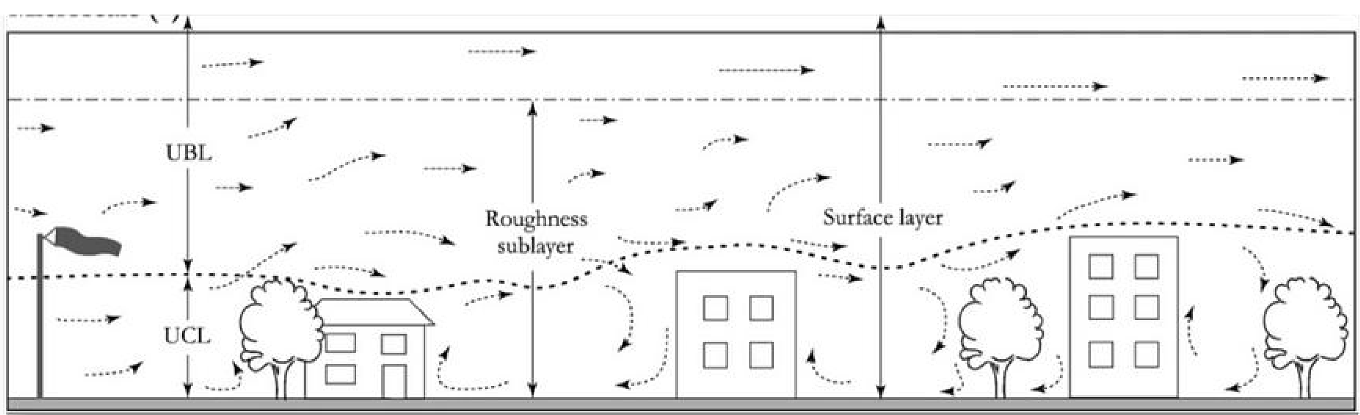


Figure 13. Diagram showing urban roughness surface layer, Urban Canopy Layer UCL, Urban Boundary Layer UBL, and the mixing of hot and cooler air.
Source: Gunawardena et al., (2017)

Urban Heat Islands (UHI) are closely linked to atmospheric layers because the heat generated by cities alters the air temperature in the lower atmosphere, creating a localized warming effect. This warming impacts the urban boundary layer, a section of the atmosphere directly influenced by surface conditions, including buildings and roads. As a result, the UHI phenomenon can change air circulation, humidity, and overall atmospheric stability in and around urban areas.

Urban heat islands (UHIs) can be categorized based on their formation and characteristics into two main types: surface and atmospheric heat islands. Canopy layer urban heat islands (UCL) are a subset of atmospheric heat islands and represent the most observed form, often discussed when examining the UHI effect.

Atmospheric urban heat islands generally have weaker intensity during the late morning and throughout the day, becoming more pronounced after sunset as heat stored in urban infrastructure is gradually released. The timing and strength of this peak are influenced by various factors, including the properties of urban and rural surfaces, the season, and prevailing weather conditions.

Surface temperatures play a crucial role in influencing air temperatures, particularly in the canopy layer close to the ground. Areas with vegetation, such as parks, typically have cooler surfaces and contribute to lowering air temperatures, while densely built-up areas tend to increase air temperatures. However, due to atmospheric mixing, the relationship between surface and air temperatures is not always straightforward. As a result, air temperatures often exhibit less variation than surface temperatures across different areas. This chapter will explore the various layers of the UHI effect, focusing on their distinct characteristics, formation processes, and the factors that influence their intensity and timing, and overall describes them in Table 2.

Features	SLUHI	ALUHI
Temporal Development	Present at all times of the day and night	May be small or non-existent during the day
	Most intense during the day and in the summer	Most intense at night or predawn and in the winter
Peak Intensity (Most intense UHI conditions)	Day: 10 to 15°C (18 to 27°F)	Day: -1 to 3°C (-1.8 to 5.4°F)
	Night: 5 to 10°C (9 to 18°F)	Night: 7 to 12°C (12.6 to 21.6°F)
Typical Identification Method	Remote sensing	Fixed weather stations
		Mobile traverses
Typical Depiction	Thermal Image	Isotherm map
		Temperature graph

Table 2. *Comparison between SLUHI and ALUHI*

3.2.1 Surface Layer Urban Heat Islands – SLUHI

On a hot summer day, urban surfaces such as roofs and pavements can heat up significantly, reaching temperatures 27 to 50°C (50 to 90°F) higher than the surrounding air.

In contrast, shaded or moist surfaces, usually found in rural areas, stay much closer to the ambient air temperature. Surface urban heat islands (SUHIs) are present both during the day and night but are most intense when the sun is shining at its peak.

During the day, urban areas can experience surface temperature differences from rural areas ranging between 10 to 15°C (18 to 27°F), while these differences are typically smaller at night, averaging 5 to 10°C (9 to 18°F). The intensity of surface urban heat islands is influenced by various factors, including changes in the sun's intensity, ground cover, and weather conditions. As a result, SUHIs are most prominent in the summer months, when the sun is stronger, and the days are longer.

The size and strength of these heat islands can fluctuate seasonally, with the largest temperature differences often occurring during summer due to the increased solar radiation and changes in vegetation cover. To monitor and assess these temperature variations, scientists rely on a mix of direct and indirect methods, such as numerical models, remote sensing technologies, and empirical data to estimate surface temperatures. Remote sensing is commonly used for estimating surface temperatures from a distance by analysing satellite or aerial images, offering an effective way to track heat islands over large areas.

In summary, surface urban heat islands create noticeable temperature differences between urban and rural areas, with urban regions heating up more due to human activities, materials, and limited green spaces. These heat islands are most pronounced during the day but can still affect the environment throughout the day and night, especially in urban centres.

3.2.2 Atmospheric Layer Urban Heat Islands – ALUHI

Atmospheric urban heat islands occur when the air in urban areas is warmer than in nearby rural areas. Atmospheric heat islands tend to be less intense than surface heat islands. On average, large cities can have air temperatures that are 1 to 3°C higher than surrounding rural areas. These heat islands are typically categorized into two types:

- **Canopy Layer Urban Heat Islands (CLUHI) –** These occur in the air layer where people live, extending from the ground up to just below the tops of buildings and trees.
- **Boundary Layer Urban Heat Islands (BLUHI) –** These begin at the roof and treetop levels, reaching upwards to where the urban environment no longer affects the atmosphere. This layer typically extends up to one mile (1.5 km) from the surface.

Among these, canopy layer urban heat islands are the most seen and discussed, which is why the term "atmospheric urban heat islands" is often used to refer to them in general discussions.

These heat islands tend to be less noticeable during the daytime and peak more noticeably after sunset, when urban areas gradually release stored heat. The exact timing of this peak can vary depending on factors such as the types of surfaces in urban and rural areas, the season, and the prevailing weather conditions. For example, urban surfaces like roads, buildings, and pavements absorb heat during the day and slowly release it once the sun sets, causing the air in cities to remain warmer longer than in rural areas. This phenomenon can significantly impact local temperatures, leading to discomfort and higher energy consumption, especially during hot months. The variations in the intensity and timing of the peak also highlight the complex relationship between urban landscapes and atmospheric conditions.

3.3 FORMATION OF UHI: FACTORS INFLUENCING INTENSITY AND OCCURRENCE

The UHI effect occurs when urban areas experience higher temperatures than their surrounding rural environments due to human activities and altered land surfaces. Several factors contribute to the intensity and occurrence of UHI, including the type of materials used in urban infrastructure, building density, and limited green spaces. Additionally, anthropogenic heat from transportation, industry, and air conditioning further amplifies urban warming. As a first steps it's important to understand these key factors, which are crucial for mitigating UHI impacts and improving urban climate resilience.

3.3.1 Urban Morphology

One important factor that contributes to the development of urban heat islands (UHI), particularly at night, is urban geometry. Urban geometry refers to the shape and arrangement of buildings within a city, including their size, spacing, and layout. This factor influences wind patterns, energy absorption, and how surfaces in the city release heat back into the atmosphere. In cities, surfaces and buildings are often partially blocked by other structures, making them large thermal masses that retain heat and release it slowly. As a result, urban areas, especially at night, are typically warmer than rural areas. This phenomenon, known as the nighttime atmospheric heat island, can be dangerous, especially during heatwaves, and may lead to serious health risks for people living in these areas.

A key area of focus for researchers when studying urban geometry is something known as "urban canyons." An urban canyon is a street that is flanked by tall buildings, creating a narrow, enclosed space. During the day, urban canyons have both positive and negative effects on temperature. On the one hand, the tall buildings can provide shade, which helps reduce temperatures by blocking sunlight from directly reaching the ground. However, the building surfaces in these canyons also reflect and absorb sunlight, which increases the amount of heat in the area. This heat is then trapped, as the buildings' surfaces have low reflectivity, meaning they absorb more solar radiation than they release, further raising the temperature in the canyon and the surrounding urban environment.

At night, the situation becomes even more challenging. Urban canyons tend to restrict cooling because the buildings block the heat that would normally escape into the atmosphere. Since these structures hold onto heat, they prevent the urban environment from cooling down quickly after sunset, making the temperature difference between urban and rural areas more pronounced. This can exacerbate the UHI effect, leaving cities warmer throughout the night, which can continue to strain the health and well-being of city residents.

Urban geometry plays a crucial role in shaping the overall temperature dynamics within a city. It affects how wind flows through the area, how energy is absorbed by surfaces like roads and buildings, and how these surfaces release or retain heat. Narrow streets and tall buildings in an urban area can prevent efficient airflow, leading to higher temperatures in densely built-up zones. The overall heat island effect is particularly strong in urban canyons because of the way the buildings are arranged. These canyons create areas where heat is both trapped and absorbed, making it difficult for temperatures to decrease, especially at night.

In summary, the way buildings are designed and arranged within a city has a significant impact on the development of urban heat islands. The size and shape of streets and the height of buildings can create conditions where heat is absorbed during the day and retained at night. Understanding urban geometry and its influence on temperature is essential for managing and mitigating the UHI effect, particularly in dense urban centres where the risk of heat-related health issues is higher.

Sky View Factor – SVF

Sky View Factor (SVF) indicates how much of the sky is visible from a specific point on the surface. This factor is essential for understanding the balance of radiation at the surface. In open areas with a high SVF (close to 1), more direct sunlight reaches the ground, whereas in urban areas with lower SVF, reflections from buildings can affect the amount of radiation. Longwave radiation is either absorbed by or reflected from surfaces, with some of it being emitted. The three-dimensional nature of urban environments allows more interaction of radiation. In open spaces, longwave radiation reflects in all directions, but in cities, buildings limit this process. Street canyons also reduce heat release because of surrounding structures.

The geometry of urban surfaces significantly influences the local climate, particularly the urban heat island effect. One major factor is sky obstruction, which slows down the cooling of the ground at night, especially under clear and calm conditions. Buildings trap heat, preventing it from escaping into the air, causing higher temperatures in urban areas. The materials used in these buildings and the heat they emit also play a role in how much radiation is absorbed and released, which in turn affects temperature. As SVF increases, more heat is lost to the atmosphere.

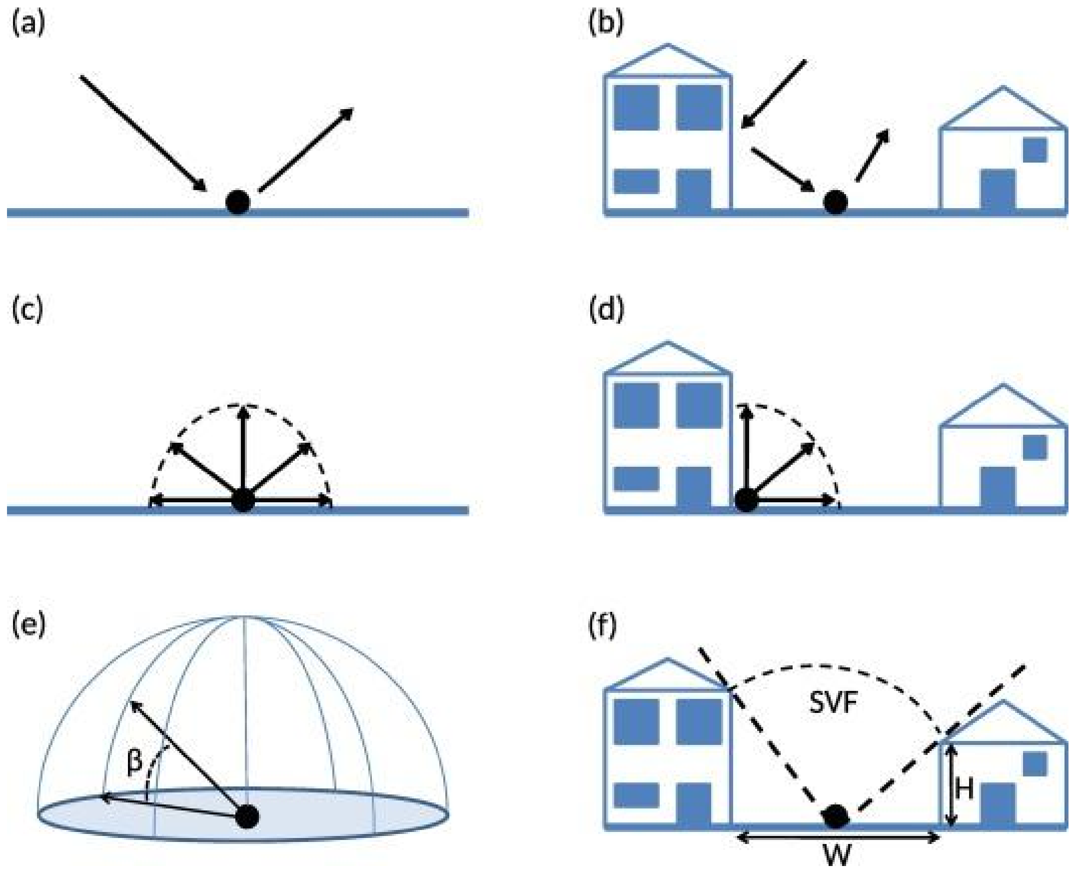


Figure 14. Radiation components in an open field and street canyon and, SVF calculations illustrated.
(a) Short wave radiation in an open field.
(b) Short wave radiation in a street canyon.
(c) Emission of long wave radiation in an open field.
(d) Emission of long wave radiation in a street canyon.
(e) SVF calculated in 3D; were, β is the angle from the centre point to the maximum obstacle height.
(f) SVF in a 2D street canyon; where W is the street width and H is the building height.
Source: De Wolff, 2008; Hämmerle et al., 2011

SVF is an important part of urban geometry and determines how much radiation a surface receives compared to the total radiation in the environment. Which can be calculated with formula:

$$ASVF = \frac{Total\ hemisphere\ area}{Visible\ sky\ area} \text{ or } ASVF = \frac{1}{2}(1 - \frac{H}{W}) \quad (2)$$

Where:

- H is the height of the buildings
- W is the width of the canyon or street

Research shows that SVF, especially in crowded areas, can strongly influence the formation of urban heat islands by affecting long-wave radiation loss during the night. Studies indicate that SVF can raise temperatures by as much as 7°C. The strength of the heat island effect is also influenced by the SVF, especially in low wind conditions, since less air movement means less heat is removed from the surface. The method of measuring SVF, such as using fisheye photography, can also impact the results, depending on where the photos are taken.

Canyon Verticality Ratio – H/W

The height-to-width ratio (H/W) of urban canyons is a key factor influencing ventilation, specifically airflow and ventilation efficiency. This ratio helps urban designers evaluate the airflow status in a quick and practical way. However, past research primarily concentrated on idealized canyon geometries rather than real urban settings. This study aims to explore if the relationships between H/W, airflow, and ventilation efficiency observed in idealized conditions also apply to urban environments. To begin, a review of the existing literature helps clarify how H/W affects ventilation performance in theoretical models.

In an urban context, the H/W ratio can still impact ventilation, but other environmental factors complicate the airflow, leading to different flow patterns that weaken the connection between H/W and the effectiveness of ventilation. With rapid urbanization and growing environmental challenges, improving ventilation in cities could help address several issues, such as air pollution and heat buildup. Modifying urban space design can be an effective way to improve ventilation performance. Using morphological indicators like H/W can support urban designers in making better, faster decisions to enhance airflow.

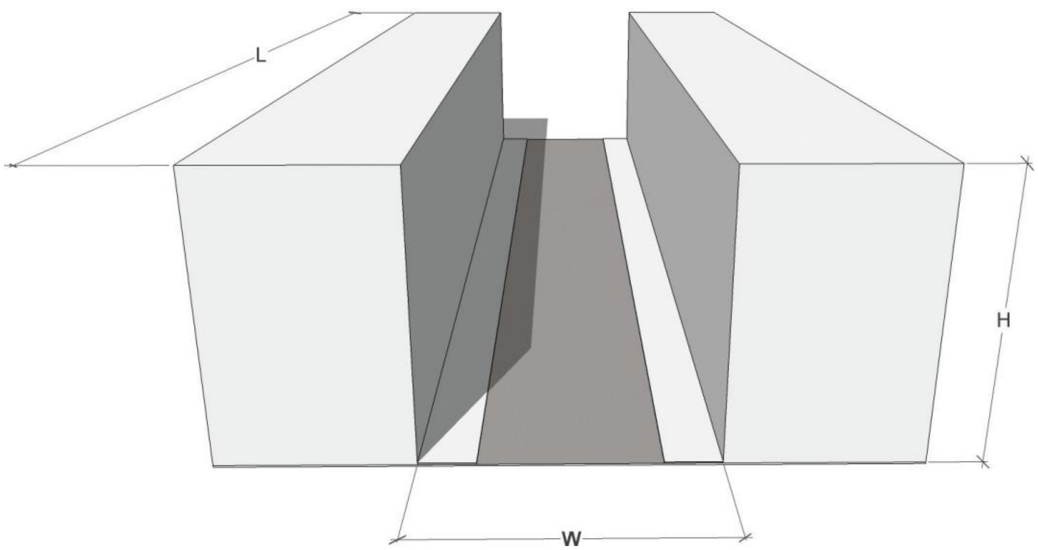


Figure 15. *Illustration of H/W*

Many researchers have studied how the H/W ratio influences airflow and ventilation in canyons. Some of them identified different flow types based on H/W values: isolated rough flow occurs when H/W is less than 0.35, wake interference flow happens between 0.35 and 0.65, and skimming flow occurs when H/W exceeds 0.65. Other studies have looked at how H/W affects ventilation efficiency. And others discovered that as H/W increases, the air exchange rate and purification flow rate decrease, while the average residence time and frequency of visits increase. Despite this, most research has focused on idealized models, with fewer studies examining these dynamics in the complexity of real urban environments.

Site Coverage Ratio - ρ_{urb}

The Site Coverage Ratio (SCR) refers to the percentage of a site's total area that is covered by buildings or other built structures, such as pavements, roads, or other impermeable surfaces. It is often used in urban planning and zoning regulations to determine the amount of land that can be developed in a given area.

The SCR is calculated as:

$$\rho_{urb} = \frac{Area\ of\ built\ structures}{Total\ area\ of\ site} \times 100\% \quad (3)$$

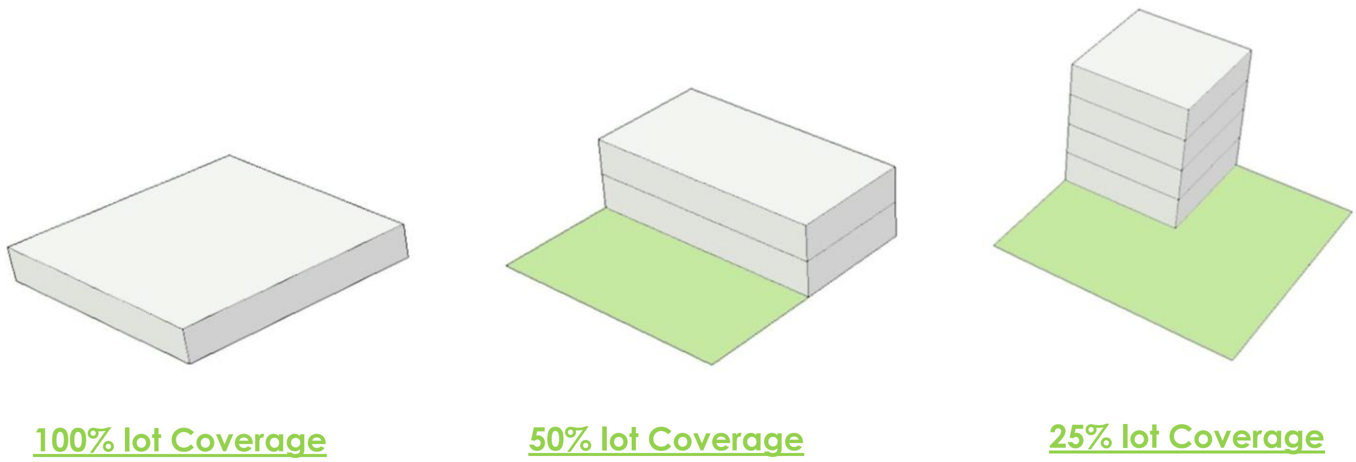


Figure 16. Illustration for Site Coverage Ratios

The Site Coverage Ratio (SCR) plays a crucial role in determining the microclimate of urban areas by measuring the proportion of land covered by buildings and structures. A higher SCR indicates that more land is occupied by impervious surfaces like concrete, asphalt, and buildings, which absorb and retain heat during the day. At night, these surfaces release the stored heat, contributing to the Urban Heat Island (UHI) effect, making urban areas significantly warmer than their rural counterparts, especially during the night.

As SCR increases, space for green areas, such as parks and trees, diminishes. Green spaces are vital for cooling the environment through evapotranspiration, where plants release moisture into the air, lowering temperatures. In areas with a high SCR, there is often a reduction in vegetation, which limits the cooling effect of plants and worsens environmental conditions. With fewer open spaces, the wind is also obstructed, limiting natural airflow and reducing ventilation. Stagnant air further increases local temperatures, exacerbating the UHI effect.

High SCR areas also feature more impervious surfaces, which prevent rainwater from being absorbed by the ground. This leads to higher surface runoff, increased flooding risks, and reduced groundwater replenishment. Consequently, urban areas with high SCRs feel hotter and drier. In contrast, lower SCRs allow for better drainage, which helps reduce the risk of flooding and keeps the environment cooler by enabling better absorption of rainwater.

The relationship between SCR and the UHI effect is strong, with a higher SCR leading to more heat-retaining surfaces and less vegetation to cool the area. The impervious surfaces absorb heat during the day and release it at night, causing higher nighttime temperatures. This heat retention is particularly noticeable in areas with high SCR, where the cooling benefits of vegetation are limited.

Additionally, high SCR areas typically have higher thermal mass in buildings and roads, meaning they store more heat during the day. While this can be beneficial in cooler climates, it exacerbates the UHI effect in warmer cities, as the stored heat is released slowly at night, preventing rapid cooling.

In conclusion, high SCR levels contribute to more impervious surfaces, less greenery, limited airflow, and greater heat retention, all of which intensify the UHI effect. Urban planners can address these issues by reducing the SCR or increasing green spaces, helping to mitigate the UHI effect and create cooler, more sustainable urban environments.

Façade to Site Ratio - FSR

The facade-to-site ratio (FSR) measures the proportion of a building's facade area relative to the total site area. This ratio affects how a building interacts with its environment and influences the local microclimate. A higher FSR means more built surface area compared to open space, while a lower FSR allows for more green space. Buildings with large facades tend to absorb and retain more heat, especially those made from materials like glass and concrete. This heat is released at night, contributing to higher nighttime temperatures and intensifying the urban heat island effect. In contrast, buildings with a lower FSR allow for more green spaces, which can reduce heat retention and contribute to cooler microclimates. A high FSR also reduces open spaces, hindering airflow and ventilation, leading to stagnant air and higher temperatures. Lower FSRs provide more space for airflow, helping to disperse heat. Additionally, buildings with a higher FSR leave less room for vegetation, which helps cool the environment through evapotranspiration. With more greenery, the temperature is regulated and air quality improved. High FSR areas are also less permeable, preventing rainwater absorption and increasing surface runoff, raising flood risks and reducing groundwater recharge. Lower FSRs allow for better water drainage and help mitigate flooding. In summary, the facade-to-site ratio plays a crucial role in influencing temperature, air quality, and water management in urban areas. A higher FSR can contribute to a hotter, less ventilated environment, while a lower FSR helps create a cooler, more sustainable urban microclimate.

Calculated as follows:

$$FSR = \frac{Area\ of\ all\ facades}{Area\ of\ built\ site} \quad (4)$$

Average Building Height - h_{bld}

The Average Building Height refers to the mean height of buildings in each area or across a specific group of buildings. It is typically calculated by taking the total height of all buildings in the area and dividing it by the number of buildings. This measurement provides a general sense of the vertical scale or density of development in a region.

The formula for average building height is:

$$h_{bld} = \frac{\sum Height\ of\ each\ Building}{Number\ of\ Buildings} \quad (5)$$

The Average Building Height of a region can significantly impact its microclimate, which refers to local atmospheric conditions. Tall buildings or a higher average building height affect factors like temperature, wind patterns, sunlight exposure, and air quality, all of which influence the comfort and well-being of residents and workers.

Tall buildings contribute to the urban heat island effect, where heat is trapped between structures, leading to higher temperatures than in surrounding areas. This effect is amplified by reduced airflow, which inhibits the natural cooling of the environment. Additionally, tall buildings can alter wind patterns, creating stronger winds at ground level or wind tunnels, which may increase discomfort and risk for erosion. The impact on sunlight is also notable, as taller buildings cast longer shadows, reducing sunlight exposure in certain areas and limiting the effectiveness of passive solar heating.

Higher building density often leads to a decline in air quality, as limited airflow prevents proper pollutant dispersion, resulting in a build-up of contaminants. This can impair natural ventilation and further degrade the environmental conditions.

In conclusion, the average building height plays an important role in shaping a region's microclimate. Urban planners must account for these factors to create sustainable, comfortable environments that balance development with environmental well-being.

3.3.2 Properties of Urban Surfaces

Urban surfaces play a crucial role in shaping the Urban Heat Island (UHI) effect by absorbing, reflecting, and re-emitting solar energy. The properties of these surfaces, such as thermal capacity, reflectance, and absorbance, significantly influence the intensity of UHI. In urban areas, materials like roads, rooftops, and pavements tend to have low reflectance (low albedo), meaning they absorb more solar energy and reflect less compared to rural areas. As a result, urban surfaces absorb more heat, raising surface temperatures and contributing to the UHI effect.

The thermal capacity of materials determines how much heat they can store. Urban surfaces made from materials like steel and concrete store more heat than natural surfaces like soil or sand, causing central urban areas to absorb more heat. This heat is then released at night, keeping temperatures higher in urban areas than in surrounding rural areas. As a result, temperature fluctuations (diurnal variations) are much smaller in UHI-affected cities compared to rural areas.

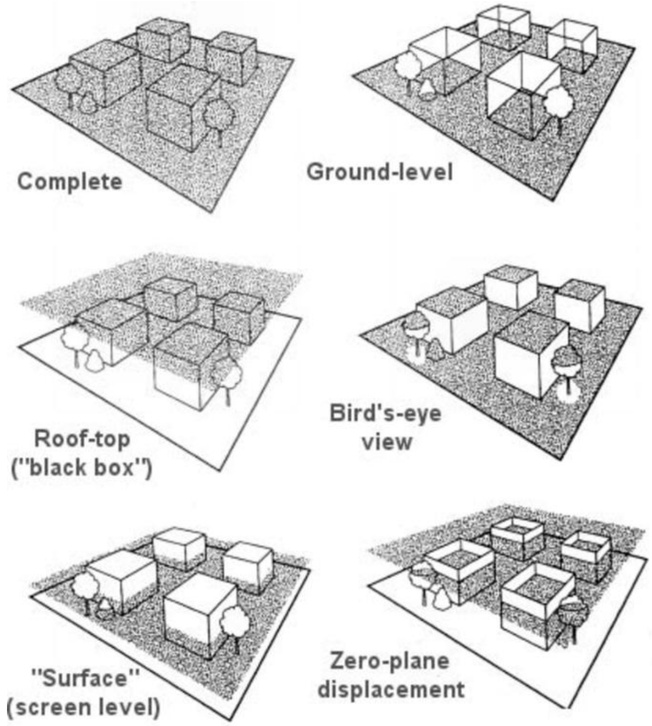


Figure 17. Schematic illustration of different definitions of the urban surface.
Source: Voogt and Oke, 1997

Strategies like installing reflective or green roofs can help reduce urban temperatures. Studies show that these measures can lower temperatures by 1.5 °C and 1.9 °C, respectively, leading to energy savings of up to 16.9% and 11.8%. The properties of materials, such as their solar reflectance, thermal emissivity, and heat storage capacity, play a key role in UHI formation. These properties determine how much sunlight is reflected, absorbed, or re-emitted.

Solar energy consists of ultraviolet (UV) rays, visible light, and infrared radiation. UV rays make up 5% of solar energy, visible light 43%, and infrared radiation, which we feel as heat, accounts for 52%. Darker urban surfaces absorb more heat, while lighter surfaces reflect more. Researchers are exploring cool materials with special pigments that reflect infrared energy, even if they are darker in colour, offering a potential solution to mitigate UHI.

3.3.3 Vegetation in Urban Areas

In rural areas, the landscape is often dominated by vegetation and open land. Plants, especially trees, provide shade, which helps to lower surface temperatures. Additionally, they cool the surrounding air through a process called evapotranspiration, where plants release water vapor into the air, helping to reduce heat. However, in urban environments, dry and impermeable surfaces, such as concrete roads, parking lots, and roofs, are more common. As cities grow, more vegetation is replaced by these hard surfaces, reducing the cooling effects of shade and moisture. This change in land cover leads to higher surface and air temperatures in urban areas.

Unlike rural areas, where vegetation provides natural cooling, urban spaces have fewer plants and less moisture in the air. This means that less water is evaporated, and surfaces tend to absorb more heat from the sun, which is then released into the atmosphere. The loss of trees and green spaces means there is less shade, so more of the sun's heat is absorbed by the exposed surfaces. Without enough moisture to cool the air through evaporation, the temperature in urban areas remains elevated.

In cities, up to 75% of the land surface is covered by impervious materials like asphalt and concrete, while natural landscapes typically have only about 10% of their surfaces as impervious. Natural ground cover is better at retaining moisture and providing a cooling effect, which is why urban areas often experience higher temperatures compared to rural areas.

3.3.4 Anthropogenic Heat

Anthropogenic heat refers to heat generated by human activities, including manufacturing, transportation, heating and cooling systems, lighting, and the metabolism of humans and animals. This heat contributes to the formation of Urban Heat Islands (UHI), where cities experience higher temperatures compared to rural areas. In urban environments, buildings tend to be more energy-intensive, leading to an increase in anthropogenic heat, which further amplifies the UHI effect.

Urban climate is influenced by the heat and moisture produced as a result of energy consumption within cities. Anthropogenic heat can be emitted directly into the atmosphere from sources like chimneys, air conditioners, and heaters, or indirectly from buildings through processes like convection and radiation. The main sectors that contribute to anthropogenic heat generation are transportation, buildings, industry, and human metabolism. For instance, cooling systems in buildings require energy to expel heat, adding to the overall heat in the environment.

The heat rejected by buildings can be quantified using the formula:

$$R = E + P + M + L + AC \quad (6)$$

Where:

- E is the heat transferred into the building from the outside environment
- P represents heat from plug loads, such as appliances
- M is heat from human metabolism
- L refers to the heat generated by lighting
- AC is the additional energy consumed by air conditioning systems

Some air conditioning systems use evaporative cooling to release heat, mostly in the form of evaporated water. The largest portion of anthropogenic heat in urban areas comes from buildings' mechanical systems for heating, cooling, and ventilation. Studies have shown that anthropogenic heat emissions in cities can range from 15 to 150 W/m², depending on the specific urban context.

Vehicles also significantly contribute to anthropogenic heat, especially in cities. In dense urban areas, the cumulative effect of heat from human activities adds to the formation of atmospheric heat islands, particularly during the winter months. Unlike rural areas, where anthropogenic heat is less of a concern, urban areas experience a constant rise in temperature throughout the year due to the energy used for various activities.

In summary, anthropogenic heat is a key factor in the intensification of the UHI effect, particularly in cities where energy consumption and human activity are concentrated. This heat comes from various sources, including buildings, transportation, and industrial processes, and its impact on urban temperature patterns is most significant in densely built environments.

