Co-funded by the
Erasmus+ Programme
of the European Union

Optimization Of The Urban Microclimate For Building Energy Demand And Thermal Comfort Under Climate Change

Case study of a vulnerable neighbourhood in Madrid city

Shoaib Amin
(S2142016)

A thesis submitted for the Joint programme of
Master’s in Urban Climate & Sustainability

August 2023

Author Amin Shoaib	**Publication Type** Thesis	**Completion year** 2023
	Number of pages: 83	
Supervisor I Prof./Dr. Rohinton Emmanuel	**Supervisor II** Prof./Dr. Jose Miguel Nieto	**Supervisor III** Dr. Emanuela Giancola

Title

Optimization Of The Urban Microclimate For Building Energy Demand And Thermal Comfort Under Climate Change
Case study of a vulnerable neighbourhood in Madrid City

Degree: Master's in Urban Climate & Sustainability

Abstract

Buildings in the EU are responsible for 40% of energy consumption and 36% of GHG emissions. This means that a major contribution from the construction and building sector is required to achieve the climate neutrality targets set by the European Green Deal. Conversely, the issues of energy poverty, energy inefficiency in buildings, urban heat island (UHI) and climate change are the challenges the built environment faces that impede the progress towards carbon neutrality. The potential of retrofitting strategies in improving the building performance is simulated using weather files from rural stations neglecting the impact of UHI. This leads to over-evaluation of the performance. Due to this approach, the impact on heating demand, probable increase in cooling energy demand due to future climate change and negative consequences of improvement in envelope such as worsening of indoor and outdoor thermal comfort are often not accounted for. This study proposes a tailored workflow to progressively study the challenges faced by urban planners and building energy modellers using the latest tools such as Urban Weather Generator (UWG), ENVImet, Ladybug Tools and EnergyPlus. Firstly, the study uses reference and RCP 8.5 2050 weather files to evaluate annual building energy demand with and without UHI influence. Secondly, the potential benefit of envelope retrofitting combined with UHI is simulated as an 18% decrease in annual heating energy demand under reference and extreme climate conditions. While the minimum effect of envelope retrofitting is observed on cooling energy demand, the improvement in urban microclimate shows a strong premise for tackling the cooling needs and the challenges of outdoor and indoor thermal comfort. Assessing the potential of research-backed planning strategies, the study demonstrates that for the design day of 21st July, the peak cooling energy demand will increase by 120% from reference climate to future extreme climate. Continuous canopies of dense trees along with hedges and reflective roads with an albedo of 0.4 can reduce this increase to 77%. Furthermore, the daily averaged indoor operative temperature is reduced by 1.9 °C. Similarly, thermal comfort measured as static PET shows improvement from extreme stress to moderate heat stress and strong heat stress at 13:00:00 and 17:00:00 on 21 July measured at 2 meters from the facade. Further assessment of dynamic comfort shows a significant decrease in the range of change of comfort i.e., from +12 to +3. The findings urge the research and planning community to investigate holistically the impact of different variations of urban green infrastructure and reflective materials to combat the issues of energy poverty and thermal comfort under extreme climatic conditions.

Keywords

Climate Change, Building Retrofitting, Urban District Energy Modelling, Urban Weather Generator, UHI, ENVImet

Originality statement. I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.	**Signature**

TABLE OF CONTENT

Chapter 1: Introduction 9

- 1.1. Rationale 9
- 1.2. Research Question 10
- 1.3. Aims & Objectives 10
- 1.4. Outline Of The Methodology 11
- 1.5. Structure Of The Report 12

Chapter 2: Literature Review 13

- 2.1. Overview Of The Challenges Faced By The European Built Environment 13
- 2.2. Review Of The Planning Strategies To Tackle The Challenges 14
- 2.3. The Local Urban Context Of Madrid City 16
- 2.4. Review Of The Methodologies And Workflows 17
- 2.5. Summary Of Literature Review And Research Gaps 20

Chapter 3: Methodology 21

- 3.1. Case Study Area 21
- 3.2. Summary Of The Workflow 23
- 3.3. Comparison Of Microclimate Tools Used 25
- 3.4. Dragonfly Model Development 26
- 3.5. Urban Weather Generator (UWG) 27
- 3.6. Envi-Met Design Scenarios 29
- 3.7. Energy Demand And Indoor Operative Temperatures 32
- 3.8. Outdoor Thermal Comfort Assessment 33

Chapter 4: Results And Discussion 35

- 4.1. Boundary Climate Conditions For The Case Study Area 35
- 4.2. Impact Of Urban Heat Island (UHI) On Building Performance 37
  - 4.2.1. Annual Variation Of UHI Intensity 37
  - 4.2.2. Energy Demand Under Current Weather Conditions 38
  - 4.2.3. Energy Demand Under Rcp 8.5 Weather Conditions 41
- 4.3. Phase 2: Optimization Of The Urban Environment 43
  - 4.3.1. Pilot Scale Study 43
  - 4.3.2. Full-Scale Study 47
  - 4.3.3. Energy Demand 53
  - 4.3.4. Indoor Thermal Comfort 55
  - 4.3.5. Outdoor Thermal Comfort 56

Chapter 5: Implications And Conclusions 61

- 5.1. Summary Of Findings 61

  5.2. Implications And Recommendations 62
  5.3. Limitations Of The Study 65
  5.4. Directions For Further Studies 68
  5.5. Conclusion 70
References 73
Appendices 79

ACKNOWLEDGMENT

Throughout the preceding two years, the exploration of European culture has catalyzed substantial enhancements in both my professional aptitude and personal development. This progress would not have materialized without the concerted endeavours of all stakeholders who have been instrumental in the establishment and progression of the Erasmus+ programme. Their efforts and my odyssey through the Master in Urban Climate and Sustainability (MUrCS) program have engendered a profound sense of purpose, motivating me to actively pursue the realization of an inclusive, resilient, and sustainable future.

I extend my sincere gratitude to the exceptional mentors, colleagues and friends that I have met on this journey for their invaluable and instrumental contribution to the successful execution of this master's thesis, which is representative of my overall learning experience in the MUrCS program and marks a significant milestone in my research journey.

Firstly, I would like to express my gratitude to Professor Rohinton Emmanuel, Professor Jose Miguel Nieto and Dr. Emanuela Giancola for their immense support and guidance throughout the execution of this study. Professor Rohinton's wealth of knowledge and keen insight have been instrumental in helping me fine-tune my study approach and enhance my research abilities. Thanks to his experience and sharp acumen, I have been able to make significant progress in my academic pursuits and research endeavours. I am deeply grateful to Professor Jose for his unwavering support during my time in Huelva, Spain, and for his invaluable guidance in the realm of academic writing. His mentorship has been instrumental in making my mobility experience both enriching and academically rewarding.

This study owes its very existence to the exceptional support and mentorship of Dr. Emanuela Giancola, without whom this endeavour would not have been feasible. Her gracious invitation to participate in her project URBAN therCOM at CIEMAT opened the door for me to make a meaningful contribution. Throughout the journey, Dr. Giancola's unwavering dedication, astute guidance, and meticulous attention to detail have been the foundation of this study, adding immense value to its outcomes. I am truly indebted to her for this invaluable experience and the opportunity to learn from such an inspiring mentor. Furthermore, the technical guidance of Dr. Silvia Soutullo, Dr. Emanuele Naboni and Marcello Turrini has been pivotal in shaping the outcomes of this study.

I am extremely grateful to the MUrCS family for being my support system throughout my two-year journey. The experiences shared and the memories made will always be cherished.

Finally, I owe an immeasurable debt of gratitude to my family and friends for their unwavering belief in my abilities and their constant encouragement. Their love and understanding have been my pillars of strength throughout this amazing experience.

LIST OF FIGURES

Figure 1: Outline of methodology workflow 21
Figure 2: The multidisciplinary approach of the mateMad project strategy and the objective of the URBAN therCOM subproject 23
Figure 3: Rhino 3D model(left) and Dragonfly model (Right)...24
Figure 4: Design Day extraction from EPW files 25
Figure 5: Example workflow to generate building program types and construction sets for two building construction type cases i.e., 1979 and 2006. 27
Figure 6: U-value of the construction material used in the model for different structural elements. 27
Figure 7: Schematics of Universal Weather Generator (UWG) 27
Figure 8: Grasshopper UWG workflow..28
Figure 9: ENVImet V5.5.1 model Full scale(left) and Pilot scale (right)..............................30
Figure 10: Pilot scale scenarios...30
Figure 11: Description of full-scale ENVImet simulation scenarios.....................................31
Figure 12: ENVImet base case (Actual and RCP 8.5) and Optimized scenario (RCP 8.5 2050) 32
Figure 13: Morpho Workflow to develop and simulate ENVImet scenarios. 32
Figure 14: Energy demand assessment workflow 33
Figure 15: Virtual Walk routes for the base case and optimized scenarios 34
Figure 16: Annual Dry bulb temperature of Madrid City...35
Figure 17: Hottest and coldest week from the TMY file. 35
Figure 18: Annual variation of Relative humidity %..36
Figure 19: The wind speed variation for the climatic context of Madrid City 36
Figure 20: Wind rose for wind directions for the yearly data...37
Figure 21: Comparison of UHI morphed file and rural file for dry bulb temperatures for monthly per hour values using reference TMY 37
Figure 22: The difference in dry bulb temperature for morphed and rural files......................38
Figure 23: Monthly variation of heating and cooling energy demand for current representative weather file. 38
Figure 24: Changes in annual energy demand for current weather under UHI and retrofitting scenario. 39
Figure 25: Monthly variation of heating and cooling energy demand for RCP 8.5 2050 climate change file. 41
Figure 26: Annual variation of heating and cooling energy demand for RCP 8.5 2050 climate change 42
Figure 27: Dry bulb temperature under RCP 8.5 2050 climate scenario..................................42
Figure 28: Sun angle at 1300(left) and 1700 hrs (right) 44
Figure 29: Comparison between 4 scenarios for building envelope material brick. 44
Figure 30: Comparison between 4 scenarios for building envelope material ETICS.............45
Figure 31: Absolute differences between surface temperature between the base case and reflective material pilot scale scenario..45
Figure 32: ENVImet Surface material 2D model for the reflective material pilot scenario....45
Figure 33: Comparison of SW radiation reflected and LW radiation emitted........................46
Figure 34: Absolute differences of MRT across base case and reflective material scenario. .46
Figure 35: Description of areas within the model...46
Figure 36: Comparison of outside and inside wall temperature for brick(reference) and ETICS (observation). 47
Figure 37: Optimized scenario pilot scale vs. optimized scenario full scale. 47
Figure 38: Potential Air temperature 0700(left)), 1300 (center), 1900(right) on 21st July. 48

Figure 39: Wind speed @17:00:00 for RCP 8.5 no change scenario. 49
Figure 40: Wind Speed @ 17:00:00 for base case 2022 scenario. 49
Figure 41: Impact of urban context on wind speed...49
Figure 42: Variation in relative humidity between basecase 2022 and RCP 8.5 no change scenario. 50
Figure 43: Absolute differences of wall temperature and surface temperature between RCP 8.5 no change scenario as reference and RCP 8.5 optimization scenario as observation.........50
Figure 44: Absolute differences in SVF between RCP 8.5 no change scenario and RCP 8.5 optimization scenarios resulting from dense trees and hedges. 51
Figure 45: Comparison of hourly wind speed at facade across three scenarios 51
Figure 46: Wind speed at 1.4 meters for RCP 8.5 optimization scenario...............................51
Figure 47: Spatial variation of relative humidity for RCP 8.5 optimization scenario. 51
Figure 48: SW received and LW emitted for RCP 8.5 optimization scenario.........................52
Figure 49: Air temperature at vegetation at 17:00:00 hours in RCP 8.5 optimization scenario. 53
Figure 50: Spatial variation of direct SW radiation received for sparse and dense vegetation in the RCP 8.5 optimization scenario. 53
Figure 51: Absolute values of cooling energy demand intensity for three full scale scenarios. 54
Figure 52: Hourly variation of critical microclimatic parameters for three simulated scenarios 54
Figure 53: Absolute differences between RCP 8.5 no change and RCP 8.5 optimization scenario. 55
Figure 54: Wall temperature outside node and MRT @ 1.4 meters simulated at 17:00:00 for basecase and RCP 8.5 no change scenario...56
Figure 55: Wall temperature and MRT @ 1.4 meters simulated at 17:00:00 for RCP 8.5 2050 optimization scenario. 57
Figure 56: Static PET simulated @86,60 receptor point located at 2 meters from the facade across the RCP 8.5 no change and RCP 8.5 2050 optimization scenario at different time of the day. 57
Figure 57: Variation PET for 07:00:00 and 13:00:00 hours 58
Figure 58: Variation PET for 17:00:00 and 22:00:00 hours 59
Figure 59: Dynamic PET assessment @17:00:00 across three simulated scenarios. 59
Figure 60: Graphical representation of changes in dynamic PET across three scenarios. The horizontal axis represents increase in dPET through the simulated walk...............................60
Figure 61: Weather Sensor location and proximity to case study area for future validation...67

LIST OF TABLES

Table 1: Building properties 26
Table 2: UWG model properties 28
Table 3: Vegetation properties for UWG as per the base case 28
Table 4: ENVImet model and simulation settings 29
Table 5: Thermal comfort simulation settings 33
Table 6: Summary of annual energy demand for current weather file 38
Table 7: Variation in annual energy demand under climate change across UHI and retrofitting scenario. 41
Table 8: Summary of box plots for envelope material brick 44
Table 9: Summary of box plots for envelope material ETICS 45
Table 10: Correlation matrix between simulated variables across the three full scale scenarios. 52
Table 11: Summary of daily averaged operative temperatures for 21 July across three scenarios. 55
Table 12: PESTEL analysis of the implications and recommendations based on the findings. 65

ABBREVIATIONS

LES- Large eddy simulations
LAD- Leaf Area Density
LAI- Leaf Area Index
RANS - Reynolds-averaged Navier–Stokes equations
TMY- Typical meteorological year
UBEM- Urban Building Energy Modelling
UCM - Urban Climate Model
UGI – Urban green Infrastructure
UWG – Urban Weather Generator
UHI- Urban Heat Island

CHAPTER 1: INTRODUCTION

1.1. RATIONALE

European Union (EU) has targeted to be climate neutral by 2050, and this objective is at the core of European Green Deal and aligns with EU's commitment to climate action in accordance with Paris agreement (European Commission, 2023). In this regards, European commission has laid out a roadmap for low carbon Europe which require major contributions to come from the building and construction sector. Analysis of Odyssee-Mure European database shows that 27% of total energy consumption is attributed to residential buildings with dwelling consuming around 200 kWh /m2 /y on average (ODYSSEE and MURE, 2012).. Santamouris (2016) research focuses on major problems faced by the built environment in Europe. The research describes them as building energy consumption, energy poverty and the local climate change. In Southern European countries, cooling represents 10% of the total energy consumption per dwelling. However, this is likely to be much higher under climate change (Isaac & van Vuuren, 2009) as the residential sector will rely more on use of air conditioning systems to adapt to higher temperatures (Santamouris, 2016). Similarly, energy poverty is another obstacle to EUs roadmap to climate neutrality. The levels of energy poverty are not yet defined by a central institution in EU. However, several research have attempted at quantifying the percentage of people facing energy poverty in European countries and it's a well-known phenomenon (Kolokotsa & Santamouris, 2014), Using the methodologies developed in research to quantify energy poverty, the percentage calculated for Spain is 31% with highest being in Bulgaria and Cyprus 65% (Santamouris, 2016). The energy performance of building directive (EPBD) developed by EU focuses on the energy efficiency through energy renovation as a way forward to tackle the issues of energy consumption, energy poverty and reducing emissions. However, issues at the building level are not independent of the challenges faced by the urban environment. Urban heat island (UHI) phenomenon has a major impact on low income and vulnerable population of the cities (Santamouris & Kolokotsa, 2015). UHI results in urban areas experiencing different weather than rural environment due to combination of urban morphology and use of artificial materials (Oke, 1988). Urban form alters the wind speed and direction and the exchange of shortwave (SW) and longwave radiations (LW). While artificial materials absorb heat and release it in form of LW radiation. This is due to difference in thermal properties (solar reflectance, thermal absorbance etc) of artificial materials (concrete, basalt, granite, asphalt etc) and natural materials such as soil. However, the effect of urban form and fabric on local climate, thermal comfort and energy consumption has been extensively researched (Emmanuel & Steemers, 2018, Salvati, Coch Roura & Cecere, 2017, Santamouris, *et al.,* 2015). Futcher, Mills and Emmanuel (2018) argued that even for buildings that are dominated by internal loads, neglecting the urban impact can lead to significant energy penalties. (Santamouris, 2016), proposed strategies to tackle energy poverty, building energy consumption and UHI with consideration to European context. However, if these strategies are adopted locally without consideration of the urban context can result in adverse impacts as shown in several studies (Maronga, Winkler & Li, 2022, Salvati and Kolokotroni, 2023). Therefore, there is a need to study holistically the interaction of urban challenges and mitigation potential of planning strategies to effectively design for climate change adaption.

1.2. RESEARCH QUESTION

In the light of discussion in Section 1.1, the research focuses on addressing the following questions:

I. What tools and workflow can be used to study the relationship between urban environment and built environment at scales larger than of a building.
II. What is the impact of urban microclimate on the energy demand under current and future climate conditions for the studied area.
III. What sustainable urban strategies can be deployed to optimize the relationship between urban environment and the built environment and what is their simulated impact in local study context.
IV. Will these strategies enable mitigation of the adverse impacts of conventional energy efficiency strategies such as envelope retrofitting.

1.3. AIMS & OBJECTIVES

The focus of the study conducted is to understand and optimize the urban microclimate to minimize the unintended impact on building energy demand, indoor and outdoor thermal comfort in an urban district of Barrio Orcasur in Madrid City. The objectives of the study are enlisted below:

A. Developing a tailored workflow to effectively study the relationship between buildings and urban environment with latest tools available.

B. Understanding the impact local Urban Heat Island on building energy demand under reference and climate change conditions.
C. Evaluation of progressive measures to reduce heating and cooling energy demand under reference and future climate.
D. Assessing the sustainable urban planning strategies potential in optimizing the triadic relationship of energy demand, indoor and outdoor thermal comfort.

1.4. OUTLINE OF THE METHODOLOGY

A detailed review of the methodologies validated by previous studies was conducted. Studies with overlapping aim and objectives were critically assessed and optimized workflow was developed. The overall workflow is based on GIS technology, 3D designs, mathematical and computational modelling of microclimate, energy demand and thermal comfort. The main tools used in this study are: 1) ArcGIS Pro 2) Rhino 3D 3) Ladybug Tools 4) Morpho Plugin 5) ENVImet v 5.5.1. 6) EnergyPlus 7) Urban Weather Generator 8) Radiance 9) Grasshopper Programming Interface.

The methodology was divided into two phases. Phase 1 was focused on the objective A and B while phase 2 was associated with objectives C and D of the study. In phase 2 of the study, pilot scales studies were conducted to achieve a balance between computation and time resources to test several simulation variations. The final part of the phase 2 was designed based on the findings of the pilot scale and was executed at full scale. Hence was more computationally intensive and time consuming. However, the results of the study were more accurate and were crucial in investigating the relationship between urban microclimate and its impact on the energy demand and comfort of the urban block.

The research philosophy followed in this study is centred around Positivism. The general approach is deductive. The emphasis is on the use of quantitative data, empirical observation and scientific methods to establish causal relationships. The general objective of this study is to analyse a complex urban system and to predict its behaviour under various simulated microclimatic conditions.

1.5. STRUCTURE OF THE REPORT

Chapter 1: briefly discusses the current understanding of the topic in focus, the areas that need to be further addressed and what aims and objectives this study outlines to do so. The research philosophy and methodology are briefly touched to set a foundation for future information explored in next chapters.

Chapter 2: carries out the detailed literature review starting from the scale of European Union and zooms into the local context. The literature reviews the recent studies on strategies to tackle the problems and examines the methodologies to study them through comparative study.

Chapter 3: describes the methodology adopted in detail to allow replication of this study and enabling validation and comparison of results with similar studies performed in different urban contexts.

Chapter 4: presents the results achieved from execution of the methodology and provides discussion in comparison to similar research studies.

Chapter 5: summarizes the findings of this study and discusses its implications. It further provides recommendations and acknowledge the limitation providing suggesting for future research.

CHAPTER 2: LITERATURE REVIEW

The focus of this study is to assess and optimize the microclimate for building energy demand, outdoor and indoor thermal comfort using planning control strategies suggested in the research. With this regard, the review evaluates the complex nature of these problems and proposed adaption and mitigation strategies both at European level and in the local context of Madrid City.

2.1. OVERVIEW OF THE CHALLENGES FACED BY THE EUROPEAN BUILT ENVIRONMENT

Santamouris (2016) research focuses on introducing a zero concept to tackle the challenges faced at the European level in the building sector. The article evaluates the actual status, the synergies between the problems and their impact. Particularly for energy consumption, it states that 27% of the total energy consumption is attributed to residential buildings with average building energy consumption for Spain stated as 150 kWh/m2/y (ODYSSEE and MURE, 2012). Attributed to increase use of air conditioning, cooling represents 10% of the total energy consumption. The study further highlights that the increasing ambient temperatures deteriorates outdoor conditions and reduces the cooling potential of heat sinks (natural ventilation) eventually increasing the cost of peak and regular electricity. This forces the poor to use mechanical heating ventilating and air conditioning (HVAC) or forced to live under lower comfort and health levels. Furthermore, the economic inability in poor areas decreases the potential of application of mitigation measures and increase the intensity of local climate change. Santamouris, and Kolokotsa (2015) studied the combined effect of climatic conditions and urban overheating on energy demand on vulnerable population. The study attempted at establishing a relation between energy penalty and ambient temperatures. It was empirically demonstrated that the change of 1 K in ambient temperatures can increase energy demand by 1.66% in hot climates and 0.542% in mild climates. For Spain, the energy penalty of overheating is close 0.6 MWh/K which corresponds to approximately 2% increase in total electrical load. It is also argued that low-quality housing may have higher energy penalties than calculated mainly due to low thermal quality of the building envelope. Not only this was shown to have energy penalties but significantly higher health risks for low-income population. The study signifies the need for integrated assessment at the design stage of urban planning projects due to the complexity of early decisions in building and urban form. Salvati et al (2017) highlights the impact of urban context, specifically compactness of urban form on building energy demand in a Mediterranean setting: Barcelona, Spain. Firstly, compactness of urban form can vary the solar availability (i.e., the increase or decrease of the shadowing effect). Secondly it alters the UHI intensity (i.e., air and surface temperature and wind speeds). The results of the study conducted state that although the dense urban environment increases the UHI, overall, the benefit of shadowing in reducing building energy consumption is more within the specific context of Barcelona. However, the study did not consider any implication this might have for outdoor thermal comfort. Similarly, Futcher, Mills and Emmanuel (2018) studied the impact of urban form on building energy consumption in London United Kingdom. The researchers argues that although the emphasis for office building design is to maximize their own energy performance due to being internally dominant in terms of energy load (Futcher, 2017), this might be counter intuitive at larger urban scales such as: neighbourhood. As a result, there might be benefits or penalties that are neglected at the design stage. This argument is further strengthened in the residential context where natural ventilation is heavily relied upon and buildings are mostly external load dominant. In a special issue, Emmanuel & Steemers (2018), focused on understanding the relationships between urban form, density and microclimate and highlighted the need for a neighbourhood scale assessment of local climate that includes thermal comfort and building energy demand. Furthermore, the research highlights the need for an alternative approach to study holistically the impact of these three urban elements.

2.2. REVIEW OF THE PLANNING STRATEGIES TO TACKLE THE CHALLENGES

One of the several studies reviewed suggested strategies to mitigate urban heat island by use of high albedo material including cool pavements and reflective coatings in reducing the ambient temperatures and increasing indoor thermal comfort as low-cost solutions. (Santamouris et al., 2011). To tackle energy poverty, Santamouris (2016) study discusses deep retrofitting strategy and its positive impact on social, financial and environmental challenges. Despite that the strategies discussed in the reviewed research articles have been proven to be effective through experimental demonstration, there needs to be further investigation on how each strategy behaves in a specific context. For instance, a study conducted in Berlin Germany concluded that area wide building retrofits can have negative effect on the outdoor thermal environment (Maronga *et al.,* 2022). The study compared non retrofitted building scenario and a fully retrofitted case using large eddy simulations (LES) and demonstrated the adverse impact on urban microclimate due to retrofitting. The results of the study showed the cooling potential of the urban atmosphere during the early morning but a warming effect from noon to the early night. As the simulations were run over seven days, the cooling effect in the morning diminishes and the warming effect increases as the simulation progressed. The research attributed these conclusions to decoupling of outer building materials such as plaster from inner building material leading to more heating of outer surface and thus higher air temperatures. In contrast, for indoor temperatures, it was concluded that they remained cooler throughout the simulations. Similarly, another study examining indoor thermal comfort for naturally ventilated buildings found out that climate change might have worsened impact on operative temperatures inside the buildings (Salvati and Kolokotroni, 2023). The study used physics-based modelling and RANS based simulations tools to evaluate the impact of changing climate on indoor thermal comfort. The methodology utilized TMY file for actual conditions and morphed weather file to reflect weather conditions in 2050 under extreme climate scenario of RCP 8.5. The case study for the study were the two cities of Cadiz and London in Spain and United Kingdom. The study concluded that accounting for increasing regional temperatures and urban heat island, the discomfort hours increase by 24-26% and the predictive temperatures to be above 30.8 °C for 74% of the hottest month of July. Similarly, another study also investigated the potential of reflective materials in improving outdoor thermal comfort (Salvati et al., 2022). The study concluded that the aspect ratio of urban canyon is a major determinant for impact on outdoor thermal comfort. The study suggests on a combination of increasing road reflectivity and lowering façade reflectivity in lower parts as best strategy to improve thermal comfort in the urban climate and building setting of London, United Kingdom.

