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Nature-Based Urbanism for Enhancing Senior Citizens' Outdoor Thermal Comfort in High-Density Mediterranean Cities: ENVI-met Findings

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Abstract: As climate change intensifies the frequency and severity of urban heatwaves, elderly populations are becoming increasingly vulnerable to outdoor thermal stress, particularly in dense Mediterranean cities. This study addresses the critical need for micro-scale, climate-responsive design strategies that enhance thermal comfort for aging residents in historically underserved urban neighborhoods. Focusing on the refugee-built area of Nikea in Greater Athens, this research explores the effectiveness of nature-based solutions (NBS) in mitigating extreme heat through spatial interventions tailored to the needs of older adults. Using ENVI-met 5.6.1, two scenarios were simulated: a baseline scenario reflecting existing urban conditions and an optimal scenario incorporating mature tree planting and water features. The results are analyzed across three key time points—morning, peak afternoon, and evening—to capture diurnal thermal variations. The findings demonstrate that NBS significantly reduce the Physiological Equivalent Temperature (PET), with peak improvements exceeding 14 °C in shaded zones. This study highlights the value of fine-grained, nature-based urban interventions in promoting thermal equity and supporting climate adaptation for vulnerable populations.

Keywords: vegetation; heatwaves; senior adults; elderly; cities; fountains; water; ENVI-met; PET; dynamic thermal comfort; green urbanism; sustainable urban design; NBS; nature-based solutions

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1. Introduction

Nature-based urbanism constitutes an interdisciplinary planning and design paradigm that integrates natural processes and ecological systems into urban environments to enhance climate resilience, ecological functionality, and social well-being. Rooted in the principles of sustainability and regenerative design, it advocates for the strategic deployment of green and blue infrastructures as multifunctional solutions for addressing contemporary environmental challenges. As articulated in Nature-Based Solutions for Sustainable Urban Planning, nature-based solutions (NBS) are defined as planning and design strategies that utilize natural processes to tackle urban issues while simultaneously delivering environmental, social, and economic co-benefits [1]. In the context of this study, NBS functions as an umbrella term encompassing the climate-adaptive interventions proposed for the case study area. Within this framework, green infrastructure (e.g., mature tree planting) and blue

infrastructure (e.g., water features) are treated as operational subcategories representing the tangible components of a holistic, nature-based design strategy. A series of scenario-based simulation and measurement studies in Mediterranean cities have established that interventions featuring increased tree canopy and urban vegetation consistently achieve greater reductions in PET and UTCI than non-vegetative measures, such as cool pavements or reflective surfaces. For instance, the research on urban centers demonstrates that dense greening can lower PET by as much as 10–15 °C under peak summer conditions, outperforming material-based approaches, with additional benefits observed when combining NBS with cool materials [2–5].

From this point of view, outdoor public spaces are strong components of nature-based urbanism since they promote human well-being, providing environments that support relaxation, social interaction, and physical activity, all of which contribute to better mental and physical health [6–8]. As cities face increasing climate-related challenges, the resilience of outdoor public spaces must be prioritized to ensure they remain functional and accessible for all, particularly vulnerable groups [9]. These spaces offer opportunities to connect with nature, reduce stress, and enhance overall life satisfaction [10,11]. Thoughtful design that takes into account the diverse needs of various demographics—such as age, gender, and mobility—ensures that public spaces are inclusive and accessible for all [12–14]. Considering these factors, spaces can foster a sense of belonging and community, allowing individuals from different walks of life to feel welcomed and engaged. While outdoor public spaces are integral to human well-being, their design must not only address the diverse needs of different demographics, but also account for increasing environmental risks [7,15].

One such risk is the rising frequency and intensity of heatwaves, which pose significant health threats, especially to vulnerable populations. Recent studies have shown that heat-related mortality among older adults has increased significantly, particularly in urban environments with an insufficient green infrastructure [16–18]. Among these, the elderly are particularly at risk due to age-related declines in the body's ability to regulate temperature [9]. Studies suggest that the age of 60 years serves as a threshold for vulnerability to heat stress, while others highlight increased concerns for individuals over 80 years old [19]. Even in healthy aging, the body's capacity to regulate temperature declines, increasing susceptibility to heat stress, dehydration, cardiovascular complications, and the exacerbation of chronic diseases [20]. Physiological factors, such as diminished sweat gland function, impaired circulation, and chronic diseases—including cardiovascular disorders, diabetes, and respiratory conditions—exacerbate these risks [21]. Medications, both independently and in combination, can interact with the aging process and chronic diseases, leading to alterations in homeostatic mechanisms that regulate body temperature during heat stress [22]. Beyond physiological vulnerabilities, social and environmental factors significantly influence elderly individuals' susceptibility to heatwaves. Social isolation may also limit their access to immediate assistance during extreme heat events [23]. Also, reduced mobility, financial constraints, and energy poverty issues further increase exposure risks. Elderly individuals from lower-income backgrounds are often at even greater risk, as they may lack access to air conditioning, cooling centers, or medical assistance during extreme heat events [24].

Urban environments, characterized by heat-retaining materials and limited greenery, amplify thermal stress, disproportionately affecting older populations [25]. Urban morphology plays a critical role in shaping microclimatic conditions, as narrow streets and high-rise buildings can trap heat, exacerbating the urban heat island effect [26]. Mitigating the impact of heatwaves on the elderly requires a multi-dimensional approach, integrating medical interventions, community support, and urban design strategies. Medical and be-

havioral adaptations are essential, such as maintaining hydration, monitoring medications, avoiding outdoor exposure during peak heat hours, and utilizing cooling methods. Public health initiatives, including heat alert systems, community outreach programs, and cooling centers, play a crucial role in reducing heat-related mortality among older adults [27,28].

Urban planning and design are pivotal in enhancing outdoor thermal comfort for the elderly. Community-driven approaches, where elderly residents contribute to the design of urban interventions, can improve the effectiveness and social acceptance of climate adaptation strategies [29]. Age-friendly urban spaces should incorporate shaded areas, hydration stations, well-ventilated walkways, and reflective materials to minimize heat absorption [30–32]. Green infrastructure, such as trees and water features, significantly contributes to reducing the urban heat island effect, creating more thermally comfortable environments [2]. In addition to vegetation, blue infrastructure—such as fountains, ponds, and misting systems—can provide evaporative cooling, further enhancing thermal comfort [33]. Physiologically Equivalent Temperature (PET) is a key metric for assessing thermal comfort, integrating factors such as air temperature, humidity, solar radiation, and wind speed to provide a comprehensive understanding of outdoor heat exposure [34–36]. By employing dynamic PET analysis, urban planners can evaluate real-time thermal conditions and implement targeted cooling strategies. Integrating these urban design strategies into local climate adaptation policies and heat action plans is essential for achieving resilience [37]. Advanced modeling tools, like ENVI-met, further support the optimization of outdoor thermal comfort by simulating microclimate conditions and assessing the long-term impact of urban interventions [38–41]. Through static and dynamic PET simulations, planners can refine designs to ensure effective cooling strategies, ultimately reducing heat stress among elderly populations [42].

These evidence-based approaches reinforce the importance of interdisciplinary collaboration in creating resilient urban spaces that prioritize the health and well-being of older adults during extreme heat events. Addressing heatwave risks for the elderly requires a convergence of medical expertise, social policies, and sustainable urban design [43]. With the frequency of extreme heat events expected to rise, developing age-inclusive urban environments should be a priority for policymakers, urban planners, and public health officials alike [44]. By integrating physiological insights, community-driven interventions, and microclimate modeling, cities can develop effective strategies to enhance thermal comfort and resilience. Future research should explore how combinations of green and blue infrastructures, alongside innovative materials, can optimize outdoor thermal comfort for older citizens [45,46]. As climate change intensifies, prioritizing age-friendly environments will be critical in safeguarding the health and quality of life of older populations worldwide.

To contextualize the present study within the broader field of urban thermal comfort research, Table 1 summarizes key studies that employed PET and/or ENVI-met simulations to evaluate the effectiveness of various microclimatic interventions. These works span Mediterranean and comparable urban settings, and highlight strategies ranging from tree planting and shading to material reflectivity and spatial reconfiguration. This synthesis helps situate the current study's focus on micro-scale interventions and elderly populations within a robust and evolving body of literature.

Delving into the selected case study, this research distinguishes itself from the existing thermal comfort literature—often focusing on tropical or temperate cities—by investigating the specific urban and climatic conditions of high-density Mediterranean environments. In particular, it centers on historic Asia Minor refugee settlements in Greece, which emerged in the early-20th century under the pressures of mass displacement and urgent housing needs. These settlements developed rapidly, resulting in a compact urban fabric marked by narrow streets, minimal vegetation, and traditional construction materials. Unlike the

spacious, planned layouts common in other European cities, these neighborhoods continue to exhibit unique microclimatic characteristics shaped by their dense morphology.

Table 1. Summary of selected studies on outdoor thermal comfort and nature-based urban interventions.

Author(s)	Location/Context	Focus	Methods/Model	Key Findings
Laureti et al. (2018) [47]	Rome, Italy	Urban overheating mitigation in historic areas	ENVI-met, PET	Tree shading reduced PET by 8–12 °C; primary cooling via Tmrt reduction.
Tseliou et al. (2022) [41]	Athens, Greece	Tree configurations in an urban square	ENVI-met, PET	Dense tree canopies significantly lowered PET; supporting the use of optimal geometry.
Koletsis et al. (2019) [48]	Athens, Greece (Syntagma Sq.)	Validation of ENVI-met simulations	In situ vs. ENVI-met	High correlation found; ENVI-met accurately models Mediterranean microclimates.
Gatto et al. (2021) [40]	Lecce, Italy	Greening scenarios for thermal comfort improvement	ENVI-met, PET	Green infrastructure reduced PET up to 10 °C in southern Italian cities.
Pantavou et al. (2014) [49]	Athens, Greece	Calibration of thermal indices (e.g., PET, UTCI)	Field data, empirical model	PET performs well in Mediterranean outdoor spaces for evaluating heat stress.
Tsiros and Hoffman (2014) [50]	Athens, Greece (courtyards)	Semi-enclosed outdoor comfort in summer	Field measurements, PET	Garden spaces provided cooler PET values than adjacent open areas.
Battisti et al. (2018) [3]	Rome, Italy (University Campus)	Cooling strategies for roofs and pavements	ENVI-met	Shading had a greater PET reduction than cool pavements.
Gómez et al. (2013) [33]	Valencia, Spain	Ecological design for comfort in open urban spaces	PET	PET is suitable for evaluating design impacts on elderly populations.
Nouri et al. (2022) [35]	Ankara, Turkey	PET under extreme heat in vulnerable dwellings	PET, local extremes	Indoor PET correlated with outdoor stress; relevant for elderly individuals' vulnerability.
Piselli et al. (2018) [5]	Perugia, Italy	Microclimate mitigation based on citizen perception	In situ monitoring, pedestrian surveys, ENVI-met	Vegetation increase was preferred by users and significantly improved thermal comfort in simulations; green solutions were most effective against anthropogenic heat.
Sylliris et al. (2023) [4]	Thessaloniki, Greece	Climate resilience and air quality on Mediterranean urban roads	ENVI-met, PET, air quality modeling	Pedestrianization with trees and cool materials reduced PET by up to 15 °C and NOx by 87%; green interventions were most effective in high-density zones.

A critical focus of this study is the thermal comfort of the elderly—a population that is not only demographically prominent in such areas, but also physiologically more vulnerable to extreme heat due to reduced metabolic rates and impaired thermoregulation. Addressing a significant gap in the literature, this research prioritizes micro-scale thermal comfort assessments in dense Mediterranean contexts, where street-level and courtyard-specific dynamics are often overlooked in broader urban-scale analyses. Through fine-grained spatial simulation and evaluation, this study provides a deeper insight into the effectiveness of nature-based interventions in mitigating heat stress at the scale most relevant to everyday experiences. In light of the intensifying heatwaves in the Mediterranean, understanding how a historically produced urban form interacts with elderly vulnerability is both urgent and essential for future climate-resilient urban design.

The current study consists of three stages, beginning with pre-field work. The pre-field work stage includes a contextualization of the research problem through an extensive literature review. The general review explores the challenges related to thermal comfort for senior adults in outdoor spaces and examines the impact of heat stress during Mediterranean heatwaves (Figure 1). Following this, a more specific literature review is conducted to assess the existing research on optimizing thermal comfort in outdoor environments. This step also identifies the research gaps and modifies new studies. The insights gained from this stage lead to the formulation of the research questions, which guide the subsequent phases of this study. The research questions are presented below:

- RQ1: What is the impact of existing urban conditions in a densely built neighborhood of Greater Athens on the outdoor thermal comfort of senior adults during extreme heat events?
- RQ2: How do nature-based interventions, such as mature trees and water features, mitigate thermal stress by reducing Physiologically Equivalent Temperature (PET) and enhancing dynamic thermal comfort for elderly individuals?
- RQ3: How effective are established urban design strategies in enhancing thermal resilience for vulnerable populations, such as senior adults?