3.4 HOW TO MEASURE UHI AND WHAT TO MEASURE

By researchers, there are several indexes used to measure the Urban Heat Island (UHI) effect, each focusing on different aspects of temperature variations within urban environments. Some common UHI indexes include:

1. **Land Surface Temperature (LST) Index**[26]: This index measures the temperature of the Earth's surface, typically derived from remote sensing data. It helps in identifying hot spots within urban areas and assessing the intensity of UHI.
2. **Difference in Air Temperature (ΔT)**[27]: This index calculates the temperature difference between urban and rural areas. A higher ΔT indicates a stronger UHI effect, with urban areas experiencing warmer temperatures than surrounding rural regions.
3. **Normalized Difference Vegetation Index (NDVI)**[28]: While primarily used to assess vegetation health, NDVI can also be used to estimate the cooling effect of greenery in cities. Areas with higher vegetation tend to have lower UHI intensities.
4. **Urban Heat Island Intensity (UHII)**[29]: This index directly measures the difference in temperature between the urban area and its rural surroundings. It is commonly used to monitor the severity of UHI in cities over time.
5. **Urban-Climate Vulnerability Index (U-CVI)**[30]: This more comprehensive index combines factors like temperature, air quality, and urban density to assess the overall vulnerability of urban areas to the UHI effect and its potential impacts on public health.

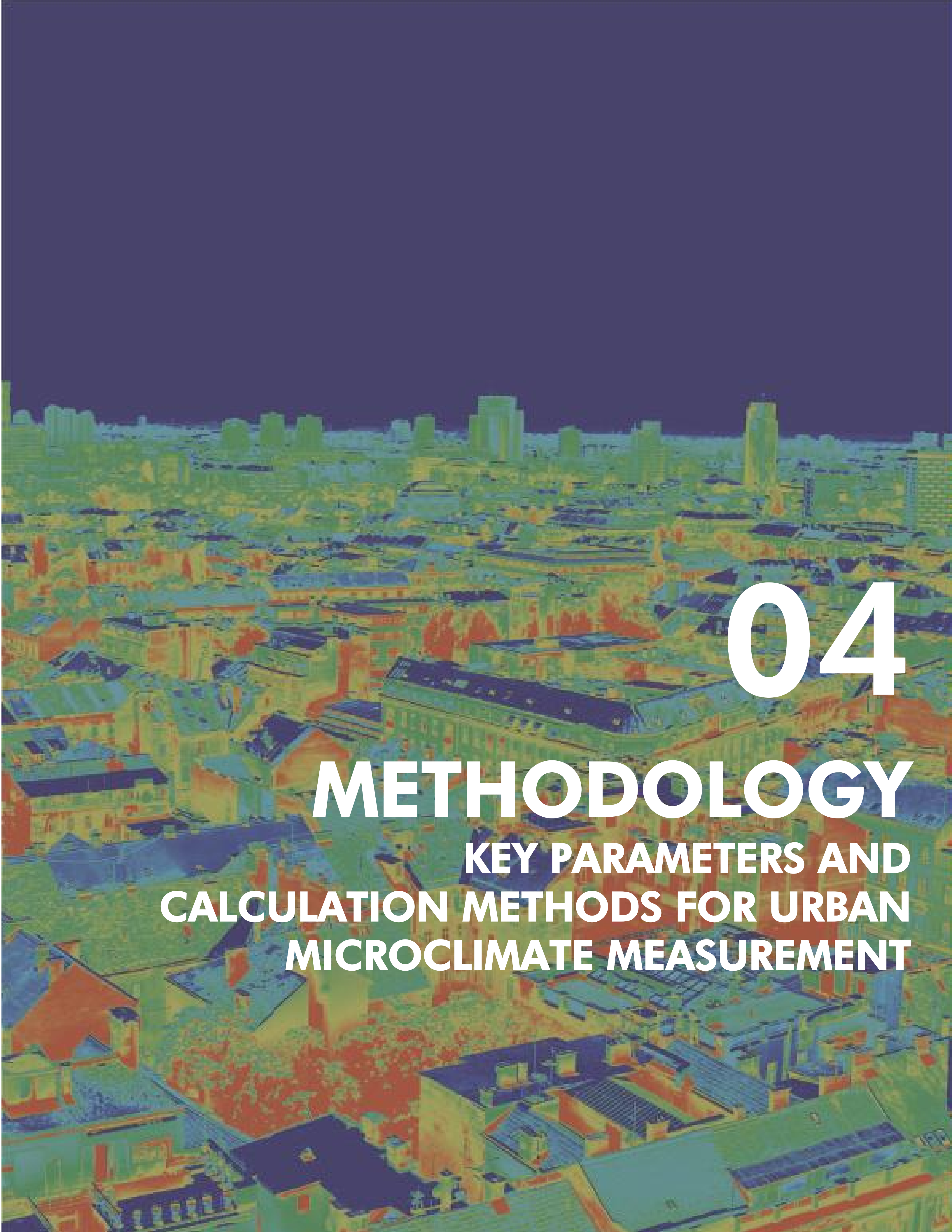
These indexes are valuable for urban planners and policymakers to understand UHI patterns and implement strategies for mitigating the negative effects of urban heat.

Having thoroughly explored the concept of the Urban Heat Island (UHI) effect, including its definition, causes, and consequences on urban ecosystems and human well-being, it is imperative to shift our focus toward the practical aspect of this phenomenon: how can UHI be measured and quantified within a specific location? Understanding UHI's spatial distribution and intensity is crucial for urban planners, policymakers, and environmentalists in mitigating its negative effects, such as increased energy consumption, poor air quality,

[26] *Roth, M., Oke, T. R., & Emery, W. J. (1989). "Satellite-derived urban heat island intensity."*
[27] *Voogt, J. A., & Oke, T. R. (2003). "Thermal remote sensing of urban climates."*
[28] *Roth, M., Oke, T. R., & Emery, W. J. (1989). "Satellite-derived urban heat island intensity."*
[29] *Oke, T. R. (1973). "City size and the urban heat island."*
[30] *Hamin, E., & Gurran, N. (2009). "Urban form and climate change: Balancing adaptation and mitigation."*

and heightened health risks. To move from theory to application, it is essential to identify and explore the methodologies available to assess UHI.

The measurement of UHI is a multifaceted process that requires both remote and in-situ approaches to capture the temperature variations between urban and rural areas. As cities continue to expand, assessing the spatial and temporal dynamics of UHI becomes increasingly important to implement effective mitigation strategies. The following section will delve into the various methods employed to measure UHI, including satellite remote sensing, aerial thermal imaging, and ground-based temperature measurements. Each of these techniques offers unique insights into the urban heat phenomenon and presents specific challenges and opportunities in terms of accuracy, scalability, and data availability. By examining these methodologies, this chapter will provide a comprehensive overview of how UHI can be measured in different urban contexts and how these measurements can be utilized to inform urban sustainability initiatives and climate adaptation strategies.



04

METHODOLOGY

KEY PARAMETERS AND CALCULATION METHODS FOR URBAN MICROCLIMATE MEASUREMENT

4. METHODOLOGY

This chapter outlines the research methodology used to investigate outdoor thermal comfort and the Urban Heat Island (UHI) phenomenon, concentrating on how environmental factors affect human comfort in urban settings. The main goal is to identify and explore the primary elements that influence thermal comfort, such as air temperature, humidity levels, wind speed, solar radiation, and the characteristics of the urban landscape.

A structured framework for data collection, measurement techniques, and analytical tools is provided to effectively quantify the UHI effect on a given specific area. By investigating the dynamics between various microclimatic variables, the study seeks to evaluate both the spatial and temporal variations in outdoor thermal comfort across urban context. Additionally, the role of the built environment, land use patterns, and green space distribution in contributing to the UHI phenomenon is considered.

Before delving into the detailed methodology, it is essential to establish the primary research questions that underpin this study. These questions are designed to provide a clear focus for the investigation, guiding the analysis of the key factors that influence outdoor thermal comfort and the Urban Heat Island (UHI) effect. They aim to explore the interplay between environmental variables, urban morphology, and human comfort, thus framing the direction for the subsequent data collection, modelling, and analysis. The following research questions serve as the foundation for this methodological approach:

- **How is the Urban Heat Stress Index (UTCI) perceived in relation to existing environmental parameters?**
- **What is the baseline intensity of the Urban Heat Island (UHI) effect?**
- **How do urban morphology and design characteristics influence the intensity and occurrence of the UHI effect in the canopy layer?**
- **What is the baseline impact of solar radiation, shading, intensity of vegetation and wind/airflow on the UHI effect?**

As was already mentioned, the Urban Heat Island effect is a significant environmental issue caused by changes in land surfaces due to urbanization. As cities expand and their structures evolve, several factors contribute to the intensification of UHI, resulting in higher temperatures in urban areas compared to nearby rural regions. Understanding the key factors that influence the formation and intensity of UHI is crucial for shaping the methodology and evaluation process. By examining the interactions between these factors, we can gain a better understanding of how UHIs develop and explore potential solutions to reduce their impact on urban environments and public health. The key parameters will be assessed in relation to urban morphology and building scale, as outlined in Table 3.

CATEGORY	PARAMETERS	UHI EFFECT		CONTROLLABILITY	
		Direct	***Indirect***	***Controllable***	***Uncontrollable***
Climatic and Environmental Parameters	Air Temperature	✓	✗		✗
	Wind Speed	✓			✗
	Mean radiant Temperature	✓		✓	
	Solar Radiation	✓			✗
	Relative Humidity	✓		✓	
	Geographical Location	✓	✗		✗
Urban Morphology	Sky View Factor	✓	✗	✓	
	Canyon Verticality Ration	✓	✗	✓	
	Site Coverage Ratio	✓	✗	✓	
	Façade to Site Ratio	✓	✗	✓	
	Average Building Height	✓	✗	✓	
Building Scale	Location		✗	✓	
	Orientation		✗	✓	
	Form		✗	✓	
	Skin Material Characteristics	✓	✗	✓	

Table 3*. Key parameters for UHI mitigation*

To effectively structure the methodology for evaluating UHI contributions, it is important to assess these key parameters in relation to urban morphology and building scale. The following case study explores these parameters in greater depth, providing a practical application of the theoretical framework. By examining real-world examples, we can better understand the relationship between urban design, environmental factors, and UHI intensity, ultimately guiding the development of sustainable urban solutions.

4.2 KEY PARAMETERS

To focus on the various approaches and tools for assessing the performance, impact, and effectiveness of design solutions, strategies, or systems in real-world contexts, different key parameters have been defined. It highlights the importance of using appropriate metrics and methods to ensure that outcomes align with desired objectives and sustainability goals. While accurate monitoring of these parameters is essential for understanding the complex interactions between urban morphology and local climate, enabling effective urban planning and climate adaptation strategies.

Before assessing the structured approach for defining variable impacts to urban microclimate and mitigation strategies from design solutions perspective, existing environmental situation must be evaluated. As it was explained in subchapter 3.1.5, we can have different methods for quantifying sensation of thermal comfort in outdoor environments. All of them have their significant parameters needs to be taken into account, but for developing assess influence of canopy urban layer on inhabitants, method established by International Society of Biometeorology in 1999 will be used, Universal Thermal Climate Index (UTCI).

4.2.1 UTCI

Universal Thermal Comfort Index represents measurement for physilogical resonse to weather conditiones. The advanced multi-node thermo-regulation model developed by Fiala et al. forms the foundation for the UTCI which refers to an organism's ability to maintain its core body temperature within a specific range, regardless of significant variations in the surrounding environmental temperature.[31] It takes into consideration environmental parameters such as relative humidity, temperature of an air, solar radiation and wind speed to meet following goals:

1. Relevant to the physiological processes of heat exchange across the full spectrum of thermal conditions.
2. Suitable for both whole-body thermal assessments and localized skin cooling, such as in the case of frostbite.
3. Applicable across all climate types, seasons, and spatial scales, from microclimates to broader geographical areas.
4. Valuable for critical applications in human biometeorology, including Public Weather Services, Public Health Initiatives, Precautionary Planning, and Climate Impact Studies.
5. Serves as a temperature-based scale for evaluating thermal comfort and stress.

According to BioKlima - Universal Tool for Bioclimatic and Thermophysiological Studies[32] input data for calculating UTCI includes not only meteorological parameters but also subjective, non-meteorological parameters, like metabolic rate and thermal resistance of clothing. As an outcome of an evaluation sensation of outdoor thermal comfort can be split in 10 groups, as it is shown in Table 5.

Range (°C)	< -40	-27	-13	0	9	26	32	38	> 46	
Stress Category	Extreme Cold Stress	Very Strong Stress	Stong Cold Stress	Moderate Cold Stress	Slight Cold Stress	No Thermal Stress	Moderate Heat Stress	Strong Heat Stress	Very Strong Heat Stress	Extreme Heat Stress

Table 4. *Thermal sensation and different groups of UTCI*[33]

[31] Fiala, D., Havenith, G., Brode, P., Kampmann, B., Jendritzky, G., 2012. UTCI-Fiala multimode model of human heat transfer and temperature regulation. Int. J. Biometeorol.
[32] https://www.igipz.pan.pl/Bioklima-zgik.html
[33] Young, A., 2017. Universal Thermal Climate Index. http://www.utci.org/utci_doku.php. (Accessed 15 April 2017).

According to Fiala et al.'s multi-node model, variables such as metabolic rate and clothing insulation are not explicitly included due to their variability and subjective nature. While these factors are crucial for determining heat exchange and can be incorporated into more detailed individual assessments, their exclusion allows for a broader and more generalized evaluation of environmental thermal stress. This approach assumes average human activity levels and typical clothing types, making it more applicable across a wide range of settings and facilitating its use for general environmental assessments.

According to Fiala et.al we can use formula given in previous chapters, as following:

$$UTCI = 3.21 + (0.872 \times Ta) + (0.2459 \times Tmr) - (2.5078 \times V) - (0.0176 \times RH) \quad (1)$$ [34]

Where:

- T_a – Temperature of an air [°C]
- T_{mr} – Mean Radiant Temperature [°C]
- V – Wind velocity at 10m above the ground [m/s]
- RH – Relative humidity of air [%]

Based on climatic data of a case study, the existing UTCI for an Area Bonadies and its surrounding urban patterns can be assessed by analysing key environmental parameters such as air temperature, mean radiant temperature, wind speed, and relative humidity. By inputting these variables into the UTCI model, we can evaluate the thermal comfort and stress levels experienced by individuals on a specific location, providing valuable insights into the area's climate impact on human well-being.

4.2.2 $UHI_{Intensity}$

The UHI intensity refers to the difference in temperature between urban areas and their surrounding rural counterparts, which is influenced by various environmental and urban design factors, to examine UHI intensity, its formation, measurement, and the key factors that contribute to its development within urban environments. It can be calculated using temperature data from ground-based measurements or remotely sensed data from satellites. Understanding this intensity is crucial for evaluating the extent of the UHI effect and its implications for urban planning and public health. Since this intensity is defined as the temperature difference between the urban area and a nearby rural area (or any cooler reference location), we can use formula[35]:

$$UHI_{Intensity} = T_{Urban} - T_{Rural} \quad (7)$$

Where:

- T_{urb} ambient air temperature measured in the urban area

[34] *Fiala, D., Havenith, G., Brode, P., Kampmann, B., Jendritzky, G., 2012. UTCI-Fiala multimode model of human heat transfer and temperature regulation*

[35] *Oke, T. R. (1982). The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society*

- T_{rural} temperature of an air, taken from a nearby rural location or less developed area to act as a baseline for comparison

The baseline calculation of UHI intensity is essential to establish reference conditions for comparison. By establishing this baseline, we can assess the magnitude of the UHI effect and track changes over time or in response to specific mitigation strategies. This foundational assessment sets the stage for deeper analysis and the development of effective UHI mitigation approaches.

4.2.3 SVF

Urban morphology of a city is defined by the height, length, width and distances between buildings, which can affect on formation of urban environment and overall it's thermal characteristics, especially in a high-dense environments. Sky View Factor is one of the tool to identify interaction between urban geometry and air temperature. It measures how much of sky is visible from a particular point on a ground level, which helps to understand amount of heat exchange between environment and human body. SVF will be important to understand microclimate of Area Bonadies and its surroundings, to determine areas that can possible experience excessive hear or insufficient coolings, due to solar radiation and wind.

Simplified expression often used in urban microclimates or thermal comfort, while assessing canopy layers, suggested by by Oke (1987) and Stewart and Oke (2012) is given as:

$$ASVF = \frac{Total\ hemisphere\ area}{Visible\ sky\ area} \text{ or } ASVF = \frac{1}{2}(1 - \frac{H}{W}) \quad (3)$$

Where:

- H is the height of the buildings
- W is the width of the canyon or street

Ranges of SVF can vary from 0 to 1 (Oke,1987), where:

- **SVF=0** Represents completely obstructed views of the sky, such as in very narrow street canyons or densely built urban environments. These areas are usually where heat tends to accumulate, contribution to the UHI effect.

- **SVF=1** Represents clear, unobstructed skies. This occurs in open fields or areas with little to no vertical obstruction, and with less thermal retention, typically leading to cooler outdoor environments.

- **0.2 < SVF < 0.8** represents intermediate values (Stewart and Oke, 2012 common in moderately dense cities, where buildings partially block the sky vies due to other buildings, vegetation or other structures, creating areas with both sun exposure and shaded regions.

Sky View Factor (SVF) will be a critical measure for assessing outdoor thermal comfort, as it indicates the degree of sky visibility from a location, directly influencing heat exchange between the environment and the human body. Higher SVF values (close to 1) will mean to promote better heat dissipation and cooling, resulting in lower temperatures and improved comfort. In contrast, lower SVF values (close to 0), typically found in areas with dense obstructions like buildings and trees, trap heat and reduce cooling, leading to higher temperatures and reduced comfort, which will also identify Urban Heat Island (UHI) effect locations. SVF also impacts solar radiation; higher SVF areas receive more direct sunlight, which can increase surface temperatures and heat stress, whereas lower SVF areas will provide shading, potentially reducing solar radiation but limiting natural cooling.

Understanding SVF will help to identify behavious of microclimate and design strategies, such as type of an adaptive facades that complement the surrounding environment. For example, in areas with low SVF and high solar exposure, facades can be designed to provide additional shading or reduce heat absorption, mitigating the impact of poor sky exposure. Conversely, in areas with higher SVF, facades could be optimized to allow more sunlight during colder months while providing necessary shading in the summer.

4.2.4 H/W

The Height-to-Width (H/W) ratio is a crucial determinant of the urban microclimate, particularly in street canyons or densely built environments. This ratio, which compares the height of buildings (H) to the width of the street or open space (W), affects several key aspects of urban thermal dynamics:

1. **Solar Exposure and Shading**: A high H/W ratio, often found in narrow streets with tall buildings, can block sunlight, leading to cooler conditions during hot periods but reducing natural warmth in colder months. In contrast, a low H/W ratio, typical of wide streets with shorter buildings, allows greater solar access, potentially raising surface temperatures and increasing heat stress in urban spaces (Oke, 1987).

2. **Airflow and Ventilation**: A higher H/W ratio can obstruct wind flow, creating stagnant air pockets and reducing natural cooling, while a lower ratio enhances ventilation, facilitating the movement of air and cooling of the area (Stewart & Oke, 2012).

3. **Urban Heat Island (UHI) Effect**: High H/W ratios limit exposure to the sky and hinder airflow, exacerbating the UHI effect, which raises local temperatures due to heat retention. Lower ratios allow for better heat dissipation but may still contribute to heat stress due to increased solar radiation (Matzarakis et al. 2000).

4. **Microclimate Variation**: Variations in the H/W ratio influence local temperature, humidity, and wind conditions, which urban planners can manipulate to improve thermal comfort by altering the urban fabric (Fiala et al., 2012).

5. **Design and Mitigation Strategies**: Knowledge of the H/W ratio can form urban design strategies. In high H/W areas, planners might introduce greenery or reflective

materials to mitigate heat, whereas, in low H/W areas, shading or strategic building placement can optimize thermal comfort (Givoni, 1998).

The H/W ratio significantly shapes urban climates by influencing solar exposure, airflow, and thermal retention. Understanding and optimizing this ratio are critical for mitigating heat stress and improving outdoor comfort in urban settings, which graphically is given in Figure 18.

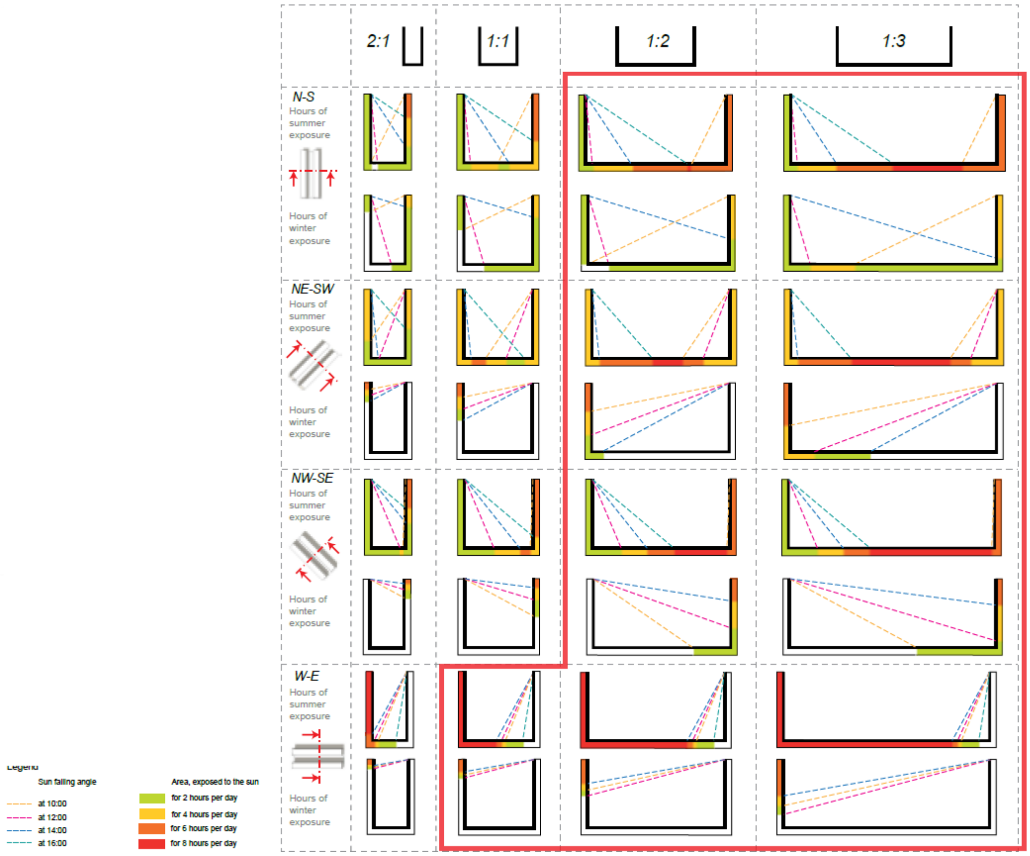


Figure 18. *Diurnal solar exposure analysis of street canyons*
Source: Hotkevica, 2013

For quantitative distinguishment of H/W ratios, we need to set the ranges for values.

1. **Low H/W Ratio (≤ 1):** Typically found in open spaces or wide streets with low-rise buildings. This type of range provides better airflow and natural ventilation, increases solar exposure due to wider streets and leads to higher surface temperatures (Oke, 1987).
2. **Medium H/W Ratio (1 to 2):** Found in moderately dense areas with medium-rise buildings, such as suburban or commercial streets. Guarantees balanced amount of sunlight and shading. Also, can have moderate airflow, with occasional wind blockages from buildings (Stewart & Oke, 2012).
3. **High H/W Ratio (>2):** Found in high-density urban areas with tall buildings in narrow streets. With a significant shading and reduced solar exposure, which can cool the environment in hot weather but limit natural heating in winter. Poor airflow, creating

stagnant air zones and exacerbating heat retention which creates higher potential for Urban Heat Island (UHI) effects (Matzarakis et al., 2000).

Evaluating H/W ratios and its ranges will give us critical points regarding thermal comfort and microclimate. As a design strategy method type of adaptive façade can be chosen depending on thermal needs and requirements. Adaptive Facades will take the role of dynamic building elements that adjust to environmental conditions such as temperature, sunlight, and wind. By providing shade, controlling solar gain, and promoting natural ventilation, adaptive facades reduce the reliance on mechanical cooling systems and improve both indoor and outdoor thermal comfort. In areas with high H/W ratios, these facades can mitigate solar radiation and enhance airflow, while in areas with low H/W ratios, they help regulate heat gain and optimize airflow, preventing heat buildup.

Ultimately, the synergy between H/W ratio adjustments and adaptive facades addresses both the static and dynamic elements of urban design, effectively managing heat stress and enhancing outdoor comfort in urban environments.

4.2.5 ρ_{urb}

The ρ_{urb} plays another important role in influencing the Urban Heat Island (UHI) effect and the urban microclimate as it's discussed in 3.3.1 subchapter. It helps urban planners design cities that are more resilient to heat, promote sustainable development, and improve the quality of life. The UHI effect refers to higher temperatures in urban areas compared to surrounding rural areas, caused by impervious surfaces like buildings and roads that absorb and trap heat. For detailed distinguishment of Site Coverage ratio, we can set ranges given in different research documents, depending on uses of land:

1. **Low-density Residential Areas:** ρ_{urb} typically ranges between 0.20 and 0.35 (meaning 20%-35% of the total site area is covered by buildings). These areas have larger setbacks and more open space. Usually, areas where single-family houses in suburban areas are located [36].
2. **Medium-Density Residential Areas:** ρ_{urb} ranges from 0.35 to 0.50. These areas have a mix of open spaces and some building coverage. In towns where multi-family homes are located [37].
3. **High-Density Residential or Mixed-Use Areas:** ρ_{urb} can range from 0.50 to 0.70. Higher ratios are allowed in places with significant vertical development or integrated uses like residential, commercial and/or retail [38].

[36] *Niemelä, J. Urban Ecology: Patterns, Processes, and Applications. Oxford University Press, 2014*
[37] *Huang, L., & Wang, Z. Influence of façade-to-ground ratio and solar orientation on the thermal performance of buildings. Energy Procedia, 2020*
[38] *Tsiros, I., & Psiloglou, B. The Role of Building Height in Outdoor Thermal Comfort and Urban Heat Island Mitigation. Urban Climate, 2013*

4. **Commercial and Industrial Zones:** ρ_{urb} can be 0.70 or higher in certain industrial zones where the focus is on maximizing built area for businesses. In some cases, up to 0.90 or even higher might be permissible, depending on the local regulations [39].
5. **Public Open Space and Green Areas:** For parks or other public recreational spaces, ρ_{urb} is typically close to 0, as these areas are meant to be free from construction[40].

Urban microclimates are shaped by the distribution of given buildings, open spaces, and natural elements, with high-density areas facing challenges like elevated temperatures, limited cooling, and obstructed airflow due to dense built coverage and insufficient green spaces. Tall buildings block wind, compromising ventilation, while reduced open spaces hinder temperature regulation. Additionally, high urban density impedes natural groundwater recharge, increasing runoff and flood risks, which further disrupt the microclimate.

This methodology focuses on identifying areas of high and low urban density (ρ_{urb}) and proposes strategies to mitigate the adverse effects of higher density. Solutions include integrating green spaces such as parks, urban forests, and tree-lined streets, which naturally cool the environment and enhance air quality. Adaptive façades on buildings and features like green roofs, vegetated walls, and urban gardens can also reduce the urban heat island (UHI) effect by providing shade and improving temperature regulation. These elements additionally enhance stormwater management and reduce surface runoff, improving resilience to flooding.

In contrast to high-density zones, areas with lower built coverage benefit from better airflow and more moderated temperatures, contributing to improved microclimate conditions. By maintaining a balance between built environments and open spaces, this approach seeks to enhance energy efficiency and the liability of urban areas, increasing resilience to extreme weather events such as heatwaves and floods while improving overall climate conditions, air quality, and public health.

4.2.6 FSR

Facade doesn’r have only cruitial role in shaping internal environment and it’s thermal characteristics, but also for outdoor environment. Externally, not only aesthetical appeal, but its a way of communication between indoor and urban contexts. That’s why design metric that compares total areaa of a facade to the total occupied area of site needs to be measured as it’s given in following formula:

$$FSR = \frac{Area\ of\ all\ facades}{Area\ of\ built\ site} \quad (4)$$

[39] *Yuan, Z., & Liu, C. Impacts of built environment on urban microclimate: A study of commercial and industrial zones. Urban Climate, 2019*

[40] *Jennings, V., et al. Urban green spaces: A review of the benefits and challenges of green spaces. Urban Forestry & Urban Greening, 2012*

By measuring FSR we can define amount of sunlight penetration, airflow and visual asthetics, but before it's important to set all the ranges for quantitative measurements.

1. **Low Ratio FSR< 0.5 –** As indication of low dense residential areas, if ratio is low we can assume that space is open with satisfactory ventilation, more green space and better environmental performance. Buildings which will have low FSR can be considered as source of natural cooling, stormwater management and resilience to extreme weather conditions [41].
2. **Medium Ratio 0.5<FSR<1.0 –** represents a balance between built form and open space. This is typical for mid-rise buildings or townhouses in urban environments. These designs allow for efficient land use, maintaining good airflow and providing spaces for vegetation (e.g., courtyards and green roofs), enhancing the local microclimate [42].
3. **High Ratio 1.0<FSR –** buildings are typically found in dense urban centers or high-rise developments. These structures maximize site coverage and building volume, which can lead to a reduction in open space, increased heat island effects, and poor airflow. However, they are often necessary for accommodating higher population densities in urban settings [43].

An understanding of the various impacts associated with different façade-to-site ratio (FSR) ranges enables the identification of strategies to mitigate negative environmental consequences. Low FSR designs contribute to sustainability by maximizing open space, thereby enhancing natural ventilation and reducing heat retention. Medium FSR offers a balanced approach, optimizing site utilization while maintaining a sufficient proportion of open areas for improved environmental performance. In contrast, high FSR necessitates the adoption of innovative design solutions to mitigate adverse effects, such as increased heat retention and degraded air quality, which are commonly observed in densely built environments.

Based on these understanding of how different façade-to-site ratio (FSR) ranges influence environmental outcomes, in following chapters will be identifies critical points where these impacts are most pronounced. And by addressing these points, we can develop effective mitigation strategies to tackle issues such as heat retention, poor air quality, and reduced sustainability, ensuring that the urban environment remains resilient and livable.

4.2.7 h_{urb}

According to another urban variable outdoor thermal comfort can be measured by affecting factors such as solar exposure, wind flow and air circulation withing urban environment. Taller buildings tend to create more shaded areas at ground level, which can provide relief from heat in dense urban areas, but they may also block airflow, leading to a

[41] *Wong, N.H., et al. The effect of façade design on the indoor thermal environment in buildings: A review. Energy and Buildings, 2014*

[42] *Huang, L., & Wang, Z. Influence of façade-to-ground ratio and solar orientation on the thermal performance of buildings. Energy Procedia, 2020*

[43] *Erell, E., & Williamson, T. Urban Microclimates: Designing the Spaces Between Buildings, 2017*

buildup of heat in certain spaces. In contrast, shorter buildings allow for greater air circulation and can promote better ventilation, but they may expose outdoor spaces to more direct sunlight, which can increase heat retention. For this differentiation we need to distinguish in a quantitative way urban areas according to building height.

1. **Low-Rise Urban Areas ($1 \leq h_{urb} \leq 4$ Stories):** residential areas typically feature more open space, improved airflow, and greater potential for natural ventilation, all of which contribute to better outdoor thermal comfort. These areas experience a less intense heat island effect due to the lower building heights, which allow for increased natural cooling through wind and shading from vegetation[44].
2. **Mid-Rise Urban Areas ($5 \leq h_{urb} \leq 10$ Stories):** including mixed-use residential, office, and commercial zones, strike a balance between space and urban development. While these areas offer better shading and reduced direct sunlight exposure, they can also hinder airflow and limit natural cooling at ground level. The building heights in these areas are often designed to create livable environments, incorporating green spaces to enhance outdoor thermal comfort[45].
3. **High-Rise Urban Areas ($11 \leq h_{urb}$ Stories):** typically found in densely packed city centers, are characterized by dense construction and limited open space. While taller buildings provide more shading at ground level, they can also intensify the urban heat island effect by trapping heat in narrow streets and restricting airflow. This high-density design often results in reduced outdoor thermal comfort due to heat retention and limited natural cooling[46].

Identifying the appropriate average building height can be essential for optimizing urban environments, as it directly impacts outdoor thermal comfort and overall livability. In areas with high building density, taller structures often exacerbate heat retention, reduce airflow, and intensify the urban heat island effect. To mitigate these negative effects, it is critical to incorporate strategies such as integrating green spaces, vertical gardens, and advanced technological solutions. These design solutions help enhance natural cooling, improve air quality, and reduce energy consumption. By carefully considering building height and implementing suitable strategies, cities can create more comfortable, sustainable environments, ensuring that urban development does not compromise outdoor thermal comfort or contribute to climate-related challenges.