Several research have also studied the impact of vegetation on energy savings and outdoor thermal comfort. With this regard, in a review conducted on "Numerical simulation to assess the impact of urban green infrastructure on building energy use" (Zhu et al., 2023), acknowledged the need to seek for sustainable urban design with consideration to rapid urbanization. The study divides the urban green infrastructure (UGI) into two categories 1) Site-Scale vegetation and 2) building-integrated vegetation and stressed on the role numerical simulations play in evaluation and optimization of design strategies. The study discusses the main aerodynamic effect of vegetation as reduction in air velocity and increase of turbulence generated by the canopy. The study highlights the limitation of BEM models to integrate site-scale modelling of vegetation for its microclimate and shading quantification. This presents an interesting notion. As sustainable urban plans aimed at improving outdoor environment often don't consider the building energy performance and the energy modelling often don't account for the urban planning controls. This necessitates the development of tailored workflow suitable for both purposes.

Another study conducted focused on the role of UGI as planning control in reducing air temperatures (Santamouris and Osmond, 2020) The researchers found out that for a maximum UGI fraction, the drop was between 1.8°C to 2.3°C. However, as discussed in the previous research conducted, the role of reduced wind speed has been highlighted as limiting for removal of heat in high aspect ratio situations (greater than 1). The researchers stated the decrease of wind speed due to trees effecting vertical mixing and pollutant dispersion. This not only effects the building energy consumption but the health and overall comfort in outdoors. Therefore, this creates a question of whether street canyon vegetation will be suitable for the aspect ratios in case study under focus. Some areas experience low winds speeds measured at 10-meter heights during summer season. Shall the cooling effect from evapotranspiration and shading be neglected due to this consideration? Therefore, this needs to be explored in specific urban, climate and seasonal context.

Adaption of planning controls that are generally concluded to have positive or negative impact can potentially exacerbate the worsening situation of energy poverty, energy consumption and urban microclimate or result in neglect of overall benefits from a strategy. Based on this first, an accurate characterization of the vulnerable areas shall be done and then mitigation strategies shall be studied using the latest tools available to estimate the potential of each measure considered as part of the planning control.

2.3. THE LOCAL URBAN CONTEXT OF MADRID CITY

In conclusion of research articles reviewed above, it is argued that is necessary to have a deeper understanding of the local urban context and then evaluate the strategies before implementation to achieve optimal results considering its implication under climate change. (Martín-Consuegra *et al.,* 2020) studied multidimensional index of fuel poverty in deprived neighbourhoods of Madrid. The study mapped the spatial distribution of energy inefficiency and deprived neighbourhoods and identified overlapping areas. The study resulted in composition of the multidimensional index called (IMPE) (Martín-Consuegra *et al.,* 2020) based on four factors:

1) Low household income 2) High energy prices/costs 3) Energy inefficiency and 4) Vulnerable population.

López Moreno et al. (2020) studied the influence of microclimate and outdoor thermal sensation in the city of Madrid. The study uses classification of urban typologies provided by Statistical institute of the community of Madrid along with measured data from the Climatic Network of the Madrid's City Hall (CNM). The study uses Sky Helios Pro software to simulate representative neighbourhoods of different typologies. Universal Thermal comfort Index (UTCI) is used to evaluate the outdoor thermal comfort across the identified typologies. Although in all urban typologies "no thermal stress" has been observed, UHI effect is found to be dominant at night and higher in compact high-rise typologies i.e., +2 C compared with disperse typologies. Whereas no significant change in UTCI is noticed during daytime across the assessed urban typologies. The research stresses the need to plan strategies to tackle thermal stress with focus on high rise urban typologies which account for 34% of the built environment.

Soutullo *et al* (2020) studies the impact of climate trends on the thermal performance of residential buildings in Madrid. The research uses two typical meteorological files and one experimental file representing average values registered during the last decade (2010-2020). The authors study the cooling and heating loads using TRNSYS for two cases 1) for building built before 1979 2) the ones complying with Spanish Technical Code 2006. The research studies the adaptive thermal comfort alongside energy needs of the residential blocks. Based on the results, the study highlights the urgent need for area wide retrofitting of urban blocks in city of Madrid. The study stresses on the need to incorporate impact of climate change on urban environment before proposing plans for retrofitting buildings. The authors further argue that to achieve European objectives, retrofitting measures shall be evaluated against climate projections for 2050. This will allow for development of policies that enable energy rehabilitation of the buildings.

2.4. REVIEW OF THE METHODOLOGIES AND WORKFLOWS

Having a sound understanding of the local urban context, the next challenge that arise is the methodologies and workflows required to accurately study the impact of different planning strategies integrating both the urban environment and building physics. Natanian and Auer (2020) demonstrated a holistic workflow for design of nearly zero urban block using

EnergyPlus and Envi-met plugin in Rhino 3D and Grasshopper. The study's focus was simulating idealized urban forms for environmental performance assessment. The methodology tested various Floor Area ratio (FAR) and window to wall ratios (WWR) for different urban typologies. The results highlighted key performance indicators (KPI) and trade-offs. The study discusses limitations associated with computation resource intensity and on smoothness of workflow in simultaneously calculating outdoor thermal comfort, daylight and energy consumption. The research stresses on further investigating the performative impact of vegetation in urban generative design.

Alyakoob (2023) predicted the cooling loads for an office building in Arizona USA. The model used microclimatic parameters as independent variables (mean air temperature, mean absolute humidity, shading levels and direct shortwave radiation). The results of the study found out that reduced air temperature has a positive effect on cooling loads of the modelled buildings i.e., reduction in energy use. However, the machine learning approach relies on actual building energy consumption data which is not available in most studies. The research suggests exploring the impact of simulated scenarios generated by ENVI-met in future studies.

Ge et al. (2023) deployed the one way coupling of ENVI-met with EnergyPlus to assess cooling energy saving from vegetation planting in the city of Xian in China under hot climatic conditions. The simulation was based on 27 cases with three building density scenarios each simulated with 9 vegetation configurations. This resulted in sky view factor (SVF) of 0.41, 0.44, and 0.51 for three building configurations with leaf area index (LAI) ranging from 1.27 to 6.36. The research states that to account for impact of vegetation on microclimate, data from the simulation shall be extracted at the height below and top of the tree canopy and corresponding thermal zones (two zones in this study) at those heights shall be simulated for energy savings. The author also highlights that the method has advantage in quantification of change in energy demand at specific locations. The coupling was performed using Grasshopper and ladybug plugins. The simulations were performed for 31 hours for hottest day, 31st July obtained from the typical meteorological year (TMY) file. The results were analysed only for the last 24 hours. The ENVI-met version 4.4.6 and Energy Plus 8.9 were used. The vegetation configurations consisted of trees with different leaf area density (LAD) profiles. The study further suggests studying the impact of large urban greening on cooling energy demand.

Maronga, Winkler & Li (2022) developed a methodology to evaluate the impact of building retrofitting on the outdoor thermal comfort in the center of Berlin city, Germany. The methodology is based on PALM, LES model. The study mentions use of three models. Building surface model (BSM), land surface model (LSM) to calculate radiative temperatures for each surface and combine with Radiative transfer model (RTM) to calculate the energy balance. The RTM model is further coupled to provide radiative flux above the urban canopy layer. The methodology workflow also accounts for the waste heat flux from the air conditioning used by transferring it to the atmosphere. The author states that this waste heat is distributed equally over all surface elements as position of the air conditioning are usually unknown. OpenStreetMap was used to classify the materials used for horizontal surfaces. The study argued that as the focus was on an idealized case, data quality and correctness are not a primary concern. The simulation was done for 7 days for two different building construction materials. The findings of study points at investigating the observations provided in the climate and building context of Madrid, Spain.

Salvati & Kolokotroni (2023) utilized a UWG and one way coupling of ENVImet and EnergyPlus to study the energy demand and indoor thermal for comfort current and future weather files. The case study areas were Cadiz, Spain and London, United Kingdom. The methodology first used UWG to study UHI impact at local scale and then use ENVI-met to study spatial distribution of wind speed and direction at microscale to carry out accurate assessment of change in natural ventilation potential. The study calculated wind pressure using the output from ENVImet and compared it with the standard approach using undisturbed wind speed and pressure coefficients for assessment of ventilation potential. The study also highlights the effect wall temperature of surrounding buildings have on the thermal performance of the opposite facing buildings. The study used surrounding surface component in Energy plus to account for this. For the EnergyPlus simulations, the author combined the air temperatures from the UWG model and the surface temperatures from the ENVImet model to execute a more accurate calculation of radiation exchanges. The study concluded in observation of decrease in natural ventilation potential and as a result decrease in indoor thermal comfort providing notion of whether building retrofitting is suitable with climate change considerations. In the present study this is further studied and potential of planning strategies in improving the outdoor environment and subsequently the natural ventilation potential is evaluated.

2.5. SUMMARY OF LITERATURE REVIEW AND RESEARCH GAPS

Considering the literature review conducted it is imperative that to achieve the climate neutrality by 2050, urban issues diminishing the efficacy of energy efficiency measures shall be addressed holistically. This includes the effect of UHI on energy demand, indoor and outdoor thermal comfort. These challenges if not addressed holistically can intensify the energy consumption, energy poverty and impact of local climate change. Several research have shown the impact of UHI on the above-mentioned urban challenges, and it is quite significant. Under climate change influence, the vulnerable population will be suffering the most because of low income, living in buildings with poor energy performance and the growing issue of ageing in European population. With this regard, several studies have been done in Madrid city to map areas vulnerable to energy poverty and UHI effect has been well studied. Study of climate trends also indicates rising temperatures and lowering relative humidity indicating to a warmer and drier future. To adapt to these challenges, the research has proposed several planning strategies that include retrofitting measures at building scale to address the issue of energy efficiency. To reduce the impact of UHI, studies have also researched the mitigation potential of reflective "cool" material and vegetation and proposed recommendations. However, adapting these strategies without evaluation under the local urban context can have implications. Research has shown that addition of insulation can result in decoupling of inner and outer wall worsening the outdoor thermal comfort. Also subject to influence is indoor thermal comfort, as heat is observed to be trapped inside retrofitted buildings. This is further amplified as potential of natural ventilation is reduced under future climate change scenarios due to higher temperatures in outdoors even at night in summers. Similarly, although vegetation has been proven to improve the outdoor thermal comfort, but planning vegetation with only this aspect in consideration can minimize the benefits that vegetation can provide for buildings through shading and reducing the LW exchange between surfaces. Studies that research these aspects comprehensively are required. Therefore, this study is an attempt to bridge the knowledge gap highlighted throughout the Chapter 2 and with the findings and discussion in Chapter 3 and 4 endeavours to provide insights to urban planners and building energy modellers. This study strives to expedite the progress towards improved urban climate and sustainable cities.

CHAPTER 3: METHODOLOGY

This chapter describes the methodology adopted and the workflow developed to study the research objectives. To achieve the aim of the study, it was divided phases. Study design phase focused on selection and retrieving information of case study area. Phase 1 was related to the assessment of the impact of urban microclimate and Phase 2 was associated with optimization of the urban environment and quantifying its effect on the cooling energy demand, indoor operative temperatures and outdoor thermal comfort. Figure 1 outlines the workflow executed in this study.

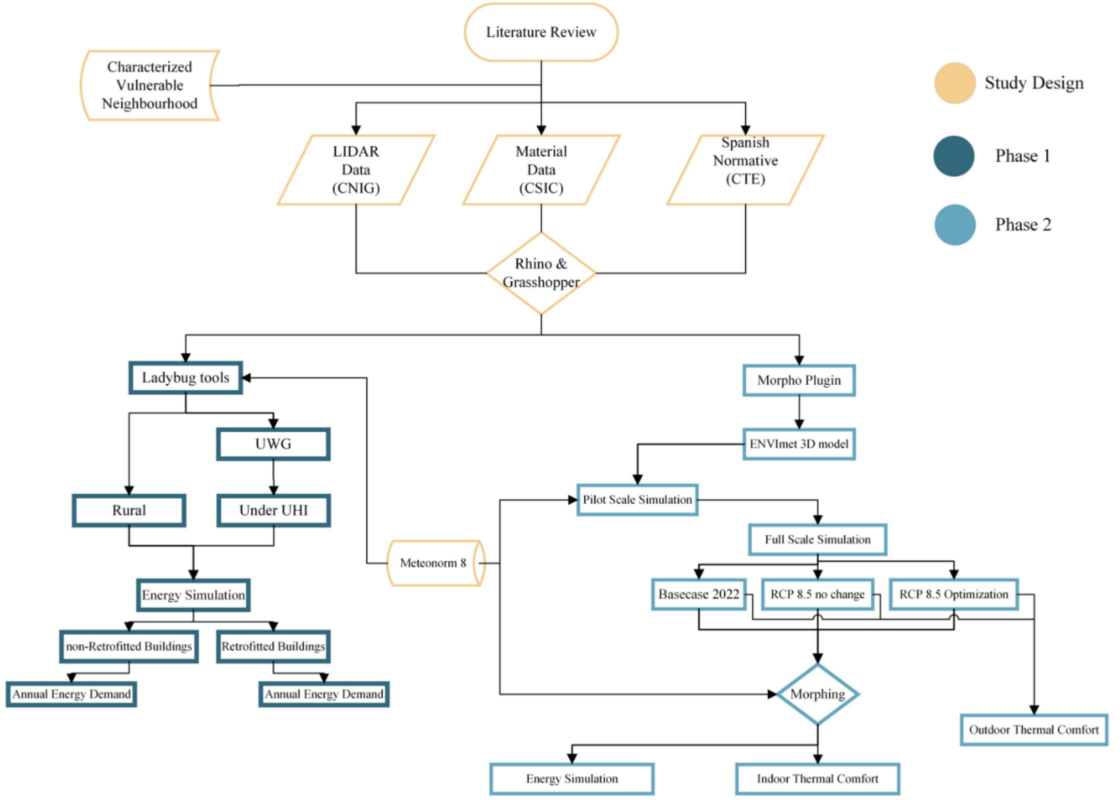


Figure 1: Outline of methodology workflow

3.1. CASE STUDY AREA

The case study area chosen for this research is called Barrio Orcasur and is in the south of Madrid City. Madrid and its metropolitan area have a Mediterranean climate i.e., Koppen classification of Csa which transitions to a cold semi-arid climate (BSk), with mild cool winters and hot summers. The focused study area consists of buildings mostly built before 1979 and was chosen based on the review of the studies conducted to characterize the different neighbourhoods of Madrid city for energy poverty, urban heat island impact and energy inefficiency and the classification of the residential urban areas according to representative Homogeneous Urban Zones (HUZ). (López Moreno,.2020) studied the influence of urban morphologies on the microclimate and classification of residential areas according to HUZ (López-Moreno *et al.,* 2022), (Martín-Consuegra *et al.,* 2020) researched on spatial data analysis for eradication of fuel poverty in urban retrofitting and (Soutullo *et al.,* 2020) conducted a study on impact of thermal performance of building under climate trends. The case study area is also chosen as one of two areas focus of URBAN therCOM (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, 2022), part of mateMAD coordinated project (PID2020-114873RB-C31). Overall, the general aim of MateMAD focuses on optimizing urban materials for more liveable and sustainable cities whereas URBAN therCOM focuses on executing the modelling of outdoor thermal comfort and energy demand in urban areas with a comprehensive digital workflow that implements mutual relationships between these two aspects and relevant urban factors such as microclimate, materials and typologies. This research study is aligned with the subproject (SP) 3 that is associated with developing a modelling approach for evaluation of the effect of material substitution on outdoor environment quality and energy demand. However, this study further introduces another aspect| of UGI and investigates how if planned alongside area wide building retrofitting can tackle the adverse impacts researched in the literature reviewed in Chapter 1.

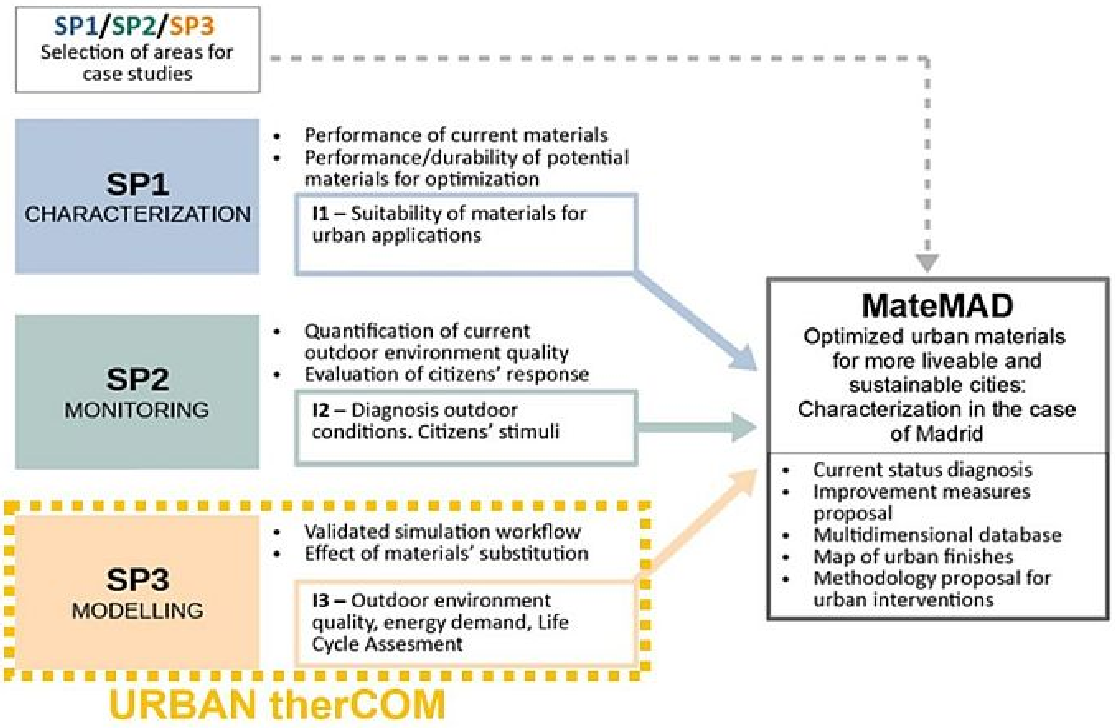


Figure 2: The multidisciplinary approach of the mateMad project strategy and the objective of the URBAN therCOM subproject

3.2. SUMMARY OF THE WORKFLOW

The first step in developing the simulation workflow was to obtain information regarding the built environment and urban area. This included information on building footprint and the information on vegetation type and heights. Using the LIDAR data obtained from (Organismo autónomo centro nacional de información geográfica, 2021), this information was extracted at a resolution of 5m. ArcGIS Pro was used to process the LIDAR data and to extract the necessary data using spatial analyst tools.

The spatial information was utilized to develop a 3D model in Rhinoceros (Rhino), a computer aided design (CAD) software. Grasshopper, a visual programming interface was used to import the geometry and to develop ENVImet and dragonfly models for microclimate and energy simulations. Morpho Plugin integrates ENVImet within the grasshopper environment and enables development of INX files (ENVImet models), assignment of simulation parameter (SIMX files) and execution of simulations. The surface material characteristics were provided by authors of the research study conducted on opaque materials in Madrid (Pérez *et al.,* 2022), member of consortium of mateMAD project as Eduardo Torroja Institute of Construction Sciences of Spanish National Research Council (CSIC).

The ladybug tools (ladybug, honeybee, dragonfly) allow environmental analysis and integration with engines like Radiance and EnergyPlus for ray tracing and energy simulations. In this study, an additional simulation interface (Urban Renewable Building and Neighbourhood optimization) URBANopt (URBANopt, 2022) was used to study the energy modelling at an urban block scale which is not yet feasible with standalone Open studio and EnergyPlus. Furthermore, dragonfly component provides access to Urban weather generator, a python-based tool to modify the EPW files accounting for the UHI impact. During the phase 1 of the study, UWG was used to study the impact UHI has on energy demand for actual TMY files and future weather files for RCP 8.5 scenario 2050. To assess the energy performance of the building models, one reference TMY and one climate change morphed RCP 8.5 2050 file provided by the climate database of the Meteonorm 8 has been used. Building retrofitting strategies under reference and extreme future climatic conditions were evaluated. Building related information such as window to wall ratio, solar heat gain coefficient, ventilation and infiltration rates, natural ventilation schedule, occupancy schedules were based on previous research conducted in Madrid city on characterization of building and information provided by Spanish technical code on buildings built before 1979 and new legislation based on the 2006 version of the code.

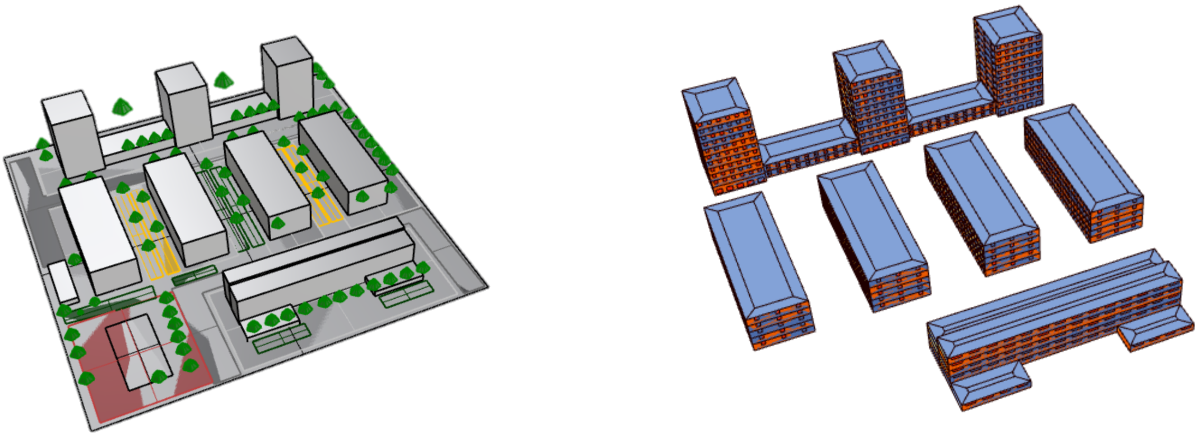
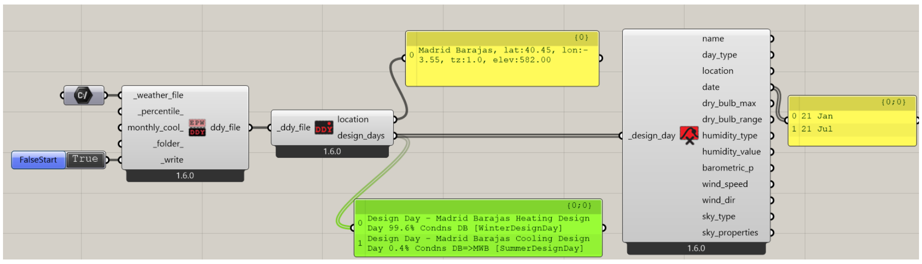


Figure 3: Rhino 3D model(left) and Dragonfly model (Right)

In phase 2 related to optimization of the urban environment, the output from ENVImet simulations was used as input for energy demand assessment, indoor and outdoor thermal comfort assessment. This was done for 8 pilot scale scenarios and based on the finding of pilot scale study, 3 additional full-scale scenarios were run. Elements software was used to modify the EPW files for the 21st July i.e., design day extracted from ddy file generated from EPW. The output from ENVImet simulations was further used to calculate outdoor thermal comfort.



```
{0}
0 Madrid Barajas, lat:40.45, lon:-
  3.55, tz:1.0, elev:582.00
```

```
{0;0}
0 Design Day - Madrid Barajas Heating Design
  Day 99.6% Condns DB [WinterDesignDay]
1 Design Day - Madrid Barajas Cooling Design
  Day 0.4% Condns DB=>MWB [SummerDesignDay]
```

```
{0;0}
0 21 Jan
1 21 Jul
```

Figure 4: Design Day extraction from EPW files

3.3. COMPARISON OF MICROCLIMATE TOOLS USED

The study uses urban weather generator and ENVImet tools for microclimate simulation and EnergyPlus and supporting API to run urban building energy simulation. Several studies have reviewed the strengths and weakness of these tools. Therefore, the emphasis is on the suitability of the tools for the aim and objectives of this research. Much of the debate in the suitability of microclimate simulation tools is the compromise between computational cost and accuracy. While more accurate tools include, computational fluid dynamics (CFD), Weather Research and Forecasting (WRF), ENVImet etc, physics-based tools like Urban weather generator developed by Bueno (2012) lower the computational cost and therefore increase the temporal and spatial scale. (Mao & Norford, 2021) argue that seeking the best simulation tool at the planning stage might be counterproductive as no system behaves like its model and it may lead to “overengineering”.

However, this study explores the applicability of both physics based and CFD based tools exploring various spatial temporal scales and accuracies. As discussed in Chapter 1, UHI can have a net positive or a net negative impact on energy demand as nighttime UHI can lower the heating energy demand. Studying this phenomenon at annual temporal scales using CFD based tools is nearly impossible as only representative weeks or days can be studies and less can be said about the annual energy demands. Therefore, in phase 1 first assessment of UHI for two different climate files against retrofitting strategy focused on heating demand were carried out using UWG. Phase 2 was concerned with quantifying the benefit of sustainable urban planning controls which primarily included reflective materials and UGI. UWG doesn’t perform well in quantifying the evapotranspiration and shading effect of trees and does not account for moisture balance. As the goal was accurately assessing the impact of vegetation and reflective materials on microclimatic parameters, therefore ENVI-met was the tool of choice. Furthermore, as the phase 2 was further divided into pilot scale and full-scale study, the workflow utilized both simple forcing and full forcing. This allows for studying many variations in scenarios with less accuracy and based on the findings narrowing down the scenarios. Overall, the study demonstrates a progressive approach benefitting from all the functionality of latest tools easily accessible.

3.4. DRAGONFLY MODEL DEVELOPMENT

Dragonfly plugin in Ladybug tools allows development of the model that can be taken as an input to UWG module for studying UHI impact and Urban opt module for urban block building energy modelling.

	Parameter	Case 1979	Case 2006
Building Properties	Perimeter Offset	4	4
	Conditioned	No	No
	Floor to floor	3	3
	Exterior Wall (U-value)	2.2. W/m²K	0.57 W/m²K
	Ventilation Control	26	26
	Building shading distance	50 meters	50 meters
Program Type	Occupancy Schedule	Midrise Apartment (ASHRAE)	Midrise Apartment (ASHRAE)
	Infiltration	0.0008 m3/m2	0.0003 m3/m2
	Ventilation	4 ac/h	4 ac/h
	Cooling Setpoint	26 °C	26 °C
	Heating Setpoint	21 °C	21 °C

Table 1: Building properties

The perimeter offset of 4 was based on the research conducted by Natanian and Auer (2020). The ventilation, infiltration and cooling setpoints were set according to the guidelines by Spanish Technical Code (Ministerio de Transportes, Movilidad y Agenda Urbana, 2006) according to the specification defined for buildings built before 1979 and according to the code published in 2006 which was the reference for simulation of retrofitted buildings.