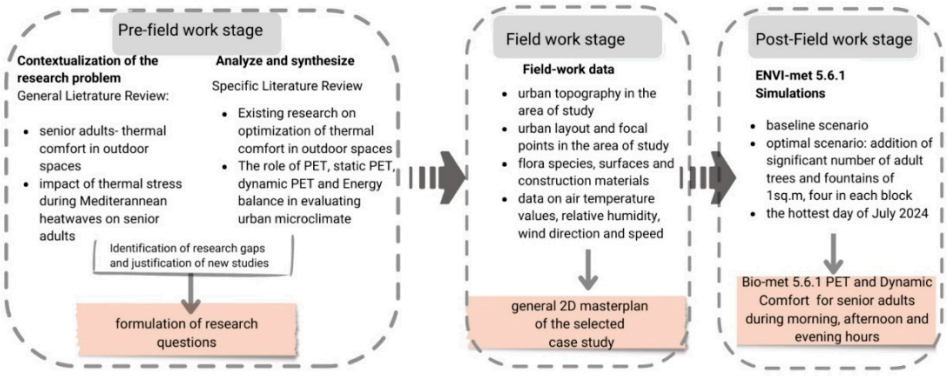


Figure 1. Methodology scheme; the authors' work.

2. Materials and Methods

This study followed a structured methodology divided into three main stages: the pre-fieldwork stage, fieldwork stage, and post-fieldwork stage. These stages were designed to systematically analyze and optimize thermal comfort for senior adults in outdoor spaces, particularly during Mediterranean heatwaves.

2.1. Data Collection

The selected case study area is situated within the capital of Greece. Located within Athens, the study area experiences a hot Mediterranean climate with dry summers, classi-

fied as Csa according to the Köppen–Geiger system. This climate type is characterized by generally mild temperatures and moderate seasonal fluctuations [2]. It was designed as an urban refugee settlement in the aftermath of the Asia Minor Catastrophe of 1922 [51]. Following a Hippodamian grid, the area consists of rectangular city blocks (around 57 × 82 m each) with a communal open space in the middle, characterized by a high building and population density [52]. It is essential to note that this study is part of a broader research project involving multiple ENVI-met simulations aimed at investigating the potential for improving outdoor thermal conditions in the selected area [2,53]. It includes unpublished data and findings that focus on the specific needs of elderly individuals. Building on the previous research, elderly individuals represent a substantial segment of the area's population [54]. The data from relevant sources position Nikea as part of the working-class and historically disadvantaged strata of the Athens urban region, reflecting long-standing patterns of inequality and segregation, including forms of energy poverty. Consequently, this study aims to explore the specific aspects of senior-friendly design in a historically disadvantaged area to address their needs effectively [55,56].

The fieldwork stage focused on collecting the relevant field data to analyze the physical characteristics of the selected study area (Figures 1 and 2). This involved examining the urban topography, urban layout, and focal points, as well as identifying the flora species, surface materials, and construction elements that influence microclimate conditions. The data gathered were then synthesized into a general 2D masterplan, which served as the foundational reference for further analysis and simulations.

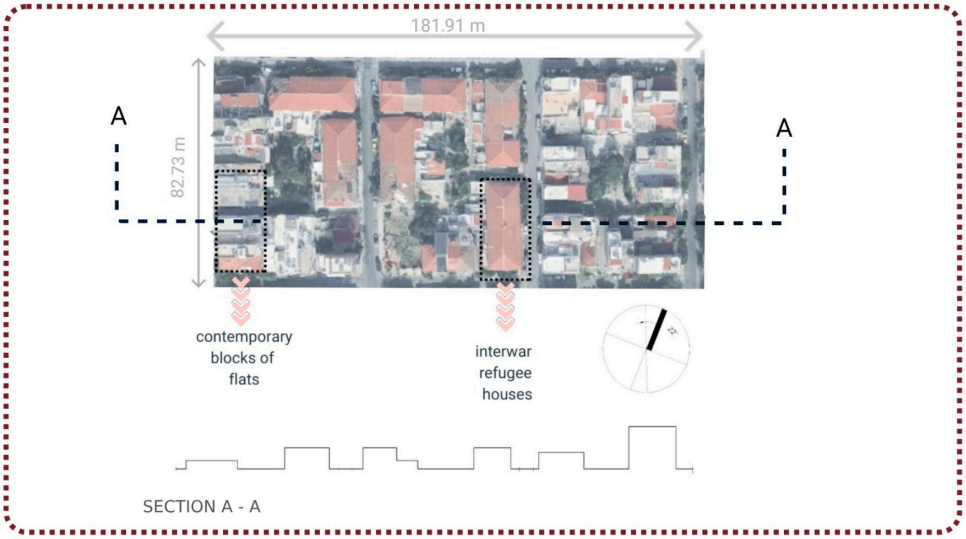


Figure 2. Aerial view of the selected case study area and section A-A.

2.2. Environmental Simulations and Scenario Development

In the post-field work stage (Figure 1), this study employed ENVI-met 5.6.1 simulations to evaluate different thermal comfort scenarios. The first step was to establish a baseline scenario that reflected the existing urban conditions. An optimal scenario was then proposed, incorporating a significant number of adult trees and fountains (each measuring 1 square meter, with four per block, Figure 3) to enhance thermal comfort. The simulation was conducted on the hottest day of July 2024, ensuring the results account for extreme heat conditions. Building on the authors' previous research, within the context of a Mediterranean city, urban design should prioritize the warmer period of the year, which is characterized by a longer duration and more pronounced thermal discomfort. In contrast, the environmental conditions during the cooler period generally support thermal comfort for the majority of the day, suggesting that no modifications to the environmental

conditions are required in urban planning during this time [57]. On the selected July 2023 day (23 July 2023), the highest recorded air temperature was 41.7 °C at 3:00 p.m., while the lowest temperature was documented as 30.9 °C at 6:00 a.m. Relative humidity peaked at 54% at 6:00 a.m. and decreased to a minimum of 23% at 3:09 p.m. The average wind speed was measured at 4.6 km/h (1.27 m/s), with a wind direction of 180°. These data were derived from the Meteosearch website and were utilized as inputs for the ENVI-met software to initialize the microclimatic simulations. The robustness of the results is typically established through model validation, a process that was not undertaken in this study due to the requirement for on-site measurements. However, the reliability of the model was confirmed in the previous research conducted by the authors, where validation was carried out in Athens, thereby supporting the credibility of the findings presented here [48].

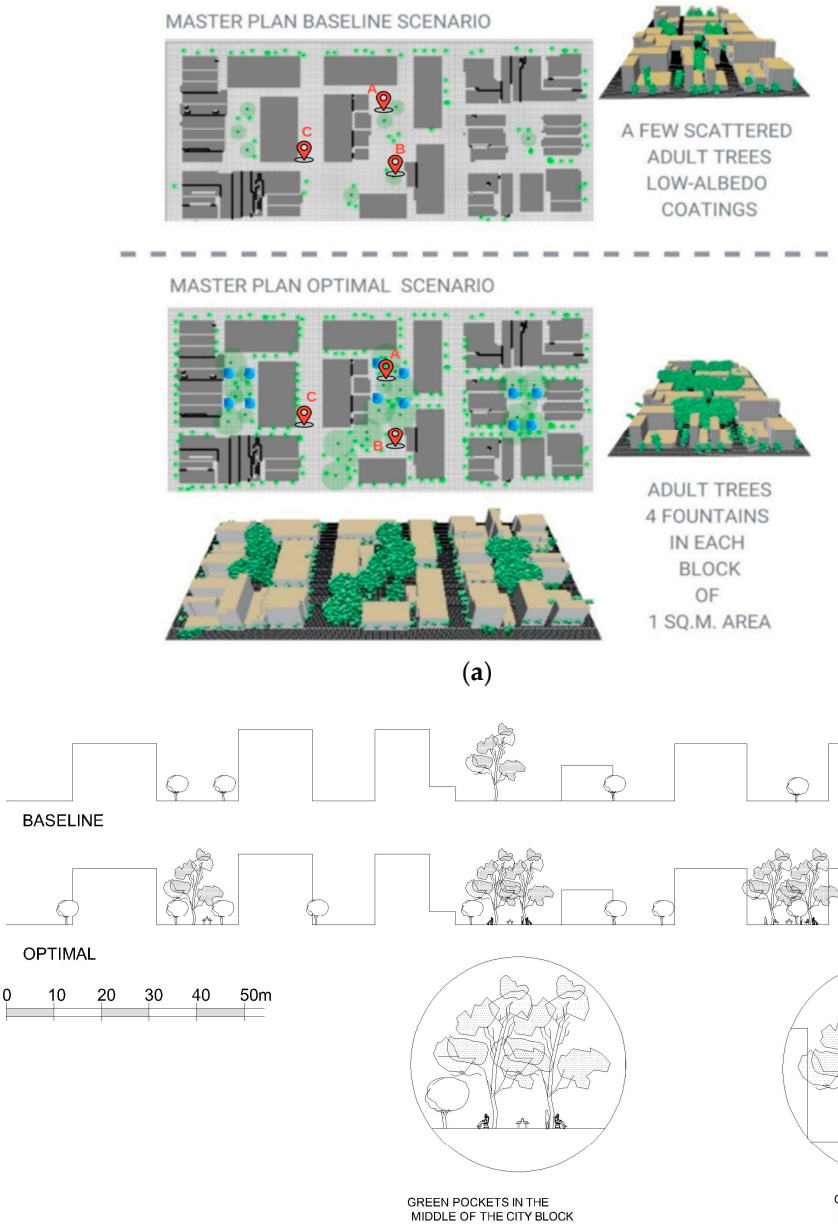


Figure 3. (**a**) Two-dimensional and 3d images of the study area in baseline and optimal scenarios and the 3 points, A, B, and C, for further analysis. (**b**) Sections, baseline, and optimal scenarios; the authors' work.

The total duration of the simulation for each scenario was 48 h. The simulation was conducted using ENVI-met version 5.6.1, which generates microclimatic data at 10 min intervals by default; this setting was retained to ensure consistency with standard modeling practices and was not manually modified. The designated study area spans approximately 181.91 square meters in length and 82.73 square meters in width (Figure 2). In the ENVI-met model, the spatial configuration consisted of 182 grids along the x-axis, 83 grids along the y-axis, and 30 grids along the z-axis. Each grid cell was uniformly sized at 1 m in all directions (dx = 1 m, dy = 1 m, dz = 1 m). Details on grid sensitivity provide a 1 m × 1 m resolution, selected based on the scale of the neighborhood and prior model validation in Athens (Table 2). The model was oriented at an angle of −22 degrees relative to the north grid. The site's geographic coordinates were approximately 23.67° longitude and 37.98° latitude. The study location, Nikaia-Agios Ioannis Rentis, falls within the Eastern European Standard Time zone. The designated soil profiles for the nesting grids included [0200ST] Asphalt Road (Soil A) and [0200PP] Pavement Concrete, categorized as worn and unclean. Building heights ranged from 3 to 15 m, with the majority of buildings standing at approximately 7.5 m in height. Tree height ranged from 3 m along the pavements to 15 m in the central areas of each city block, within the open communal spaces. The area included medium-sized trees with a cylindrical trunk and spherical canopy.

Table 2. ENVI-met input parameters for simulation.

Parameter	Value	Source/Notes
Simulation Date	23 July 2023	Hottest day of the year during the 2023 heatwave
Simulation Duration	06:00 to 20:00 (14 h)	Covers full daytime exposure
Air Temperature (06:00)	28.1 °C	Meteosearch.gr: Athens Station
Maximum Air Temperature	42.3 °C (approx. 15:00)	Meteosearch.gr: Athens Station
Relative Humidity	28–53%	Varies throughout the day
Wind Speed	1.2 m/s	Measured at 10 m height
Wind Direction	North (0°)	Constant direction assumed

The optimal scenario applied in this study was developed based on the findings from the previous research by the authors [28], which explored the thermal performance of various climate-adaptive design strategies in a comparable Mediterranean microclimate. That work identified the most effective configurations in terms of the shading potential and evaporative cooling—specifically the use of mature trees and water features. These interventions were selected for their demonstrated ability to significantly reduce PET values and enhance outdoor thermal comfort. The same principles were adapted and applied to the spatial and social characteristics of the current study area to construct the optimal design scenario. For the optimal scenario, the geometry of the tree canopy plays a crucial role in shading [2]. The newly planted trees, with their heart-shaped canopy, are bound to provide a broader shaded area compared to the cylindrical canopy of the existing trees, as observed in the earlier research. It is important to note that vegetation was modeled using ENVI-met's predefined tree database. For the baseline scenario, existing medium-sized trees were assigned the software's default cylindrical canopy profile, which features a relatively uniform Leaf Area Density (LAD) distribution along the vertical axis. In contrast, the optimized scenario incorporated newly introduced trees with heart-shaped canopies, corresponding to ENVI-met's standard "tree_hs" (heart-shaped) LAD profile. This profile concentrates foliage in the upper-middle canopy zone, enhancing the shading performance. No custom LAD configurations were applied; both tree types utilized the

default LAD values provided by ENVI-met to ensure consistency and reproducibility across the simulation runs (see Table 3 below). Albedo values reflect typical ranges for mature tree canopies under ENVI-met defaults. Transpiration efficiency was determined by canopy structure and foliage distribution, with heart-shaped canopies offering enhanced evaporative cooling due to denser upper foliage layers (Table 4).