4.2.8 Reflectivity Impact

Reflectivity as an ability of a surface or a material to reflect sunlight or solar radiation, can be considered one of the environmental parameters for guaranteeing outdoor thermal comfort. Reflectivity plays a key role in managing urban thermal comfort and mitigating the urban heat island (UHI) effect. Materials with high reflectivity (such as light-coloured

[44] *Erell, E., & Williamson, T. Urban Microclimates: Designing the Spaces Between Buildings. Routledge, 2017*
[45] *Huang, L., & Wang, Z. Influence of façade-to-ground ratio and solar orientation on the thermal performance of buildings. Energy Procedia, 2020*
[46] *Siros, I., & Psiloglou, B. The Role of Building Height in Outdoor Thermal Comfort and Urban Heat Island Mitigation. Urban Climate, 2013*

roofs or pavements, facades) reflect more sunlight, reducing the amount of heat absorbed by urban surfaces. This results in lower surface temperatures and improves outdoor thermal comfort, especially in densely built areas. To quantify this impact of reflectivity formula of albedo can be used, which will estimate how much solar radiation is reflected by a surface compared to how much is absorbed.

$$\propto = \frac{R}{I} \quad \mathbf{(8)}$$

Where:

- $\propto$ - is albedo, measurement of surface reflectivity
- R - Amount of reflected solar radiation, W/m²
- I - Amount of incident solar radiation, W/m²

According to different research[47], albedo is a ratio that ranges from 0 to 1. Zero indicates that the surface absorbs all the light and reflects none (e.g., a black surface). One indicates that the surface reflects all the light and absorbs none (e.g., a perfectly mirrored or white surface). If in the urban and outdoor thermal comfort contexts, higher albedo reduces amount of heat absorbed by surfaces, it will also result lowering the ambient temperature, which will be particularly important during the UHI mitigation process.

For it is possible to evaluate the temperature impact based on reflectivity of a material or a surface, considering albedo's effect on heat absorption and radiation balance[48]:

$$Q_{absorbed} = I \times \left(1 - \alpha_{facade}\right) \quad \mathbf{(9)}$$

Where:

- I - Amount of incident solar radiation, W/m²
- $\propto$ - is albedo, measurement of surface reflectivity
- $Q_{absorbed}$ solar energy absorbed by the façade

Measuring the solar energy absorbed by a facade is essential for understanding how it contributes to local temperature regulation and outdoor thermal comfort. Facades that absorb excessive solar energy can exacerbate heat buildup, leading to uncomfortable conditions and increased UHI effects. By accurately assessing solar absorption, urban planners can design facades that reduce heat retention, enhance shading, and improve air circulation to create more comfortable outdoor environments.

More precisely, reflectivity significantly influences the urban microclimate, impacting local temperatures, air quality, and overall environmental comfort. Its role is particularly crucial in mitigating the UHI effect, enhancing thermal comfort, and reducing heat stress. Surfaces with high albedo - such as light-coloured roofs, pavements, and walls-reflect more sunlight

[47] *Oke, T.R. Boundary Layer Climates. Routledge, 1987*

[48] *Santamouris, M. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, 2014*

and absorb less heat, will help to detect places which mostly needs reducing the UHI effect. This results in cooler urban environments, lower heat-related health risks, and reduced energy consumption. High reflectivity also improves outdoor thermal comfort and will impact on UTCI by cooling the surrounding air, while low-reflectivity surfaces, such as asphalt, trap heat and create discomfort, especially during heatwaves. Furthermore, reflective surfaces help improve air quality by reducing the formation of pollutants in canopy layer. This integration of reflectivity into urban planning through albedo measurements can be vital for evaluating climate change risks and identifying areas suitable for mitigation strategies, such as green roofs and reflective materials and facades. (Santamouris, 2014).

4.2.9 Shading Effect

Knowing material or a surface albedo gives us also possibilities measuring shaded areas and the amount of solar radiation blocked, which is critical for evaluating how much heat is prevented from reaching surfaces and surrounding air, directly influencing outdoor thermal comfort. Effective shading reduces solar heat gain, which lowers local temperatures, mitigates the UHI effect, and creates cooler, more comfortable outdoor spaces. The shading effect can be quantified using the following formula:

$$Q_{Shade} = I \times A_{Shade} \left(1 - \alpha_{facade}\right) \quad \mathbf{(10)}$$

Where:

- Q_{Shade} is the amount of solar energy blocked or reduced by shading, W/m²
- I - Amount of incident solar radiation, W/m²
- $\propto$ - is albedo, measurement of surface reflectivity
- A_{Shaded} - is the area of the surface that is shaded, m²

This formula helps determine how much solar radiation is blocked by shading elements, and by quantifying these factors, urban designers can optimize shading strategies, such as vegetation, shading devices or facades with abilities to block solar energy and building orientations, to improve microclimates and as an overall goal to enhance public well-being.[49]

4.2.10 Wind and Airflow Effect

Another key factor in determining outdoor thermal comfort is convective hear transfer, as it governs the rate of heat exchange between building surfaces and the surrounding air. Increased convective heat transfer, influenced by variables such as wind speed and air temperature, promotes cooling by aiding in the dissipation of heat from surfaces, thereby reducing discomfort during warmer conditions. In contrast, low convective heat transfer,

[49] *Santamouris, M. Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, 2014*

especially in calm conditions, can result in stagnant air around surfaces, trapping heat and intensifying outdoor thermal stress, particularly in urban environments.

For its evaluation we can use formula:

$$Q_{Convective} = h_c \times A_{Facade} \, (T_{air} - T_{Surface}) \quad \textbf{(11)}$$

Where:

- $Q_{Convective}$ - is the convective heat transfer rate (W), which is the amount of heat transferred from the surface to the air.
- h_c - the convective heat transfer coefficient (W/m²·K), a measure of the heat transfer per unit area per unit temperature difference.
- A_{Facade} - is the area of the building facade (m²), the surface area through which heat transfer occurs.
- T_{air} - is the air temperature in °C, the temperature of the surrounding air
- $T_{Surface}$ - is the surface temperature in or °C, the temperature of the building facade

This formula expresses the rate of heat transfer between the surface and air due to the temperature difference and helps estimate the heat transfer from a building facade to the surrounding air, which plays a role in determining outdoor thermal comfort and understanding energy performance in the context of urban microclimates.

The convective heat transfer coefficient plays a crucial role in heat loss or gain from surfaces exposed to outdoor conditions, directly influencing outdoor thermal comfort, as much as its importance, also evaluation is getting difficult due to its variability factors. Key factors affecting h_c include wind speed, with higher speeds enhancing heat transfer; surface roughness, as rough surfaces disturb the boundary layer, promoting convection; air temperature and properties, which determine the heat transfer rate; and the orientation and geometry of surfaces, with wind-exposed surfaces typically experiencing higher convective heat transfer. These factors collectively shape the effectiveness of heat dissipation and the overall thermal comfort in urban environments (Siros & Psiloglou, 2013).

For these reasons, setting typical values is needed depending on wind speeds[50]:

- **Still air:** For low wind speeds (calm air), the value of h_c is typically around 5 to 15 W/m²·K.
- **Moderate wind speeds:** For outdoor conditions with light wind (5–10 m/s), the convective heat transfer coefficient can range between 10 to 30 W/m²·K.
- **High wind speeds:** In areas with strong winds (above 10 m/s), the convective heat transfer coefficient can be as high as 30 to 60 W/m²·K.

Another substance that is difficult to quantify, is temperature of a surfaces, due to its dependence on different factors like albedo, wind and air movement, time of the day and seasonal changes. In summary, the surface temperature ranges for various surfaces in

[50] *Fanger, P.O. Thermal Comfort: Analysis and Applications in Environmental Engineering, 1970*

urban environments vary widely depending on material type, location, and environmental factors. These ranges are essential for understanding the impact of urban heat islands and for designing strategies to mitigate heat stress and improve outdoor thermal comfort. Due to it we can use generalized, empirical estimation, based on air temperature and solar radiation intensity:

$$T_{Surface} = T_{Air} + \left(\frac{I_{Solar} \times (1-\propto)}{h_c}\right) \quad \mathbf{(12)}$$

With all the simplifications given above, Wind and airflow effect of outdoor thermal comfort by enhancing natural ventilation and facilitating cooling can be evaluated. Increased wind speeds promote the exchange of heat between the surface and surrounding air, which helps reduce surface temperatures and improve overall thermal comfort. Proper airflow can mitigate the urban heat island effect, especially in densely built environments, by carrying away excess heat. On the other hand, insufficient wind and stagnant air can lead to heat accumulation and discomfort, exacerbating heat stress during hot weather. Optimizing wind patterns through urban design, such as strategically placing open spaces and buildings, can significantly enhance outdoor comfort.

After introducing the key concepts of urban morphology, the Universal Thermal Climate Index (UTCI), and environmental parameter measurement, laying the groundwork for the subsequent application of GIS tools in urban design. Urban morphology, which studies the physical organization of urban areas - such as building density, street patterns, and open spaces - affects local microclimates, influencing thermal comfort in cities. The UTCI, a metric that integrates environmental factors like air temperature, humidity, wind speed, and solar radiation, has been highlighted as an essential tool for assessing human thermal comfort. It helps incorporate environmental considerations into urban design, fostering healthier and more comfortable urban environments. Accurate measurements are crucial for analysing the impact of built environments on local climates, enabling informed design decisions that prioritize thermal comfort. By connecting urban morphology with climatic data, application chapter will provide a framework for identifying key areas where urban design and microclimatic conditions intersect to affect human comfort. This framework also offers opportunities for implementing localized strategies to mitigate thermal discomfort.

Shifting from theoretical concepts, research transitions to the practical use of Geographic Information System (GIS) tools. GIS serves as a critical tool for visualizing, analysing, and interpreting spatial and climatic data, allowing for dynamic modelling and simulation of different design scenarios. These tools help identify patterns, assess environmental impacts, and evaluate adaptive facade strategies in response to specific urban climates conditions. The following chapter will explore the GIS software tools employed in this study, discussing their functions and type of analysis, that can be relevant in future selecting adaptive facade technologies, thus bridging theoretical foundations with practical urban design applications.

05

APPLICATION USING ARCGIS SOFTWARE

CASE STUDY, ARCGIS TOOLS AND DATABASE, OUTDOOR MICROCLIMATE MAPS

5. APPLICATION USING ARCGIS TOOLS

Due to its crucial behaviour study of urban microclimate in understanding the complex interactions between environmental factors and human activities. These microclimates, which refer to the localized variations in temperature, humidity, wind speed, and other atmospheric conditions, are influenced by a variety of factors such as geography, urbanization, and vegetation of a specific case study location. Mapping these microclimates is essential for urban planning, environmental monitoring, and climate change studies.

Geographic Information Systems (GIS), particularly tools like ArcGIS, have become invaluable for collecting, analysing, and visualizing spatial data related to microclimates. ArcGIS offers a range of powerful tools for mapping, modelling, and interpreting environmental data, allowing researchers and decision-makers to gain insights into microclimatic variations across different landscapes.

This chapter focuses on the use of ArcGIS tools and databases in order to compare existing fixed façade and alternatively adaptive façade technology in terms of urban microclimate. It explores the integration of spatial data with environmental variables to produce detailed, accurate graphical representations that reflect the variability of microclimates in outdoor settings. The chapter highlights the methodologies involved, the specific tools within ArcGIS that are particularly suited for this task, and the practical applications of these maps in various fields, including urban design, environmental management, and public health on a given area. Through this exploration, the chapter aims to demonstrate how GIS technologies can enhance our understanding of microclimatic conditions and inform decisions that contribute to more sustainable and liveable urban environments.

5.1 CASE STUDY – CITTÀ DI RIVOLI, AREA BONADIES AND ITS SURROUNDINGS

Rivoli, located in the Piemonte region of Italy, lies approximately 15 kilometres west of Turin, strategically positioning it as a key intermediary between the metropolitan area of Turin and its surrounding regions. This central location allows Rivoli to serve as a vital connector within the broader urban system of the region. Given Turin's future urban planning, Rivoli, particularly the Area Bonadies and urban patterns around, are currently undergoing development, with plans to integrate it into Turin's expanding urban infrastructure. Its location is characterized by geographical parameters which are given in Table 5.

According to European Environment Agency (EEA) we can say that the topography surrounding Rivoli demonstrates considerable variations in elevation, with a maximum elevation difference of 200 meters within a 3-kilometer radius, and an average elevation of 368 meters above sea level. Expanding to a 16-kilometer radius, the elevation range increases significantly, reaching a variation of 1,448 meters. At a broader scale, within a 80-

kilometer radius, elevation changes are even more pronounced, with a total variation of 3,937 meters.

Figure 19. Location of Rivoli
Source: Wikimedia Commons

In terms of land use, the area within 3 kilometres of Rivoli is predominantly covered by cropland (50%), followed by artificial surfaces (32%) and trees (14%). Within a 16-kilometer radius, cropland accounts for 37% of the area, while tree cover occupies 29%. At the 80-kilometer scale, cropland comprises 35%, and trees cover 31% of the land.

One notable development is the planned metro stop in the Bonadies area, which will enhance connectivity and make the region more accessible to a growing population. As an intermediate area, it functions as a key connection point between urban and suburban zones, influencing the broader dynamics of urban growth and regional planning. As an intermediate urban area, Rivoli plays a crucial role in regional urban dynamics, acting as a "hinge" that links various urban systems.

***Figure 20.** Area Bonadies and its surroundings geographical location*

Province	Torino
Commune	Rivoli
Sea Level (s.l.m)	327
Exposure	SE
Longitude (WGS84)	7.325458° E
Latitude (WGS84)	45.042037° N

Table 5. *Geographical location of Area Bonadies and its surroundings*
Source: Google Earth

Since the Area Bonadies and its surroundings (Figure 20) is still in the development phase, it offers an opportunity for early-stage investigations, such as analysing its urban microclimate. This is particularly relevant, as the area is expected to experience increased accessibility and a growing population in the near future, which means higher requirements for thermal comfort. The following case study aims to explore these emerging dynamics, providing insights into the potential challenges and opportunities related to the urban microclimate in this developing area.

5.1.1 Climatic Data

The climate of Rivoli, a municipality located in the Piedmont region of northern Italy, Climatic Zone E, characterized by a temperate climate with distinct seasonal variations. Data was collected from the historical database of ARPA Piemonte, provided by the Rivoli La Perosa station (Table 6). As its geographical location, it experiences moderate temperatures throughout the year, with warm summers and cold winters. Understanding the climatic conditions of the location is essential for assessing the impact of weather patterns on local agriculture, infrastructure, and daily life. This chapter will provide a detailed overview of the climatic data for Rivoli, including temperature variations, precipitation patterns, and seasonal transitions, offering insights into the region's meteorological trends and their implications. Which will be baseline of environmental parameters, for further application process in following chapters.

Province	Torino
Commune	Rivoli
Station	Rivoli La Perosa
Sea Level (s.l.m)	368
Exposure	SE
Longitude (WGS84)	7.49891° E
Latitude (WGS84)	45.07987° N
Sensors for Data Collection	Anemometer Pluviometer Thermometer

Table 6. *Data from Rivoli La Perosa Station*

Average Temperature

According to ARPA Piemonte[51] In Rivoli, the warm season lasts for 3.1 months, typically from June 8 to September 10, with average daily high temperatures surpassing 24°C. The peak of summer occurs in July, when temperatures reach an average high of 28°C and a low of 18°C.

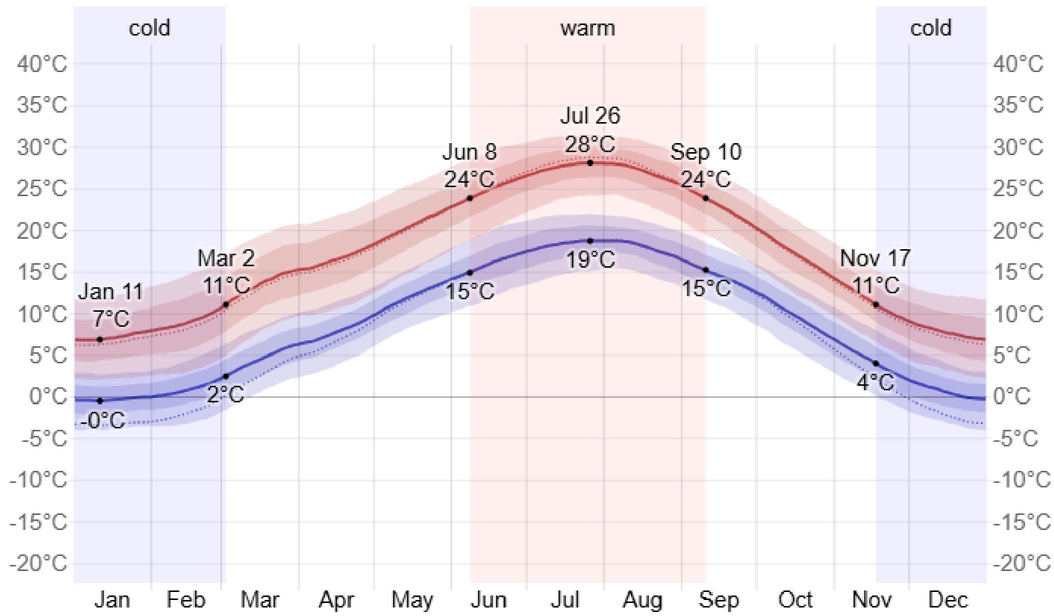


Figure 21. *Monthly average high (Red Line) and low (Blue Line) temperatures*
Source: Weather Spark

The colder months span 3.5 months, from November 17 to March 2, with daily highs usually staying below 11°C. January sees the lowest temperatures, averaging a high of 7°C and a low of -0°C. Overall annual average temperature changes are given in Figure 21.

During the application case of July 28, 2024, with 29°C will be taken as air temperature, always considering the worst-case scenario for effective risk management and ensuring preparedness for extreme events. It will allow for the development of robust adaptation strategies that can accommodate the full range of potential climate impacts, addressing uncertainties in predictions.

Cloud Cover

Another important environmental parameter can be Cloud Cover (Figure 22), the extent of sky coverage by clouds varies considerably throughout the year, reflecting seasonal patterns. The period with the least cloud cover starts around June 16 and continues for approximately 3.1 months, concluding around September 19. July stands as the month with the clearest skies, where the sky is clear, mostly clear, or partly cloudy for 72% of the time on average. In contrast, the cloudier period commences around September 19 and lasts

[51] *Agenzia Regionale per la Protezione Ambientale - https://www.arpa.piemonte.it/*

for 8.9 months, ending around June 16. May is the month with the most cloud cover, with the sky being overcast or mostly cloudy 52% of the time on average.

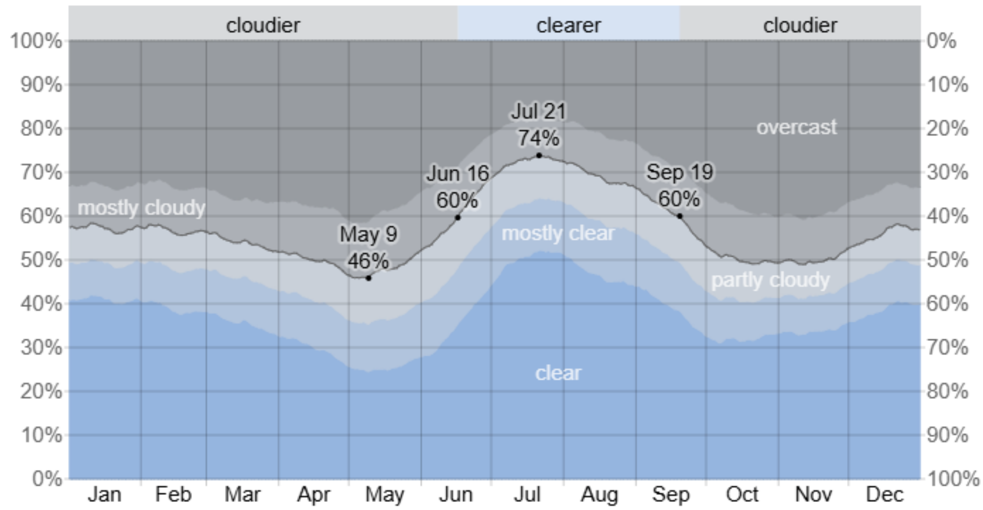


Figure 22. *Cloud cover categories in Rivoli*
Source: Weather Spark

Precipitation

In Rivoli, a wet day is defined as one in which precipitation reaches at least 1.00 millimetres, whether in the form of liquid or its equivalent. The frequency of wet days fluctuates across the year, with the wetter season lasting 7.0 months, from April 2 to November 4, during which there is a greater than 22% likelihood of experiencing a wet day. May records the highest number of wet days, with an average of 9.5 days experiencing at least 1.00 millimetre of precipitation.

Conversely, the drier season spans 5.0 months, from November 4 to April 2, with February being the month least likely to have wet days, averaging only 3.9 days with measurable precipitation.

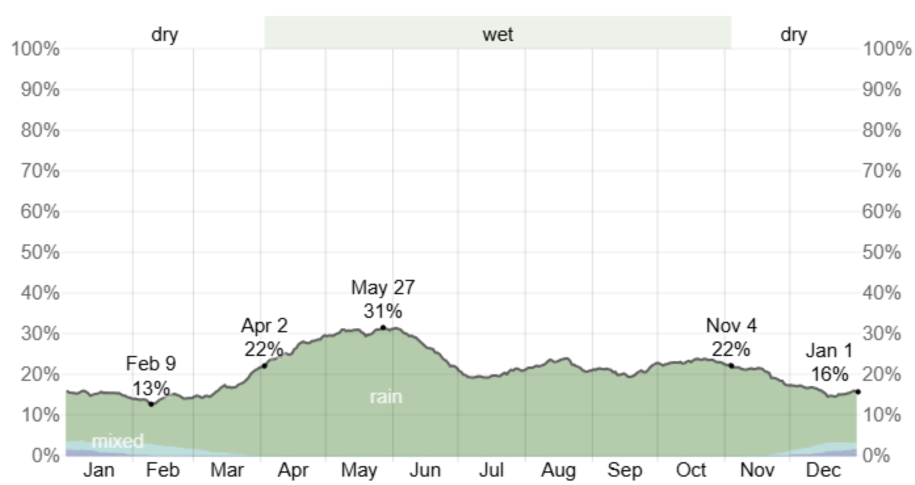


Figure 23. *Daily chance of precipitation in Rivoli*
Source: Weather Spark

Precipitation is further categorized into rain, snow, or a combination of both. Among the wet days, May also stands out as the month with the most days of rain alone, averaging 9.5 such days. Throughout the year, rain is the most prevalent form of precipitation, peaking in likelihood on May 27, when the probability of rain alone is 31%.

Rainfall and Snowfall

What regards rainfall, displays considerable seasonal variation throughout the year, with precipitation occurring consistently across all months (Figure 24). The highest monthly rainfall is observed in May, averaging 76 millimetres, while January experiences the least amount of rainfall, with an average of 23 millimetres. To capture the variation within months, rainfall is measured over a sliding 31-day period, cantered on each day of the year, providing a more detailed view of daily fluctuations.

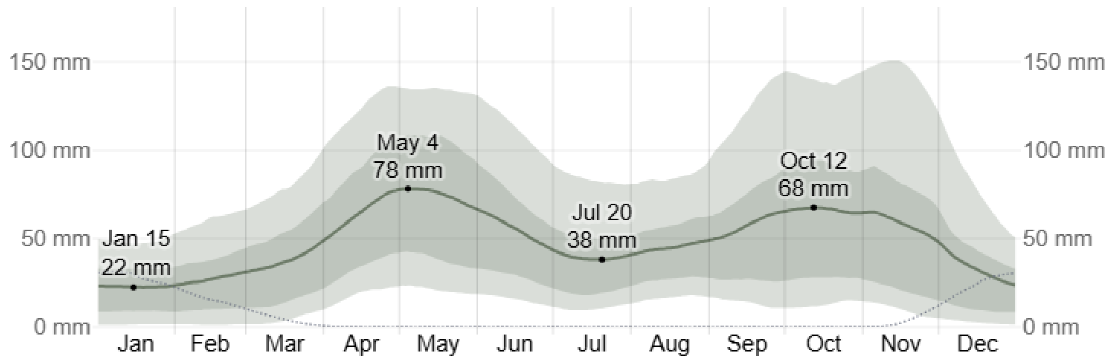


Figure 24. Average monthly rainfall
Source: Weather Spark

Snowfall in Rivoli also follows a seasonal pattern, with snow accumulation tracked over the same sliding 31-day intervals. The snowy season lasts 1.2 months, from December 17 to January 24, during which snowfall exceeds twenty-five millimetres over a 31-day period. January is the month with the highest snowfall, averaging twenty-nine millimetres. Conversely, the snow-free period spans 11 months, from January 24 to December 17, with July recording the least snow, with no measurable accumulation on average.

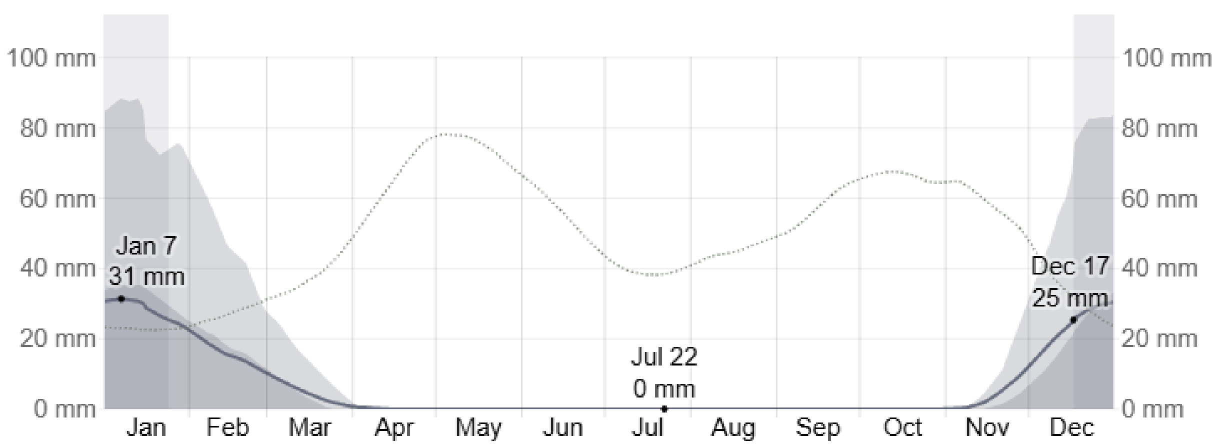


Figure 25. Average monthly rainfall
Source: Weather Spark

Daylight and Solar Energy

The availability of sunlight in Rivoli varies significantly throughout the year, influencing both daylight hours and solar energy potential. Seasonal changes in solar radiation impact energy generation, with longer daylight periods in summer providing higher solar energy yields compared to the shorter days of winter as it's shown in Figure 26.

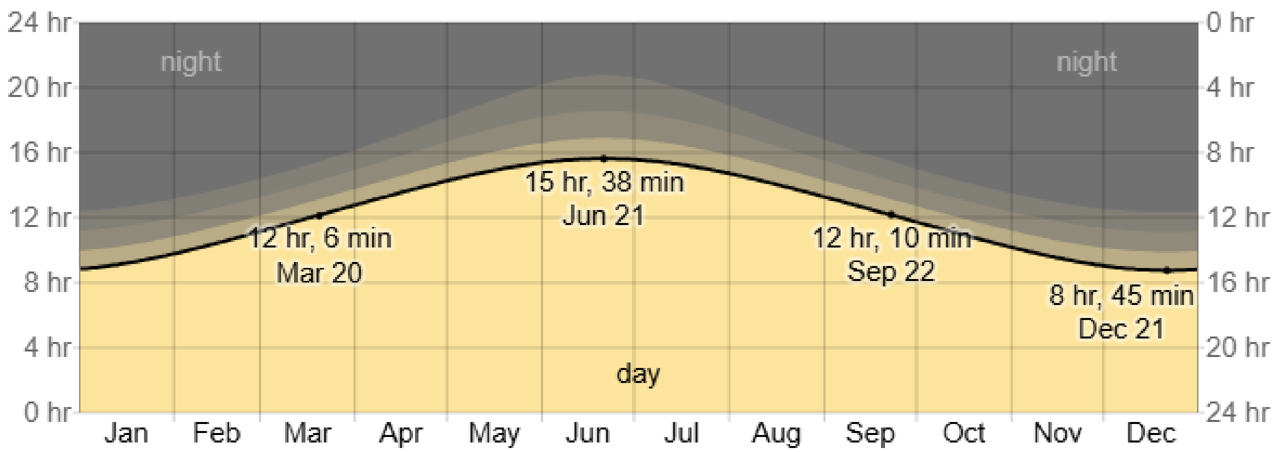


Figure 26. Hours of daylight and twilight in Rivoli
Source: Weather Spark

Changes in daylight will also have influence on the incident shortwave solar energy which reaches different surfaces, considering seasonal variations in day length, solar elevation, and atmospheric absorption. Shortwave radiation, which includes visible light and ultraviolet radiation, varies significantly throughout the year as given in Figure 27.

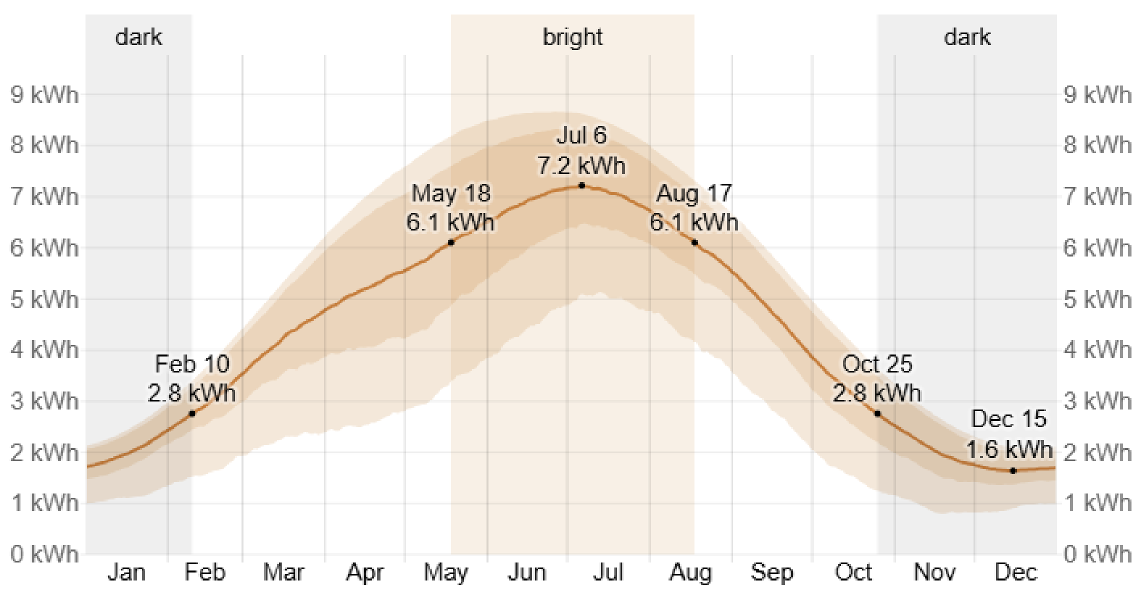


Figure 27. Average Daily Incident Shortwave Solar Energy
Source: Weather Spark

As it's shown in Figure 27 the period with the highest solar energy occurs from May 18 to August 17, lasting 3.0 months, with average daily incident shortwave energy exceeding 6.1 kWh per square meter. The peak solar energy month is July, averaging 7.0 kWh. Conversely, the darker period, from October 25 to February 10, lasts 3.5 months, with daily incident energy falling below 2.8 kWh per square meter. December records the lowest solar energy, averaging only 1.7 kWh.

Relative Humidity

As Humidity plays a crucial role in outdoor thermal comfort as it affects the body's ability to regulate temperature through perspiration, influencing on subjective perception, how hot or cold the environment feels.

Relative humidity determines the efficiency of sweat evaporation, which in turn regulates the body's cooling mechanism. A lower dew points results in a drier sensation, while higher dew points contribute to a more humid and uncomfortable environment. Unlike temperature, which can fluctuate significantly between day and night, the dew point remains relatively stable, meaning that while nighttime temperatures may decrease, a humid day is often followed by a similarly humid night.

Rivoli experiences notable seasonal shifts in perceived humidity (Figure 28), with the most uncomfortable period lasting for 2.9 months, from June 10 to September 7. During this time, the comfort level is classified as muggy, oppressive, or even unbearable at least 8% of the time. July, in particular, records the highest frequency of muggy days, with an average of 8.9 days marked by such conditions. In contrast, the least humid day of the year is February 28, when muggy conditions are virtually non-existent.