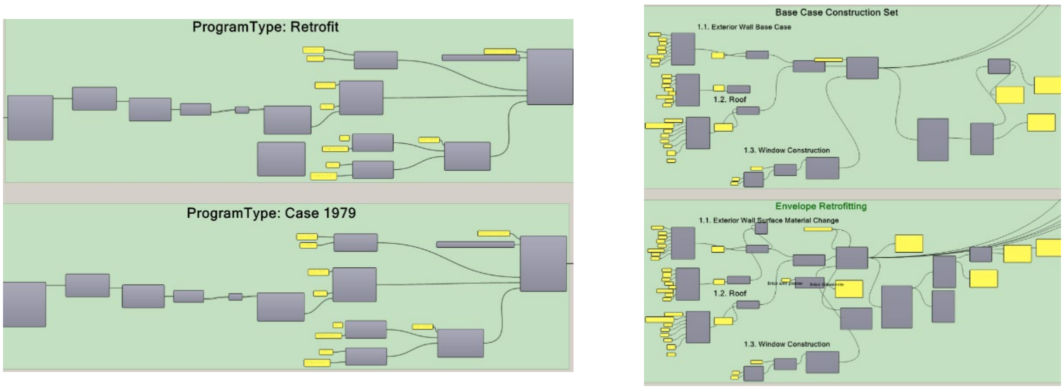


Figure 5: Example workflow to generate building program types and constructions sets for two building construction type cases i.e., 1979 and 2006.

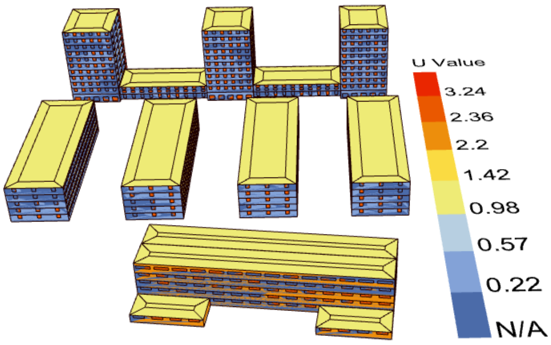


Figure 6: U-value of the construction material used in the model for different structural elements.

3.5. URBAN WEATHER GENERATOR (UWG)

As described in the previous sections, UWG is a physics-based microclimate simulation tool that bridges the gap between building physics and urban microclimate (Bueno *et al.,* 2012). The UWG consists of four modules that generates UHI profile based on rural data and urban site information (Mao and Norford,2021).

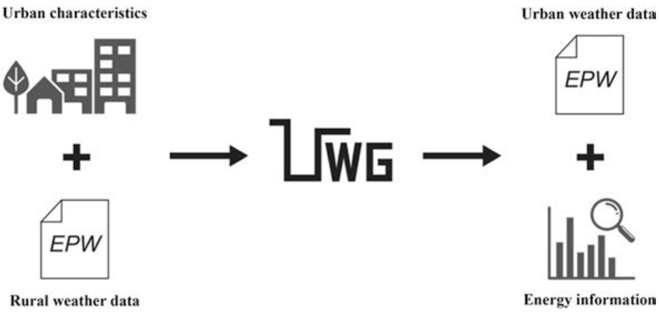
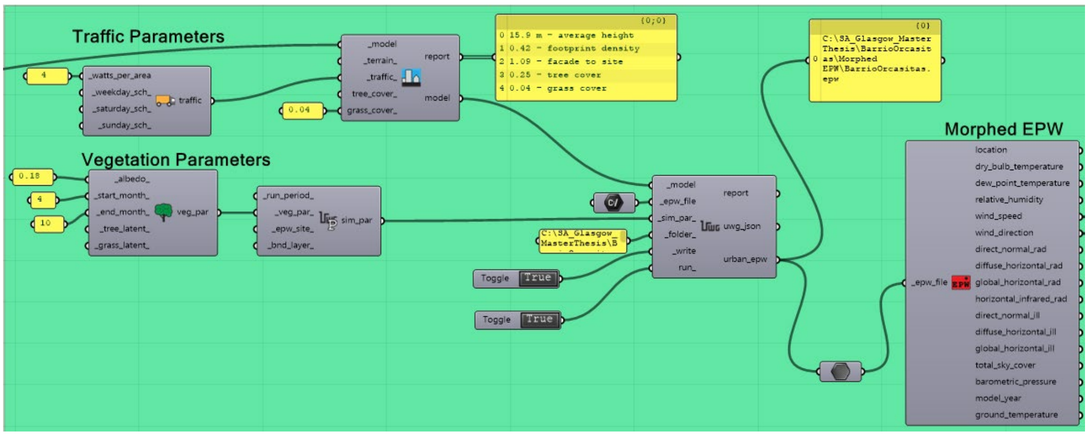


Figure 7: Schematics of Urban Weather Generator (UWG)

(Extract from Palme and Salvati, 2021, p.253, fig. 15.5)

Integration of UWG within Dragonfly plugin of Ladybug tools facilitates both the urban designers and building energy modellers to study UHI at large temporal and spatial scales. A detailed review performed of UWG by Mao and Norford (2021) concludes that the simplified parametrization used in UWG might be suitable for use in early design stages but might not perform well enough in advanced analysis for deeper understanding. Several recent studies have demonstrated the use of UWG to study urban microclimate impact and its impact on energy demand, indoor and outdoor thermal comfort (Cascone & Leuzzo, 2023, Khraiwesh & Genovese, 2023, Salvati & Kolokotroni, 2023, Salvati et al., 2020, Naboni *et al.,* 2019).

Based on this analysis, UWG was used in the phase 1 of the study to evaluate the impact of UHI and to generate modified EPW files.



```
{0;0}
0 15.9 m - average height
1 0.42 - footprint density
2 1.09 - facade to site
3 0.25 - tree cover
4 0.04 - grass cover
```

```
{0}
0 C:\SA_Glasgow_MasterThesis\BarrioOrcasitas\Morphed EPW\BarrioOrcasitas.epw
```

Figure 8: Grasshopper UWG workflow

Average Height of Buildings	16.3 meter
Footprint density	0.4
Aspect Ratio	0.75
Façade to site ratio	1.07
Tree Cover	0.23
Grass Cover	0.04

Table 2: UWG model properties

Vegetation Albedo	0.18
Evapotranspiration start month	4
Evapotranspiration end month	10

Table 3: Vegetation properties for UWG as per the base case

Waste heat generated from air conditioning was accounted as a fraction of 0.25 each building. The fraction indicates the use of air conditioning systems. The anthropogenic heat from traffic vehicles was also accounted by using a value of 4 suggested by the UWG model for a typical neighbourhood.

3.6. ENVI-MET DESIGN SCENARIOS

As discussed in section 3.2., ENVI-met simulation was divided into two parts: i) Pilot Scale study ii) Full Scale Study. The table 4 summarizes the setting for geometry and simulation files for both cases.

Property	Pilot Scale	Full Scale
Grid Dimensions	100 x 80 x 30 Grids	129 x 123 x 36
X, Y and Z grid sizes	dx, dy, dz = 2 meter	dx, dy, dz = 2 meter
Core XY domain size	200m x 160m	258 x 246 m
Highest Building in domain	16 m	34 m
Simulation Day	21st July 2022	21st July 2050
Simulation Time	30 hours	30 hours
Start Time	00:00:00	00:00:00
Forcing Type	Simple forcing	Full Forcing
Data to be forced	-	1)Wind 2) Air temperature 3) Radiation/Clouds 4) Relative Humidity

Table 4: ENVImet model and simulation settings

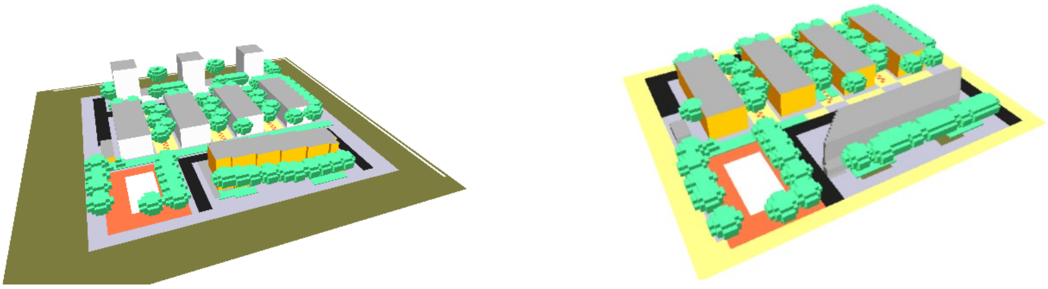
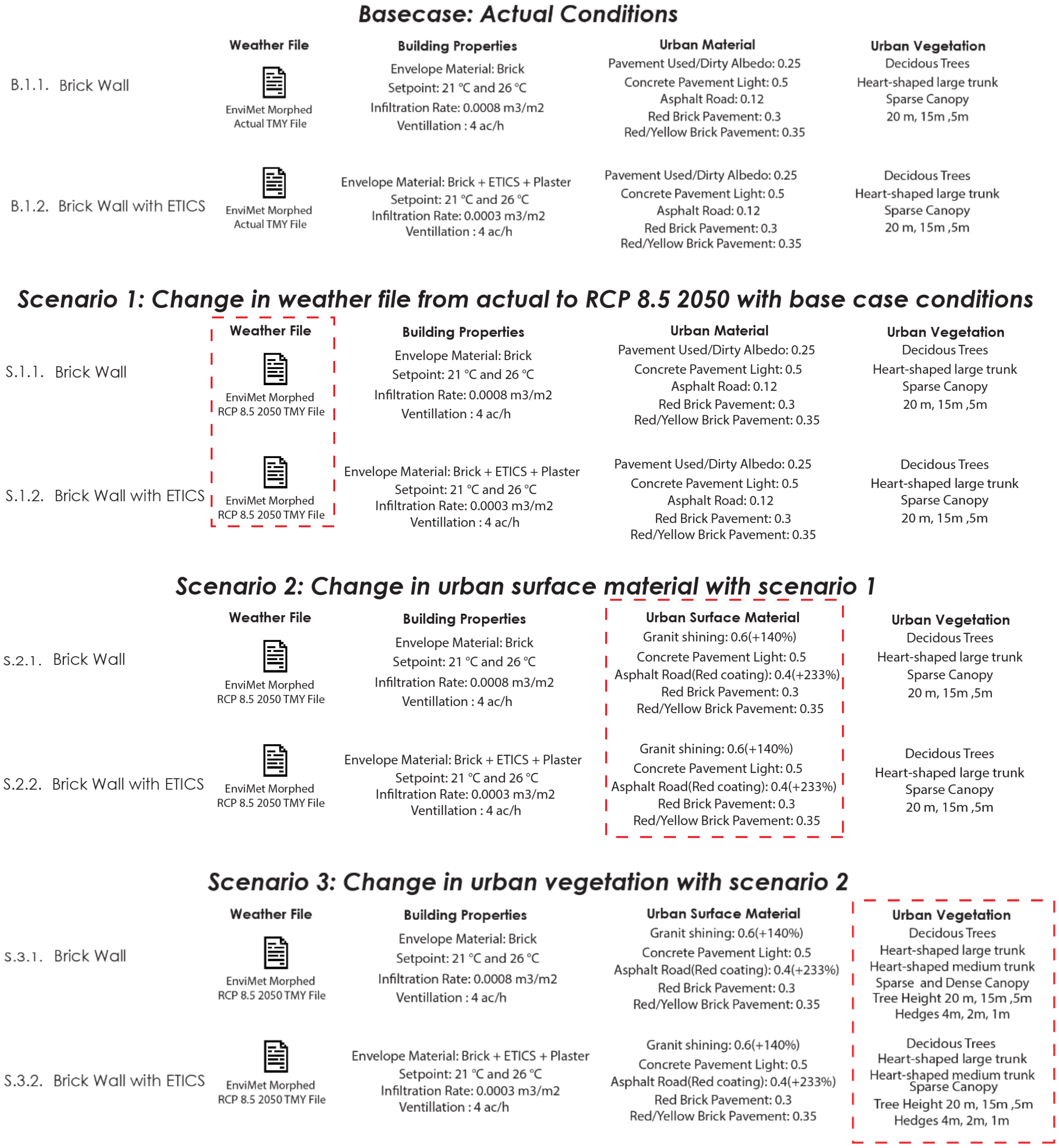


Figure 9: ENVImet V5.5.1 model Full scale(left) and Pilot scale (right)



Basecase: Actual Conditions

	Weather File	Building Properties	Urban Material	Urban Vegetation
B.1.1. Brick Wall	EnviMet Morphed Actual TMY File	Envelope Material: Brick Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0008 m3/m2 Ventillation : 4 ac/h	Pavement Used/Dirty Albedo: 0.25 Concrete Pavement Light: 0.5 Asphalt Road: 0.12 Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Sparse Canopy 20 m, 15m ,5m
B.1.2. Brick Wall with ETICS	EnviMet Morphed Actual TMY File	Envelope Material: Brick + ETICS + Plaster Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0003 m3/m2 Ventillation : 4 ac/h	Pavement Used/Dirty Albedo: 0.25 Concrete Pavement Light: 0.5 Asphalt Road: 0.12 Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Sparse Canopy 20 m, 15m ,5m

Scenario 1: Change in weather file from actual to RCP 8.5 2050 with base case conditions

	Weather File	Building Properties	Urban Material	Urban Vegetation
S.1.1. Brick Wall	EnviMet Morphed RCP 8.5 2050 TMY File	Envelope Material: Brick Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0008 m3/m2 Ventillation : 4 ac/h	Pavement Used/Dirty Albedo: 0.25 Concrete Pavement Light: 0.5 Asphalt Road: 0.12 Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Sparse Canopy 20 m, 15m ,5m
S.1.2. Brick Wall with ETICS	EnviMet Morphed RCP 8.5 2050 TMY File	Envelope Material: Brick + ETICS + Plaster Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0003 m3/m2 Ventillation : 4 ac/h	Pavement Used/Dirty Albedo: 0.25 Concrete Pavement Light: 0.5 Asphalt Road: 0.12 Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Sparse Canopy 20 m, 15m ,5m

Scenario 2: Change in urban surface material with scenario 1

	Weather File	Building Properties	Urban Surface Material	Urban Vegetation
S.2.1. Brick Wall	EnviMet Morphed RCP 8.5 2050 TMY File	Envelope Material: Brick Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0008 m3/m2 Ventillation : 4 ac/h	Granit shining: 0.6(+140%) Concrete Pavement Light: 0.5 Asphalt Road(Red coating): 0.4(+233%) Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Sparse Canopy 20 m, 15m ,5m
S.2.2. Brick Wall with ETICS	EnviMet Morphed RCP 8.5 2050 TMY File	Envelope Material: Brick + ETICS + Plaster Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0003 m3/m2 Ventillation : 4 ac/h	Granit shining: 0.6(+140%) Concrete Pavement Light: 0.5 Asphalt Road(Red coating): 0.4(+233%) Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Sparse Canopy 20 m, 15m ,5m

Scenario 3: Change in urban vegetation with scenario 2

	Weather File	Building Properties	Urban Surface Material	Urban Vegetation
S.3.1. Brick Wall	EnviMet Morphed RCP 8.5 2050 TMY File	Envelope Material: Brick Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0008 m3/m2 Ventillation : 4 ac/h	Granit shining: 0.6(+140%) Concrete Pavement Light: 0.5 Asphalt Road(Red coating): 0.4(+233%) Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Heart-shaped medium trunk Sparse and Dense Canopy Tree Height 20 m, 15m ,5m Hedges 4m, 2m, 1m
S.3.2. Brick Wall with ETICS	EnviMet Morphed RCP 8.5 2050 TMY File	Envelope Material: Brick + ETICS + Plaster Setpoint: 21 °C and 26 °C Infiltration Rate: 0.0003 m3/m2 Ventillation : 4 ac/h	Granit shining: 0.6(+140%) Concrete Pavement Light: 0.5 Asphalt Road(Red coating): 0.4(+233%) Red Brick Pavement: 0.3 Red/Yellow Brick Pavement: 0.35	Decidous Trees Heart-shaped large trunk Heart-shaped medium trunk Sparse Canopy Tree Height 20 m, 15m ,5m Hedges 4m, 2m, 1m

Figure 10: Pilot scale scenarios

The mitigation strategies simulated such as reflective material and dense trees along with low vegetation were based on the research conducted by Salvati et.al. (2022), (Tsoka, S., Leduc and Rodler, 2021) and Santamouris (2016). Salvati et.al. (2022) recommended the use of high road reflectivity with lower façade reflectivity as the optimal strategy to reduce the air temperature in the street canyon for the climate setting of London. (Tsoka, Leduc and Rodler, 2021) assessed the impact of foliage density on the cooling energy saving potential and concluded that as LAD value increases by 1 m2/m3 the average daily reduction in air temperature of 0.22 and 0.15 for specific floors in the studied building. The higher energy savings of up to 54% were achieved when trees formed a continuous canopy and found a direct correlation between foliage density and estimated cooling energy saving. However, the study did not study the long wave exchanges that occur between the surfaces and lower floors and how this can be tackled using planting low vegetation such as hedges of 4m, 2m, 1m etc which can provide comfort at pedestrian height at the same time reducing the view factors between surfaces. This was tested additionally in this study. The strategies reviewed in this study and adopted for the methodology are also suggested by Santamouris (2016) as means to tackle energy poverty, building energy consumption and urban heat island.

#	Scenario	Weather File	Building Material	Surface Material	Vegetation
1	Base Case 2022	Reference TMY	Retrofitted Building (Case 2006): ETICS Context Building (Case 1979): Brick	Actual Condition	Actual Condition
2	RCP 8.5 no change	RCP 8.5 2050	Retrofitted Building (Case 2006): ETICS Context Building (Case 1979): Brick	Actual Condition	Actual Condition
3	RCP 8.5 Reflective material with dense trees and low vegetation	RCP 8.5 2050	Retrofitted Building (Case 2006): ETICS Context Building (Case 1979): Brick	Reflective Roads Albedo 0.4 (Salvati et.al, 2022)	• Abstract Dense Trees forming continuous canopies (Tsoka, Leduc and Rodler, 2021) • Hedges(4m,2m,1m)

Figure 11: Description of full scale ENVImet simulation scenarios.

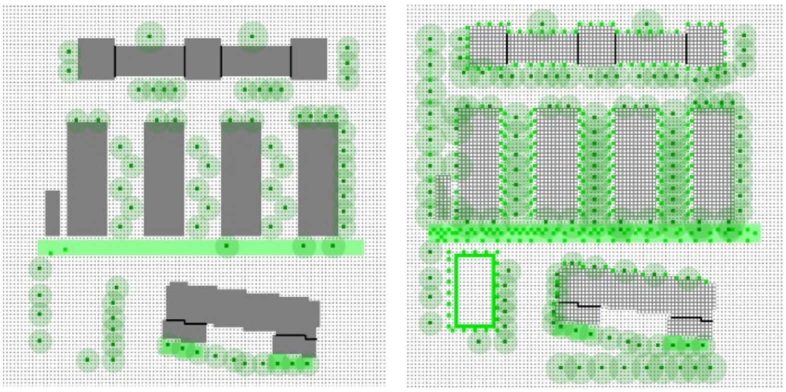
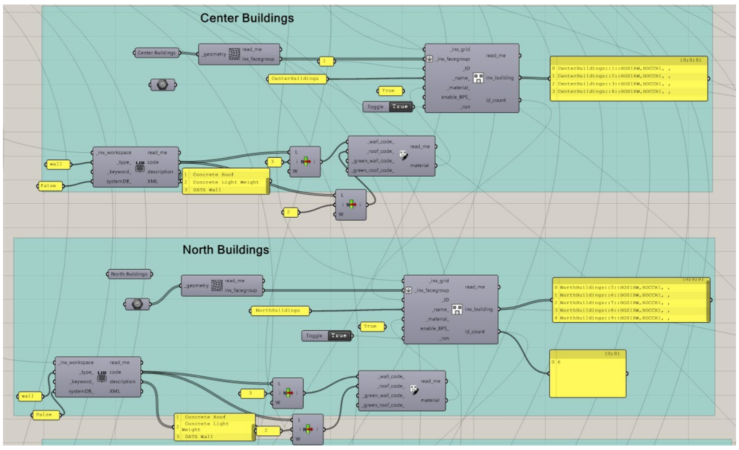


Figure 12: ENVImet base case (Actual and RCP 8.5) and Optimized scenario (RCP 8.5 2050)

Finally, to ensure that the simulations are run smoothly without increasing the computational cost, two things were ensured 1) Sudden changes in wind direction were identified using simulation check in ENVImet core and were modified 2) Model Inspector was used to ensure that enough space was provided for the stabilization of flows without use of nesting grids.



```
{0;0;0}
0 CenterBuildings::1::BOS1BW,BOCCR1, ,
1 CenterBuildings::2::BOS1BW,BOCCR1, ,
2 CenterBuildings::3::BOS1BW,BOCCR1, ,
3 CenterBuildings::4::BOS1BW,BOCCR1, ,
```

```
1 Concrete Roof
2 Concrete Light Weight
3 SATE Wall
```

```
{0;0;0}
0 NorthBuildings::5::BOS1BW,BOCCR1, ,
1 NorthBuildings::6::BOS1BW,BOCCR1, ,
2 NorthBuildings::7::BOS1BW,BOCCR1, ,
3 NorthBuildings::8::BOS1BW,BOCCR1, ,
4 NorthBuildings::9::BOS1BW,BOCCR1, ,
```

```
{0;0}
0 6
```

```
1 Concrete Roof
2 Concrete Light
Weight
3 SATE Wall
```

Figure 13: Morpho Workflow to develop and simulate ENVImet scenarios.

The overall workflow was carried using Morpho plugin in Rhino 3D programming interface, Grasshopper. Custom wall material consisting of External thermal insulation composite system was generated in ENVImet Database for retrofitted buildings.

3.7. ENERGY DEMAND AND INDOOR OPERATIVE TEMPERATURES

The process of energy demand and indoor operative temperatures started with development of dragonfly model using the grasshopper workflow which is discussed in the section 3.4. In comparison to all the previous research studies conducted following the one-way coupling approach, this study combined the ENVImet with an application programming interface

URBANopt (URBANopt, 2022). Recent studies have researched the integration of URBANopt in district scale planning and design (Charan *et al.,* 2021) and on studying design for zero energy and carbon at multiscale building (Fallahi *et al.,* 2022). This integration enables simulation at large urban scales which standalone EnergyPlus is not yet capable of handling.

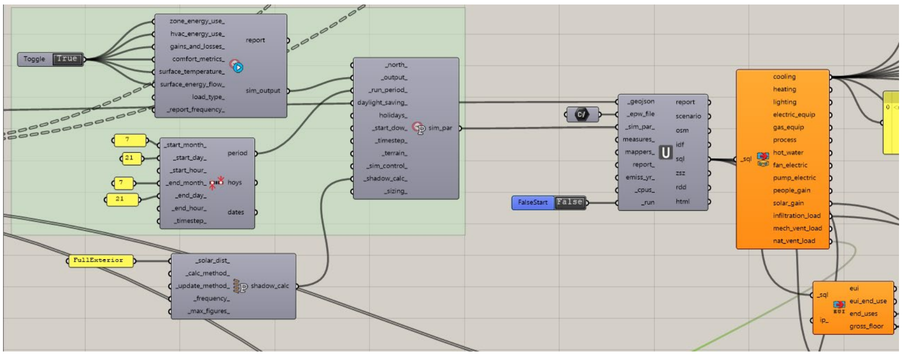


Figure 14: Energy demand assessment workflow

As shown in figure 14, the URBANopt component takes input as geojson file generated in section 3.4 along with simulation parameters and EPW file. The geojson file contains the information related to building geometry and properties along with exact location. The simulation parameters contain information about which parameters to calculate (such as zone energy use, comfort metrics, surface temperatures etc) and information on analysis period that was 21st July as design day. The EPW files contains the weather information. The two weather files used (TMY reference and RCP 8.5 2050 files) were manually morphed based on each one of the ENVImet simulation performed (in total 11 (8 Pilot scale + 3 Full Scale)) for phase 2. In contrary to this, in phase 1 the UWG automatically morphed the weather file to incorporate the UHI impact. The energy demand was derived from the read room energy results and the indoor operative temperatures were derived from the read room comfort results component.

3.8. OUTDOOR THERMAL COMFORT ASSESSMENT

Parameters	Static PET	Dynamic PET
Person	Old Person, male (80-year-old)	Old Person, male (80-year-old)
Clothing	0.5 clo	0.5 clo
Time	17:00:00	17:00:00
Vertical Range of analysis	Up to 1.4 meter	-
Starting Climate Environment	-	Neutral
Route	-	See Figure 15

Table 5: Thermal comfort simulation settings

For outdoor thermal comfort analysis, Physiological Equivalent Temperature (PET) was used as the metric. Both static PET and dynamic PET which is a new feature in version 5.5 of ENVImet were used. The settings used are described in the table 5. The reason for selection of an old person for simulation was that one of the characterization parameters of the study area as vulnerable was the population age > 65 in these areas (Martín-Consuegra *et al.,* 2020). Summer clothing indicated by 0.5 clo was used as the simulation was done for the hottest day of the TMY files 21st July. The hour was chosen as 1700 based on the initial analysis of the temperature profile through the day and highest temperatures were recorded at this and the adjacent hours. Vertical range of analysis was 1.4 as this is height of human perception. For dynamic PET (dPET), for the starting climate environment, the, neutral(no thermal stress) were assumed. For the chosen route of walk, it was designed to cover most of the study area to assess the change in comfort. Stops were made in open areas and range of comfort was assessed between the base case scenarios and the optimization scenario.

