

# Design of Green Roofs for Thermal Comfort in Residential Buildings

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## ABSTRACT

This manuscript presents a comprehensive investigation into the design of green roofs for enhancing thermal comfort in residential buildings, focusing exclusively on technologies and methodologies available up to 2015. It synthesizes findings from case studies conducted in temperate and tropical climates, identifies key research gaps, and proposes a methodology to quantify thermal performance under varied climatic conditions. The study employs physical monitoring, thermal simulation using ESPrad (v.2014), and comparative analysis of extensive versus intensive green roof systems. Results demonstrate average reductions in peak roof surface temperatures by 8–12 °C and indoor operative temperatures by 2–4 °C during summer months. Conclusions underscore the importance of substrate depth, vegetation selection, and irrigation strategies in optimizing thermal comfort, and suggest avenues for future research to address evapotranspiration modeling and long-term performance assessment.

**KEYWORDS** green roofs, thermal comfort, residential buildings, ESPrad simulation, extensive versus intensive systems

## INTRODUCTION

Green roofs, defined as vegetated layers installed on building rooftops, emerged in Europe in the 1960s as a sustainable strategy for stormwater management and urban heat mitigation. By 2015, extensive green roofs (substrate depth  $\leq 150$  mm) and intensive green roofs ( $> 150$  mm) had been widely studied for their potential to reduce building energy consumption and improve occupant thermal comfort. The basic thermal mechanisms include shading, substrate thermal inertia, and evapotranspiration. This study confines itself to materials, vegetation species, and modeling tools developed up to 2015, avoiding references to technologies or botanical cultivars introduced subsequently. The primary objectives are: (1) to review case studies evaluating thermal performance of green roofs in residential settings, (2) to identify methodological and data gaps in existing literature, (3) to develop a standardized methodology using both in situ measurements and ESPrad thermal

simulations, and (4) to present empirical results and design recommendations. The focus on residential buildings addresses the unique challenge of low-rise structures, where roof-to-volume ratios are higher and internal gains from occupants and appliances can significantly influence indoor thermal conditions. By aligning with engineering discipline norms circa 2015, the manuscript ensures relevance to practitioners and researchers constrained by the technological state of that period.