Table 3. Default ENVI-met LAD profiles for tree canopies used in this study.

Relative Height (% of Tree Height)	LAD (m^2/m^3)—Cylindrical Canopy	LAD (m^2/m^3)—Heart-Shaped Canopy
0–20%	0.5	0.0
20–40%	0.5	0.5
40–60%	0.5	1.2
60–80%	0.5	1.5
80–100%	0.5	1.0

Table 4. Tree canopy albedo and transpiration efficiency (ENVI-met defaults).

Tree Canopy Type	Albedo	Transpiration Efficiency
Cylindrical Canopy	0.20–0.25	Moderate
Heart-Shaped Canopy	0.20–0.25	High

2.3. Data Analysis

Bio-met 5.6.1 PET and Dynamic Comfort models were used to assess the thermal comfort levels for senior adults (default option: 80-year-old male, 0.5 clo, preferred speed of 0.9 m/s) at different times of the day, including morning, afternoon, and evening. Biomet is a post-processor tool for estimating Biometeorological Indices from ENVI-met model output files and it summarizes the impact of the four basic meteorological parameters, air temperature, radiative temperature, wind speed, and humidity, on the human thermal sensation. In ENVI-met simulations, static PET uses fixed values for metabolic rate and clothing insulation, representing thermal comfort under constant environmental conditions. In contrast, dynamic PET accounts for changes in these parameters over time, simulating how individuals adapt their behavior and clothing in response to fluctuating weather conditions. Dynamic PET provides a more realistic assessment of thermal comfort by incorporating human responses to changing environments.

It is important to note that the Mediterranean PET scale was employed for the interpretation and analysis of the results (Table 5). Moreover, three characteristic points within the study area were selected to investigate the differences between the baseline and optimal scenarios. Specifically, Point A is located in an unshaded area of the baseline scenario, while Point B is situated in a shaded area of the same scenario. Point C is positioned along an adjacent street. These points exhibit variations in both the shade levels and surface albedo. Point A has a typical concrete pavement albedo, Point B is characterized by soil, and Point C by asphalt. In the optimal scenario, Points A, B, and C are subject to different conditions, owing to the addition of mature trees, fountains, and tree-lined streets, as illustrated in Figure 3. Key parameters analyzed include PET* (°C), wind speed (m/s), air temperature (°C), mean radiant temperature (°C), specific humidity (g/kg), all evaluated during peak heat hours at 3 p.m.

Table 5. Original and Mediterranean PET scale [57].

PET (°C).	Mediterranean Scale [b]	Thermal Comfort Assessment
Original Scale [a]		
>41.1	>40.0	Very hot
35.1 to 41.0	34.0 to 40.0	Hot
29.1 to 35.0	28.0 to 34.0	Warm
23.1 to 29.0	26.0 to 28.0	Slightly warm
18.1 to 23.0	19.0 to 26.0	Neutral
13.1 to 18.0	15.0 to 19.0	Slightly cool
8.1 to 13.0	12.0 to 15.0	Cool
4.1 to 8.0	8.0 to 12.0	Cold
<4.0	<8.0	Very cold

[a] Matzarakis and Mayer, 1996 [58]. [b] Cohen et al., 2013 [59].

It is important to note that all ENVI-met simulations conducted in this study are based on the physiological parameters specific to senior adults, as defined by the software's dedicated configuration settings. In contrast to most comparable studies, which typically utilize a 35-year-old reference individual, this research focuses exclusively on the thermal responses of elderly populations—a demographic characterized by distinct thermophysiological traits. This targeted approach allowed for a more accurate assessment of thermal comfort and vulnerability among older adults within the studied urban environments. In addition, all spatial outputs are direct results from the ENVI-met software and are presented in their default visual format.

By following this structured methodology, this study aimed to provide insights into the effectiveness of urban design interventions in mitigating thermal stress for vulnerable populations, contributing to the development of more resilient and inclusive outdoor spaces.

3. Results

The selection of the three time points—9:00 a.m., 3:00 p.m., and 8:00 p.m.—was informed by both ENVI-met simulation guidelines and behavioral observations from the previous research conducted by the authors in similar urban contexts. These time points were chosen to capture distinct phases of daily thermal variation: morning (9:00 a.m.), when older adults often engage in errands or light outdoor activity; peak heat (3:00 p.m.), which typically reflects the most thermally stressful period; and early evening (8:00 p.m.), when temperatures begin to drop but accumulated surface heat may still affect thermal comfort. Notably, the 8:00 p.m. time point was selected based on the findings from the authors' prior study, which documented that elderly residents tend to gather in communal outdoor spaces around 7:30 p.m. (19:30), making this period critical for evaluating the lingering effects of daytime heat. By analyzing PET values at these intervals, this study captures key exposure windows that align with daily elderly activity patterns and informs time-sensitive mitigation strategies.

3.1. Baseline Scenario—9 a.m.

The diagram in Figure 4 illustrates the environmental conditions affecting elderly individuals at 9 a.m. in the baseline scenario. Key parameters, such as air temperature, humidity, wind speed, and thermal comfort indices, are depicted. PET values vary from 34.45 to 61.85 °C, indicating "Hot" and "Very-hot" thermal conditions from early in the morning. The data suggest a relatively moderate thermal environment, with values indicating a stable energy balance. However, early signs of thermal discomfort may be present, particularly in areas with limited shade or high surface heat retention, such as along the main vehicular roads and the inner parts of the blocks, where no vegetation

is present. The diagram, thus, highlights the differences in urban and vegetated zones, showing how localized microclimates impact thermal comfort. The effects of varied solar radiation exposure are also evident, affecting heat dissipation rates and individual comfort levels. As presented in Figure 4, shaded areas provide lower PET values (from 43.45 to 41.49 °C).

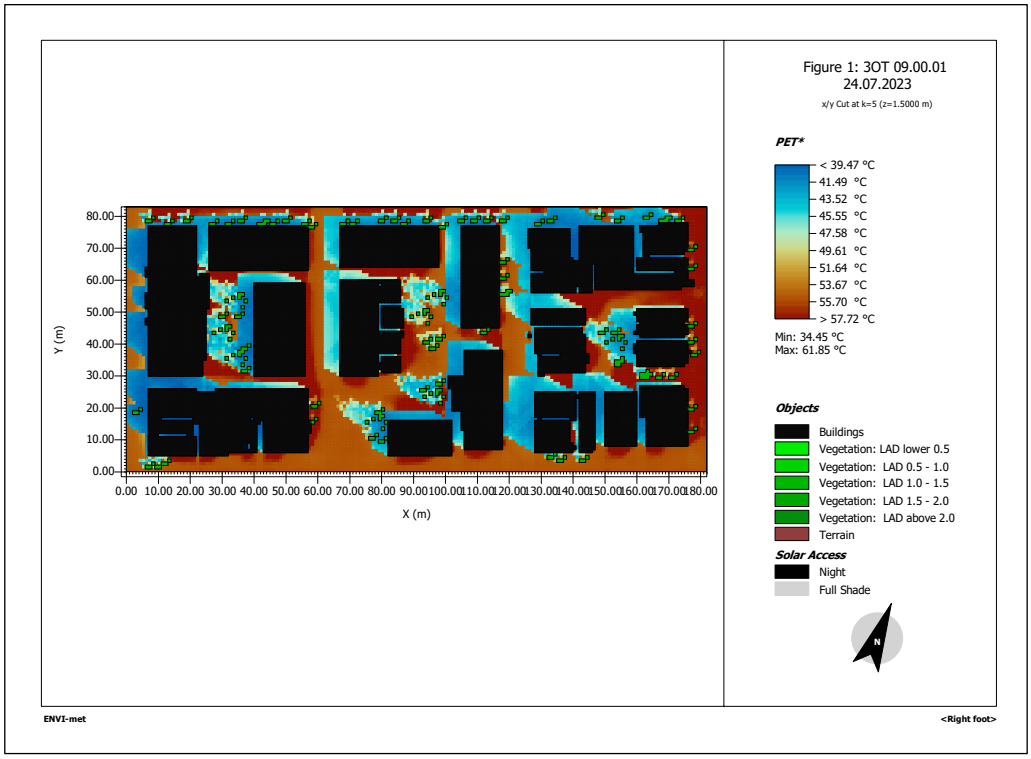


Figure 4. Baseline scenario, 23/07/2023, PET, male 80 years old, 9:00 a.m.

3.2. Baseline Scenario: 3 p.m.

The diagram in Figure 5 presents the conditions at 3 p.m., a critical period due to peak ambient temperatures. The results indicate increased thermal discomfort levels, with higher Physiologically Equivalent Temperature (PET) values and energy balance deviations. PET values vary from 38.14 to 62.39 °C indicating "Hot" and "Very-hot" thermal conditions. The elderly population is particularly susceptible to these conditions, as shown by elevated discomfort indicators. The diagram visualizes significant heat accumulation in paved areas and urban heat islands, emphasizing the need for shading and cooling strategies. Thermal strain is pronounced, suggesting that without mitigation measures, individuals in these environments may experience severe thermal discomfort and increased health risks. The influence of building orientation and material reflectivity is also noticeable, affecting the temperature distribution across different urban sections. To be more specific, shaded areas by adjacent buildings provide pockets with lower PET values up to 49.86 °C, while non-vegetated enclaves exposed to direct sunlight provide higher PET values, around 62.39 °C. It is important to note, though, that all enclaves of the examined area show high levels of thermal discomfort with values that rise higher than 39 °C.

3.3. Baseline Scenario: 8 p.m.

The evening scenario demonstrates a decline in temperature and overall thermal load. PET values vary from 36.35 to 45.79 °C, indicating "Hot" and "Very-hot" thermal conditions and, therefore, residual heat from the day may still contribute to discomfort, particularly in urban pockets with high thermal mass. The diagram in Figure 6 shows

a gradual return to more tolerable conditions, yet variations in energy balance suggest localized thermal retention effects. Buildings, pavements, and unshaded surfaces continue to emit heat, which may prolong the thermal strain into the night. The elderly, especially those with limited mobility, may still experience elevated physiological stress, highlighting the need for better nighttime ventilation and cooling solutions. The persistence of high ground surface temperatures in certain urban pockets indicates a need for strategies such as increased nighttime airflow, enhanced vegetation, or modified materials with lower thermal conductivity.

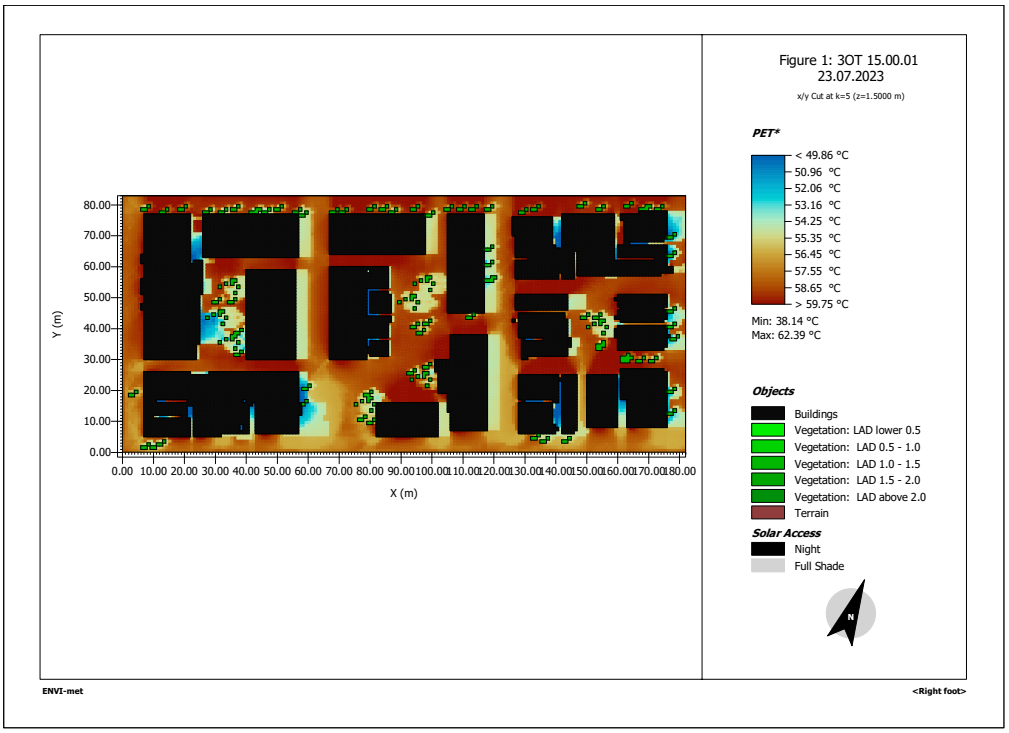


Figure 5. Baseline scenario: 3 p.m.