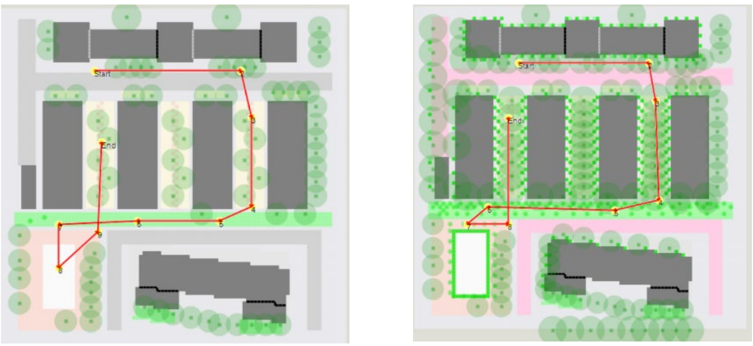


Figure 15: Virtual Walk routes for base case and optimized scenarios

CHAPTER 4: RESULTS AND DISCUSSION

4.1. BOUNDARY CLIMATE CONDITIONS FOR THE CASE STUDY AREA

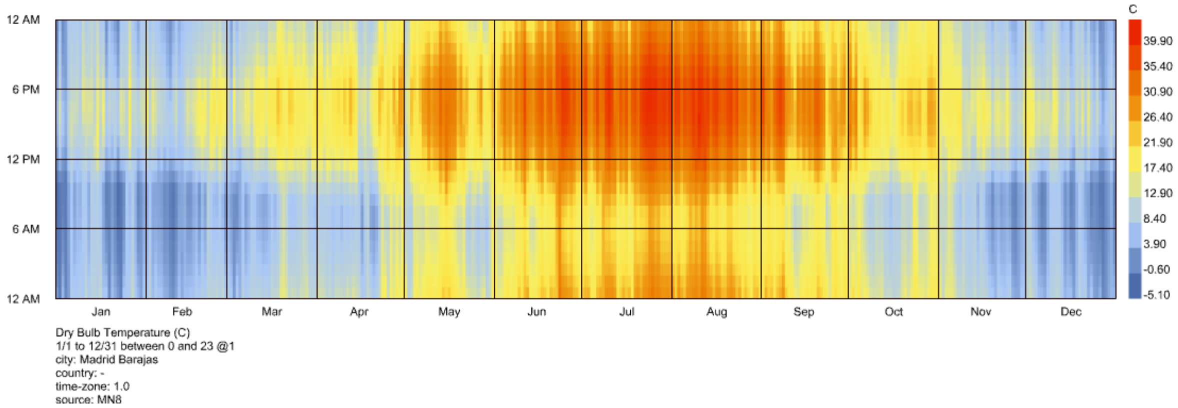


Figure 16: Annual Dry bulb temperature of Madrid City

The Madrid city is in climate zone 3B according to ASHRAE climate classification. The analysis of the rural EPW file obtained from Meteonorm 8 (2023) provides a broad picture of the Mediterranean climate of Madrid City for the reference TMY file. The highest temperature recorded are observed to be 39.90 °C and the minimum as -5.10 °C. The hottest week recorded is between 20 and 26 July while the coldest week is recorded between 22 and 28 December for reference TMY file. The results of the RCP 8.5 2050 are shown in figure 27.

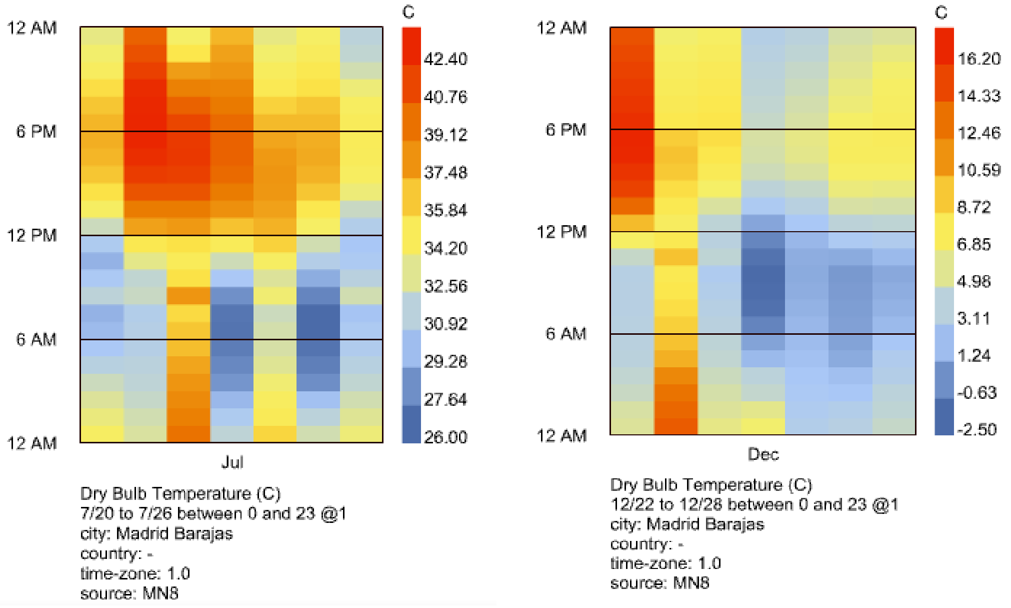


Figure 17: Hottest and coldest week from the TMY file.

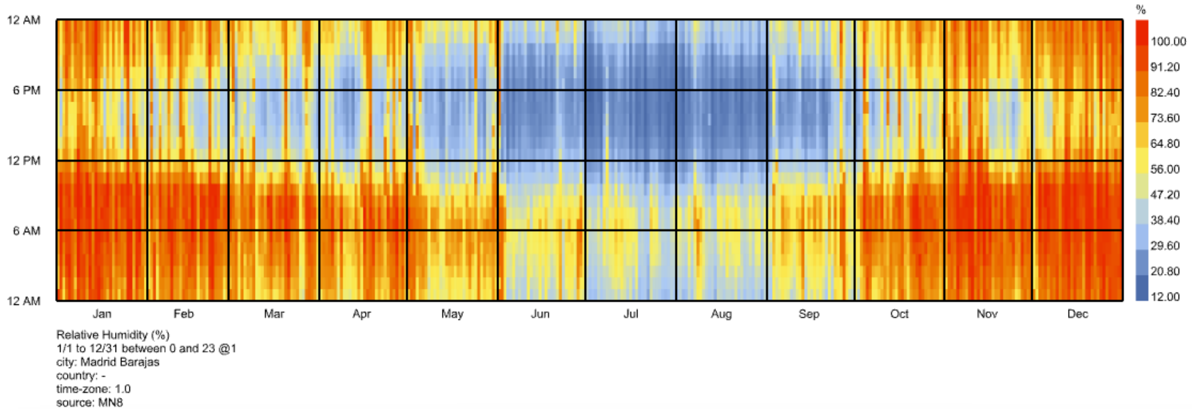


Figure 18: Annual variation of Relative humidity %

From figure 18, it can be inferred that relative humidity is higher in winter months and lower in summer months. During the summers, the values between 12 pm and 12 am are much lower while the dry bulb temperatures are higher as shown in Figure 16.

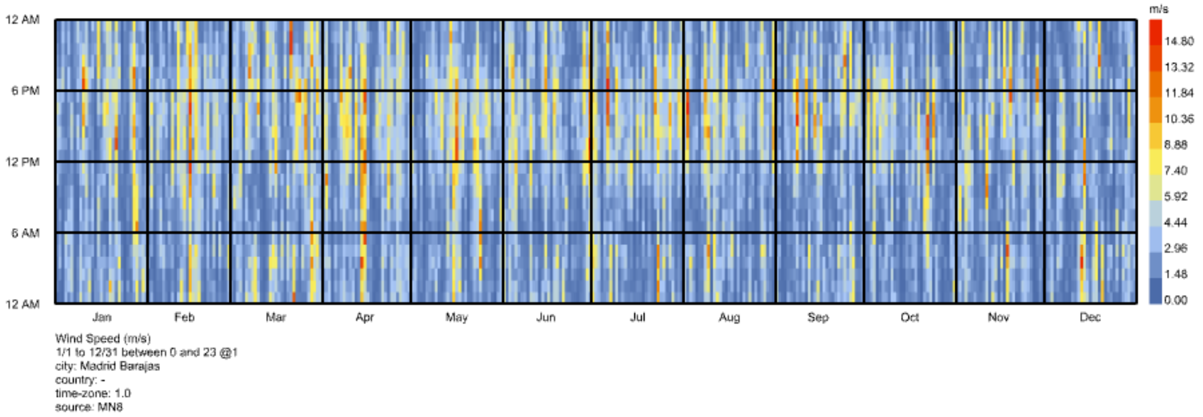
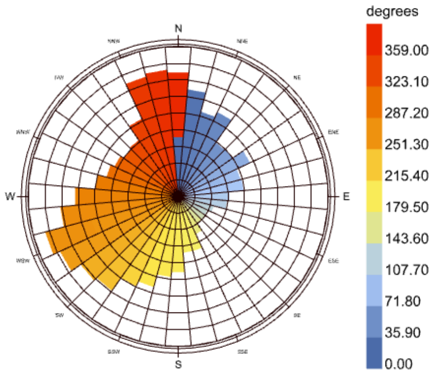


Figure 19: The wind speed variation for climatic context of Madrid City

The wind speeds measured in m/s varies from 14.8 to 0.00 anually. It can be seen in figure 19, that on average the wind speeds are between 1.48 m/s and 4.44 m/s. While Figure 20 shows the prevailing wind directions across the year.



Wind Direction (degrees)
city: Madrid Barajas
country: -
time-zone: 1.0
source: MN8
period: 1/1 to 12/31 between 0 and 23 @1
Each closed polyline shows frequency of 0.6% = 50 hours.

Figure 20: Wind rose for wind directions for the yearly data.

4.2. IMPACT OF URBAN HEAT ISLAND (UHI) ON BUILDING PERFORMANCE

4.2.1. ANNUAL VARIATION OF UHI INTENSITY

Using UWG, the workflow generated morphed weather file to account for the impact of UHI for the current climatic conditions. The nighttime UHI can be clearly seen from figure 21 and 22. The strongest effect can be seen between midnight which increases till after the sunrise and then almost no difference is seen during the daytime as depicted in Figure 22. The highest differences in temperature and frequency of occurring can be seen in the months of June and July. The maximum difference recorded is simulated as +12.9 in summer and -3.2 in winter.

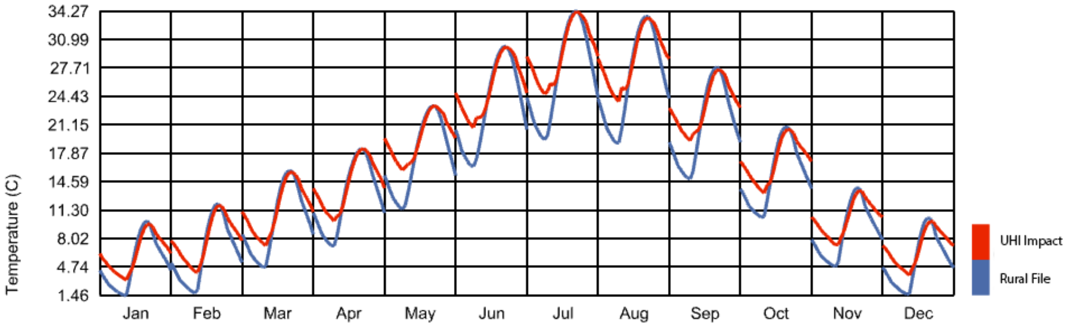


Figure 21: Comparison of UHI morphed file and rural file for dry bulb temperatures for monthly per hour values using reference TMY

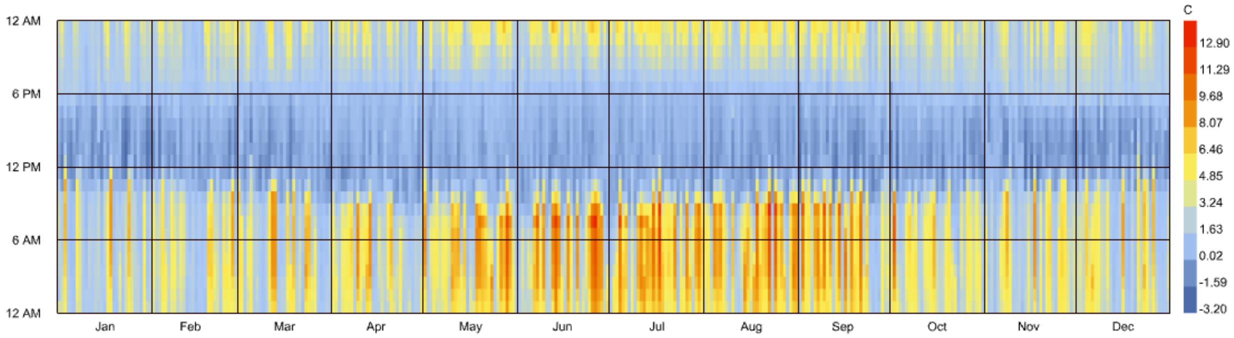


Figure 22: The difference in dry bulb temperature for morphed and rural file.

4.2.2. ENERGY DEMAND UNDER CURRENT WEATHER CONDITIONS

For the reference TMY file without UHI impact, the annual cooling energy demand and heating demand normalized by gross floor area were simulated as 91.3 kWh/m^2/year and 185.9 kWh/m^2/year. The gross floor area was calculated as 51,032 m^2. The highest monthly cooling is observed in the month of July with peak monthly demand for heating in December. The table 6 summarizes the annual heating and demand values for rural and morphed files for base case and retrofitted buildings.

Energy Demand(kWh/m2/y)	Current Weather file	Current Weather File + UHI	Current Weather File + UHI + Retrofitting
Cooling Demand	91.3	239.3	234.8
Heating Demand	185.9	179.5	146.8

Table 6: Summary of annual energy demand for current weather file

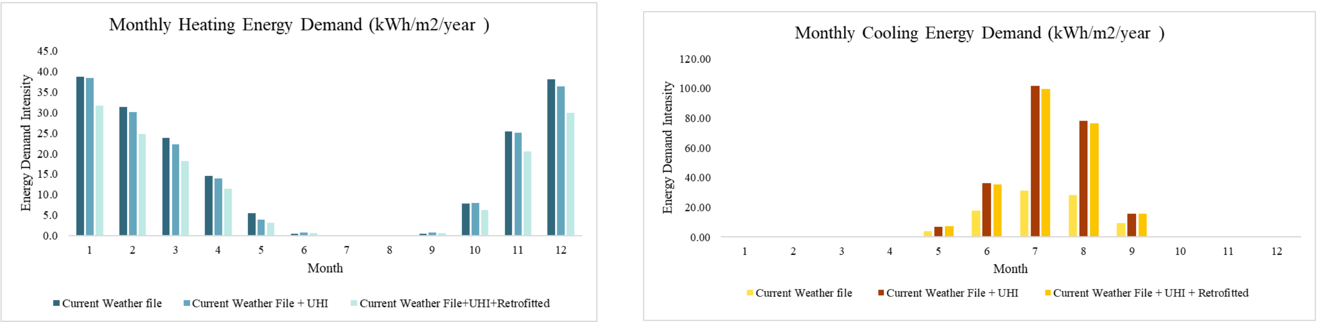


Figure 23: Monthly variation of heating and cooling energy demand for current representative weather file.

By analysing the impact of UHI, it can be seen from figure 23 and 24 that there is a positive impact on the heating demand whereas a negative impact is observable for the cooling energy demand. The annual heating demand decreases from 185.9 kWh/m2/y to 179.5 kWh/m2/y representing a decrease of 3%. Retrofitting buildings further decrease the heating demand by 18% with absolute value of 146.8 kWh/m2/y.

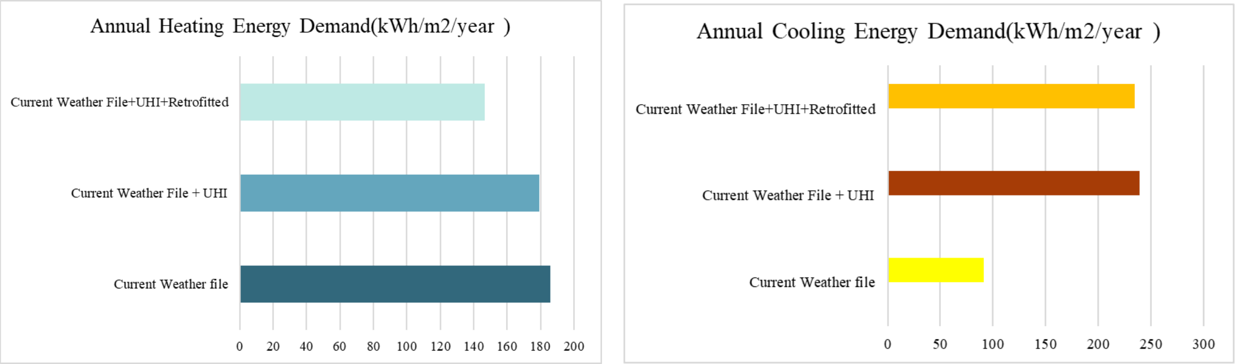


Figure 24: Changes in annual energy demand for current weather under UHI and retrofitting scenario.

In case of cooling energy demand, under the impact of UHI, the absolute value increase by 148 kWh representing a percentage change of +162%. Whereas only -2% decrease in cooling demand is simulated for retrofitted buildings. This indicates that retrofitting building under current climate conditions have minimal impact on cooling demand by significant effect on reducing the heating demand. Furthermore, comparing the absolute values for cooling and heating demand with and without UHI demonstrate that the current perspective of looking at energy poverty from heating demand requirements (Martín-Consuegra *et al.,* 2020) might need to shift. Based on the rural files energy simulations, the annual cooling demand will be 50 % less than the heating demand. However, under the implication of UHI, the annual cooling energy demand is 33% higher than heating demand. The results of the study align with the other studies evaluating the impact of UHI on building energy demand. Fanchiotti, Carnielo and Zinzi (2012) used measured temperature data to quantify the impact of UHI on residential buildings for the period July - September 2021 using TRNSYS software in Rome. The results indicated increase of 57% in cooling loads for maximum UHI intensity of 4.5°C. Similarly, Santamouris *et al.* (2001) evaluated the impact of urban climate on building energy consumption in Athens Greece. The results indicate maximum UHI intensity of 10 °C and increase in cooling load of 120%. The maximum UHI intensity simulated in this study was 12.9 °C and increase in cooing demand of 160%. The results align with the review of literature in similar climatic context. However, there is a need to validate the results of UWG with measured data. The results for overall impact of UHI suggest an opposite conclusion to the one study done in the climate of Seville, Spain conducted using Unified LIDER-CALENER software. The study found out that the overall impact of UHI was positive meaning that the increase of cooling demand was compensated with the reduction in heating demand (Romero

Rodríguez *et al.,* 2022) which is not the case according to the results of the present study with case study area in Madrid. However, the comparison study was done for just two buildings residential and commercial. Commercial buildings are mostly dominant by internal loads as shown by (Futcher *et al.,* 2017)

Whereas in the present study the whole urban block was considered, and daily average energy demand was computed for 345 thermal zones. Furthermore, the climate change aspect was not considered in the study. The impact of variation was only demonstrated between rural and urban data for weather parameters. Therefore, there is a need to study the impact of UHI on whole urban blocks for climate change scenarios in terms of energy demand to establish a holistic perspective and for a more thorough comparison.

Furthermore, the results indicate a need to study the assessment of energy demand under climate change as highlighted as a research gap by Soutullo *et al.* (2020).The temperatures in all future scenarios will be higher and the impact of UHI will be severe. Soutullo *et al.*(2020) results indicate that accounting for climate variation across different weather files, the annual temperatures increased by 1.8°C and relative humidity decreased by 9% meaning a warmer and drier climate. The differences were achieved with comparison between synthetic files such as EPWs and the updated monitored data at CIEMAT in the last decade (2010-2020). Based on these variations, the study found out that the annual heating requirements decrease by 22% while annual cooling requirements increase by 22% as well. Based on these results, energy demands were assessed for the climate change scenario RCP 8.5 2050.

4.2.3. ENERGY DEMAND UNDER RCP 8.5 WEATHER CONDITIONS

The table 7 presents the summary of results for annual absolute values for heating and cooling demand under RCP 8.5 scenario in 2050:

Energy Demand(kWh/m2/y)	**RCP 8.5 2050**	**RCP 8.5 2050 + UHI**	**RCP 8.5 2050 + UHI + Retrofitting**
Cooling Demand	305.2	387.5	378.7
Heating Demand	186.0	149.7	122.4

Table 7: Variation in annual energy demand under climate change across UHI and retrofitting scenario.

Based on the results simulated, it can be observed that without accounting for UHI effect, the regional climate change will increase the cooling energy demand from 91.3 to 305.2 kWh/m2/y, a concerning rise of 234%. Under UHI implications this will increase by further 27%. While retrofitting buildings will only results in decrease of 2.27%. The results indicate that while UHI impact simulated is concerning in present, the major cause of increasing cooling demand would be the regional changes in weather. Therefore, studies shall focus on evaluating climate adaption strategies at local scale to combat climate change and UHI together.

On the other hand, it is evident that under the combined effect warmer and drier climate and the impact of UHI accounted for, the heating demand will decrease from 179.5 to 122.4 kWh/m2/y.

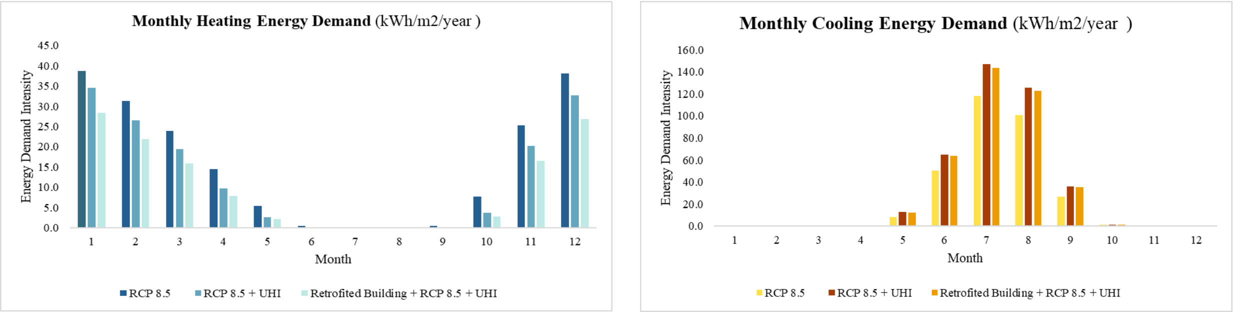


Figure 25: Monthly variation of heating and cooling energy demand for RCP 8.5 2050 climate change file.

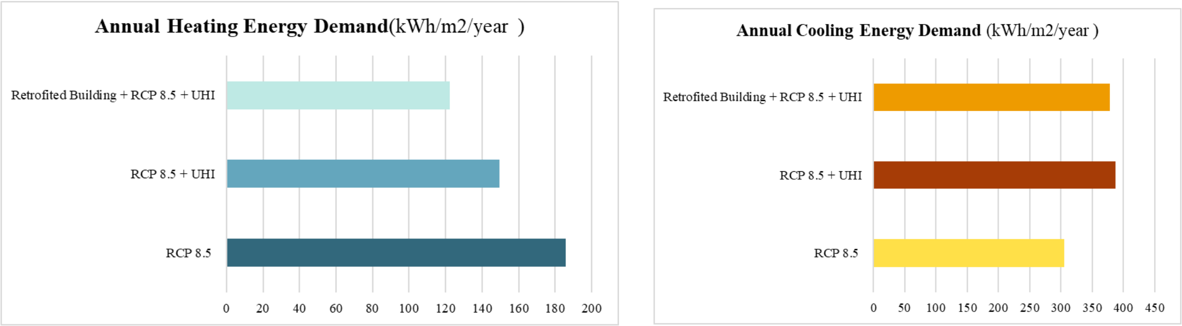


Figure 26: Annual variation of heating and cooling energy demand for RCP 8.5 2050 climate change

Overall, the results align with the study conducted by Yang, Javanroodi and Nik (2021). The authors assessed energy performance of European residential building stock and inferred that on average the heating demand will decrease, and the cooling demand will increase. The authors also observed that the highest average temperatures will be recorded in Madrid (Spain) and Dipkarpaz (Cyprus) exceeding more than 40 °C. The researcher further argues the need to study both long term and short-term variation in climate to assess adaption potential of sustainable solutions.

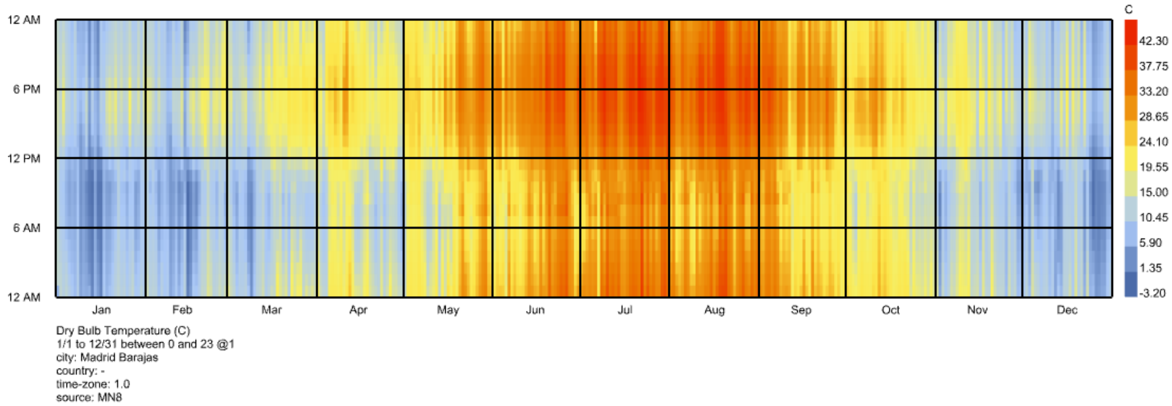


Figure 27: Dry bulb temperature under RCP 8.5 2050 climate scenario.

However, retrofitting buildings can have impact on the outdoor and indoor thermal comfort which is explored in phase 2 and focus on optimizing the urban environment to tackle the adverse impact if any. Furthermore, in accordance with the notion presented by Romero Rodríguez *et al.* (2022) study that energy saving measures shall be accompanied with various improvement and optimization measures. This will allow to develop a catalogue of cost-effective solutions. This study done in Mediterranean climate of Seville further advises to first prioritize the reduction of heating demand through improvement in building thermal envelope and then focusing on reduction in cooling demand. Therefore, aligned with this methodology, the first phase of this research shows that for future climate scenarios such as RCP 8.5, the optimal solution for reducing the heating demand is retrofitting building according to Spanish Technical code. This has the potential to improve the energy efficiency rating from category G (179.6 kWh/m2/y) to F (122.4 kWh/m2/y) under the worst climate scenario. Although it shall be noted that an overall warmer and drier climate plays a major role in it.

