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Dynamic Thermal and Energy Performance Assessment of a Green Roof in a Hotel Room Using OpenStudio and EnergyPlus under Northern Italian Climate Conditions

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Abstract

Green roofs are increasingly recognized as effective passive strategies for improving building energy performance and mitigating urban environmental impacts. This thesis investigates the thermal and energy performance of a vegetated roof system applied to a hotel building located in Verbania, Northern Italy, using dynamic building energy simulation.

A detailed energy model of a representative hotel room was developed using OpenStudio and EnergyPlus. A conventional roof configuration was first simulated to establish baseline thermal and energy performance conditions. Subsequently, the roof assembly was replaced with a vegetated roof modeled through the EnergyPlus EcoRoof module, allowing a direct comparison between conventional and green roof scenarios under identical climatic, operational, and occupancy conditions.

The analysis focused on roof heat transfer mechanisms, indoor thermal behavior, HVAC energy demand, and annual roof energy balance. Particular attention was devoted to the contribution of solar radiation, convection, evapotranspiration, thermal storage, and conductive heat transfer within the green roof system. The study also evaluated the seasonal behavior of the roof during representative summer and winter periods.

Simulation results indicate that the green roof modifies the roof energy balance by converting a significant portion of absorbed solar energy into latent heat through evapotranspiration, reducing heat transfer toward the indoor environment. Consequently, roof surface temperatures and summer heat gains are reduced, indoor temperature fluctuations are attenuated, and cooling energy demand decreases compared with the conventional roof configuration. The vegetated roof also improves overall thermal stability throughout the year.

The findings demonstrate the potential of green roofs as an effective passive design strategy for hotel buildings under Northern Italian climatic conditions. In addition to reducing cooling loads and improving thermal performance, the study provides a detailed simulation-based evaluation of green roof energy balance mechanisms, contributing to the understanding of how vegetation and substrate layers influence building energy behavior.

Sommario

I tetti verdi sono sempre più riconosciuti come strategie passive efficaci per migliorare le prestazioni energetiche degli edifici e mitigare gli impatti ambientali urbani. Questa tesi analizza le prestazioni termiche ed energetiche di un sistema di copertura vegetata applicato a un edificio alberghiero situato a Verbania, nel Nord Italia, mediante simulazioni dinamiche energetiche dell'edificio.

È stato sviluppato un modello energetico dettagliato di una camera d'albergo rappresentativa utilizzando OpenStudio ed EnergyPlus. Una configurazione di copertura convenzionale è stata inizialmente simulata per definire le condizioni di riferimento delle prestazioni termiche ed energetiche. Successivamente, la copertura è stata sostituita con un sistema di tetto verde modellato tramite il modulo EcoRoof di EnergyPlus, consentendo un confronto diretto tra gli scenari con copertura convenzionale e copertura vegetata in condizioni climatiche, operative e di occupazione identiche.

L'analisi si è concentrata sui meccanismi di trasferimento del calore attraverso la copertura, sul comportamento termico interno, sui carichi di riscaldamento e raffrescamento e sul bilancio energetico annuale della copertura. Particolare attenzione è stata dedicata ai contributi della radiazione solare, della convezione, dell'evapotraspirazione, dell'accumulo termico e della conduzione del calore all'interno del sistema di copertura vegetata.

I risultati delle simulazioni indicano che il tetto verde modifica il bilancio energetico della copertura convertendo parte dell'energia solare assorbita in calore latente attraverso l'evapotraspirazione, riducendo il trasferimento di calore verso l'ambiente interno. Di conseguenza, si osservano una riduzione delle temperature superficiali della copertura e dei guadagni termici estivi, un'attenuazione delle fluttuazioni della temperatura interna e una diminuzione della domanda di raffrescamento rispetto alla configurazione convenzionale. La copertura vegetata migliora inoltre la stabilità termica complessiva durante l'intero anno.

I risultati dimostrano il potenziale dei tetti verdi come efficace strategia passiva per gli edifici alberghieri nelle condizioni climatiche del Nord Italia. Lo studio fornisce una valutazione basata su simulazioni dei meccanismi di bilancio energetico delle coperture vegetate e contribuisce alla comprensione dell'influenza degli strati vegetali e del substrato sulle prestazioni energetiche dell'edificio.

1 Introduction

1.1 Background and Motivation

Buildings are among the largest contributors to global energy consumption and greenhouse gas emissions, making energy efficiency a major challenge in contemporary building engineering. A significant portion of building energy demand is associated with Heating, Ventilation, and Air Conditioning (HVAC) systems, particularly in hotel buildings characterized by continuous occupancy, high internal gains, and strict indoor comfort requirements.

In recent decades, increasing attention has been directed toward passive energy-saving strategies capable of improving thermal performance while reducing operational energy demand. Among these strategies, green roofs have emerged as an important solution due to their ability to reduce roof heat transfer, improve thermal insulation, mitigate urban heat island effects, and moderate indoor temperature fluctuations.

The thermal behavior of green roofs depends on several factors, including vegetation characteristics, substrate properties, climatic conditions, moisture content, and interactions between the roof system and the surrounding environment. Previous studies have demonstrated that green roofs can significantly reduce summer heat gains and cooling demand while contributing to improved thermal stability throughout the year. However, their effectiveness strongly depends on local climatic conditions, building typology, roof characteristics, and operational conditions.

Hotel buildings represent a particularly relevant case study because their continuous occupancy patterns, high internal gains, and strict comfort requirements generate substantial heating and cooling demands throughout the year. These characteristics make hotel buildings suitable for evaluating both active and passive energy-saving strategies and for investigating the potential benefits of green roof implementation under realistic operating conditions.

Dynamic building energy simulation has become one of the most effective approaches for assessing building thermal behavior and energy performance under realistic operating conditions. OpenStudio, coupled with the EnergyPlus simulation engine, enables the analysis of transient heat transfer processes, HVAC operation, indoor thermal comfort, and passive technologies such as green roofs under varying climatic conditions.

Despite the extensive body of research on green roofs, relatively limited studies have focused specifically on hotel buildings located in Northern Italy and on the detailed analysis of roof energy balance mechanisms under local climatic conditions. Furthermore, the interactions between evapotranspiration, thermal storage, conductive heat transfer, and overall building energy performance remain areas requiring further investigation through dynamic simulation.

Within this context, the present thesis investigates the thermal and energy performance of a green roof applied to a representative hotel room located in Verbania, Northern Italy, using dynamic building energy simulation. A conventional roof configuration is compared with a vegetated roof system modeled through the EnergyPlus EcoRoof approach in order to evaluate differences in roof heat transfer, indoor thermal behavior, seasonal heating and cooling loads, and annual energy performance. Particular attention is devoted to the analysis of roof energy balance and to understanding how evapotranspiration, thermal storage, and vegetation-induced heat flux modifications influence building thermal performance.

1.2 Green Roofs and Building Thermal Performance

Green roofs are multilayer vegetated roofing systems typically composed of vegetation, growing substrate, drainage layers, waterproofing membranes, and structural support components. Depending on substrate depth, vegetation characteristics, and maintenance requirements, they are generally classified as extensive or intensive systems (Getter & Rowe, 2006; Jaffal et al., 2012).

From a thermal perspective, green roofs influence building performance through several interacting physical mechanisms, including additional thermal insulation, vegetation shading, evapotranspiration, thermal mass effects, and moisture storage within the substrate. These processes modify the roof energy balance and reduce heat transfer through the roof assembly, thereby moderating temperature fluctuations between indoor and outdoor environments (Ouldboukhitine et al., 2011; Djedjig et al., 2015).

During summer, vegetation intercepts a portion of incoming solar radiation, while evapotranspiration dissipates absorbed energy as latent heat. As a result, roof surface temperatures are reduced, peak heat fluxes are attenuated, and cooling demand can be significantly lowered (Getter et al., 2011; Fioretti et al., 2010; Ouldboukhitine et al., 2011). The substrate layer further contributes by delaying and attenuating heat transfer through the roof structure, thereby improving indoor thermal stability. During winter, the additional roof layers may provide supplementary thermal resistance and reduce conductive heat losses; however, their effectiveness depends strongly on climatic conditions, substrate moisture content, vegetation characteristics, and the thermal properties of the original roof system (Vera et al., 2017; Coma et al., 2017).

Numerous studies have demonstrated that green roofs are particularly effective in regions characterized by high solar radiation and pronounced seasonal temperature variations. In addition to their thermal benefits, they contribute to improved urban microclimates, stormwater management, biodiversity enhancement, and overall environmental sustainability (Santamouris et al., 2007; Eksi et al., 2017; Tadeu et al., 2021). Nevertheless, the interaction between vegetated roofs, building energy demand, HVAC operation, and climatic conditions remains highly dynamic

and complex, as roof performance depends on continuously varying environmental conditions and transient heat transfer processes (Vera et al., 2017; Coma et al., 2017).

Because of these interacting processes, the thermal behavior of green roofs cannot be adequately described using steady-state approaches alone. Dynamic building energy simulation therefore represents an essential tool for evaluating transient heat transfer phenomena, roof energy balance, indoor thermal conditions, and energy demand under realistic operating conditions. Simulation platforms such as EnergyPlus and OpenStudio enable the integration of climatic conditions, occupancy schedules, internal gains, HVAC operation, and roof thermal behavior within a unified modeling framework, providing a comprehensive understanding of how vegetation and substrate layers influence building thermal and energy performance (Silva et al., 2016; Vera et al., 2017).

1.3 Research Objectives

The main objective of this thesis is to evaluate the thermal and energy performance of a green roof system applied to a hotel building under Northern Italian climatic conditions through dynamic building energy simulation.

To achieve this objective, the research aims to:

- Analyze the thermal behavior and energy performance of a representative hotel room under realistic climatic and operational conditions.
- Evaluate seasonal heating and cooling loads using dynamic simulation techniques.
- Investigate the influence of green roof implementation on roof heat transfer mechanisms and indoor thermal conditions.
- Analyze the roof energy balance of a vegetated roof system, considering the contributions of solar radiation, convection, evapotranspiration, thermal storage, and conductive heat transfer.
- Compare the thermal and energy performance of conventional and vegetated roof configurations under identical climatic, occupancy, and operational conditions.
- Assess the effectiveness of green roofs as a passive energy-saving strategy by evaluating their impact on cooling demand, thermal stability, and overall building energy performance.

1.4 Scope of the Study

This thesis focuses on the thermal and energy assessment of a green roof system applied to a hotel building through dynamic building energy simulation. The case study is located in Verbania, Northern Italy, and the analysis concentrates on a representative hotel room while accounting for its interaction with the surrounding conditioned spaces and the overall building environment.

The research specifically investigates:

- Roof heat transfer mechanisms and thermal behavior
- Seasonal heating and cooling loads
- Indoor thermal stability and indoor thermal conditions
- Roof energy balance and heat flux distribution
- Annual building energy performance
- Comparative performance between conventional and vegetated roof configurations
- Dynamic building energy simulation using OpenStudio and EnergyPlus

Particular attention is devoted to the analysis of roof energy balance, with emphasis on the roles of solar radiation, convection, evapotranspiration, thermal storage, and conductive heat transfer within the vegetated roof system. The study also examines how these mechanisms influence indoor thermal conditions and building energy demand throughout the year.

The scope of the research is limited to the thermal and energy performance of the roof system and its interaction with the building environment. Structural, hydrological, ecological, maintenance, and economic aspects of green roofs are not considered and are therefore beyond the scope of this study.

1.5 Thesis Structure

The thesis is organized into a logical sequence of chapters that progressively develop the research from the theoretical background to the analysis, discussion, and conclusions of the simulation study.

- Chapter 2 presents the climatic analysis of the selected location and describes the environmental and building context of the case study.
- Chapter 3 reviews the literature on green roof systems, building thermal performance, heat transfer mechanisms, HVAC operation, and dynamic building energy simulation.
- Chapter 4 describes the research methodology, including the building modeling process, envelope characteristics, internal gains, HVAC configuration, control strategies, and simulation parameters.
- Chapter 5 presents the baseline simulation results and evaluates the thermal and energy performance of the selected hotel room under conventional roof conditions.
- Chapter 6 introduces the green roof model implemented in OpenStudio and EnergyPlus, including the EcoRoof methodology, energy balance formulation, simulation procedure, and selected output variables.
- Chapter 7 presents and discusses the simulation results, focusing on roof thermal behavior, energy balance analysis, indoor thermal performance, HVAC loads, and the comparison between conventional and vegetated roof configurations.
- Chapter 8 presents the conclusions of the study, summarizes the main findings, discusses the contribution and limitations of the research, and outlines future research and design opportunities.

This structure allows the research to progress systematically from climatic and theoretical analysis through simulation methodology and green roof modeling toward a comprehensive evaluation of thermal performance, roof energy balance, and the overall effectiveness of green roof implementation under realistic operating conditions.

2 Climate Analysis and Building Context

2.1 Geographic and Climatic Context

Verbania is located on the western shore of Lake Maggiore in Northern Italy and is characterized by a humid temperate climate with continental influences. The region experiences distinct seasonal variations, with relatively cold winters, warm summers, and moderate conditions during spring and autumn.

The proximity of Lake Maggiore influences the local microclimate by partially moderating temperature fluctuations and contributing to relatively high humidity levels throughout the year. As a result, outdoor environmental conditions vary considerably between seasons, affecting the thermal behavior of buildings and their energy requirements.

Climatic conditions play a fundamental role in building performance because outdoor temperature, solar radiation, humidity, and wind directly influence heat transfer through the building envelope, indoor environmental conditions, and HVAC operation. Understanding these climatic characteristics is therefore essential for evaluating building energy performance under realistic operating conditions.

The climatic profile of Verbania provides a representative framework for investigating the thermal and energy behavior of buildings under varying seasonal conditions. The following sections analyze the main climatic variables used in this study, including outdoor air temperature, relative humidity, and thermal comfort-related conditions.

2.2 Outdoor Dry-Bulb Temperature Analysis

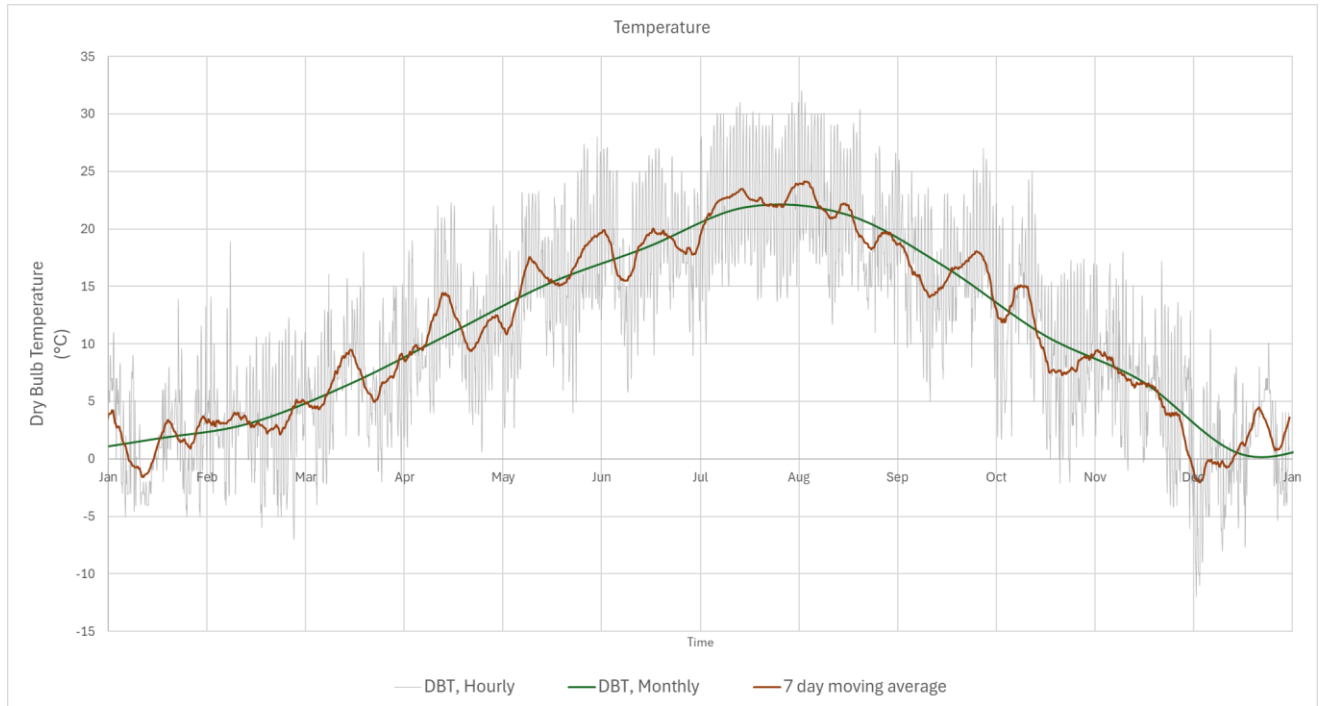


Figure 1, Annual outdoor dry-bulb temperature profile

Figure 1 presents the annual variation of outdoor dry-bulb temperature in Verbania using hourly values, monthly averages, and a 7-day moving average. The results show a clear seasonal pattern, with temperatures gradually increasing from winter to summer and decreasing again during autumn.

The lowest temperatures occur during the winter months (December–February), when hourly values occasionally fall below 0°C. Conversely, the highest temperatures are observed during July and August, with monthly average temperatures reaching approximately 22–23°C and peak hourly values exceeding 30°C.

The hourly temperature profile reveals considerable short-term variability throughout the year, while the monthly average curve highlights the overall seasonal trend. The 7-day moving average smooths short-term fluctuations and provides a clearer representation of the temperature evolution over time.

Spring and autumn act as transitional seasons, characterized by moderate outdoor temperatures and gradual changes between winter and summer conditions. The annual temperature profile therefore reflects the pronounced seasonal variability typical of the Northern Italian climate and provides the basis for understanding the thermal boundary conditions adopted in the subsequent energy simulations.

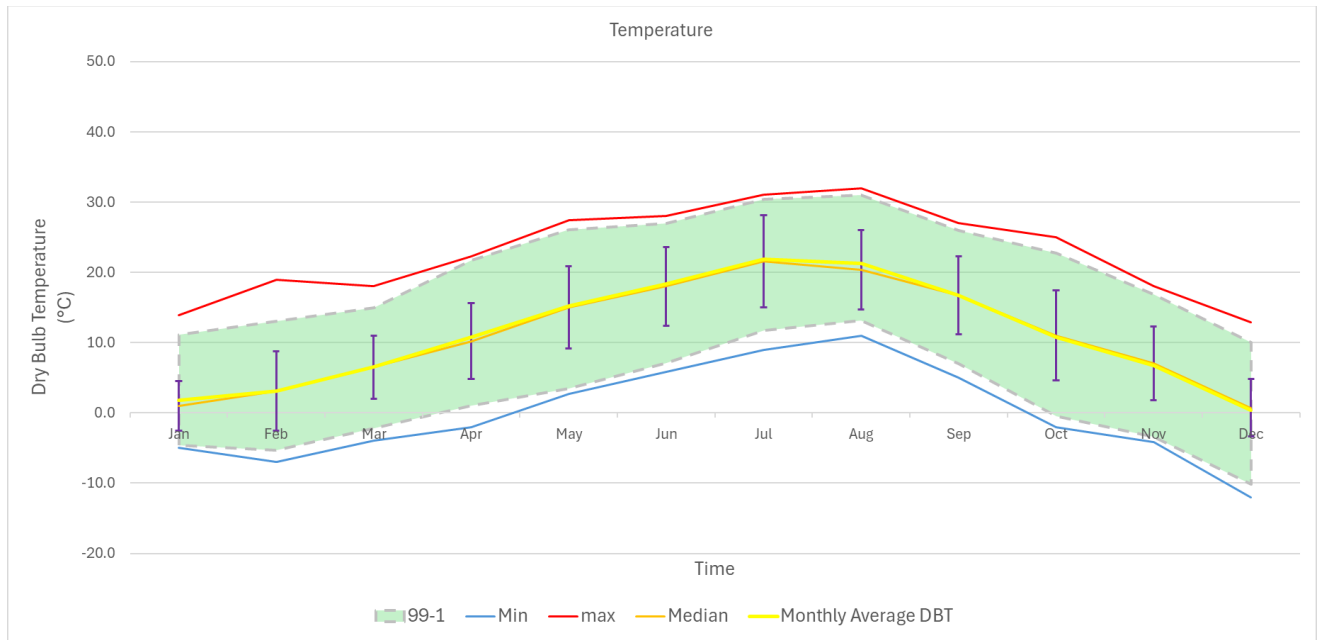


Figure 2, Monthly temperature statistics

Figure 2 provides a summary of the monthly outdoor temperature distribution in Verbania. The results show a progressive increase in temperature from winter to summer, reaching peak values in July and August, followed by a gradual decrease during autumn. The relatively wide gap between minimum and maximum temperatures indicates noticeable seasonal variability, while the percentile range highlights the typical spread of outdoor conditions experienced throughout the year.

2.3 Relative Humidity Analysis

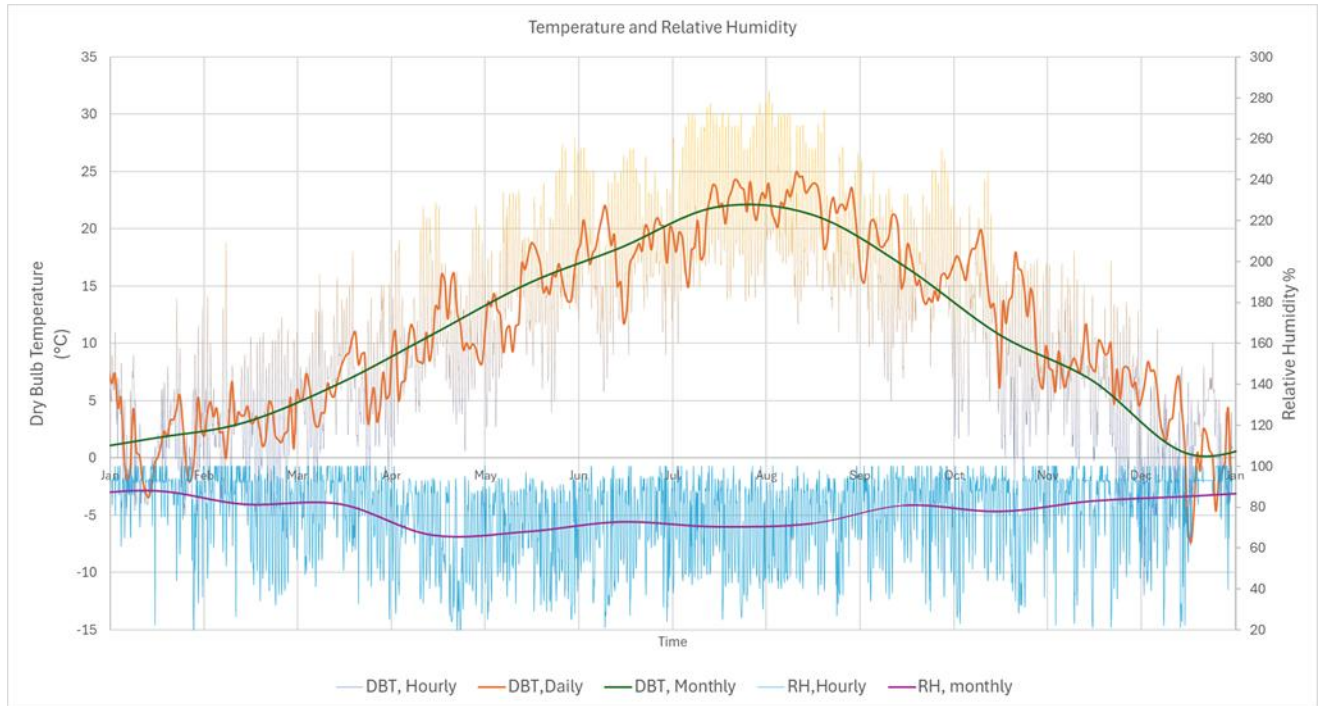


Figure 3, annual variation of outdoor relative humidity

Figure 3 presents the annual variation of outdoor relative humidity together with the corresponding dry-bulb temperature profile in Verbania. The results indicate that relative humidity remains relatively high throughout the year, reflecting the influence of Lake Maggiore on the local climate.