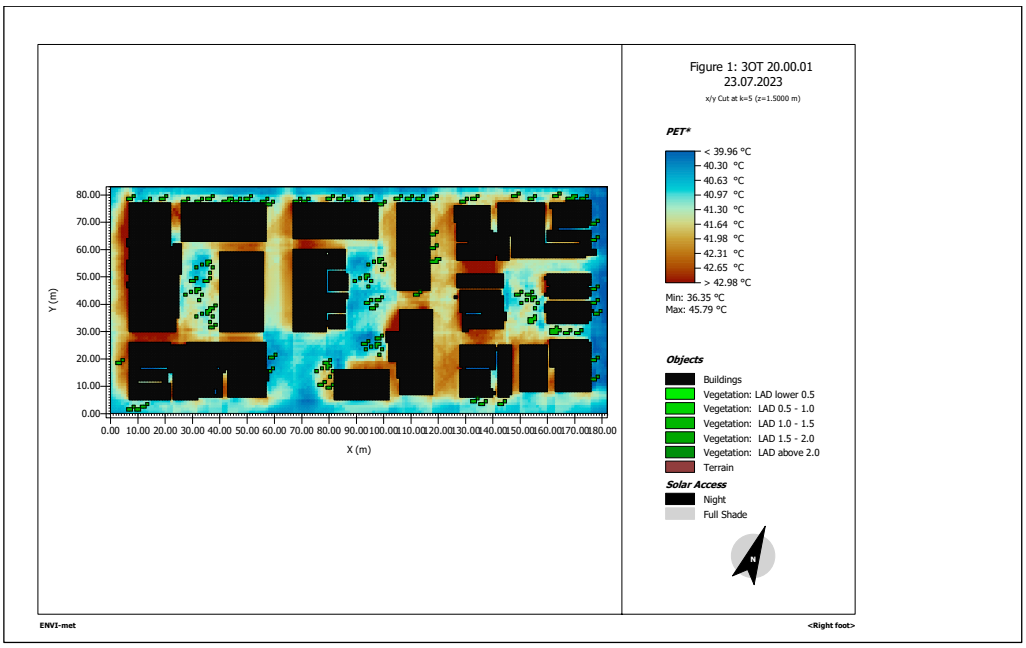


Figure 6. Baseline scenario, PET, 8 p.m.

3.4. Optimal Scenario—9 a.m.

In the optimal scenario at 9 a.m. (Figure 7), the diagram highlights improved thermal conditions through various mitigation measures. PET values vary from 34.23 to 61.79 °C ("Hot" and "Very-hot" thermal conditions). Compared to the baseline, air temperature and PET values are lower, indicating enhanced thermal comfort. The modifications applied in this scenario contribute to a more stable energy balance, reducing early-day discomfort. Figure 7 also shows a more uniform temperature distribution, suggesting that interventions successfully minimized localized heat extremes. The inclusion of shaded pedestrian areas and enhanced natural ventilation pathways further enhances overall thermal resilience in the morning hours.

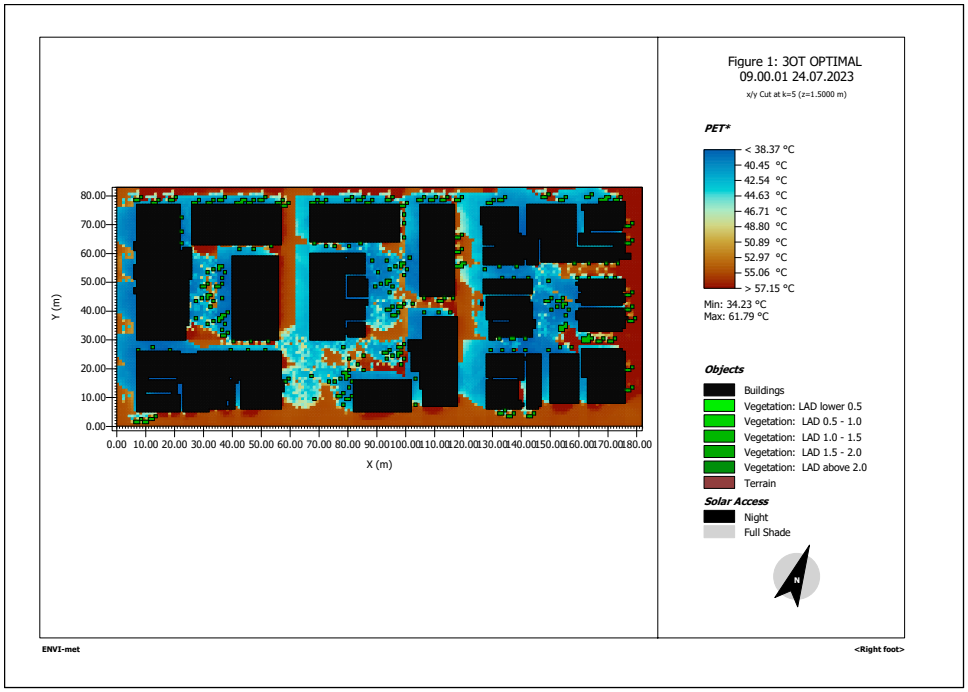


Figure 7. Optimal scenario, 9 a.m., PET.

3.5. Optimal Scenario—3 p.m.

Figure 8 presents conditions during peak afternoon hours under the optimal scenario. PET values vary from 37.94 to 61.86 °C ("Hot" and "Very-hot" thermal conditions). Compared to the baseline, significant reductions in thermal discomfort markers are evident. Lower PET values, through improved shading, contribute to an overall enhancement in thermal comfort. Figure 8 showcases a more sustainable thermal environment, where green infrastructure, passive cooling, and urban design elements help to mitigate extreme heat exposure, reducing potential health risks. The presence of water features in urban designs further contributes to cooling effects, demonstrating the multifaceted approach to heat mitigation.

3.6. Optimal Scenario—8 p.m.

The nighttime conditions in the optimal scenario depict a further improvement in thermal comfort compared to the baseline. In the optimal scenario, PET values at 8 p.m. vary from 36.36 to 44.67 °C ("Hot" and "Very-hot" thermal conditions). Figure 9 demonstrates a more consistent decline in the thermal load, mitigating late-evening heat stress effects. The presence of natural ventilation corridors and strategic landscaping contributes to improved cooling, making the nighttime experience more comfortable. The optimal scenario illustrates the long-term benefits of climate-responsive urban planning. The reduction

in retained heat in key urban sections suggests that well-planned mitigation techniques can significantly lower nighttime discomfort levels, leading to an overall improvement in livability.

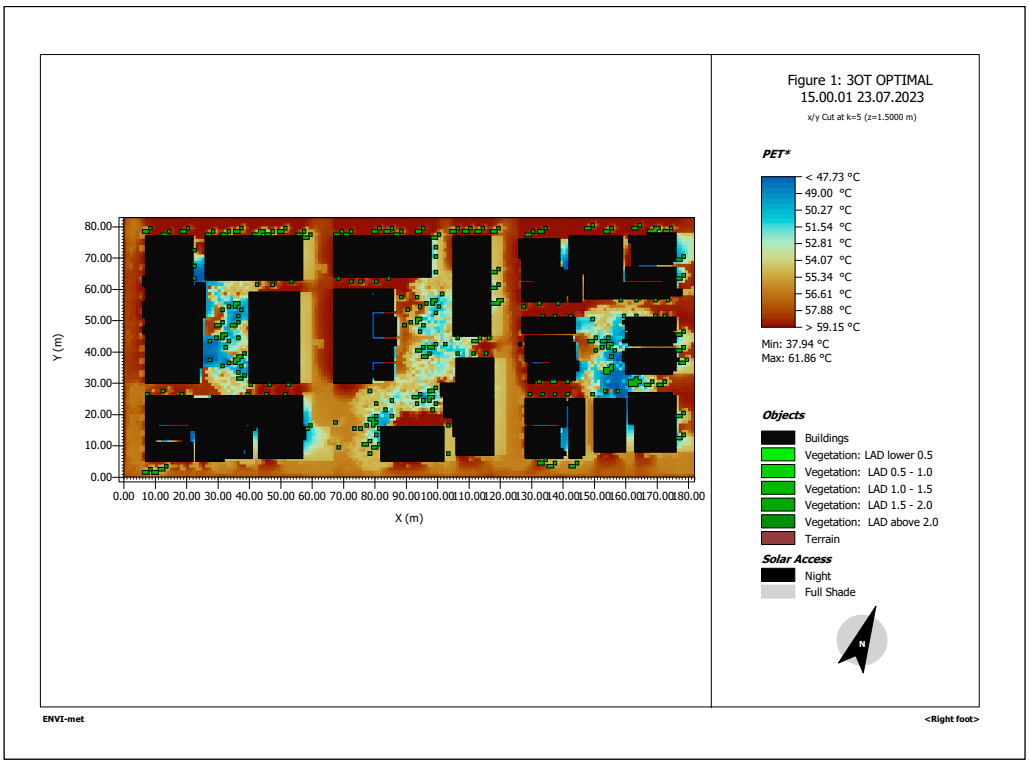


Figure 8. Optimal scenario, PET, 3 p.m.

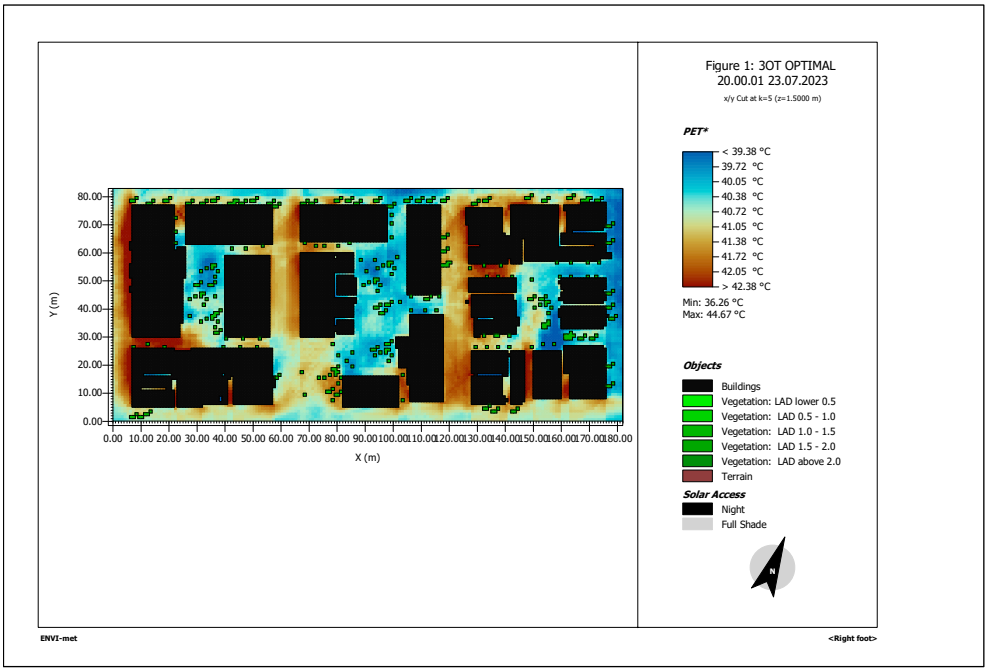


Figure 9. Optimal scenario, PET, 8 p.m.