4.3. PHASE 2: OPTIMIZATION OF THE URBAN ENVIRONMENT

Based on the results and discussion in phase 1 of the study, the next phase focuses on improvement of urban microclimate to decrease cooling energy demand and managing the negative impacts resulting from retrofitting of buildings. This will be assessed by simulating the combined effect of vegetation and reflective materials using ENVImet V5.5.1. and EnergyPlus one way coupling.

4.3.1. PILOT SCALE STUDY

The detailed settings for the ENVImet 5.5.1 pilot scale simulation are described in figure 10 and the theoretical reasoning is discussed in the literature review section. However, to establish the context in qualitative terms: the pilot scale studies were done for two different envelope materials 1) Brick Wall 2) Brick wall with External thermal composite insulation system against the current weather file and future RCP 8.5 2050 weather file. The reason for this was the study done in Madrid that concluded and justified the need to study different envelope retrofitting strategies under climate change (Soutullo *et al.,* 2020). This generated 4 pilot scale simulations. Secondly based on the study done in Berlin Germany and Cadiz, Spain. The first study observed worsening of outdoor thermal comfort under retrofitting strategies (Maronga *et al.,* 2022) and the latter's results showed adverse impact on indoor operative temperatures under climate change (Salvati & Kolokotroni, 2023). Thus, hinting a need to study retrofitted and non-retrofitted buildings under chosen planning strategies aimed at improved thermal comfort and energy demand (Santamouris, 2016) resulting in 4 additional pilot scale simulations. Total of 8 pilot scale simulation were executed with the small section of the case study area and simple forcing to reduce the computational time. The downside of this is that in simple forcing, ENVImet uses a single orientation and keeps the wind speed same throughout the simulation. Therefore, only temperature related metrics are compared in the pilot scale study (Di Nunzio, 2021).

For comparison of performance of materials, the output at time 13:00:00 were considered and for analysis of façade related parameters the output at 17:00:00 hours were analysed. This is because of the sun position illustrated in figure 28.

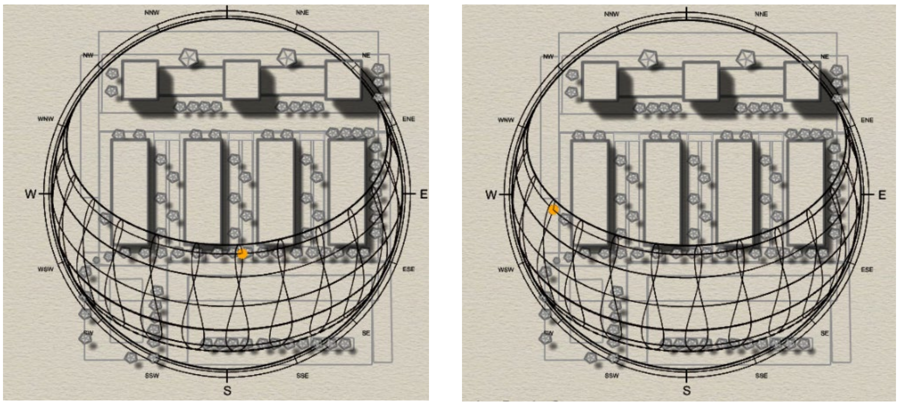


Figure 28: Sun angle at 1300(left) and 1700 hrs (right)

Based on the visualization of the results in figure 29, use of reflective material and vegetation combined can have improvement effects on air temperatures in front of façade extracted from dynamic building output files.

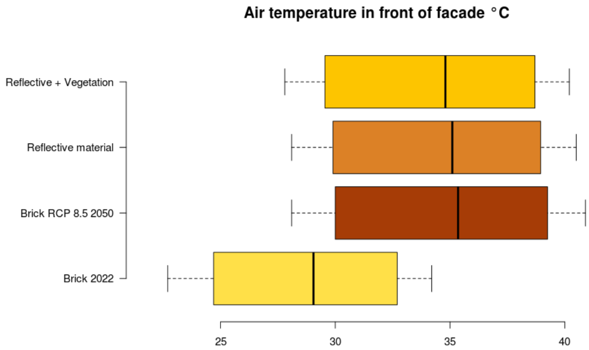
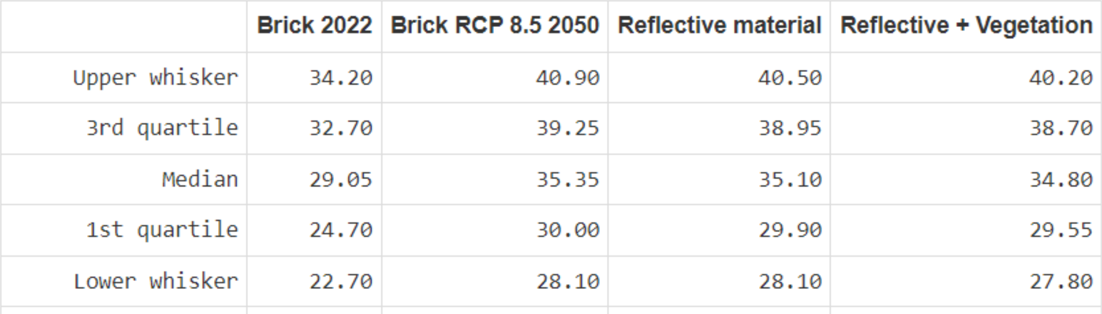


Figure 29: Comparison between 4 scenarios for building envelope material brick.



	Brick 2022	Brick RCP 8.5 2050	Reflective material	Reflective + Vegetation
Upper whisker	34.20	40.90	40.50	40.20
3rd quartile	32.70	39.25	38.95	38.70
Median	29.05	35.35	35.10	34.80
1st quartile	24.70	30.00	29.90	29.55
Lower whisker	22.70	28.10	28.10	27.80

Table 8: Summary of box plots for envelope material brick

However, based on the summary of box plots in table 8, the difference achieved are not that significant. This is justified as only a small section of the whole case study was studied with simple forcing in ENVImet. Similarly observable difference can be seen for air temperature in front of facade for the envelope material ETICS illustrated in figure 30 and table 9.

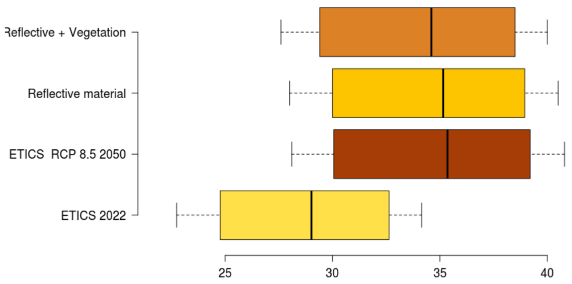
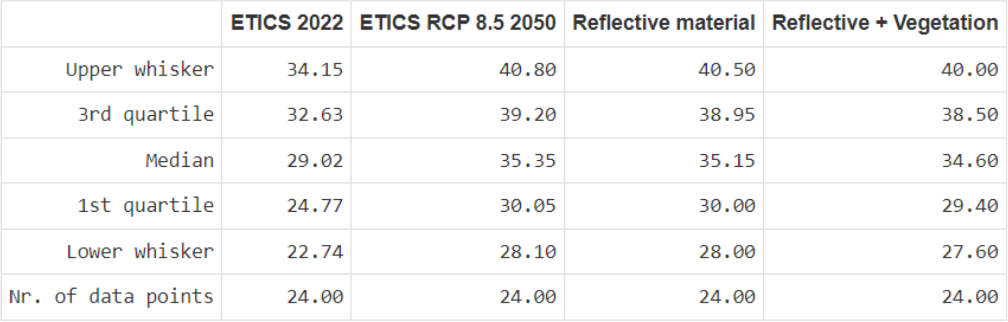


Figure 30: Comparison between 4 scenarios for building envelope material ETICS.



	ETICS 2022	ETICS RCP 8.5 2050	Reflective material	Reflective + Vegetation
Upper whisker	34.15	40.80	40.50	40.00
3rd quartile	32.63	39.20	38.95	38.50
Median	29.02	35.35	35.15	34.60
1st quartile	24.77	30.05	30.00	29.40
Lower whisker	22.74	28.10	28.00	27.60
Nr. of data points	24.00	24.00	24.00	24.00

Table 9: Summary of box plots for envelope material ETICS

Comparison of average surface temperatures across base case scenario and reflective material demonstrated improvements by reduction. The differences are more observable between midnight and early morning.

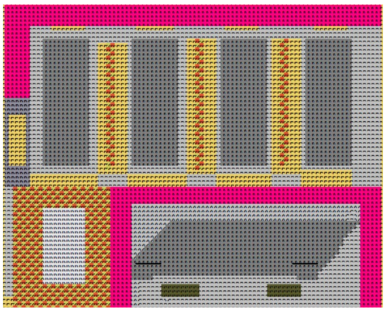


Figure 31: ENVImet Surface material 2D model for reflective material pilot scenario.

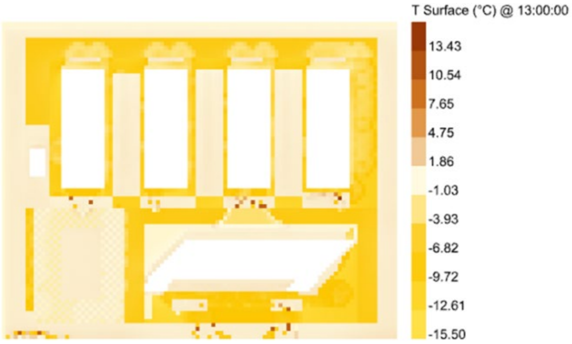


Figure 32: Absolute differences between surface temperature between base case and reflective material pilot scale scenario.

One notable observation here is that reflective materials perform better in open areas. Within shaded areas, the reflection is mostly trapped as it can be seen in Figure 33. The lighter shades represent more SW reflected and less radiation emitted as absolute difference.

Figure 33: Comparison of SW radiation reflected and LW radiation emitted.

Within shaded surfaces, the potential to reflect SW radiation is decreased and the LW radiation emitted is trapped due to reduced sky-view factor shown in figure 44. Therefore, for the full-scale study, reflective coating was only utilized for roads and for open areas that were pedestrianized, the focus was more on greening solutions with less reflective material in street canyons. The strategy of using reflective materials for only main streets is in accordance with the results of (Salvati *et al.,* 2022). Further analysis of mean radiant temperature (MRT) differences across base case and material scenario resonates with the result of the study mentioned. It can be seen from figure 34 that differences in MRT temperature measured at 1.4 meter is higher near and around dense built environment whereas less in open areas such as southwest of the figure 34.

Figure 35: Description of areas within the model.

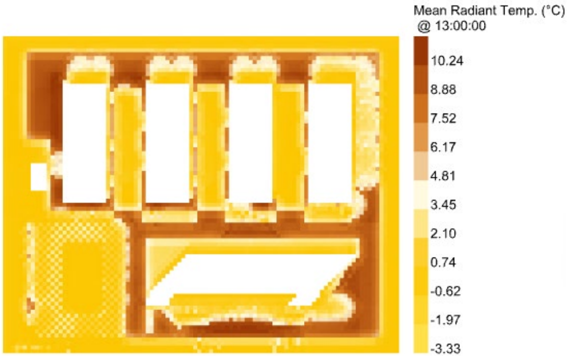


Figure 34: Absolute differences of MRT across basecase and reflective material scenario.

Furthermore, comparison envelope material was performed between Brick and ETICS for two microclimate parameters: 1) Wall Temperature at node 1, representing outside of façade 2)

Wall Temperature at node 7, representing inside wall. Absolute differences were computed. The ETICS material was the observation scenarios while the brick material scenario was used as reference case. Higher reduction in wall temperatures can be seen on the south facade mainly because of higher albedo of outer plaster used in ETICS compared to that of brick as shown in figure 36.

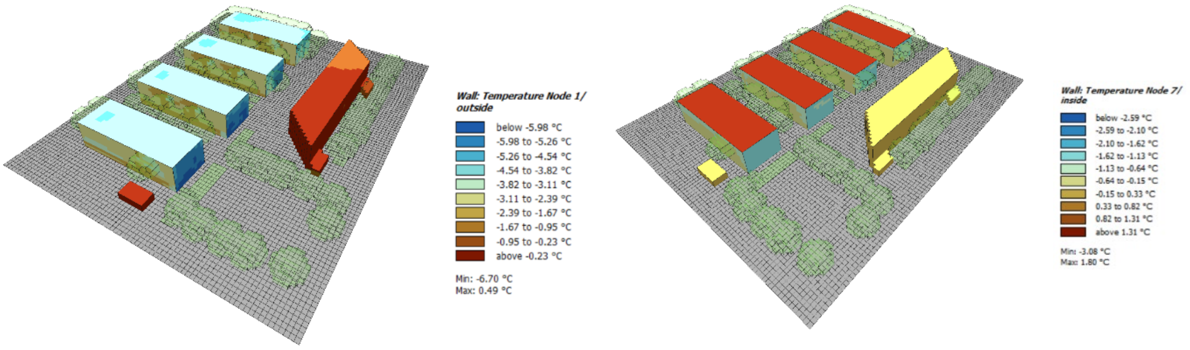


Figure 36: Comparison of outside and inside wall temperature for brick(reference) and ETICS (observation).

This reduction decreases in magnitude inside the street canyons due to shading. However, the overall performance of ETICS material for outside wall temperature is better. In contrast, the indoor wall temperature is simulated to be slightly higher with maximum value recorded as 1.8 °C.

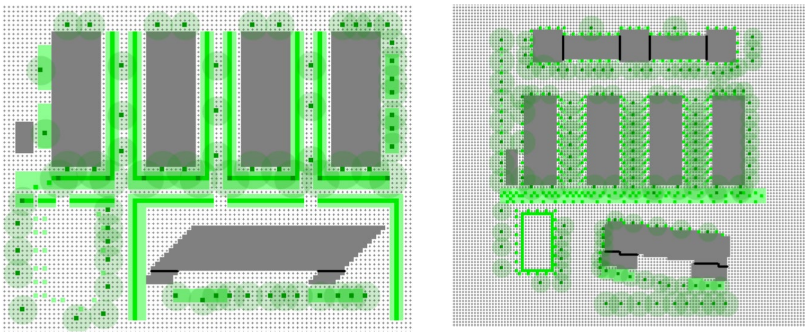


Figure 37: Optimized scenario pilot scale vs optimized scenario full scale.

4.3.2. FULL SCALE STUDY

Based on the results of the pilot scale study, further three scenarios were developed for detailed assessment at full scale. Vegetation adjustments were made to the scenario based on the study done by Tsoka, Leduc and Rodler (2021). The study observed increasing cooling effect of continuous canopies and dense vegetation. Therefore, they were introduced within the street canyon and on the south facing facades. Furthermore, (Ge et al., 2023), suggested to evaluate the cooling savings that can be achieved from large urban green spaces. An attempt was made to incorporate this into the model by greening the areas outside the canyon as well. Furthermore, based on the LIDAR data assessment and site visit, it was observed that the area lacked low vegetation which has potential benefits at pedestrian level and when planted close to facade might provide positive results in improving the outdoor thermal comfort. Additionally planting of hedges of 1m, 2m and 4 m can also reduce the LW exchanges between the horizontal surfaces and lower facade. In absence of any low vegetation, the exchanges at this level are the highest. Moreover, in pilot scale scenarios, the solution tested for open areas that are pedestrianized was reflective material and for full scale, it was low hedges of 2 meter. Grass and facade level greening were opted out. The reason for not simulating grass was mainly social as the residents previously removed the existing grass within street canyon due to maintenance concerns. Considering warmer and drier future climate discussed before, facade greening was also opted out. This shows a progressive approach in testing solution incorporating economic and technological dimensions.

4.3.2.1. COMPARISON OF BASE CASE 2022 AND RCP 8.5 2050 NO CHANGE SCENARIO

The model geometry and simulation settings are described in table 4 and scenario description is provided in figure 11. The comparison of base case 2022 scenario and RCP 8.5 2050 no change scenario for potential air temperature is shown in figure 38 for morning (0700), afternoon (1300) and evening time (1900). Higher temperature difference of 5-9 °C (darker shades) can be observed for morning and evening hours whereas for 1300 hrs, lighter shades are more dominant (4-6 °C).

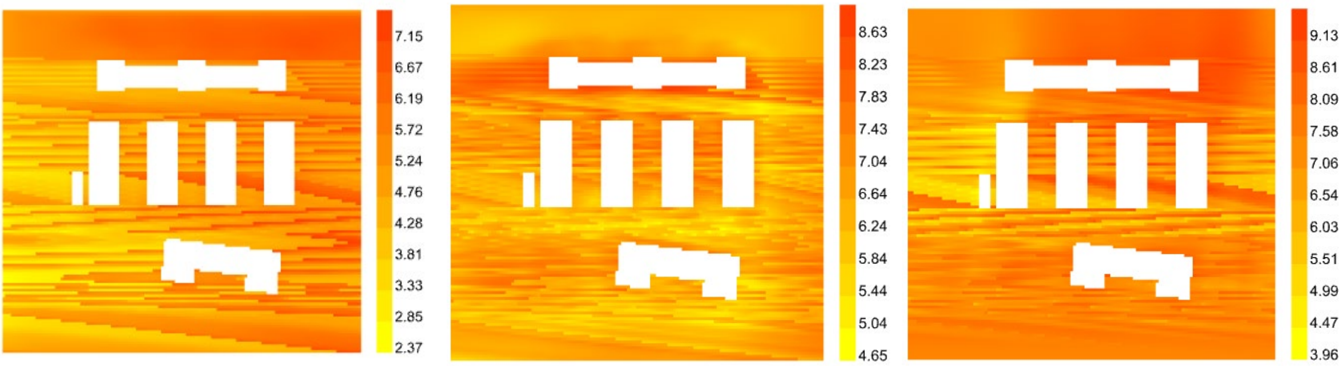


Figure 38: Potential Air temperature 0700(left)), 1300 (center), 1900(right) on 21st July.

The wind speeds for basecase 2022 and RCP 8.5 no change scenario is shown in figure 39 and 40. No significant changes are observed. The minimum values range between 0.00 – 0.03 m/s and maximum values range between 1.75-1.81 m/s. The comparison with rural files demonstrates the reduction in wind speed due to roughness of urban fabric illustrated in figure 41.

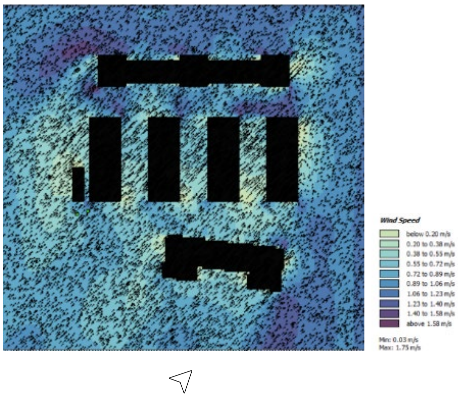


Figure 40: Wind Speed @ 17:00:00 for basecase 2022 scenario.

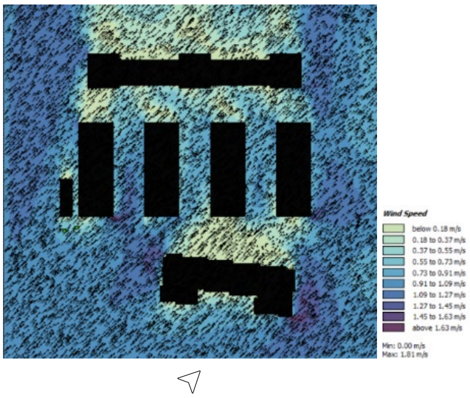


Figure 39: Wind speed @17:00:00 for RCP 8.5 no change scenario.

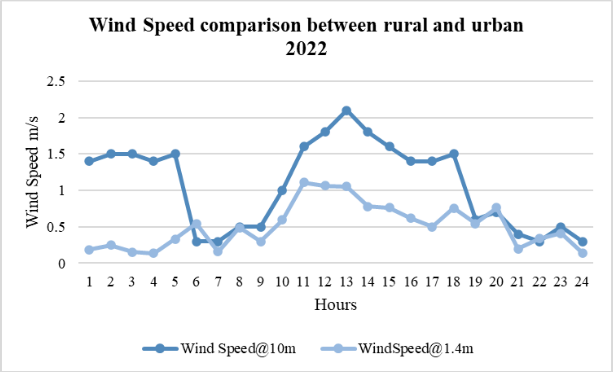


Figure 41: Impact of urban context on wind speed

The combination of higher temperatures and lower wind speed can significantly increase the cooling load of the buildings (Salvati *et al.,*2020). Similarly reduced wind speed and higher temperatures can negatively impact the outdoor thermal comfort. Similar for relative humidity value, reduced values are observable for RCP 8.5 no change scenario indicating a drier climate as shown in figure 42.

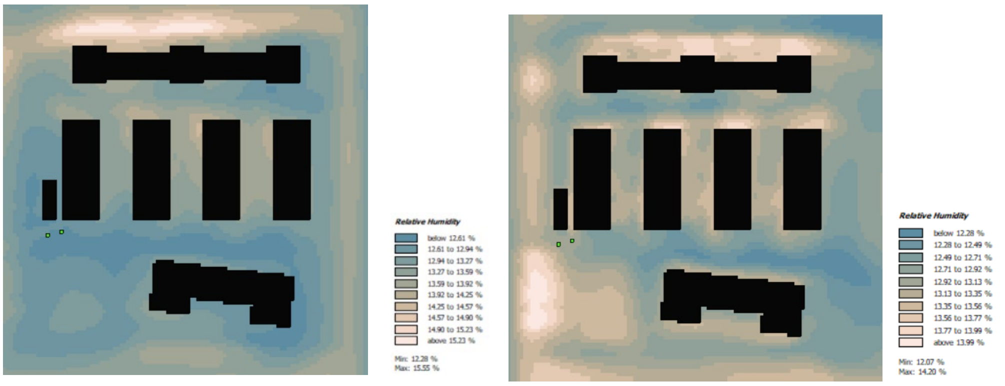


Figure 42: Variation in relative humidity between basecase 2022 and RCP 8.5 no change scenario.

4.3.2.2. COMPARISON RCP 8.5 NO CHANGE SCENARIO AND OPTIMIZATION SCENARIO RCP 8.5 2050

For the analysis of output from optimization scenario, focus was on the parameters related to building facade. The figure 43 shows display both the air temperature at facade and surface temperatures. Firstly, comparison of air temperature at facade showed improvements ranging from 0.11 to 6.79 °C. This can be attributed to the combined effect of evapotranspiration and shading resulting from dense trees and low vegetation within the street canyons. Furthermore, as shown in the figure 44, the surface temperatures within street canyon are observed to be higher for surface material sandy soil by about 5.15 °C.

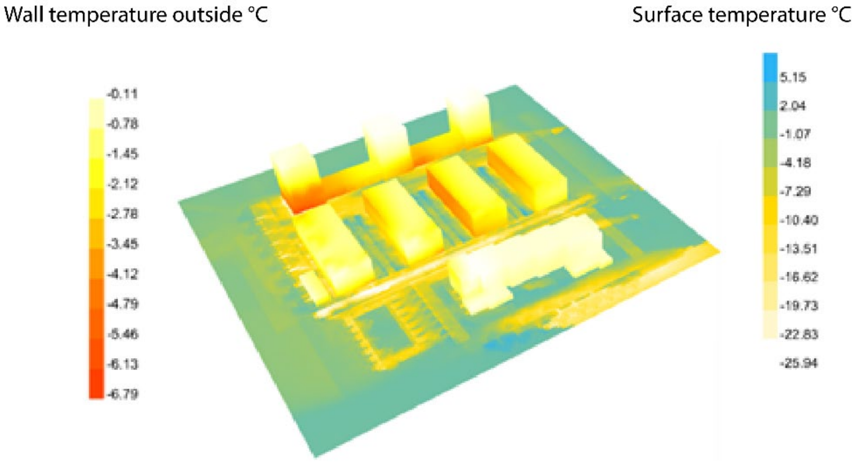


Figure 43: Absolute differences of wall temperature and surface temperature between RCP 8.5 no change scenario as reference and RCP 8.5 optimization scenario as observation.

Under extreme conditions, open soil retains and traps heat. This is further exacerbated by the reduced sky view factor within street canyons due to dense trees and hedges as shown in figure 44.

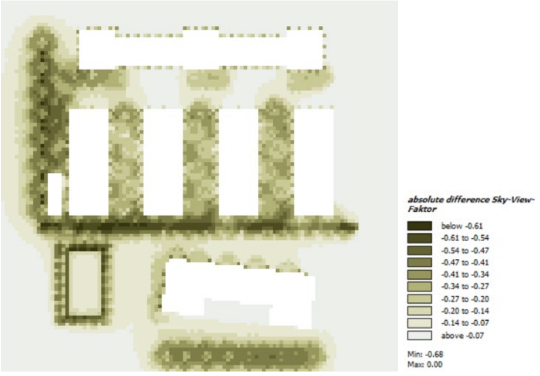


Figure 44: Absolute differences in SVF between RCP 8.5 no change scenario and RCP 8.5 optimization scenarios resulting from dense trees and hedges.

Comparison of wind speed across the three scenarios shows no significant reduction in wind speed due to introduction of dense trees and low vegetation in the trees. This can be mainly attributed to replacement of sparse trees within street canyon with dense taller trees. Nevertheless, the background wind speed is very minimal itself.