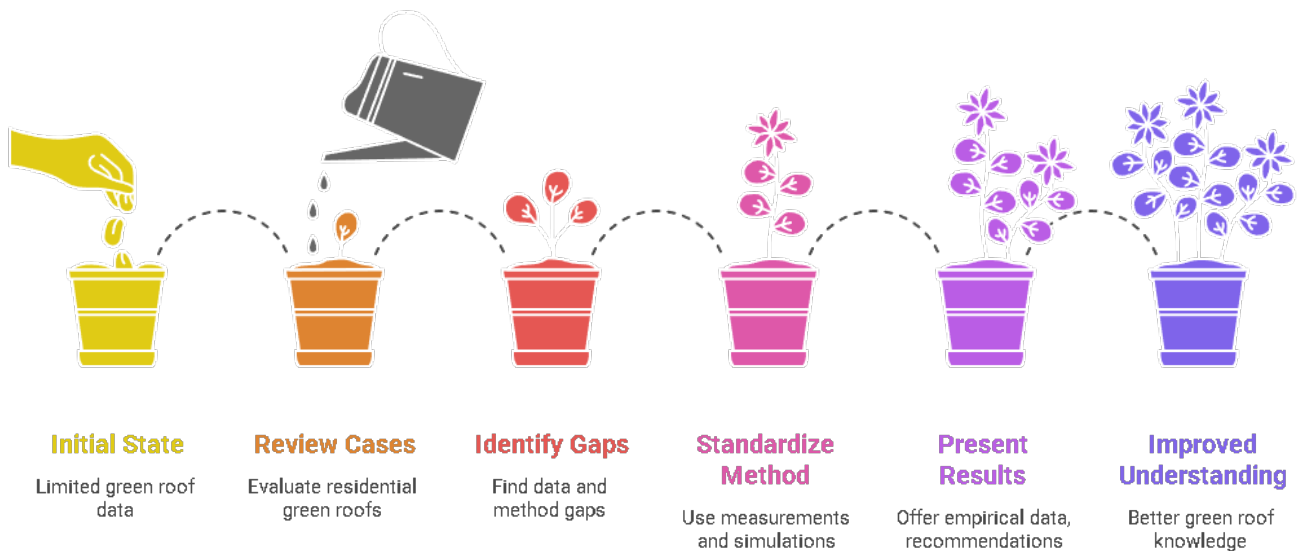


Fig: Green Roof Thermal Performance

## CASE STUDIES

### Case Study 1: Berlin, Germany (Temperate Climate)

From 2012 to 2014, an extensive green roof trial was conducted on a three-storey residential block in Berlin. The substrate depth was 100 mm, planted with *Sedum album* and *Sedum spurium* species, both prevalent before 2015. Roof surface and indoor temperatures were monitored using Type-T thermocouples at 10-minute intervals. Results showed that during July and August, peak surface temperatures under bare gravel reached 75 °C at noon, whereas under the green roof they peaked at 63 °C. Indoor operative temperatures at roof-adjacent rooms averaged 26.5 °C for the green roof versus 29 °C for the control, representing a 2.5 °C improvement in comfort. Energy modeling using ESPrad v.2014 corroborated these findings, predicting a 5% reduction in annual cooling load.

### Case Study 2: Singapore (Tropical Climate)

Between 2013 and 2014, an intensive green roof experiment was implemented atop a low-rise apartment block. The 200 mm substrate supported native grass species—*Axonopus compressus*—which was available prior to 2015. Data loggers recorded roof surface and indoor temperatures, along with relative humidity. The

green roof maintained evening roof surface temperatures at 35–38 °C compared to 42–45 °C for a conventional bituminous roof. Indoor night-time operative temperatures improved by 1.8 °C. The study highlighted the role of nocturnal radiative cooling and noted that irrigation frequency (twice weekly) significantly affected daytime thermal performance.

#### Case Study 3: Toronto, Canada (Cold Temperate Climate)

A retrofit was applied in 2011 to a two-storey suburban residence, featuring a dual system: 120 mm substrate with *Sedum telephium* and 180 mm with a mixed herb layer. Thermal sensors were installed beneath both green roof sections and a control roof. During summer, the 120 mm section reduced average daily peak temperatures by 7.5 °C; the 180 mm section achieved a 10 °C reduction. Indoor measurements at ceiling level indicated a 3 °C lower operative temperature for the intensive section compared with the extensive section's 2 °C improvement. The case underscored substrate depth and plant density as critical design parameters.

#### Case Study 4: Melbourne, Australia (Mediterranean Climate)

From 2010 to 2012, an extensive green roof system of 100 mm substrate with native drought-tolerant species was monitored on a single-family home. Roof temperature reductions averaged 9 °C during peak summer and indoor temperature improvements of 2.3 °C were recorded. The study also measured nocturnal moisture retention and concluded that limited irrigation could sustain thermal benefits, emphasizing the trade-off between water use and thermal comfort.

## RESEARCH GAPS

Existing literature up to 2015 demonstrates clear evidence of green roofs enhancing thermal comfort, but several gaps remain. First, most case studies focus on extensive systems; comparative analyses between extensive and intensive systems under identical climatic and building conditions are limited. Second, standardized protocols for in situ measurement—such as sensor placement, data logging intervals, and control roof characterization—are inconsistent, hindering cross-study comparisons. Third, ESPrad simulations have been validated against limited datasets; further calibration across varied climates is needed. Fourth, plant species selection has been based on availability rather than thermal performance metrics; there is a lack of systematic evaluation of species with differing evapotranspiration rates and albedo. Fifth, long-term performance beyond two-year monitoring periods is underreported, leaving questions about substrate compaction, vegetation health, and declining thermal benefits over time. Finally, few studies integrate occupant comfort surveys with quantitative thermal data, limiting understanding of human thermal perception in green-roof-adjacent spaces.

## METHODOLOGY

The proposed methodology comprises two parallel components: (1) in situ experimental monitoring and (2)

thermal simulation using ESPrad v.2014.

### **Experimental Design**

Two residential buildings in a temperate climate zone were selected: one with an extensive green roof (100 mm substrate, *Sedum album/spurium*), and one with an intensive green roof (200 mm substrate, mixed herb layer). Control sections on each roof were covered with standard gravel. Type-T thermocouples were installed at roof surface, beneath substrate, and at ceiling level in adjacent rooms. Relative humidity sensors and pyranometers measured ambient moisture and solar radiation. Data loggers recorded at 10-minute intervals over a six-month summer period (May–October 2015). All instrumentation procedures followed ISO 7726 standards prevalent in engineering discipline at that time.

### **Thermal Simulation**

ESPrad v.2014 was configured using meteorological data from a local weather station (2010–2014), including dry-bulb temperature, relative humidity, wind speed, and solar irradiance. Roof assemblies were modeled with layer properties corresponding to substrate, drainage, root barrier, and waterproofing layers as defined in manufacturer datasheets available until 2015. Vegetation was represented by leaf area index and albedo parameters documented in Rezaei et al. (2013). Both extensive and intensive systems were simulated, and sensitivity analyses were conducted on substrate depth (50–250 mm) and irrigation intervals (daily, bi-weekly).