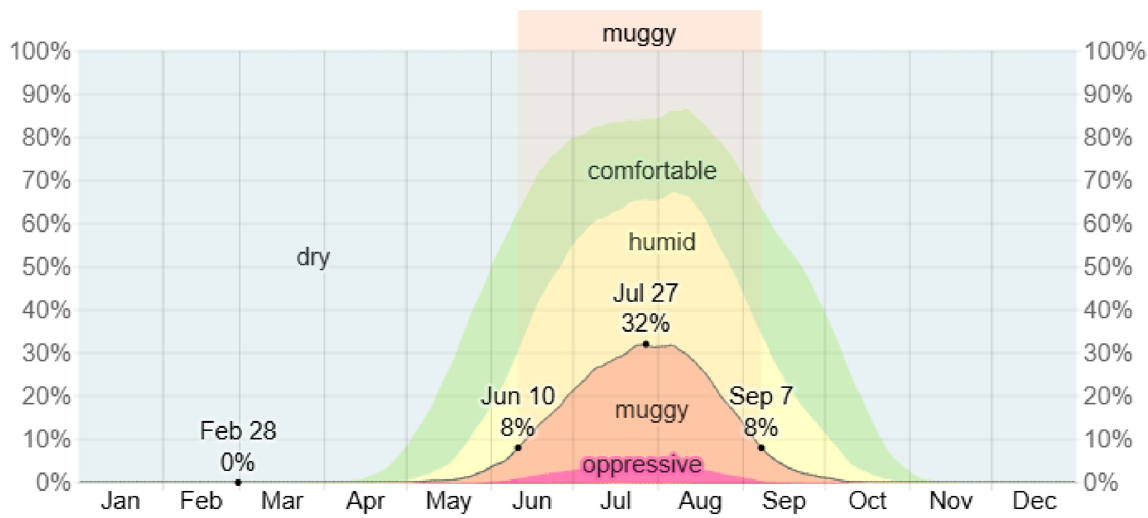


Figure 28. *Humidity levels in Rivoli*
Source: Weather Spark

Wind

Wind as another environmental parameter affection on urban microclimate, needs to be examined on hourly average bases, including both speed and direction, at a height of 10 meters above the ground. Wind patterns at a specific location are influenced by local topography and various other environmental factors, with instantaneous fluctuations in speed and direction being more pronounced than hourly averages.

In Rivoli, the average hourly wind speed remains relatively constant throughout the year, fluctuating only slightly within a narrow range of 2.1 meters per second, with variations not exceeding 0.2 meters per second shown in Figure 29.

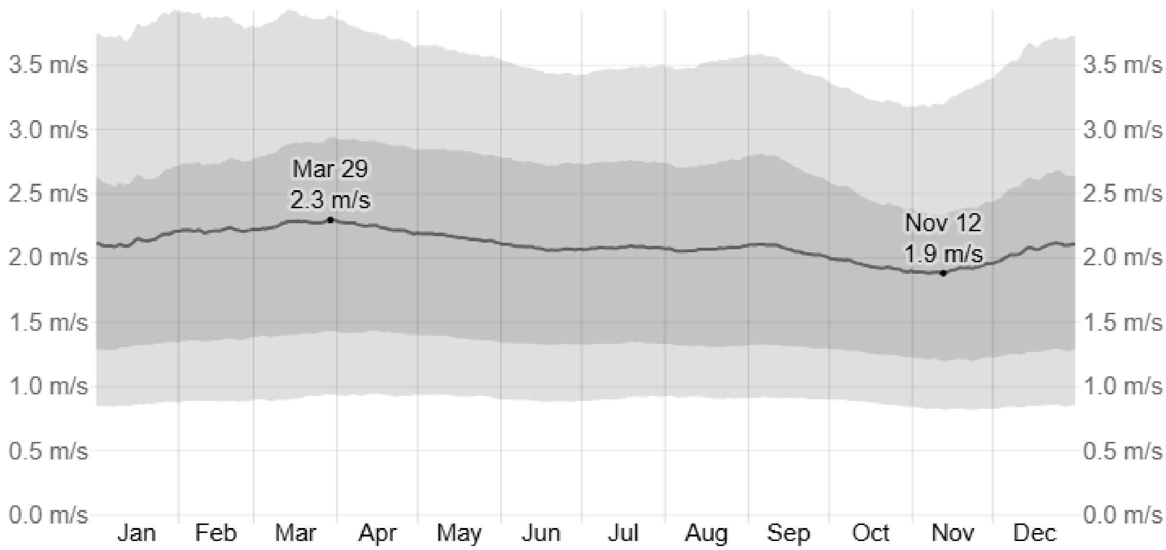


Figure 29*. Average wind speed in Rivoli*
Source: Weather Spark

According to information provided a comprehensive overview of the climatic conditions in Rivoli, highlighting significant seasonal variations in temperature, precipitation, humidity, solar energy, and wind patterns. The data reveals distinct differences between the warmer and colder periods, with notable fluctuations in rainfall, snowfall, and cloud cover. Humidity, dew point, and solar radiation also play key roles in determining comfort levels throughout the year. With this foundation of climatic understanding, the following chapter will explore the practical applications of this data, focusing on how it can be utilized for urban planning, identifying critical places withing Area Bonadies and its surroundings, energy management, and adaptation strategies.

UHI Intensity in Rivoli

In Rivoli, a town known for its unique combination of historical architecture and modern urbanization, the UHI effect presents distinct challenges. As urbanization has increased, so too has the intensity of UHI, particularly in densely populated areas, commercial districts, and regions with extensive impervious surfaces like roads and buildings. Rivoli's specific geographical layout and climate conditions amplify these effects, making it an ideal case study for understanding the intensity of UHI in urban environments and analysinc particular areas in city to spot critical conditions for future mitigation strategies.

Geoportale, the biggest database for Piemonte region, also provides general conditions of Rivoli City regarding UHI intensity. More specifically, mapping of:

- Criticità da isolie di calore nelle aree urbane/Heat island criticality in urban areas
- Indice Vegetazione normalizzato (NDVI)/ Normalized Difference Vegetation Index (NDVI)

- Temperatura al suolo (LST)/Land Surface Temperature

Which gives us information that in all three points mentioned above, Area Bonadies and its surroundings are in critical conditions as its given in Figure 30.

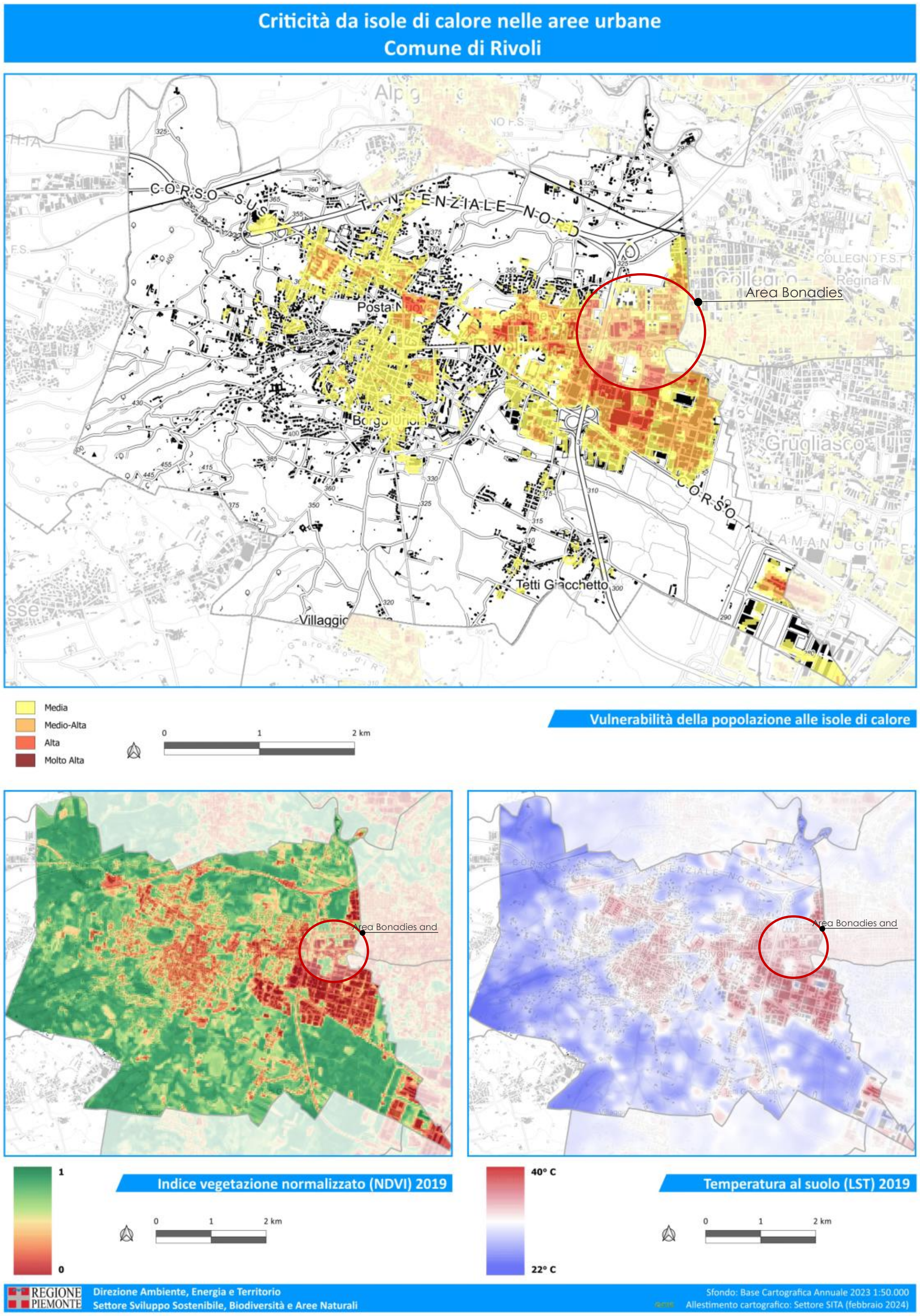


Figure 30. UHI Intensity in Rivoli
Source: Geoportale Piemonte

5.2 SOFTWARES FOR URBAN MICROCLIMATE ANALYSIS

Urban microclimate analysis plays a pivotal role in understanding how cities interact with their local environment, influencing everything from energy efficiency to public health. With the rapid pace of urbanization and climate change, assessing the microclimate within urban areas has become essential for planning sustainable and liveable cities. As well as essential topic is, various software tools are available for urban microclimate analysis, examining their capabilities, strengths, and limitations. These tools offer diverse approaches for simulating, modelling, and analysing the complex interactions between urban structures, green spaces, and the atmosphere. By delving into the functionalities of these software packages, main goal is to provide a comprehensive overview of reshaping our understanding of urban climates and helping create more resilient urban environments.[52]

During the development of this paper, ENVI-MET and GIS tools emerge as the most commonly used software for urban microclimate analysis across a wide range of studies, but they differ significantly in terms of their approach, capabilities, and specific applications.

5.2.1 ENVI-Met and GIS Tools

ENVI-MET is a specialized simulation software primarily designed for modelling and visualizing the microclimate of urban environments. It focuses on the intricate interactions between air temperature, humidity, wind, and radiation within urban contexts. ENVI-MET utilizes computational fluid dynamics (CFD) and detailed three-dimensional models to simulate the effects of urban features such as buildings and vegetation on the local climate[53]. Although it offers highly detailed and accurate representations of localized microclimates, making it particularly useful for assessing specific urban spaces, evaluating design alternatives (e.g., green roofs or street layouts), and studying pedestrian comfort regarding thermal conditions and airflow, the software has certain limitations. ENVI-MET requires a considerable level of expertise to operate effectively, and the setup of models can be time-intensive, particularly when dealing with large or complex urban areas.

In contrast, GIS tools like ArcGIS, QGIS, and other urban planning software provide a more extensive and spatially comprehensive approach to urban microclimate analysis. GIS tools excel at integrating various spatial data types, including land use, vegetation coverage, and topography, which enables a more holistic understanding of urban climate dynamics. These tools facilitate the incorporation of climate data, remote sensing information, and other geospatial datasets to monitor trends and patterns over larger urban areas. GIS tools are especially valuable for modelling urban heat islands, mapping vegetation density, and tracking long-term climate changes—crucial aspects of urban climate studies[54]. Although

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[52] *Imhoff, M. L., et al. Remote sensing of urban heat islands: A comprehensive review. Environmental Monitoring and Assessment, 2010*

[53] *Bruse, M., & Fleer, H. Simulating surface-plant-air interactions inside urban environments with a three-dimensional numerical model. Environmental Modelling & Software, 1998*

[54] *Schilling, J., & Logan, S. GIS-based urban planning: Modelling microclimates and impacts. Journal of Urban Planning, 2008*

GIS tools may not offer the same level of detailed, dynamic simulation as ENVI-MET, they are more accessible, with user-friendly interfaces and a broad range of applications in urban planning and policy formulation.

Ultimately, GIS tools are better suited for urban microclimate analysis due to their adaptability, ease of use, and capacity to process large-scale spatial data. They allow for the integration of diverse datasets and enable comprehensive, macro-level analysis of urban climate patterns. The wide-ranging capabilities of GIS tools make them the preferred choice for urban planners and researchers focused on large-scale assessments and spatial analysis. While ENVI-MET is advantageous for precise, site-specific microclimate investigations, GIS tools offer a more versatile and efficient approach to understanding and addressing urban climate challenges on a broader scale.

5.3 ARCGIS PRO FOR URBAN MICROCLIMATE

ArcGIS, developed by Esri, is a widely used Geographic Information System (GIS) platform known for its powerful tools in spatial data management, analysis, and visualization, making it particularly relevant for urban microclimate analysis. By integrating diverse spatial data such as land use, vegetation, topography, and climate information, ArcGIS allows users to gain a comprehensive understanding of how urban environments influence local climates. This capability is essential for urban planners, environmental scientists, and researchers investigating the effects of urbanization on local climates (Goodchild & Janelle, 2010).

ArcGIS excels in integrating various types of geospatial data, enabling users to map and analyse the interactions between urban features and their microclimatic effects. It can be used to assess how factors like street layouts, building height, and vegetation density contribute to urban heat island (UHI) effects, temperature variations, and airflow patterns. Through its ability to model the UHI effect, ArcGIS helps identify hotspots of higher urban temperatures and analyse strategies for mitigating these effects, such as incorporating more green spaces or using reflective building materials (Voogt & Oke, 2003). It also provides valuable insights into the role of vegetation and green spaces, allowing urban planners to assess their cooling effects and enhance strategies for urban greening, such as planting trees or creating green roofs (Jim & Chen, 2006).

In addition, ArcGIS supports climate and environmental data analysis by integrating climate variables like temperature, precipitation, and wind speed. By using remote sensing technologies, it enables long-term studies of climate changes and their interaction with urban landscapes. Although ArcGIS is not primarily a dynamic simulation tool like ENVI-MET, it offers a range of modelling capabilities through extensions such as ArcHydro, Spatial Analyst, and 3D Analyst, which help simulate urban processes like water flow, heat distribution, and pollutant dispersion. Its 3D visualization tools also allow for the creation of detailed urban models that help visualize the impact of various urban design choices on microclimates, such as how building height or street orientation can affect wind flow and air quality (Gago et al., 2013).

This software is widely applied in urban microclimate studies, particularly for mitigating urban heat islands by identifying temperature variations and developing strategies for improvement. It is also instrumental in studying the relationship between building design and energy efficiency, as well as in analysing how urban greening efforts contribute to temperature reduction and enhanced biodiversity. Moreover, ArcGIS supports air quality assessments by integrating pollutant dispersion models with spatial data to evaluate urban air quality and guide pollution control efforts (Xie & Li, 2016).

In conclusion, while ArcGIS may not provide the high-resolution dynamic simulations that some specialized microclimate models offer, its ability to integrate and visualize large-scale spatial data makes it an invaluable tool for urban microclimate analysis. It is essential for understanding the complex interactions between urban features and environmental factors and supports informed urban planning decisions aimed at improving sustainability and mitigating the effects of climate change via different tools of a software.

5.4 DATA COLLECTION AND PREPARATION

Data collection and preparation are essential initial steps in any project, as they provide the foundational information required for accurate analysis and informed decision-making. This chapter focuses on gathering and preparing critical data to assess the impact of climatic conditions on a specific location around Area Bonadies and its surroundings. The precision and quality of the data are crucial to ensuring the accuracy and relevance of the analysis. The data collection process encompasses several key aspects, including building geometry and environmental factors, all of which play a vital role in the decision-making process for selecting facade technologies aimed at improving energy efficiency and enhancing the surrounding microclimate. The first aspect of data collection involves obtaining detailed geometric information about the buildings and its facade, such as the building's footprint, elevation models, and materials, which precisely to be modelled to evaluate how these features influence the building's interaction with its environment.

The second aspect involves gathering environmental data, including historical climate information such as solar radiation, temperature, humidity, and wind speed. This data will allow for simulations to assess how different weather conditions forms urban environment, and can evaluate UTCI.

The chapter also explores the use of GIS tools, such as ArcGIS, to process, analyse, and visualize the collected data. These tools, including ArcGIS Analysis and Spatial Analyst, enable users to model and compare the effects of different facade designs on the building and its environment. By the end of this chapter, readers will be equipped with the necessary data to move forward with the mitigation strategies.

5.4.1 Geometrical Data

The Geometrical Data subchapter focuses on the collection and preparation of detailed building geometry, including the building's footprint, elevation models, and facade characteristics. For given case study of Area Bonadies and its surroundings, and in general for any specific place located in Piedmont region, mentioned data above can be found on Geoportale. The GeoPortale represents, in compliance with the Regional Law of 1 December 2017, n. 21, (" Regional infrastructure for geographic information"), one of the main constituents of the regional geographic infrastructure as a point of exposure of shared geographic information.[55] On a given platform it's possible to find The Territorial Reference Database of Piedmontese Bodies (BDTRE[56]), is designed to integrate geographical information from various sources, including regional offices, local authorities, and both public and private organizations. Its purpose is to ensure that the data is valid, accurate, consistent, complete, and up to date in mostly Shapefile formats and not only it is made available in various formats (both vector and raster) and through diverse types of services, all of which follow key national and European standards.

Vector data represents distinct geometric shapes (such as points, lines, and polygons) of objects and links them to related alphanumeric information. The data is commonly published in the shapefile format, which remains one of the most widely used formats for vector data in file systems. It is an open and interoperable format, compatible with most major GIS software, both open-source and proprietary.

Most of the data related to urban morphology and its parameters, as discussed in previous chapters, is already available in database classes. Specifically, geometric data such as width, length, height, volume, area, perimeter, and others are provided not only for buildings (Figure 31), but also for infrastructure elements like roads, land parcels, and green spaces. This data allows us to use tools like the Calculation Field in the attribute tables of ArcGIS Pro to evaluate urban parameters such as Sky View Factor (SVF), Height-to-Width Ratio (H/W), Site Coverage Ratio, and Average Building Height.

	OBJECTID *	Shape *	OID_1 *	UN_VOL_AV	Shape_Length	Shape_Area	H_W	SVF	Join_Count	Shape_Length	FACADE
1	1	Polygon ZM	1846318860	7	140.882751	1243.13562	0.981369	0.009316	5	140.882751	986.17926
2	2	Polygon ZM	1846318878	4	47.692163	102.38135	0.493495	0.253253	2	47.692163	190.768653
3	3	Polygon ZM	1846319257	6	79.103987	259.676575	0.183893	0.408053	3	79.103987	474.623924

Figure 31. *Example of Buildings Shapefile attribute table*
Source: Data from Geoportale

Having established the foundation with detailed geometric data, the next step is to explore the environmental data, which plays a crucial role in assessing the impact of urban morphology on the surrounding microclimate and energy performance. While geometric data provides essential insights into the physical characteristics of urban areas, it is not sufficient on its own for a complete evaluation of the urban microclimate, as environmental factors must also be considered to fully understand the interactions between the built environment and its surroundings.

[55] *https://geoportale.igr.piemonte.it/cms/*
[56] *La Base Dati Territoriale di Riferimento degli Enti piemontesi*

5.4.2 Environmental Data

The collection data for environmental parameters and analysis of climate-related factors, such as temperature, humidity, solar radiation, and wind speed, which are essential for evaluating the impact of urban morphology on the local microclimate and energy efficiency can be more complex, regarding what data is available.

A more detailed analysis of environmental factors, including specific dates and durations, is necessary for this study. For various reasons, but one of the most important approaches also provides valuable insights into climate change trends and informs urban planning strategies to better manage the effects of extreme weather events, it has been decided to focus on the most extreme conditions observed during both the summer and winter seasons. After careful consideration, the summer season has been selected for this analysis. Specifically, data from July 2024 was chosen, as it represents a recent period that allows for a comprehensive examination of heat island effects. The data for this period has been retrieved from the ARPA Piemonte historic database in .CSV format for further analysis.

Environmental parameters as input for GIS databases, though it may require accessing multiple sources for specific datasets. To where and how it's possible to find GIS-compatible environmental data for Rivoli, Italy can be different as follows:

- **Temperature and Humidity Data**
  - *ARPA Piemonte (Regional Environmental Protection Agency of Piedmont)*: This agency provides various environmental data, including temperature and humidity, which may be available in GIS-compatible formats (shapefiles, rasters, or as downloadable .CSV files that is possible to be imported into ArcGIS Pro).
  - *Copernicus Climate Data Store*: The Copernicus Climate Data Store offers historical climate data, which can be downloaded in various formats, including NetCDF and CSV. These can be converted into raster data for use in ArcGIS Pro.
  - *Meteo.it* and *Servizio Meteorologico dell'Aeronautica Militare*: These meteorological services offer weather data, but it might be necessary to request the data in a GIS-friendly format or manually process the data into shapefiles or rasters.

- **Solar Radiation Data**
  - *NASA POWER*: The NASA POWER data service provides solar radiation data and is available in GIS-compatible formats such as NetCDF or TIFF. Which can be directly imported into ArcGIS Pro for analysis.
  - *ARPA Piemonte (Regional Environmental Protection Agency of Piedmont)*: as the format of raster TIFF.
- **Wind Speed Data**
  - *ERA5 (European Climate Assessment & Dataset)*: ERA5 provides high-resolution climate data (including wind speed) in NetCDF format, which can be imported into ArcGIS Pro for spatial analysis and mapping.

- *Copernicus Climate Data Store*: This platform also offers wind speed data, which you can download in formats compatible with GIS applications like ArcGIS Pro.

Although some of this data may not be readily available in a GIS database format, platforms such as ARPA Piemonte, NASA, Copernicus, and ERA5 offer downloadable datasets that can be imported into ArcGIS Pro for further analysis. These datasets may require conversion into compatible formats, such as transforming .CSV files into shapefiles, or utilizing GIS tools like Raster Interpolation to generate meaningful visualizations and spatial analyses.

When working with environmental parameters such as temperature, humidity, solar radiation, and wind speed, it is crucial to define the appropriate time ranges for analysis. These time ranges can include annual, monthly, or specific periods or days of the year, depending on the focus of the study. Establishing the correct time intervals allows for accurate assessment of seasonal variations and the influence of time-specific environmental conditions on the urban microclimate. By selecting the relevant timeframes, and specific locations as points, the analysis can yield more precise insights into how environmental factors impact building performance and energy efficiency throughout the year.

5.5 MODELS

The amount of data provided by different sources can be wide, so for its data management tools are needed to provide structured frameworks that guide the entire analysis process. Tools for it are Conceptual and Logical Models that is formed from main research questions.

The conceptual model helps clarify the real-world problem by breaking it down into key components and relationships, ensuring the analysis is grounded in the issue at hand. Meanwhile, the logical model outlines the specific steps, tools, and methods needed to manipulate and interpret the data, ensuring the process is repeatable and error-free. These models help organize and integrate data effectively, making the analysis more efficient by avoiding redundancy and streamlining the workflow.

Additionally, main goal is to ensure that the analysis is reproducible and scalable, making it easier to replicate or apply to different contexts. By anticipating potential issues, the models mitigate risks and optimize the analysis process, saving time and resources for management and organizational reasons.

5.5.1 Conceptual Model

As defining conceptual model of a project for ARCGIS PRO, foundational blueprint for understanding and organizing spatial data in a way that reflects real-world relationships is forming. It helps define the scope of the analysis by breaking down complex geographic data have been found, into entities and their interrelationships, providing a clear framework for data collection, management, and interpretation. The model is not concerned with the technical specifics of data storage or processing but rather focuses on what needs to be represented and how different components of the analysis interact.

In a conceptual model, each entity, such as buildings, streets, urban morphology, and land use, must be precisely defined to ensure that the analysis accurately represents the real-world scenario; after filtering all the relevant data from BDTRE, it became possible to carefully define these entities, real objects that should be represented, along with their formats and required attribute fields, ensuring that the necessary data could be effectively used for the analysis.

- Buildings – Polygon
- Land – Polygon
- Greenery – Polygon
- Urban Morphology – Alphanumerical Table
- Climatic Data – Alphanumerical Table
- Streets – Polyline

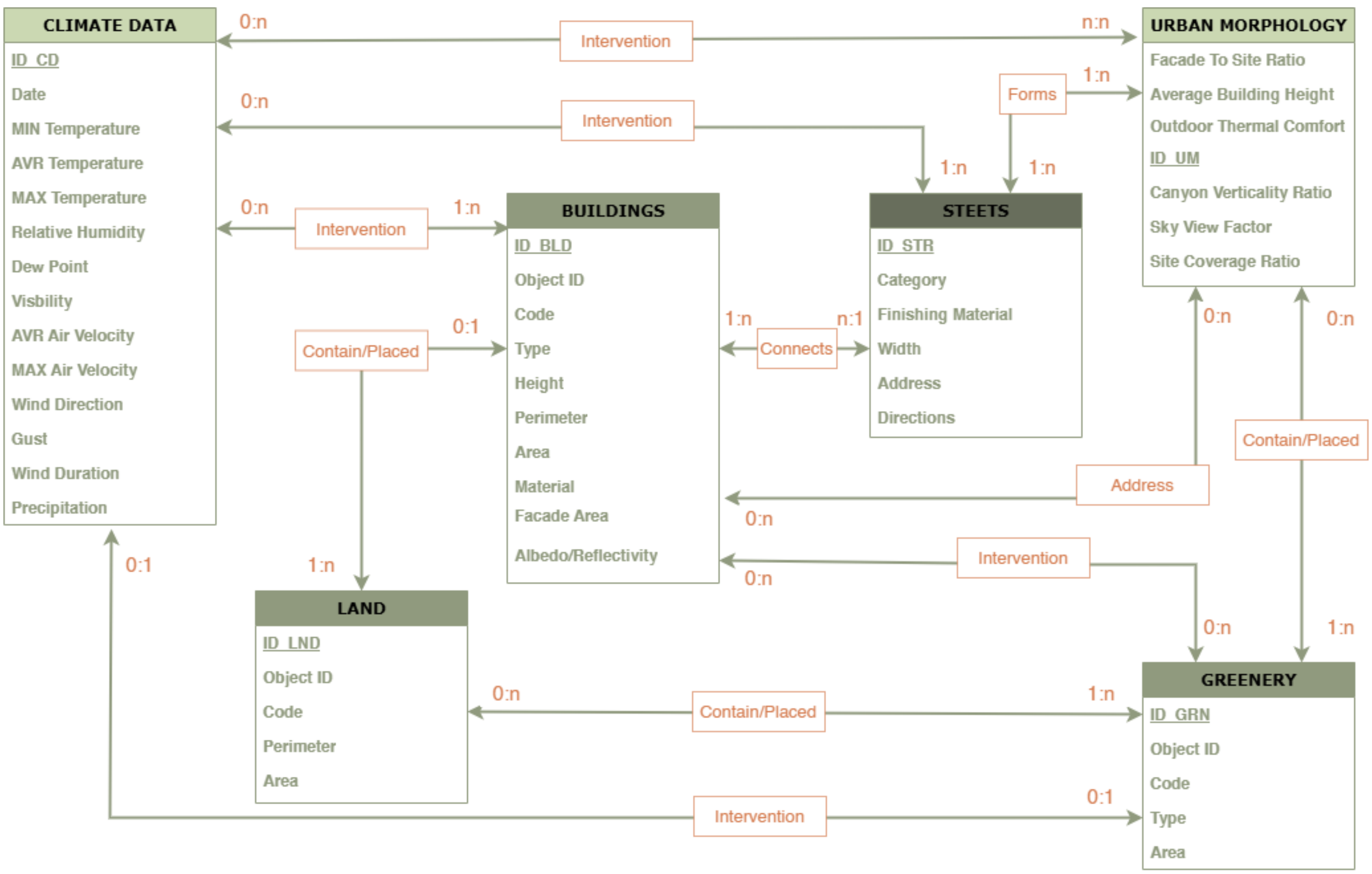


Figure 32. Conceptual Model
Source: Developed by a candidate.

What regards connections between two or multiple entities, cardinalities have been identified as numerical, indicating how many instances of one entity can be associated with instances of another entity. It defines the possible connections or interactions between these entities within the model. For example, in a relationship between Buildings and Streets the cardinality could specify whether one building is linked to multiple streets (one-to-many), or each street is connected to only one building (many-to-one). Understanding cardinality is essential for structuring the data correctly and ensuring that the relationships are accurately represented in the logical model.

5.5.2 Logical Model

A Logical Model is a structured representation of how data is organized and related for analysis, focusing on the entities involved and how they interact within a given system. It means to take the conceptual model, which outlines real-world concepts and their relationships, and translates it into a more detailed and structured framework for practical implementation.

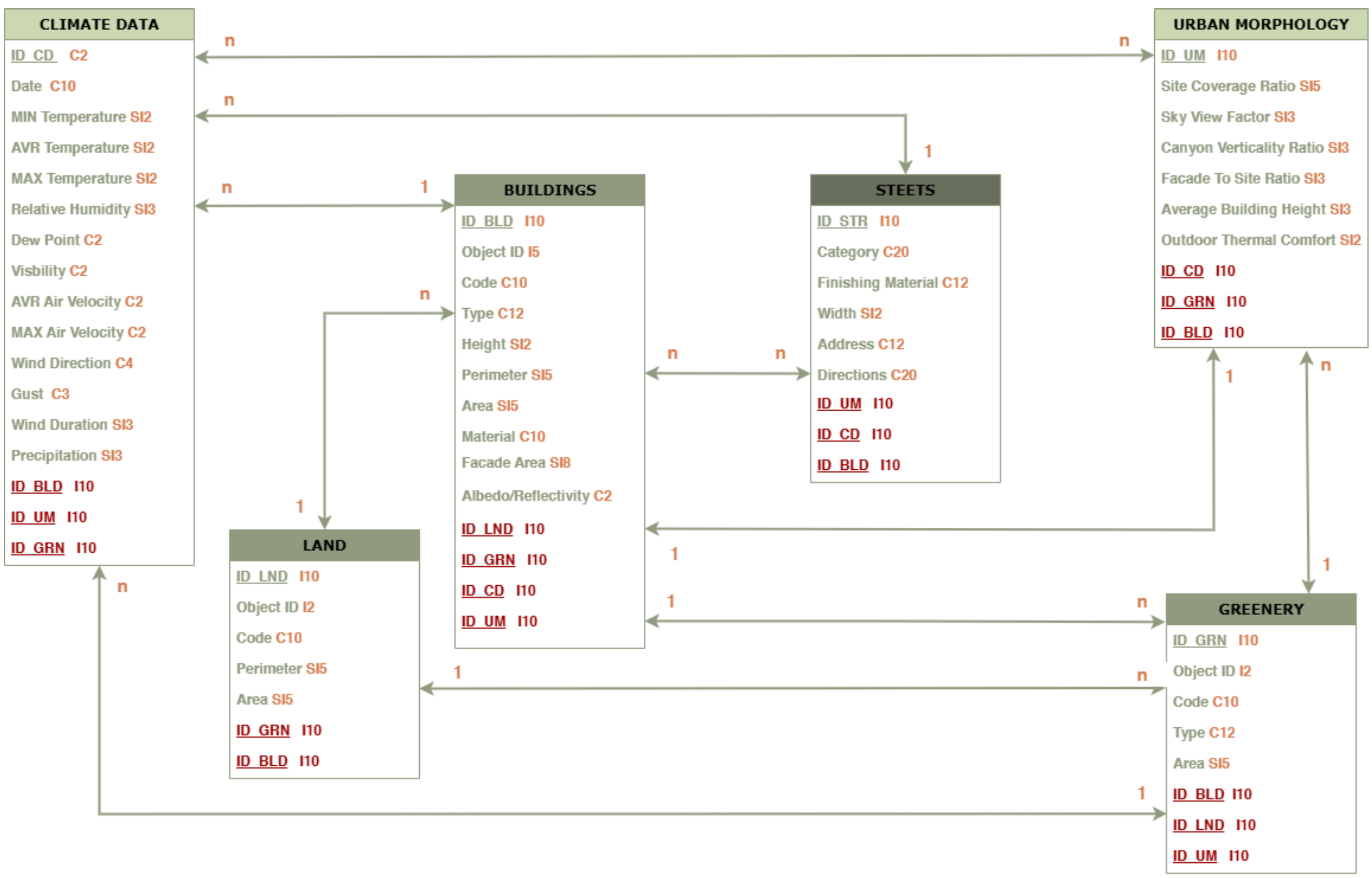


Figure 33. Logical Model
Source: Developed by a candidate.