3.7. Comparison Between Baseline and Optimal Scenarios

This set of diagrams provides a direct comparison between the baseline and optimal scenarios at three key time points (9 a.m., 3 p.m., and 8 p.m.). The data reveal that mitigation strategies significantly lower thermal stress, particularly during peak hours. The optimal

scenario exhibits a more stable energy balance and reduced PET values across all periods. The comparison underscores the effectiveness of adaptive measures, including shading through green infrastructure, in enhancing elderly individuals' thermal comfort. The visual representation of the temperature distribution in both scenarios further highlights the effectiveness of interventions in reducing urban heat stress. The statistical differences in temperature gradients between the two scenarios serve as concrete evidence of the benefits of climate-sensitive urban planning. Temperature differences are expressed in Kelvin (K) as per ENVI-met default output. These represent absolute differences in PET values between the baseline and optimal scenarios. The use of Kelvin follows the software's standardized visualization protocol and was not altered to maintain the integrity of the simulation results. To be more specific, the absolute difference in PET values, at 9 a.m., varies from −11.17 K to 22.45 K (Figure 10). During the hottest period of the day, at 3 p.m., the absolute difference in PET values varies from 2.17 to 14.55 K (Figure 11). In addition, at 8 p.m., the absolute PET difference varies from −0.56 to 4.78 K (Figure 12). Negative values indicate areas where localized PET slightly increased due to reduced airflow or radiation trapping effects, but these are minimal and occur in very specific spots. Overall, thermal conditions improved across the area.

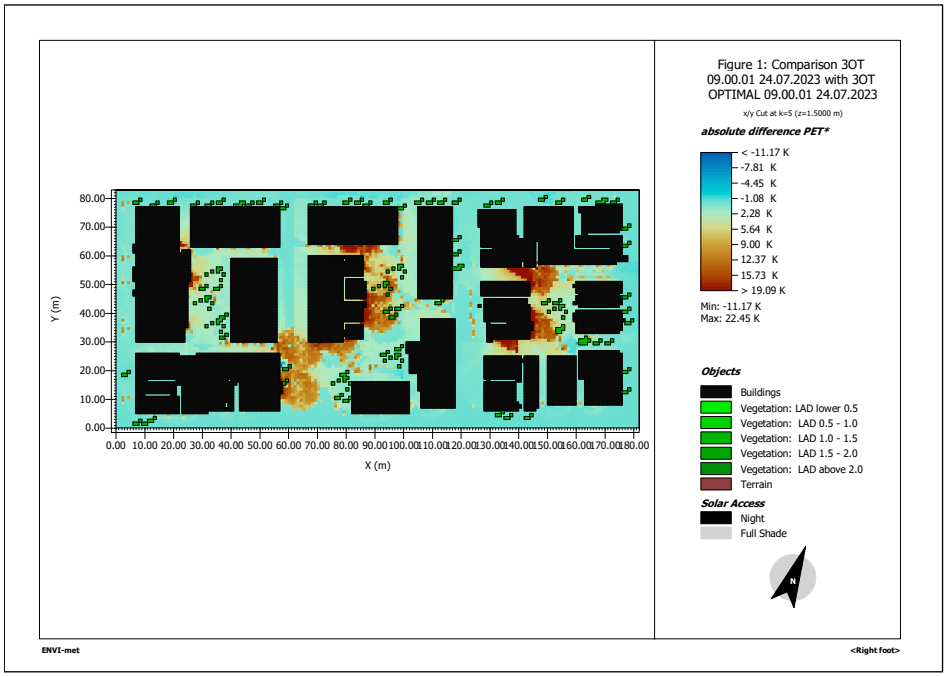


Figure 10. Absolute difference PET, baseline, and optimal scenarios, 9 a.m.

3.8. Comparative PET Analysis Across Urban Scenarios and Time Periods

Table 6 provides a comprehensive overview of the Physiologically Equivalent Temperature (PET) ranges observed in both the baseline and optimized urban design scenarios at three critical times of the day: 9:00 a.m., 3:00 p.m., and 8:00 p.m. The table reflects the results of the ENVI-met simulations conducted on the hottest day of the year (23 July 2023), specifically calibrated for an elderly demographic—an 80-year-old male—to assess vulnerability to thermal stress in a dense Mediterranean urban environment. In the baseline scenario, PET values remain consistently high throughout the day, ranging from 34.45 °C to 61.85 °C in the morning, peaking at 62.39 °C in the afternoon, and only slightly decreasing by 8:00 p.m., with values still ranging between 36.35 °C and 45.79 °C. These levels fall within the "Hot" to "Very-Hot" thermal stress categories, indicating that even early-morning and evening periods offer minimal thermal relief for older adults.

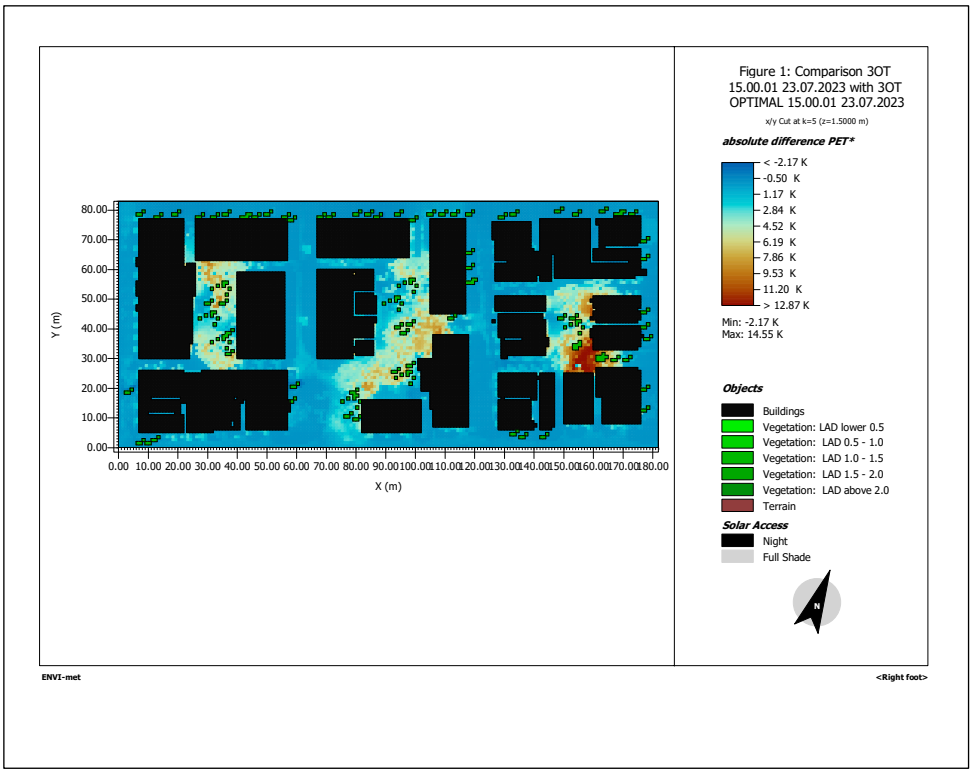


Figure 11. Absolute difference in PET values, 3 p.m.

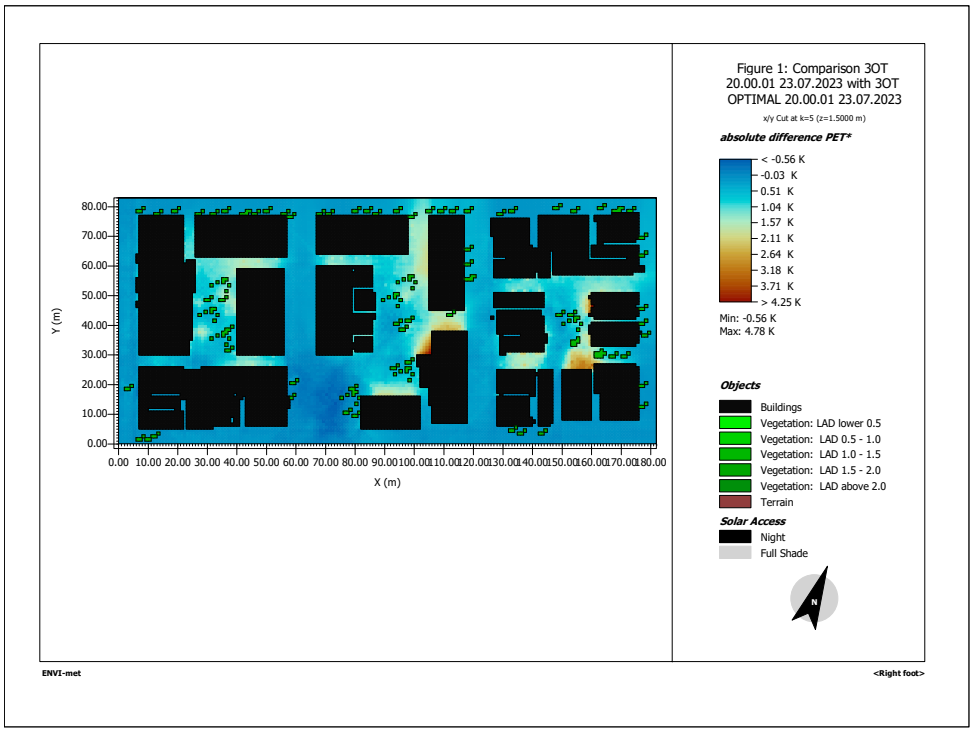


Figure 12. Absolute PET difference, 8 p.m.

In contrast, the optimized scenario, which introduces a combination of mature trees, water features, and shaded pedestrian areas, exhibits noticeable reductions in PET values across all times of the day. Morning PET values in this scenario range from 34.23 °C to 61.79 °C, with localized differences between the two scenarios reaching up to 22.45 °C, particularly in areas with enhanced shading. During the most thermally stressful time—3:00 p.m.—PET reductions range from 2.17 °C to 14.55 °C, demonstrating the strong

impact of green infrastructure on mitigating extreme heat. While evening reductions are more moderate (ranging from −0.56 °C to 4.78 °C), they still reflect a measurable improvement in thermal comfort, attributed to improved ventilation and reduced surface heat retention due to natural elements. The overall pattern suggests that nature-based interventions are most effective during peak sunlight hours, when shading from tree canopies and evaporative cooling from water features are at their most impactful. Furthermore, the optimized scenario demonstrates a more balanced and spatially uniform thermal environment, reducing the extremes of discomfort that characterize the baseline. This analysis underscores the critical role of climate-sensitive urban design in enhancing outdoor thermal comfort for vulnerable populations, particularly the elderly, during extreme heat events. It highlights the importance of integrating green and blue infrastructures into dense urban neighborhoods to build resilience against the escalating risks of climate change.

Table 6. Summary of PET values by scenario and time of day.

Time of Day	Scenario	PET Range (°C)	Thermal Stress Category
9:00 a.m.	Baseline	34.45–61.85	Hot to Very Hot
	Optimal	34.23–61.79	Hot to Very Hot
	Difference in PET	−11.17 to 22.45	Reduction evident in shaded areas
3:00 p.m.	Baseline	38.14–62.39	Hot to Very Hot
	Optimal	37.94–61.86	Hot to Very Hot
	Difference in PET	2.17–14.55	Significant comfort improvement
8:00 p.m.	Baseline	36.35–45.79	Hot to Very Hot
	Optimal	36.36–44.67	Hot to Very Hot
	Difference in PET	−0.56–4.78	Modest improvement in thermal comfort

3.9. Further Analysis of Peak Temperature Hours. Dynamic Comfort, Dpet, Static PET, and Energy Balance. Comparison Between Baseline and Optimal Scenarios

The following diagrams focusing on 3 p.m. provide additional insights into heat stress during the hottest period of the day. The baseline scenario exhibits high PET values, indicating significant thermal discomfort. In contrast, the optimal scenario showcases mitigative effects, including lower PET values and a more balanced energy profile. These findings suggest the importance of urban planning interventions in reducing heat-related risks. The research results provided below (Figures 13–18) highlight the stark contrast in heat absorption and dissipation between scenarios, reinforcing the need for well-integrated passive cooling strategies. The comparison also demonstrates the proportional influence of various mitigation factors, reinforcing the importance of a multi-layered approach to thermal management. In particular, this section examines dynamic comfort parameters, including Dpet, static PET, and energy balance variations. The results indicate that, under the baseline scenario, fluctuations in PET values correlate with heightened discomfort during peak hours. Conversely, the optimal scenario demonstrates a more consistent and favorable thermal environment, reflecting the efficacy of intervention measures. The effectiveness of cooling interventions, such as urban greening and water elements, is evident through the stabilized comfort indices. To be more specific, static PET values in the baseline scenario range from 46.06 to 61 °C (Figure 13), while in the optimal from 42.77 to 60 °C (Figure 16). In addition, dPET values in the baseline scenario vary from 21.78 to 23.43 °C (Figure 14), while in the optimal range from 21.78 to 22.98 °C (Figure 17). As for energy balance, values range from 248.47 to 525.16 W (Figure 15) in the baseline scenario, whereas in the optimal range we observe lower values that vary from 192.14 to 523.36 W (Figure 18).