A clear inverse relationship between temperature and relative humidity can be observed. Higher relative humidity values generally occur during the colder months, while lower values are recorded during summer when outdoor temperatures reach their annual maximum. Despite this seasonal variation, monthly average relative humidity remains within a relatively narrow range, indicating consistently humid outdoor conditions throughout the year.

The hourly relative humidity profile also exhibits considerable short-term variability, reflecting changing weather conditions and atmospheric moisture content. However, the monthly trend remains relatively stable compared with the annual temperature profile.

Overall, the results confirm that Verbania is characterized by persistently humid climatic conditions. Together with the observed seasonal temperature variation, these humidity patterns contribute to the environmental boundary conditions considered in the dynamic energy simulations.

2.4 Thermal Comfort and Seasonal Conditions

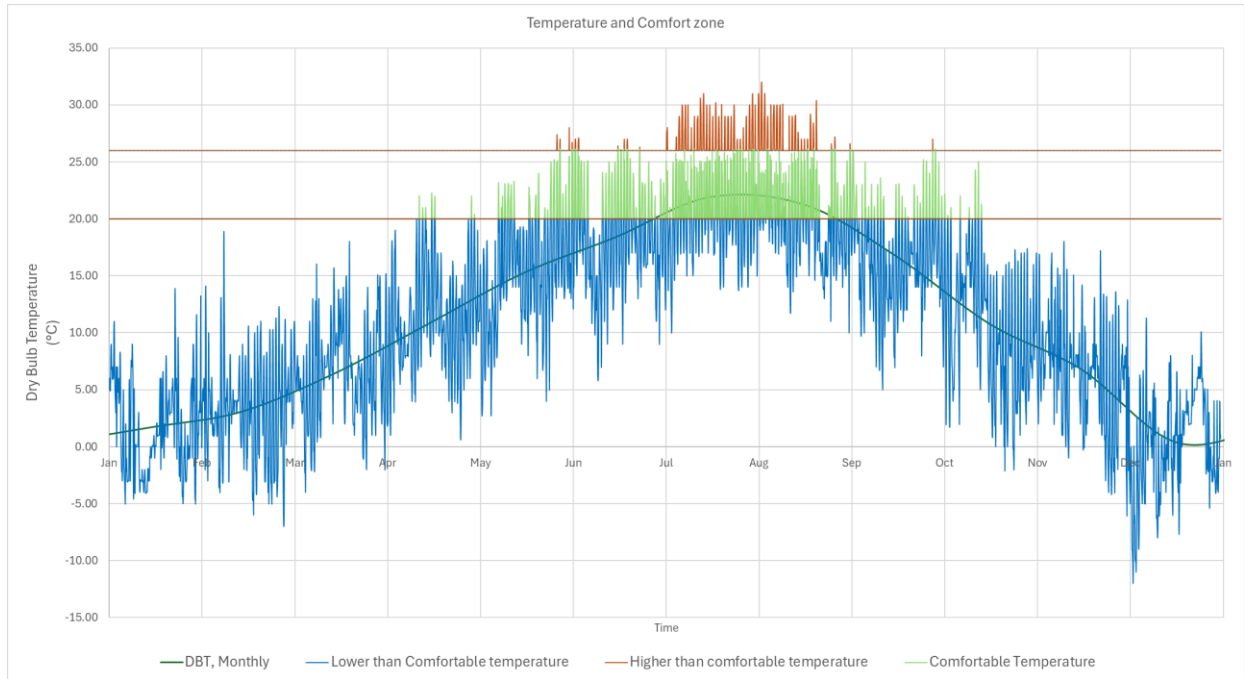


Figure 4, Annual Outdoor Dry-Bulb Temperature Profile Relative to the Thermal Comfort Range

Figure 4 compares the outdoor dry-bulb temperature profile with a simplified thermal comfort range defined between 20°C and 26°C. The results show that outdoor conditions remain below the comfort range for a substantial portion of the year, particularly from October to April, indicating predominantly heating-dominated climatic conditions.

During the summer months, outdoor temperatures frequently fall within the comfort range, especially between June and September. However, several periods in July and August exceed the upper comfort limit of 26°C, with peak temperatures occasionally reaching above 30°C. These conditions indicate the potential for summertime overheating and increased cooling requirements.

The analysis also highlights the limited duration of naturally comfortable outdoor conditions throughout the year. Most hours are either below or above the selected comfort range, emphasizing the importance of building envelope performance and environmental control strategies in maintaining acceptable indoor conditions.

Overall, the climatic profile of Verbania can be characterized as predominantly heating-dominated, with shorter periods of summer overheating. These characteristics provide a suitable framework for evaluating the potential contribution of green roof systems to reducing roof heat gains, improving indoor thermal stability, and moderating seasonal energy demand.

3 State of the Art

3.1 Green Roof Systems and Sustainable Building Design

The building sector is responsible for a substantial share of global energy consumption and greenhouse gas emissions, increasing the need for sustainable design strategies that improve environmental performance while reducing operational energy demand. Among the various nature-based solutions proposed for the built environment, green roofs have gained significant attention due to their ability to integrate ecological functions with building design and urban sustainability objectives.

A green roof is a vegetated roofing system composed of multiple functional layers, typically including vegetation, growing substrate, filter and drainage layers, waterproofing membranes, root barriers, and structural support components. Unlike conventional roof assemblies, green roofs incorporate living vegetation and engineered substrates, creating a multifunctional system that interacts continuously with climatic and environmental conditions (Sailor et al., 2012; Mukherjee et al., 2013).

Green roofs are generally classified into two main categories: extensive and intensive systems. Extensive green roofs typically use shallow substrate depths, commonly ranging from 5 to 15 cm, and support low-maintenance vegetation such as sedums, grasses, and mosses. Their relatively low weight and limited maintenance requirements make them suitable for a wide range of retrofit and new-build applications. Intensive green roofs, by contrast, employ deeper substrates that may exceed 20 cm and can support more diverse vegetation, including shrubs and small trees. Although intensive systems offer greater ecological and landscape potential, they require higher structural capacity, irrigation, and maintenance efforts (Jim & Tsang, 2011; Jaffal et al., 2012; Eksi et al., 2017).

The increasing adoption of green roofs is closely linked to the challenges associated with urbanization. Dense urban areas are characterized by extensive impervious surfaces, reduced vegetation cover, and limited opportunities for ecological integration. By introducing vegetated surfaces into the built environment, green roofs can contribute to more sustainable urban development strategies while enhancing the environmental quality of cities (Santamouris et al., 2007; Tadeu et al., 2021; Jamei et al., 2023).

Despite their growing popularity, green roofs cannot be considered standardized solutions with uniform performance. Their characteristics vary considerably according to design choices and local conditions. Key design parameters include substrate depth, vegetation type, Leaf Area Index (LAI), plant height, irrigation strategy, and substrate moisture conditions. Furthermore, the effectiveness of a green roof depends on factors such as climate, building typology, and roof construction. Consequently, green roofs should be regarded as climate-sensitive and design-

dependent systems whose performance must be evaluated within their specific environmental and operational context (Sailor et al., 2012; Silva, 2014; Mukherjee et al., 2013; Jamei et al., 2023).

3.2 Thermal and Energy Performance of Green Roofs

The thermal performance of green roofs is governed by a combination of interacting physical processes that distinguish them from conventional roof systems. Unlike traditional roofs, which primarily exchange heat through conduction, convection, and radiation, green roofs introduce additional mechanisms associated with vegetation, substrate properties, and moisture dynamics. These processes continuously interact with changing environmental conditions, resulting in a dynamic thermal response that varies throughout the day and across seasons.

One of the primary mechanisms is solar shading provided by the vegetation layer. Plant canopies intercept a portion of incoming solar radiation before it reaches the roof surface, thereby reducing solar heat gains and limiting roof surface temperature increases during periods of high solar exposure. The effectiveness of this process depends on vegetation characteristics such as canopy density, plant coverage, and Leaf Area Index (LAI), which influence the amount of radiation absorbed, reflected, and transmitted through the vegetation layer.

Evapotranspiration represents another important component of the green roof energy balance. Through evaporation from the substrate and transpiration from plant leaves, part of the absorbed solar energy is converted into latent heat and released to the atmosphere. This process contributes to cooling the roof surface and surrounding air, particularly during periods of adequate moisture availability and high solar radiation. Several studies identify evapotranspiration as one of the dominant mechanisms responsible for the cooling potential of vegetated roofs in warm climates (Jim & Peng, 2012; Schweitzer & Erell, 2013).

The substrate layer also plays a significant role in determining thermal behaviour. In addition to providing support for vegetation growth, the growing medium acts as a thermal storage layer capable of absorbing, storing, and gradually releasing heat. This thermal inertia modifies heat transfer through the roof assembly and contributes to a more stable thermal response compared with conventional roofing systems (Fioretti et al., 2010; Djedjig et al., 2015).

As a consequence of these combined mechanisms, green roofs exhibit characteristic dynamic thermal behaviour. Experimental studies have reported reductions in peak roof surface temperatures together with delayed heat transfer through the roof assembly. Thermal time lags typically ranging between 3 and 5 hours and decrement factors between approximately 0.13 and 0.20 have been observed, indicating that vegetated roofs can both attenuate and delay heat flux reaching the indoor environment (Fioretti et al., 2010; Porcaro et al., 2019).

Moisture content further influences thermal performance by affecting both heat transfer and evapotranspiration processes. While increased moisture availability enhances evaporative cooling potential, it may also increase the thermal conductivity of the substrate. Consequently, the thermal behaviour of green roofs depends on the complex interaction between moisture conditions, vegetation characteristics, substrate properties, and prevailing climatic conditions (Coma et al., 2017; Wasim & Nine, 2017).

Because these processes occur simultaneously and vary continuously over time, the thermal response of green roofs cannot be adequately represented using steady-state assumptions. Instead, their behaviour is inherently transient and depends on the interaction between vegetation, substrate, atmospheric conditions, and roof construction characteristics. Understanding these mechanisms is essential for accurately assessing the thermal and energy performance of green roof systems.

3.3 Impact on Building Energy Performance

The influence of green roofs on building energy demand has been extensively investigated through both experimental measurements and dynamic building energy simulations. The literature consistently demonstrates that vegetated roofs can contribute to lower annual energy consumption by reducing heat transfer through the roof assembly and moderating the thermal loads imposed on HVAC systems. However, the magnitude of these benefits varies considerably according to climate, building characteristics, roof construction, vegetation properties, and operational conditions.

Cooling energy reduction is the most consistently reported benefit. Numerous studies conducted in Mediterranean, temperate, subtropical, and warm climates have shown that green roofs can significantly decrease cooling demand, particularly during periods of high solar radiation. Reported annual cooling energy savings commonly range between 10% and 30%, although both lower and higher values have been documented depending on local climatic conditions, building configuration, and modelling assumptions (Santamouris et al., 2007; Ouldboukhite et al., 2011; Silva, 2014; Jamei et al., 2023).

The effectiveness of green roofs is strongly influenced by design and operational characteristics. Simulation studies have demonstrated that parameters such as substrate depth, vegetation density, Leaf Area Index (LAI), plant height, irrigation strategy, and moisture availability can substantially affect annual energy performance. Sailor et al. reported improved building energy performance with increasing substrate depth and vegetation coverage, while Silva (2014) found that thicker substrates and higher LAI values generally enhance cooling energy savings. Similarly, Mukherjee et al. identified substrate depth and vegetation characteristics as key variables affecting overall

building energy demand. More recent studies have further highlighted the importance of moisture-related parameters, with Wasim and Nine (2017) and Jamei et al. (2023) demonstrating that optimal combinations of vegetation and moisture conditions are necessary to maximize energy savings.

The interaction between green roofs and HVAC systems has also received considerable attention. By reducing roof heat gains and moderating indoor temperature fluctuations, green roofs can decrease cooling system operation, reduce peak cooling demand, and improve overall HVAC efficiency. These benefits are particularly relevant in buildings where roof solar gains represent a significant portion of total cooling demand. Additional improvements have been reported when green roofs are combined with complementary passive strategies such as natural ventilation, night cooling, and adaptive cooling approaches (Chen et al., 2019; Ascione et al., 2025).

In contrast, the influence of green roofs on heating demand remains less consistent. While vegetated roofs may provide additional resistance to heat losses during winter, increased substrate moisture can partially offset insulation benefits by increasing thermal conductivity. Consequently, reported heating energy savings are generally smaller than cooling savings and vary significantly depending on climate, roof insulation levels, and building operation. In some cases, studies have reported only marginal heating reductions, while others have identified slight heating penalties associated with reduced winter solar gains (Getter et al., 2011; Vera et al., 2017).

Building typology also plays an important role in determining performance. Buildings with large roof exposure, high cooling requirements, or relatively low roof insulation generally exhibit greater potential for energy savings. Hotel buildings represent a particularly relevant application because they operate continuously throughout the year and are characterized by substantial internal gains, ventilation requirements, intensive HVAC operation, and strict thermal comfort expectations. In such buildings, strategies capable of reducing cooling demand while maintaining indoor comfort can provide meaningful benefits in terms of energy efficiency, operational costs, and sustainability.

Overall, the literature demonstrates that green roofs can contribute significantly to reducing building energy demand, particularly in cooling-dominated climates. However, the magnitude of the benefit depends on the interaction between climate, roof design, vegetation properties, moisture availability, insulation levels, building characteristics, and operational conditions. These findings highlight the importance of project-specific evaluation through dynamic simulation approaches capable of representing realistic operating conditions.

3.4 Building Energy Simulation and Green Roof Modeling

Dynamic building energy simulation has become one of the principal tools for evaluating green roof performance. Unlike steady-state methods, dynamic simulations can represent variations in weather conditions, solar radiation, occupancy schedules, internal gains, ventilation rates, and HVAC operation throughout the year. This capability allows researchers to assess green roof performance under realistic operating conditions and to investigate the interaction between roof systems and overall building energy demand.

Several simulation platforms have been applied to green roof research, including EnergyPlus, TRNSYS, DesignBuilder, and OpenStudio. These tools integrate building geometry, envelope characteristics, climatic data, operational schedules, and energy systems within a unified modelling framework, enabling the evaluation of thermal behaviour, indoor environmental conditions, and annual energy performance (Silva et al., 2016; Vera et al., 2017).

Among the available approaches, the EnergyPlus EcoRoof model is one of the most widely adopted methods for simulating vegetated roofs. Based on the work of Sailor, the model represents the energy balance of green roof systems by incorporating vegetation, substrate, moisture dynamics, and roof heat transfer processes. Through this framework, researchers can analyse roof energy balance, HVAC loads, indoor thermal conditions, and annual energy consumption under different climatic scenarios (Djedjig et al., 2015; Silva, 2014; Wang et al., 2024).

The reliability of simulation results depends strongly on the quality of model inputs and assumptions. Accurate representation of vegetation characteristics, substrate properties, climatic conditions, and building operational parameters is essential for obtaining meaningful predictions. Consequently, calibration and validation against experimental measurements are often recommended to improve model reliability and reduce uncertainty.

Despite their widespread use, current modelling approaches still present limitations. Many simulation tools rely on simplified representations of vegetation dynamics and moisture-related processes, while seasonal plant growth, moisture-dependent thermal properties, freeze–thaw effects, and complex water transport mechanisms are often only partially represented. These simplifications may influence prediction accuracy, particularly when evaluating long-term performance under varying climatic conditions (Fioretti et al., 2010; Ouldboukhite et al., 2011; Mousavi et al., 2023; Pimentel & Tassi, 2024).

Nevertheless, dynamic simulation remains one of the most reliable and widely accepted approaches for assessing green roof performance. Its ability to evaluate multiple design alternatives, climatic scenarios, and operational conditions makes it an essential tool for supporting green roof design, optimization, and decision-making in sustainable building applications

3.5 Indoor Thermal Comfort

In addition to reducing building energy demand, green roofs can contribute significantly to improving indoor thermal comfort. Numerous experimental and simulation studies have reported reductions in indoor operative temperatures, overheating hours, and thermal discomfort indicators such as Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) (Zinzi & Agnoli, 2012; Porcaro et al., 2019; Vertal et al., 2025).

Research consistently shows that green roofs can moderate indoor environmental conditions, particularly during warm periods when roof solar gains contribute substantially to indoor overheating. Several studies have reported reductions in indoor operative temperatures together with improvements in thermal comfort indices, indicating a lower risk of occupant discomfort during summer conditions (La Roche & Berardi, 2014; Djedjig et al., 2015).

The comfort benefits of green roofs are particularly relevant in buildings exposed to high solar radiation or characterized by significant cooling requirements. In these situations, reductions in overheating frequency and indoor temperature fluctuations can improve occupant well-being while simultaneously reducing dependence on mechanical cooling systems.

Buildings with continuous occupancy, such as hotels, offices, and residential facilities, may particularly benefit from improved thermal stability. These building types typically exhibit substantial internal heat gains from occupants, lighting, equipment, and ventilation systems, increasing the likelihood of thermal discomfort during warm periods. Consequently, strategies that help maintain indoor conditions within acceptable comfort ranges can contribute to both occupant satisfaction and operational efficiency.

Several studies have also investigated the combined application of green roofs with other passive design measures. The integration of vegetated roofs with adaptive strategies such as natural ventilation and night cooling has been shown to further reduce overheating hours and improve indoor comfort conditions, particularly in Mediterranean and cooling-dominated climates (Chen et al., 2019; Ascione et al., 2025).

Overall, the literature indicates that green roofs can improve indoor thermal comfort by reducing overheating risk, moderating indoor temperature variations, and supporting more stable indoor environmental conditions. However, the magnitude of these benefits depends on climate, building typology, roof design, occupancy patterns, and operational conditions, highlighting the need for project-specific evaluation.

3.6 Environmental and Sustainability Benefits

In addition to their contributions to building thermal performance and energy efficiency, green roofs provide a broad range of environmental benefits that support sustainable urban development. As multifunctional nature-based solutions, they operate at both the building and urban scales, contributing to climate adaptation, environmental quality, and urban resilience.

One of the most extensively documented benefits of green roofs is stormwater management. By retaining rainfall within the vegetation and substrate layers, green roofs reduce runoff volumes and delay peak discharge rates during precipitation events. This capacity can help alleviate pressure on urban drainage systems and reduce the risk of localized flooding. The effectiveness of stormwater retention depends on factors such as substrate depth, vegetation type, rainfall intensity, and antecedent moisture conditions (Eksi et al., 2017; Schweitzer & Erell, 2013).

Green roofs can also enhance urban biodiversity by creating habitats for plants, insects, birds, and pollinators within densely developed areas. In urban environments where natural green spaces are limited, vegetated roofs provide opportunities to support ecological networks and contribute to the restoration of ecosystem functions. Intensive green roofs, in particular, can accommodate greater species diversity due to their deeper substrates and more complex vegetation structures (Jim & Tsang, 2011; Tadeu et al., 2021).

Another important contribution concerns the mitigation of the Urban Heat Island (UHI) effect. Numerous studies have shown that green roofs can reduce surface temperatures and contribute to improved urban microclimatic conditions. At the city scale, widespread implementation of vegetated roofs has the potential to lower ambient temperatures, improve outdoor thermal conditions, and support climate adaptation strategies in densely urbanized areas (Santamouris et al., 2007; Jamei et al., 2023).

Additional environmental benefits include improved air quality through the capture of airborne particulates, noise attenuation, increased urban green space, and enhanced visual and aesthetic quality. These contributions extend beyond energy performance and support broader sustainability objectives related to public health, environmental quality, and urban livability.

Life Cycle Assessment (LCA) studies provide a comprehensive perspective on the overall environmental performance of green roofs. Although vegetated roof systems generally require greater material use and embodied environmental impacts during construction compared with conventional roofs, long-term operational energy savings together with ecosystem services such as stormwater retention, biodiversity support, and urban heat island mitigation can partially offset these impacts over the building life cycle (Cascone, 2022; Vera et al., 2017; Sclaro & Ghisi, 2025).

Overall, the literature demonstrates that green roofs should not be viewed solely as building energy-saving technologies. Rather, they represent multifunctional systems capable of simultaneously improving environmental performance, supporting ecosystem services, enhancing urban resilience, and contributing to more sustainable and climate-adaptive cities.

3.7 Optimization and Emerging Research Trends

As green roof research has matured, the focus has progressively shifted from evaluating performance benefits toward identifying optimal design solutions capable of maximizing environmental, thermal, and energy-related outcomes. Rather than assessing individual design parameters in isolation, recent studies increasingly adopt integrated approaches that consider the interactions between vegetation, substrate properties, climatic conditions, building characteristics, and operational requirements.

Advances in building performance simulation have played a central role in this transition. Dynamic simulation tools now enable extensive parametric analyses in which multiple design alternatives can be evaluated simultaneously. These approaches allow researchers and designers to investigate the sensitivity of green roof performance to different design variables and to identify configurations that achieve improved overall performance under specific climatic and operational conditions.

More recently, multi-objective optimization methods have been introduced to address the inherently multifunctional nature of green roofs. Instead of focusing exclusively on energy savings, these approaches simultaneously consider multiple performance indicators, including thermal comfort, stormwater retention, urban heat island mitigation, environmental impacts, and life-cycle performance. As a result, optimization frameworks can support more balanced and informed design decisions that reflect broader sustainability objectives.

Emerging research has also explored the application of artificial intelligence and data-driven techniques to support green roof analysis and design. Machine learning approaches, including Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and predictive modelling techniques, have been investigated as tools for performance forecasting, uncertainty analysis, and design optimization (Mousavi et al., 2023; Wang et al., 2024). Although these methods offer promising computational efficiency, they are generally employed as complementary tools alongside physically based simulation models rather than as direct replacements.

Another important trend involves the increasing integration of green roof research within broader urban sustainability and climate adaptation frameworks. Recent studies emphasize the need to

evaluate green roofs not only at the building scale but also in relation to urban microclimates, resilience strategies, ecosystem services, and city-wide environmental performance. This shift reflects the growing recognition that green roofs function as components of larger urban systems rather than isolated building technologies.

Future research is expected to further develop climate-responsive design methodologies capable of adapting green roof configurations to specific environmental conditions, building types, and operational requirements. Greater attention is also likely to be directed toward long-term monitoring, model validation, uncertainty quantification, and the integration of real-time environmental data into simulation and optimization workflows.

Overall, the literature indicates a clear evolution from performance assessment toward optimization-oriented, data-driven, and climate-adaptive design approaches. This trend reflects the increasing maturity of green roof research and its expanding role within sustainable building design and urban resilience strategies.

3.8 Research Gaps

Despite the extensive body of literature investigating green roof performance, several important research gaps remain.

A significant limitation concerns the interaction between green roofs and modern highly insulated building envelopes. While numerous studies have demonstrated the potential of vegetated roofs to reduce cooling demand and improve thermal performance, several authors have observed that these benefits tend to decrease as roof insulation levels increase. However, the extent of this interaction remains insufficiently understood, particularly for buildings designed according to contemporary energy-efficiency standards (Ouldboukhitine et al., 2011; Vera et al., 2017). Further investigation is therefore required to evaluate the effectiveness of green roofs in modern building applications.

Another important gap relates to building typology. Existing research has predominantly focused on residential, office, educational, and experimental buildings. Comparatively fewer studies have investigated hotel buildings, despite their distinctive operational characteristics. Hotels are characterized by continuous occupancy, substantial internal gains, intensive HVAC operation, ventilation requirements, and strict thermal comfort expectations. These factors generate thermal and energy profiles that differ significantly from those of other building categories and may influence the effectiveness of passive roof strategies.

A further limitation concerns the analysis of roof energy balance mechanisms. Much of the existing literature focuses on overall indicators such as annual energy consumption, cooling demand reduction, or indoor thermal comfort improvements. In contrast, relatively few studies provide a detailed examination of the individual heat transfer processes governing green roof performance, including solar gains, long-wave radiation exchange, convection, evapotranspiration, thermal storage, and conductive heat transfer. A more comprehensive understanding of these mechanisms is essential for improving both design decisions and performance interpretation.

Geographical coverage also remains uneven. Although green roof performance has been extensively studied in North America, Northern Europe, and parts of Asia, comparatively limited research has examined their behaviour under the climatic conditions of Northern Italy. Because climatic factors directly influence vegetation behaviour, moisture dynamics, thermal response, and building energy demand, site-specific investigations are necessary to evaluate the applicability of existing findings to local contexts.

