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Evaluating the effects of green roofs and green façade as an urban heat island adaptation strategy

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Abstract. The present study investigated the potential cooling effect of green roofs and green façades on a residential neighborhood in Athens during a typical summer day. The numerical model ENVI-met was employed to simulate the thermal environment of the study area at the existing configuration. Then, different design interventions focusing on the application of green façade and green roofs on the rooftops of the existing buildings were developed in order to evaluate the potential amelioration of the adverse thermal conditions. Thermal conditions were assessed based on basic meteorological parameter values and well-known thermal indices estimations. Results showed that at a two-floor building rooftop, the thermal conditions improved only slightly. Most importantly, the inclusive green roofs did not configure a significant cooling effect compared to that of low-height vegetation existing in the exclusive green roofs. Finally, results showed that the synergetic effect of green roofs and green façade produced a greater amelioration of thermal comfort conditions, compared to that produced by the green roofs solely. The greatest amelioration of thermal sensation conditions was achieved by the combination of inclusive green roofs and green façade.

1 INTRODUCTION

As urbanization increases, the boundaries of cities expand. It is projected that by 2050 two out of three people will leave in cities, and many of them will be transited to megacities (cities with more than ten million inhabitants) [1]. The increasing urban population is leading to significant modifications in the urban climate, especially in urban areas that lack organized, scientific-based urban planning, producing undesirable environmental phenomena such as the urban heat island (UHI) [2]. Studies have reported that these adverse thermal environments then lead to increased levels of thermal stress and thermal discomfort conditions and increase the heat-related mortality risk [3, 4].

It is well-acknowledged that green spaces in cities ameliorate thermal conditions and mitigate urban heat island [5]. Therefore several studies in the last decades attempted to improve the thermal environment in cities by increasing the urban vegetation through parks [6], squares [7], or courtyards [8].

Green walls and green roofs can effectively replace ground greenery especially when space limitations at the city scale make difficult the addition of green spaces [9]. The conversion of typical building and wall surfaces with low albedo into green walls and green roofs with higher albedo may be effective in reducing both the surface [10] and the air temperatures [10, 11] improving the urban environment.

Green walls can be distinguished into living walls and green façade [12]. In the case of living walls, the growing medium is vertical and adheres to the building envelope [13, 14], whereas in the case of green façade, the growing medium is horizontal, and therefore the plants grow vertically [13, 14].

Green roofs can be classified into extensive, where the thickness of the substrate layer can be up to 15cm and may host mostly drought-tolerant species [15, 16], and intensive with a substrate layer depth of more than 15cm allowing the plantation of shrubs and small trees and can be used as a roof garden [15, 16, 17].

Comparing the two green roof types, extensive green roofs can be easier installed in existing building roofs without the requirement of modifications in the existing structure [18]. On the other hand, intensive green roofs are preferred to be installed in new and on-purpose design buildings [12]. Therefore, the costs related to the installation of inclusive green roofs are higher [19].

The aim of this research is to showcase new insights into the cooling effects of green roofs and green façade in a residential area of Athens, a city with a Mediterranean climate. The existing configuration of the study area was evaluated with respect to the thermal conditions of a typical day in July. The environmental

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software ENVI-met [20] was applied to simulate the microclimatic conditions of the study area. Then, different design scenarios were developed, with respect to the implementation of green roofs and green façade, in order to ameliorate the adverse environmental conditions. Thermal conditions were assessed and compared according to the air temperature values and the estimations of the well-known thermal index, the Physiologically equivalent temperature [21].

2 Methods

2.1. Study area and climatic conditions

The Municipality of Aigaleo (37°59′0″N 23°40′0″E) is located in the western area of Athens and is elevated at 50 m above sea level. The examined area constitutes of nine urban residential blocks, seven of which consist of multistorey building apartments (2 to 6 floors), whereas the two central ones consist of a square and a church with a churchyard **(Fig 1a)**. Athens has a hot-summer Mediterranean climate (Köppen climate classification: Csa) with an average summer temperature of 27.3 °C. July is the hottest month of the year with an average monthly temperature of 28.3 °C.