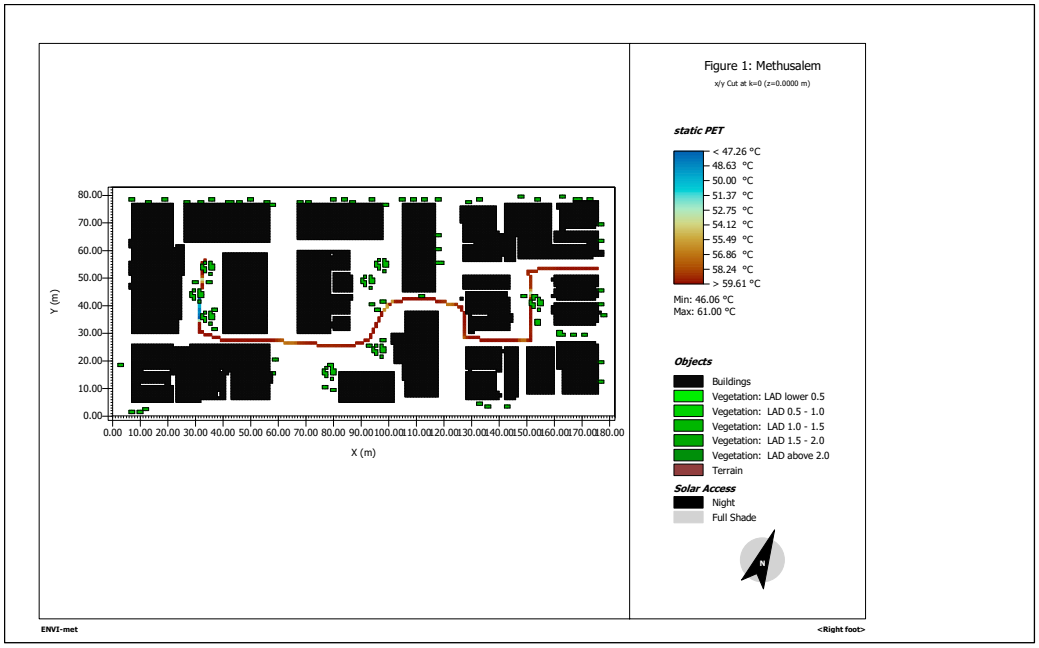


Figure 13. Baseline scenario, static PET, 3 p.m.

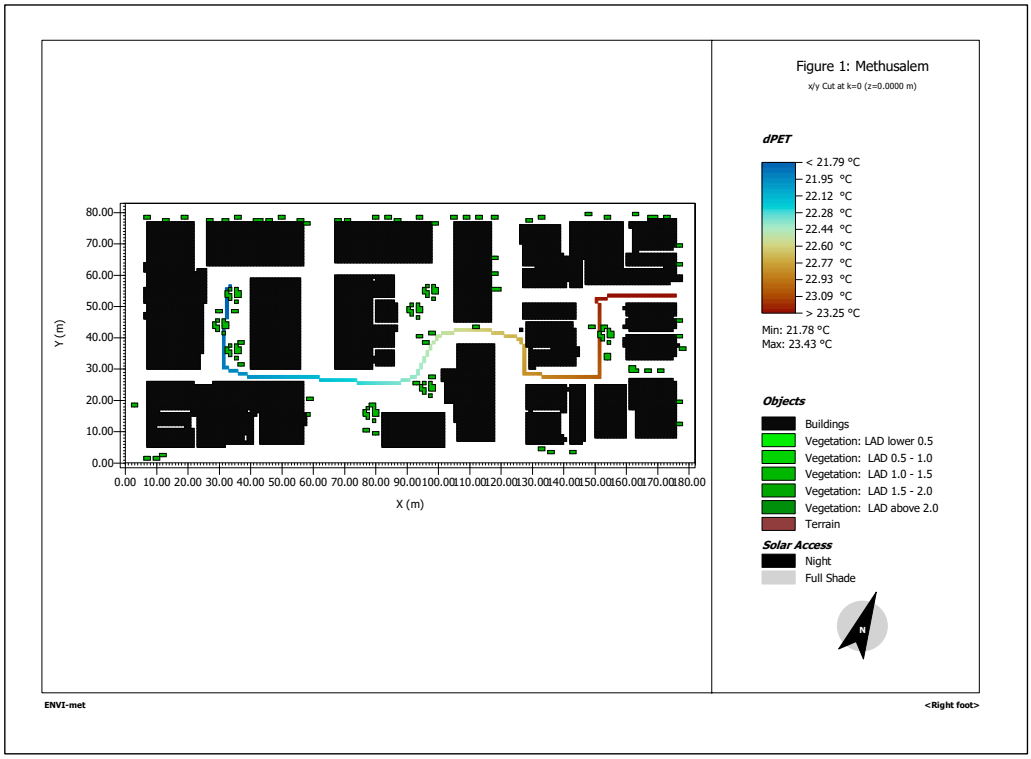


Figure 14. dPET, baseline scenario, 3 p.m.

The optimal scenario consistently outperforms the baseline in terms of thermal comfort and energy balance stability. The data suggest that implementing targeted mitigation strategies can substantially improve the well-being of elderly individuals, particularly during periods of extreme heat exposure. The visuals reinforce these conclusions by illustrating the spatial distribution of thermal discomfort and energy flux, making it clear that urban design plays a crucial role in shaping comfort and resilience to extreme weather conditions.

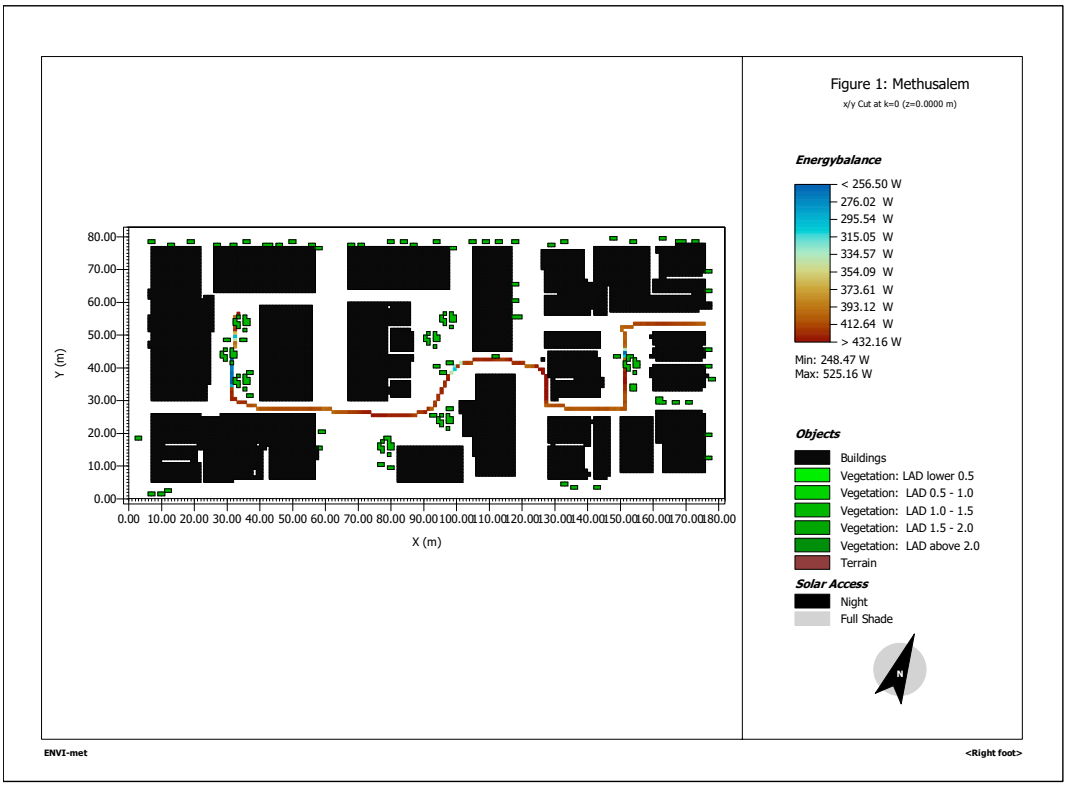


Figure 15. Energy balance, baseline scenario, 3 p.m.

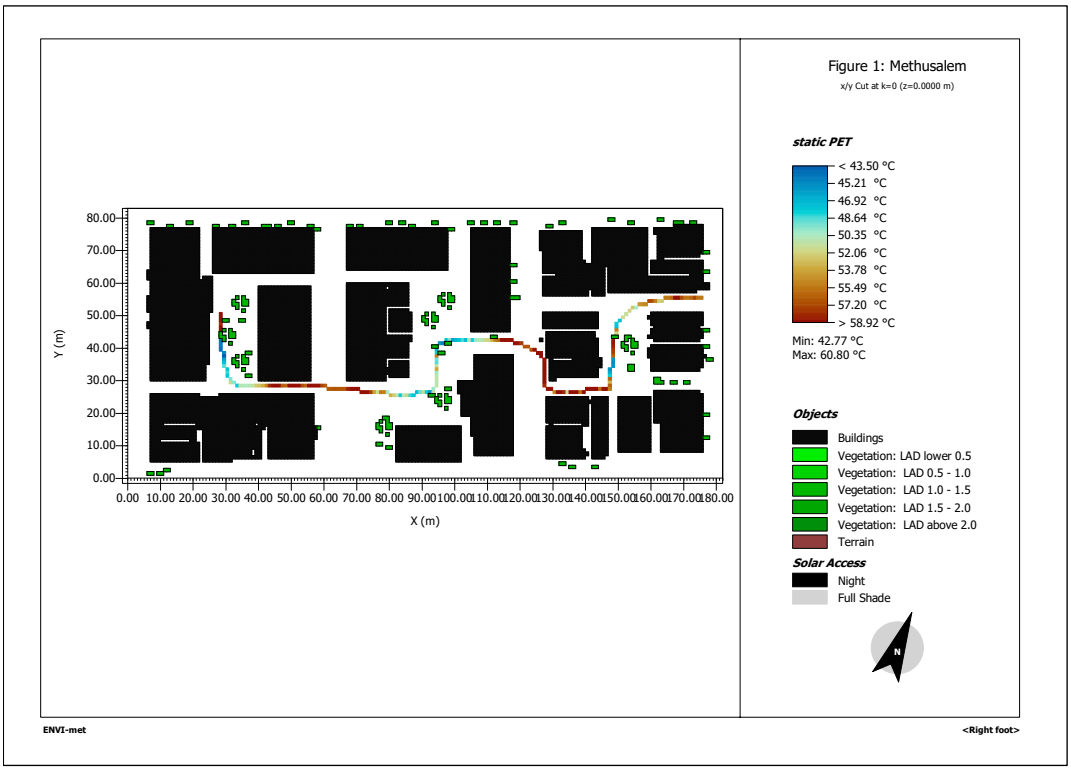


Figure 16. Static PET, optimal scenario, 3 p.m.

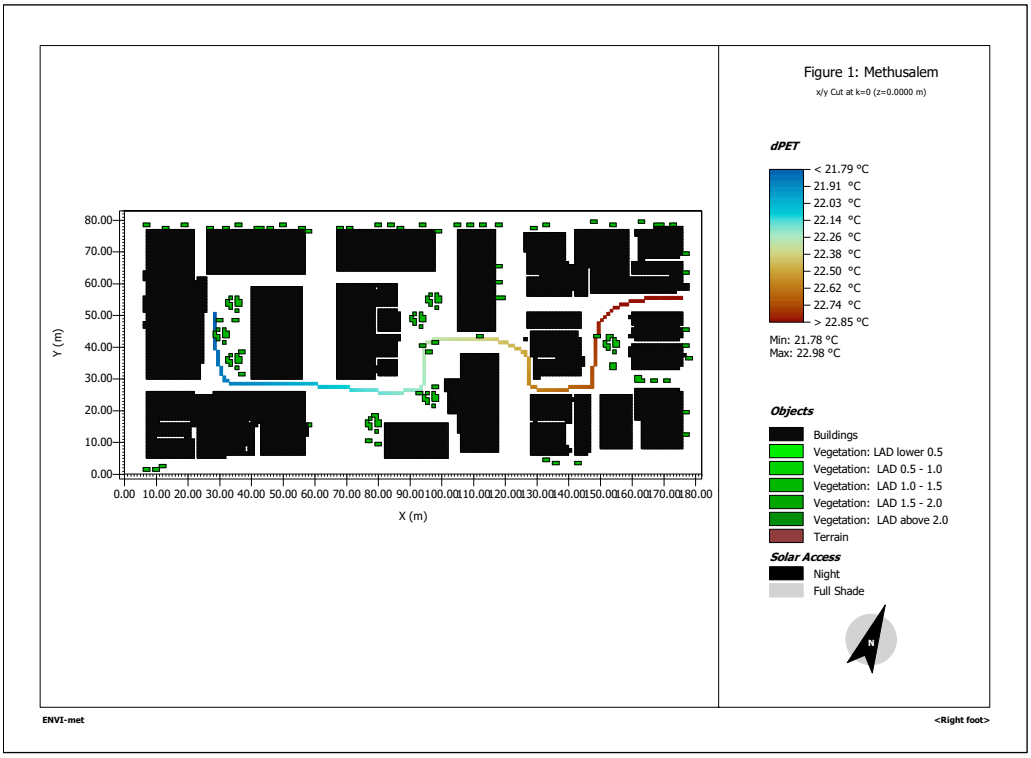


Figure 17. dPET, optimal scenario, 3 p.m.