Finally, while dynamic simulation tools such as EnergyPlus have become widely adopted, relatively few studies combine detailed roof energy balance analysis with building energy assessment in hotel environments under Northern Italian climatic conditions. This combination represents a relevant research opportunity for improving the understanding of green roof performance in real-world building applications.

To address these gaps, the present thesis investigates the thermal and energy performance of a green roof system applied to a representative hotel room located in Verbania, Northern Italy, using dynamic building energy simulation. Particular attention is devoted to the comparative assessment of conventional and vegetated roof configurations, with a detailed analysis of roof energy balance components, indoor thermal behaviour, HVAC loads, and annual energy performance using the EnergyPlus simulation engine.

3.9 Summary

The literature review demonstrates that green roofs are multifunctional systems capable of contributing to building energy efficiency, indoor environmental quality, and urban sustainability. Their performance is governed by complex interactions among vegetation, substrate properties, climatic conditions, and building characteristics, making them highly climate-sensitive and design-dependent solutions.

Previous studies have shown that green roofs can improve thermal performance, reduce cooling energy demand, enhance indoor thermal comfort, and provide additional environmental benefits such as stormwater management, urban heat island mitigation, and biodiversity support. The magnitude of these benefits depends on factors including climate, roof design, vegetation characteristics, moisture conditions, insulation levels, and building operational profiles.

The review further highlights the importance of dynamic simulation approaches for evaluating green roof performance. Tools such as EnergyPlus enable the analysis of transient thermal behaviour, building energy demand, indoor thermal conditions, and roof energy balance under realistic operating scenarios. Recent research trends increasingly focus on optimization-oriented and climate-responsive design approaches supported by advanced simulation and data-driven methods.

Despite the substantial progress achieved in recent decades, important research gaps remain regarding the performance of green roofs in highly insulated buildings, their application to hotel environments, the detailed analysis of roof energy balance mechanisms, and their behaviour under specific climatic conditions such as those found in Northern Italy.

These gaps provide the basis for the present research, which investigates the thermal and energy performance of a green roof system applied to a representative hotel room located in Verbania, Northern Italy. Using dynamic building energy simulation, the study evaluates roof energy balance components, indoor thermal behaviour, HVAC loads, and annual energy performance through a comparative analysis of conventional and vegetated roof configurations.

4 Methodology

4.1 Research Methodology Overview

The methodology adopted in this thesis is based on dynamic building energy simulation aimed at evaluating the thermal and energy performance of a hotel room under realistic climatic and operational conditions. The research combines building energy modeling, HVAC system simulation, green roof implementation, and comparative performance analysis using OpenStudio coupled with the EnergyPlus simulation engine.

Initially, a baseline energy model of the selected hotel room was established by defining the building envelope characteristics, internal gains, occupancy schedules, ventilation rates, and HVAC system operation under realistic climatic conditions. This model served as the reference case for investigating the room's thermal behavior and annual energy performance.

Subsequently, a green roof system was implemented using the EnergyPlus EcoRoof model available within OpenStudio. This enabled a direct comparison between a conventional roof configuration and a vegetated roof system while maintaining identical building characteristics, occupancy conditions, HVAC settings, and weather data.

The simulation results were then analysed and compared in terms of roof energy balance, heat transfer mechanisms, indoor thermal behaviour, HVAC loads, and annual energy performance. This approach allowed the assessment of the potential benefits of green roof technology in improving building energy efficiency and thermal comfort in the selected case study.

The methodology focuses on evaluating:

- Indoor thermal behavior
- Roof heat transfer mechanisms
- Seasonal heating and cooling loads
- HVAC operational response
- Annual energy balance
- Roof energy balance components
- Thermal and energy impacts of green roof implementation

The overall workflow of the study is summarized in the following sequence:

1. Development of the baseline building model in OpenStudio.
2. Definition of building envelope properties and internal gains.
3. HVAC system modeling and control strategy implementation.
4. Baseline annual dynamic simulation.
5. Green roof implementation using the EnergyPlus EcoRoof approach.
6. Comparative simulation between conventional and green roof scenarios.
7. Evaluation of roof energy balance and heat transfer mechanisms.

8. Analysis of indoor thermal conditions and HVAC performance.
9. Assessment of annual energy performance and green roof benefits.

This methodological framework enables a systematic evaluation of green roof performance under realistic climatic and operational conditions. By comparing conventional and vegetated roof configurations within the same simulation environment, the approach isolates the influence of the green roof while maintaining identical building characteristics, occupancy patterns, HVAC operation, and weather conditions. This allows a reliable assessment of roof energy balance mechanisms, indoor thermal behaviour, HVAC loads, and annual energy performance.

4.2 Case Study Description

The case study analyzed in this research consists of a hotel building located in Verbania, near Lake Maggiore in Northern Italy. The region is characterized by a humid temperate climate with continental influence, resulting in cold winters, warm summers, and significant seasonal temperature variations. The building was selected because its location, occupancy profile, and operational characteristics provide a suitable context for evaluating the thermal and energy performance of green roof systems under realistic climatic conditions.



Figure 5, Site Plan



Figure 6, View of Location

Although the entire hotel building was represented within the simulation model, the analysis focused on a representative hotel room selected as the primary thermal zone for detailed investigation. The selected room reflects typical hotel accommodation conditions, including occupancy-related internal gains, ventilation requirements, and continuous indoor comfort demands. As a result, it provides an appropriate case for studying the interaction between the building envelope, internal loads, outdoor climate, and roof performance.

To ensure realistic thermal behavior, all spaces adjacent to the selected room were included in the model. These neighboring zones were conditioned using Ideal Air Loads systems, allowing indoor temperatures to be maintained while simplifying the HVAC representation. This approach preserves realistic heat transfer between conditioned spaces and avoids the inaccuracies associated with adiabatic boundary assumptions.

The model includes external walls, internal partitions, glazing systems, floors, ceilings, and roof assemblies based on the architectural layout of the hotel floor. Particular attention was devoted to accurately representing the thermal characteristics of the selected room, as heat transfer through the building envelope significantly influences annual heating and cooling loads.

Building orientation, façade exposure, and surrounding geometry were incorporated to account for realistic solar gains, shading effects, and thermal interactions between adjacent zones. These factors influence indoor thermal conditions, seasonal energy demand, and overall building performance.

The selected room was therefore analyzed as part of an interconnected building system rather than as an isolated thermal zone. This modeling strategy provides a more realistic representation of heat transfer processes and energy flows, thereby improving the reliability of the annual simulations and the assessment of green roof performance.

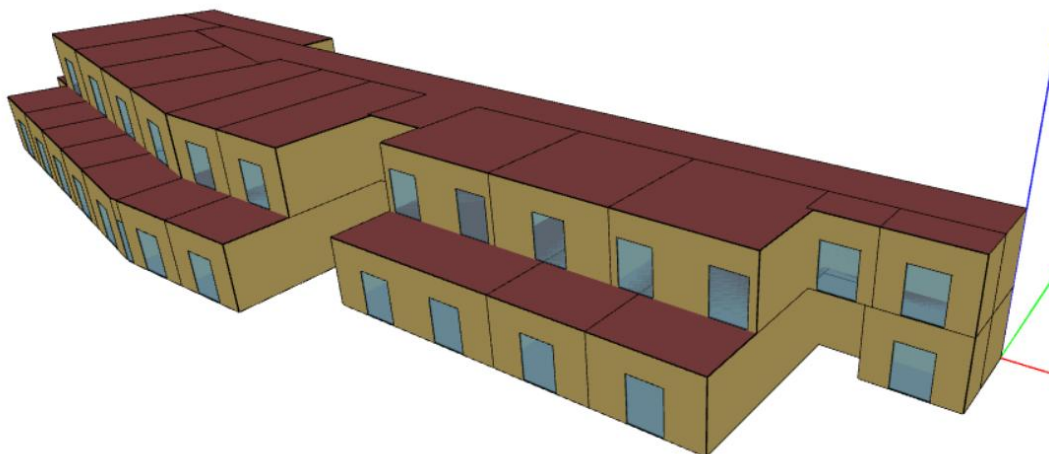


Figure 7, Hotel model used for energy simulations

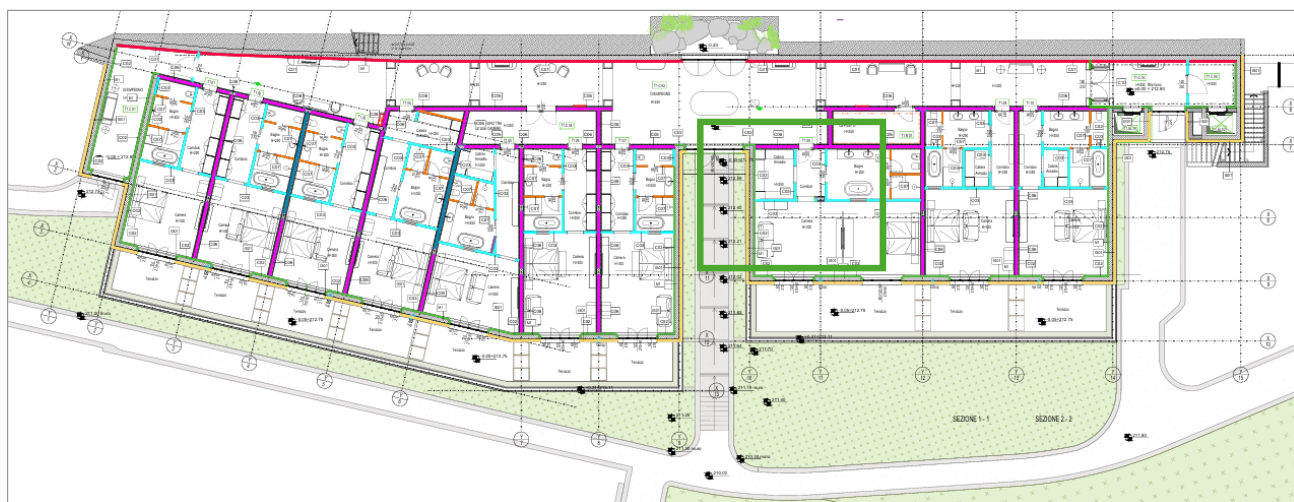


Figure 8, Ground Floor

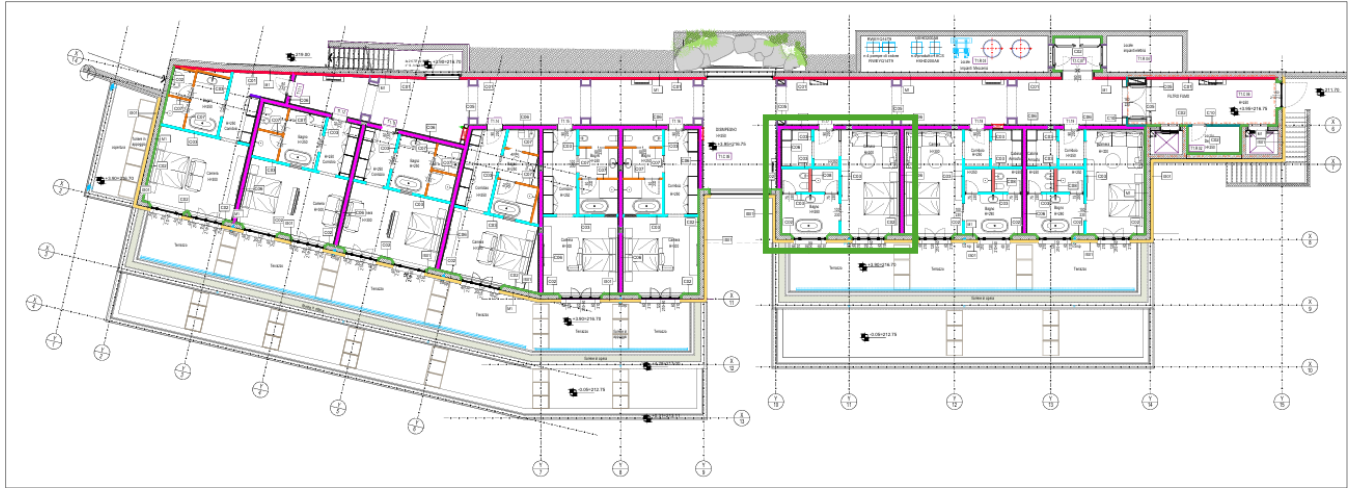


Figure 9, First Floor

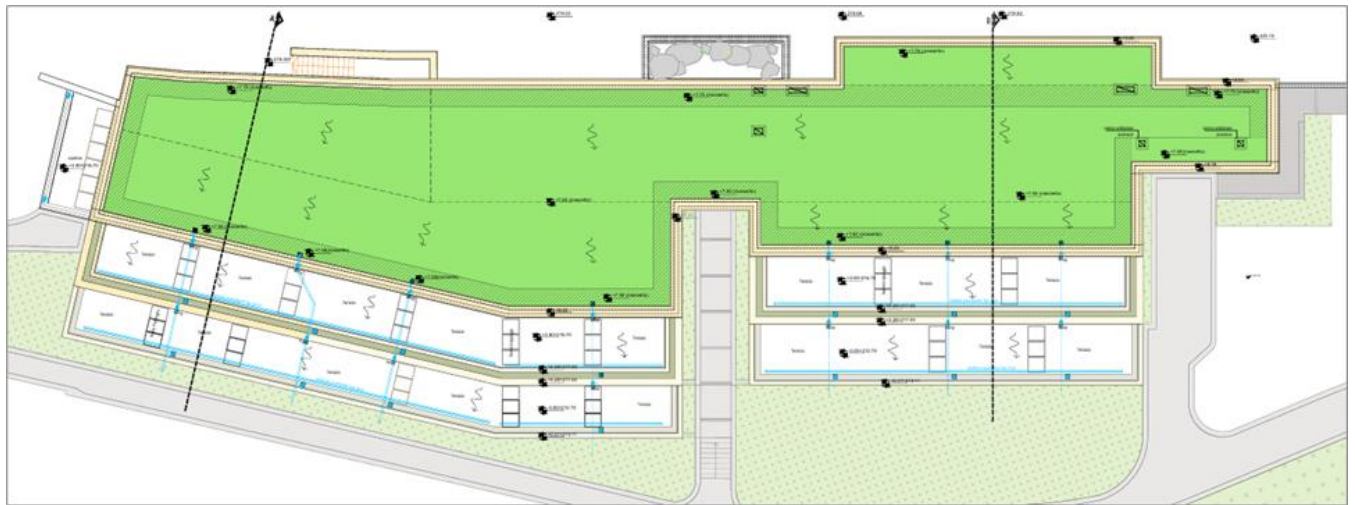


Figure 10, Roof Plan

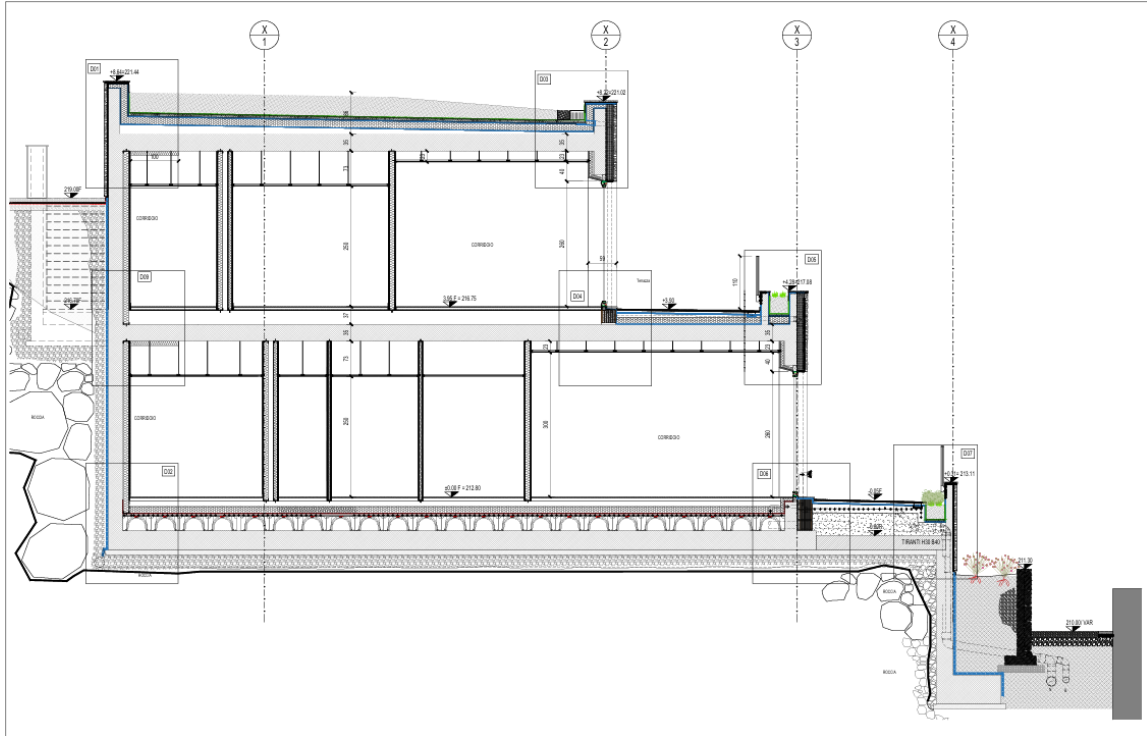


Figure 11, Section

4.3 Building Envelope Characteristics

The building envelope was modeled using multilayer construction assemblies representing the thermal characteristics of the hotel building. The envelope model includes external walls, roof constructions, glazing systems, floor assemblies, and internal partitions, all of which play a significant role in determining heat transfer between indoor and outdoor environments.

The external wall was modeled as a multilayer assembly consisting of natural stone cladding, cement mortar, rock wool insulation, cast concrete, an air cavity, additional rock wool insulation, and internal plasterboard finishes. The wall has a total thickness of 590 mm, a thermal resistance of $6.98 \text{ m}^2\text{K/W}$, and a thermal transmittance (U-value) of $0.140 \text{ W/m}^2\text{K}$, indicating a highly insulated building envelope. The combination of dual insulation layers and a massive concrete core provides both excellent thermal resistance and substantial thermal inertia, reducing heat losses during winter, limiting heat gains during summer, and contributing to improved indoor thermal comfort and energy efficiency.

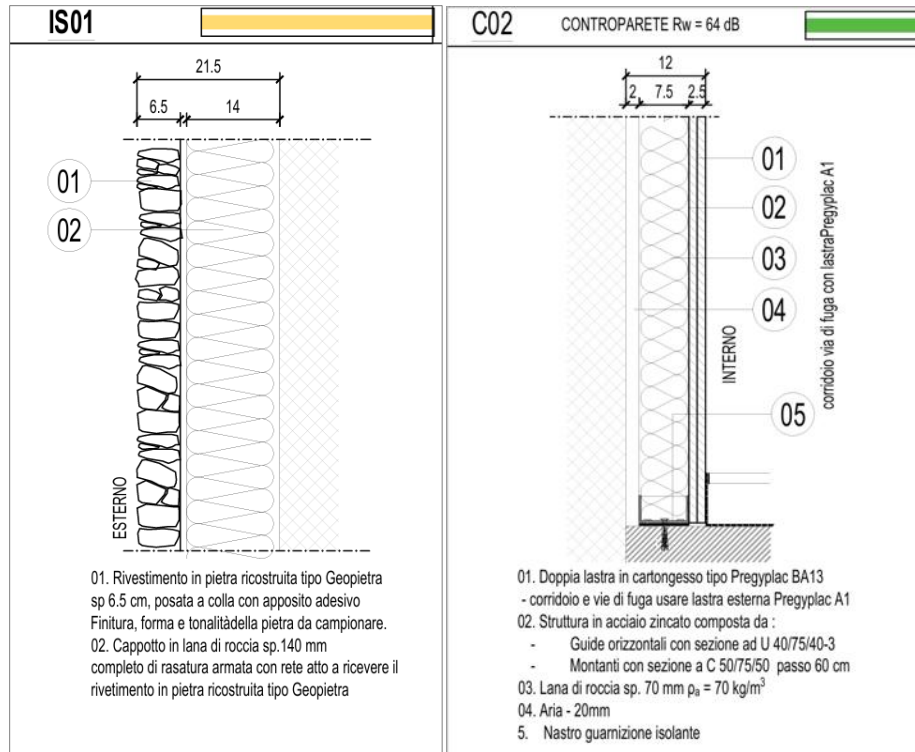


Figure 12, The external wall Stratigraphy

Table 1, The external wall Thermal and physical properties

Layer	Material	Thickness (mm)	Conductivity λ (W/m·K)	Density (kg/m ³)
1	Solid Rock	65	3.00	2700
2	Cement Mortar	10	2.80	2250
3	Rock Wool Insulation	145	0.034	70
4	Cast Concrete (Medium)	250	0.7195	800
5	Air Cavity	20	0.667	1.28
6	Rock Wool Insulation	75	0.034	70
7	Plasterboard	12.5	0.20	900
8	Plasterboard	12.5	0.20	900

Value

Property	
Construction Type	External Wall
Total Thickness	590 mm
Thermal Resistance (R-value)	6.98 m ² K/W
Thermal Transmittance (U-value)	0.140 W/m ² K
Surface Mass	435.9 kg/m ²
Thermal Mass	24.5 kJ/m ² K

The roof was modeled as a multilayer flat roof assembly consisting of a waterproof membrane, 150 mm of rock wool insulation, a screed layer, and a reinforced concrete deck. The total roof thickness is 560 mm, providing a thermal resistance of 4.67 m²K/W and a thermal transmittance (U-value) of 0.208 W/m²K. The substantial concrete deck results in a high surface mass of approximately 915 kg/m², which significantly increases the thermal storage capacity of the roof. This combination of insulation and thermal mass helps reduce heat transfer through the roof, mitigates indoor temperature fluctuations, and contributes to lower heating and cooling energy demands throughout the year.

Table 2, The Roof Thermal and physical properties

Layer	Material	Thickness (mm)	Conductivity λ (W/m·K)	Density (kg/m ³)
1	Membrane	10	0.170	1200
2	Rock Wool Insulation	150	0.034	70
3	Screed	50	1.08	1600
4	Concrete Deck	350	2.30	2322

Property	
Construction Type	Flat Roof
Total Thickness	560 mm
Thermal Resistance (R-value)	4.67 m ² K/W
Thermal Transmittance (U-value)	0.208 W/m ² K
Surface Mass	915.2 kg/m ²
Thermal Mass	193.1 kJ/m ² K

In the later stages of the study, this conventional roof configuration was replaced with a vegetated roof system in order to evaluate the thermal impact of green roof implementation on roof heat transfer, indoor thermal stability, and annual energy performance.

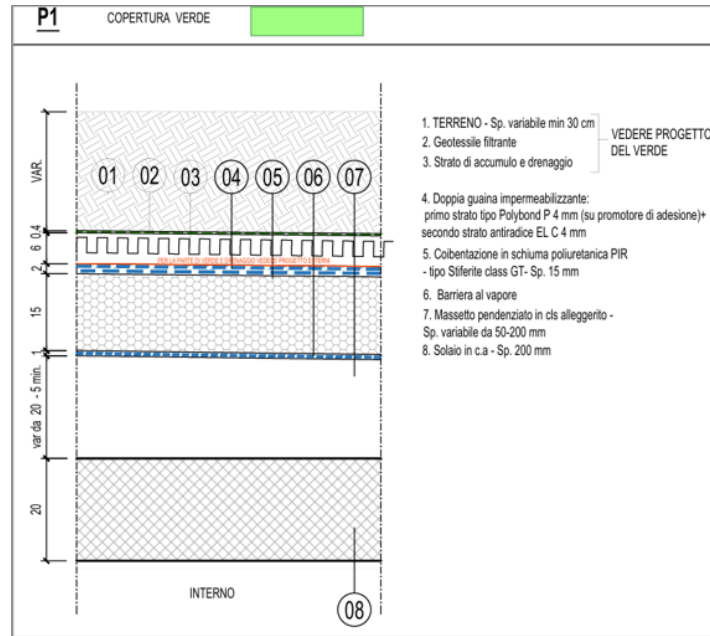


Figure 13, The Green Roof Stratigraphy

The internal partition walls were modeled as lightweight double-stud gypsum board constructions with integrated rock wool insulation and an intermediate air cavity. The assembly consists of multiple plasterboard layers, two insulated cavities containing 75 mm rock wool insulation, and a central 115 mm air gap, resulting in a total thickness of 340 mm. The partition achieves a thermal transmittance (U-value) of 0.192 W/m²K and a thermal resistance of approximately 4.96 m²K/W. In addition to providing thermal separation between adjacent spaces, the double-frame configuration and mineral wool insulation significantly enhance acoustic performance, achieving a sound reduction index of approximately $R_w = 65$ dB, thereby improving indoor comfort and privacy.