As a core components of a logical model include entities, attribute fields, relationships, cardinality, and data types and formats. Which in this case is defined by:

- SI – Short Numerical and number of characters
- In - Integer Numerical and number of characters
- LI - Long Numerical Integer and number of characters
- C – Strings as Text/Date/Time and number of characters

Cardinalities in logical model refers to the number of instances of one entity that can be related to instances of another. It helps define the type of relationship between entities as previously. Data types and formats are critical components of a logical model, as they define how data is stored and processed. In a logical model, the cardinality between buildings and streets typically follows three relationships: many-to-many, one-to-many, or one-to-one. In a many-to-many relationship, a building can be connected to multiple streets, and a street can serve multiple buildings, which is common in dense urban areas. In a one-to-many relationship, a building may be associated with one street, but a street can have many buildings along it, typical of residential or commercial districts.

In summary, a logical model organizes data in a way that clearly defines the entities, their attributes, relationships, and cardinalities, while also specifying the data types and formats required for effective analysis. This structured approach ensures that data is prepared for efficient processing and accurate decision-making, making it a crucial step in the modelling and analysis process.

5.6 EVALUATION AND OUTCOMES THOUGHT ARCGIS TOOLS

This chapter focuses on utilizing ArcGIS Pro to analyse the Area Bonadies and its surroundings location through various shapefiles for diverse types of analysis. The shapefiles contain spatial features such as points, lines, and polygons, which define the area's boundaries and represent its various attributes and characteristics.

The first step involved importing and visualizing the data, followed by exploring and querying its attributes. Different spatial analysis techniques were applied to filter the data, retaining only the relevant information based on a logical model. These techniques were used to address specific questions related to the location and its features. Additionally, the chapter discusses the creation of maps and visualizations to effectively present the results of the analysis. Through the application of these tools, the goal was to extract meaningful insights about the Area Bonadies and its surroundings location and its significance for decision-making and planning given in Annex 2.

5.6.1 UTCIs in Area Bonadies and its surroundings

For UTCI evaluation, environmental data is essential as indicated in Formula 1, but it is not enough on its own. Even if all the climate data for a specific location is provided by the ARPA Piemonte historical database for July 2024, surface temperatures of urban environments, such as the mean radiant temperatures, were still missing. For this reason, a Land Surface Temperature (LST) TIFF file was downloaded from the Geoportale to define specific values for different surface temperatures.

First, import the LST TIFF raster data into ArcGIS Pro by adding it to the map. Then, convert the LST raster into point data using the "*Export Raster to Points*" tool. This will create a point feature class where each point corresponds to a specific temperature value, which can be grouped in 5 different classes as ranges. Afterward, review attribute table of the point feature class to verify that the temperature values are correctly represented, typically under the "*Value*" field, with adjust the temperature units converting from Fahrenheit to Celsius, which gives us Annex 4 with a different land surface temperature.

Next step has been to collect the necessary environmental parameters required for UTCI calculation, such as air temperature (T_a), relative humidity (RH), wind speed (V_a), and solar radiation (T_{mr}). These parameters have been gathered from meteorological data sources like ARPA Piemonte. They have been imported as .CSV standalone table Figure 34 . Since we are considering worse conditions for summer season, according to data from mentioned table, values of 28 July have been chosen, as with tool of "*Field Calculation*", with a Python expression type, for each point given in Annex 4, UTCI have been evaluated as graduated values and shown in Annex 3.

LOCALITA	DATA	TMEDIA °C	TMIN °C	TMAX °C	PUNTORUGIADA °C	UMIDITA %	VISIBILITA km	FENOMENI	Velocità media (m/s)	Velocità raffica (m/s)	Settore prevalente	Tempo permanenza (min)	Durata calma (min)	Vento classe	Precipitazione (mm)	Precipitazione classe
Rivoli	01/07/2024	22	17	28	18	79	21	pioggia temporale	1.9	12.1	SSE	290	90	AZ0YYZ	12	AZ
Rivoli	02/07/2024	23	16	28	14	63	19	<Null>	1.4	6.1	SSW	280	100	AZ0YYZ	0	AZ
Rivoli	03/07/2024	20	18	23	15	76	21	pioggia	1.8	6.7	ENE	360	20	AZ0ZZZ	2.2	AZ
Rivoli	04/07/2024	21	15	27	14	66	20	<Null>	1.3	5.8	SW	220	50	AZ0ZZZ	0	AZ
Rivoli	05/07/2024	23	17	28	16	65	19	<Null>	1.8	5.9	WSW	380	40	AZ0ZZZ	0	AZ
Rivoli	06/07/2024	22	20	24	18	76	19	pioggia	1.6	6.1	NE	290	20	AZ0ZZZ	1	AZ
Rivoli	07/07/2024	21	19	25	19	87	17	pioggia temporale	1.8	9.5	E	290	160	AZ0YYZ	16.5	AZ
Rivoli	08/07/2024	24	20	28	19	76	19	pioggia	1.2	5.1	ESE	230	80	AZ0YYZ	0	AZ
Rivoli	09/07/2024	25	20	30	19	68	20	<Null>	1.6	6	SW	390	30	AZ0ZZZ	0	AZ
Rivoli	10/07/2024	27	21	31	20	67	22	<Null>	1.9	5.7	SW	480	10	AZ0ZZZ	0	AZ
Rivoli	11/07/2024	27	22	32	21	70	19	pioggia temporale	1.9	11.6	SW	320	10	AZ0ZZZ	6.3	AZ
Rivoli	12/07/2024	22	19	26	19	85	21	pioggia temporale	1.9	7.6	WSW	340	10	AZ0ZZZ	7.7	AZ
Rivoli	13/07/2024	23	18	28	17	71	20	<Null>	1.7	6	SW	300	10	AZ0ZZZ	0	AZ
Rivoli	14/07/2024	25	19	29	18	67	19	<Null>	2.1	6.8	SW	500	0	AZ0ZZZ	0	AZ
Rivoli	15/07/2024	25	21	29	19	67	19	<Null>	2	5.4	WSW	370	10	AZ0ZZZ	0	AZ
Rivoli	16/07/2024	27	21	31	20	66	20	<Null>	1.8	5.8	SW	320	20	AZ0ZZZ	0	AZ
Rivoli	17/07/2024	27	21	31	20	70	20	<Null>	1.7	6	WSW	270	20	AZ0ZZZ	0	AZ
Rivoli	18/07/2024	27	23	32	20	66	20	<Null>	2	6.2	SW	380	30	AZ0ZZZ	0.4	AZ
Rivoli	19/07/2024	27	23	31	20	67	21	<Null>	1.8	7.6	SW	340	10	AZ0ZZZ	0	AZ
Rivoli	20/07/2024	26	20	32	18	65	18	<Null>	2.2	7.6	SW	290	10	AZ0ZZZ	0.4	AZ
Rivoli	21/07/2024	25	21	28	19	71	18	pioggia temporale	2.6	10	WSW	370	40	AZ0ZZZ	0.8	AZ
Rivoli	22/07/2024	26	19	32	17	59	20	<Null>	2.5	7.3	SW	520	10	AZ0ZZZ	0	AZ
Rivoli	23/07/2024	27	23	31	20	66	21	<Null>	1.6	6.1	W	180	10	AZ0ZZZ	0	AZ
Rivoli	24/07/2024	27	21	31	18	60	17	<Null>	1.9	5.7	WSW	330	0	AZ0ZZZ	0	AZ
Rivoli	25/07/2024	26	23	30	19	67	21	<Null>	1.6	6.5	W	270	80	AZ0YYZ	0	AZ
Rivoli	26/07/2024	27	23	30	20	70	20	pioggia temporale	1.7	5.8	NE	300	20	AZ0ZZZ	2.6	AZ
Rivoli	27/07/2024	27	22	31	21	71	21	pioggia temporale	1.4	5.5	WSW	280	150	AZ0YYZ	0	AZ
Rivoli	28/07/2024	29	23	34	21	64	21	<Null>	2.1	5.6	WSW	390	20	AZ0ZZZ	0	AZ
Rivoli	29/07/2024	28	23	32	21	67	20	<Null>	1.6	6.9	W	230	130	AZ0YYZ	0	AZ
Rivoli	30/07/2024	28	23	32	22	72	20	pioggia temporale	1.9	8.8	WSW	410	40	AZ0ZZZ	0.4	AY
Rivoli	31/07/2024	28	23	33	20	64	19	pioggia	2.5	8.5	WSW	540	0	AZ0ZZZ	0	AZ

Figure 34. *Climatic data of Rivoli as ARCGIS PRO attributes table*
Source: ARPA Piemonte

According to evaluation, Area Bonadies and its surroundings is in UTCI stress category of - Very Strong Heat Stress, with temperature ranges of 41.59°C - 42.38 °C.

This category indicates that the environmental conditions are extremely hot in specific locations, and they can have a significant negative impact on health, particularly for vulnerable populations like the elderly, children, or people with pre-existing health conditions. At this level, the body's ability to regulate its internal temperature is severely challenged, and people may experience symptoms like dehydration, heat exhaustion, and even heatstroke if exposed to these conditions for extended periods without proper hydration or cooling mitigation strategies.

5.6.2 UHI Intensity

Urban Heat Island (UHI) intensity refers to the temperature difference between urban areas and their surrounding rural environments. To calculate this intensity, Land Surface Temperature (LST) data, provided in the form of TIFF file (Figure 35) has been used. These files represent surface temperature variations across Piemonte Region, but in case scale has been contracted up to Rivoli, Area Bonadies and its surroundings, allowing to assess temperature differences between urban and rural environments. By calculating UHI intensity, it's possible to better understand the impact of urbanization on local climate conditions.

In ArcGIS Pro, the process of calculating UHI intensity involves extracting LST values from the TIFF files and analysing them to determine the temperature differences between urban and surrounding rural areas. Usually started by converting the raster data (LST TIFF) into point values using the "Raster to Point" tool. This tool creates points at the locations of each pixel in the raster layer and assigns specific temperature values corresponding to the LST at each location, as it was shown in Annex 4.

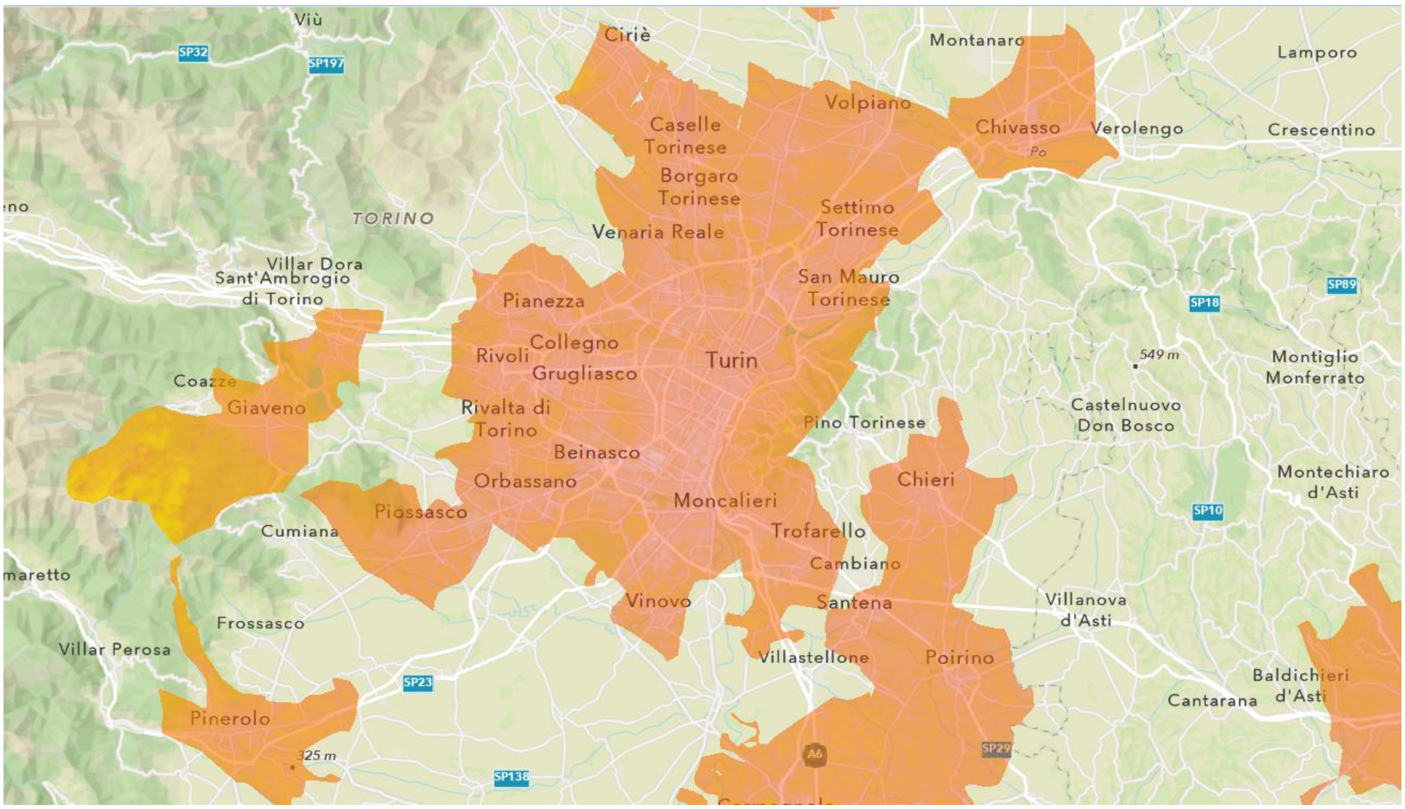


Figure 35. *Land Surface Temperature TIFF file in ARCGIS PRO software*
Source: Geoportale

Once the LST values as point data have been extracted, it's possible to perform further spatial analysis to calculate UHI intensity. This involves comparing the extracted temperature values in urban areas to those in rural areas and determining the temperature difference that represents the UHI intensity. That also consider other factors, such as land use, vegetation cover, and urban density, to better understand the underlying causes of UHI intensity.

To measure the difference between the maximum and minimum values in an attribute field in ArcGIS Pro, Once the table is open, located the field needed to be analyse, and sort it in either ascending or descending order to identify the maximum and minimum values, which in case of Area Bonadies and its surroundings LST gave us numbers of – MIN 31.79°C and MAX 34.99°C.

To calculate the difference between these values, the *Field Calculator* tool can be used. By right clicking the field name in the attribute table and selecting *Field Calculator*, which allows us to apply Formula 7 as an expression of Phyton to calculate the difference between the maximum and minimum values in the field:

- For maximum value: max_value =!RASTERVALU!.maximum()=34.98631 °C
- For minimum value min_value =!RASTERVALU!.minimum()=31.79256 °C
- For difference = max_value - min_value=34.98631-31.79256=3.19≈3.2°C

The results indicate that the Urban Heat Island (UHI) intensity is 3.2°C, suggesting a noticeable temperature difference between urban and surrounding areas. This value reflects the extent of heat accumulation in the urban environment, which may contribute to higher energy consumption and affect local air quality. The findings highlight the significance of addressing UHI effects, particularly in densely populated urban regions, to mitigate environmental and health impacts.

This approach allows us to accurately evaluate UHI effects, providing useful insights that can inform urban planning and environmental strategies aimed at reducing the negative impacts of urban heat with different types of mitigation strategies.

5.6.3 Land Surface Temperature

To evaluate Land Surface Temperature (LST) using ArcGIS Pro for adaptive facade solutions, the first step is to acquire satellite imagery that includes thermal infrared (TIR) bands. These bands are essential for capturing the thermal emissions from the Earth's surface. Data has been obtained from Geoportale database as TIFF file.

Once the data is obtained, it must be properly processed. The thermal infrared data is imported into ArcGIS Pro, where it undergoes radiometric calibration and geo-referencing. This ensures the data is accurate and aligned geographically. ArcGIS Pro provides tools such as Raster Calculator and Infrared to Temperature to assist in these steps, converting the raw thermal infrared readings into temperature values.

With the data processed, the LST is calculated using different algorithms. These algorithms convert the thermal infrared data into temperature measurements, typically displayed in degrees Celsius. The result is a raster dataset that represents temperature distribution across the study area. For instance, temperature values might range from 31.79°C to 32.35°C in cooler zones and 34.01°C to 34.99°C in hotter regions. As at the end it resulted in Annex 4. The cooler areas generally correspond to locations with more vegetation or reflective surfaces, while the hotter zones are typically more densely built with limited green space.

After calculating the LST, analysis can be performed to identify areas affected by the urban heat island effect, which is marked by higher LST values. These regions are the most suitable for implementing adaptive facades. Solutions such as facades with high thermal insulation, photovoltaic panels, or green facades can be considered. Additionally, areas that experience significant solar radiation may benefit from dynamic shading systems or facades with thermochromic materials that adapt to sunlight intensity, reducing heat absorption.

To refine facade designs further, the Solar Radiation tool in ArcGIS Pro can be used to simulate how much sunlight various building surfaces receive as indicated in Annex 9. This helps identify the parts of the facade most exposed to sunlight, which may need additional protection. Combining solar radiation data with LST results enables the design of facades that minimize heat gain while improving indoor thermal comfort.

5.6.4 Canyon Verticality Ratio

In ArcGIS Pro, conducting a Canyon Verticality Ratio (CVR) analysis involves comparing the relative vertical exaggeration of a canyon with its overall horizontal dimensions to quantify how steep or deep the canyon is in relation to its width. This analysis can be crucial for understanding the canyon's formation and geomorphological features.

For beginning it was necessary to have heights of buildings in Area Bonadies and its surroundings. Due to lack of field information in shapefile UN_VOL_2023 of BDTRE, which according to attached document should include volumetric heights of buildings in Rivoli, all the heights have been calculated manually. Another crucial step is to measure the canyon's horizontal width, which corresponds to the distance between the two points at the edges of the cross-section between buildings by *Field Calculator* tool. With these two values, we can compute the Canyon Verticality Ratio, again by mean of *Field Calculator* in attribute tables and get Annex 5 as results with specified symbology characteristics. The CVR is calculated by dividing the maximum depth or height of the canyon by the horizontal width as explained in Chapter 3.3.1.

In urban climate analysis CVR helps assess how canyon-like urban configurations, with their height-to-width proportions, influence air flow, sunlight penetration, and microclimates. During adaptive facade technology decision-making, understanding the CVR can guide the design of building facades that optimize energy efficiency, thermal comfort, and light exposure by considering the canyon's impact on the local environment.

5.6.5 Normalized Difference Vegetation Index

Another step was to evaluate the Normalized Difference Vegetation Index (NDVI) from a TIFF (Figure 36) file using ArcGIS Pro Provided by database of Geoportale mapping system, the first step involves importing the relevant satellite imagery into the software. This typically includes multispectral data, such as from Landsat or Sentinel-2 satellites, where the imagery contains the necessary bands for NDVI calculation - usually the red and near-infrared bands. The TIFF file containing this multispectral data is opened in ArcGIS Pro as a raster layer.

Next, the NDVI is calculated using the *Raster Calculator* tool within ArcGIS Pro. The NDVI formula involves using the red and near-infrared bands of the satellite imagery. In the Raster

Calculator, the red band is subtracted from the near-infrared band, and the result is then divided by the sum of the near-infrared and red bands. This step transforms the raw data into NDVI values that range from -1 to 1, where higher values indicate dense, healthy vegetation, and lower values suggest sparse or no vegetation.

Once the NDVI is calculated, the output is a new raster layer that displays the NDVI values across the study area. But it needs and an *Extraction Raster to Points* tool for more precise values. For example, areas with values ranging from 0.06 to 0.19 represent regions with minimal or sparse vegetation, possibly urban areas, barren land, or agricultural fields. In contrast, areas with values ranging from 0.51 to 0.70 indicate healthier, denser vegetation, often associated with forests, parks, or well-vegetated areas.

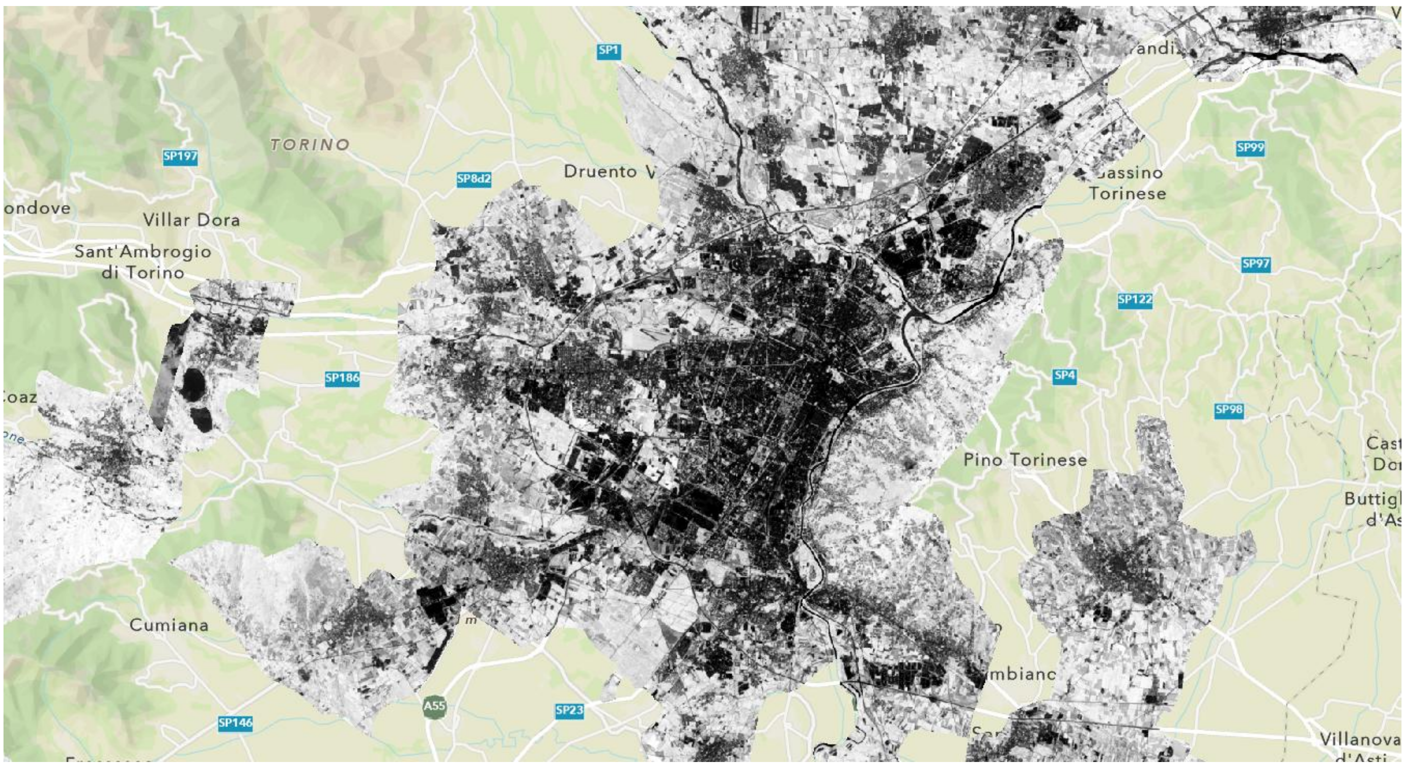


Figure 36. *NDVI TIFF file in ARCGIS PRO*
Source: Geoportale

To further refine the analysis, the resulting NDVI raster has been classified into different classes based on the calculated values. For instance, low NDVI values corresponds to urban or industrial zones, while higher NDVI values is linked to green spaces. This information can be used in adaptive facade solutions to identify areas that might benefit from green facades or additional vegetation to help improve the local microclimate and thermal comfort.

Finally, the results, including NDVI values and any associated classifications, can be visualized in ArcGIS Pro through color-coding to better interpret the vegetation density across the study area. Maps and visual outputs can then be generated to support the development of building designs that incorporate green facades, based on the NDVI analysis and its correlation to the local environment.

5.6.6 Wind Analysis

In ArcGIS Pro, a wind analysis was carried out using a TIFF file containing relevant meteorological data, such as wind speed and direction provided from Global Wind Atlas. The analysis began by ensuring that the TIFF file was correctly loaded and georeferenced within the software. All data layers were aligned and prepared for processing.

The Spatial Analyst extension was utilized to process the TIFF data, allowing the wind data to be applied to the landscape model. This facilitated an analysis of wind patterns across the study area, considering various topographical features. Tools such as the "Raster Calculator" were employed to manipulate the wind data, examining the influence of local terrain on wind behaviour. *Wind Chill* tool was also used to estimate wind characteristics in regions where direct measurements were unavailable.

From this process, wind direction and speed maps were generated, which visually represented how wind interacted with the terrain. These outputs were analysed and interpreted to draw conclusional point with longitude and latitude and about potential wind energy locations or the environmental impact of wind patterns in the area.

Ultimately, the wind analysis in ArcGIS Pro provided an integrated approach to understanding wind behavior, transforming the TIFF data into valuable insights for applications in environmental assessments and energy planning as given in Annex 11.

5.6.7 Sky View Factor

The Sky View Factor (SVF) evaluation process in ArcGIS Pro begins by preparing the necessary data layers, typically a Digital Surface Model (DSM) or a Digital Elevation Model (DEM), to represent the study area's terrain and built structures. These raster layers are imported into ArcGIS Pro for analysis, as they provide the topographic context required to assess the visibility of the sky from the ground level.

In ArcGIS Pro, the SVF is calculated using specialized tools, such as the "Sky View Factor" tool, which is often part of the Spatial Analyst or 3D Analyst extensions. The tool evaluates the extent to which the sky is visible from each raster cell by considering the surrounding terrain and structures. This analysis generates a new raster layer, where each cell's value represents the proportion of the sky visible from that location. Typically, the results are expressed in a range from 0 to 1, with a value of 1 indicating full visibility of the sky and 0 indicating total obstruction due to nearby structures as it was explained during previous chapters.

To perform the calculation, the software uses the elevation differences in the DSM or DEM, simulating a line-of-sight analysis from each cell to the surrounding area. This method considers the height of buildings and other structures that might block the view of the sky. As a result, cells with higher buildings surrounding them will have lower SVF values, while areas with fewer obstructions will have higher values.

Once the SVF values are calculated, they are stored in the raster's attribute fields, allowing for further analysis and visualization. The results can be displayed using a colour gradient after *Extracting Raster as Polygons* to represent various levels of sky visibility across the study area given in Annex 7. Areas with low SVF values typically indicate urban canyons or dense structures, while areas with higher SVF values may be more open or have fewer obstructions.

The SVF results are then used to inform decisions about adaptive façade strategies, urban planning, and microclimate improvements. In areas with low SVF values, adaptive facades could be employed to mitigate the effects of reduced sky visibility, such as incorporating shading elements, vegetation, or reflective materials. In contrast, areas with high SVF values could benefit from designs that make the most of available sunlight, potentially using passive solar heating or energy generation techniques like solar panels. Thus, SVF analysis in ArcGIS Pro offers valuable insights for designing buildings and environments that optimize comfort and energy efficiency based on the surrounding urban landscape.

5.6.8 Site Coverage Ratio

For Site Coverage Ratio (SCR) evaluation using ArcGIS Pro, the process has started with preparing the relevant datasets, specifically the land area and building footprint information. The first step involves importing the necessary spatial data, typically in the form of polygon shapefiles or feature classes, that represent the boundaries of the site and the building footprints. These datasets may be obtained through land use zoning maps, urban planning datasets, or remote sensing data, depending on the study area.

Once the data is loaded into ArcGIS Pro, the next step is to calculate the total land area of the site. This can be done using the *Calculate Geometry* tool, which is available in the attribute table of the site boundary feature class. This tool computes the area of each polygon in the dataset, and the result is stored in a new field that represents the total land area.

Similarly, for the buildings, the building footprints or the structures of interest are also calculated. The building polygons are selected and, again, the *Calculate Geometry* tool is used to calculate the area of each building footprint. This information is stored in the attribute table of the building feature class.

After obtaining the individual building areas, the next step is to summarize the building areas to obtain a total building area for the entire site. This can be done using the "Summarize" tool in ArcGIS Pro, where the tool aggregates the building areas and calculates a total sum for all the building footprints on the site.

Once the total building area and the total land area have been calculated, the Site Coverage Ratio (SCR) is derived by dividing the total building area by the total land area. This ratio provides a measure of how much of the site is occupied by buildings, which is an important metric in urban planning and environmental analysis.

Finally, the SCR value is recorded in Annex 8 and can be analysed to determine how dense the development is. For areas with high SCR values, meaning a substantial portion of the land is covered by buildings, strategies like adaptive facades with better thermal insulation, natural ventilation, or reflective materials might be considered to improve environmental comfort. In contrast, sites with lower SCR values, indicating more open space, may offer greater opportunities for incorporating green infrastructure, such as green walls or living facades, to mitigate urban heat effects.

By following these steps, ArcGIS Pro enables a detailed and methodical evaluation of the Site Coverage Ratio, providing valuable insights into the land use and urban density that can inform design and mitigation strategies.

5.6.9 Solar Radiation Area

Evaluation of solar radiation has been done by using the Land Surface Temperature (LST) raster in ArcGIS Pro, the process begins with obtaining the necessary LST data from Geoportale. The Solar Radiation tool requires a Digital Elevation Model (DEM) to simulate how solar radiation is distributed across the landscape with change of elevation across the canyon layer. The LST data is then incorporated into this model to refine the solar radiation calculation, as temperature variations can affect how solar radiation is absorbed by different areas. This means areas with higher surface temperatures, indicated by the LST data, may absorb more solar radiation.

To conduct the analysis, parameters such as the time of year, like July - 2024, DEM, and the area of interest are specified. The output from the Solar Radiation tool is a raster layer that shows how much solar radiation each part of the landscape receives as given in Annex 9. The LST data helps to adjust this model to reflect temperature differences, thus providing a more accurate view of solar radiation exposure.

The final results allow for better identification of areas that may need shading or thermal management and can be used to make informed decisions about solar panel placement, shading devices, or heat mitigation strategies. By combining LST data with solar radiation analysis in ArcGIS Pro, a more comprehensive understanding of how heat and solar radiation interact across a landscape is achieved, which is valuable for designing adaptive facades and improving thermal comfort.

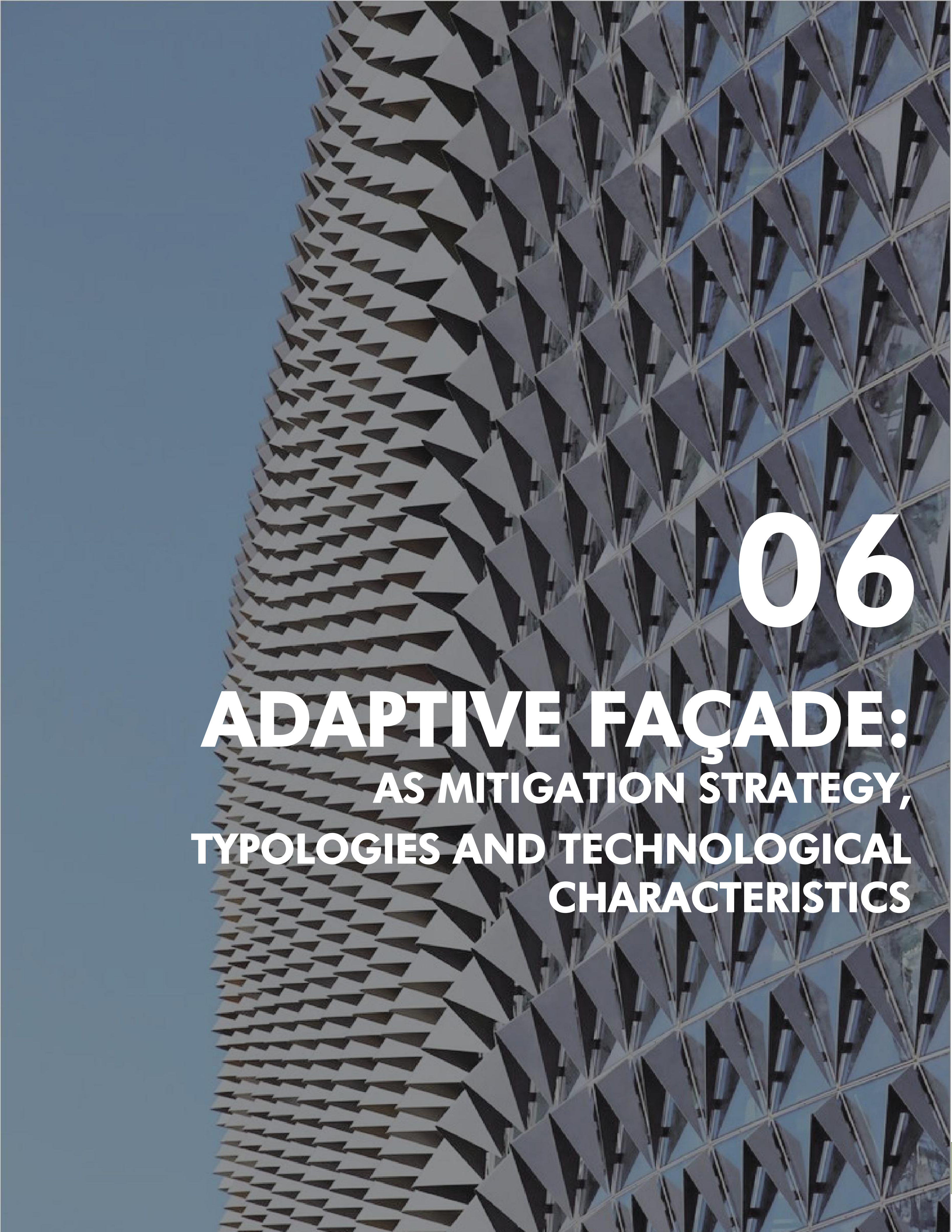
The analysis of various environmental factors in Area Bonadies and its surroundings provides a comprehensive understanding of the region's microclimatic conditions and highlights the need for adaptive facade solutions to address thermal discomfort, urban heat island effects, and energy efficiency concerns. The UTCI analysis demonstrates significant thermal stress, which is further exacerbated by high UHI intensity, indicating a need for facades that can mitigate heat absorption and promote cooling. The Land Surface Temperature analysis reveals areas with elevated temperatures, emphasizing the necessity for facades that enhance thermal insulation and shading.