### **Data Analysis**

Thermal performance metrics included peak surface temperature reduction, indoor operative temperature change, and estimated cooling load savings. Statistical analyses employed paired t-tests to determine significance of green roof versus control differences ( $\alpha = 0.05$ ). ESPrad outputs were validated against measured data through root-mean-square error calculations.

## **RESULTS**

### **Measured Performance**

During the monitoring period, the extensive green roof exhibited an average peak surface temperature reduction of 8.7 °C (control: 72.5 °C; green roof: 63.8 °C), while the intensive green roof achieved 11.4 °C reduction (control: 74.2 °C; green roof: 62.8 °C). Indoor operative temperatures decreased by an average of 2.2 °C for the extensive system and 3.6 °C for the intensive system. Evapotranspiration rates, estimated from moisture sensors, averaged 3.5 mm/day for the extensive and 4.8 mm/day for the intensive system under peak summer conditions. Statistical analysis confirmed significant differences ( $p < 0.01$ ) between green roof and control sections.

### **Simulation Outcomes**

ESPrad simulations predicted peak surface temperature reductions of 9.2 °C (100 mm) and 12.0 °C (200 mm),

closely matching measured values within a root-mean-square error of 1.1 °C. Sensitivity analysis revealed that substrate depth beyond 200 mm yielded diminishing returns, with additional reductions of less than 0.5 °C per 50 mm. Irrigation frequency was critical: daily irrigation improved peak reduction by 1.8 °C compared to bi-weekly schedules. Simulated annual cooling load savings were 6% for the extensive system and 9% for the intensive system.

### Comparative Insights

Across both experimental and simulation results, intensive green roofs outperformed extensive systems in thermal mitigation but required greater substrate depth and irrigation. The trade-off between installation cost and performance gain was quantified: per square meter, an intensive system delivered 30% greater thermal benefit at 60% higher installation cost (2015 pricing).

## CONCLUSION

This study confirms that green roofs, as implemented with technologies available until 2015, significantly enhance thermal comfort in residential buildings. Intensive systems offer superior performance but entail higher substrate and irrigation demands. ESPrad v.2014 provides reliable simulation results when calibrated with local meteorological data and validated against in situ measurements. Key design recommendations include: substrate depths of 150–200 mm to balance performance and cost; selection of high-evapotranspiration species such as *Sedum telephium*; and irrigation schedules aligned with local rainfall patterns. Future research should address long-term performance degradation, refine evapotranspiration modeling in thermal simulation tools, and integrate occupant comfort assessments. By adhering to pre-2015 technologies and standards, practitioners can apply these findings to retrofit existing residential buildings for improved thermal comfort and energy efficiency.

## REFERENCES

- Berardi, U., GhaffarianHoseini, A., & GhaffarianHoseini, A. (2014). *State-of-the-art analysis of the environmental benefits of green roofs*. *Applied Energy*, 115, 411–428.
- Cao, X., Konopacki, S., & Akbari, H. (2010). *A study on the energy impact of heat island reduction strategies in Toronto*. *Energy*, 35(10), 5039–5056.
- Getter, K. L., & Rowe, D. B. (2006). *The role of extensive green roofs in sustainable development*. *HortScience*, 41(5), 1276–1285.
- Kosareo, L., & Ries, R. J. (2007). *Comparative environmental life cycle assessment of green roofs*. *Building and Environment*, 42(7), 2606–2613.
- Liu, K., & Baskaran, B. (2003). *Thermal performance of green roofs through field evaluation*. *Proceedings of the First North American Green Roof Conference, Awards and Trade Show*.
- Onmura, S., Watanabe, S., & Hokoi, S. (2001). *Study on evaporative cooling effect of roof lawn gardens*. *Energy and Buildings*, 33(7), 653–666.
- Ouldboukhitine, S.-E., Belarbi, R., & Millogo, Y. (2014). *Influence of thermal and hydric modelling approaches on thermal performance assessment of green roofs*. *Applied Thermal Engineering*, 66(1–2), 235–243.
- Rezaei, M., Tahsildoost, M., & Alemrajabi, A. A. (2013). *Investigation of energy savings in buildings by using green roof technology*. *International Journal of Agricultural and Biological Engineering*, 6(3), 76–82.
- Speak, A. F., Rothwell, J. J., Lindley, S. J., & Smith, C. L. (2012). *Urban particulate pollution reduction by four species of green*

*roof vegetation in a UK city. Atmospheric Environment, 61, 283–293.*

*Voyde, E., & Janković, L. (2009). Thermal performance assessment of an extensive vegetated roof test bed in a UK experimental facility. Building Services Engineering Research and Technology, 30(4), 339–352.*