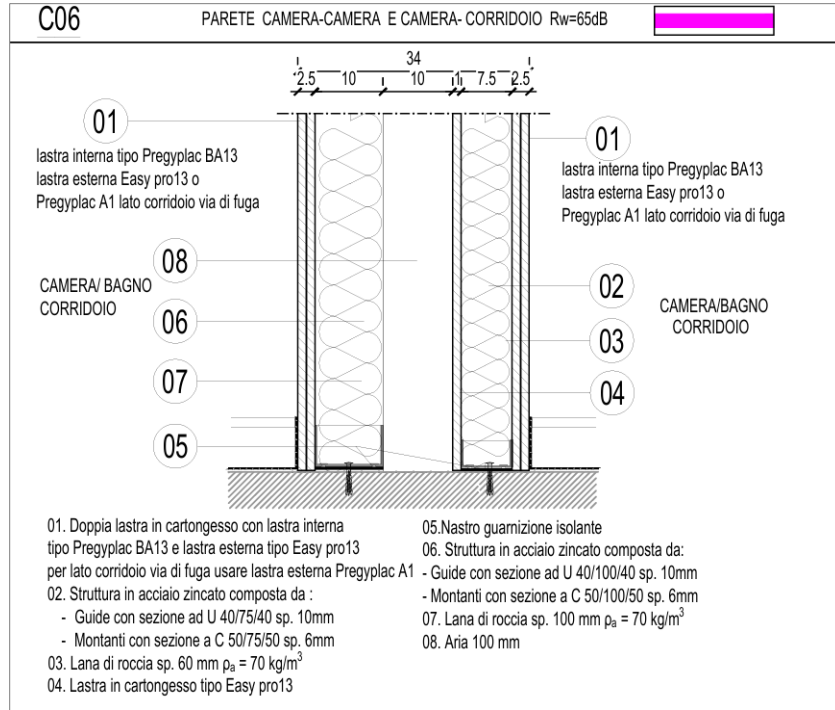


Figure 14, The Internal Wall Stratigraphy

Table 3, The Internal Wall Thermal and physical properties

Layer	Material	Thickness (mm)	Conductivity λ (W/m·K)	Density (kg/m ³)
1	Plasterboard	12.5	0.20	900
2	Plasterboard	12.5	0.20	900
3	Rock Wool Insulation	75	0.034	70
4	Plasterboard	12.5	0.20	900
5	Air Cavity	115	0.667	1.28
6	Plasterboard	12.5	0.20	900
7	Rock Wool Insulation	75	0.034	70
8	Plasterboard	12.5	0.20	900
9	Plasterboard	12.5	0.20	900

Property	Value
Construction Type	Internal Partition
Total Thickness	340 mm
Thermal Resistance (R-value)	4.96 m ² K/W
Thermal Transmittance (U-value)	0.192 W/m ² K
Surface Mass	78.1 kg/m ²
Thermal Mass	24.5 kJ/m ² K

The ground floor slab was modeled as a thermally insulated floor assembly in direct contact with the ground. The construction consists of a ceramic tile finish, conventional concrete screed, lightweight concrete screed, rock wool insulation, a radon-proof membrane, and a reinforced concrete slab. The total assembly thickness is 391 mm and provides a thermal resistance of 4.48 m²K/W, corresponding to a thermal transmittance (U-value) of 0.223 W/m²K.

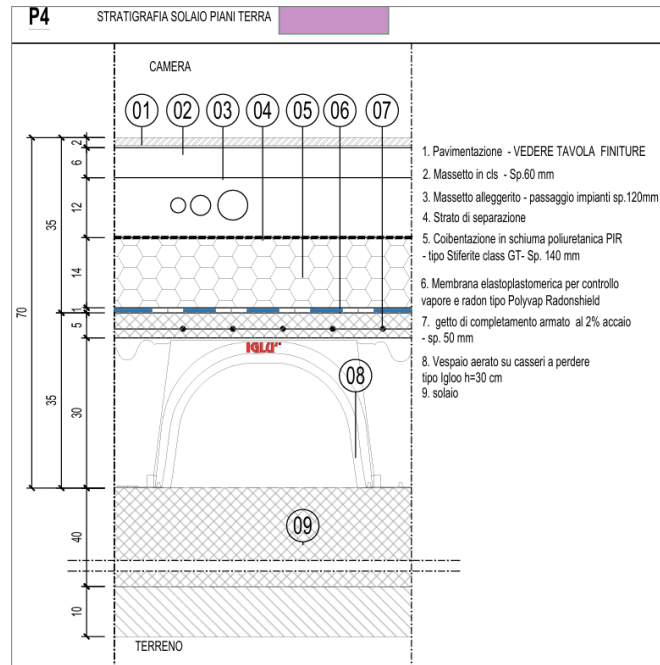


Figure 15, The ground floor Stratigraphy

Table 4, The ground floor Thermal and physical properties

Layer	Material	Thickness (mm)	Conductivity λ (W/m·K)	Density (kg/m ³)
1	Ceramic Tile Flooring (Gres)	20	1.470	1700
2	Ordinary Concrete Screed	60	1.060	1700
3	Lightweight Concrete Screed	120	0.580	1400
4	Rock Wool Insulation	140	0.035	70
5	Radon Barrier Membrane	1	0.400	360
6	Reinforced Concrete Slab	50	2.500	2400

Property	Value
Construction Type	Ground Floor Slab
Total Thickness	391 mm
Thermal Resistance (R-value)	4.477 m ² K/W
Thermal Transmittance (U-value)	0.223 W/m ² K
Surface Mass	431 kg/m ²
Thermal Mass	431 kJ/m ² K*

The external windows were modeled as high-performance triple-glazed units composed of three 6 mm clear float glass panes separated by two 16 mm argon-filled cavities. The glazing system achieves a glass U-value of 0.55 W/m²K, while the overall window U-value including the frame is 1.06 W/m²K. The window assembly provides good thermal insulation and daylight availability, with a visible light transmittance of 76% and a solar heat gain coefficient (g-value) of 0.63. The argon-filled cavities reduce conductive and convective heat transfer through glazing, contributing to lower heating and cooling loads while maintaining high visual comfort.

Table 5, The external windows Thermal and physical properties

Layer	Material	Thickness (mm)	Conductivity λ (W/m·K)	Gas Fill
1	Clear Float Glass	6	1.06	—
2	Argon-Filled Cavity	16	—	Argon
3	Clear Float Glass	6	1.06	—
4	Argon-Filled Cavity	16	—	Argon
5	Clear Float Glass	6	1.06	—

Property	Value
Glazing Type	Triple Glazing
Total Thickness	50 mm
Net U-value (including frame)	1.06 W/m ² K
Glass U-value	0.55 W/m ² K
Net R-value	1.80 m ² K/W
Solar Heat Gain Coefficient (g-value)	0.63
Visible Light Transmittance (VLT)	0.76
Glass Panes	3 × 6 mm
Gas Cavities	2 × 16 mm Argon

Overall, the modeled envelope demonstrates relatively good thermal performance in limiting conductive heat transfer. However, the results also indicate that solar gains through glazing surfaces remain a significant contributor to summer cooling demand. This suggests that additional passive optimization strategies, including improved solar shading, advanced glazing technologies, and green roof implementation, may further improve the thermal and energy performance of the building.

4.4 Internal Gains and Operational Schedules

Internal gains were defined in the simulation model to reproduce realistic operating conditions for the selected hotel room. These gains represent the heat released within the indoor environment by occupants, lighting systems, and electrical equipment during normal building operation.

Occupancy gains were modeled based on a typical hotel room configuration with two occupants. Human presence contributes both sensible and latent heat to the indoor environment. Sensible heat directly affects indoor air temperature and thermal comfort conditions, while latent heat influences indoor humidity levels through moisture generation. In the simulation model, each occupant was assigned a sensible heat gain of approximately 75 W/person and a latent heat gain of approximately 55 W/person, representing typical metabolic activity under standard indoor operating conditions.

Lighting gains were also included in the simulation model to represent the thermal contribution of artificial lighting systems. A lighting power density of approximately 5 W/m² was assigned based on realistic hotel room operating conditions. Although lighting systems are primarily intended for visual comfort, a substantial portion of electrical energy consumed by lighting is eventually converted into heat within the indoor environment.

Electrical equipment gains were modeled using an equipment load of approximately 3 W/m². These gains represent heat released by typical hotel room appliances and electronic devices such as televisions, chargers, small electrical equipment, and auxiliary systems. Similar to lighting gains, equipment loads primarily contribute sensible heat to the indoor environment and influence seasonal cooling demand.

Table 6, Occupancy, lighting, and equipment internal gains used in the hotel room energy model

Internal Gain Source	Parameter	Value	Unit
Occupancy (People)	Number of occupants	2	persons
	Sensible heat gain	75	W/person
	Latent heat gain	55	W/person
	Diversity factor	1.0	-
	Occupancy schedule	Annual Occupation	Profile
Lighting	Lighting power density	5	W/m ²
	Maximum power consumption	5	W/m ²
	Radiant fraction	0.45	-
	Meter	Electricity: Meter 1	-
	Lighting schedule	Annual Lighting	Profile
Electrical Equipment	Equipment power density	3	W/m ²
	Maximum power consumption	3	W/m ²
	Radiant fraction	0.35	-
	Meter	Electricity: Meter 1	-
	Equipment schedule	Annual Appliance	Profile

Operational schedules were implemented to reproduce realistic variations in occupancy, lighting usage, and equipment operation throughout daily building use. These schedules allow the simulation model to account for temporal variation in internal heat generation rather than assuming constant operating conditions throughout the year. The inclusion of dynamic operational schedules improves the realism of the simulation and allows more accurate representation of seasonal HVAC operation and annual energy demand.

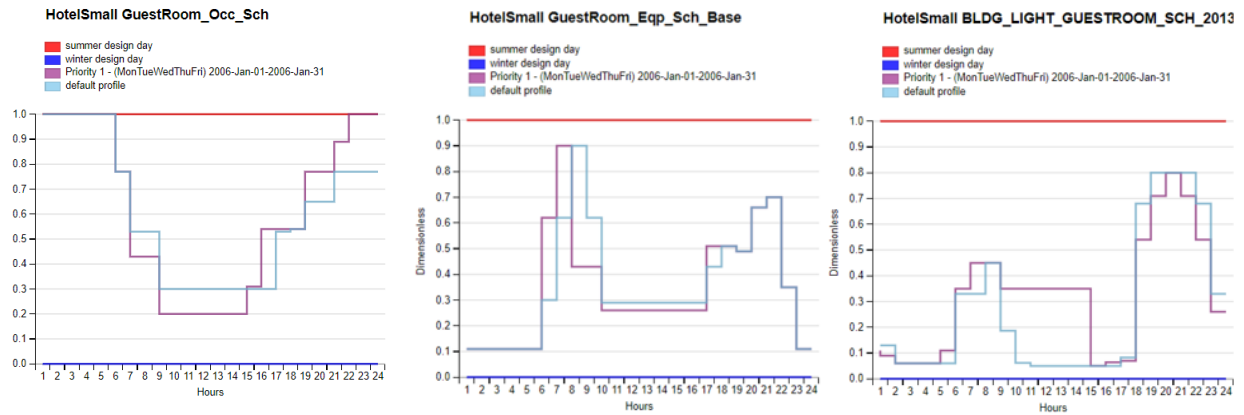


Figure 16, Occupancy, Equipment and Lighting Schedule

The adopted schedules reflect typical hotel room operation patterns, characterized by high occupancy during nighttime hours, reduced daytime activity, and increased occupancy and equipment use during the evening period. Lighting operation follows a similar pattern, with higher utilization during morning and evening hours and reduced use during daytime due to daylight availability.

4.5 HVAC System Configuration

The analyzed hotel room is primarily conditioned by a local Four-Pipe Fan Coil Unit (FCU), while a central Air Loop HVAC system provides outdoor ventilation air and distributes conditioned air to the thermal zone. This HVAC configuration was developed to maintain indoor thermal comfort and acceptable indoor air quality under varying climatic conditions and occupancy levels throughout the year.

The conditioned space is connected to a single-zone Air Loop HVAC system that supplies outdoor ventilation air and distributes conditioned air to the thermal zone. Outdoor air is introduced through the Air Loop HVAC outdoor air system and combined with mechanical air distribution to ensure adequate fresh-air supply while maintaining energy efficiency.

The primary conditioning equipment serving the selected room is a Four-Pipe Fan Coil Unit (FCU). This system includes separate hot-water and chilled-water coils connected to dedicated hot-water and chilled-water plant loops. The fan coil unit can provide both heating and cooling independently according to the thermal requirements of the zone.

Based on the system sizing results, the fan coil unit operates with a design airflow rate of 0.152 m³/s and a heating capacity of approximately 2.40 kW. Air circulation is provided by an integrated fan operating with an efficiency of 70%, a pressure rise of 250 Pa, and a motor efficiency of 90%.

Heating energy is supplied through a hot-water loop served by a boiler with an autosized heating capacity of approximately 2.98 kW and a nominal thermal efficiency of 90%. The hot-water loop was sized using a design exit temperature of approximately 82°C, while the operational supply water temperature is controlled at approximately 67°C through a scheduled setpoint manager.

Table 7, Heating System Parameters

Hot Water Loop				
Object	Description	Value	Sizing	Count
(supply)				
Pump:VariableSpeed	Water Flow Rate	0.0001 m ³ /s	Autosized	
	Rated Pump Head	119,563 Pa		
	Motor Efficiency	90.0 %		
Boiler:HotWater	Heating Capacity	2,982.8 W	Autosized	
	Water Flow Rate	0.0001 m ³ /s	Autosized	
	Nominal Thermal Efficiency	90.0 %		
SetpointManager:Scheduled	Control Variable - Temperature	67.0 to 67.0 C		
(demand)				
Coil:Heating:Water	Air Loop	Air Loop HVAC 1		
Air Terminal Connections				1

Cooling energy is provided through a chilled-water loop connected to an electric chiller. The chiller has a design cooling capacity of approximately 3.50 kW and operates with a co-efficient performance (COP) equal to 5.5. Chilled water is supplied to the cooling coil at approximately 6.7°C.

Table 8, Cooling System Parameters

Chilled Water Loop				
Object	Description	Value	Sizing	Count
(supply)				
Pump:VariableSpeed	Water Flow Rate	0.0001 m ³ /s	Autosized	
	Rated Pump Head	179,352 Pa		
	Motor Efficiency	90.0 %		
Chiller:Electric:EIR	Cooling Capacity	3,500.0 W	Hard Sized	
	Water Flow Rate	0.0001 m ³ /s	Autosized	
	Reference COP	5.5		
	Fraction of Compressor Electric Consumption Rejected by Condenser	1.0		
SetpointManager:Scheduled	Control Variable - Temperature	6.7 to 6.7 C		
(demand)				
Coil:Cooling:Water	Air Loop	Air Loop HVAC 1		
Air Terminal Connections				1

The ventilation system supplies a maximum outdoor airflow rate of 72 m³/h (20 L/s), corresponding to the design occupancy of two persons. Mechanical air distribution is provided through a constant-volume air terminal system connected to the thermal zone.

The overall HVAC configuration combines local fan coil conditioning, centralized outdoor air ventilation, hot-water heating, chilled-water cooling, and automatic temperature control strategies. This integrated system allows the room to maintain thermal comfort while re-responding effectively to seasonal climatic variations and internal heat gains.

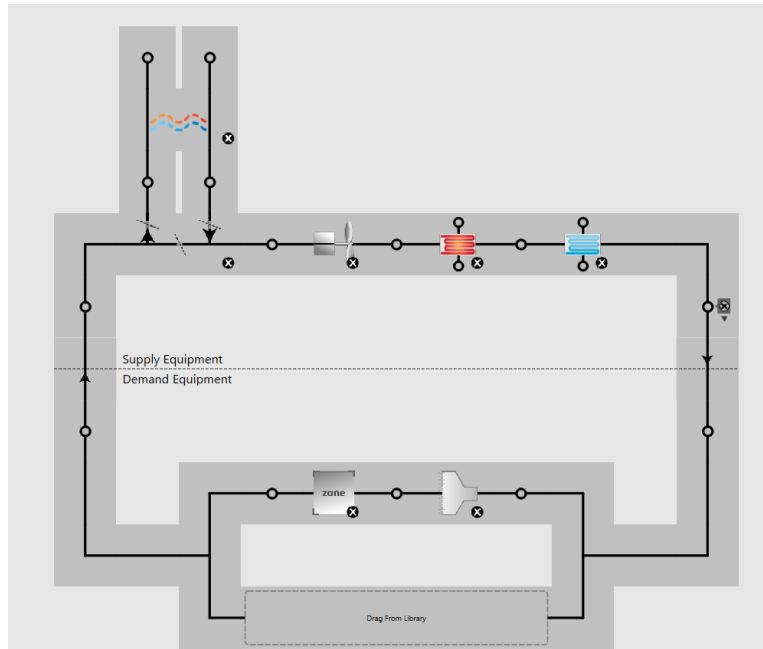


Figure 17, HVAC System

Table 9, Fan coil unit sizing results generated by EnergyPlus/OpenStudio

Hotel_8_a5e0fc72

Object	Description	Value	Sizing	Count
ZoneHVAC:FourPipeFanCoil	Air Flow Rate	0.1520 m ³ /s	Hard Sized	
	Heating Capacity	2,402.3 W	Autosized	
	Water Flow Rate	0.0001 m ³ /s	Hard Sized	
	Fan Efficiency	70.0 %		
	Pressure Rise	250.00 Pa		
	Motor Efficiency	90.0 %		

4.6 Ventilation and Control Strategy

The HVAC system operation is governed by a combined thermal comfort and ventilation control strategy designed to maintain stable indoor environmental conditions while minimizing unnecessary energy consumption. The implemented control sequence regulates indoor temperature through predefined setpoints and provides outdoor air ventilation according to the ventilation requirements of the conditioned zone.

4.6.1 Temperature Control

Indoor thermal comfort is maintained through a combination of zone temperature setpoints and seasonal HVAC plant availability schedules. The conditioned hotel room operates with a heating setpoint of 20°C and a cooling setpoint of 26°C, representing the desired thermal comfort range for occupants.

The HVAC system follows a seasonal operation strategy. The heating plant, consisting of the boiler and hot-water loop, is available from approximately 15 October to 15 April. During this period, when the indoor temperature falls below the heating setpoint of 20°C, the hot-water coil within the four-pipe fan coil unit provides the required heating to compensate for heat losses through the building envelope and ventilation air.

The cooling plant, consisting of the electric chiller and chilled-water loop, is available from approximately 15 May to 15 September. During this period, when the indoor temperature exceeds the cooling setpoint of 26°C, the chilled-water coil operates to remove excess heat generated by solar radiation, outdoor climatic conditions, occupants, lighting, and electrical equipment.

Between the heating and cooling seasons, during the transitional periods (approximately 15 April–15 May and 15 September–15 October), neither the heating nor cooling plant is available. During these periods, indoor conditions are influenced primarily by the building thermal mass, outdoor environmental conditions, internal gains, and the ventilation system.

The supply air temperature is automatically regulated through scheduled setpoint managers. During system sizing, the zone-level design supply air temperatures were defined as 30°C for heating and 16°C for cooling, while the central air loop was sized using supply temperatures of 16.7°C and 12.8°C, respectively.

This seasonal scheduling strategy prevents simultaneous operation of the heating and cooling plants, improves overall system efficiency, and reflects the typical operational practice adopted in hotel buildings located in temperate climates.

Table 10, HVAC Control Parameters

Thermal Zones	Total Floor Area	97 m ²		1
Thermal Zones	Cooling Setpoint Range	26.0 to 26.0 C		
Thermal Zones	Heating Setpoint Range	20.0 to 20.0 C		
Terminal Types Used	AirTerminal:SingleDuct:ConstantVolume:NoReheat			1
(controls)				
HVAC Operation Schedule		Always On Discrete		
Night Cycle Setting		StayOff		
Economizer Setting		NoEconomizer		
Demand Controlled Ventilation Status		On		
Central Heating Design Supply Air Temperature		16.7 C		
Central Cooling Design Supply Air Temperature		12.8 C		
Load to Size On		VentilationRequirement		



4.6.2 Ventilation Control

Ventilation is controlled through a Demand-Controlled Ventilation (DCV) strategy based on indoor occupancy and air-quality requirements. Instead of maintaining a constant outdoor airflow rate throughout the year, the ventilation system adjusts the amount of fresh air supplied according to indoor conditions.

The design outdoor air ventilation rate of 20 L/s (72 m³/h) was selected in accordance with EN 16798-1 Category II indoor air quality requirements, corresponding to two occupants at approximately 10 L/s per person.

Table 11, Air Loop HVAC ventilation and sizing parameters used in the simulation model

Air Loop HVAC 1			
Object	Description	Value	Sizing
<i>(supply)</i>			
AirLoopHVAC:OutdoorAirSystem	Minimum Outdoor Air Flow Rate	0 m ³ /h	Hard Sized
	Maximum Outdoor Air Flow Rate	72 m ³ /h	Autosized
Fan:ConstantVolume	Air Flow Rate	0.1945 m ³ /s	Hard Sized
	Fan Efficiency	70.0 %	
	Pressure Rise	250.00 Pa	
	Motor Efficiency	100.0 %	
Coil:Heating:Water	Heating Capacity	580.6 W	Autosized
	Water Flow Rate	0.0000 m ³ /s	Autosized
	Plant Loop	Hot Water Loop	
Coil:Cooling:Water	Air Flow Rate	0.0200 m ³ /s	Autosized
	Water Flow Rate	0.0000 m ³ /s	Autosized
	Plant Loop	Chilled Water Loop	

The DCV strategy allows the system to reduce unnecessary ventilation during periods of low occupancy while increasing fresh-air supply when indoor air quality deteriorates. This approach reduces heating and cooling loads associated with outdoor air treatment and improves overall HVAC energy efficiency.

The ventilation system operates continuously through the Air Loop HVAC configuration, while airflow rates are automatically adjusted according to the implemented control logic.

4.6.3 Indoor Air Quality Performance

Indoor air quality performance was evaluated through annual monitoring of indoor CO₂ concentration levels. The simulation results showed that the hotel room-maintained CO₂ concentrations within the safe threshold of 1000 ppm throughout the entire year. No hours were recorded in either the caution (>1000 ppm) or hazard (>5000 ppm) ranges.

The results indicate that the implemented demand-controlled ventilation system provided sufficient outdoor air to maintain acceptable indoor air quality during all occupied periods. Consequently, occupant exposure to elevated CO₂ concentrations was effectively avoided, ensuring compliance with the selected indoor air quality criteria.

4.7 Simulation Parameters

The building energy simulations were performed using OpenStudio coupled with the EnergyPlus simulation engine under annual operating conditions. The simulation period extended from January 1 to December 31, allowing the evaluation of building thermal behavior and energy performance throughout an entire year.

Weather data were obtained from the EnergyPlus Typical Meteorological Year (TMY) weather file corresponding to Novara-Cameri, Italy. This weather station is located in close proximity to the case study location in Verbania and presents similar climatic characteristics. The weather file provides hourly meteorological data, including outdoor temperature, relative humidity, solar radiation, wind speed, and wind direction, which are required for dynamic energy simulation.

Table 12, Weather file and climatic data used for the energy simulations

Weather Summary	
	Value
Weather File	Novara-Cameri - ITA IGDG WMO#=160640
Latitude	45.65
Longitude	8.67
Elevation	178 m
Time Zone	1.00
North Axis Angle	0.00
ASHRAE Climate Zone	

A timestep of 6 timesteps per hour, corresponding to a calculation interval of 10 minutes, was adopted in order to accurately capture transient thermal effects, solar gains, and HVAC system response. Solar radiation calculations were performed using the *FullExteriorWithReflections* algorithm, which accounts for direct, diffuse, and reflected solar radiation incident on external building surfaces.