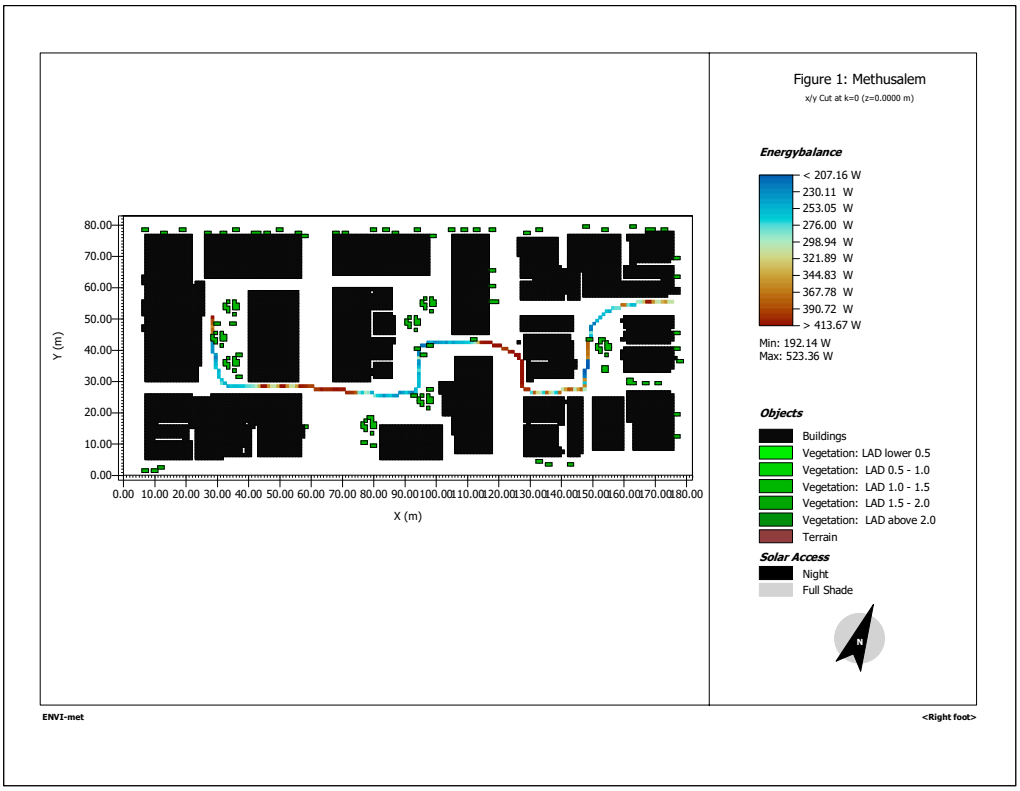


Figure 18. Energy balance, optimal scenario, 3 p.m.

3.10. Further Analysis of Peak Temperature Hours and a Comparison of Three Characteristic Points Within the Area of Study—Baseline and Optimal Scenarios

To examine the localized thermal performance of the proposed interventions during the peak heat period, three characteristic points within the study area were analyzed at

3:00 p.m., the time of highest solar radiation and thermal stress. These points were selected to represent diverse spatial conditions within the urban environment (Figure 3, Section 2):

- Point A: An unshaded concrete-paved alley with high solar exposure;
- Point B: A partially shaded courtyard with soil surface and minimal vegetation;
- Point C: A narrow asphalt street flanked by buildings, exhibiting typical urban canyon effects.

3.10.1. Baseline Scenario

In the baseline scenario, thermal conditions were consistently harsh across all three points (Figure 19):

- Point A recorded a PET of 60.7 °C, reflecting the combination of direct solar radiation and low albedo surfaces.
- Point B showed a PET of 56.2 °C, slightly lower due to partial shading and reduced surface reflectivity.
- Point C experienced a PET of 58.9 °C, driven by surface heat storage and limited airflow within the street canyon.

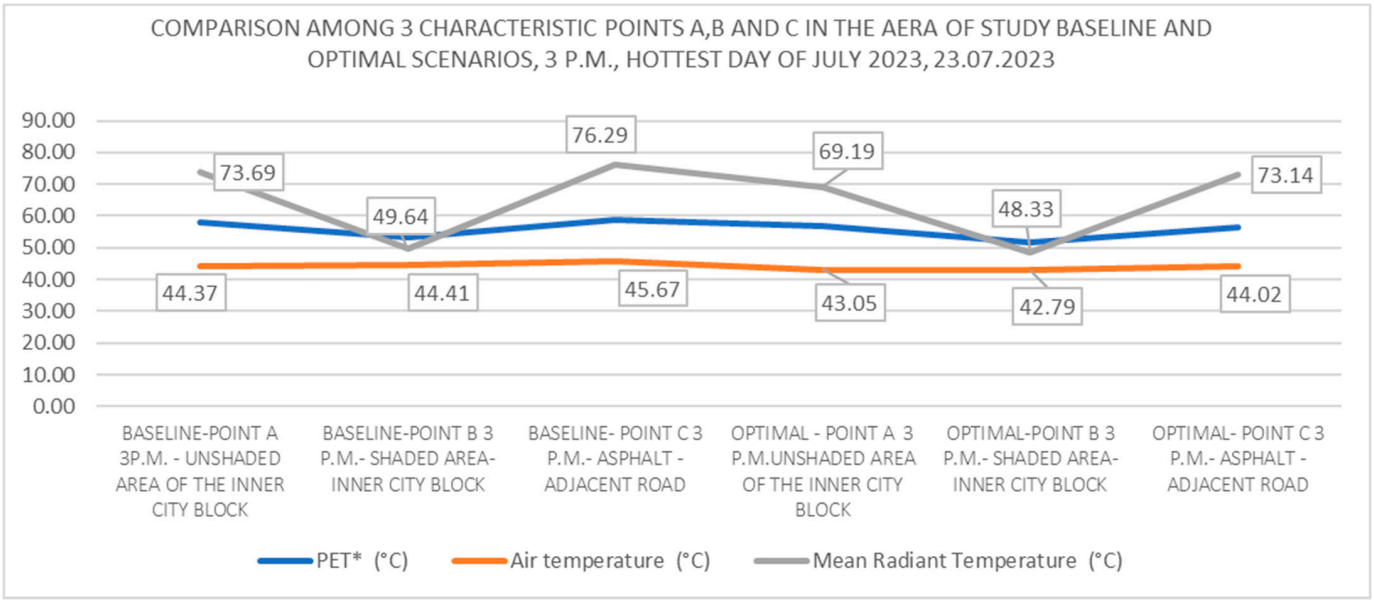


Figure 19. PET, air temperature, mean radiant temperature; 3 p.m. Hottest day of July 2023; comparison between baseline and optimal scenarios.

3.10.2. Optimal Scenario

With the application of nature-based interventions in the optimal scenario, PET values decreased significantly (Figure 19):

- Point A saw the most pronounced improvement, with the PET dropping to 46.2 °C, indicating a reduction of 14.5 °C, largely attributed to dense tree shading and proximity to a newly added water feature.
- Point B reached a PET of 43.7 °C, marking a PET drop of 12.5 °C, resulting from added vegetation, increased soil permeability, and canopy coverage.
- Point C demonstrated a moderate reduction, with the PET reduced to 47.8 °C, representing an 11.1 °C decrease, aided by strategic tree placement and improved shading along the street corridor.

Mean radiant temperature (Tmrt) exhibited substantial differences between the baseline and optimal scenarios, particularly in open, unshaded areas, such as Point A. In the

baseline condition, Tmrt contributed heavily to extreme PET values, exceeding 60 °C due to direct solar radiation and heat accumulation on exposed surfaces. The optimal scenario, with added tree canopies and reflective ground cover, significantly reduced Tmrt in key areas, highlighting the effectiveness of shading in lowering radiant heat exposure (Figure 19).

Air temperature, though less variable across micro-locations than Tmrt, also showed slight reductions in the optimized scenario. These differences, though modest—typically ranging around 1–2 °C—played a supporting role in improving overall thermal comfort. The combination of reduced air temperature and lower Tmrt in shaded or vegetated zones underscores the importance of integrating green infrastructure for effective thermal mitigation (Figure 19).

Wind speed played a secondary yet influential role in the thermal dynamics of the study area during the peak heat hour of 3:00 p.m. As shown in the simulation results (Figure 20), the baseline scenario exhibits low average wind speeds across the urban canyon-like environment, particularly at Point C, where the enclosed geometry limits airflow. In contrast, the optimal scenario demonstrated localized increases in wind speed, especially near vegetated corridors and open courtyards, suggesting improved ventilation due to the strategic placement of trees. The trendline in the graph (Figure 20) shows a slight upward trend in wind speed across the different points and scenarios. Despite the actual wind speed values fluctuating noticeably, the overall trend suggests a small general increase in wind speed from the baseline to the optimal conditions. The suggested modifications not only enhanced air circulation, but also contributed to more effective dispersion of heat and pollutants, thereby moderating perceived thermal stress among the elderly.

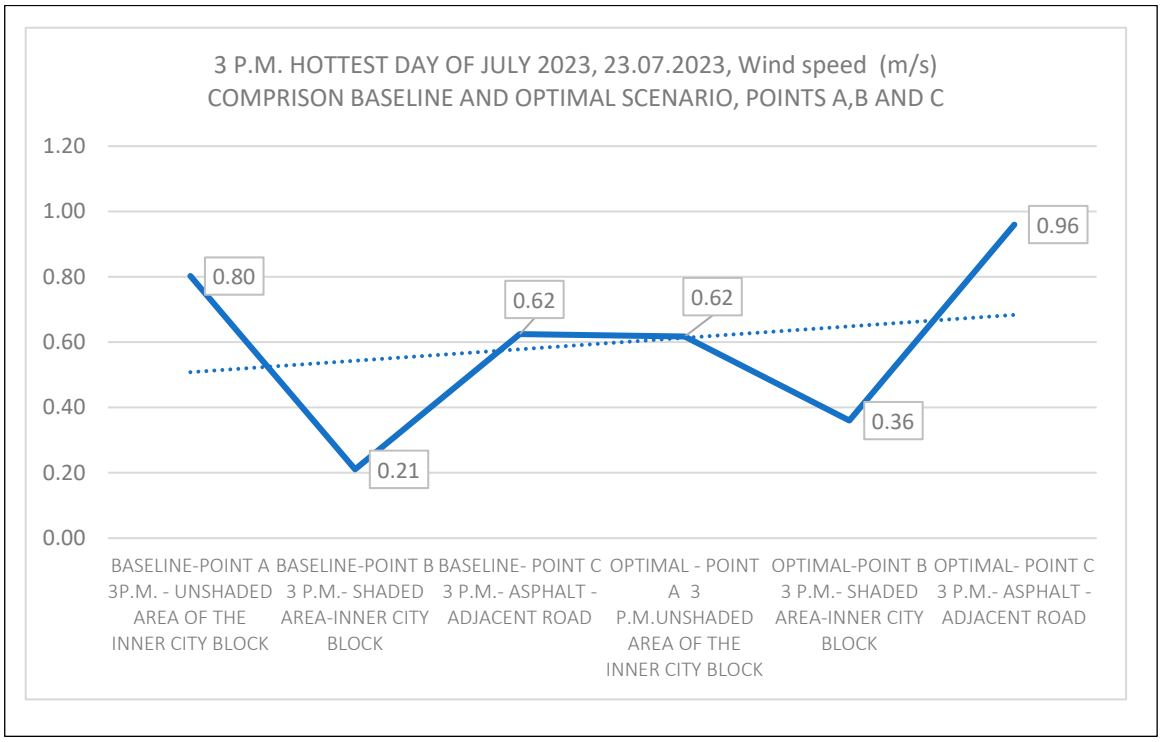


Figure 20. Wind speed; (m/s) 3 p.m. Hottest day of July 2023; comparison between baseline and optimal scenarios.

Specific humidity, another critical variable affecting thermal comfort, showed a modest but meaningful increase in the optimal scenario compared to the baseline (Figure 21). This change was primarily observed around newly installed water features and areas with increased vegetation, where localized evapotranspiration contributed to higher moisture

levels in the air. The trendline in the graph (Figure 21) shows a gradual upward trend in specific humidity levels across the different points and scenarios. Although the actual specific humidity values fluctuate—with noticeable peaks and dips—the overall trendline indicates a slight general increase in specific humidity from the baseline to the optimal conditions. While elevated specific humidity can sometimes intensify discomfort under humid conditions, in this Mediterranean context—characterized by arid peak summer conditions—the slight rise in humidity enhanced the evaporative cooling effect without reaching oppressive levels. These findings underscore the complementary role of wind and humidity in shaping microclimate dynamics and reinforcing the effectiveness of nature-based interventions.

