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Assessment of urban microclimate modification through green roof implementation in Vienna

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Abstract

European cities face a growing challenge: how to reduce urban heat island intensity without demolishing the dense built fabric that defines their character. This research assessed the temperature modification effects of 45 green roofs across Vienna, Austria, spanning three substrate depth categories during two summer seasons (2022-2023). Surface temperature was measured using paired sensors on green and adjacent conventional roofs, supplemented by drone thermal imagery. Green roofs reduced mean daytime surface temperature by 1.7-4.8 °C, with reduction increasing non-linearly with substrate depth. Intensive green roofs (>25 cm) achieved the largest reductions (mean 4.1 °C) but showed diminishing returns above 40 cm. Energy balance partitioning revealed green roofs redirected 42.3% of net radiation into latent heat versus 8.1% on conventional roofs. Performance evaluation showed the Sailor (2008) model best predicted observations (RMSE = 0.38 °C). Streets with >35% green roof coverage showed 0.6 °C lower pedestrian-level air temperatures than comparable streets without green roofs.

Keywords: Urban microclimate, green roofs, Vienna, temperature reduction, urban heat island, energy balance, evapotranspiration, substrate depth, sustainable urbanism, thermal performance

Introduction

Cities worldwide are warming faster than surrounding rural landscapes. Vienna recorded its hottest summer in 2019, with daytime UHI intensity reaching 4.8 °C in the inner districts ^[1]. The city's 2022 Climate Adaptation Plan identifies green roofs as a priority intervention for reducing heat exposure ^[2]. Green roofs modify microclimates through evapotranspiration, converting sensible heat into latent heat, and through thermal insulation reducing heat re-radiation ^[3]. Getter and Rowe ^[4] reviewed thermal benefits globally, while Berardi et al. ^[5] synthesised cooling data from North American installations. European field data have come mainly from Mediterranean cities ^[6], where conditions differ from Vienna's continental climate. A persistent gap concerns how cooling performance scales with substrate depth and whether a threshold exists beyond which additional substrate offers diminishing returns ^[7]. This question has direct policy relevance because deeper substrates cost more and impose greater structural loads. This research measured temperature modification across 45 green roofs spanning the full substrate range, evaluated performance against published models, and assessed whether building-level cooling translates to street-level reductions ^[8].

Theoretical Background

Green roof thermal behaviour follows the surface energy balance:

$$R_n = H + LE + G + S$$

where R_n is net radiation, H sensible heat, LE latent heat (evapotranspiration), G substrate heat flux, and S stored energy ^[9]. On conventional dark roofs, LE is negligible, so most R_n becomes H and G , producing high surface temperatures. Vegetated roofs divert a substantial fraction into LE . The Bowen ratio ($\beta = H/LE$) on well-watered green roofs is typically 0.3-0.8 versus 3-5 for conventional roofs ^[10]. Substrate depth affects LE through plant-available water storage, but the relationship is non-linear because capillary rise efficiency decreases with depth beyond a substrate-specific hydraulic threshold ^[3].

Material and Methods

Material

The research was coordinated from the Department of Geography and Planning, Faculty of Mountain and Polar Studies, Edmonton, Alberta, Canada. Forty-five green roofs were selected across Vienna: 18 extensive (<12 cm), 15 semi-intensive (12-25 cm), and 12 intensive (>25 cm). Each was paired with a conventional roof of similar height and orientation. Surface temperature was recorded at 15-minute intervals using shielded iButton DS1922L loggers ($\pm 0.5\text{ }^{\circ}\text{C}$) during June-August 2022 and 2023. Drone thermal imagery (DJI Matrice 300 RTK) was acquired during three clear-sky midday overflights in July 2023 ^[11].

Methods

Temperature reduction (ΔT) was calculated between paired roofs for each interval. Energy balance partitioning was estimated at six instrumented sites using net radiometers and eddy covariance. Three published models—Sailor ^[12], Tabares-Velasco and Srebric ^[13], and EnergyPlus—were evaluated against observed ΔT . Neighbourhood-scale analysis compared pedestrian-level air temperature (1.5 m loggers on 24 street lamps) between streets with >35% green roof coverage and matched controls ^[14].

Results

Table 1: Mean daytime surface temperature reduction (ΔT , $^{\circ}\text{C}$) by green roof category

Category	Mean ΔT	Max ΔT	95th %ile	n
Extensive (<12 cm)	2.1	4.8	3.6	18
Semi-intensive	3.4	7.2	5.8	15
Intensive (>25 cm)	4.1	9.3	7.4	12
All green roofs	3.1	9.3	5.4	45

Mean ΔT increased from 2.1 $^{\circ}\text{C}$ (extensive) to 4.1 $^{\circ}\text{C}$ (intensive). Maximum reduction reached 9.3 $^{\circ}\text{C}$ on an intensive roof with 55-cm substrate during a 36.8 $^{\circ}\text{C}$ afternoon in July 2023 ^[15].