For HVAC sizing calculations, a heating sizing factor of 1.25 and a cooling sizing factor of 1.15 were applied to ensure adequate system capacity under peak operating conditions. The simulation employed a minimum of 1 warmup day and a maximum of 25 warmup days to achieve numerical convergence and stable initial conditions before the annual simulation period.

5 Baseline Simulation Results

5.1 Indoor Temperature Performance

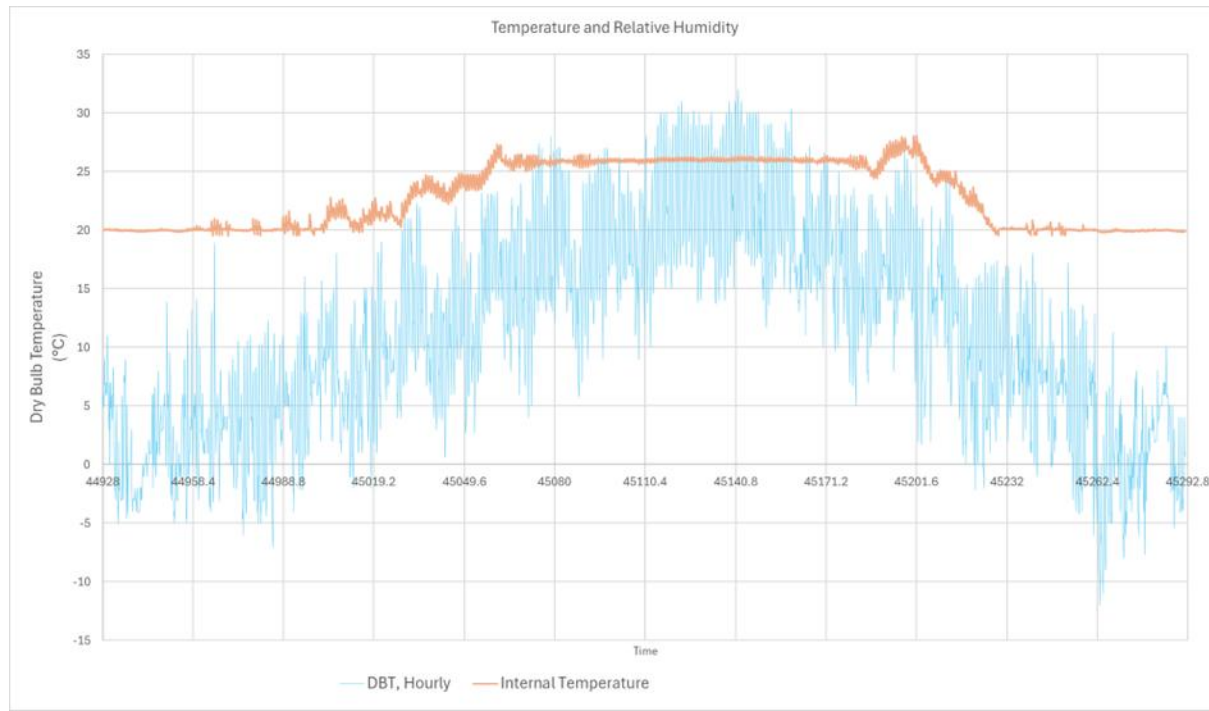


Figure 18, Annual indoor temperature response under baseline roof conditions compared with outdoor dry-bulb temperature.

The simulation results show that the HVAC system maintains relatively stable indoor thermal conditions throughout the year despite significant seasonal variations in outdoor air temperature. Outdoor temperatures fluctuate considerably, ranging from sub-zero values during winter to values above 30°C during summer. In contrast, the indoor temperature remains much more stable, generally close to the defined comfort range of 20–26°C.

During winter, the indoor temperature is maintained around the heating setpoint of 20°C, indicating that the heating system compensates for envelope and ventilation heat losses. During summer, the indoor temperature increases and remains mostly close to the cooling setpoint of 26°C, with limited periods slightly above this value. This behavior indicates increased cooling demand during the warmest periods due to outdoor temperature, solar gains, and internal heat gains.

During spring and autumn, outdoor temperatures are closer to indoor comfort conditions, resulting in reduced heating and cooling requirements. Overall, the results confirm that the HVAC system significantly reduces indoor temperature fluctuations compared to outdoor conditions and provides generally stable thermal comfort conditions throughout the year.

5.2 Ventilation Performance

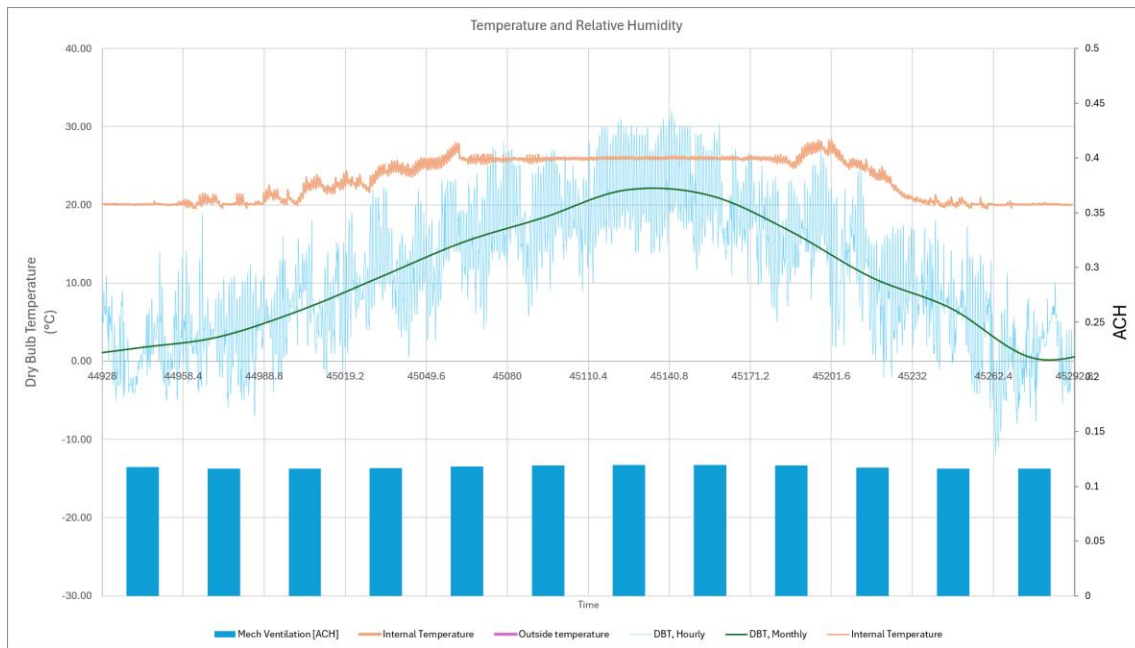


Figure 19, Annual variation of mechanical ventilation rate (ACH) in relation to outdoor and indoor temperature conditions.

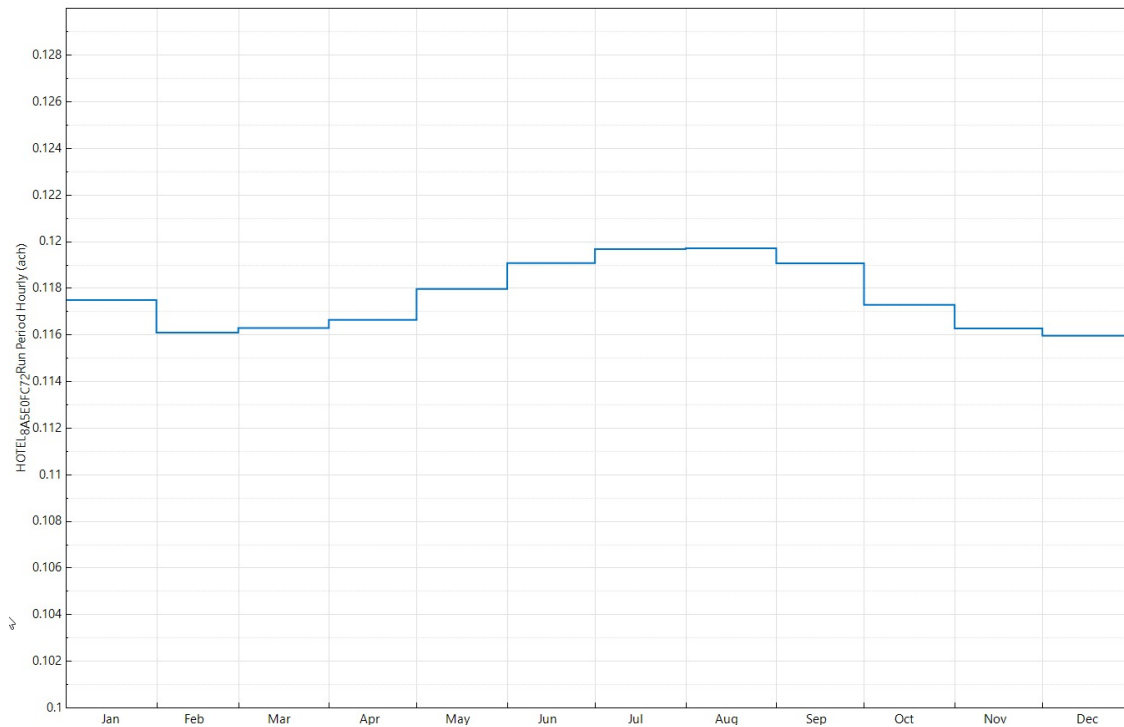


Figure 20, Monthly average ventilation rate (ACH) under the demand-controlled ventilation strategy

The annual ventilation results indicate that the mechanical ventilation rate remains relatively stable throughout the year, varying between approximately 0.116 and 0.120 ACH. Although minor seasonal fluctuations can be observed, the overall variation is limited and the ventilation profile remains nearly constant over the simulation period.

The highest ventilation rates occur during the summer months, while slightly lower values are observed during winter. However, the difference between the minimum and maximum monthly average ACH values is less than 4%, indicating that ventilation performance is largely independent of seasonal climatic conditions.

This behavior is consistent with the occupancy assumptions adopted in the model, where occupancy schedules remain essentially unchanged throughout the year. Consequently, the outdoor air requirement remains relatively constant, resulting in a stable mechanical ventilation rate across all seasons.

Overall, the results demonstrate that the ventilation system provides a continuous and reliable supply of fresh air throughout the year, supporting indoor air quality while maintaining consistent ventilation performance.

5.3 Heating and Cooling Loads

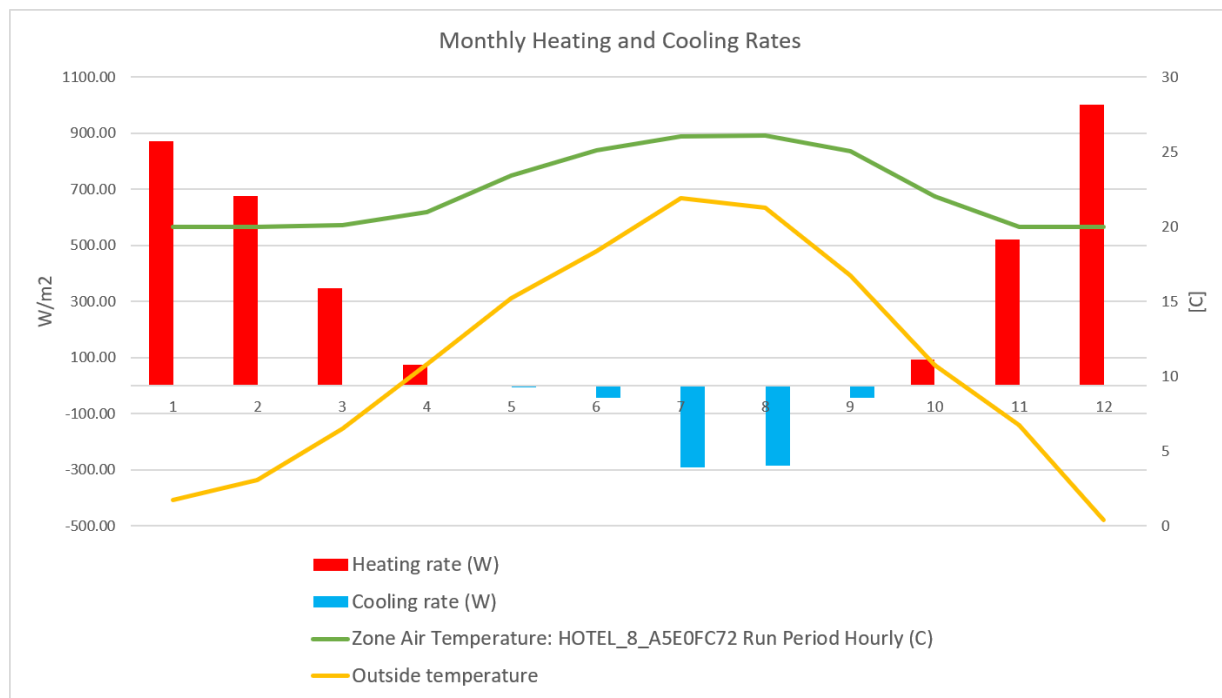


Figure 21, Monthly Heating/Cooling Loads

The results illustrate the seasonal variation of heating and cooling requirements in the simulated hotel room and their relationship with outdoor climatic conditions. During the winter months, low outdoor temperatures increase heat transfer from the indoor environment to the exterior, resulting in significant heating demand. The highest heating loads occur between December and February, when outdoor temperatures reach their minimum values.

As outdoor temperatures increase during spring, the heating demand gradually decreases and becomes negligible. During the summer period, higher outdoor temperatures and increased solar gains lead to cooling requirements, with the maximum cooling demand observed in July and August. Cooling loads then decrease progressively during autumn as outdoor temperatures decline.

The indoor air temperature remains relatively stable throughout the year, generally within the comfort range maintained by the HVAC system. In contrast, outdoor temperatures show substantial seasonal fluctuations, varying from approximately 2°C in winter to around 22°C in summer.

Overall, the results highlight the strong influence of seasonal climatic conditions on building energy demand. Heating loads dominate during the colder months due to increased heat losses through the building envelope, while cooling loads occur primarily during the summer months as a consequence of higher outdoor temperatures and solar heat gains. These results provide a baseline reference for evaluating the impact of future design interventions and energy-efficiency strategies.

5.4 Energy Balance Analysis

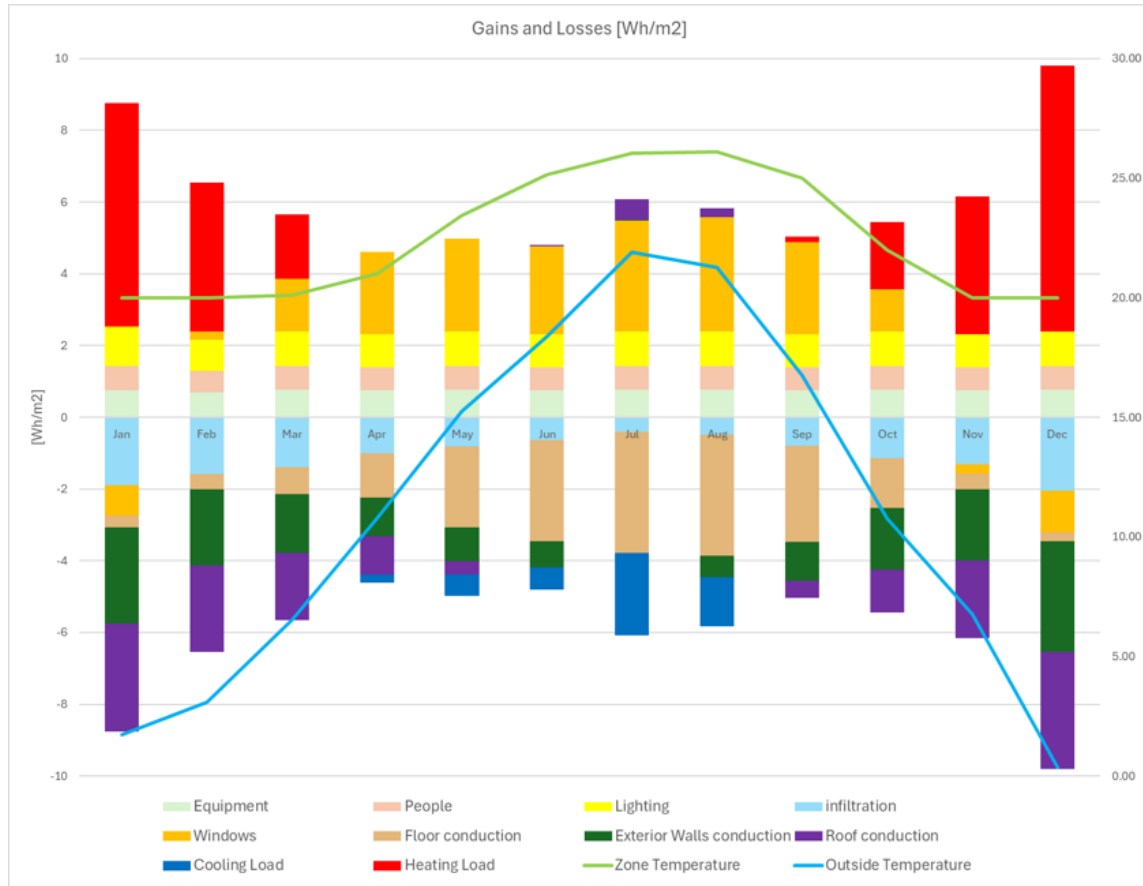


Figure 22, Monthly energy balance of the baseline model

The monthly energy balance obtained from the OpenStudio/EnergyPlus simulation provides a detailed representation of the principal heat gains and losses affecting the selected hotel room throughout the year. The results decompose the thermal balance into contributions from occupants, lighting, equipment, infiltration, windows, roof conduction, external wall conduction, floor conduction, and HVAC heating and cooling loads.

As shown in Figure 24, a clear seasonal pattern can be observed. During the winter months (November–March), outdoor temperatures remain significantly below indoor comfort conditions, resulting in increased heat losses through the building envelope. Roof conduction, external wall conduction, window heat transfer, and infiltration represent the dominant heat loss mechanisms during this period. Consequently, heating demand becomes the largest positive component of the energy balance, reaching its maximum values during December and January.

As outdoor temperatures increase during spring, envelope heat losses gradually decrease and heating demand is reduced. During the summer period (June–August), the thermal balance shifts from heating-dominated to cooling-dominated operation. Internal gains from occupants, lighting,

and equipment remain relatively constant throughout the year due to fixed operational schedules, while increased outdoor temperatures lead to higher cooling requirements. Cooling loads reach their highest values during July and August, corresponding to the warmest outdoor conditions.

The results further indicate that conductive heat transfer through the roof, walls, windows, and floor varies significantly with seasonal temperature differences between indoor and outdoor environments. In contrast, internal gains remain comparatively stable, providing a consistent contribution to the thermal balance regardless of season.

Despite substantial variations in outdoor temperature, the indoor zone temperature remains within a relatively narrow range throughout the year. This demonstrates the effectiveness of the building envelope and HVAC system in maintaining stable indoor thermal conditions while continuously balancing seasonal heat gains and losses.

Overall, the energy balance analysis identifies the dominant thermal mechanisms affecting building performance and establishes the baseline reference case against which the green roof scenario will be evaluated in the subsequent chapters.

6 Green Roof Modeling

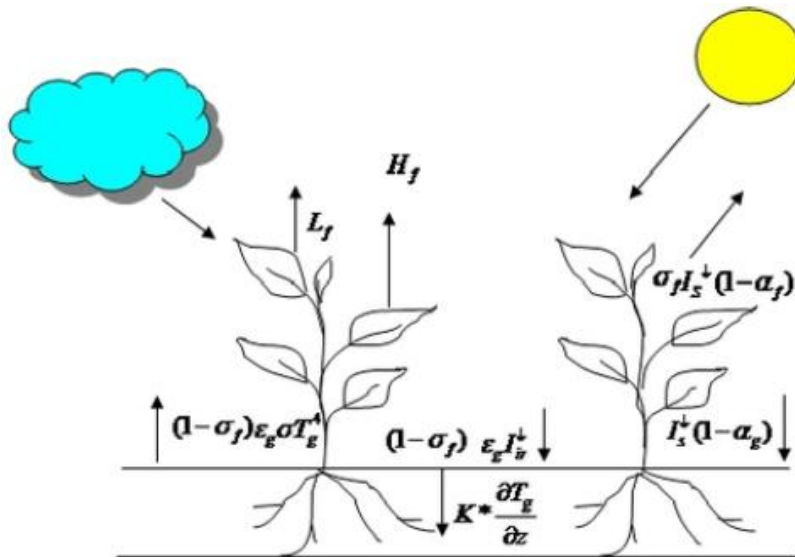
6.1 Green Roof Model Description

To evaluate the thermal performance of vegetated roofs, the EnergyPlus EcoRoof model was implemented through OpenStudio. Unlike conventional roofing systems, green roofs introduce additional physical processes including vegetation shading, evapotranspiration, moisture-dependent heat transfer, soil heat storage, and radiative interactions between the plant canopy, soil substrate, and atmosphere.

The EcoRoof model is based on the Fast All-Season Soil Strength (FASST) vegetation model and simultaneously solves the energy balances of the vegetation canopy and the soil surface at every simulation timestep. The model accounts for:

- Shortwave solar radiation absorption
- Longwave radiative exchange
- Sensible heat transfer by convection
- Latent heat transfer due to evapotranspiration
- Heat conduction through the soil substrate
- Thermal energy storage within the roof system

The temperatures of the vegetation layer (T_f) and soil surface (T_g) are obtained by solving two coupled energy balance equations, allowing EnergyPlus to represent the dynamic thermal behavior of vegetated roofing systems.



6.2 EcoRoof Model Implementation

The simulations were conducted using OpenStudio coupled with the EnergyPlus simulation engine. The vegetated roof was modeled using the Material:RoofVegetation object provided by EnergyPlus.

The EcoRoof model simulates coupled heat and moisture transfer processes occurring within the vegetation canopy and soil substrate. The model includes:

- vegetation canopy energy balance;
- soil energy balance;
- evapotranspiration processes;
- convective and radiative exchanges;
- conductive heat transfer through the roof system.

6.2.1 Green Roof Parameters

Several physical parameters were defined for the green roof model, including:

Vegetation Parameters

- Leaf Area Index (LAI)
- plant height;
- leaf reflectivity;
- leaf emissivity;
- stomatal resistance.

These parameters directly affect shading, convection, and evapotranspiration processes.

Soil Parameters

- soil thickness;
- thermal conductivity;
- density;
- specific heat capacity;
- moisture content.

The soil layer strongly influences thermal storage, conductive heat transfer, and evaporation potential.

The screenshot displays the EnergyPlus EcoRoof model interface. The left sidebar lists material categories: Materials, Gas Window Materials, Gas Mixture Window Materials, Blind Window Materials, Daylight Redirection Device Window Materials, Screen Window Materials, Shade Window Materials, Infrared Transparent Materials, Roof Vegetation Materials, and Refraction Extinction Method Glazing Window Materials. The central area is titled 'Name: Sedum Vegetation' and contains various input fields for parameters such as Height Of Plants (0.100000 m), Leaf Area Index (3.000000), Leaf Reflectivity (0.220000), Leaf Emissivity (0.950000), Minimum Stomatal Resistance (180.000000 s/m), and Soil Layer Name (Green Roof Soil). The right sidebar shows a list of materials with 'Sedum Vegetation' selected, and a detailed list of parameters including Roughness (Smooth), Thickness (0.200000 m), Conductivity Of Dry Soil (0.350000 W/m·K), Density Of Dry Soil (1100.000000 kg/m³), Specific Heat Of Dry Soil (1200.000000 J/kg·K), Thermal Absorptance (0.900000), Solar Absorptance (0.700000), Visible Absorptance (0.750000), Saturation Volumetric Moisture Content Of The Soil Layer (0.300000), Residual Volumetric Moisture Content Of The Soil Layer (0.010000), and Initial Volumetric Moisture Content Of The Soil Layer (0.100000).