2.2 Environmental Simulations and thermal conditions evaluation

The microclimatic and thermal conditions of the existing configuration of the study area (**Fig. 1b**) were evaluated with respect to the thermal environment during a typical summer day (11.7.2022), the microclimatic characteristics of which are presented in **Table 1.** The thermal conditions of the examined area were simulated by the 3D environmental software ENVI-met 5.1.1 [20]. Therefore, the model area was composed of 85 x 117 x 40 grid cells, with a resolution of 2.5 x 2.5 x 2.5 (x, y, z). Microclimatic outcomes are presented at a height of 7m, 1m meter above the rooftop of a two-floor residential building at the spots that are highlighted with red bullets (**Fig. 1c**). The hourly air temperature values and the bioclimatic index Physiologically Equivalent Temperature (PET) [21] were used to estimate the thermal comfort conditions at the examined date. The ENI-met BioMet tool [22] was used to calculate the PET (°C). The thermal conditions were also assessed after the application of three design scenarios. The thermal perception scale of PET is shown in **Table 2.**

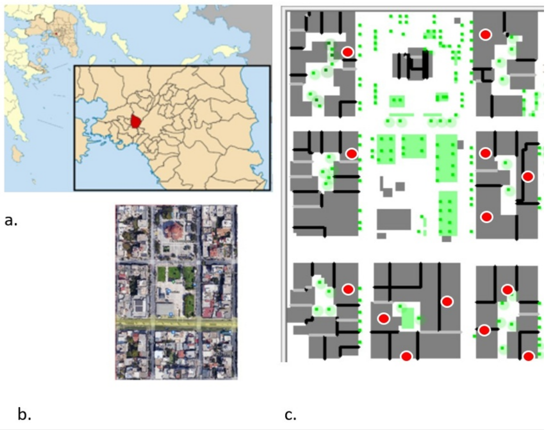


Figure 1a Satellite view of the study area **b.** 2D area input file for ENVI-met of the (Red dots: the examined reference points at rooftops (7m height); Green dots: trees in the study area; grey objects: buildings; green areas: grass; white areas: pavement and avenue).

Table 1. Microclimatic characteristics and ENVI-met input data at the examined date.

Climatic variable*	11 July 2022
Mean Air temperature	27.0 (°C)
Minimum air temperature	23.1 (°C) (05:20)
Maximum air temperature	31.4 (°C) (17:00)
Wind speed	1.5m*s^{-1}
Wind speed direction	NNE
Minimum Relative Humidity	31%
Maximum Relative Humidity	57%

*www.meteo.gr

Table 2. Physiologically Equivalent Temperature (PET, °C) thermal perception scale.

PET/ °C	Thermal perception
<4.1	Very cold
4.1-8.0	Cold
8.1-13.0	Cool
13.1-18.0	Slightly cool
18.1-23.0	Comfortable/ Neutral
23.1-29.0	Slightly warm
29.1-35.0	Warm
35.1-41.0	Hot
>41.0	Very hot

*Source: [23]

2.3 Adaptive strategies

In addition to the existing configuration (bare rooftop) of the examined area, four design scenarios were developed.

Existing configuration: Seven residential blocks with multistorey building apartments (2 to 6 floors). Building materials: albedo= 0.45, emissivity=0.9.

Design Scenario 1: The rooftops of all the residential buildings were covered by exclusive green roofs. Plant species: Ivy (Hedera helix), Plant thickness: 30cm, LAI (m^2/m^2), 1.5, substrate: NO.

Design Scenario 2: The rooftops and the external walls of all the residential buildings were covered by the same plant species as in Design Scenario 1.

Design Scenario 3: The rooftops of all the residential buildings were covered by inclusive green roofs. Plant species: Evergreen tree 1m, dense. LAI (m^2/m^2): 2.0. Albedo: 0.5, Emissivity: 0.96. Substrate: 30cm loam and 25cm Styrofoam.