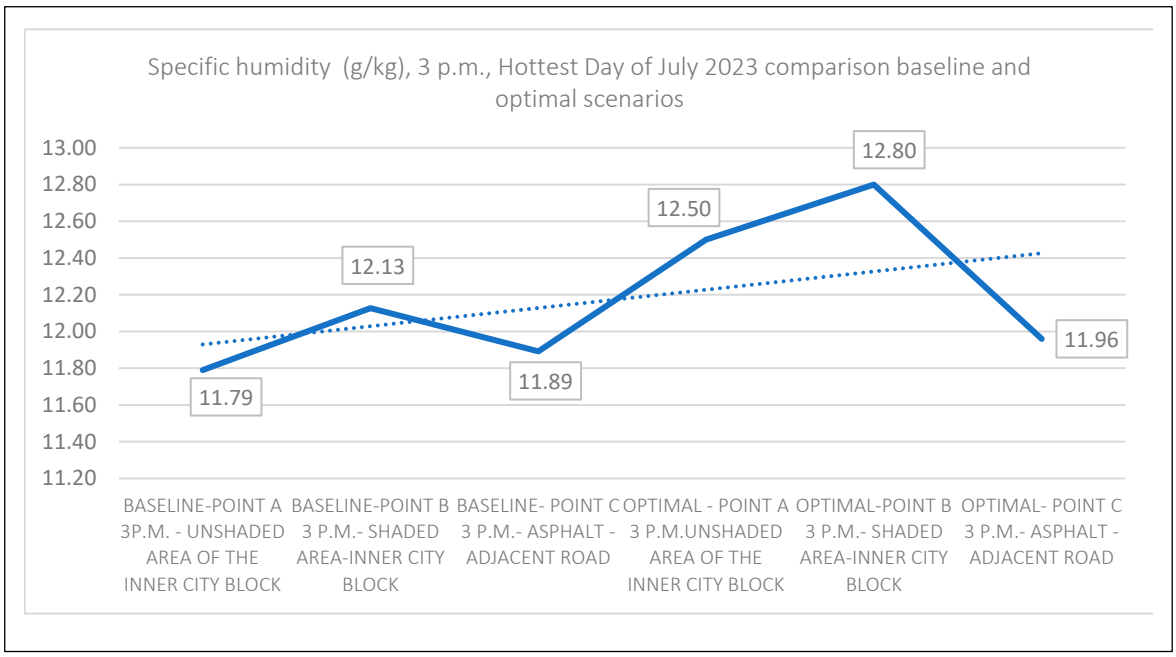


Figure 21. Specific humidity (g/kg); 3 p.m. Hottest day of July 2023; comparison between baseline and optimal scenarios.

The point-based analysis underscores the spatial heterogeneity of urban heat stress and demonstrates how micro-scale interventions produce measurable thermal benefits. The highest PET reductions were observed in previously unshaded or sparsely vegetated areas that received mature trees and water features (fountains). In all cases, the optimized conditions shifted thermal environments closer to upper comfort thresholds, despite remaining in the "hot" category according to PET classification. These findings highlight the critical importance of surface type, solar exposure, and vegetation configuration in achieving thermally resilient outdoor environments, especially for elderly populations in dense Mediterranean settings.

4. Discussion

The findings of this study highlight the significant impact of urban design interventions in mitigating heat stress for senior adults during extreme heat events. By employing ENVI-met simulations, this study assessed thermal comfort in a densely built neighborhood of Greater Athens under both baseline and optimized scenarios. The results indicate that the integration of mature trees and water features contributes to substantial reductions in Physiologically Equivalent Temperature (PET) values, particularly during peak afternoon hours when heat stress is most pronounced. A key observation from the baseline scenario

is the pronounced heat stress experienced in non-vegetated areas, where PET values exceed critical thresholds for thermal discomfort.

The findings are consistent with the previous research suggesting that intense urbanization, characterized by urban surfaces with a high thermal mass, contributes to prolonged heat retention and intensifies the urban heat island effect [60]. The optimal scenario, however, demonstrates the effectiveness of shading and evaporative cooling in reducing PET values, with absolute reductions reaching up to 22.45 K in the morning, 14.55 K in the afternoon, and 4.78 K in the evening. These findings support the argument that nature-based solutions play a vital role in enhancing outdoor thermal comfort, highlighting the special benefits for vulnerable populations, such as the elderly [60–65]. In addition to static PET analysis, this study examined dynamic thermal comfort parameters, including dPET and energy balance variations. The optimized scenario consistently outperformed the baseline condition, with energy balance reductions reaching up to 191.92 W during peak afternoon hours. This result suggests that targeted urban interventions can significantly moderate the energy flux experienced by individuals, thereby reducing strain and the risk of heat-related illnesses.

The findings indicate that nature-based interventions in high-density Mediterranean cities produce significant Physiologically Equivalent Temperature (PET) reductions, with maximum decreases of up to 12 °C observed under tree shading [4,47]. A breakdown of the contributions of different mechanisms suggests that tree shading accounts for the largest share, typically contributing 60–80% of the total PET reduction, while evapotranspiration and soil thermal properties provide secondary contributions of 10–25% and 5–15%, respectively [47,66]. The primary reason for shading's dominant role is its direct modification of the mean radiant temperature (Tmrt), the key meteorological factor influencing the PET in high-solar environments. Studies indicate that dense canopy coverage can lower Tmrt by 15–20 °C, leading to PET reductions of over 10 °C in shaded zones. Shading blocks shortwave solar radiation, reducing surface heating and preventing dangerous heat exposure during peak afternoon hours. PET reductions are especially pronounced in urban squares and streets where trees provide overhead coverage and lower direct solar exposure [4,47,48].

Evapotranspiration enhances cooling through latent heat flux, but its contribution is limited in water-scarce Mediterranean environments [67]. Studies show that, without consistent soil moisture availability, vegetation's latent cooling potential declines dramatically during peak dry season months [47]. Models indicate that tree-pit irrigation and engineered soils improve transpiration efficiency, allowing evapotranspiration cooling to contribute up to 20–25% of total PET reductions in well-optimized scenarios [40]. The observation of PET reductions up to 12 °C in well-shaded environments aligns with the existing findings from Mediterranean cities, such as Rome, Athens, and Thessaloniki [47,49]. Similar studies report PET drops in the range of 10–15 °C in shaded areas compared to unshaded streets, reinforcing the central role of tree canopies [50,66]. In Rome, tree shading provided the most substantial cooling effects, with PET reductions in the range of 8–12 °C, comparable to our reported values [3]. In Athens, thermal comfort benefits were notable in urban spaces with extensive canopy cover, where PET reductions reached the range of 6–10 °C during peak sun hours [50,66]. In Thessaloniki, tree-based shading cooled streets by up to 12 °C, but cooling pavement materials provided only marginal additional benefits [4].

A critical gap in the existing literature is the lack of elderly focused PET assessments. While general PET reductions are well-documented, few studies explicitly examine how older adults perceive and physiologically respond to these cooling interventions. Older adults exhibit reduced sweat efficiency and impaired thermoregulation, making direct temperature reductions via shading more beneficial than reliance on evaporative cooling [33].

Thermal comfort perception differs; studies suggest that elderly populations experience heat stress at lower PET thresholds than younger individuals, making even modest shading improvements critically important [4,68].

The reduction in energy balance in optimized urban scenarios is particularly significant for elderly populations, as aging is associated with altered thermoregulation and metabolic energy expenditure. Senior adults experience lower resting metabolic rates and impaired energy balance regulation, increasing their susceptibility to heat strain [69]. Energy balance is vital for successful aging, as it supports metabolic function and resilience to environmental stressors [70]. This study's findings, showing up to 191.92 W reduction in energy flux through nature-based interventions, highlight the role of optimized urban environments in mitigating heat strain for elderly populations. By enhancing thermal comfort, climate-responsive urban planning can promote healthier and more resilient aging in high-density Mediterranean cities. Moreover, this study's findings have important implications for urban planning and policymaking. The results underscore the necessity of incorporating green infrastructure in high-density urban environments to enhance microclimatic conditions and protect at-risk populations [17]. The observed improvements in thermal comfort also highlight the need for interdisciplinary collaboration between urban planners, environmental scientists, and public health officials to develop holistic strategies that enhance urban resilience to climate change-induced heat extremes. Beyond evaluating thermal performance, the proposed interventions were considered through the lens of cost-effectiveness, through interdisciplinary integration. While a detailed economic analysis is beyond the scope of this study, tree planting—particularly of mature trees—emerges as a relatively low-cost and low-maintenance strategy compared to artificial shading structures or large-scale infrastructure changes. Vegetation-based interventions offer long-term benefits with minimal upkeep. Furthermore, this study proposes a framework for "elder-friendly microclimate design", integrating insights from urban planning, climate adaptation, and public health disciplines. One important limitation of this study lies in its reliance on the simulation data from a single day—specifically, the hottest day of the 2023 summer season. While this approach effectively captures the thermal impact of interventions under extreme heat conditions, it does not account for the variability of thermal comfort across different weather patterns or seasons. Consequently, the findings are most applicable to peak heatwave scenarios and may not fully represent year-round microclimatic dynamics. Future research should incorporate multi-day and seasonal simulations to assess the long-term performance and resilience of nature-based interventions under a broader range of climatic conditions. Such an approach would enhance the generalizability of the results and support more comprehensive planning for thermal comfort across diverse urban settings.

5. Conclusions

This study demonstrates that strategic urban design interventions, particularly the incorporation of mature trees and water features, can significantly enhance outdoor thermal comfort for senior adults during Mediterranean heatwaves. ENVI-met simulations provided quantifiable evidence of thermal improvements, with optimized scenarios yielding lower PET values and enhanced energy balance stability. The findings emphasize the importance of integrating nature-based solutions into urban planning to mitigate heat stress, particularly in neighborhoods characterized by high building and population density. Given the increasing frequency of extreme heat events, policymakers must incorporate nature-based solutions into urban climate adaptation plans. Municipal authorities should prioritize the expansion of green and blue infrastructures through regulatory frameworks, financial incentives, and community-driven initiatives. Integrating these interventions into zoning regulations and urban regeneration programs will ensure their long-term

sustainability and maximize their benefits for vulnerable populations, particularly senior citizens. The implementation of shading and cooling elements not only reduces ambient temperatures, but also contributes to broader climate adaptation strategies, reinforcing the role of sustainable urban development in fostering resilient cities. To provide an initial framework for future application based on this study's findings, this research concludes with a prioritization of nature-based interventions for urban thermal comfort as presented in Table 7.

Table 7. Prioritization of nature-based interventions for urban thermal comfort.

Intervention	Thermal Effectiveness	Feasibility in Dense Urban Areas	Policy and Planning Integration
Mature Tree Planting	High PET reduction (up to 14.5 °C during peak hours)	High—easily integrated into pavements, courtyards	Include in urban regeneration plans and long-term greening strategies for heat-prone neighborhoods
Fountain Installation	Moderate PET reduction via localized evaporative cooling	Medium—requires available open space and infrastructure	Recommend for central communal areas; coordinate with public space revitalization efforts
Optimized Tree Canopy Design (Height and Shape)	High—improves shading and microclimate regulation	High—applicable to both existing and new plantings	Adopt species selection standards prioritizing dense and elevated canopies
Spatial Planning for Elderly Activity	Indirect thermal benefit by maximizing shaded exposure	High—adaptable to local use patterns	Integrate into age-friendly urban design frameworks; target shading along common walking routes

Future research should explore the long-term impact of such interventions, considering seasonal variations and the potential for adaptive design solutions that evolve with changing climate patterns. However, this study has certain limitations. The use of ENVI-met simulations provides valuable insights into microclimatic conditions, yet real-world observational data would further validate the effectiveness of the proposed interventions. Additionally, while this research focuses on thermal comfort improvements, other social and behavioral factors—such as elderly individuals' perceptions and adaptive responses to heat—should be considered in future studies. Additionally, studies incorporating real-world observational data alongside simulation models would provide a more comprehensive understanding of the effectiveness of different mitigation strategies. Further research should also explore how elderly individuals interact with climate-adaptive urban environments in everyday life. Combining qualitative approaches, such as interviews and surveys, with quantitative microclimatic analyses would provide a holistic understanding of thermal comfort needs. Moreover, experimental studies incorporating physiological measurements could offer deeper insights into the actual health benefits of urban cooling interventions. By prioritizing age-friendly urban environments, policymakers can help safeguard vulnerable populations against the escalating risks posed by extreme heat events, ensuring equitable access to safe and comfortable public spaces.

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