Figure 23, Green roof parameters implemented in the EnergyPlus EcoRoof model

Table 13, Key vegetation and soil properties adopted for the green roof EcoRoof model in EnergyPlus

Category	Parameter	Value	Unit
Vegetation	Plant Height	0.10	m
Vegetation	Leaf Area Index (LAI)	3.0	-
Vegetation	Leaf Reflectivity	0.22	-
Vegetation	Leaf Emissivity	0.95	-
Vegetation	Minimum Stomatal Resistance	180	s/m
Soil	Soil Thickness	0.20	m
Soil	Dry Soil Conductivity	0.35	W/m·K
Soil	Dry Soil Density	1100	kg/m³
Soil	Specific Heat Capacity	1200	J/kg·K
Soil	Solar Absorptance	0.70	-
Soil	Saturation Moisture Content	0.30	m³/m³
Soil	Initial Moisture Content	0.10	m³/m³

6.3 Green Roof Energy Balance Theory

The thermal behavior of a green roof is governed by the conservation of energy. Incoming solar radiation is distributed among several heat transfer mechanisms, including sensible heat exchange with the ambient air, latent heat dissipation through evapotranspiration, longwave radiative exchange, and conductive heat transfer through the roof assembly.

6.3.1 Foliage Energy Balance

According to the EnergyPlus EcoRoof Engineering Reference, the energy balance of the vegetation canopy is expressed as:

$$F_f = \sigma_f [I_s(1 - \alpha_f) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4] + H_f + L_f$$

where:

- F_f = net heat flux to the foliage layer (W/m²)
- I_s = incoming shortwave solar radiation
- α_f = foliage albedo
- I_{ir} = incoming longwave radiation
- ε_f = foliage emissivity
- σ = Stefan–Boltzmann constant
- T_f = foliage temperature (K)
- H_f = foliage sensible heat flux (W/m²)
- L_f = foliage latent heat flux (W/m²)

This equation accounts for:

- Solar radiation absorbed by the vegetation
- Longwave radiation exchange
- Sensible heat transfer between leaves and air
- Latent heat transfer associated with transpiration

The above equation can be simplified as:

$$F_f = R_{SW,f} + R_{LW,f} + H_f + L_f$$

where:

- $R_{SW,f}$ = absorbed shortwave solar radiation
- $R_{LW,f}$ = net longwave radiation exchange

- H_f = sensible heat flux
- L_f = latent heat flux due to transpiration

The simplified equation highlights the main physical processes governing the vegetation layer. The canopy absorbs solar and thermal radiation and redistributes this energy through sensible heat transfer and evapotranspiration.

6.3.2 Soil Energy Balance

According to the EnergyPlus EcoRoof Engineering Reference, the energy balance at the soil surface is expressed as:

$$F_g = (1 - \sigma_f)[I_s(1 - \alpha_g) + \varepsilon_g I_{ir} - \varepsilon_g \sigma T_g^4] + H_g + L_g + Q_{cond}$$

where:

- F_g = net heat flux at the soil surface (W/m²)
- σ_f = vegetation coverage fraction
- I_s = incoming shortwave solar radiation
- α_g = soil albedo
- I_{ir} = incoming longwave radiation
- ε_g = soil emissivity
- σ = Stefan–Boltzmann constant
- T_g = soil surface temperature (K)
- H_g = soil sensible heat flux (W/m²)
- L_g = soil latent heat flux (W/m²)
- Q_{cond} = conductive heat transfer into the roof substrate (W/m²)

This equation accounts for:

- Solar radiation absorbed by the soil surface
- Longwave radiation exchange between the soil, vegetation, and atmosphere
- Sensible heat transfer between the soil and the surrounding air
- Latent heat transfer due to soil evaporation
- Heat conduction through the roof assembly

The soil energy balance can be simplified as:

$$F_g = R_{SW,g} + R_{LW,g} + H_g + L_g + Q_{cond}$$

where:

- $R_{SW,g}$ = absorbed shortwave solar radiation by the soil
- $R_{LW,g}$ = net longwave radiation exchange
- H_g = sensible heat flux from the soil
- L_g = latent heat flux due to soil evaporation
- Q_{cond} = conductive heat transfer into the roof structure

The simplified equation highlights the main heat transfer mechanisms occurring at the soil surface. The absorbed radiative energy is redistributed through sensible heat exchange with the surrounding air, latent heat losses caused by evaporation, and conductive heat transfer into the underlying roof layers. The conductive term represents the thermal energy transferred through the roof assembly and is directly related to building heating and cooling loads.

6.3.3 Total Roof Energy Balance

The foliage and soil energy balances can be combined to represent the overall thermal behaviour of the green roof system. At roof scale, the energy balance can be expressed as:

$$R_{net} = H_{total} + LE_{total} + Q_{cond} + S$$

where:

- R_{net} = net radiative energy exchange (shortwave + longwave radiation)
- H_{total} = total sensible heat flux

$$H_{total} = H_f + H_g$$

- LE_{total} = total latent heat flux

$$LE_{total} = L_f + L_g$$

- Q_{cond} = conductive heat transfer through the roof assembly
- S = thermal energy storage within the vegetation-soil system

This equation represents the conservation of energy for the complete green roof system. The incoming radiative energy is redistributed through sensible heat transfer to the atmosphere, latent heat dissipation through evapotranspiration, conductive heat transfer into the building, and temporary thermal storage within the soil and vegetation layers.

Unlike the foliage and soil energy balances presented previously, this equation is not solved directly by EnergyPlus. Instead, it provides a convenient framework for interpreting the thermal behaviour of the roof and for reconstructing the overall energy balance from simulation outputs.

6.3.4 Radiation Reconstruction Used in This Study

Because EnergyPlus does not directly report the total net radiative exchange of the EcoRoof system, the net radiation term was reconstructed from the available outputs.

Neglecting the storage term, the roof-scale balance becomes:

$$R_{net} = -(H_{total} + LE_{total} + Q_{cond})$$

where:

$$H_{total} = H_f + H_g$$

and

$$LE_{total} = L_f + L_g$$

This reconstructed net radiation term was used throughout the present analysis to evaluate the overall energy balance of the green roof and compare its behaviour with that of the conventional roof.

6.4 Simulation Methodology

Two roof configurations were analyzed:

Case 1 – Conventional Roof

The reference case consists of a standard roof assembly without vegetation.

Case 2 – Green Roof

The second case employs the EnergyPlus EcoRoof model, incorporating:

- Vegetation canopy
- Growing substrate
- Evapotranspiration processes
- Soil heat storage
- Vegetation shading effects

All remaining building characteristics, occupancy schedules, HVAC settings, weather data, and construction properties were maintained identical between the two simulations to isolate the effect of the vegetated roof.

6.5 Output Variables

The following EnergyPlus outputs were extracted from OpenStudio for the analysis:

Thermal Behaviour

- Roof outside surface temperature
- Roof inside surface temperature
- Indoor air temperature

Heat Transfer Components

- Soil sensible heat flux
- Vegetation sensible heat flux
- Soil latent heat flux
- Vegetation latent heat flux
- Surface conduction heat transfer rate

Radiation Components

- Incident solar radiation
- Sky diffuse solar radiation
- Net longwave radiation

These outputs were used to reconstruct the overall roof energy balance.

7 Results and Discussion

This chapter presents and discusses the thermal and energy performance of the green roof system compared with a conventional bare roof. The analysis is based on the results obtained from the EnergyPlus/OpenStudio simulations and focuses on the mechanisms governing heat transfer through the roof assembly and their influence on indoor thermal conditions.

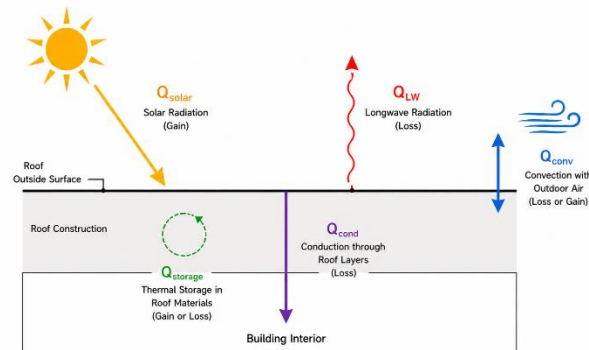
The study investigates both annual and seasonal behaviour of the roof systems. First, the overall energy balance of the conventional roof and the green roof is examined in order to identify the dominant heat transfer processes and the redistribution of absorbed solar energy. Particular attention is given to the role of vegetation and substrate layers in modifying the pathways of energy exchange through shading, thermal storage, and evapotranspiration.

To better understand the dynamic thermal response of the roof systems, representative winter and summer months (January and July) are analysed in detail. These months were selected because they represent the most critical heating and cooling periods of the year. The hourly evolution of surface temperatures, radiative exchanges, convective heat transfer, conductive heat transfer, sensible heat fluxes, latent heat fluxes, and heat storage components is evaluated to highlight the seasonal differences in roof performance.

Finally, the thermal behaviour of the green roof is directly compared with that of the conventional roof, and the resulting impact on indoor conditions and HVAC energy demand is assessed. The objective is to quantify the contribution of the green roof to reducing heat gains during summer, limiting heat losses during winter, improving thermal stability, and enhancing the overall energy efficiency of the building.

7.1 Annual Energy Balance Analysis

7.1.1 Conventional Roof Energy Balance



A clear understanding of the heat transfer mechanisms acting on the roof surface is essential for interpreting the energy balance results. In a conventional (bare) roof, energy is exchanged with the surrounding environment through solar radiation, longwave radiative exchange, convection with outdoor air, conduction through the roof layers, and thermal storage within the roof construction. Together, these processes determine how the absorbed solar energy is distributed and ultimately influence the thermal performance of the roof.

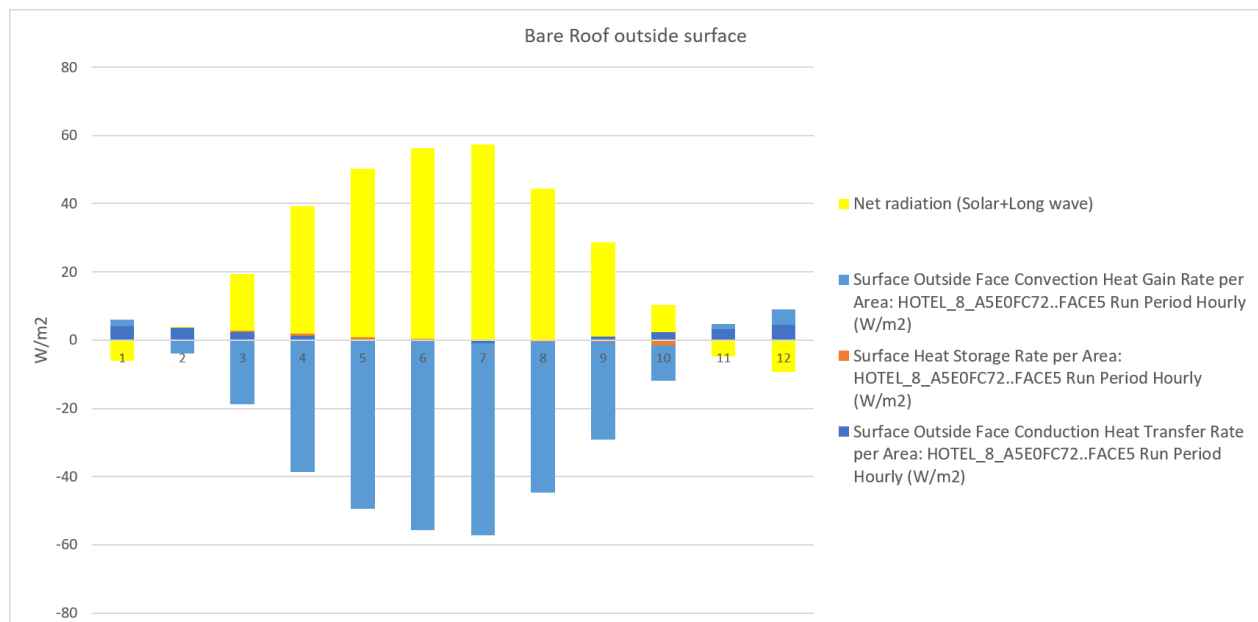


Figure 24, Monthly Energy Balance of the Conventional (Bare) Roof Outside Surface

Figure 26 shows the monthly energy balance of the conventional roof external surface using the simplified balance:

$$Q_{net,rad} + Q_{conv} + Q_{cond} + Q_{storage} = 0$$

where

$$Q_{net,rad} = Q_{solar} + Q_{LW}$$

where the net radiation term represents the combined contribution of absorbed solar radiation and longwave radiative exchange. Net radiation is the dominant positive energy input throughout the year and reaches its maximum during June and July, reflecting the strong influence of seasonal solar availability on roof thermal behaviour.

The absorbed radiative energy is mainly balanced by conductive and convective heat transfer. During summer, conductive heat transfer reaches its highest magnitude, indicating that a substantial portion of the absorbed energy penetrates into the roof assembly. At the same time, increased roof surface temperatures enhance convective heat exchange with the outdoor air, providing an additional pathway for heat dissipation.

The storage term remains close to zero on a monthly basis, suggesting that the roof does not accumulate significant thermal energy over long-term averaged conditions. Unlike vegetated roofs, the conventional roof lacks a latent heat dissipation mechanism associated with evapotranspiration. Consequently, absorbed solar energy is primarily redistributed through conduction and convection, leading to increased heat transfer through the building envelope and higher surface temperatures during the warm season.

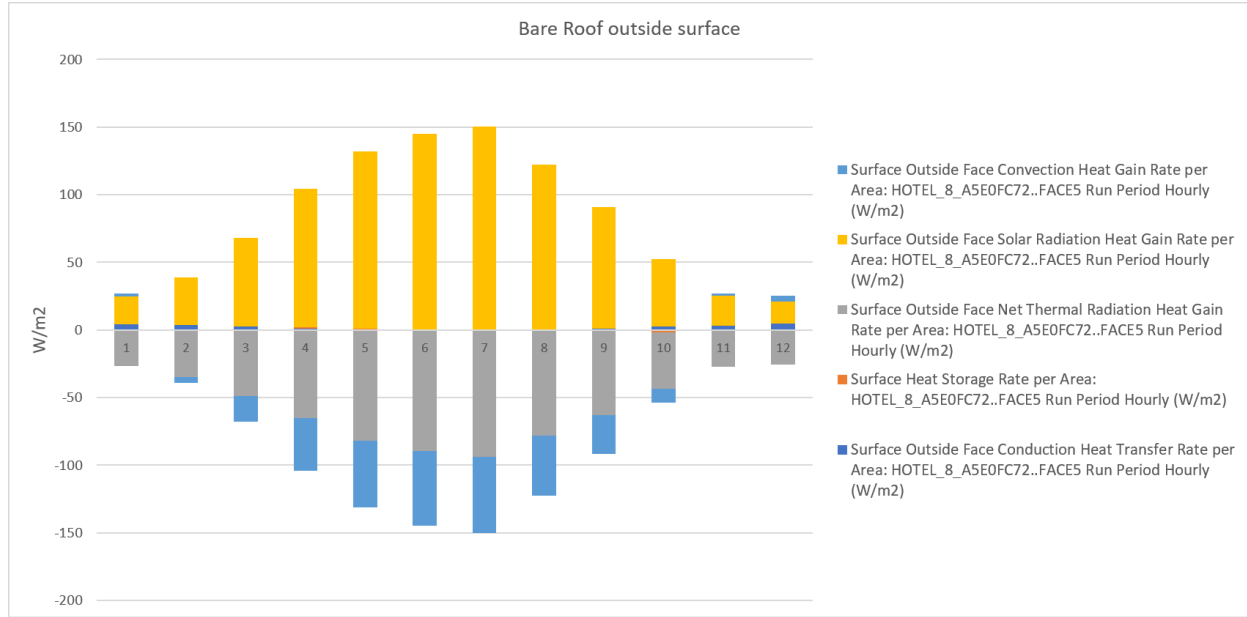


Figure 25, Radiation Decomposition and Heat Transfer Components of the Conventional Roof External Surface

Figure 27 provides a more detailed view of the conventional roof balance by separating solar radiation and longwave radiation:

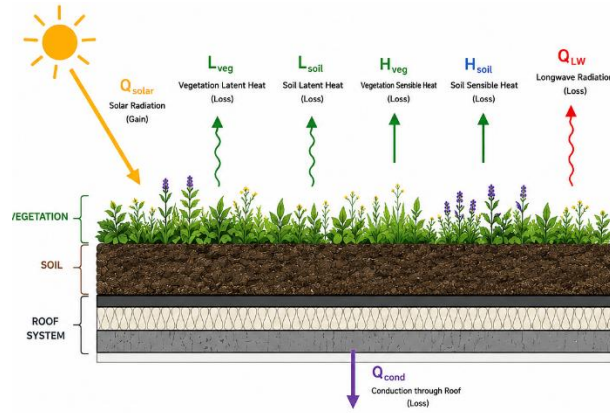
$$Q_{solar} + Q_{LW} + Q_{conv} + Q_{cond} + Q_{storage} = 0$$

This graph explains the composition of the net radiation term used in Figure 1. Solar radiation acts as the main positive heat gain, while longwave radiation is negative throughout the year, showing that the roof continuously emits thermal radiation toward the sky.

During summer, solar radiation reaches its maximum values, approximately 145–150 W/m². At the same time, longwave radiative losses also become larger, reaching approximately –90 to –95 W/m². This occurs because higher roof surface temperatures increase thermal emission. As a result, the final net radiation is much smaller than the solar input alone.

This figure is useful because it shows that the conventional roof receives a large solar load, loses part of it through longwave emission, and then dissipates the remaining energy mainly through convection and conduction. Since the bare roof has no evapotranspiration mechanism, a significant fraction of the absorbed energy contributes to roof heating and conductive heat transfer toward the building.

7.1.2 Green Roof Energy Balance



Unlike a conventional roof, a green roof dissipates a significant fraction of the absorbed solar energy through evapotranspiration. Consequently, latent heat transfer becomes the dominant energy dissipation mechanism during the warm season, reducing roof temperature and limiting conductive heat transfer into the building.

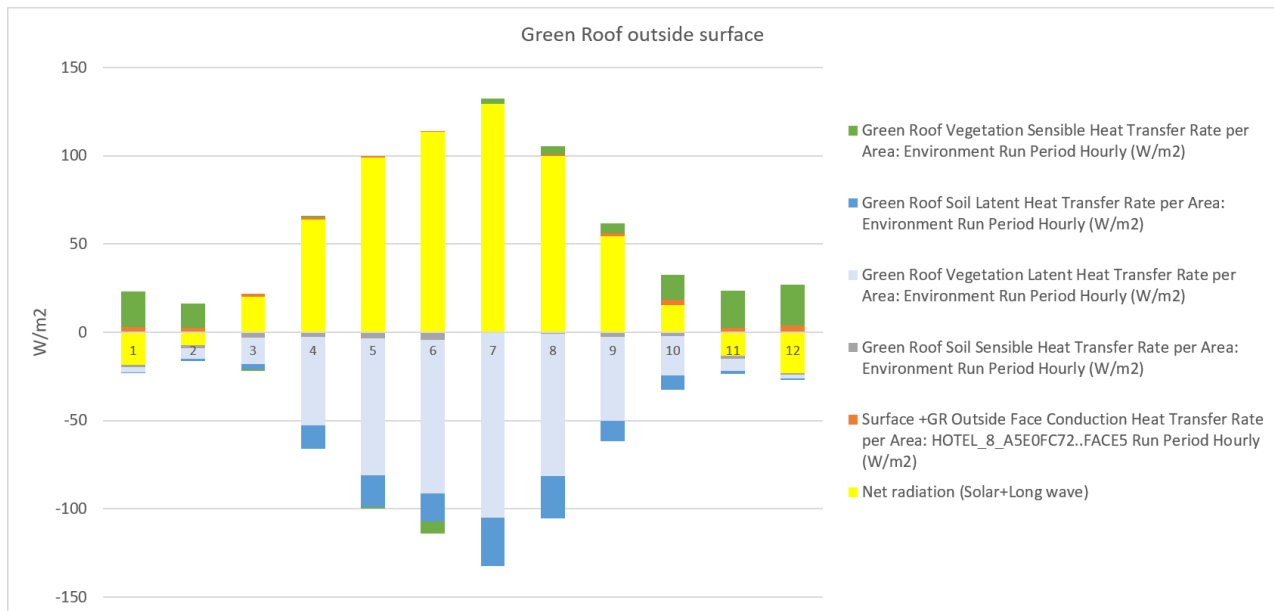


Figure 26, Monthly Energy Balance Components of the Green Roof External Surface

Figure 28 shows the monthly energy balance of the green roof external surface. The simplified green roof balance can be written as:

$$Q_{net\ rad} = Q_{sens} + Q_{latent} + Q_{cond}$$

where:

$$Q_{net\ rad} = Q_{solar} + Q_{LW}$$

$$Q_{sens} = H_{veg} + H_{soil}$$

$$Q_{latent} = L_{veg} + L_{soil}$$

Unlike the conventional roof, the green roof redistributes absorbed radiative energy among several mechanisms, including sensible heat transfer, latent heat transfer from vegetation and soil, and conductive heat transfer through the roof assembly.

The most important feature of this graph is the large latent heat flux during spring and summer. The vegetation latent heat flux and soil latent heat flux increase strongly during the warm months, especially from May to August. This indicates that a substantial portion of the absorbed radiative energy is used for evapotranspiration rather than being converted into sensible heating or conduction.

The sensible heat fluxes are smaller than the latent heat fluxes, showing that evapotranspiration is the dominant heat dissipation mechanism in the green roof system. Conductive heat transfer remains limited, even during periods of high net radiation. This confirms that much of the absorbed energy is removed from the roof system before it can penetrate into the building envelope.

Therefore, Figure 4 demonstrates the key physical difference between the two roof systems. In the bare roof, absorbed radiation is mainly balanced by convection and conduction. In the green roof, a large fraction of the absorbed energy is redirected into latent heat transfer, which reduces roof temperature and limits conductive heat transfer.

7.1.3 Conventional vs Green Roof Annual Comparison

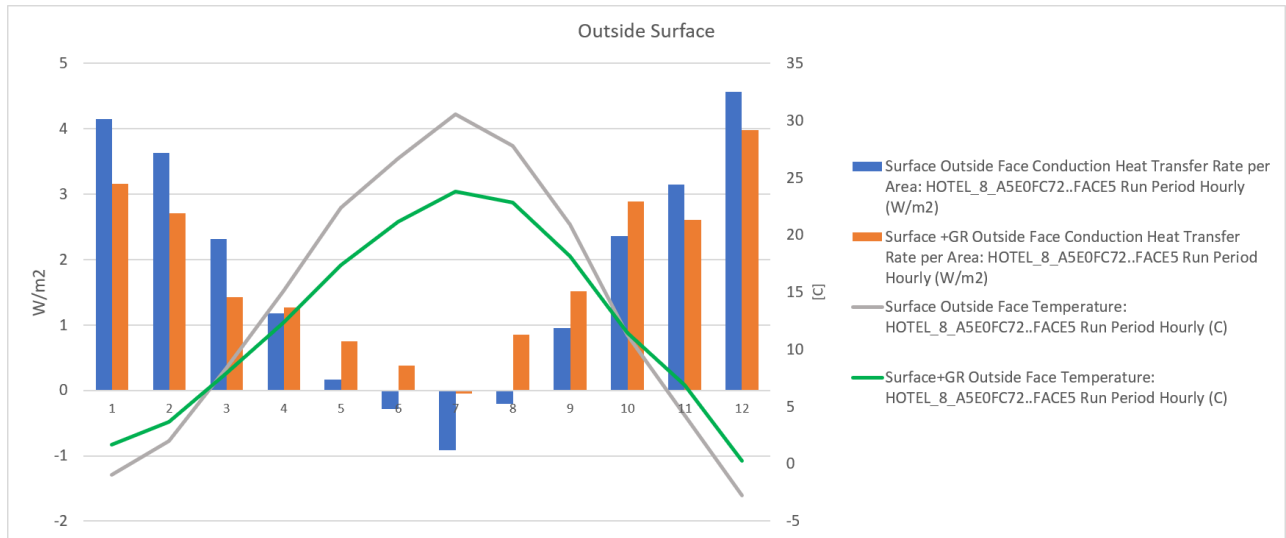


Figure 27, Comparison of External Surface Temperature and Conductive Heat Transfer for the Conventional and Green Roof Systems

Figure 29 compares the external surface temperature and conductive heat transfer of the conventional and green roof systems. The conductive heat transfer can be related to the temperature difference across the roof assembly as:

$$Q_{cond} = U(T_{out,surf} - T_{in,surf})$$

where:

- Q_{cond} = conductive heat transfer through the roof assembly (W/m²)
- U = overall thermal transmittance of the roof (W/m²·K)
- $T_{out,surf}$ = external roof surface temperature (°C)
- $T_{in,surf}$ = internal roof surface temperature (°C)

The conventional roof reaches higher external surface temperatures than the green roof throughout most of the year, with the largest difference occurring during summer. In July, the bare roof reaches approximately 30°C, while the green roof remains around 25°C. This reduction is mainly due to vegetation shading and evapotranspiration, which dissipate part of the absorbed energy before it increases the roof surface temperature.