Design Scenario 4: The rooftops of all the residential buildings were covered by the same plant species as Design Scenario 3. The external walls of all the residential buildings were covered by the same plant species as in Design Scenario 1.

3 Results

This section analyzes the cooling effects of the different green roofs and green façade configurations on the rooftop (≈7m above ground), 1 meter higher than a two-floor building apartment height. The Physiologically equivalent temperature index (PET, °C) and the air temperature (Tair, °C) were employed to access the thermal conditions induced after the interventions. Results are presented at local standard time (LST).

3.1. Existing configuration (bare rooftop)

The daily average Tair at the existing configuration (bare roof) was 29.09 °C, whereas between 12:00 and 18:00 it increased to 31.71 °C. The maximum Tair (32,26 °C) was induced at 16:00. **Figure 2a** shows the spatial distribution of thermal conditions in the study area at 16:00, representing the time of the day with the maximum heat load. As can be seen, PET, at the existing configuration, and more precisely at the examined spots, is estimated higher than 44.76 ◦C, corresponding to the 'Very Hot' category of its assessment scale. Lower PET values are estimated in the areas affected by trees, mainly within the courtyards. In these areas, PET values fluctuate between 38.0°C and 40.54 °C, falling within the 'Hot' category. The daily average PET was 34.73 °C, falling within the 'Warm' category, whereas between 12:00 and 18:00 it was increased to 43,46 °C, falling within the 'Very Hot' category. The maximum PET (46,43 °C) was obtained at 16:00.

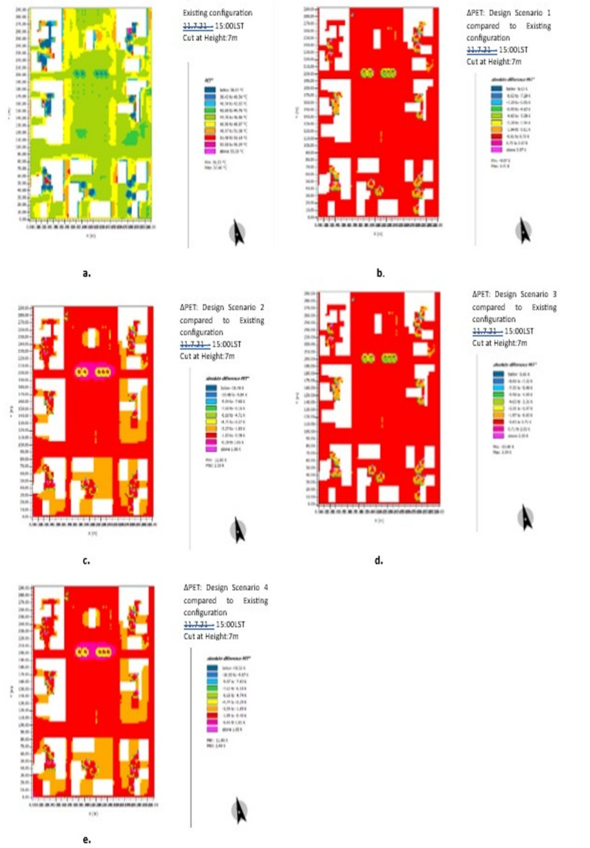
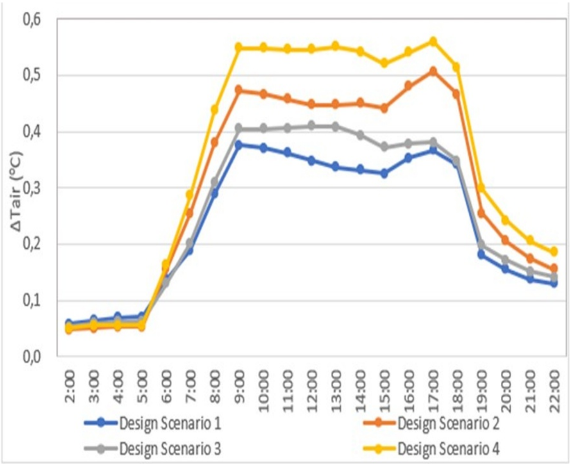