In urban canyons, where the Canyon Verticality Ratio suggests high building density, adaptive facades must respond to solar exposure and enhance natural ventilation. The

NDVI analysis highlighted areas with limited vegetation, which could benefit from green facades to reduce heat island effects and improve air quality. Additionally, the Sky View Factor analysis points to regions with limited sky exposure, indicating a need for facades that facilitate better ventilation and shading.

The Site Coverage Ratio analysis suggests that densely built areas require facades that provide insulation, moisture control, and shading to mitigate thermal discomfort. Finally, the Solar Radiation analysis identifies areas with high solar exposure, where dynamic, solar-responsive facades such as BIPV systems could significantly reduce energy consumption.

Overall, the results from the various ArcGIS Pro tools can guide the selection of adaptive facade solutions. These solutions should focus on incorporating dynamic shading, green infrastructure, and energy-efficient materials to improve the urban microclimate, reduce energy consumption, and increase occupant comfort in Area Bonadies and its surroundings and it's surrounding areas. The analysis successfully identifies areas where adaptive facades can be deployed for maximum impact, offering a tailored approach to building design that responds to local environmental challenges.



06

ADAPTIVE FAÇADE:

AS MITIGATION STRATEGY, TYPOLOGIES AND TECHNOLOGICAL CHARACTERISTICS

6. ADAPTIVE FAÇADE: TYPOLOGIES AND TECHNOLOGICAL CHARACTERISTICS

As cities continue to grow and evolve, the need for sustainable architectural solutions becomes increasingly critical. One of the most pressing challenges is managing the urban microclimate, which results from the dense concentration of buildings, infrastructure, and human activity. This often amplifies environmental issues such as the Urban Heat Island (UHI) effect.

Adaptive facades - building skins that can respond to environmental changes—have emerged as a key innovation in addressing these urban climate challenges. These dynamic systems, which adjust in response to factors like temperature, sunlight, and wind, not only improve building energy efficiency but also help mitigate the negative impacts of the urban microclimate. By integrating advanced materials, sensors, and real-time responsiveness, adaptive facades offer an opportunity to create more climate-resilient urban environments.

This chapter explores the relationship between adaptive facades and urban microclimates, examining how these advanced systems can play a crucial role in improving the urban thermal environment, reducing energy demand, and enhancing outdoor comfort for occupants. The analysis conducted in previous studies helps identify which types of adaptive facade technologies are most suitable for specific locations, based on their unique climatic conditions.

6.1 URBAN AND ARCHITECTURAL DESIGN SOLUTIONS FOR UHI MITIGATION

Even though the urban heat island (UHI) effect has a significant impact on urban areas, there are strategies to reduce its effects and lessen the associated stresses. These strategies can aim to decrease heat generated by human activities, improve buildings, and enhance surface covers. Urban morphology can also be improved by adjusting the placement and orientation of buildings. These measures are useful not only for long-term urban planning but also for short-term interventions.

Urban and architectural design can help reduce UHI effects on the urban environment and improve microclimates in a positive way. The list of potential solutions is extensive and includes using light-coloured materials, installing solar shading devices, integrating vertical and horizontal greenery, enhancing energy efficiency, improving insulation to handle thermal stress, and applying innovative technologies for both buildings and urban services. As discussed earlier, UHIs can result from various factors, and addressing these can lead to specific actions to mitigate the problem. For instance, improving surface materials to reduce heat retention can help lower daytime temperatures. This includes greening the environment, using water-absorbing construction materials, applying reflective surfaces, and redesigning urban layouts based on careful analysis.

To develop a detailed set of mitigation measures for UHI, an analysis tables can be created to provide useful information, such as:

- The scale of the solution
- The duration of its effect on the microclimate
- Its effectiveness during day and night
- The type of stakeholders involved in solving the issue

N	Description	Scale	Period	Degree of Effect		Administered by
				Night	Day	
	IMPROVEMENT OF URBAN STRUCTURE					
1	Improvement of the orientation of buildings	City Blocks to Cities	Medium/Long	B	B	Local Governments
2	Improvement of land use	Cities	Long	A	A	Local Governments
3	Creation of eco-energy cities	Wards to Cities	Medium/Long	B	B	Local Governments
4	Creation of a recycling-based society	Wards to Cities	Long	B	B	Local Governments

N	Description	Scale	Period	Degree of Effect		Administered by
				Night	Day	
	IMPROVEMENT OF ARTIFICIAL SURFACES BY REDUCING SENSIBLE HEAT TRANSFER AND EXPANSION OF LATENT HEAT TRANSFER					
1	Improvement in the reflectivity and water-retentivity of paving materials	Cities	Short	B	B	Local Governments
2	Adoption of colored and permeable paving materials	Cities	Short	B	B	Local Governments
3	Greening	Wards to Cities	Medim/Long	A	A	
4	Greening of buildings and adoption of water-retentive materials (reduction of sensible heat)	Buildings	Short/Medium	A	A	Individuals, Business Institutions, Local Governments
5	Open water spaces	Wards to Cities	Medium/Long	B	A	Local Governments

N	Description	Scale	Period	Degree of Effect		Administered by
				Night	Day	
	REDUCTION AND/OR SUBSTITUTION OF ANTHROPOGENIC HEAT RELEASE					
1	Improvement in the efficiency of energy-using products	Individuals	Short	B	B	Individuals, business institutions, local governments
2	Improvement in the efficiency of air conditioning systems	Individuals	Short	B	B	Individuals, business institutions, local governments
3	Optimal operation of air conditioning systems	Buildings	Short	B	B	Individuals, business institutions, local governments
4	Improvement in the heat insulation and thermo-shield of buildings	Buildings	Short/Medium	A	A	Individuals, business institutions, local governments

5	High-performance heat insulation materials (interior heat insulation materials)	Buildings	Short/Medium	C	C	Individuals, business institutions, local governments
6	High-performance heat insulation and thermo-shield materials (exterior heat insulating materials)	Buildings	Short/Medium	A	D	Individuals, business institutions, local governments
7	Greening of buildings and adoption of water-retentive materials (Exterior heat insulating materials)	Buildings	Short/Medium	A	A	Individuals, business institutions, local governments
8	Light colored walls and highly reflective roofing materials	Buildings	Short	A	A	Individuals, business institutions, local governments
9	Introduction of traffic-control measures	Cities	Medium/Long	B	C	Individuals, business institutions, local governments
10	Introduction of district heating and cooling	City Blocks	Medium	A	A	business institutions, local governments
11	Use of untapped energy	City Blocks to Cities	Medium/Long	B	B	business institutions, local governments
12	Use of natural energy	Buildings to Cities	Short/Medium	B	B	Individuals, business institutions, local governments
13	Photovoltaic generation	Buildings to Cities	Short/Medium	B	B	Individuals, business institutions, local governments
14	Use of solar heat	Buildings to Cities	Short/Medium	B	B	Individuals, business institutions, local governments

Table 7. *Mitigation Measures*[57]

To improve the atmospheric layers and promote healthier urban spaces, adaptation processes need to be put in place. These processes focus on environmentally friendly changes, like creating climate-resilient spaces with appropriate infrastructure designs that can withstand various impacts, such as heatwaves, floods, storms, and droughts. Achieving these objectives requires the adoption of sustainable practices in urban development. This can include using energy-efficient materials, applying sustainable building technologies, and reducing environmental footprints by implementing eco-friendly transport systems, all of which contribute to better quality of life.

6.2 THE SYMBIOTIC RELATIONSHIP: ADAPTIVE FAÇADE AND URBAN MICROCLIMATE

The relationship between urban microclimate and adaptive facades is characterized by a dynamic interaction where each influences the other to enhance building performance and optimize energy use in an urban environment. Façade design and properties can't be only considered from building scale point of view, but also from urban. As its explained previous chapters, an urban microclimate refers to the localized climate conditions within a city, shaped by factors such as buildings, streets, vegetation, air pollution, and human activity. The microclimate within a city also varies based on factors like wind, temperature, humidity, and solar radiation, creating distinct microenvironments that influence design and comfort. Main aim and definition of an adaptive facades help buildings better and

[57] *Yamamoto, Y. (2006). Measures to Mitigate Urban Heat Islands. Environment and Energy Research Unit*

continuously respond to the microclimate within urban areas, contributing to more energy-efficient and comfortable environments. They mitigate the effects of extreme temperatures and other climate-related factors while improving sustainability in urban design. Design choices of an adaptive facades can be made based on urban climate analysis as was indicated in Application chapter.

From one perspective, due to their definitions, it may not be immediately clear how adaptive facades and design solutions influence the urban microclimate. However, the impact of these solutions can be quite extensive:

1. **Mitigating UHI –** potentiality to mitigate the urban heat island (UHI) effect, a phenomenon where cities experience elevated temperatures compared to surrounding rural areas due to the absorption of heat by buildings and infrastructure[58]. By adjusting their characteristics dynamically, such as increasing shading or reflecting sunlight, adaptive facades help to reduce heat gain both within buildings and in the surrounding environment[59]. For example, facades equipped with adjustable shading devices can block direct sunlight during warmer periods, thus preventing excessive heat absorption by building surfaces[60]. This not only lowers the internal temperature of the building but also reduces the amount of heat radiated into the urban surroundings, ultimately helping to moderate local temperature variations and alleviate the UHI effect[61].
2. **Improved Air Quality and Ventilation –** Adaptive facades can significantly improve air quality in the urban microclimate by responding to fluctuations in wind speed, direction, and air pollution levels. Some adaptive facades are designed with ventilated openings or integrated filtration systems that adjust automatically based on real-time environmental data, allowing the facade to optimize natural ventilation. This enhanced air circulation helps dilute pollutants and prevents the accumulation of heat and stagnant air around the building, thus improving both indoor and outdoor air quality. Such systems are particularly beneficial in densely built urban areas with limited green spaces, where the risk of air pollution and poor ventilation is high. By promoting better airflow, adaptive facades contribute to healthier environments for building occupants and the surrounding community[62].
3. **Solar Radiation and Shading –** To adjust their shading in response to the time of day or seasonal variations play a crucial role in regulating the amount of solar radiation entering a building. This dynamic adjustment not only enhances indoor thermal comfort but also influences the surrounding urban microclimate and outdoor thermal

[58] *Santamouris, M. Cooling the Cities – A Review of Innovative Technologies and Policies. Energy and Buildings, 2014*
[59] *Lazrak, N., Chabane, F. A., & Azzouz, M. Influence of Adaptive Facades on Urban Microclimates. Journal of Urban Planning and Development, 2020*
[60] *Erell, E., Pecker, A., & Shaviv, E. Urban Heat Island Mitigation: A New Tool for Achieving Sustainable Development. Environmental Science & Technology, 2011*
[61] *Wang, L., Yang, L., & Chen, Y. Mitigation of Urban Heat Island Using Smart Facade Design: A Review. Building and Environment, 2020*
[62] *Perez, G., Garcia, R., & Lopez, J. Ventilated Facades: A Sustainable Solution for Urban Air Quality. Sustainable Cities and Society, 2016*

comfort by reducing the amount of heat absorbed by building surfaces. By strategically blocking or reflecting sunlight, adaptive facades help manage the heat load within the building and its environment, preventing excessive heat buildup. This reduction in heat absorption can potentially lower overall urban temperatures, contributing to a more comfortable and sustainable urban environment[63].

4. **Wind and Precipitation –** Urban microclimates often experience localized wind patterns due to its environmental parameters and urban morphology, which can either improve or diminish outdoor comfort depending on their intensity and direction. Adaptive facades can address these variations in wind exposure by either channeling airflow around the building or providing shelter from strong winds, thus improving the comfort of the surrounding environment. In addition, adaptive facades can play a role in managing precipitation by redirecting rainwater or adjusting their surface properties to prevent unwanted moisture buildup inside the building or in nearby public spaces[64]. For example, in areas with high rainfall, facades that can adjust their angles or enhance their water-resistant properties help reduce water exposure and effectively manage stormwater runoff, reducing the risk of water damage[65].
5. **Energy Efficiency and Thermal Comfort –** In cities with fluctuating temperatures, adaptive facades optimizing indoor thermal comfort by responding to external weather conditions. These facades can adjust their insulation properties or modify ventilation openings, allowing for improved climate control within the building and reducing the need for mechanical heating or cooling systems. By minimizing reliance on energy-intensive HVAC systems, adaptive facades contribute to lower energy consumption, reduce greenhouse gas emissions, and promote a more sustainable urban environment[66]. As a result, these facades not only enhance the comfort of building occupants but also help regulate the local microclimate, fostering a healthier and more energy-efficient urban space[67].

Having established the significant role of adaptive facades in influencing the urban microclimate and promoting sustainability, it is important to delve into broader urban and architectural design solutions aimed at mitigating the urban heat island effect (UHI). The next chapter will focus to specific strategies and design approaches that can be employed at both the urban and architectural scales to address UHI. These solutions encompass a range of interventions, from green roofs and reflective surfaces to urban planning practices that prioritize vegetation, water management, and sustainable materials. By exploring

[63] *Maziarz, A., Kwiatkowski, M., & Zakrzewski, P. Solar Shading Systems: Improving Energy Efficiency and Reducing Urban Heat Island Effect. Energy and Buildings, 2018*
[64] *Benedetti, L., Ciuffo, B., & Gallo, M. Adaptive Facades for Improved Urban Resilience to Wind and Precipitation. Urban Climate, 2019*
[65] *Ceverino, C., Sosa, M., & León, R. The Role of Building Envelopes in Managing Stormwater Runoff and Wind Exposure. Building and Environment, 2018*
[66] *Zhang, X., Zhang, L., & Liu, W. Adaptive Facades for Energy Efficiency and Thermal Comfort in Urban Buildings. Energy and Buildings, 2017*
[67] *Lima, A., Ferreira, L., & Silva, A. The Role of Adaptive Facades in Improving Urban Energy Efficiency. Journal of Green Building, 2016*

these solutions, we can gain a deeper understanding of how cities can be reimagined to reduce the impacts of UHI, enhance environmental quality, and create healthy environments for inhabitants.

6.3 THE ROLE OF BUILDING FAÇADE

The exterior design of a building is crucial for its overall performance, contributing significantly to interior comfort and energy efficiency. As the focus on energy conservation increases, there is an urgent demand for sophisticated exterior systems. Scientists are exploring adaptable building exteriors that can respond dynamically to changing outdoor weather patterns and changing indoor requirements.

These flexible systems allow for continuous improvement, balancing external environmental conditions with the internal comfort requirements of buildings, and ensuring sustainability, at least on a local urban level. In doing so, they can significantly reduce energy consumption and reliance on energy-intensive mechanical systems while preserving a desirable indoor and outdoor environment. Moreover, building façades play a crucial role in shaping both the aesthetic and functional aspects of a structure, impacting the surrounding area by influencing views, daylighting, air circulation, and overall occupant well-being.

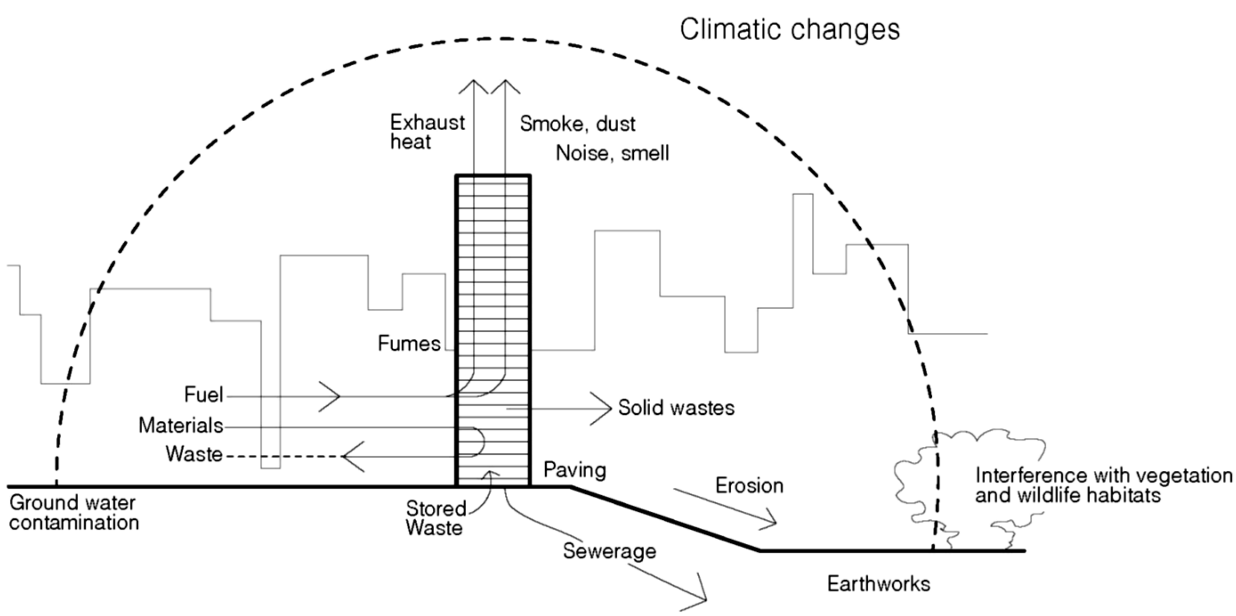


Figure 37. Building environment impacts on its surroundings
Source: Yeang, The Green Skyscraper, 2000

Façade design follows a systematic approach involving multiple stages: conceptualization, specification of functional and technical needs, thorough design, coordination of implementation, and construction. Ongoing feedback is essential throughout these phases to ensure that the facade meets the overall design goals and effectively integrates with the building's architectural, structural, and service components. The importance of the facade goes beyond aesthetics; it plays a crucial role in the entire building process, influencing design choices, and affecting operational performance.

6.3.1 Façade as Part of Building Envelope

The building envelope or enclosure can be defined simply as the barrier between a structure's interior, climate-controlled area and its exterior, unregulated environment. Elements typically considered part of envelopes or enclosures include:

- Foundations
- Floors
- Ceilings
- Walls
- Façades
- Windows and Doors
- Roofs

Figure 38. *Simple building envelope components*
Source: Iko Commercial - Simple Building Envelope

The concept of building envelopes has been analyzed from several perspectives. The definition of a building envelope by the City of Bremerton, Washington, is "the three-dimensional space within which a structure is permitted to occupy. Height, floor area ratio, setbacks, lot coverage, and similar restrictions establish the building envelope'. On the contrary, D. Bixby defined it as "The exterior appearance that we first see of a building… the boundary that separates the building from the space around it" Nevertheless, the fact is that first appearance of what we see on the building is defined as a facade. A facade specifically refers to the exterior face or surface of a building, particularly the front or main side, which is often designed for visual impact and does not include other building elements. While the façade is primarily concerned with the visual and functional aspects of the building's exterior, the building envelope emphasizes the technical performance and environmental control of the entire external enclosure system. Both are interdependent, as the façade relies on the robustness of the building envelope to deliver its intended performance goals, while the façade contributes to the overall performance of the building envelope.

The building envelope, as defined by the U.S. Department of Energy, is the component that separates conditioned spaces from unconditioned spaces or outside air. It plays a crucial role in protecting inhabitants from environmental factors like extreme temperatures, water, and pollutants. M. Wigginton and J. Harris describe the envelope as the outer layer that shields a building from environmental forces, ensuring comfort and privacy. They further characterize it as the "intelligent skin" that controls light, heat, sound, ventilation, and air quality inside a building. C. Schittich views the envelope as a transition between the building and urban space, emphasizing its role in regulating the internal environment.

The building envelope serves two main functions: it is influenced by its material composition and spatial context, and it ensures internal comfort, covering thermal, acoustic, visual, and olfactory well-being. There are four types of building envelopes: Conservative (energy efficiency with conventional materials), Selective (manages energy flows actively), Regenerative (produces energy and benefits ecosystems), and Adaptive (smart or dynamic systems that adjust to enhance internal comfort and minimize energy use).

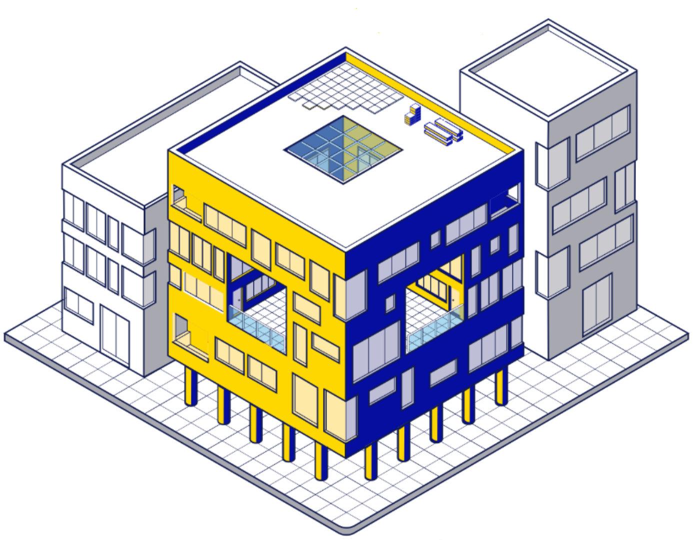


Figure 39. *Building envelope graphical representation*
Source: Made Expo

The facade is a critical part of the envelope, acting as a mediator between the internal and external environments. It impacts energy efficiency and urban microclimates, addressing challenges like heat transfer, moisture control, solar radiation, and noise. Adaptive facades can adjust to changing conditions, addressing these challenges while enhancing building performance. While the concept of adaptive facades is still developing, they are seen as flexible systems that can change in shape, location, and configuration to meet the building's needs. Terms like "adaptive," "smart," and "interactive" are often used interchangeably but require clearer definitions to better understand their implications in building design.

6.3.2 Technological Evolution of Adaptive Facade

The history of adaptive facades can be traced back to various technological advancements and architectural innovations aimed at enhancing building performance and occupant comfort. These facade systems emerged as a response to the increasing need for energy-efficient building designs, particularly in the context of sustainability and environmental stewardship.

Early developments in facade technology included the introduction of high-performance glazing systems, such as triple and quad glazing, which became standard in Europe due to stringent building codes. However, the adoption of similar technologies in other regions, like the U.S., faced resistance due to economic concerns and industry pushback against the higher costs associated with these advancements.

The origins of adaptive facades can be linked to numerous technological developments and architectural breakthroughs designed to improve building efficiency and user comfort. These innovative facade systems were developed in response to the growing demand for energy-efficient building designs, particularly considering sustainability concerns and environmental responsibility.[68]

Facade technology saw significant progress with the advent of high efficiency glazing systems, such as triple and quad glazing, which became commonplace in Europe due to rigorous building regulations. However, the uptake of these advanced technologies in other regions, including the United States, met with resistance, primarily due to economic factors and industry opposition to the higher costs associated with implementing these innovative solutions.

Traditional farmhouses, despite their era's constraints, had already maximized energy conservation. They utilized livestock-generated heat for warming and employed materials like straw and hay for both bedding and insulation. Their windows featured folding shutters that created a thermal buffer between the glass and shutter at night, resembling a double-skin facade. This construction method persists in alpine regions today. Double-skin structures remain one of the most used functional principles for protecting against external environmental factors through the facade envelope. Before insulated glass was developed, a second window was installed to use the space between two windows as a thermal buffer. This box window configuration, combining two single glass panes, produces higher insulation values and can be adjusted to suit current weather conditions. As glass usage increased in modern times, problems with excessive cooling in winter and overheating in summer became more prevalent.

In 1929, Le Corbusier introduced a concept for a building envelope that positively impacted indoor climate in his work "Precisions: On the Present State of Architecture and City Planning". He proposed the idea of the 'mur neutralisant' or neutralizing wall. Although Le Corbusier's ideas were ahead of their time and never fully implemented, his concept can be viewed as a predecessor to the exhaust-air facade. This facade type regulates the environment of usable spaces independently of exterior conditions by combining a double-skin structure with an air-conditioning unit.

[68] *Smith, J., & Johnson, A. Advancements in Building Facade Technologies: History and Future Trends. Architectural Press., 2019*

"We have seen that these neutralizing walls are in glass, in stone, or in both. They are made up of two membranes with a space of a few centimeters between them. [...]"

"The house is sealed fast! No dust can enter it. Neither flies nor mosquitos. No noise! "

Contemporary environmental design utilizes the space between facade layers to establish a buffer zone, creating an intermediate environment that bridges the interior and exterior. An alternative approach views the facade as a regulatory layer, like a filter, positioned between the inside and outside. This layer enables the exchange of environmental conditions through the facade based on specific needs. These structures, referred to as collector facades, primarily harness environmental energy through passive methods and engage with the external climate within their outer shell.

During the 1940s, Buckminster Fuller conceived ideas for a dome-like structure that would serve as an outer shell, creating a self-contained microclimate using only passive methods. The structure's cooling, ventilation, and heating were to be achieved solely through the interaction of wind and sun with the envelope. Although these innovative concepts were never implemented, they paved the way for the advancement of solar architecture in the United States throughout the 1960s and 1970s, primarily manifesting as environmentally friendly single-family homes featuring solar facades and collectors. In 1981, Mike Davies introduced the concept of a polyvalent wall, which incorporated multiple functional layers within a glass component to provide protection from sun and heat, and automatically adjust its functions based on current conditions. The wall was designed to generate its own energy. The term 'intelligent facade' originated from this polyvalent wall concept, which has been instrumental in driving new facade technologies over the past two decades. The 1972 oil crisis and the subsequent recognition of resource limitations led to considerations of harnessing the energy from solar radiation falling on facade surfaces. These developments resulted in the environmentally conscious building movement of the 1980s, which gave rise to collector facades that actively produce energy.

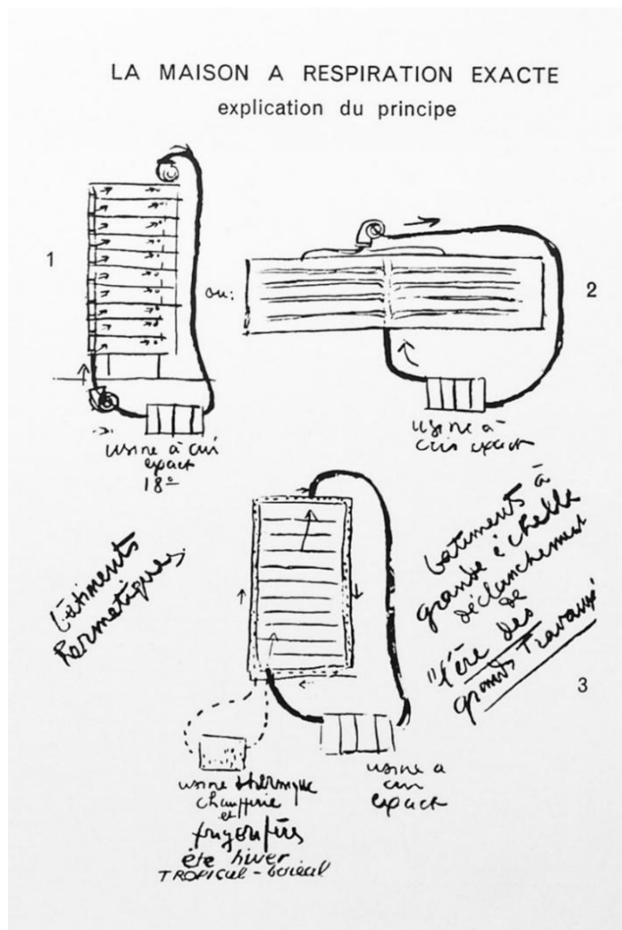


***Figure 40**. Mur neutralisant, Le Corbusier conceptual representation of Adaptive Facade*

Historically, most studies have concentrated on flat facades, neglecting any complexities and interactions with urban layouts. With the development of different façade typologies, also their effects not only on indoor spaces but also, on outdoor thermal environments became obvious. Nowadays, designing urban façade represents a transformative approach in architectural design, emphasizing sustainability, user comfort and energy efficiency, which is also known as concept of Paradigm Shift[69]. These shift moves from traditional static designs to dynamic systems that continuously and repeatedly responds to environmental conditions, while enhancing building performance and occupants experience.

6.4 LEVERAGING ENVIRONMENTAL ANALYSIS FOR ADAPTIVE FAÇADE DESIGN IN URBAN ENVIRONMENTS

In the context of rapid urbanization and the escalating challenges posed by climate change, adaptive building designs have become essential for ensuring energy efficiency, occupant comfort, and environmental sustainability. Among the various elements that contribute to the overall performance of modern architecture, the façade plays a pivotal role in managing heat gain, natural lighting, ventilation, and overall energy consumption. To design facades that effectively respond to the dynamic environmental conditions of a specific site, urban planners and architects must consider a range of factors influencing the local microclimate.

This chapter delves into the integration of several key environmental parameters, including Sky View Factor (SVF), Universal Thermal Climate Index (UTCI), Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), Site Coverage Ratio, Canyon Verticality Ratio, Solar Radiation, Wind Analysis, and Shadow Analysis, which can be obtained during the application phase using tools like ArcGIS Pro. By harnessing spatial data and advanced modelling techniques, these parameters offer a comprehensive understanding of the microclimate, enabling the design of facades that respond intelligently to solar exposure, wind patterns, temperature fluctuations, and shading needs. The chapter outlines the methodology for analysing these factors and demonstrates how the insights derived from this analysis can inform the selection of appropriate façade technologies to optimize building performance and enhance urban resilience.

Among the various adaptive façade solutions available, Building-Integrated Photovoltaics (BIPV), dynamic shading systems and green façades have been chosen for their unique ability to address multiple environmental challenges simultaneously. BIPV systems not only generate renewable energy but also contribute to thermal insulation, reducing heating and cooling demands. Dynamic shading systems, on the other hand, provide real-time control over solar heat gain and daylight penetration, optimizing indoor comfort and reducing energy consumption. Green façades offer a natural solution for cooling through evapotranspiration, reduce the urban heat island effect, and improve air quality by filtering pollutants. Together, these solutions are particularly effective in addressing the multifaceted

[69] *Thomas S. Kuhn. (1962). "The Structure of Scientific Revolutions"*

issues associated with climate change, urban heat islands, and energy efficiency, making them optimal choices for adaptive façade designs. Through solar energy generation, adaptive shading, and natural cooling processes, these façades contribute to reducing heat gain, mitigating the urban heat island effect, and improving overall outdoor and indoor thermal comfort, thereby fostering more resilient and sustainable urban environments.

6.4.1 UTCI and LST Data: Dynamic Shading Systems as a Mitigation Strategy

As it resulted Area Bonadies and its surroundings and it's surrounding areas experiences significant thermal stress, as indicated by high UTCI values, signaling discomfort common in hot climates. In response, facade design must focus on reducing solar heat gain while ensuring sufficient natural daylight. Dynamic shading systems, such as motorized louvers, retractable blinds, and electrochromic glazing, offer an effective solution. These systems adapt to changing environmental conditions, providing flexibility beyond passive shading methods. By adjusting the position or opacity of shading elements based on solar exposure and UTCI values, dynamic shading can reduce reliance on mechanical cooling, particularly in hot regions.

Motorized louvers and retractable blinds adjust throughout the day, providing shading during peak heat while allowing daylight when temperatures are cooler. These systems can be controlled manually or automatically through sensors detecting solar radiation. Electrochromic glazing, which changes its optical properties in response to an electric charge, can further enhance facade performance by reducing solar heat gain and glare, thus maintaining a comfortable indoor environment.

In areas with high UTCI values, dynamic shading systems are particularly effective. They reduce solar radiation entering the building, decreasing the need for air conditioning, lowering energy costs, and improving building sustainability. Additionally, by allowing daylight while controlling heat gain, these systems enhance indoor visual comfort, a crucial aspect of thermal comfort in building design.