The lower surface temperature of the green roof reduces the temperature gradient across the roof assembly:

$$\Delta T = T_{out,surf} - T_{in,surf}$$

As a result, conductive heat transfer through the roof is reduced. This effect is particularly important during summer, when the conventional roof experiences stronger heat transfer due to higher surface temperatures. In winter, the green roof also shows reduced heat losses because the soil and vegetation layers increase the effective thermal resistance of the roof system.

Overall, Figure 3 shows that the green roof improves thermal performance by controlling the external roof temperature, which directly reduces the driving force for heat conduction.

7.1.4 Indoor Thermal Impact (Conventional vs Green Roof)

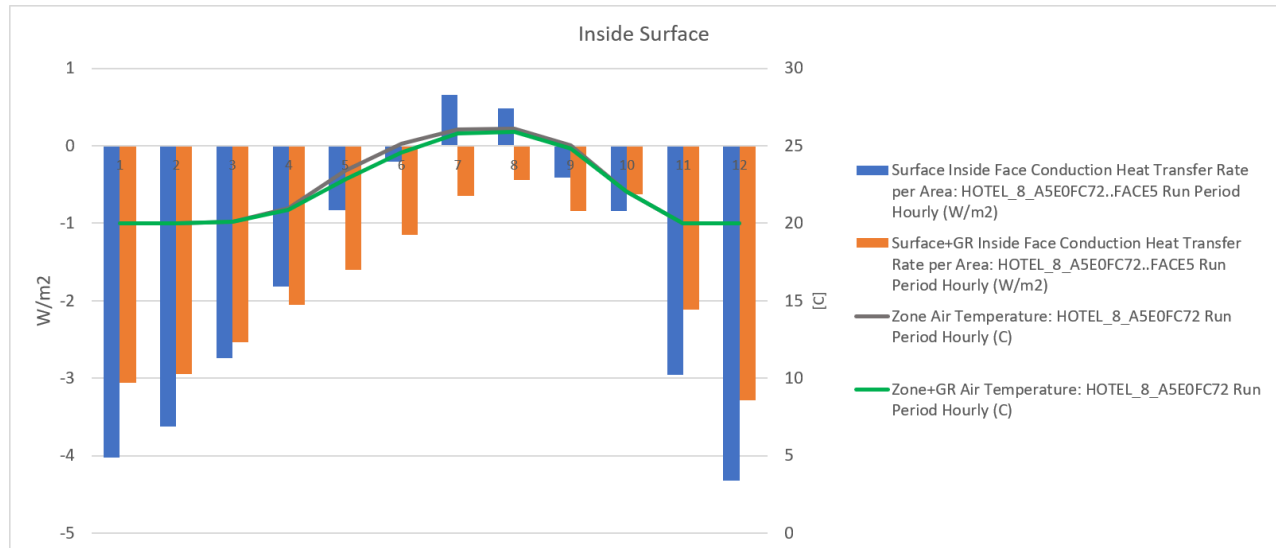


Figure 28, Comparison of Indoor Roof Heat Transfer and Indoor Air Temperature for the Conventional and Green Roof Systems

Figure 30 compares internal roof conductive heat transfer and indoor air temperature for the conventional and green roof cases. The internal conductive heat transfer can be expressed as:

$$Q_{cond,in} = U(T_{surf,in} - T_{zone})$$

where:

- $Q_{cond,in}$ = conductive heat transfer at the internal roof surface
- $T_{surf,in}$ = internal roof surface temperature
- T_{zone} = indoor air temperature

The indoor air temperatures of both cases follow a similar seasonal pattern, increasing from winter to summer and decreasing again toward winter. The difference between the two cases is relatively small because the indoor environment is moderated by the building envelope and HVAC operation. However, the green roof maintains slightly more stable indoor conditions, especially during warm months.

The internal conductive heat transfer shows a clearer difference. During winter, both roofs show negative values, indicating heat loss from the indoor space toward the colder outdoor environment. The green roof generally reduces the magnitude of this heat loss. During summer, the conductive heat transfer approaches zero or becomes slightly positive, indicating heat gain toward the indoor space. In this period, the green roof reduces conductive heat gains compared with the conventional roof.

This figure shows the final impact of the external roof energy balance on the indoor environment. The reduced internal heat transfer confirms that the green roof limits both summer heat gains and winter heat losses, improving the thermal stability of the building envelope.

7.1.5 Conventional and Green Roof Monthly HVAC Loads

To evaluate the influence of the green roof on HVAC demand, the monthly heating and cooling rates obtained from the two simulation scenarios were compared. Figure X presents the monthly variation of heating and cooling rates for both the conventional roof and green roof configurations.

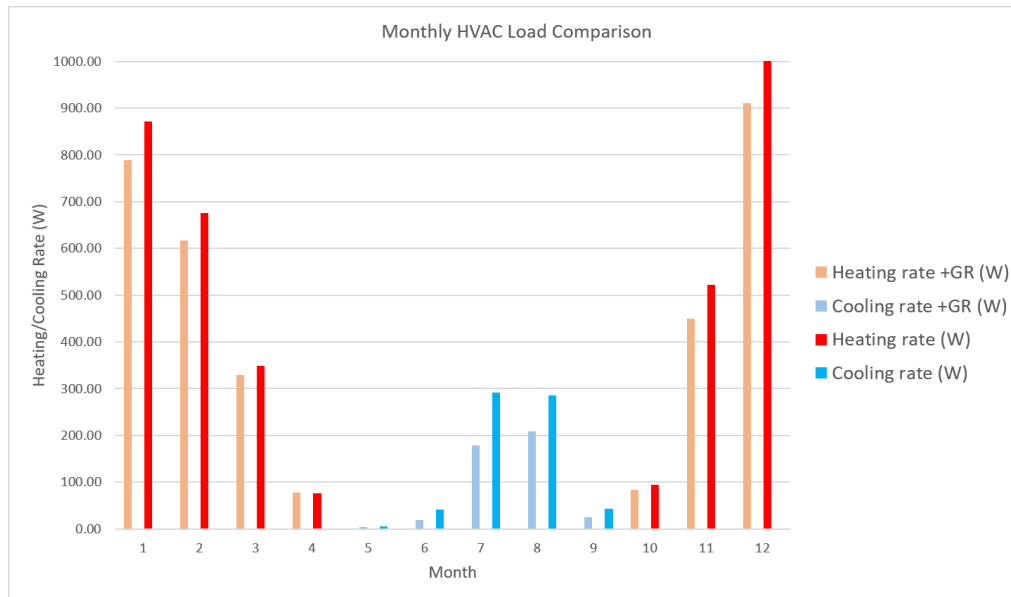


Figure 29, Monthly Heating and Cooling Rates: Green Roof vs. Conventional Roof

During the winter season (November–March), the heating demand is consistently lower in the green roof configuration compared with the conventional roof. This reduction is mainly attributed to the additional thermal resistance provided by the vegetation and substrate layers, which decrease heat losses through the roof assembly. The effect is particularly evident during the coldest months. For example, in January the required heating rate decreases from approximately 870 W to 790 W, while in December it decreases from approximately 1000 W to 910 W, corresponding to reductions of about 9–10%.

During the summer season (June–September), the green roof also significantly reduces cooling demand. The largest reductions are observed during July and August, when cooling loads reach their annual peak. In July, the cooling demand decreases from approximately 290 W for the conventional roof to 180 W for the green roof, corresponding to a reduction of approximately 38%. A similar trend is observed in August, where cooling demand decreases from approximately 285 W to 205 W. These improvements can be attributed to the combined effects of vegetation shading, thermal storage within the substrate layer, and evapotranspiration, which dissipates a substantial portion of the absorbed solar energy before it reaches the indoor environment.

The seasonal behaviour observed in the HVAC loads is consistent with the roof energy balance analysis presented in the previous sections. During summer, latent heat transfer through evapotranspiration becomes the dominant cooling mechanism, while during winter the substrate and vegetation layers primarily act as an insulating barrier that reduces conductive heat losses.

Overall, the results demonstrate that the green roof functions as a dynamic passive system, providing thermal insulation during the heating season and natural cooling during the cooling season. Consequently, the green roof improves the thermal performance of the building envelope and contributes to a reduction in HVAC energy requirements throughout the year.

7.2 Seasonal Dynamic Analysis

To evaluate the thermal performance of the green roof under different climatic conditions, two representative months were selected: July, representing peak summer conditions characterized by high solar radiation and cooling demand, and January, representing winter conditions characterized by lower solar availability and increased heating demand. The analysis was performed by examining four groups of indicators: indoor thermal behaviour, energy gain components, energy loss components, and inner surface heat transfer mechanisms. This approach allows a comprehensive understanding of how the green roof modifies heat transfer processes throughout the year and contributes to building thermal performance.

7.2.1 July Thermal Behaviour of the Green Roof

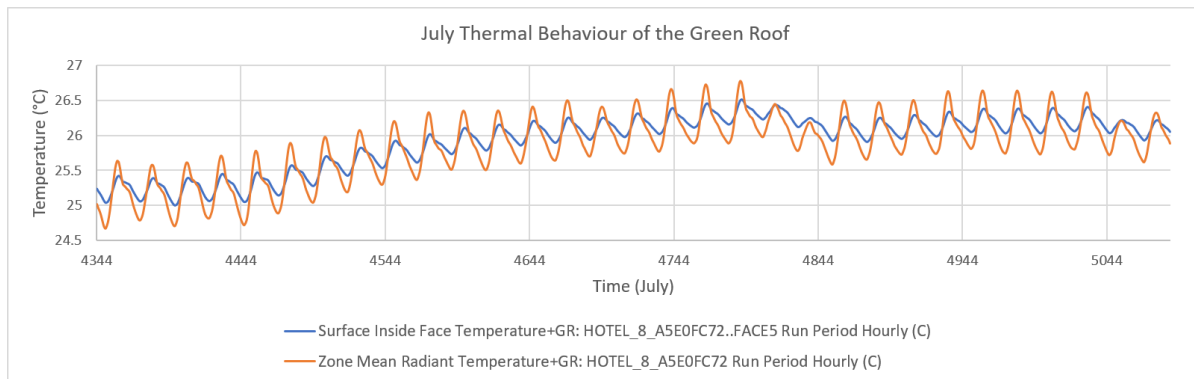


Figure 30, Hourly variation of roof inner surface temperature and zone mean radiant temperature during July under green roof conditions.

The thermal behaviour of the green roof during July was evaluated through the comparison of roof inner surface temperature and mean radiant temperature (MRT). The results show a clear daily temperature cycle driven by solar radiation and outdoor climatic conditions. Both parameters follow a similar trend throughout the month, indicating a strong relationship between the roof thermal response and the indoor radiant environment.

The roof inner surface temperature remains within a relatively narrow range despite the high summer temperatures, demonstrating the ability of the vegetation and substrate layers to attenuate external thermal fluctuations. The MRT exhibits slightly larger daily oscillations; however, it remains closely correlated with the roof surface temperature.

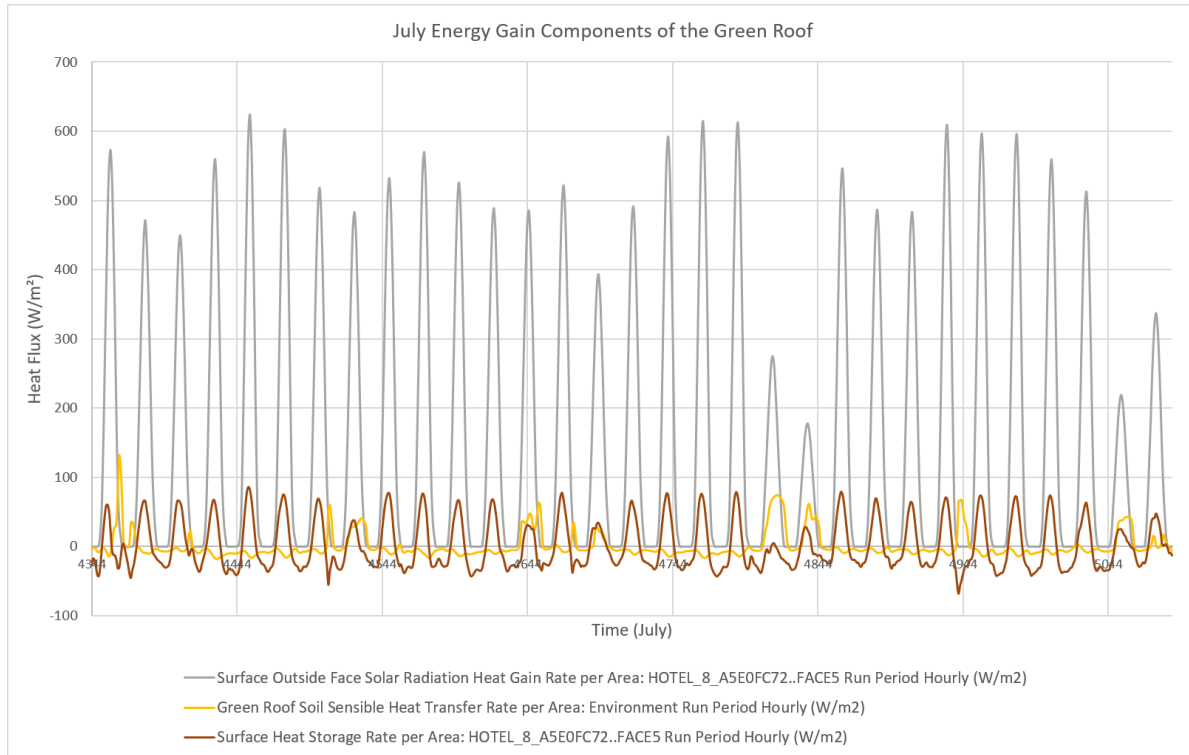


Figure 31, Hourly variation of the main energy gain mechanisms of the green roof during July

The analysis of energy gain components reveals that solar radiation is the dominant source of energy entering the roof system. Daily peaks frequently exceed 500 W/m^2 , reaching values above 600 W/m^2 during clear sky conditions. In contrast, the sensible heat transferred through the soil layer remains significantly lower. This indicates that only a fraction of the incident solar energy is converted into sensible heat within the roof assembly. The remaining energy is either stored within the roof layers, reflected, or dissipated through other heat transfer mechanisms.

The surface heat storage component exhibits a continuous alternation between positive and negative values, indicating that the roof absorbs thermal energy during daytime hours and gradually releases it during the evening and night. This behaviour highlights the thermal mass effect of the substrate layer, which contributes to delaying and attenuating heat transfer through the roof.

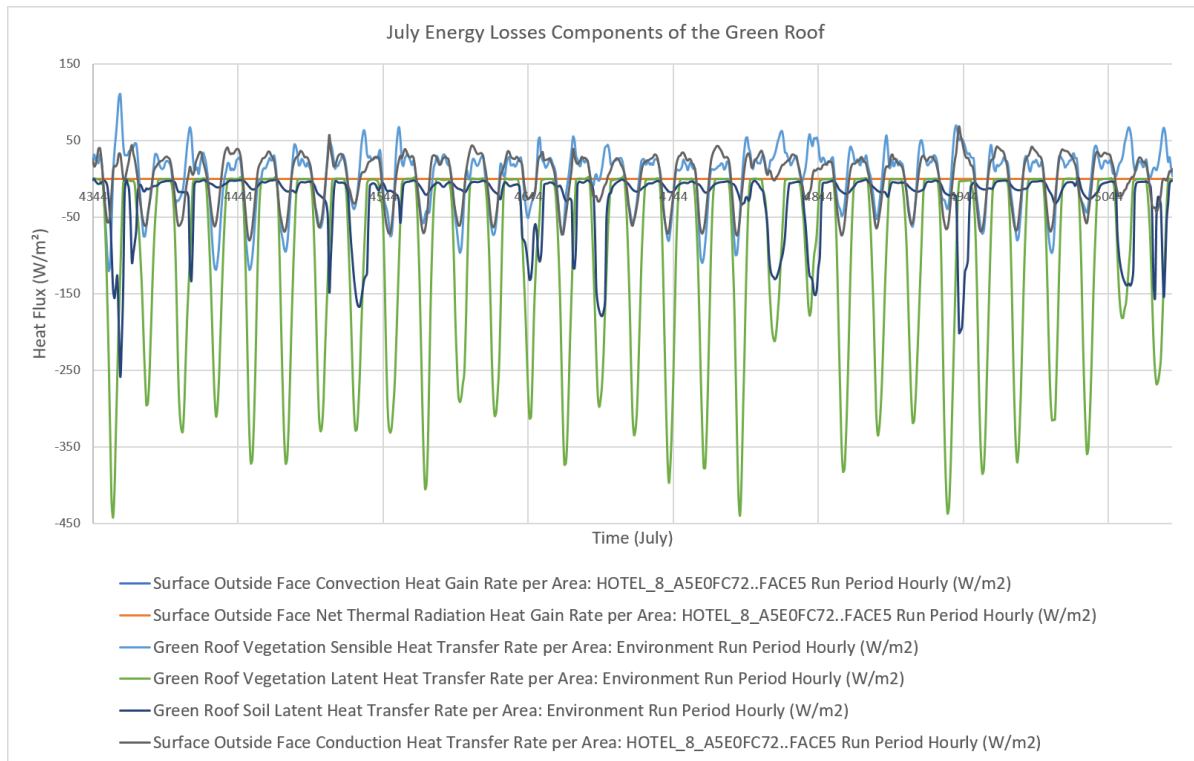


Figure 32, Hourly variation of the main energy loss mechanisms of the green roof during July

The analysis of energy losses demonstrates that vegetation latent heat transfer is the dominant cooling mechanism during summer. The magnitude of latent heat losses is substantially higher than any other heat transfer component, reaching values above 400 W/m^2 during several periods of the month. These losses are associated with evapotranspiration processes, whereby moisture evaporation from vegetation and soil removes significant amounts of thermal energy from the roof system.

Compared to latent heat transfer, convective, radiative, conductive, and soil latent heat exchanges exhibit considerably lower magnitudes. This confirms that evapotranspiration represents the primary mechanism responsible for reducing roof temperatures and mitigating summer heat gains.

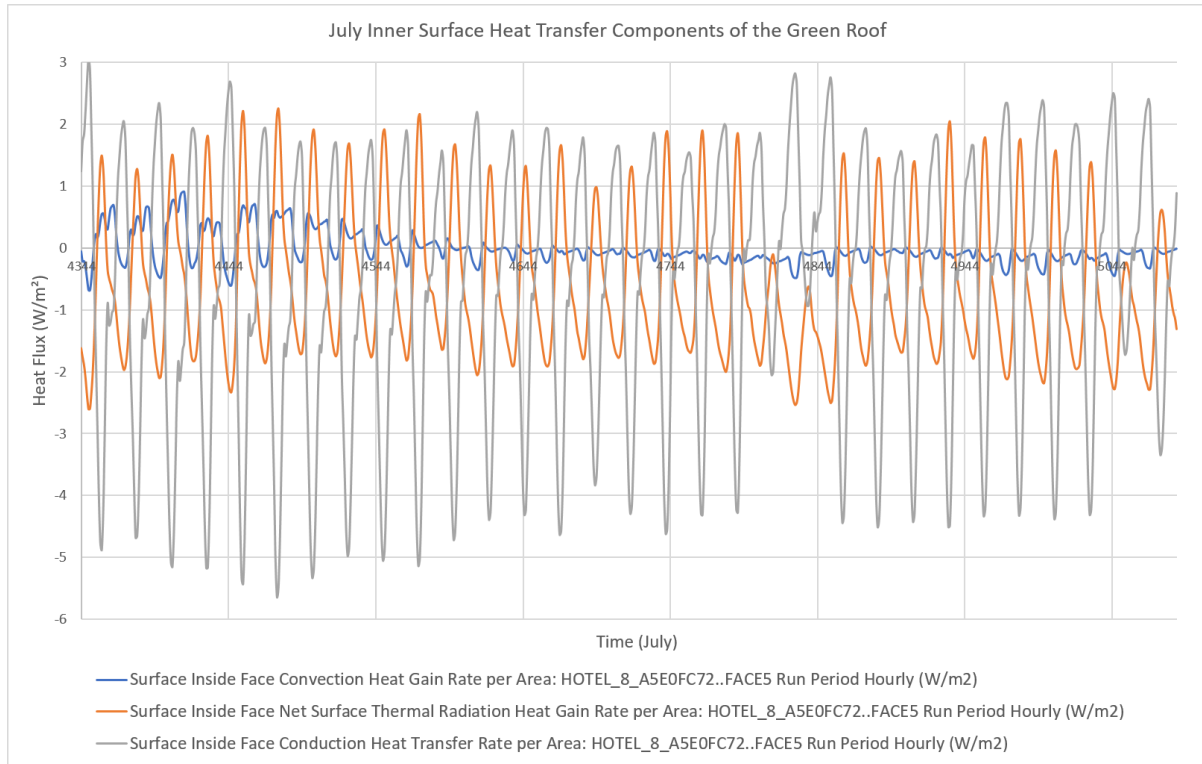


Figure 33, Hourly variation of convection, net thermal radiation, and conduction heat transfer rates at the inner roof surface under green roof conditions during July.

The inner surface heat transfer analysis further demonstrates the effectiveness of the green roof. The conductive heat flux reaching the indoor side of the roof remains relatively small throughout the month, generally below 5 W/m² in magnitude. Similarly, convective and radiative exchanges at the inner surface remain limited. These results indicate that most of the external thermal load is attenuated before reaching the occupied space, contributing to improved indoor thermal stability and reduced cooling demand.

7.2.2 January Thermal Behaviour of the Green Roof

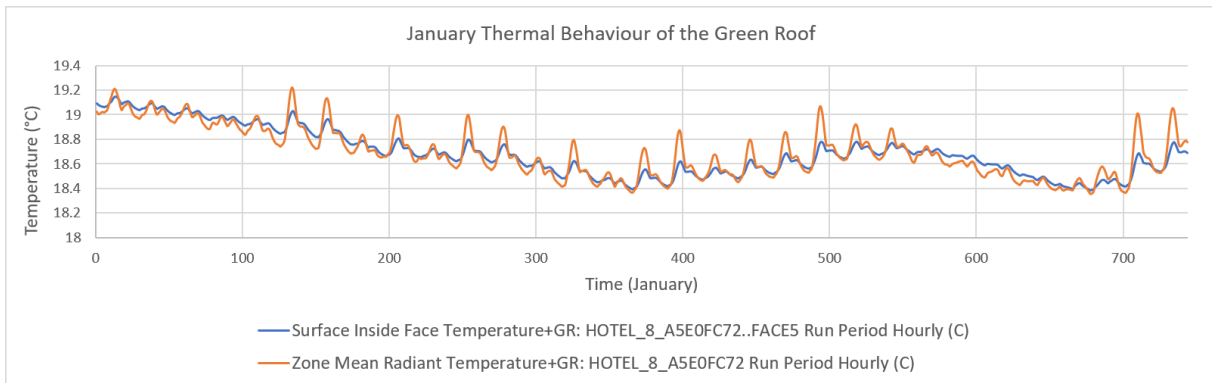


Figure 34, Hourly variation of roof inner surface temperature and zone mean radiant temperature during January under green roof conditions.