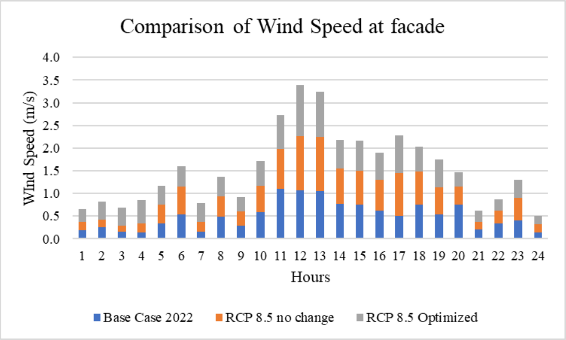


Figure 46: Comparison of hourly wind speed at facade across three scenarios

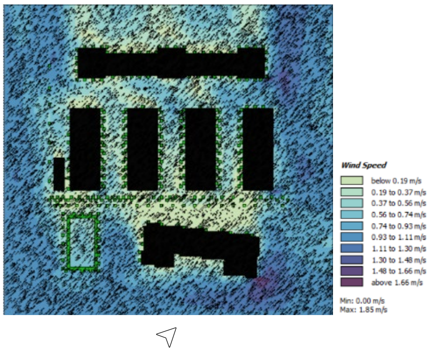


Figure 45: Wind speed at 1.4 meters for RCP 8.5 optimization scenario

For relative humidity, comparison between figure 43 and figure 47 shows increase in relative humidity of up to 7% for maximum value recorded and can be observed within street canyons where dense trees and hedges were simulated.

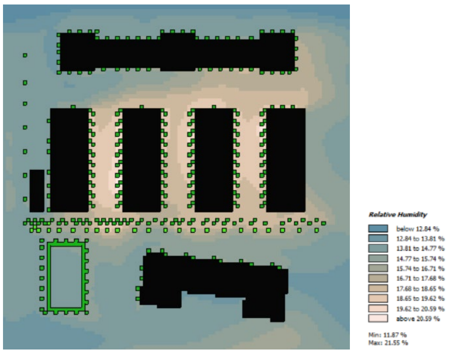


Figure 47: Spatial variation of relative humidity for RCP 8.5 optimization scenario.

Figure 48 represents the differences in SW radiation received and LW radiation received between the RCP 8.5 optimization scenario and no change scenario. The two key pieces of information that can be interpreted are that dense trees with continuous canopies reduce the SW received by providing the shading whereas the low vegetation reduces the LW exchanges between the horizontal surfaces and lower facades.

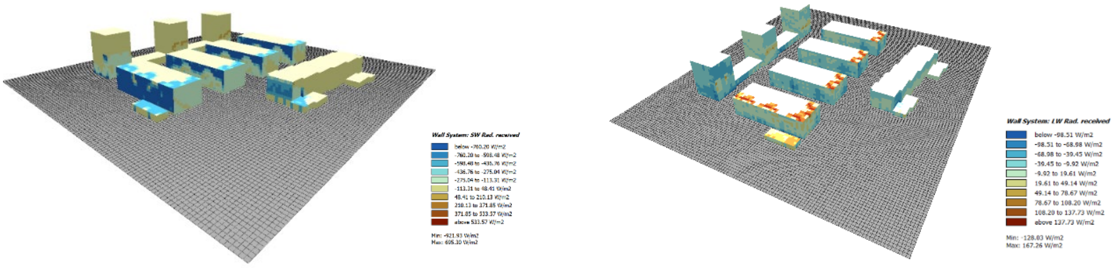
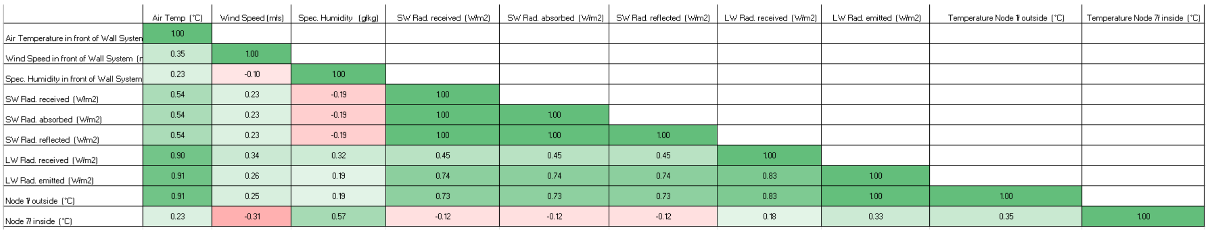


Figure 48: SW received and LW emitted for RCP 8.5 optimization scenario.

To summarize the relation between variables, a correlation matrix was developed and is shown in table 10.



	Air Temp (°C)	Wind Speed (m/s)	Spec. Humidity (g/kg)	SW Rad. received (W/m2)	SW Rad. absorbed (W/m2)	SW Rad. reflected (W/m2)	LW Rad. received (W/m2)	LW Rad. emitted (W/m2)	Temperature Node 1/ outside (°C)	Temperature Node 7/ inside (°C)
Air Temperature in front of Wall System	1.00									
Wind Speed in front of Wall System (r	0.35	1.00								
Spec. Humidity in front of Wall System	0.23	-0.10	1.00							
SW Rad. received (W/m2)	0.54	0.23	-0.19	1.00						
SW Rad. absorbed (W/m2)	0.54	0.23	-0.19	1.00	1.00					
SW Rad. reflected (W/m2)	0.54	0.23	-0.19	1.00	1.00	1.00				
LW Rad. received (W/m2)	0.90	0.34	0.32	0.45	0.45	0.45	1.00			
LW Rad. emitted (W/m2)	0.91	0.26	0.19	0.74	0.74	0.74	0.83	1.00		
Node 1/ outside (°C)	0.91	0.25	0.19	0.73	0.73	0.73	0.83	1.00	1.00	
Node 7/ inside (°C)	0.23	-0.31	0.57	-0.12	-0.12	-0.12	0.18	0.33	0.35	1.00

Table 10: Correlation matrix between simulated variables across the three full scale scenarios.

Air temperature at facade shows a positive strong correlation with LW received and emitted while wind speed shows a strong negative correlation with wall temperature inside establishing that with higher wind speed lower indoor temperatures are observable. Wall temperature outside doesn't show a very strong correlation with indoor wall temperatures mainly because of addition of insulation and resulting decoupling of indoor and outdoor walls.

While the positive impacts of the vegetation can be observed, it is important to analyse the stress that vegetation will be under extreme conditions. Lower air temperatures at vegetation are observed within street canyons as show in figure 49. This is mainly due to shading by surrounding trees and built environment resulting in lower exposure to direct SW.

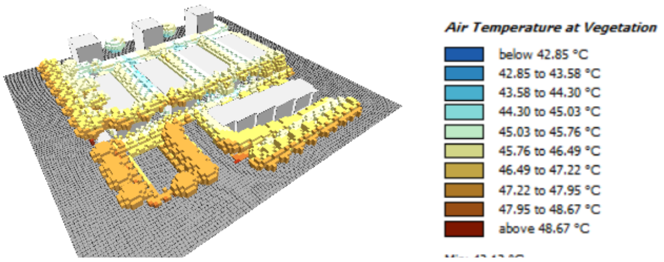


Figure 49: Air temperature at vegetation at 17:00:00 hours in RCP 8.5 optimization scenario.

Assessment of exposure to direct SW radiation shows significant lower values for denser vegetation compared to sparse vegetation as shown in figure 50. While higher temperatures are observable for both sparse and dense vegetation in open areas highlighting the importance of shading that needs to be provided by the built environment to the vegetation for optimal cooling effect under extreme conditions.

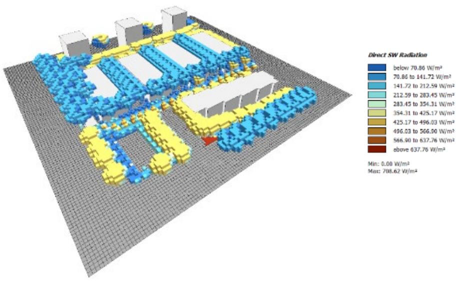


Figure 50: Spatial variation of direct SW radiation received for sparse and dense vegetation in the RCP 8.5 optimization scenario.

The results of the full-scale study were used as input to EnergyPlus and BIOmet to assess cooling energy demand, indoor thermal comfort and outdoor thermal comfort for the three scenarios.

4.3.3. ENERGY DEMAND

ENVImet v 5.5.1. provides mean values of different microclimatic parameters at the facade. Air temperature, wind speed and relative humidity were extracted at facade level and were used to morph the EPW files for 21st July. 21st July is the design day extract from stat file that accompanies the EPW file. Design days are used in energy simulations to calculate the size of

HVAC systems. Three morphed EPW files were created for three scenarios. Cooling energy demand simulations were run through EnergyPlus, and energy demand intensity was calculated for each scenario.

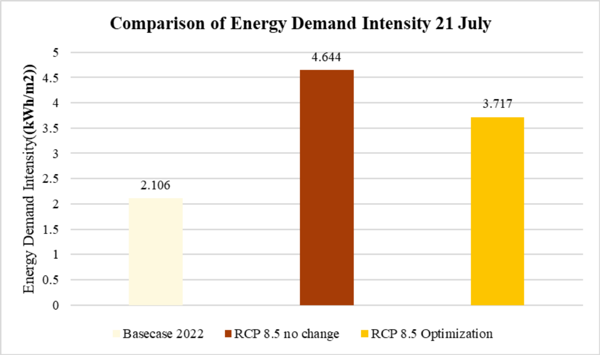


Figure 51: Absolute values of cooling energy demand intensity for three full scale scenarios.

Figure 51 shows the differences between energy demand intensity across the three scenarios. It can be interpreted that the cooling energy demand increases by 120% for design day in RCP 8.5 no change scenario. However, change in the outdoor environment mainly including dense trees with continuous canopies and hedges of 4, 2 and 1 meter along with reflective roads can limit this increase in energy demand to 76% from basecase in 2022, achieving cooling energy saving of 44% based on improvement in urban environment alone.

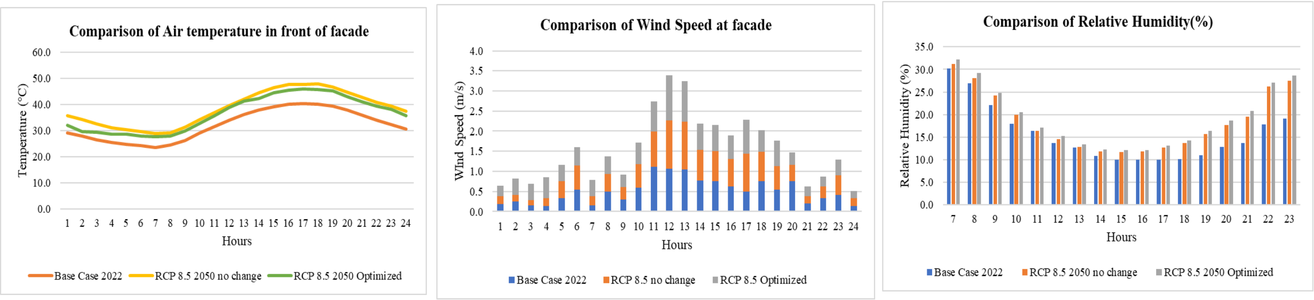


Figure 52: Hourly variation of critical microclimatic parameters for three simulated scenarios

Analysis of three critical microclimatic parameters shows, that the main reason for this was the reduction in temperatures achieved through the combination of planning strategies while wind and relative humidity played a major role as well.

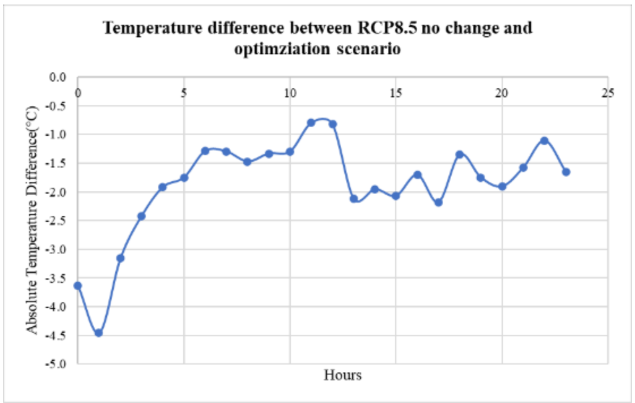


Figure 53: Absolute differences between RCP 8.5 no change and RCP 8.5 optimization scenario.

A maximum of 2.2 °C reduction was observed during the daytime while at night maximum of 4.5 °C was noticed showing potential of planning strategies simulated in tackling nighttime UHI. In comparison, (Ge *et al.,* 2023) observed a maximum reduction of 0.40 °C around buildings. The discrepancies can be attributed to the methodology used. As discussed in the literature review, that the methodology proposed in comparison study was mostly for a specific zone while the one adopted in this study is using average values at facade for the whole urban block. Another study concluded demonstrated cooling energy saving of up to 54% (44% shown in this study) can be achieved when trees formed a continuous canopy and when trees shaded the building's facade (Tsoka, Leduc and Rodler, 2021). The design strategy for vegetation was based on this study and therefore the results align with the findings.

4.3.4. INDOOR THERMAL COMFORT

Salvati and Kolokotroni (2023) studied the impact of climate change on indoor thermal comfort and found that indoor operative temperatures increase under climate change. Therefore, the study provided a notion whether retrofitting buildings can have adverse impact on the indoor comfort considering climate change and if improvements in immediate outdoor environment can increase the natural ventilation potential.

Indoor Operative Temperatures °C		
BaseCase 2022	RCP 8.5 2050 no change	RCP 8.5 Optimization
33.4 °C	39.5 °C	37.6 °C

Table 11: Summary of daily averaged operative temperatures for 21 July across three scenarios.

The results show that indoor temperatures will rise from average value of 33.4 °C across design day to 39.5 °C, representing a rise of 6.1 °C. Under optimization, this increase can be limited to 4.2 °C. The results of this study observe the increase in operative room temperatures and justify that improvement in outdoor environment can increase the natural ventilation potential. However, another concern is of reduction in wind speeds due to vegetation. The study used dense tall trees with large trunks and considered minimizing the speed reduction in canyons due to tree canopies. The results indicated no significant differences in average wind speed in front of facade across the three scenarios. Slightly higher average value for wind speed at facade were computed due to use of larger trees i.e., 20 meters compared to 15 meters.

4.3.5. OUTDOOR THERMAL COMFORT

As previous research as highlighted, that area wide building retrofitting can negatively affect the outdoor thermal comfort, higher MRT is observed in front of facade in both basecase and RCP 8.5 no change scenario (lighter shades of red pointed by white arrows in figure 54) are observed.

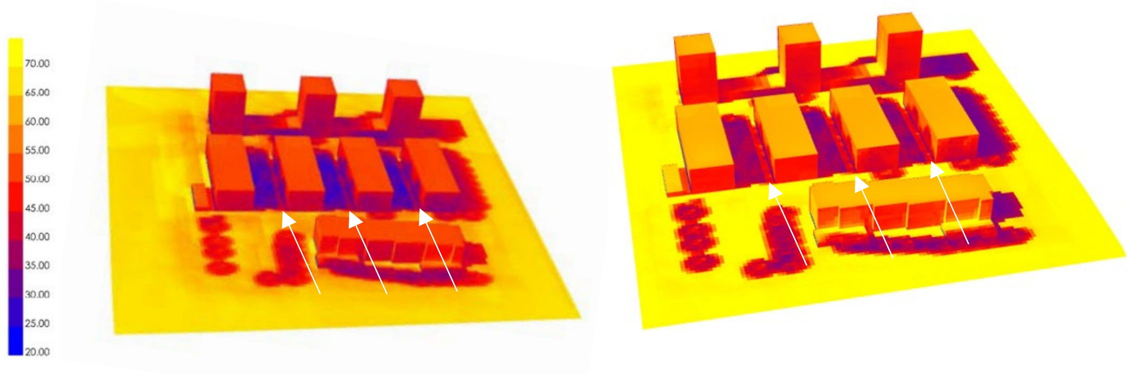


Figure 54: Wall temperature outside node and MRT @ 1.4 meters simulated at 17:00:00 for basecase and RCP 8.5 no change scenario.

However, in the RCP 8.5 2050 optimization scenario, hedges along with denser trees reduced both the wall temperatures and MRT in front of facade measured at 1.4 meters shown in figure 55. The position of sun at 17:00:00 can be visualized in figure 28.

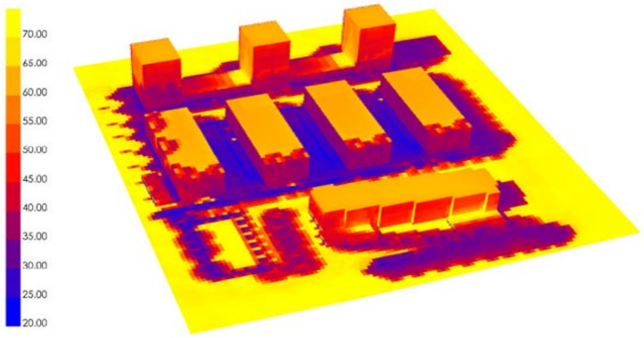


Figure 55: Wall temperature and MRT @ 1.4 meters simulated at 17:00:00 for RCP 8.5 2050 optimization scenario.

Figure 56 shows the physiological equivalent temperatures coloured on a mannequin of 80 old man standing at 2 meters from the faced at different time of the day across the two comparison scenarios. The differences are lower during early hours of the day before the sunrise and increase as the day progress with lower PET in optimization scenario. This shows the potential of shading and low vegetation in reducing the impact on outdoor thermal comfort resulting from retrofitted facades in street canyons.

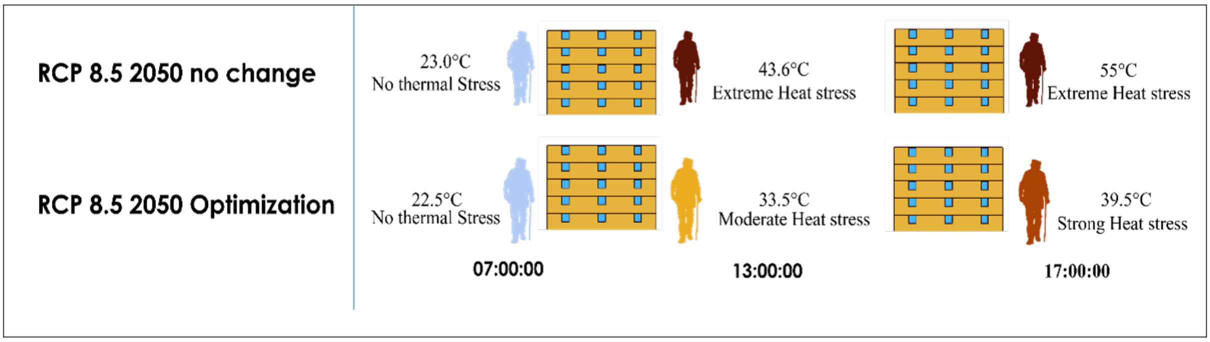


Figure 56: Static PET simulated @86,60 receptor point located at 2 meters from the facade across the RCP 8.5 no change and RCP 8.5 2050 optimization scenario at different time of the day.

Spatial variation of PET at different times of the day for RCP 8.5 no change (left) and RCP 8.5 2050 (right) optimization can be observed in figure 57 and 58. Furthermore, a new feature of ENVImet v 5.5 of calculating dynamic PET (dPET) was explored. Assessment of the dPET shows that with improvements in urban microclimate, the range of dPET (change in comfort) is considerably decreased, illustrated in figure 59 and 60.

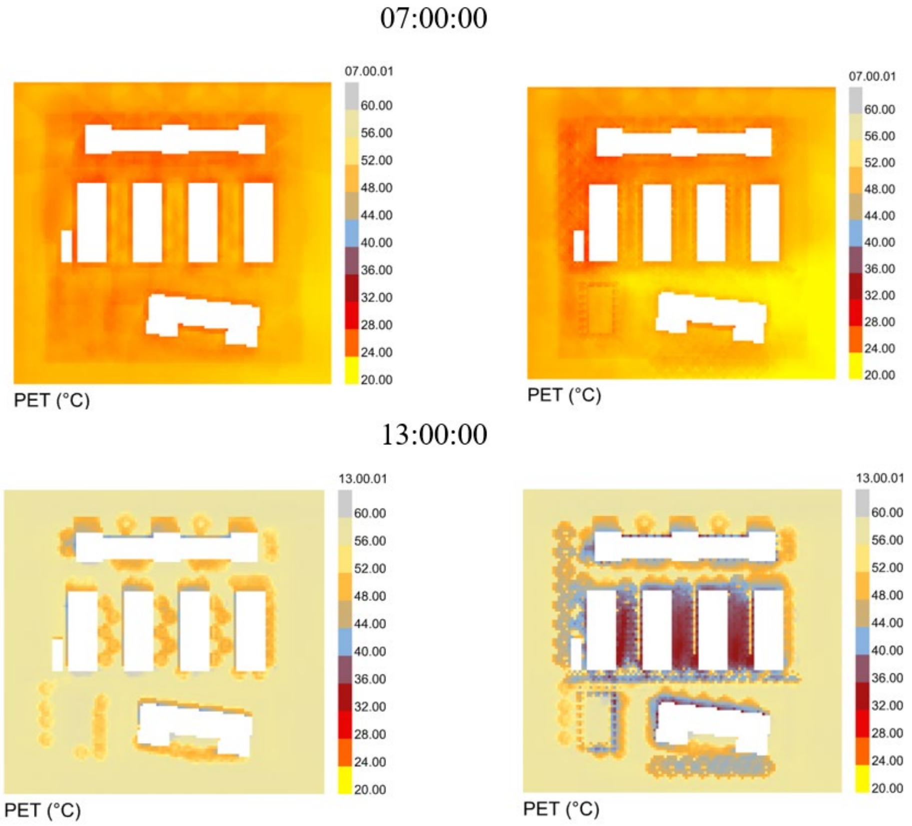


Figure 57: Variation PET for 07:00:00 and 13:00:00 hours

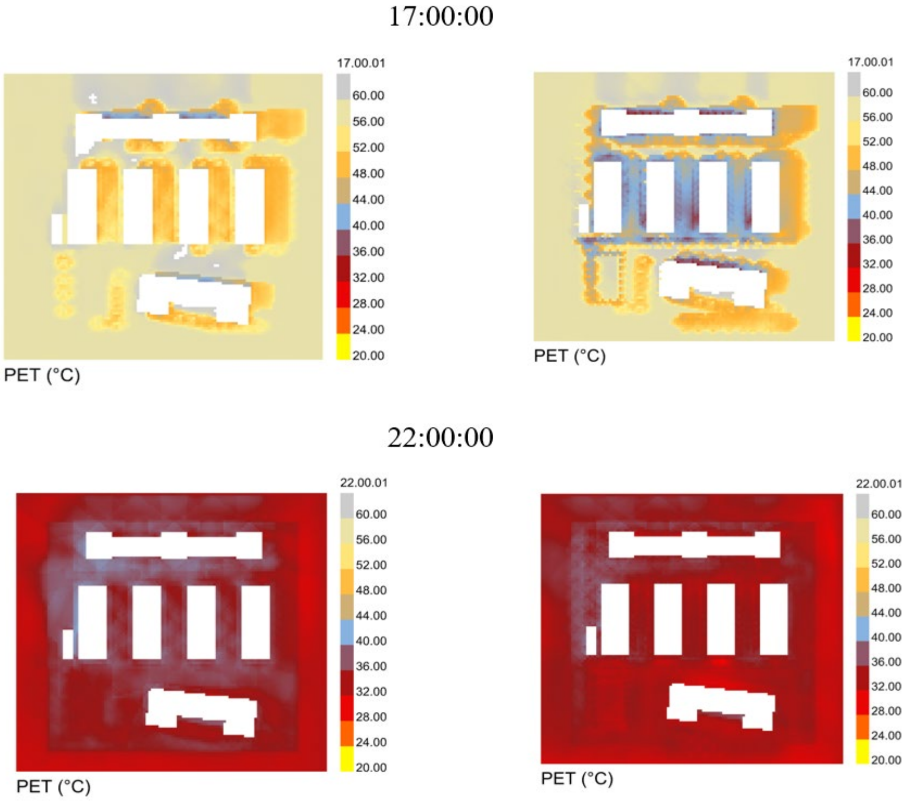


Figure 58: Variation PET for 17:00:00 and 22:00:00 hours

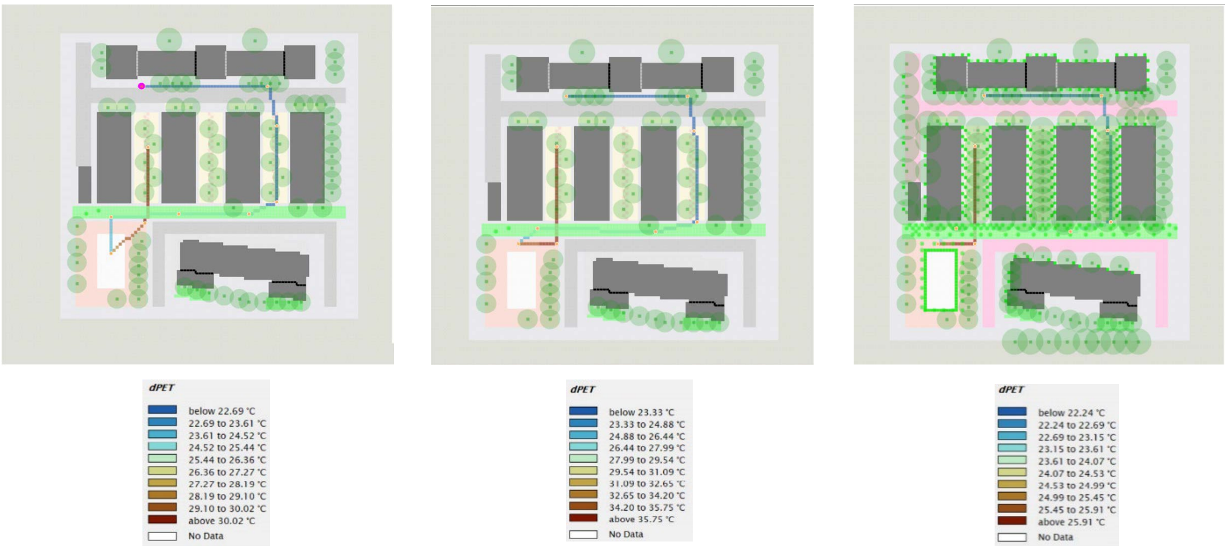


Figure 59: Dynamic PET assessment @17:00:00 across three simulated scenarios.

Figure 60: Graphical representation of changes in dynamic PET across three scenarios. The horizontal axis represents increase in dPET through the simulated walk.