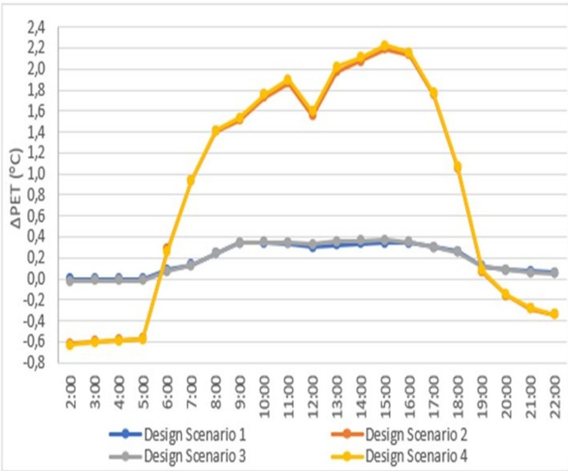
Fig. 2. The spatial distribution of PET at the **a**. existing configuration, and the ΔPET variation at **b.** Design Scenario 1, **c.** Design Scenario 2, **d.** Design Scenario 3, **e.** Design Scenario 4.

3.2. Design Scenario 1: Exclusive Green roof

Design Scenario 1 induced a slight, insignificant reduction in hourly Tair, and PET values compared to the existing configuration, as can be seen in **Figures 3**a and **3b**, respectively. The daily average Tair reduction (ΔTair) was 0.23K, whereas from 12:00 to 18:00 this was configurated at 0.35K. The maximum hourly ΔTair, 0.38K was obtained at 10:00. The daily average PET was 34,55°C ('Warm' category) with a daily average reduction (ΔPET) of 0.18K. The average PET from 12:00 to 18:00, was 43.13°C ('Very Hot' category), with an average reduction of 0.33K. The maximum hourly ΔPET, 0.38K, was obtained at 10:00. **Figure 2b** shows the spatial distribution of the ΔPET values at Design Scenario 1, with respect to the existing configuration, at 16:00. As can be seen, for the largest part of the study area, ΔPET fluctuated between -0.61 to 0.73K. Increased ΔPET was estimated in the areas affected by trees, mainly in the vicinity of the green roofs with the courtyards. In these areas, ΔPET values may reach even the 8.63K.



a.



b.

Fig. 3. The spatial distribution of PET at the **a**. existing configuration, and the ΔPET varaiation at **b.** Design Scenario 1, **c.** Design Scenario 2, **d.** Design Scenario 3, **e.** Design Scenario 4.

3.3 Design Scenario 2: Exclusive green roof and green facade

The results showed that the added green façade, along with the exclusive green roofs, in Design Scenario 2, produced a slightly increased reduction in hourly Tair, and PET values compared to Design Scenario 1 (exclusive green roofs without green façade), as can be seen in Figures 3a and 3b, respectively. The daily average ΔTair was 0.29K, whereas from 12:00 to 18:00 this was configurated at 0.46K. The maximum hourly ΔTair, 0.51K was obtained at 18:00. The daily average PET was 33,97°C (‘Warm’ category) with a daily average ΔPET of 0.76K. The average PET from 12:00 to 18:00, was 41.52°C (‘Very Hot’ category), with an average ΔPET of 1,94K. The maximum hourly ΔPET, 2.19K, was obtained at 16:00. **Figure 2c** shows the spatial distribution of the ΔPET values at Design Scenario 2, with respect to the existing configuration, at 16:00. For the largest part of the study area, ΔPET fluctuated between 0.38 to 1.83K. At the rooftops, ΔPET was slightly more intense, fluctuating between 1.83K to 3.27K, whereas the greatest ΔPET was estimated in the areas affected by trees, mainly in the vicinity of the green roofs with the courtyards. In these areas, ΔPET values reached even the 10.48K.