Electrochromic Glazing

Electrochromic glazing (ECG) is a type of dynamic glazing that changes its optical properties in response to an electric charge. This innovative technology allows the glass to transition from transparent to tinted, adjusting its light transmission based on real-time sunlight intensity. The tinting process is controlled by sensors that detect solar radiation, enabling ECG to optimize the amount of light and heat entering a building. As a result, electrochromic glazing enhances energy efficiency, improves thermal comfort, and contributes to more sustainable building designs by dynamically adapting to changing environmental conditions like:

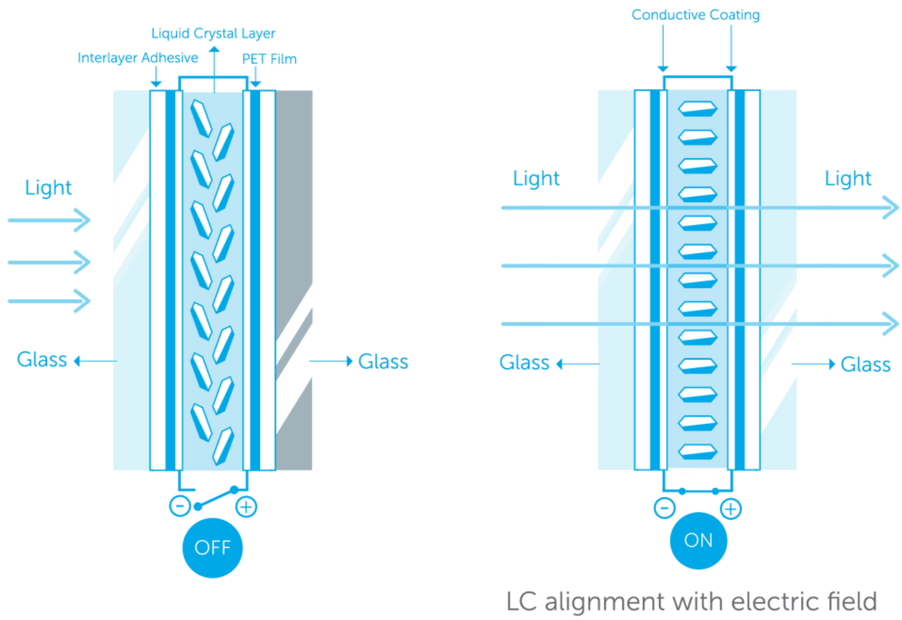


Figure 41. *How Does Electrochromic Glass Work*
Source: PDLC Smart Glass

1. **Reducing Solar Heat Gain**: Electrochromic glazing can dynamically adjust its tint in response to sunlight, reducing the amount of solar radiation entering the building. In doing so, it helps regulate the indoor temperature and prevents overheating, which is particularly important in environments with high outdoor temperatures as it had resulted during application phase. This directly impacts the mean radiant temperature component of the UTCI, reducing the heat load on the body and improving comfort. Studies[70] have shown that electrochromic windows can reduce the amount of solar heat gain by up to 70% in some cases. The reduction in solar heat gain can lower the radiant temperature component, leading to a better thermal comfort experience and lower UTCI.

2. **Improving Thermal Comfort in Mixed-Use Spaces**: Electrochromic glazing can improve comfort in mixed-use spaces, particularly when the glass adjusts to mitigate heat gain or loss based on the outdoor weather. This dynamic control of solar radiation and heat allows the interior environment to remain more comfortable, which in turn impacts UTCI by reducing the discrepancy between indoor and outdoor conditions. According to one of research[71] adaptive glazing can reduce the peak temperature in indoor environments by up to 4°C, which directly improves thermal comfort. By reducing temperature extremes, UTCI becomes more favourable, as lower radiant temperatures are associated with better comfort.

[70] Lappalainen, A., et al. "Energy-efficient electrochromic windows for controlling solar heat gain and daylight in buildings." Energy and Buildings, 2014
[71] Blanco, A., et al."Thermal and daylighting performance of electrochromic glazing: A review of simulation studies and building performance." Renewable and Sustainable Energy Reviews, 2020

3. **Reducing Energy Consumption for HVAC Systems**: By minimizing the need for air conditioning or heating (due to reduced solar heat gain in summer and heat loss in winter), electrochromic windows can help maintain a stable indoor environment. This indirectly contributes to better UTCI, as the reduced need for mechanical climate control means that indoor conditions are more likely to align with human thermal comfort preferences without drastic fluctuations. As a fact, Electrochromic windows can reduce the energy required for heating and cooling by up to 30%, which helps in stabilizing indoor temperatures. This stabilizes the indoor microclimate, leading to more comfortable conditions and better UTCI values[72].

4. **Enhancing Visual Comfort**: Another key aspect of electrochromic glazing is its ability to adjust to various light levels, reducing glare and maintaining appropriate lighting conditions indoors. Since visual comfort contributes to overall comfort, electrochromic glazing can ensure that the indoor lighting remains within optimal levels, indirectly impacting UTCI, especially when glare is reduced in the summer months. With the ability of electrochromic windows to control visible light transmittance (VLT) helps mitigate glare and ensures more consistent interior lighting, which is an important factor in thermal comfort as well. A study by Boubekri et al. (2016)[73] indicated that controlling glare can improve subjective thermal comfort in office environments.

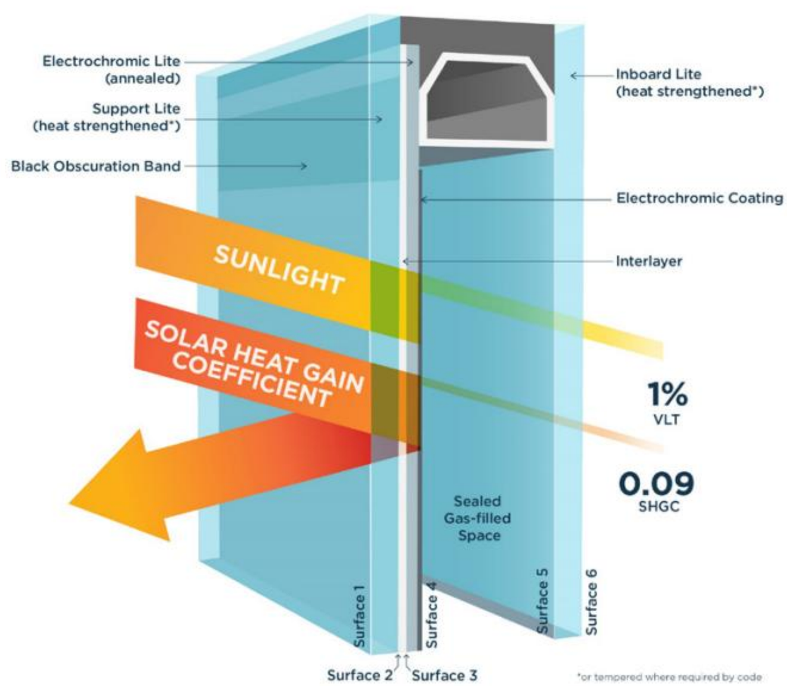


Figure 42. *Smart windowpane construction*
Source: Sage Glass

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[72] *Tian, W., et al. (2019). "Energy performance of electrochromic windows in a building: Simulation and experimental study."*
[73] *Boubekri, M., et al. (2016). "The impact of windows and daylight exposure on human health and well-being." International Journal of Environmental Research and Public Health*

Electrochromic glazing (ECG) offers a significant impact on improving outdoor thermal comfort by dynamically adjusting its optical properties in response to solar radiation. When tinted, ECG reduces the amount of solar radiation entering buildings, directly lowering radiant temperatures in outdoor environments. This is particularly valuable during summer months, when excessive solar heat gain can increase outdoor temperatures and lead to discomfort.

Simulation models such as Energy Plus and TRNSYS are commonly used to assess the performance of ECG in controlling solar heat gain, factoring in parameters like Solar Heat Gain Coefficient (SHGC) and U-value (thermal transmittance). These models help evaluate how ECG can influence outdoor thermal comfort by reducing the amount of heat absorbed by buildings and mitigating the urban heat island effect.

In conclusion, ECG contributes to outdoor thermal comfort by actively controlling heat absorption and reducing the radiative load from buildings, leading to more favourable outdoor conditions. As ECG dynamically adjusts to solar intensity, it minimizes heat buildup and lowers Land Surface Temperature (LST), enhancing comfort and sustainability in outdoor spaces. By improving the microclimate in urban areas, ECG provides a more comfortable outdoor environment and helps combat the negative effects of overheating.

Motorized Louvers

In recent years, the demand for energy-efficient and sustainable building designs has led to the development of various technologies aimed at improving indoor and outdoor thermal comfort. One such innovation is the use of motorized louvres, a dynamic shading system that offers significant benefits for managing solar heat gain, enhancing natural ventilation, and improving thermal comfort in both residential and commercial buildings. Motorized louvres consist of adjustable slats or blades that can be controlled to regulate the amount of sunlight entering a space, thereby reducing reliance on air conditioning and heating systems.

Figure 43. *Corten Honeycomb Louvres*
Source: Glasscon CHL

This chapter delves into the functionality and advantages of motorized louvres, with a focus on their impact on outdoor thermal comfort. Specifically, we will explore how these systems contribute to the reduction of radiant temperature, the improvement of LST, and the enhancement of UTCI ratings. By responding to changing environmental conditions such as solar radiation, temperature, and wind, motorized louvres play a crucial role in improving the microclimate around buildings and reducing the effects of the urban heat island (UHI) phenomenon.

1. **Solar Heat Gain and Radiant Temperature Control**: One of the primary functions of motorized louvres is to reduce solar heat gain by adjusting the angle of the slats to block or allow sunlight to penetrate a space. This adjustment directly impacts the radiant temperature of the surrounding outdoor environment. When the louvres are positioned to block sunlight, they lower the amount of heat absorbed by surfaces such as building façades and pavements, which in turn reduces the radiant temperature that contributes to high UTCI values. Studies have demonstrated that well-placed and appropriately adjusted louvres can reduce surface temperatures by up to 4°C, improving outdoor comfort during hot days[74].
2. **Effect on Land Surface Temperature (LST):** By regulating the amount of solar radiation absorbed by building surfaces, motorized louvres can reduce the LST a critical factor in urban heat island (UHI) mitigation. The ability to dynamically adjust shading helps prevent excessive heat buildup in urban areas. Research has shown that motorized louvres can reduce LST by effectively shading building surfaces during peak sunlight hours, leading to cooler surroundings and reducing heat stress[75]. This reduction in LST contributes to overall outdoor comfort, particularly in urban environments where hard surfaces tend to absorb and re-radiate heat.
3. **Improvement of UTCI**: As known UTCI is a widely used measure for assessing outdoor thermal comfort, factoring in air temperature, humidity, wind speed, and radiant temperature as discussed previous chapters. Since motorized louvres can lower radiant temperatures by blocking or reflecting solar radiation, they directly influence the radiant temperature component of UTCI. Studies have indicated that shading from motorized louvres can decrease UTCI values by up to 3-5°C in areas with high solar exposure, thereby improving thermal comfort[76]. By reducing radiant heat, motorized louvres help prevent discomfort caused by high thermal radiation, especially in outdoor spaces like terraces, courtyards, and streets.
4. **Wind and Airflow Regulation**: Another aspect of motorized louvres is their ability to influence airflow around buildings. When tilted correctly, motorized louvres can facilitate air circulation, providing natural ventilation that enhances thermal comfort. For example, in warm environments, the louvres can be adjusted to allow cool

[74] *Jiang, W., Li, X., & Zhang, Y. (2019). "Effectiveness of shading devices for reducing radiant temperature in urban environments." Energy and Buildings*
[75] *Oke, T. R. (2006). Urban Climates*
[76] *Givoni, B. (2011). Climate Considerations in Building and Urban Design*

breezes to flow through, improving convective heat transfer and lowering air temperature. This aspect has been highlighted in studies[77] which demonstrates that motorized louvres improve outdoor thermal comfort by dynamically adjusting to control solar heat gain and enhance natural ventilation. These adjustments optimize air movement and reduce radiant heat, contributing to a more comfortable and energy-efficient microclimate, particularly in urban heat island areas.

The effectiveness of motorized louvres in improving outdoor thermal comfort has been demonstrated through several studies. A study by Santamouris et al. (2018)[78] showed that dynamic shading systems, including motorized louvres, led to a 2°C reduction in the surrounding urban temperature in Mediterranean cities. This reduction in ambient temperature significantly impacts Land Surface Temperature LST and UTCI thereby improving outdoor comfort in densely built environments. Furthermore, research conducted by Miller et al. (2017)[79] assessed the performance of motorized louvres in hot climates, finding a notable reduction in UTCI values-up to 4°C-when the louvres were used to block direct sunlight during midday hours. When combined with natural ventilation, this system helped maintain a more comfortable outdoor environment, even in the face of high outdoor air temperatures.

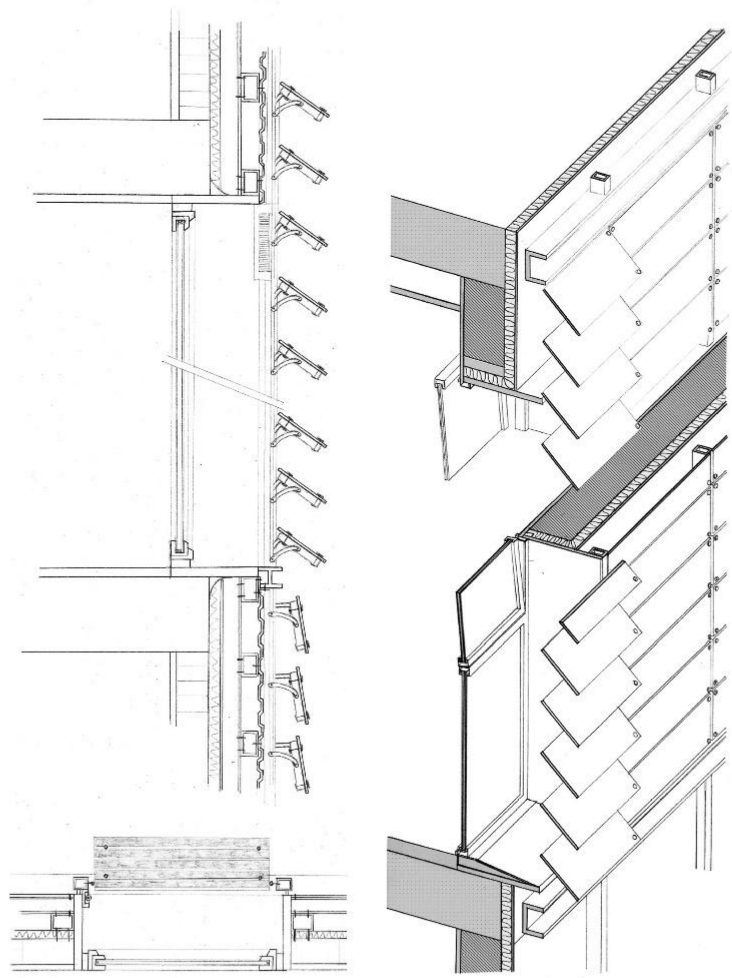

Figure 44. Motorized Louvres detail
Source: filt3rs.net.

Overall Motorized louvers can reduce heat gain by up to 60% during peak solar hours, especially when the sun is directly overhead[80]. This reduction in solar heat gain directly mitigates high UTCI values by lowering indoor temperatures. Like electrochromic glazing, motorized louvers often integrate with an automatic control system that adjusts the slats based on

[77] *Arpaci, M. A., & Yılmaz, Z. (2017). "Performance of motorized louvres in enhancing outdoor air movement and thermal comfort." Building and Environment*
[78] *Santamouris, M., et al. (2018). "Urban heat island mitigation through dynamic shading systems." Environmental Research Letters*
[79] *Miller, W., Davies, H., & Knox, R. (2017). "Improvement of UTCI through shading in hot climates." Building Research and Information*
[80] *Park, Y. J., Lee, S. H., & Ryu, H. S. (2019). Energy performance of adaptive shading systems for building facades in hot climates. Building and Environment*

sunlight intensity. For instance, at noon during the summer, the system can fully close the louvers to block direct sunlight, then gradually open them as the sun sets to allow for natural light and reduce artificial lighting needs[81].

Motorized louvres are effective in improving outdoor thermal comfort by controlling solar heat gain, reducing radiant temperatures, and mitigating Land Surface Temperature (LST), especially in urban environments. By dynamically adjusting to solar conditions, they enhance airflow and lower UTCI and LST, making them a key tool in addressing the Urban Heat Island (UHI) effect and improving outdoor comfort.

Combination of Motorized Louvres and ECG

The combined use of electrochromic glazing and motorized louvers significantly mitigates high UTCI values in hot climates. For instance, in a building exposed to intense solar radiation between 11 a.m. and 4 p.m., the combined effect of these shading systems can be observed in the following way:

Before activation of the shading systems, the UTCI might reach 40°C, indicating strong thermal discomfort due to high solar radiation and air temperature. Under these conditions, the indoor temperature would likely be around 30°C, requiring air conditioning to maintain comfort. However, when the electrochromic glazing and motorized louvers are activated, the UTCI can be reduced to 32°C, thus alleviating outdoor thermal discomfort. Simultaneously, the indoor temperature can drop to 26°C, reducing the cooling load by up to 20%. This reduction in both UTCI and indoor temperature illustrates how the combination of electrochromic glazing and motorized louvers can effectively mitigate heat stress, enhance occupant comfort, and reduce the reliance on mechanical cooling (Park et al., 2019).

Another factor as Land Surface Temperature (LST) is a key indicator of outdoor thermal comfort, especially in urban areas affected by heat islands, where high LST values indicate increased thermal stress. In these areas, adaptive facades offer an effective solution to improve outdoor thermal comfort by reducing solar heat gain and minimizing the impact of high temperatures. ArcGIS Pro has been used to analyse LST data and give results as indicated in Annex 4 to integrate it with other environmental factors to design facade systems that respond dynamically to changing outdoor conditions.

Adaptive facades, such as motorized louvers, retractable blinds, and electrochromic glazing, can be strategically employed to mitigate the effects of high LST also. By incorporating adaptive facades, particularly those that dynamically adjust to solar exposure, urban environments with high LST values can experience a significant reduction in thermal discomfort. These facades prevent excessive solar radiation from heating the surroundings, mitigating heat island effects and enhancing overall liability. Using LST data in ArcGIS Pro, facade solutions can be tailored to specific environmental conditions, ensuring that both building energy efficiency and outdoor thermal comfort are optimized. In this

[81] *Santamouris, M. (2014). Cool roofs: The state of the art-2013. Energy and Buildings*

way, adaptive facades offer an essential strategy for improving urban environments impacted by high surface temperatures.

The integration of electrochromic glazing and motorized louvers offers a highly effective adaptive shading solution for mitigating the effects of high UTCI and LST values in hot climates. These dynamic systems help reduce solar heat gain, lower indoor temperatures, and improve occupant comfort by responding to real-time environmental conditions. Electrochromic glazing reduces solar heat gain by up to 80%, while motorized louvers cut heat gain by up to 60%, which significantly reduces the need for air conditioning. Incorporating these systems into building facades enables architects and urban planners to design more energy-efficient and comfortable buildings in regions prone to high thermal discomfort, as indicated by elevated UTCI values. Integrating UTCI and LST data into the design and optimization of these systems through ArcGIS Pro allows for a data-driven approach to facade design, ensuring that shading strategies are tailored to the specific climatic and environmental conditions of each site. This approach not only improves thermal comfort but also contributes to the overall sustainability and energy efficiency of buildings in urban environments.

6.4.2 Understanding Green Façades as an Outcome of NDVI Analysis

Green facades, or living walls, are an increasingly adopted solution for improving outdoor environmental conditions in urban areas, particularly in terms of mitigating the urban heat island (UHI) effect, enhancing air quality, and promoting biodiversity. These systems utilize plant growth on vertical surfaces, offering a multifunctional approach to environmental enhancement by reducing solar heat gain, improving energy efficiency, and improving the surrounding microclimate, one of good solutions for Area Bonadies and its surroundings and it's surrounding areas, which has indications of low and moderate vegetation indexes according to NDVI analysis.

Green façades, characterized by the vertical integration of plant life onto building surfaces, have gained increasing attention as a sustainable strategy to enhance urban environments. The Normalized Difference Vegetation Index (NDVI), a remote sensing tool, is commonly employed to quantify and analyze vegetation cover, including green façades, by measuring the difference between near-infrared and visible light reflected by vegetation. NDVI analysis provides valuable insights into the density, health, and distribution of plant life on building surfaces, allowing for the evaluation of green façades potential to mitigate the urban heat island (UHI) effect and improve outdoor thermal comfort. NDVI analysis enables precise identification of green façade areas, facilitating the monitoring of vegetation growth and coverage over time. High NDVI values typically correspond to areas with denser and healthier vegetation, which provides significant cooling effects by reducing LST and increasing evapotranspiration. This cooling effect occurs as plants on green façades absorb solar radiation, release moisture into the atmosphere, and provide shade, thereby lowering the surrounding ambient temperature[82].

[82] *Getter, K. L., & Rowe, D. B. (2006). The role of green roofs in sustainable development*

Technically, green façades contribute to outdoor thermal comfort through several mechanisms. One of the main cooling effects comes from evapotranspiration, where plants release water vapor into the atmosphere. This process requires energy, which is drawn from the surrounding heat, thereby lowering the local temperature. Additionally, plants on green façades provide shading, reducing the direct impact of solar radiation on building surfaces and the surrounding area. As a result, LST can be significantly reduced, leading to a more comfortable outdoor climate, particularly during hot summer months.

Several studies have demonstrated the positive impact of green façades on thermal comfort, that can be distinguished in several key mechanisms as:

1. **Evapotranspiration:** Plants on green façades release moisture into the air through evapotranspiration, a process in which water absorbed by the roots is released as vapor from the leaves. This cooling process requires energy, which is drawn from the surrounding air, leading to a reduction in local temperature. Research has shown that evapotranspiration from vegetation can reduce ambient temperatures, improving outdoor thermal comfort, particularly in hot climates[83].
2. **Shading:** Green façades provide shading to building surfaces and their surroundings, preventing direct solar radiation from heating up the building's exterior and the ground around it. This is particularly important in reducing LST which can significantly influence outdoor thermal comfort. Plants effectively reduce the heat absorbed by surfaces such as walls, pavements, and roads, lowering the intensity of the urban heat island effect (Santamouris et al., 2018).
3. **Reduction of Radiant Heat:** By acting as a physical barrier between the sun and the building, green façades absorb and reflect less solar heat compared to traditional building materials. This process reduces the amount of heat radiated back into the surrounding environment, directly mitigating radiant heat and lowering the risk of thermal discomfort in outdoor areas[84].
4. **Improved Airflow and Ventilation:** The vertical structure of green façades allows for improved natural ventilation, helping to dissipate heat from the surrounding air. Enhanced airflow around the building reduces the buildup of heat and promotes the cooling effect. This natural ventilation also helps to improve the microclimate, making outdoor spaces more comfortable, particularly in dense urban areas[85].
5. **Albedo Effect:** The albedo or reflectivity of surfaces plays a significant role in determining how much heat is absorbed by the environment. Green façades, with their dense plant cover, reflect more sunlight than typical building materials, reducing the amount of heat absorbed. By increasing the reflectivity of building surfaces,

[83] *Getter, K. L., & Rowe, D. B. (2006). The role of green roofs in sustainable development. Hort Science*
[84] *Yang, J., et al. (2014). The impact of urban green spaces on outdoor thermal comfort and UHI. Urban Forestry & Urban Greening*
[85] *Tzoulas, K., et al. (2007). Promoting ecosystem and human health in urban areas using green infrastructure. Biodiversity and Conservation*

green façades contribute to cooler outdoor temperatures and better thermal comfort[86].

By combining these mechanisms, green façades effectively lower the ambient temperature, enhance air movement, and reduce radiant heat, all of which improve outdoor thermal comfort, particularly in urban environments where high temperatures and the urban heat island effect are common challenges.

The thermal benefits of green facades are well-documented. Plants absorb and deflect solar radiation, thus reducing the amount of heat transferred into a building and contribute to cooler outdoor temperatures. For example, a study by Villarreal & Bengtsson (2004) demonstrated that green facades can reduce solar heat gain by up to 50%, depending on the plant species, wall structure, and local climate. This is crucial in densely populated urban areas where traditional building materials exacerbate the heat island effect. The cooling effect of the plants can also extend to the surrounding environment; research has shown that green facades can reduce ambient air temperatures by as much as 4-5°C in areas with high vegetation density[87].

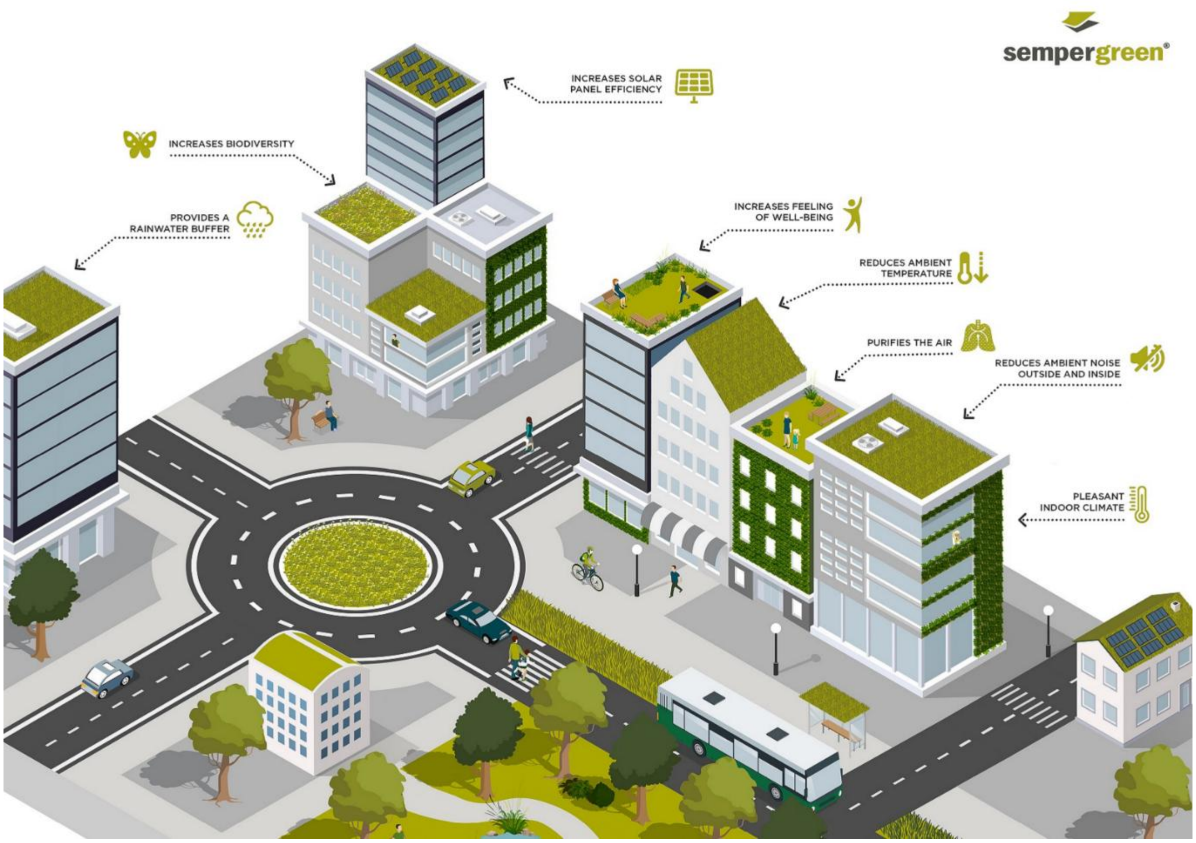

Figure 45. *Green Facade benefits to urban scale*
Source: Semper Green

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[86] *Wong, N. H., et al. (2003). The effects of green roofs on the indoor environment and energy consumption. Energy and Buildings*
[87] *Jim, C. Y., & Chen, W. Y. (2006). Effects of vegetation on the urban heat island in a tropical city. Landscape and Urban Planning*

Furthermore, green facades play a significant role in improving air quality by filtering particulate matter (PM) and absorbing carbon dioxide. According to Van den Bosch & Meyer (2017)[88], green walls have been shown to reduce particulate matter levels by up to 20%, improving urban air quality, especially in areas with high vehicular traffic. The plants also contribute to enhanced oxygen production through photosynthesis, further improving the surrounding outdoor environment. For example, vertical gardens in the "Bosco Verticale" (Vertical Forest) in Milan contribute to cleaning the air and improving microclimates by reducing the amount of dust and pollutants in the area[89].

In addition to their cooling and air-purifying effects, green facades help mitigate the urban heat island effect by improving thermal insulation and fostering evaporative cooling. Evapotranspiration as occurs when plants release moisture into the air, resulting in local temperature reductions and enhancing comfort levels. Studies have shown that evapotranspiration from green walls can account for a 20% reduction in air temperature around the building, with the cooling effect most significant during hot, dry months[90]. This reduces the reliance on air conditioning in nearby buildings and improves outdoor thermal comfort.

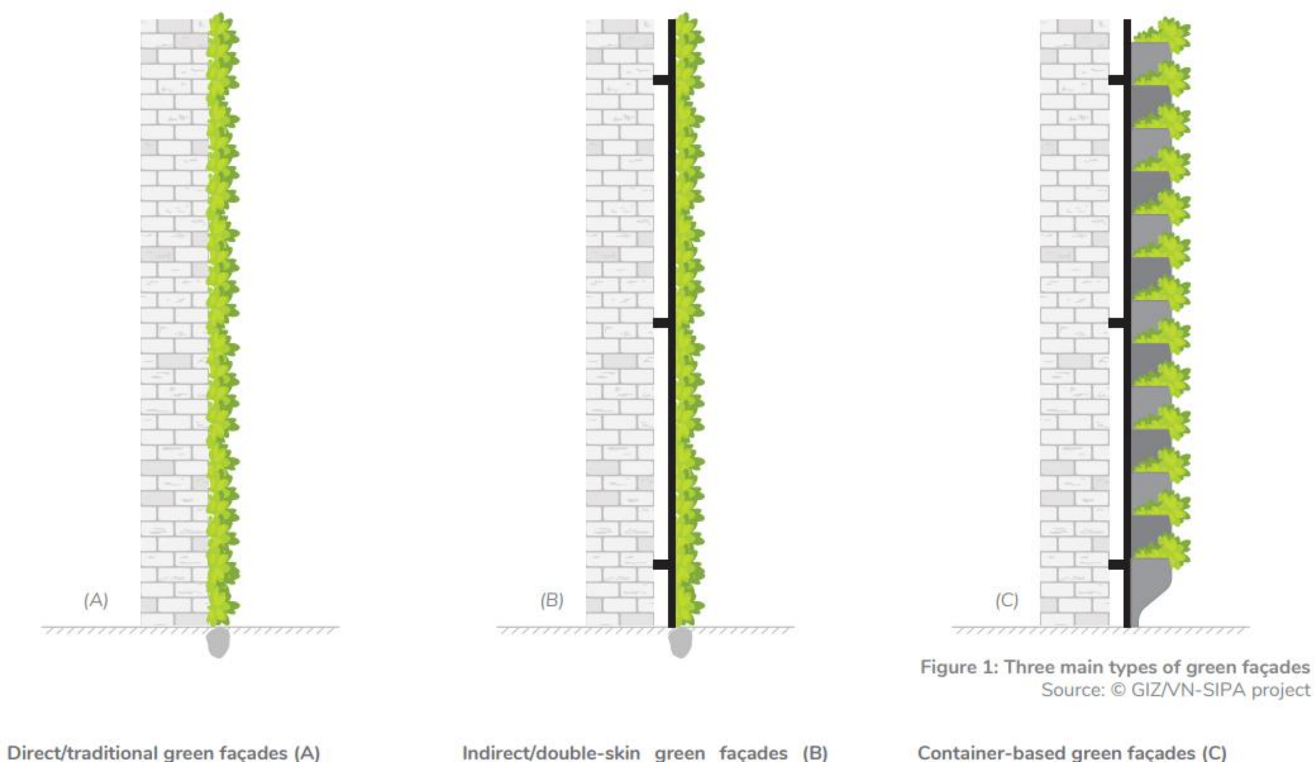

Figure 46. *Main types of Green Façades*
Source: SIPA Project

[88] *Van den Bosch, M. A., & Meyer, L. (2017). Green walls as a tool for urban air quality improvement: A review of recent studies. Building and Environment*
[89] *Cappuccino, S., et al. (2018). The contribution of green façades to air quality improvement and microclimate regulation: Case study of the Bosco Verticale, Milan. Urban Forestry & Urban Greening*
[90] *Parsons, K. (2012). Urban Heat Island: Causes, effects, and mitigation strategies. Environmental Science and Technology*

From a biodiversity perspective, green facades also support urban wildlife, providing habitats for various species of birds, insects, and microorganisms. The introduction of vegetation on building surfaces can contribute to biodiversity conservation, especially in densely built environments where green spaces are limited. Green facades can support native plant species, further enhancing local ecosystems and fostering ecological balance in urban settings[91].