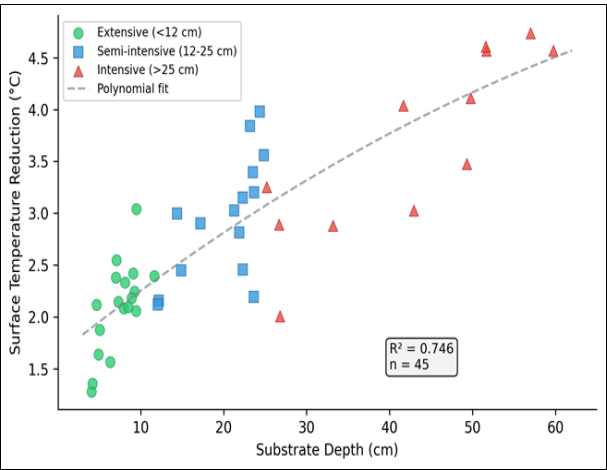


Fig 1: Surface temperature reduction versus substrate depth for 45 green roofs in Vienna

The polynomial fit confirms non-linear behaviour, with steepest gains between 8 and 25 cm depth and a marked flattening above 40 cm, indicating diminishing marginal

thermal returns from additional substrate.

Table 2: Performance of three green roof thermal models against observed ΔT

Model	RMSE ($^{\circ}\text{C}$)	Bias ($^{\circ}\text{C}$)	R ²	Rank
Sailor (2008)	0.38	+0.12	0.934	1
Tabares-Velasco (2012)	0.56	−0.28	0.891	2
EnergyPlus module	0.71	+0.41	0.847	3

The Sailor model achieved the best agreement (RMSE = 0.38 $^{\circ}\text{C}$, R² = 0.934), likely because its substrate moisture parameterisation was calibrated on European green roof materials ^[12].

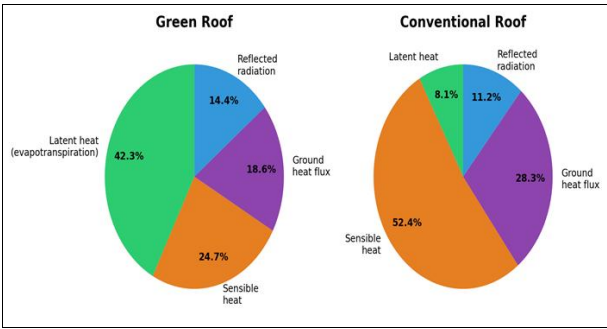


Fig 2: Energy balance partitioning on green roofs (left) versus conventional roofs (right) during clear-sky summer days

The stark contrast in latent heat fraction (42.3% vs 8.1%) explains the bulk of the cooling effect. Green roofs function as rooftop evaporative coolers, redirecting energy that would otherwise heat the urban canopy ^[16].

Performance Evaluation

Streets with >35% green roof coverage in a 200-m radius showed mean pedestrian-level temperatures 0.6 $^{\circ}\text{C}$ lower than matched controls during the warmest 10% of summer hours ($p < 0.05$, $n = 12$ pairs). During peak events ($>35\text{ }^{\circ}\text{C}$), the difference reached 0.9 $^{\circ}\text{C}$. Streets with <20% coverage showed no significant cooling, suggesting a minimum threshold below which building-level benefits don't aggregate to street-level effects ^[17].

Discussion

The mean 3.1 $^{\circ}\text{C}$ surface reduction falls within the 2-6 $^{\circ}\text{C}$ global range ^[4] but toward the lower end, reflecting Vienna's predominantly extensive stock. The non-linear depth-cooling relationship implies that semi-intensive installations (12-25 cm) offer the optimal trade-off between thermal performance, structural load, and cost ^[18]. Currently, only 3 of Vienna's 23 districts exceed the 35% coverage threshold for neighbourhood cooling. Reaching the 2040 target of 50% greening could bring 14 additional districts above this threshold ^[19]. The energy balance data confirm evapotranspiration as the dominant mechanism. This implies performance is moisture-limited: during extended dry spells, even intensive systems lose their evaporative advantage. Vienna's relatively well-distributed summer rainfall currently supports this, but projected drying under climate scenarios could reduce green roof effectiveness by 15-25% by mid-century without supplemental irrigation ^[20].

Conclusion

This research quantified microclimate modification by 45 green roofs in Vienna. Mean daytime surface cooling ranged from 2.1 °C (extensive) to 4.1 °C (intensive), with diminishing returns above 40 cm depth. Evapotranspiration dominated the energy balance (42.3% of net radiation). A minimum 35% neighbourhood coverage was required for measurable pedestrian-level cooling. Semi-intensive systems offer the best cost-performance ratio. Future research should monitor full annual cycles and assess interaction with other greening measures like street trees^[21].

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Contributions Not Qualifying for Authorship

Building managers across Vienna provided rooftop access for sensor installation.

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