CHAPTER 5: IMPLICATIONS AND CONCLUSIONS

The aim and objective of this research study focused on minimizing the impact of UHI through planning strategies under extreme climate change scenario. The review of the literature highlighted interlinkages between urban issues. Therefore, necessitating to study holistically the challenges and strategies for effectively planning towards sustainable and resilient urban areas. The study was divided into two main phases. In phase 1 of the study a tailored workflow was developed to assess the impact of UHI on the building energy demand in case study context for two weather files, reference and RCP 8.5 2050. Mitigation potential of retrofitting building was evaluated on both heating and cooling energy demand. Based on the findings of phase 1, phase 2 focused on optimizing the urban microclimate for cooling energy demand, indoor and outdoor thermal comfort. The case study area is Barrio Orcasur, a vulnerable neighbourhood in Mediterranean climate of Madrid.

5.1. SUMMARY OF FINDINGS

The results of the simulation study in phase 1 using Urban Weather Generator (UWG) demonstrate that the UHI intensity is + 12 °C under both reference and future climate change scenarios. Under extreme future climate, the dry bulb temperatures are observed to reach up to 42.3 °C (figure 27) compared to 39.9 °C (figure 16) of reference climate of Madrid City. The main difference noted was the change in diurnal range in summer with higher temperatures throughout the day in RCP 8.5 2050 scenario. Accounting for UHI and simulating the heating energy demand, there is 3% reduction observed in reference weather scenario while for RCP 8.5 2050, 20% reduction is simulated indicating a strong impact of UHI under extreme climate change situation. Evaluation of retrofitting strategies at the facade level i.e., use of External thermal composite systems (ETICS) shows promising results. Reduction of 18.2 % is observed for both weather files comparing retrofitted building scenario with non-retrofitted buildings scenario while also accounting for UHI.

Whereas for cooling energy demand, drastic increase was observed under the impact of UHI and future warmer and drier climate. In the reference climatic condition for Madrid city and with respect to the urban context of case study area, the cooling energy demand under the impact of UHI is 162% higher and improving the facade envelope of buildings will help reduce only 1.9%. However, under simulation of future extreme climate, the percentage increase resulting from higher temperatures and reduced diurnal ranges between day and night alone is 234%. In summary the results of the study show that for the study context the combined impact of future climate change and accounting for UHI in building energy performance simulation results in higher cooling energy demand than heating demand. This increase in cooling energy demand would not be compensated by reduction in heating demand and the overall impact of UHI is negative. Therefore, along with retrofitting measures, UHI mitigation strategies need to be assessed to tackle the issues of cooling energy demand and thermal comfort. The phase 2 studies the effectiveness of planning strategies recommended by research conducted in European and Mediterranean climate.

Based on the analysis of detailed urban microclimatic data from tools like ENVImet and energy modelling, the results of the phase 2 indicate the substantial potential of low-cost urban solutions such as dense trees, hedges and reflective roads. The focus of analysis was 21st July, design day. Design days are used in energy modelling to appropriately size the heating ventilation, air conditioning and cooling systems (HVAC) Analysis of TMY file shows highest temperatures in summer are recorded on the design day for Madrid City. Therefore, 21st July is a representative day for peak cooling demand analysis and thermal comfort assessment. The results demonstrate that peak energy demand intensity will rise from 2.11 to 4.64 kWh/m2/day under extreme climate change and UHI, representing percentage rise of 120%. Evaluation of optimization through sustainable planning strategies shows that this percentage rise can be limited to 77%. Assessment of indoor thermal comfort shows that optimisation of urban environment can reduce indoor operative temperatures by 1.9 °C under extreme conditions while also improving the outdoor thermal comfort in front of facade by 10.1 °C static PET measured at 13:00:00, 2 meters from façade and by 15.5 °C at 17:00:00. At 13:00:00, comparison of RCP 8.5 no change and optimization scenario show potential of improvement from extreme heat stress to moderate stress while at 17:00:00, extreme heat stress is improved to strong heat stress.

5.2. IMPLICATIONS AND RECOMMENDATIONS

The findings of this research study offer several implications on the role future climate change and UHI effect plays as a challenge in effectively planning for building energy demand and thermal comfort of the vulnerable population.

Firstly, the results of the study demonstrate the colossal impact urban context has on building energy demand further corroborating the findings of the reviewed studies. Resembling the findings of the study done by Yang, Javanroodi and Nik, (2021), the research observed concerning warming issues in future with temperatures exceeding 40 °C during daytime and nights staying considerably warmer. Along with UHI intensity of +12 °C similar to +10 °C observed in Athens, Greece (Santamouris et al., 2001), the impact on building energy demand is concerning and neglect of UHI and future climate change in urban planning and building energy efficiency studies can further aggravate the issues of energy consumption, energy poverty and health risks associated with heat. Use of rural weather files in estimating the building energy efficiency will result in understating the annual energy demand and subsequently attenuating the benefits from planning strategies focused on mitigating the issues of energy consumption and energy poverty. Disregarding UHI in performance estimations can result in exaggeration of carbon emission savings from the energy retrofitting strategies causing hindrance in achieving energy neutrality targets set by programmes such as European Green Deal. Additionally, the result of this study provokes a call to urban planners and building energy modellers to work with tools and methodologies in an interdisciplinary manner to have unified approach towards assessment of heat vulnerability and heat resilience. Making it possible to increase the effect of coping strategies (Emmanuel, 2021).

Demonstrating the application of a holistic workflow, the results of the phase 1 of the study revealed the substantial repercussions of neglecting improvements in building envelopes in Madrid City under climate change and UHI. This can lead to momentous implications on energy consumption, energy poverty and citizen wellbeing. Simulating the effect of cost-effective solution such as use of External thermal composite systems (ETICS) shows immense potential in reducing energy demand and improving the energy performance of buildings. The compelling nature of the results urges the researchers, planners and policy makers to prioritize the issue of energy inefficiency in building through use of simple and resource effective solutions.

As evidenced through results and discussion, improving the envelope can alleviate the heating energy demand and address the current perspective of energy poverty. However, under the influence of UHI and future climate change, the drastic increase in cooling energy demand and negative impact of envelope retrofitting under extreme climate conditions remains a challenge. The results analysis of the phase 2 of study illustrated the profound effect of shading and evapotranspiration from urban green infrastructure and cooling effect of reflective road in improving cooling energy demand and thermal comfort. As highlighted by Zhu et al (2023), the results further stress on the need for synergy between urban climatologists and building physicists to design integrated solutions to optimize the cost-benefit relation. Such synergies will allow close look at the properties that diminish the potential co-benefits of sustainable planning strategies. For example, as observed in this study, the performance of reflective materials is reduced under low sky view factor (SVF) while trees with sparse foliage density experience more direct SW radiation resulting in higher leaf temperatures and reduced cooling effect. Therefore, highlighting the need to study the suitability of albedo with consideration to SVF and for tools to accurately assess the performance of vegetation under various climate scenarios. Furthermore, very few studies have quantified the benefit of low vegetation such as hedges on buildings. As shown in this study, low vegetation(4m,2m,1m) planted next to the buildings can reduce the view factor between horizontal surfaces and vertical surfaces, therefore reducing the long wave exchange. Secondly, they also provide shading from reflected SW radiation. Moreover, it tackles the issues of adverse impact on outdoor thermal comfort resulting from decoupling of outer and inner walls due to addition of insulation. The implications and recommendations are further examined as PESTEL analysis in table 12.

	Implications	Recommendations
Political	• Neglect of UHI and climate change can result in policies overfocusing on heating energy demand as indicator of energy poverty • Increase in cooling energy demand and reduction in heating demand can reduce the effectiveness of policies focused on energy efficiency to reduce carbon emissions as overall energy demand will rise.	• Similar to energy performance certifications, policies shall address the urban microclimate with schemes that incorporate the impact of UHI on energy efficiency • As policies exist that address energy inefficiency issues and generating renewable energy to meet the demand. More work in policy development is required for improvement in urban environment to increase the natural ventilation potential and to increase the efficacy of natural heat sinks. This will reduce the overall energy demand with regards to climate change.
Economical	• Rising energy demand with ineffective mitigation strategies can further aggravate the energy poverty. • Unable to afford mechanical HVAC and rising cost of electricity, low-income people population will be forced in even worse living conditions.	• Allocation of resources for research of effective strategies evaluated under climate change. • Prioritizing low income and vulnerable neighbourhoods by leveraging schemes and financial tools focused on energy efficiency.
Social	• Adverse indoor and outdoor conditions resulting from envelope retrofitting and can put the ageing population at higher health risk.	• Prediction and modelling approaches to identify heat vulnerability shall be further researched and implemented in cities to protect the vulnerable population

	• Higher health risk can lead to burden on the healthcare system and can potentially increase the mortality rate.	• Coping strategies that improve the negative effects of envelope retrofitting shall be further researched and a catalogue of solution shall be developed.
Technological	• Coupling approaches that are used to study UHI and its effective are resource intensive and have lower temporal resolution. • Lack of existing technology that can predict and prevent the heat risk faced by vulnerable population during heat waves.	• Integrated approaches such as UWG with ladybug tools shall be further developed by addressing their limitation and shall be mainstreamed in urban planning and building energy modelling. • Tools like ENVImet shall be further improved to accurately assess building energy demand without the need for coupling approaches. • Technologies that couple dynamic thermal comfort tools with real time collection of data using sensors can be a way forward in successful implementation of preventive measures.
Environmental	• Undervaluation of energy demand can prevent the renewable energy to meet the consumption levels leading to extended reliance on fossil fuel generated energy. • Neglecting the impact of climate change in planning strategies evaluation can impact the biodiversity of the urban areas.	• This can impede the climate neutrality progress accelerating global warming. • Increase adoption of methodology and workflows that generate morphed weather files based on climate scenarios to effectively plan mitigation strategies and improve the environment according to future needs.
Legal	• Mitigation strategies increasing energy demand and UHI risk need support by the legal systems in place as well.	• Laws are required that enforce improvement in energy efficiency of buildings while maintaining the affordability for low-income vulnerable population.

Table 12: PESTEL analysis of the implications and recommendations based on the findings.

5.3. LIMITATIONS OF THE STUDY

Both actual and morphed RCP 8.5 2050 weather files were obtained from Meteonorm v8. The reference year of the actual file was 2005. The study done on assessing the impact of climate trends shows variations in meteorological parameters measured at CIEMAT institute between 2010-2020 and those of synthetic EPW's (Soutullo et al., 2020) such as the one obtained from Meteonorm 8. The reason for using this actual file was that Meteonorm generated the morphed RCP 8.5 2050 file based on this synthetic EPW. Meteonorm 8 does offer the option of uploading data or files to generate future scenarios based on the input data. However, considering the time availability and technical requirements to manually morph the files, this was out of the scope of this study. As the goal of the study was to highlight the change under extreme climate in building energy demand and thermal comfort and not to study the climate trends, the reference year of the actual weather file is not concerning. The weather data used is still representative in studying the phenomenon under focus. Use of more recent measured data and modelled climate change based on it will result in more accuracy.

The two strategies that are considered in this study for optimization are reflective materials and vegetation. After comparison with the data provided for urban materials from Eduardo Torroja Institute of Construction Sciences of Spanish National Research Council (CSIC) (Pérez *et al.,* 2022), there was no significant differences between the materials characterized for basecase and ones provided by ENVImet database. Therefore, in pilot and full-scale studies, similar materials were used from ENVImet database instead of generating new materials in user database. Another thing to be highlighted is that for reflective materials the research reviewed suggests the optimal value of 0.3 for albedo (Emmanuel, 2021) whereas the albedo of reflective road used in full scale study was 0.4 and granite pavement material in pilot study was 0.6. The main findings of this study are based on only the use of reflective road with 0.4 albedo. Although the results show reduced surface temperatures, higher MRT was observed at 1.4 meters. At the time of study, there was no project catalogue of potential cool materials available as laboratory testing for material properties was ongoing. Therefore, for practical use of reflective materials, further simulation study of varying albedo shall be conducted to find the optimal values for the case study area.

While for vegetation, abstract trees were used. Abstract trees allow more control of vegetation properties that effect the aerodynamics (i.e., trunk height, foliage density etc. Use of abstract trees at predesign stage is helpful in further investigating the suitable species similar to the best abstract forms of vegetation simulated. The shape and geometry of the trees was inferred from the LIDAR data during model development. To verify the material and vegetation information, a site visit was conducted as show in Appendix I.

For validation of the results of this study, at the time of this research execution, the site measurement study was ongoing and hence it was not feasible to carry out the validation. The figure 61 shows the location of installed sensor.

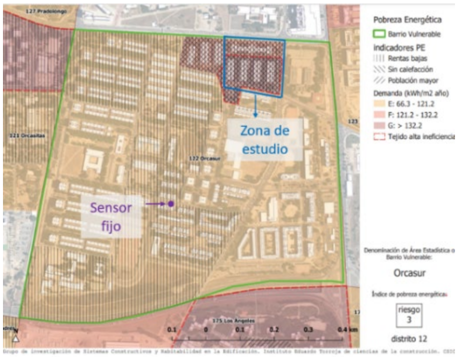


Figure 61: Weather Sensor location and proximity to case study area for future validation.

Most of the research reviewed that utilized modelling and simulation approach similar to this study verified the results using site measurements. The UWG ENVImet and Ladybug tools are extensively validated in different climatic contexts. The extensive review of these tools is carried out by Mao and Norford (2021) and Pacifici and Nieto-Tolosa (2021). For this study, the results were extensively compared with the findings reviewed in literature using validated methodologies in Chapter 4 and strong similarity was observed.

Furthermore, as the focus of this study was on the whole urban block, average values of microclimatic parameters such as air temperature, wind speed and relative humidity were computed across all building facades. Several studies have discussed an approach to account for the changes in urban environment and its influence on building performance (Palme *et al.,* 2017) (Ge *et al.,* 2023). While these approaches are suitable for assessing performance of few buildings, the coupling of URBANopt with ENVImet Building performance simulation output as meteorological data at facade level is unique to this study and therefore lacks presence in the literature reviewed. The argument presented by author is based on the three elements. First, the focus in this study was on the performance of the whole urban block. Secondly, the URBANopt API of EnergyPlus is a very recent feature that is being extensively used with focus on design of low carbon and energy positive districts (Charan *et al.,* 2021), (Fallahi *et al.,* 2022). Thirdly although ENVImet provides meteorological output at the facade level, it does so for each building and to morph the weather file, one value for each hour needs to be input for each variable. Therefore, this requires a script which was developed in this study to calculate the average values of microclimate parameters for the whole urban block. There are two main items that need to be highlighted here 1) The process is cumbersome and required a lot of validation to reduce human error in setting up the automated workflow 2) Averaging values means decrease in accuracy. However, with consideration to the scale of study, the former adds another layer of complexity while the latter is considered to have minimal impact. The workflow is shown in Appendix VI.

In the present study the focus was on examining the impacts of changes at the facade level. Therefore, no changes were made at the roof level. As roofs received the highest direct solar radiation in summer, reflective material and shading strategies at this level will further decrease the cooling energy demand. At the time of this study, roof characterization of the study area was ongoing and shall be addressed in future studies.

Additionally, to better understand the heat flux of buildings and urban environment, it is essential to run simulation for several days. Most research studies simulated 7 days (Maronga, Winkler and Li, 2022). In this the temporal scale was 30 hours which is also observed in studies that analysed the cooling effect of vegetation using ENVImet (Ge et al., 2023). However, this research recommends longer temporal scales and limited number of scenarios.

5.4. DIRECTIONS FOR FURTHER STUDIES

Future research shall use the weather files that can be obtained from the weather station close to the case study site. However, one consideration shall be noted that the UHI impact might not be as significant compared to rural station because of the proximity of weather station and the case study area. More work shall be done in design of scenarios with input of multidisciplinary experts and longer simulations >= 7 days shall be run to accurately examine the trends of heat gain retention and loss throughout the hottest or the coldest week. For ENVImet simulations, as shown by pilot and full-scale study, simple forcing shall be avoided as it doesn’t simulate wind speed (Di Nunzio, 2021). Full forcing shall be the preferred method of forcing.

Future studies shall first develop a catalogue of reflective material based on availability, applicability, and Life cycle assessment (LCA) before utilizing them in modelling. Secondly detailed landscape scenarios shall be developed by experts based on the assessment of suitability of vegetation in the study context. These scenarios then shall be handed over to the urban planners and energy modellers for use in the workflow suggested in this study. This also shows a need for multidisciplinary professionals that can work across different teams and domain areas to study the complex nature of urban climate and sustainability related challenges. Focusing on one aspect can limit the impact a sustainable strategy can have on another intertwining problem. For example, focusing on outdoor thermal by planting low trees that provide shading effect can limit the benefit that trees can have on building energy demand by providing shade to highest part of the facade (Tsoka, Leduc and Rodler, 2021).

As Yuan, Emura and Farnham (2017) indicates that reflective material with up to 0.3 albedo and grass cover of up to 20% of urban space is optimal for urban microclimate improvement in climatic context of Osaka city in Japan, similar studies shall be done in Madrid city for different urban contexts to establish thresholds values as guidance for urban design projects. Further studies shall include the strategies studies along complete envelope of the building to study these changes. This also represents the benefit of using modelling and simulation approach where causal and effect relationship can be studied by isolating certain factors and focusing on the others, demonstrating a progressive approach allowing to optimize each individual factor. Additionally, to accurately assess the performance of vegetation in improving microclimate, researchers and planners shall utilize tools like TreePass ENVImet to accurately simulate optimal microclimate for sustainability and growth of tree.

Furthermore, for future studies focusing on studying the impact of outdoor changes at urban district level on specific facade orientation, ENVImet v5.5.1 provides mean values across each orientations of facade. This will allow to study the impact of reflective material on building energy demand and indoor thermal within street canyon as well as outside. This will be necessary to assess the performance of reflective materials under different sky view factor. As this study found out that the performance of reflective horizontal material decreases with shading and might worsen the microclimate by trapping of reflected SW radiation and increase inter reflection within the shaded areas.

Most importantly, as discovered in this study, the residents have preference for certain solutions with consideration to maintenance requirements. During site visit, it was discovered that the residents removed grass present within street canyons. Therefore, future studies shall consider the input of stakeholders in simulating only those strategies that are applicable in long term. This study excluded the use of grass. However, bare soil showed higher surface temperatures than paved materials like concrete. Highlighting need for evaluation of covering the exposed soils with sustainable pavement solutions.

5.5. CONCLUSION

Based on the presentation of results and discussion in previous chapters, this study further justifies the need to study the relationship between outdoor and indoor environment under local and regional climate change. In the previous decade, a lot of research has been done to study the impact of UHI on the building energy demand and outdoor thermal comfort. Most of the studies are focused on either one of those aspects. Therefore:

- ➔ As shown in the review of literature and through the results obtained in this study, there is a need to study the interrelationships between these challenges and how different sustainable planning strategies impact them.
- ➔ The findings of this research study confirm the changes in the energy demands based on the climate change and UHI impact in the local case study area. The results align with studies done in similar Mediterranean climate context. Under UHI and increase in regional temperatures, the heating demand will decrease.
- ➔ Whereas there will be drastic increase in the cooling demand which will not be compensated by the decrease in heating demand.
- ➔ To tackle the issue of heating demand, the most effective strategy is to use insulation and improve the air tightness of the buildings. The results demonstrate that the combined effect of UHI, increase in regional temperatures and envelope retrofitting will decrease the heating demand by 34% compared to only 21% under climate change and UHI.
- ➔ With consideration to future climate, cooling demand needs to be addressed as equally important. Yang et al. (2021) analysed and concluded that Madrid City will be one of the two cities to experience highest temperatures in future. The results of this study show that cooling energy demand will be more than the heating demand and require significant changes in the outdoor thermal environment to lower the temperatures experienced in urban context and to increase the natural ventilation potential.
- ➔ The simulation results show that there will be an increase of approximately 60% in annual cooling energy demand from current representative weather to RCP 8.5 2050 climate change scenario. Assessment on the design day shows that, the increase in peak energy demand on 21st July will be 120% higher in RCP 8.5 2050 compared to base case.

- ➔ However, with combined effect of reflective roads, shading and evapotranspiration effect of trees and hedges, the impact can be limited to 77% while also improving the indoor thermal comfort by a difference of 1.9 °C.
- ➔ The research further confirms the negative effect of retrofitted façade on the outdoor thermal comfort. However, plantation of low vegetation near lower facade and shading of upper facade can minimize this impact and improve the outdoor thermal comfort.

Finally, as a final recommendation, it is suggested that similar studies shall be done in varying urban context in Mediterranean climate using the approach implemented in this research to enable comparison and establishing a strong foundation for guidance to planners and decision makers.

REFERENCES

1. Bueno, B., Norford, L., Hidalgo, J. and Pigeon, G. (2012) 'The urban weather generator', *Journal of Building Performance Simulation,* 6, pp. 1-13. Available at: https://doi.org/10.1080/19401493.2012.718797
2. Cascone, S. and Leuzzo, A. (2023) 'Thermal Comfort in the Built Environment: A Digital Workflow for the Comparison of Different Green Infrastructure Strategies', *Atmosphere,* 14(4), pp. 685. Available at: https://doi.org/10.3390/atmos14040685
3. Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (2022) *URBAN therCOM.* Available at: http://projects.ciemat.es/web/urban-thercom/home (Accessed: 20 April 2023).
4. Charan, T., Mackey, C., Irani, A., Polly, B., Ray, S., Fleming, K., El Kontar, R., Moore, N., Elgindy, T., Cutler, D., Roudsari, M.S. and Goldwasser, D. (2021) 'Integration of Open-Source URBANopt and Dragonfly Energy Modelling Capabilities into Practitioner Workflows for District-Scale Planning and Design', *Energies,* 14(18). Available at: https://doi.org/10.3390/en14185931
5. Di Nunzio, A. (2021) *ENVImet simulation types.* Available at: https://github.com/AntonelloDN/Morpho/wiki/2.1-Run-a-simulation-with-Grasshopper (Accessed: 08 May 2023).
6. Emmanuel, R. and Steemers, K. (2018) 'Connecting the realms of urban form, density and microclimate', *Building Research & Information,* 46(8), pp. 804-808. Available at: https://doi.org/10.1080/09613218.2018.1507078.
7. European Commission (2023) *European Green Deal.* Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (Accessed: 5 June 2023).
8. Fallahi, Z., Houssainy, S., Ling, J., Leach, M., Klun, L. and Slovensky, M. (2022) 'Designing for Zero Energy and Zero Carbon on a Multi-Building Scale Using URBANopt', *Proceedings of the 2022 ACEEE Summer Study on Energy Efficiency in Buildings* California 21-26 August. https://www.osti.gov/servlets/purl/1887879
9. Fanchiotti, A., Carnielo, E. and Zinzi, M. (2012) 'Impact of cool materials on urban heat islands and on buildings comfort and energy consumption'. *Proceedings of the Colorado Renewable Energy Society (CRES) Annual Conference Colorado 2012* https://hdl.handle.net/11590/279307

10. Futcher, J., Mills, G., Emmanuel, R. and Korolija, I. (2017) 'Creating sustainable cities one building at a time: Towards an integrated urban design framework', *Cities,* 66, pp. 63-71. Available at: https://doi.org/10.1016/j.cities.2017.03.009
11. Futcher, J., Mills, G. and Emmanuel, R. (2018) 'Interdependent energy relationships between buildings at the street scale', *Building research and information: the international journal of research, development and demonstration,* 46(8), pp. 829-844. Available at: https://doi.org/10.1080/09613218.2018.1499995
12. Ge, J., Wang, Y., Akbari, H., Zhou, D., Gu, Z. and Meng, X. (2023) 'Cooling energy saving by vegetation planting in high-density districts: Evaluation using the coupled simulation', *Building and environment,* 232, pp. 110054. Available at: https://doi.org/10.1016/j.buildenv.2023.110054
13. Isaac, M. and van Vuuren, D.P. (2009) 'Modelling global residential sector energy demand for heating and air conditioning in the context of climate change', *Energy Policy,* 37(2), pp. 507-521. Available at: https://doi.org/10.1016/j.enpol.2008.09.051
14. Khraiwesh, M.M and Genovese, P.V (2023) 'Outdoor Thermal Comfort Integrated with Energy Consumption for Urban Block Design Optimization: A Study of the Hot-Summer Mediterranean City of Irbid, Jordan', *Sustainability,* 15(10), pp. 8412. Available at: https://doi.org/10.3390/su15108412
15. Kolokotsa, D. and Santamouris, M. (2014) 'Energy poverty in Europe: Challenges for energy efficiency'*, Proceedings of the 5th International Conference on Information, Intelligence, Systems and Applications (IISA) IEEE* 7-9 JULY 2014*,* pp. 229. Available at: https://doi.org/10.1109/IISA.2014.6878736
16. López Moreno, H., Giancola, E., Sanchez, M.N, Tevar, J.A. and Soutullo Castro. (2020) 'Evaluation of weather conditions in urban climate studies over different Madrid neighbourhoods: Influence of urban morphologies on the microclimate', *International Solar Energy Society* Available at: https://doi.org/10.18086/eurosun.2020.09.03
17. López Moreno, H., Sanchez, M.N, Giancola, E., Tevar, J.A, Neila, F.J. and Soutullo Castro, S. (2020) ‘Outdoor thermal comfort approach in summer season for the city of Madrid Influence of urban typologies in microclimate and the outdoor thermal sensation’, *Proceedings in the 5th PLEA Conference on Passive and Low Energy Architecture* A Coruña 1st-3rd September 2020 https://doi.org/10.17979/spudc.9788497497947
18. López Moreno, H., Núñez-Piero, M., Sánchez-Guevara, C., and Neila, J. (2022) 'On the identification of Homogeneous Urban Zones for the residential buildings’ energy

evaluation', *Building and environment,* 207, pp. 108451. Available at: https://doi.org/10.1016/j.buildenv.2021.108451