3.4 Design Scenario 3: Inclusive green roof

The results showed that Design Scenario 3 induced a slight, insignificant reduction in hourly Tair, and PET values compared to the existing configuration, as can be seen in **Figures 3**a and **3b**, respectively. The daily average ΔTair was 0.25K, whereas from 12:00 to 18:00 this was configurated at 0.39K. The maximum hourly ΔTair, 0.41K was obtained from 10:00 to 14:00. The daily average PET was 34,55°C (‘Warm’ category) with a daily average reduction (ΔPET) of 0.18K. The average PET during the time range 12:00 to 18:00, was 43.11°C (‘Very Hot’ category), with an average reduction of 0.35K. The maximum hourly ΔPET, 0.37K, was obtained at 16:00. As can be seen, Design Scenario 3 produced slightly better thermal conditions compared to Design Scenario 1 (exclusive green roofs), but worst compared to Design Scenario 2 (exclusive green roofs and green façade). **Figure 2d** shows the spatial distribution of the ΔPET values at Design Scenario 3, with respect to the existing configuration, at 16:00. For the largest part of the study area, ΔPET fluctuated between 0K to 8.66K. At the rooftops, ΔPET fluctuated between 0.63 and 1.97K, whereas the greatest ΔPET was estimated in the areas affected by trees, mainly in the vicinity of the green roofs with the courtyards. In these areas, ΔPET values reached even the 8.66K.

3.5 Design Scenario 4: Inclusive green roof and green facade

Compared to the existing configuration, the daily average ΔTair induced by Design Scenario 4 was 0.34K, whereas from 12:00 to 18:00 this was configurated at 0.54K. The maximum hourly ΔTair, 0.56K was obtained at 18:00. The daily average PET was 33,96°C (‘Warm’ category) with a daily average ΔPET of 0.77K. The average PET from 12:00 to 18:00, was 41.49°C (‘Very Hot’ category), with an average ΔPET of 1.97K. The maximum hourly ΔPET, 2.22K, was obtained at 16:00. As can be seen, Design Scenario 4, produced a slightly increased reduction in hourly Tair, and PET values compared to the other design scenarios (Figures 3a and 3b, respectively). **Figure 2e** shows the spatial distribution of the ΔPET values at Design Scenario 4, at 16:00. For the largest part of the study area, ΔPET fluctuated between 0.40 to 1.85K. At the rooftops, ΔPET was slightly more intense, fluctuating between 1.85K to 3.29K, whereas the greatest ΔPET was estimated in the areas affected by trees, mainly in the vicinity of the green roofs with the courtyards. In these areas, ΔPET values reached even the 10.52K.

4 Conclusions

The study investigated the performance of green roofs and green façades in an urban residential area of Athens to improve the existing thermal conditions. For this, the environmental model ENVI-met was employed to simulate the thermal environment, both in the current configuration of the study area and after the implementation of the adaptation strategies. Results showed that at a two-floor building rooftop (≈ 7m height), the thermal conditions improved slightly. Among the examined adaptive strategies, the synergetic effect of green roofs and green façade produced a greater amelioration of thermal comfort conditions, compared to that produced by the green roofs alone. Notably, the greatest amelioration of thermal sensation conditions was achieved by the combination of inclusive green roofs and green façade (Design Scenario 4). Focusing on the efficacy of the two types of green roofs, the inclusive green roofs (Design Scenario 2) did not provide a significant cooling effect compared to the exclusive green roofs (Design Scenario 1). In all the examined scenarios the greatest ΔPET (>8.0K ΔPET), was estimated in the areas affected by trees, mainly in the vicinity of the green roofs and/ or green facades with the courtyards. In summary, the study demonstrated that implementing a combination of green roofs and green façades can lead to notable improvements in thermal conditions, especially when integrated with other adaptive strategies, offering valuable insights for urban planners and architects seeking sustainable urban design solutions.

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