To summarize, green façades significantly improve outdoor environmental conditions by mitigating heat gain, enhancing air quality, reducing the urban heat island effect, and supporting biodiversity. There are various types of green façades, including direct green façades, indirect green façades, modular green façades, living walls, and green façades with planters, each offering distinct benefits and applications. The decision of which type to implement depends on several factors, such as the building's location, climate, aesthetic preferences, structural considerations, and the specific environmental objectives to be achieved. As cities continue to grow, the integration of green façades presents a promising solution for enhancing urban resilience, improving public health, and contributing to sustainable urban development.

6.4.3 The Role of Solar Radiation and BIPV Solutions

Solar radiation is a key factor in understanding the energy dynamics of a building's facade, as it directly impacts thermal comfort, energy demand, and the performance of energy-generation systems such as photovoltaic panels. Results of application for Solar Irradiation Area, the tool modelled how much sunlight different parts of a building's facade receive, providing a detailed spatial analysis of solar exposure over time for July, 2024. For example, results of a range of 159,830.151 to 160,244.969 kWh/m², as calculated through application procedure, indicates areas of the building that are exposed to significant sunlight, making them suitable for both passive solar heating and active solar energy systems.

In regions with high solar radiation, Building-Integrated Photovoltaics (BIPV) are an ideal adaptive facade solution, to transform received solar radiation as a benefit for both building and urban scale. The main advantage of BIPV is its

Figure 47. *Gioia 22 with BIPV Adaptive Facade, Milan*
Source: Rinnovabili

[91] *Grewal, S. S., & Grewal, P. S. (2014). The role of green façades in biodiversity conservation in urban environments. Urban Ecosystems*

ability to generate electricity without requiring additional land space, which is particularly beneficial in urban environments where space is limited. Additionally, BIPV enhances the building's energy efficiency by improving insulation, reducing energy consumption for heating and cooling, and lowering the overall carbon footprint.

According to the Building Integrated PV Solution Booklet[92], Building-Integrated Photovoltaics (BIPV) refers to photovoltaic (solar power) systems that are integrated into the structure of a building rather than being installed as an external add-on. BIPV systems are designed to seamlessly blend into the building's architecture, replacing traditional building materials such as roofing, windows, or façades, with photovoltaic panels. These systems serve the dual purpose of generating renewable solar energy while also contributing to the building's overall design and performance.

BIPV systems integrate photovoltaic panels directly into a building's exterior, such as windows, facades, or roofs, effectively transforming the building skin into an energy-generating surface. These systems are particularly effective in areas with high solar exposure, where solar radiation data guides their selection. BIPV facades can play a significant role in mitigating the Urban Heat Island (UHI) effect, which occurs when urban areas experience higher temperatures than surrounding rural areas due to the use of heat-absorbing materials like concrete and asphalt. By integrating photovoltaic panels, BIPV systems reduce heat absorption and help improve outdoor thermal comfort, contributing to a cooler urban environment and with their integrated design, help address these challenges in several ways:

1. **Solar Energy Generation and Thermal Insulation:** BIPV facades directly convert solar radiation into electricity, reducing the building's dependence on external energy sources. Additionally, the photovoltaic panels themselves provide a layer of insulation, which can reduce heat transfer into the building. By blocking a portion of the solar radiation from reaching the building's surfaces, BIPV facades help lower the internal temperatures, particularly in warm climates, thereby improving thermal comfort for building occupants[93].
2. **Reflectivity and Albedo Enhancement:** Many BIPV panels are designed with reflective properties that can increase the albedo (reflectivity) of the building's surface. This helps to redirect solar radiation away from the building and surrounding areas, thus mitigating the UHI effect by reducing heat absorption. By using highly reflective materials or specialized coatings on BIPV panels, urban environments can achieve lower surface temperatures, which contributes to a more comfortable outdoor environment[94].
3. **Energy Efficiency and Reduced Heat Emission:** By generating renewable energy through BIPV, buildings become less reliant on traditional energy sources that

[92] *Building Integrated PV Solution Booklet, EU Smart Cities Information System, European Commission,2020*
[93] *Zhao, Y., & Li, L. (2017). Role of Building Integrated Photovoltaics (BIPV) in Urban Sustainability. Renewable and Sustainable Energy Reviews*
[94] *Testo, A., & D'Alessandro, F. (2019). Urban heat island mitigation strategies: A review. Building and Environment*

contribute to heat emission in urban areas. The process of generating and using electricity from renewable sources like solar power, rather than conventional fossil fuels, leads to a reduction in greenhouse gas emissions and overall urban heat. Moreover, the energy saved through efficient BIPV systems can be used to power cooling systems, further improving indoor thermal comfort and reducing energy costs (Zhao & Li, 2017).

4. **Mitigating UHI and Enhancing Outdoor Comfort:** BIPV systems contribute to the broader goal of UHI mitigation by reducing the overall heat buildup in urban environments. With their ability to reduce ambient temperatures by lowering the thermal load on building facades and minimizing the need for mechanical cooling, BIPV solutions enhance outdoor thermal comfort. In cities where high urban temperatures significantly affect outdoor public spaces, the integration of BIPV systems can help create more comfortable environments by reducing the heat island effect (Testo & D'Alessandro, 2019).

Possibility of integration with other sustainable urban solutions BIPV façades can be combined with other climate-responsive strategies, such as green facades, cool roofs, and dynamic shading systems, to provide a holistic approach to UHI mitigation and thermal comfort. For example, pairing BIPV systems with green roofs or facades enhances evapotranspiration, further cooling the environment and improving air quality. This integration strategy gives possibility to distinguish BIPV systems based on requirements and divided into three main categories: Roof systems, Façade systems, and Build-in Additions. Each type has its own unique features and uses, as it given below.

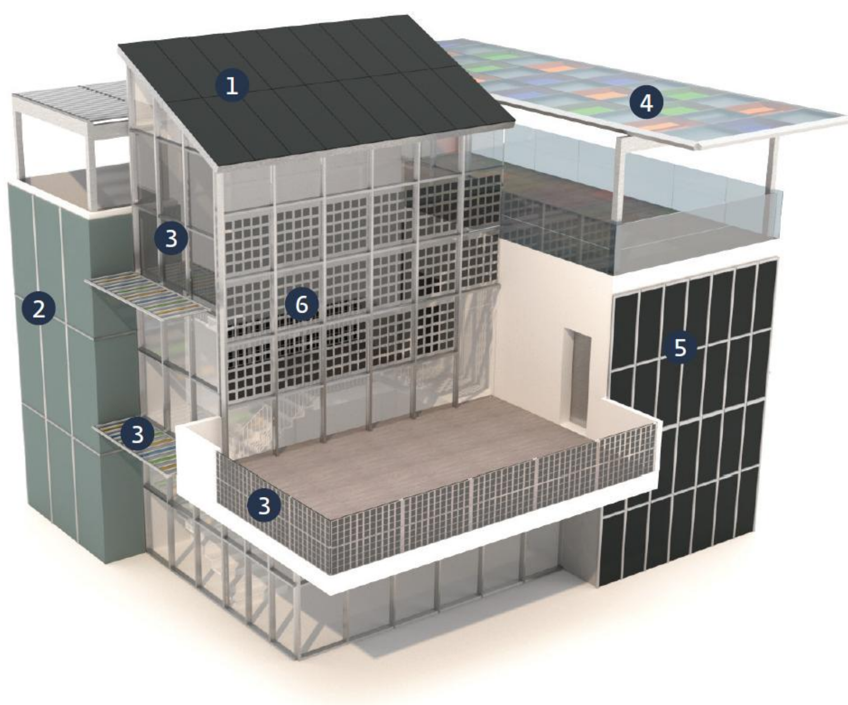

Figure 48. *Type of the BIPV system*
Source: Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholders, Status Report, 2020

1. **Discontinuous Roof -** PV elements are added to building surfaces like walls and roofs, which help cool down in summer through natural ventilation, while cold roofs are made of overlapping materials that keep water out and are good for solar energy use.
2. **Rainscreen -** Also known as cold façade, is a building design with a strong frame, an air gap for ventilation, and outer layers that help keep the building cool in summer, with various options available for construction.
3. **External Integrated Devices -** Solar shading devices, like blinds and canopies, help protect buildings from falls and control sunlight on roofs and facades.
4. **Skylight -** These are roof parts that let in light, can be clear or colored, and can be fixed or opened to protect indoor or outdoor spaces.
5. **Prefabricated System -** These are pre-made, multi-functional parts for buildings that can be installed on walls or roofs, improving efficiency, cost, quality, and safety while meeting various needs.
6. **Curtain Wall -** Curtain walls are non-structural outer walls made of glass and metal that keep air and water out, provide insulation, and can be built in different ways, from simple windows to complex designs.

Due to the numerous benefits and widespread use of BIPV systems, various aesthetic designs have emerged, like semi-transparent, opaque, coloured, rigid or flexible and can have different shapes and dimensions. Suggested options will depends on manufacturers production and their technical data, allowing for greater integration with architectural styles while still maintaining their functional energy-generating capabilities.

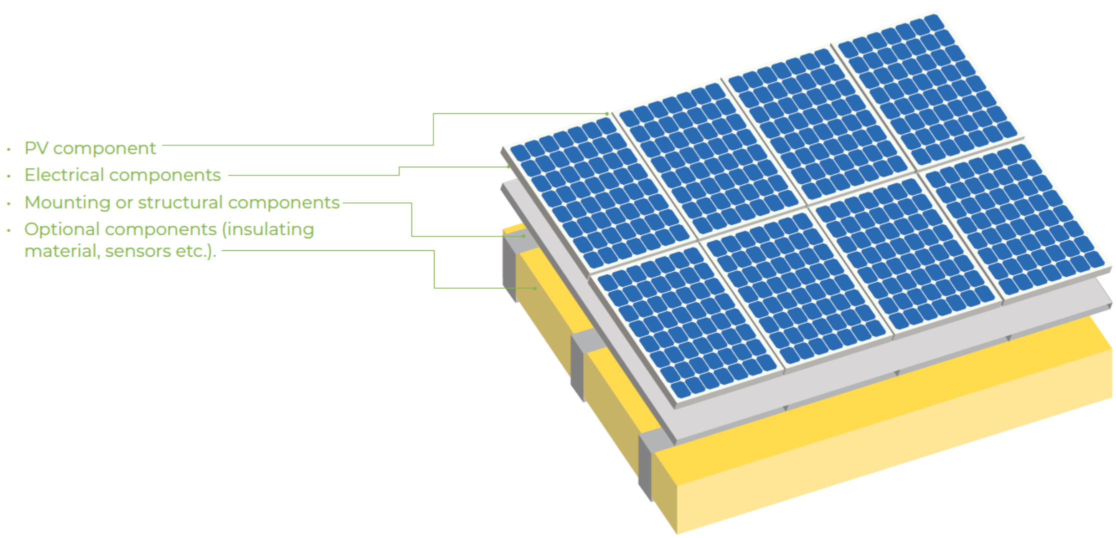

Figure 49. *Components of BIPV System*
Source: Building Integrated PV – Solution Booklet, EU Smart Cities Information System, 2020

Additionally, BIPV facades also function as shading devices, reducing solar heat gain by blocking direct sunlight from entering the building. This dual function — energy generation and thermal regulation — makes BIPV systems an effective mitigation strategy for buildings located in areas with high solar radiation. A study by Lee et al. (2018) found that integrating BIPV into building facades can reduce heat gain by up to 20%, depending on the facade design and solar exposure. For example, areas with solar radiation values in the range of 159,830.151 to 160,244.969 kWh/m² resulted from application are ideal for the deployment of BIPV systems, as these values indicate consistent and intense sunlight, which can be converted into electricity. BIPV systems in such regions can generate significant amounts of energy. According to the U.S. Department of Energy (2020), a well-placed 1 kW photovoltaic system can generate between 1,200 and 1,800 kWh of electricity annually, depending on geographical location and exposure levels. For a building facade, this could significantly offset energy consumption, especially in climates with high cooling demands.

In conclusion, the integration of Building-Integrated Photovoltaics (BIPV) facades is highlighted as an effective strategy for improving energy efficiency and thermal comfort, particularly in areas with high solar exposure. BIPV systems convert solar radiation into usable energy, significantly reducing a building's reliance on external power sources. Furthermore, incorporating thermochromic materials into BIPV facades enhances their performance by dynamically adjusting to changes in sunlight, thus regulating heat gain and reducing the need for mechanical cooling. Studies have shown that thermochromic materials can reduce energy consumption by 15-30%, depending on the materials and the building's location. Overall, BIPV systems, when combined with solar radiation analysis from tools like ArcGIS Pro, offer a comprehensive solution for enhancing building performance, reducing energy use, and contributing to sustainability efforts.

The chapter on adaptive facades focused on selecting the most effective solutions based on the environmental data obtained from various ArcGIS Pro analyses, including Land Surface Temperature, Urban Heat Island intensity, Normalized Difference Vegetation Index, Sky View Factor, Site Coverage Ratio, and Solar Radiation Area. These analyses provided a comprehensive understanding of the microclimatic conditions in Area Bonadies and its surroundings and its surrounding areas and its surroundings, identifying areas of thermal stress, dense urban structures, and high solar exposure, all of which significantly affect outdoor thermal comfort and energy efficiency.

The LST analysis reveals areas with high thermal stress, indicating the need for facades that can reduce solar heat gain. In these regions, dynamic shading systems, such as motorized louvers or electrochromic glazing, would be beneficial, as they adapt to changing solar radiation levels and help control indoor temperatures. Additionally, areas with a high UHI intensity required solutions that can mitigate heat buildup, and facades incorporating green elements, such as green walls or vegetation-integrated facades, offer cooling benefits by improving air quality and enhancing local biodiversity.

The NDVI and SVF analyses suggested that regions with limited greenery and poor sky exposure would benefit from the introduction of vegetation, which can help lower temperatures and improve ventilation. Green facades not only provide aesthetic value but also contribute to energy efficiency by reducing heat absorption and promoting natural cooling. In areas with high SCR, indicating dense urban development, facades with enhanced thermal insulation or natural ventilation systems are recommended to address heat retention and ensure occupant comfort.

Lastly, the Solar Radiation Area analysis supported the integration of solar-responsive facades, such as Building-Integrated Photovoltaics (BIPV), to harness solar energy while simultaneously reducing the building's heat load. Overall, the analysis conducted through ArcGIS Pro helps identify the most appropriate adaptive facade solutions tailored to the specific environmental conditions of Area Bonadies and its surroundings, ensuring improved thermal comfort, energy efficiency, and sustainability. These solutions effectively addressed the environmental challenges identified, improving thermal comfort, reducing energy consumption, and enhancing the sustainability of the built environment. The application of ArcGIS Pro tools has demonstrated the critical role of data-driven design in creating adaptive facades that respond to dynamic urban conditions, offering a path toward more sustainable and comfortable urban living environments.

07 CONCLUSION

7. CONCLUSION

This research has extensively explored adaptive façade systems by leveraging climatic and urban morphology data, employing ArcGIS tools to evaluate critical environmental parameters influencing urban microclimates. The study underscores the pivotal role of building façades in shaping thermal comfort within cities, emphasizing the importance of façade geometry, material properties, and thermal performance. These factors, especially within the context of urban canyons, significantly influence heat distribution and retention, directly affecting human thermal comfort. The findings, that have been chosen based on climatic data analysis, demonstrate that adaptive façade systems, such as Building Integrated Photovoltaics (BIPV), dynamic shading systems, and green walls, are effective solutions for enhancing both outdoor thermal comfort and building energy performance.

In conclusion, this research, which focused on a detailed climatic analysis of a specific location, has highlighted the importance of urban canyon geometry, orientation, and environmental conditions in shaping effective heat management strategies. The study identified the most suitable adaptive façade solutions for the area, emphasizing the role of Building-Integrated Photovoltaics (BIPV), dynamic shading systems, and green walls. BIPV systems were found to effectively harness solar radiation, reducing heat gain while generating renewable energy, while dynamic shading systems offer real-time adjustments to solar exposure, minimizing the need for mechanical cooling. Green walls, through evapotranspiration, further mitigate the urban heat island effect by lowering surface temperatures.

This integrated approach to façade design offers a comprehensive solution to improving both thermal comfort and energy efficiency in urban environments. The findings can be applied to future urban projects, particularly in areas such as the planned Rivoli Metro station around Area Bonadies and its surroundings and its surrounding areas, where these adaptive façade systems can be strategically deployed to enhance outdoor thermal comfort and sustainability.

Overall, the research demonstrates that the tailored application of adaptive façades - considering the unique climatic and urban characteristics of each location, which is also possible to apply for a bigger scale, can significantly reduce urban heat island effects, improve thermal comfort, and foster sustainable urban development. By integrating BIPV, dynamic shading, and green walls, cities can create more resilient, energy-efficient, and comfortable environments, but technological solutions will be always depending on application outcomes and needs of an urban environment. This study can serve as a starting point for analysing urban settings, playing a crucial role in the decision-making process for building-scale projects by providing valuable insights for the selection and implementation of adaptive façade systems.

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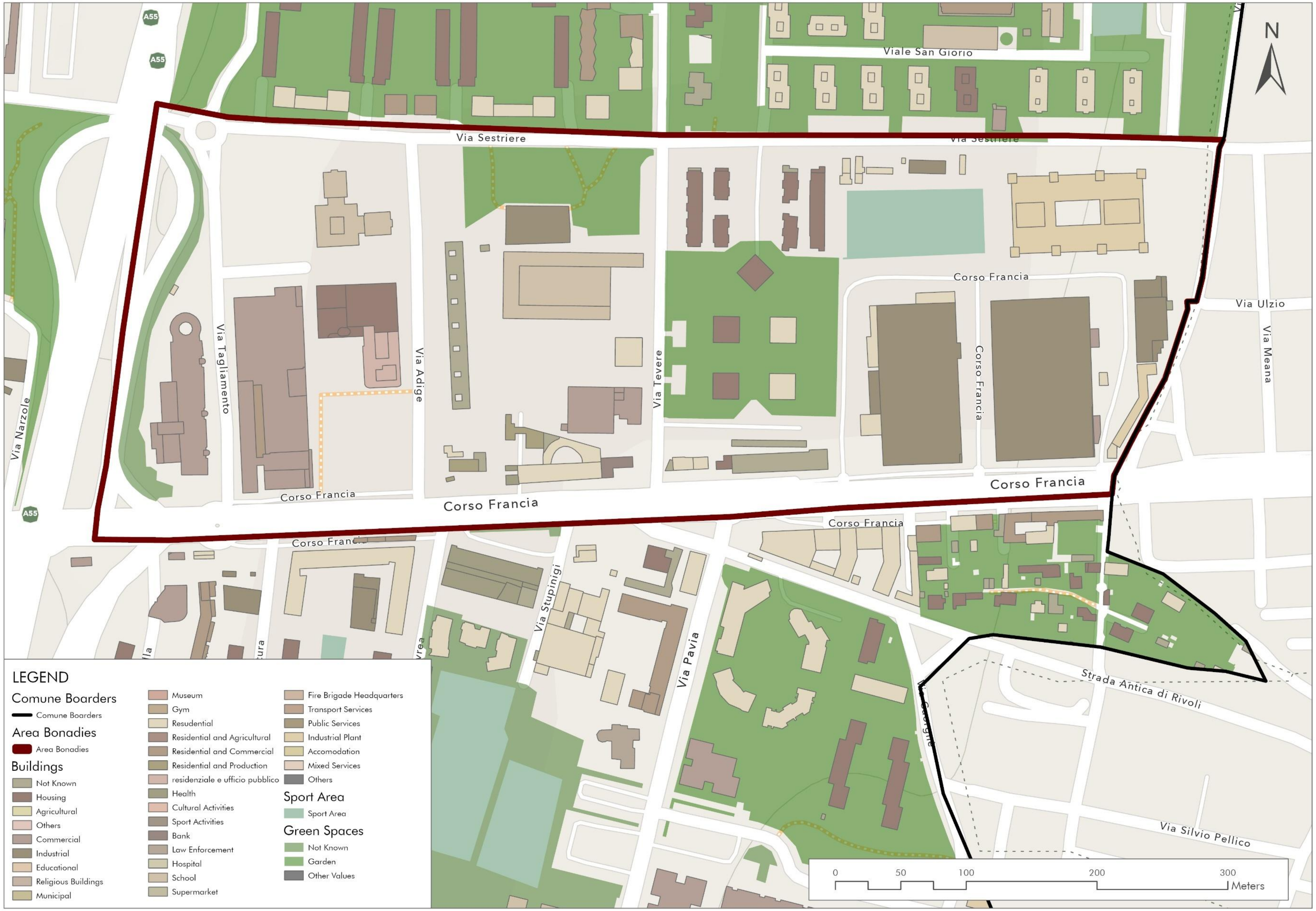
9. ANNEXES

ANNEX 1 – 3D Modelling

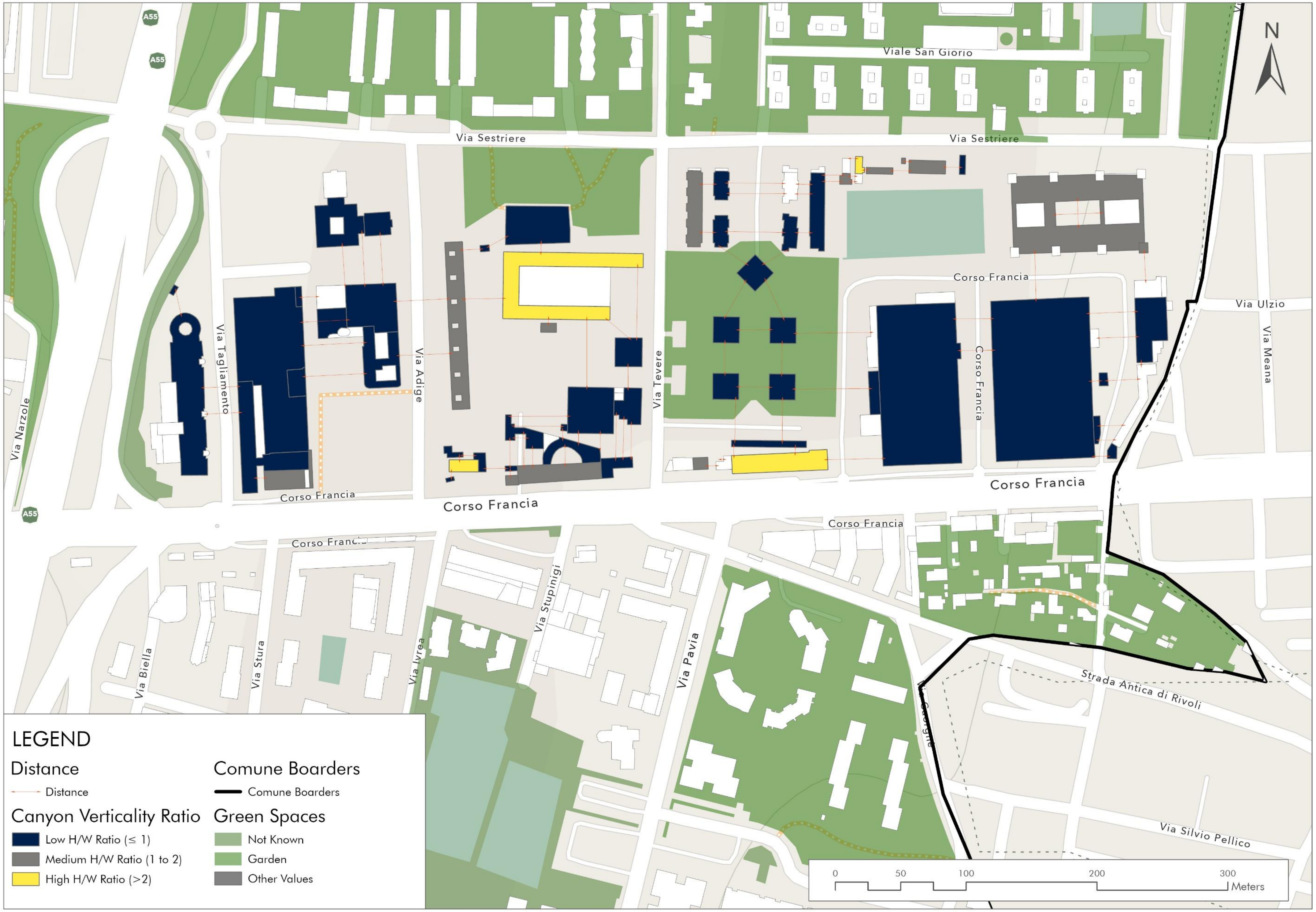
ANNEX 2 – General Plan of Area Bonadies and its surroundings



ANNEX 3 – Universal Thermal Comfort Index

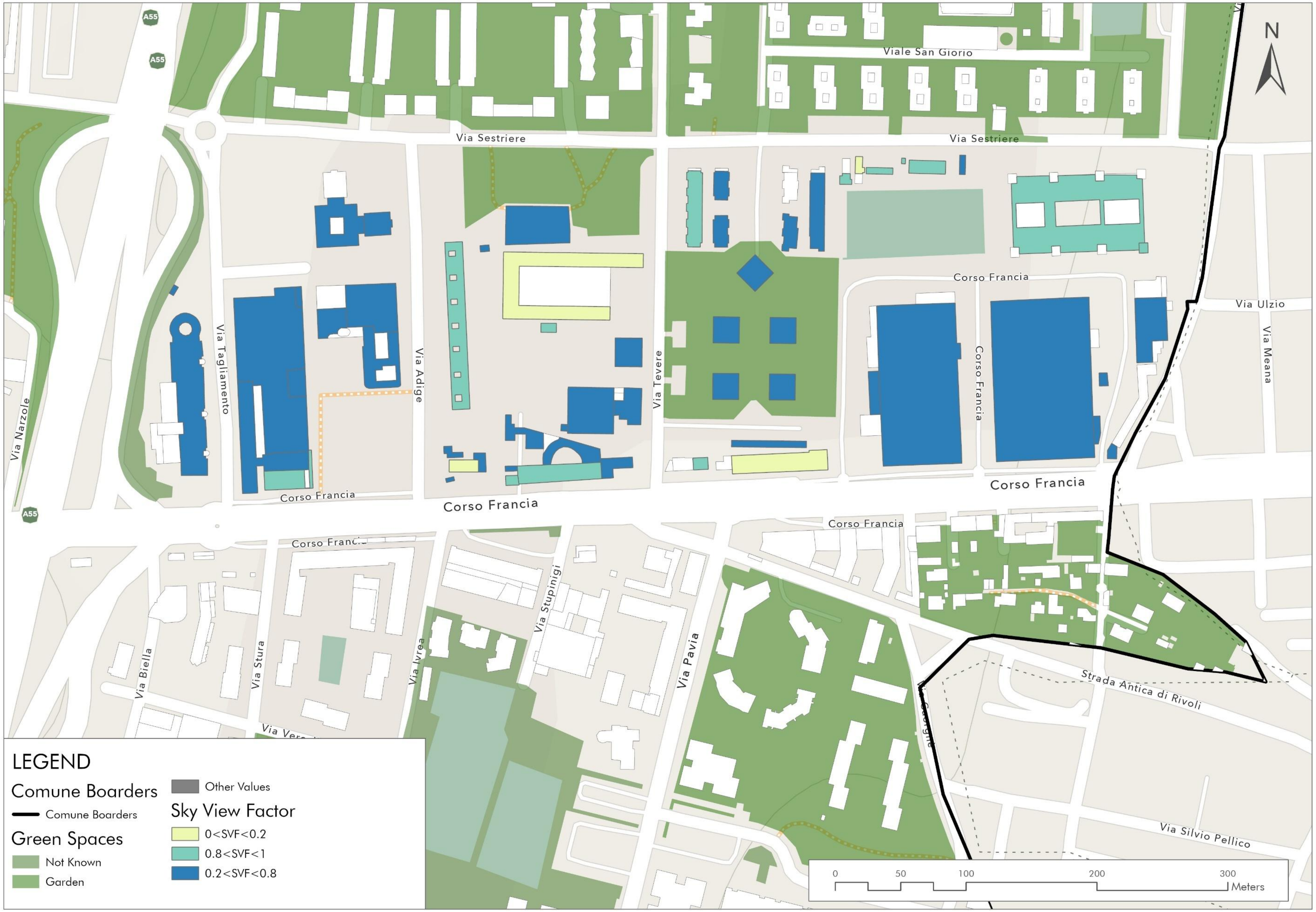
ANNEX 4 – Land Surface Temperature Values in July, 2024

ANNEX 5 – Canyon Verticality Ratio



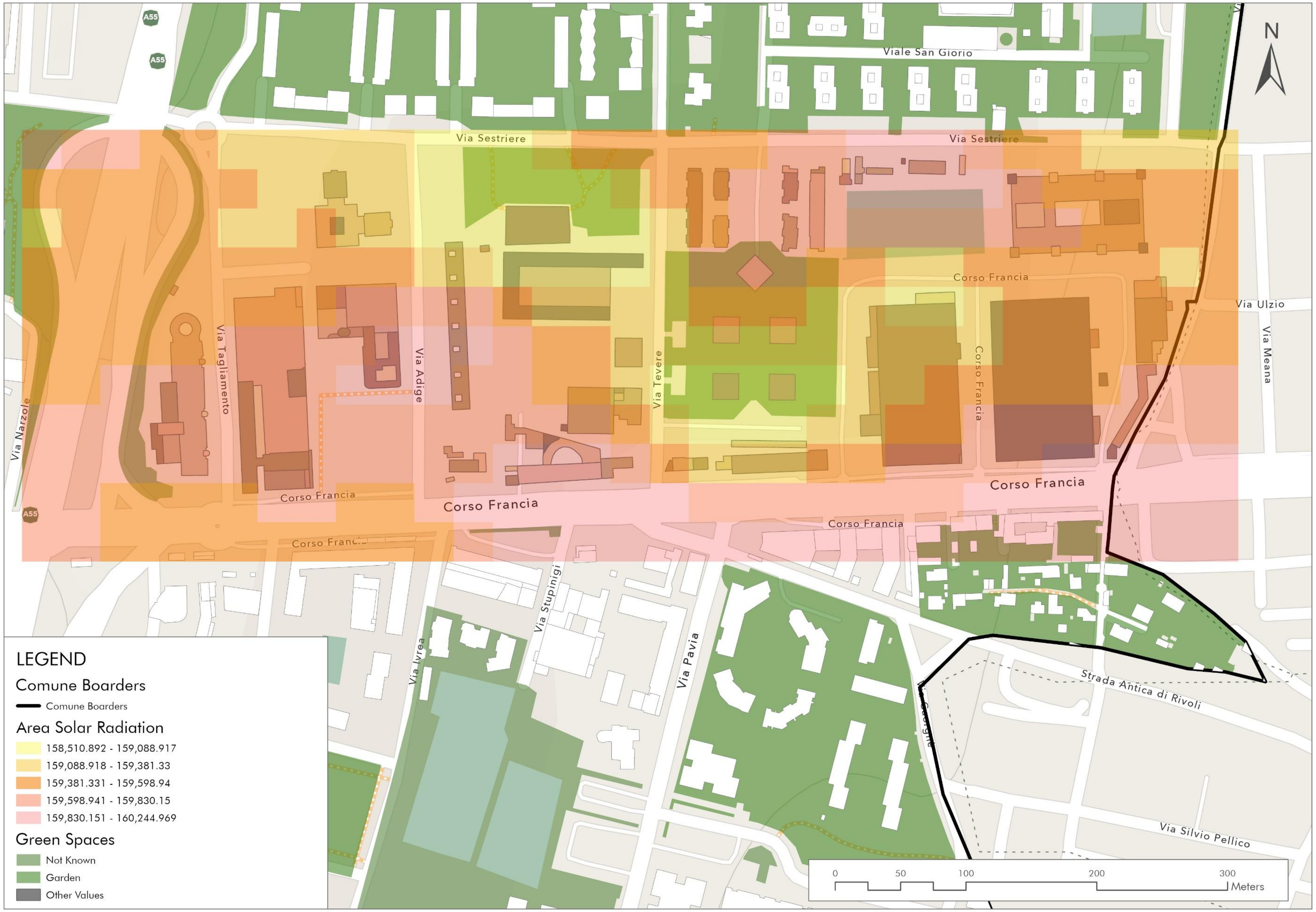
ANNEX 6 – Normalized Difference Vegetation Index

ANNEX 7 – Sky View Factor



ANNEX 8 – Site Coverage Ratio

ANNEX 9 – Solar Radiation Values for July 2024



ANNEX 10 – Shadow Analysis

ANNEX 11 – Wind Analysis