19. Mao, J. and Norford, L.K (2021) 'Urban Weather Generator: Physics-Based Microclimate Simulation for Performance-Oriented Urban Planning ', in M. Palme, A. Salvati (eds) *Urban Microclimate Modelling for Comfort and Energy Studies* Cham: Springer International Publishing, pp. 241-263.
20. Maronga, B., Winkler, M., and Li, D. (2022) 'Can Areawide Building Retrofitting Affect the Urban Microclimate? An LES Study for Berlin, Germany', *Journal of applied meteorology and climatology,* 61(7), pp. 800-817. Available at: https://doi.org/10.1175/JAMC-D-21-0216.1
21. Martín-Consuegra, F., Gómez Giménez, J.M., Alonso, C., Córdoba Hernández, R., Hernández Aja, A. and Oteiza, I. (2020) 'Multidimensional index of fuel poverty in deprived neighbourhoods. Case study of Madrid', *Energy and buildings,* 224, pp. Available at: https://doi.org/10.1016/j.enbuild.2020.110205
22. Matzarakis, A. and Mayer, H. (1997) 'Heat stress in Greece', *International journal of biometeorology,* 41(1), pp. 34-39. Available at: https://doi.org/10.1007/s004840050051
23. Meteonorm (2023) *Worldwide irradiation data.* Available at: https://meteonorm.com/en/ (Accessed: 27 April 2023).
24. Naboni, Natanian, Brizzi, Florio, Chokhachian, Galanos and Rastogi (2019) 'A digital workflow to quantify regenerative urban design in the context of a changing climate', *Renewable & sustainable energy reviews,* 113, pp. 109255. Available at: https://doi.org/10.1016/j.rser.2019.109255
25. Natanian, J. and Auer, T. (2020) 'Beyond nearly zero energy urban design: A holistic microclimatic energy and environmental quality evaluation workflow', *Sustainable cities and society,* 56, pp. 102094. Available at: https://doi.org/10.1016/j.scs.2020.102094
26. ODYSSEE and MURE (2012) *Energy Efficiency Trends and Policies in the Household and Tertiary Sectors An Analysis Based on the ODYSSEE and MURE Databases.* Available at: https://www.odyssee-mure.eu/publications/archives/energy-efficiency-trends-policies-buildings.pdf (Accessed 24 May 2023)
27. Oke, T.R. (1988) 'The urban energy balance', *Progress in Physical Geography: Earth and Environment,* 12(4), pp. 471-508.Available at: https://doi.org/10.1177/030913338801200401

28. Organismo autónomo centro nacional de información geográfica (2021) *LIDAR 2nd Coverage 2015-2021.* Available at: http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=LIDAR (Accessed: 29 March 2023)
29. Pacifici, M. and Nieto-Tolosa, M. (2021) 'Comparing ENVI-Met and Grasshopper Modelling Strategies to Assess Local Thermal Stress and Urban Heat Island Effects', in M. Palme, A. Salvati (eds.) *Urban Microclimate Modelling for Comfort and Energy Studies* Cham: Springer International Publishing, pp. 293-316.
30. Palme, M., Inostroza, L., Villacreses, G., Lobato-Cordero, A. and Carrasco, C. (2017) 'From urban climate to energy consumption. Enhancing building performance simulation by including the urban heat island effect', *Energy and Buildings,* 145, pp. 107-120. Available at: https://doi.org/10.1016/j.enbuild.2017.03.069
31. Pérez, G., Martín-Consuegra, F., de Frutos, F., Martínez, A., Oteiza, I., Frutos, B. and Alonso, C. (2022) 'Analysis of the Optical Response of Opaque Urban Envelope Materials: The Case of Madrid', *Infrastructures,* 7(9). Available at: https://doi.org/10.3390/infrastructures7090116
32. Romero Rodríguez, L., Sánchez Ramos, J., Guerrero Delgado, M.d.C. and Álvarez Domínguez, S. (2022) 'Implications of the Urban Heat Island on the selection of optimal retrofitting strategies: A case study in a Mediterranean climate', *Urban Climate,* 44, pp. 101234. Available at: https://doi.org/10.1016/j.uclim.2022.101234
33. Salvati, A. and Kolokotroni, M. (2023) 'Urban microclimate and climate change impact on the thermal performance and ventilation of multi-family residential buildings', *Energy and buildings,* 294. Doi: 10.1016/j.enbuild.2023.113224 https://doi.org/10.1016/j.enbuild.2023.113224
34. Salvati, A., Kolokotroni, M., Kotopouleas, A., Watkins, R., Giridharan, R. and Nikolopoulou, M. (2022) 'Impact of reflective materials on urban canyon albedo, outdoor and indoor microclimates', *Building and environment,* 207. https://doi.org/10.1016/j.buildenv.2021.108459
35. Salvati, A., Palme, M., Chiesa, G. and Kolokotroni, M. (2020) 'Built form, urban climate and building energy modelling: case-studies in Rome and Antofagasta', *Journal of building performance simulation,* 13(2), pp. 209-225. Available at: https://doi.org/10.1080/19401493.2019.1707876
36. Salvati, A., Coch Roura, H. and Cecere, C. (2017) 'Assessing the urban heat island and its energy impact on residential buildings in Mediterranean climate: Barcelona case

study', *Energy and buildings,* 146, pp. 38-54. Available at: https://doi.org/10.1016/j.enbuild.2017.04.025

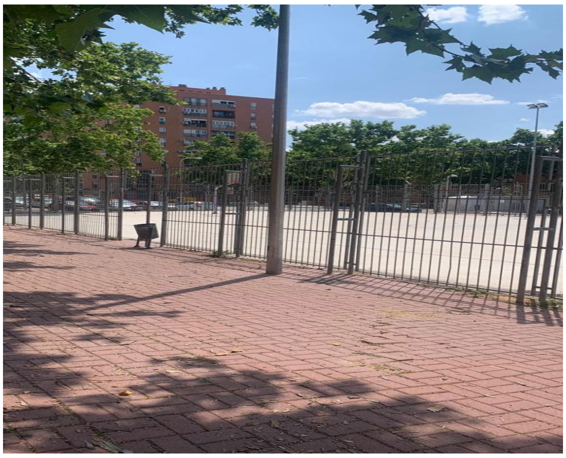
37. Santamouris, M. (2016) 'Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change', *Solar energy,* 128, pp. 61-94. Available at: https://doi.org/10.1016/j.solener.2016.01.021
38. Santamouris, M., Cartalis, C., Synnefa, A. and Kolokotsa, D. (2015) 'On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review', *Energy and buildings,* 98, pp. 119-124. Available at: https://doi.org/10.1016/j.enbuild.2014.09.052
39. Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A. and Assimakopoulos, D.N. (2001) 'On the impact of urban climate on the energy consumption of buildings', *Solar Energy,* 70(3), pp. 201-216. Available at: https://doi.org/10.1016/S0038-092X(00)00095-5
40. Santamouris, M. and Kolokotsa, D. (2015) 'On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe', *Energy and buildings,* 98, pp. 125-133. Doi: Available at: https://doi.org/10.1016/j.enbuild.2014.08.050
41. Soutullo, S., Giancola, E., Jiménez, M.J., Ferrer, J.A. and Sánchez, M.N. (2020) 'How Climate Trends Impact on the Thermal Performance of a Typical Residential Building in Madrid', *Energies,* 13(1), pp. 237. Available at: https://doi.org/10.3390/en13010237
42. Tsoka, S., Leduc, T. and Rodler, A. (2021) 'Assessing the effects of urban street trees on building cooling energy needs: The role of foliage density and planting pattern', *Sustainable cities and society,* 65, pp. 102633. Available at: https://doi.org/10.1016/j.scs.2020.102633
43. URBANopt (2022) *Urban Renewable Building And Neighbourhood optimization.* Available at: https://docs.urbanopt.net/ (Accessed: 26 April 2023).
44. Yang, Y., Javanroodi, K. and Nik, V.M. (2021) 'Climate change and energy performance of European residential building stocks – A comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment', *Applied Energy,* 298, pp. 117246. Available at: https://doi.org/10.1016/j.apenergy.2021.117246
45. Yuan, J., Emura, K. and Farnham, C. (2017) 'Is urban albedo or urban green covering more effective for urban microclimate improvement? A simulation for Osaka',

Sustainable Cities and Society, 32, pp. 78-86. Available at: https://doi.org/10.1016/j.apenergy.2021.117246

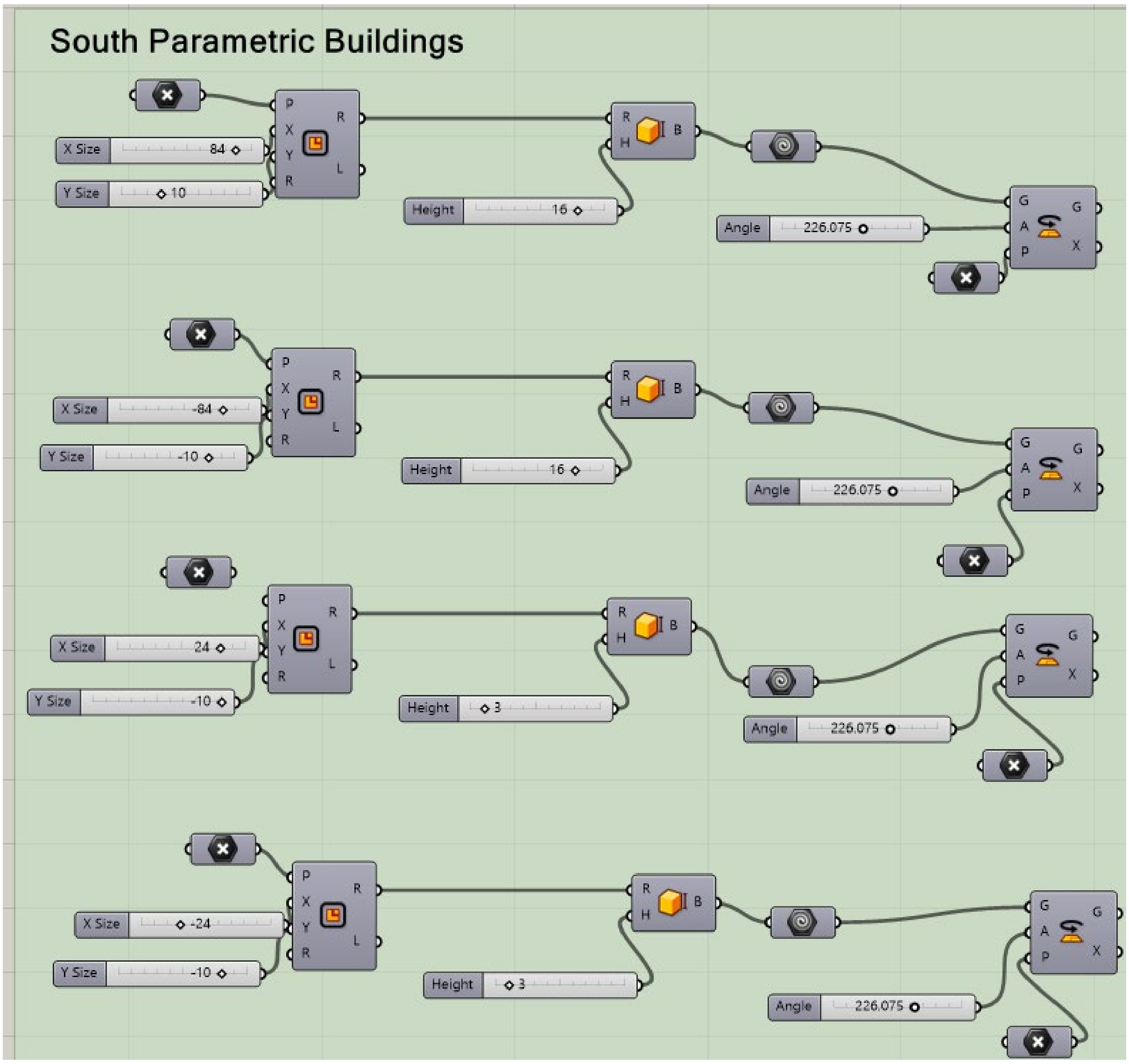
46. Zhu, S., Causone, F., Gao, N., Ye, Y., Jin, X., Zhou, X. and Shi, X. (2023) 'Numerical simulation to assess the impact of urban green infrastructure on building energy use: A review', *Building and environment,* 228, pp. 109832. Available at: https://doi.org/10.1016/j.buildenv.2022.109832

APPENDICES

Appendix I: Photos from site visit of the area



Appendix II: Workflow to develop parametric buildings



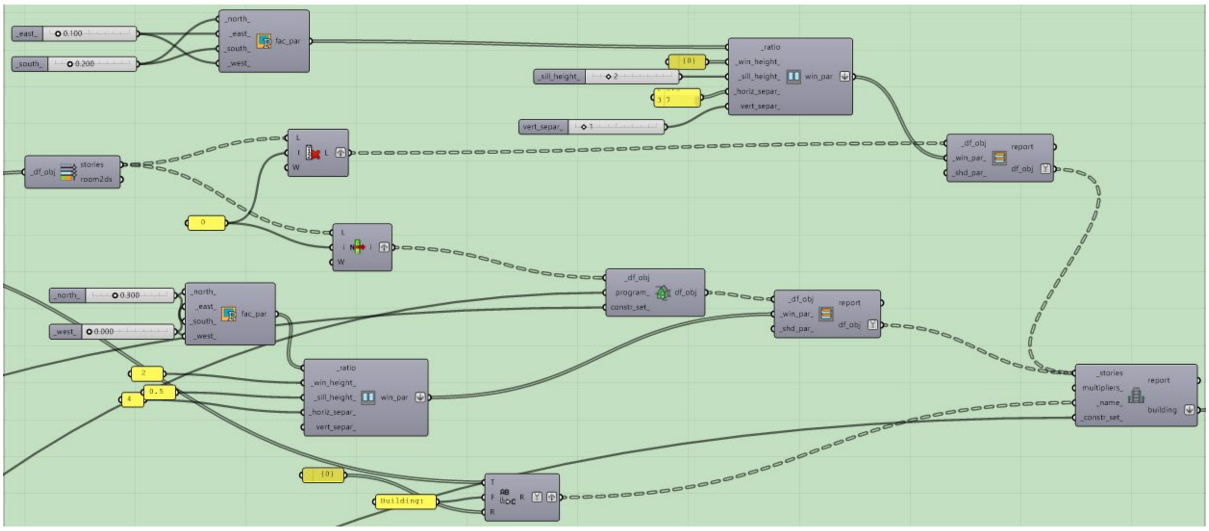
X Size 84
Y Size 10
Height 16
Angle 226.075

X Size -84
Y Size -10
Height 16
Angle 226.075

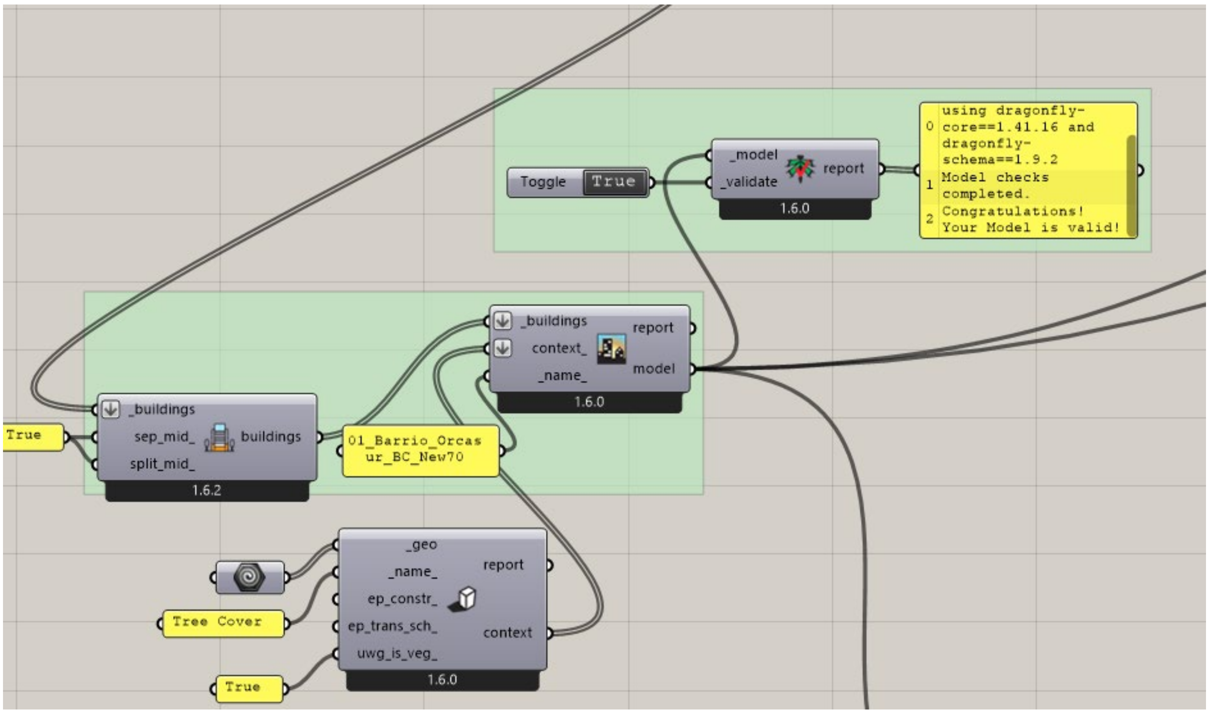
X Size 24
Y Size -10
Height 3
Angle 226.075

X Size -24
Y Size -10
Height 3
Angle 226.075

Appendix III: Workflow for assignment of window to wall ratio

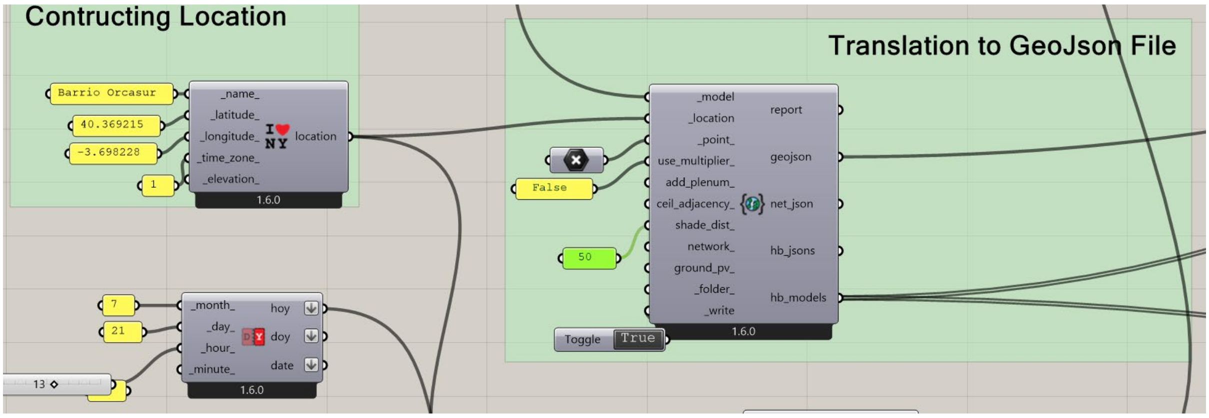


Appendix IV: Dragonfly model check

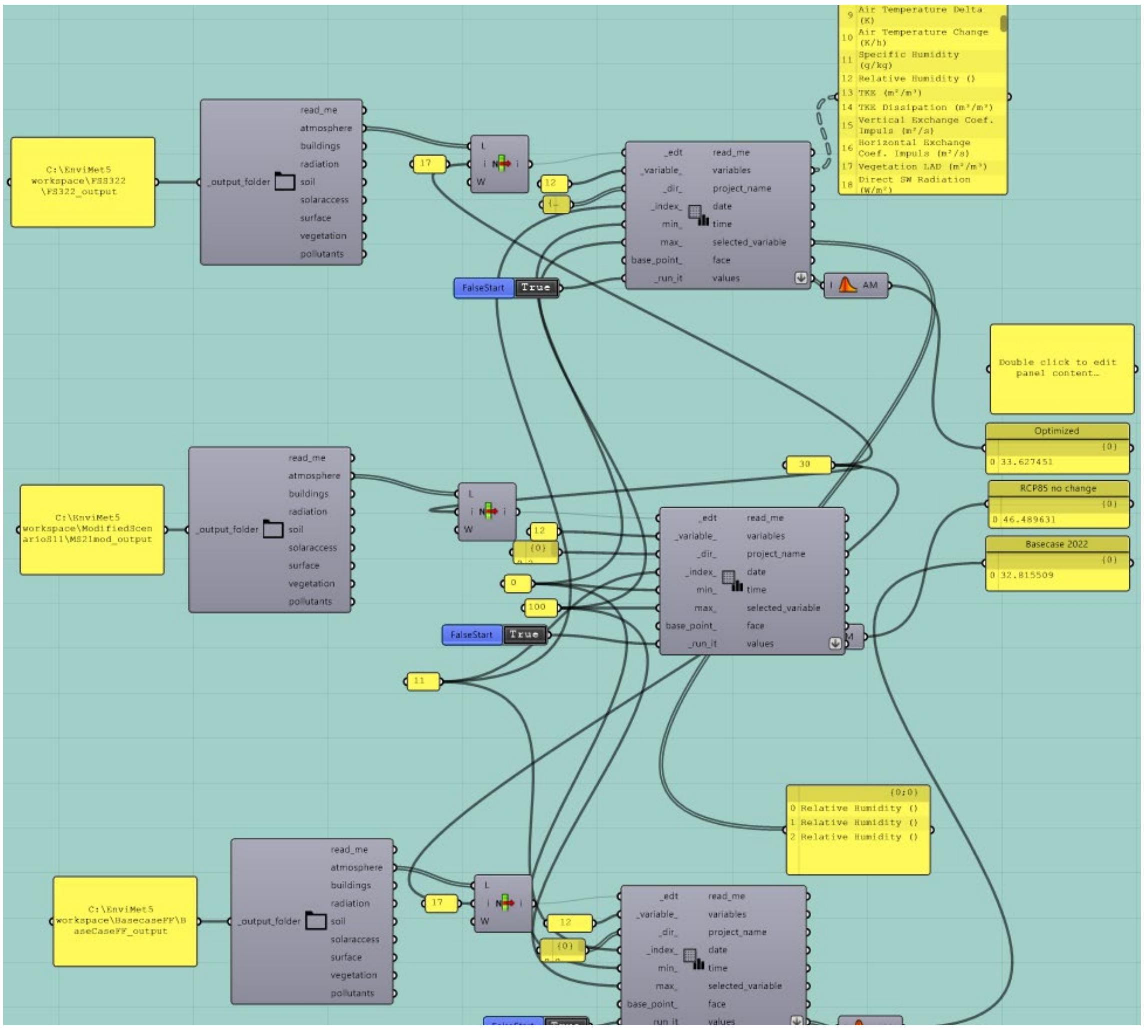


```
0 using dragonfly-
  core==1.41.16 and
  dragonfly-
  schema==1.9.2
1 Model checks
  completed.
2 Congratulations!
  Your Model is valid!
```

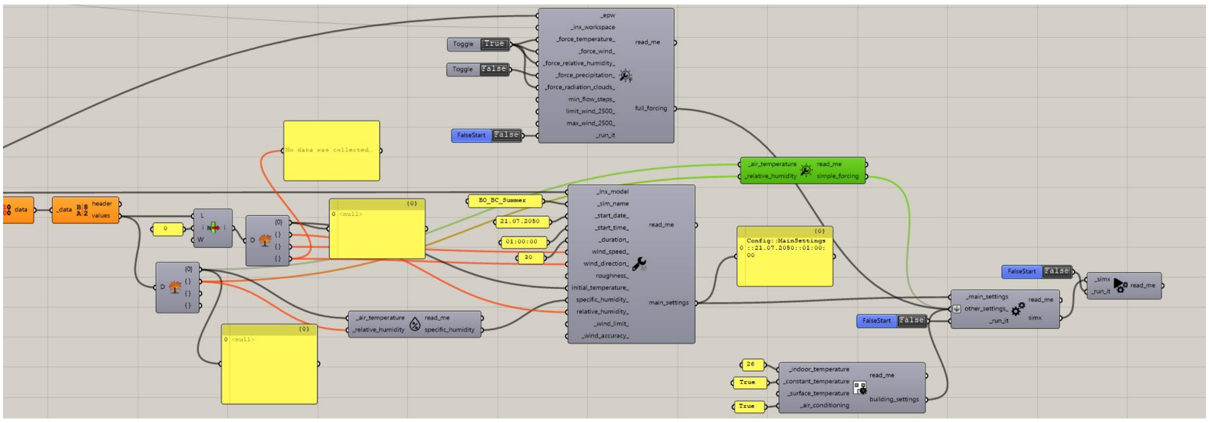
Appendix V: Workflow to create Geojson file for energy simulations



Appendix VI: Workflow to extract values for microclimatic parameters from ENVImet simulations

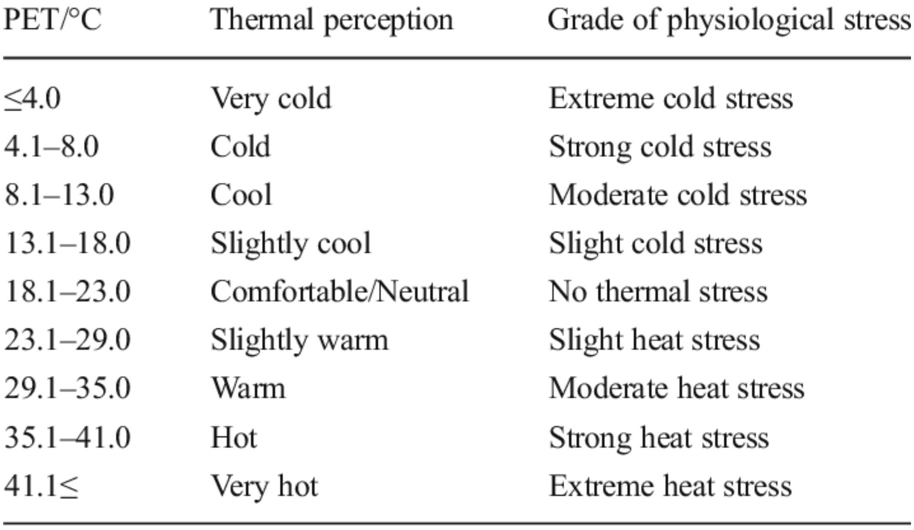


Appendix VII: Morpho workflow for assignment of SIMx file



Appendix VIII: The comfort/sensation scale of the physiological equivalent temperature (PET)

Source: (Matzarakis and Mayer, 1997)



PET/°C	Thermal perception	Grade of physiological stress
≤4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable/Neutral	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
41.1≤	Very hot	Extreme heat stress