The thermal response of the green roof during January differs significantly from the summer behaviour. Both roof inner surface temperature and mean radiant temperature remain remarkably stable throughout the month, with fluctuations limited to approximately one degree Celsius. The close overlap between the two curves indicates a highly stable indoor thermal environment and a reduced influence of outdoor climatic variations.

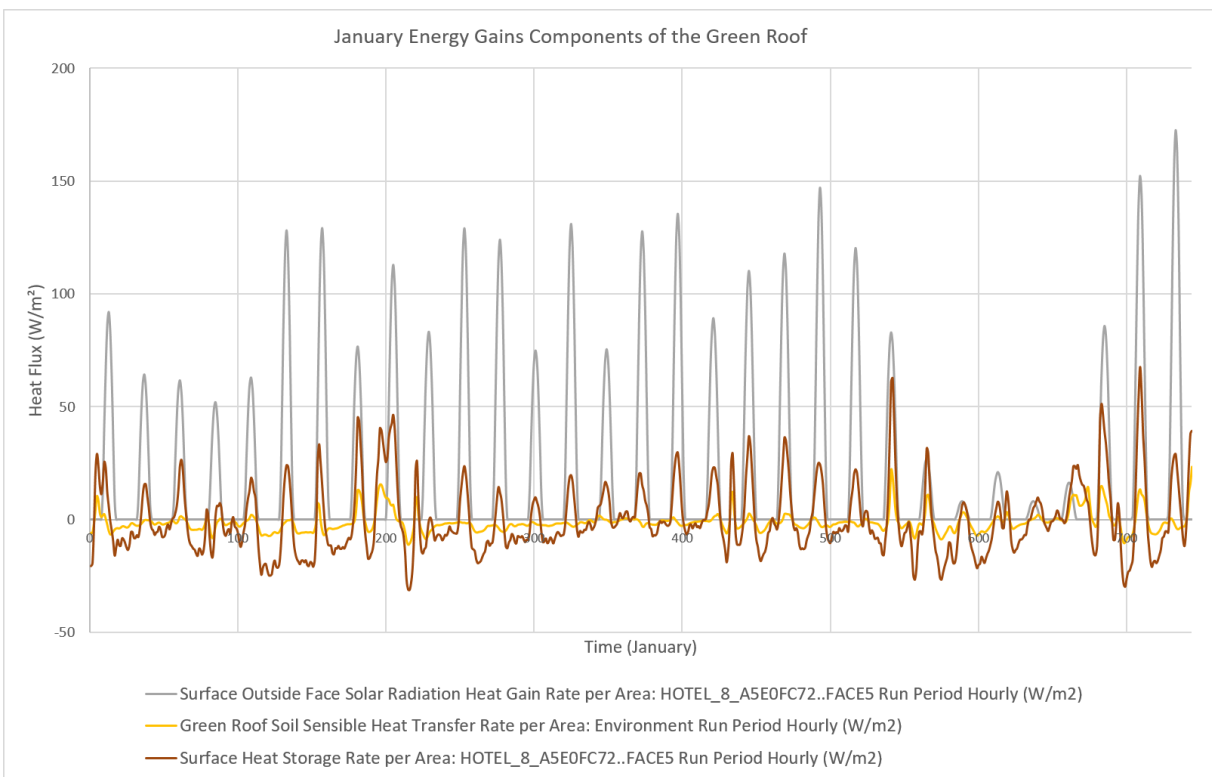


Figure 35, Hourly variation of the main energy gain mechanisms of the green roof during January

The winter energy gain analysis shows that solar radiation remains the main source of heat entering the roof system. However, the magnitude of solar gains is substantially lower than during July, reflecting the reduced solar altitude and shorter daylight hours characteristic of winter conditions. Peak solar radiation values generally remain below 180 W/m^2 , considerably lower than the summer peaks exceeding 600 W/m^2 .

The sensible heat transfer through the soil layer remains relatively small, while surface heat storage fluctuations are less pronounced than in summer. This behaviour indicates a reduced accumulation of thermal energy within the roof layers due to the lower availability of solar radiation.

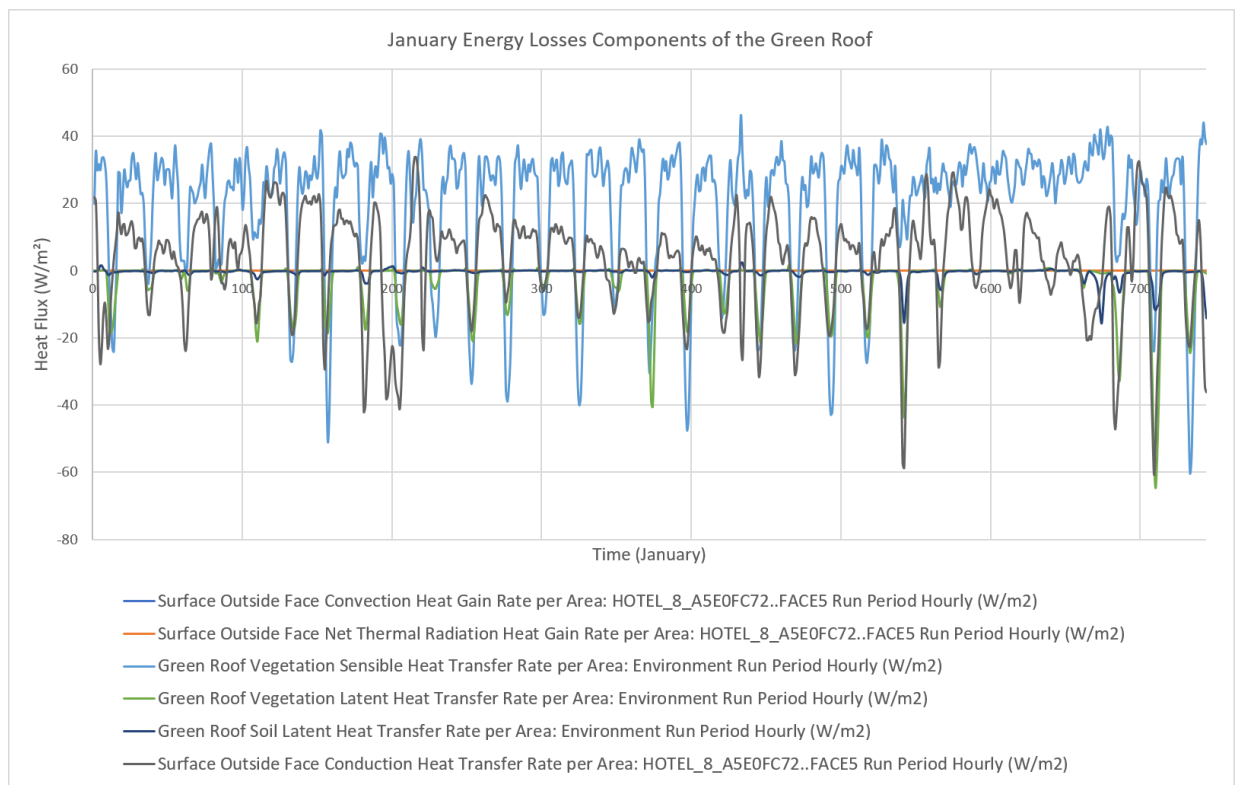


Figure 36, Hourly variation of the main energy loss mechanisms of the green roof during January

The energy loss analysis reveals a substantial reduction in latent heat transfer. Vegetation and soil latent heat losses are significantly smaller than those observed during July, reflecting the reduced evapotranspiration activity associated with lower temperatures and lower solar intensity. Consequently, convective and conductive heat transfer mechanisms become relatively more significant during winter conditions.



Figure 37, Hourly variation of convection, net thermal radiation, and conduction heat transfer rates at the inner roof surface under green roof conditions during January

The analysis of inner surface heat transfer shows that conductive heat transfer remains the dominant mechanism affecting the indoor side of the roof. Nevertheless, its magnitude remains relatively low, indicating that the green roof continues to provide an effective thermal barrier. The combined effect of vegetation and substrate layers contributes to reducing heat losses through the roof assembly and maintaining more stable indoor conditions during the heating season.

7.2.3 Seasonal Comparison: July vs January

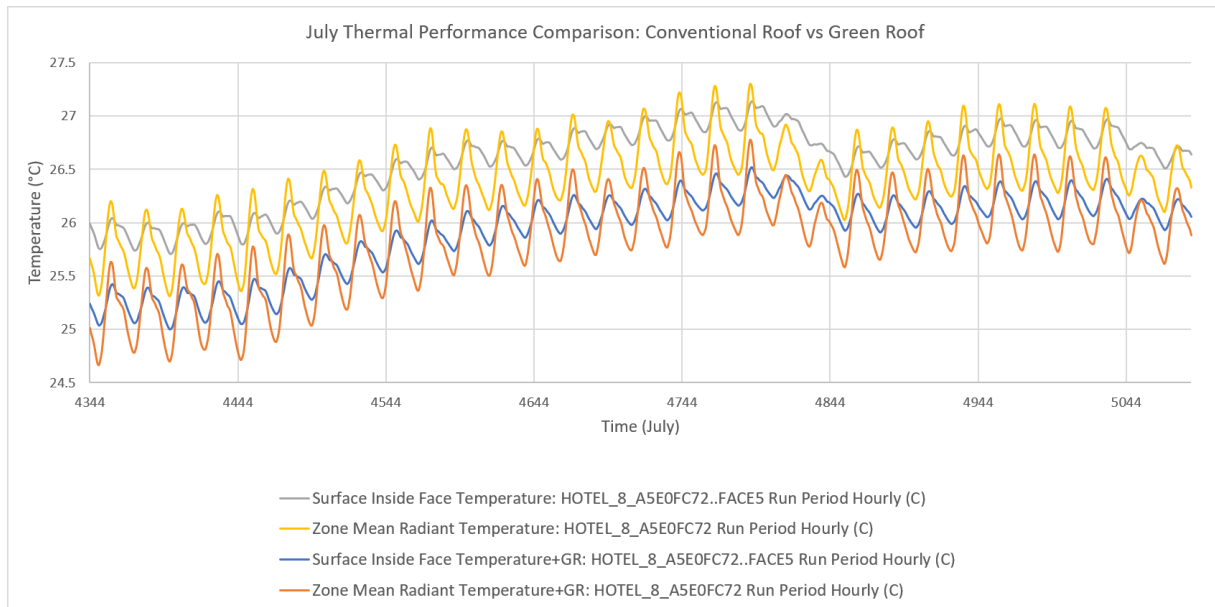


Figure 38, Hourly comparison of roof inner surface temperature and zone mean radiant temperature (MRT) between the conventional roof and green roof during July

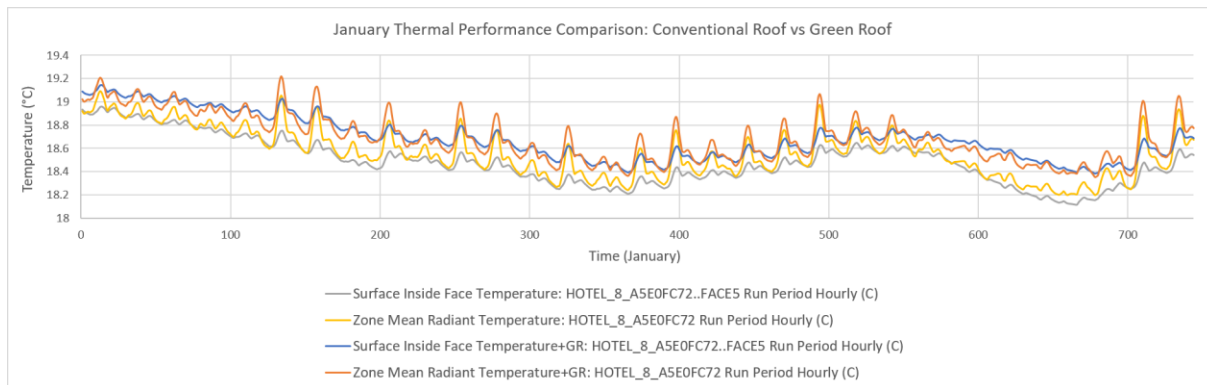


Figure 39, Hourly comparison of roof inner surface temperature and mean radiant temperature (MRT) between the conventional roof and green roof during January

The comparison between July and January clearly demonstrates the seasonal adaptability of the green roof system. During summer, the roof primarily functions as a cooling system. High levels of solar radiation are intercepted by the vegetation layer, while evapotranspiration removes substantial amounts of thermal energy from the roof. As a result, heat transfer toward the indoor environment is significantly reduced, limiting overheating and improving thermal comfort.

During winter, the role of the green roof changes. Evapotranspiration becomes less important due to reduced vegetation activity and lower temperatures. Instead, the substrate and vegetation layers act predominantly as additional insulation, reducing heat losses through the roof and contributing to more stable indoor temperatures.

The results therefore demonstrate that the green roof provides benefits throughout the entire year. In summer, it reduces cooling loads through shading, thermal storage, and evapotranspirative cooling. In winter, it limits heat losses and improves the thermal resistance of the roof assembly. This dual seasonal behaviour highlights the effectiveness of green roofs as passive building technologies capable of enhancing both energy performance and indoor environmental quality under varying climatic conditions.

7.3 Overall Discussion

The main advantage of the green roof is not simply a reduction in incoming solar radiation. Instead, its benefit arises from the redistribution of absorbed energy within the vegetation–substrate system. For the conventional roof, the dominant energy pathway can be summarized as:

Solar Radiation → Sensible Heating → Conduction

The bare roof absorbs solar radiation, its surface temperature increases, and a significant portion of the absorbed energy is transferred through the roof assembly by conduction. As a result, higher roof surface temperatures and larger conductive heat transfer rates are observed, particularly during the summer season.

In contrast, the dominant energy pathway of the green roof becomes:

Solar Radiation → Evapotranspiration → Latent Heat Loss → Reduced Conduction

In this case, a substantial fraction of the absorbed solar energy is consumed by soil evaporation and plant transpiration. This latent heat transfer removes energy from the roof system before it can significantly increase roof surface temperature or enter the building through conduction. Consequently, the green roof modifies the roof energy balance and reduces the amount of heat reaching the indoor environment.

The results presented in this chapter demonstrate that the green roof modifies the thermal behaviour of the roof system through several interacting mechanisms. Compared with the conventional bare roof, the vegetated roof introduces additional pathways for energy redistribution, including vegetation shading, substrate thermal storage, sensible heat exchange, and latent heat transfer through evapotranspiration.

The annual energy balance analysis shows that the conventional roof is mainly governed by radiative gains, convection, and conduction. Solar radiation represents the dominant heat input, particularly during the summer months. Since the conventional roof does not include vegetation or soil layers, a significant portion of the absorbed energy is transferred through the roof assembly or dissipated through surface convection and longwave radiation. As a result, the bare roof reaches higher external surface temperatures and produces stronger conductive heat transfer toward the indoor environment.

In contrast, the green roof redistributes absorbed solar energy through a more complex energy balance. The most important difference is the presence of latent heat transfer from vegetation and soil. During spring and summer, evapotranspiration becomes the dominant heat dissipation mechanism, allowing a large fraction of absorbed energy to be removed from the roof system before it reaches the building envelope. This explains why the green roof maintains lower external surface temperatures and reduces conductive heat transfer during warm periods.

The detailed July analysis confirms the effectiveness of the green roof under summer conditions. Although solar radiation reaches high values, the inner roof surface temperature and mean radiant temperature remain relatively stable. The vegetation latent heat flux is considerably larger than the other loss components, confirming that evapotranspiration is the primary cooling mechanism of the green roof during the summer period. At the inner surface, heat fluxes remain limited, showing that most of the external thermal load is attenuated before reaching the occupied space. These effects are also reflected in the HVAC results, where cooling demand is significantly reduced during the warmest months of the year.

The January analysis reveals a different seasonal behaviour. During winter, solar gains are much lower and evapotranspiration is significantly reduced. Under these conditions, the green roof acts mainly as an additional insulating layer. The substrate and vegetation layers reduce heat losses through the roof and help maintain more stable indoor surface and radiant temperatures. Consequently, heating demand is lower than that of the conventional roof, demonstrating that the green roof provides benefits not only in summer but also during the heating season.

The comparison between the conventional roof and the green roof further confirms these findings. In July, the green roof results in lower roof inner surface temperatures and lower mean radiant temperatures, indicating reduced heat transfer into the room and improved indoor thermal comfort. In January, the green roof maintains slightly higher internal surface and radiant temperatures, suggesting reduced heat losses and improved thermal resistance. The green roof therefore acts as an effective thermal buffer between the outdoor environment and the conditioned indoor space.

The HVAC load comparison supports the thermal analysis. During winter, the additional thermal resistance provided by the vegetation and substrate layers reduces heat losses and lowers heating demand. During summer, shading, thermal storage, and evapotranspiration reduce heat gains and consequently decrease cooling demand. The combined effect of these mechanisms improves the overall thermal performance of the building envelope and reduces HVAC energy requirements throughout the year.

Overall, the results demonstrate that the green roof functions as a dynamic passive system with a dual seasonal behaviour. During summer it acts primarily as a natural cooling mechanism through evapotranspiration and solar attenuation, while during winter it behaves mainly as an insulating layer that reduces heat losses. Therefore, the green roof enhances indoor thermal stability, improves roof thermal performance, and contributes to a reduction in annual HVAC energy demand.

7.4 Key Findings

The main findings of this study can be summarized as follows:

- The conventional roof energy balance is primarily governed by solar radiation, longwave radiation, convection, and conduction, with no latent heat dissipation mechanism.
- The green roof introduces additional energy redistribution pathways, particularly through vegetation and soil evapotranspiration, thermal storage within the substrate layer, and sensible heat exchange.
- During summer conditions, evapotranspiration becomes the dominant heat dissipation mechanism, removing a significant portion of the absorbed solar energy before it can be transferred into the building.
- The green roof maintains lower roof inner surface temperatures and lower mean radiant temperatures (MRT) during July compared with the conventional roof, resulting in improved indoor thermal comfort.
- During winter conditions, evapotranspiration becomes less significant and the vegetation–substrate system primarily acts as an additional insulating layer.
- The green roof reduces conductive heat transfer and heat losses through the roof assembly by increasing the effective thermal resistance of the building envelope.
- Inner surface heat fluxes remain relatively low under green roof conditions, indicating that a large portion of the external thermal load is attenuated before reaching the occupied space.
- The comparison between the conventional roof and the green roof demonstrates improved indoor thermal stability in both summer and winter conditions.
- Monthly HVAC results show that the green roof reduces cooling demand during warm months and heating demand during cold months, confirming its contribution to improved building energy performance.
- Overall, the green roof functions as a dynamic passive technology, acting primarily as a natural cooling mechanism during summer and as an insulating layer during winter, thereby enhancing thermal performance and reducing annual HVAC energy requirements.

8 Conclusions

8.1 Conclusions

This thesis investigated the thermal and energy performance of a green roof system applied to a hotel room located in Northern Italy through dynamic simulation using OpenStudio and the EnergyPlus simulation engine. A comparative analysis was conducted between a conventional roof configuration and a vegetated roof system in order to evaluate their influence on roof heat transfer, indoor thermal conditions, HVAC loads, and overall building energy performance.

The results demonstrate that the thermal behaviour of the conventional roof is primarily governed by solar radiation absorption, sensible heating, convection, and conductive heat transfer. During summer periods, increased solar radiation leads to higher roof surface temperatures and greater conductive heat transfer through the roof assembly. Since no latent heat dissipation mechanism exists in the conventional roof, a significant portion of the absorbed energy contributes directly to roof heating and cooling demand.

In contrast, the green roof introduces additional thermal processes, including vegetation shading, soil heat storage, and evapotranspiration. The energy balance analysis revealed that latent heat transfer becomes the dominant energy dissipation mechanism during warm periods. Soil evaporation and plant transpiration consume a substantial fraction of the absorbed radiative energy, thereby reducing the energy available for sensible heating and conductive heat transfer through the roof system.

The main findings of the study can be summarized as follows:

- The green roof reduces external roof surface temperatures, particularly during summer conditions.
- Evapotranspiration acts as the primary mechanism for dissipating absorbed solar energy during warm periods.
- Conductive heat transfer through the roof assembly is significantly reduced compared with the conventional roof.
- Summer heat gains transmitted toward the indoor environment are limited.
- Winter heat losses are also reduced due to the additional thermal resistance provided by the vegetation and substrate layers.
- Indoor thermal conditions become more stable throughout the year.
- The overall thermal performance of the building envelope is improved.

The comparison between the conventional and vegetated roof systems confirms that the primary benefit of the green roof arises from its ability to redistribute absorbed solar energy through evapotranspiration and thermal storage processes, thereby reducing conductive heat transfer and improving the thermal buffering capacity of the roof assembly.

Overall, the findings demonstrate that vegetated roofs can serve as an effective passive strategy for improving building thermal performance and reducing heat transfer through the roof assembly under Northern Italian climatic conditions. The study highlights the importance of considering roof-scale energy balance mechanisms when evaluating green roof performance and confirms the potential of vegetated roof systems to contribute to more energy-efficient and thermally resilient buildings.

Future research could investigate different vegetation types, substrate depths, irrigation strategies, and climatic conditions in order to further optimize green roof performance and assess their long-term impact on building energy consumption and indoor environmental quality.

8.2 Contribution of the Thesis

The main contribution of this thesis is the detailed simulation-based investigation of green roof energy balance mechanisms in a hotel building context under Northern Italian climatic conditions. Unlike many previous studies that focus primarily on overall energy savings, this research combines annual energy performance assessment with a detailed evaluation of radiation exchange, convection, conduction, thermal storage, and evapotranspiration processes within the roof system.

The study also highlights the importance of the EnergyPlus EcoRoof model for analyzing the interaction between vegetation, soil, climate, and building energy performance. By examining both annual results and representative seasonal periods, the thesis provides a clearer understanding of how green roofs behave differently in summer and winter conditions.

Another contribution of the work is the application of green roof analysis to a hotel building context. Hotel rooms are characterized by continuous comfort requirements, internal gains, ventilation needs, and HVAC operation, making them a relevant case for evaluating passive energy-saving strategies. The results show that green roofs can support energy-efficient design by reducing thermal loads and improving the thermal stability of the building envelope.

8.3 Limitations of the Study

Although the simulation results demonstrate the potential benefits of the green roof system, some limitations should be acknowledged. First, the analysis focused on a representative hotel room rather than the complete hotel building energy performance. Therefore, the results mainly describe the behavior of the selected zone and its interaction with the roof assembly.

Second, the study focused on thermal and energy performance. Structural, hydrological, ecological, maintenance, and economic aspects of green roof systems were not included. As a result, the conclusions are limited to building energy behavior and do not provide a complete life-cycle or cost-benefit assessment.

Third, the green roof parameters, including vegetation properties, soil characteristics, and moisture conditions, were assumed based on the simulation inputs. In real applications, these parameters may vary over time due to seasonal vegetation growth, rainfall, irrigation, substrate aging, and maintenance conditions. These variations can influence evapotranspiration, thermal conductivity, and overall green roof performance.

Finally, the results depend on the selected climate file, building envelope characteristics, HVAC configuration, and operational schedules. Different climates, roof insulation levels, vegetation types, and control strategies may lead to different performance outcomes.

8.4 Future Research and Design Opportunities

Future research could extend this work by investigating different vegetation types, substrate depths, soil moisture levels, and irrigation strategies. These parameters strongly influence evapotranspiration, thermal storage, and conductive heat transfer, and their optimization could improve the energy performance of green roof systems.

Further studies could also compare the performance of green roofs under different Italian climatic zones, including colder alpine climates, humid temperate regions, and warmer Mediterranean locations. This would allow a broader assessment of the climate-dependent effectiveness of vegetated roof systems.

Another possible development would be to apply the analysis to the entire hotel building rather than a single representative room. This would provide a more complete understanding of the impact of green roof implementation on total annual heating and cooling energy consumption.

Future work could also include economic analysis, life-cycle assessment, embodied carbon evaluation, stormwater retention performance, and maintenance requirements. These aspects would allow a more comprehensive evaluation of green roofs as multifunctional sustainable building technologies.

Finally, the simulation results could be validated through experimental monitoring of a real green roof installation. Measured data on roof surface temperature, substrate moisture, heat flux, indoor temperature, and HVAC energy use would improve model reliability and support more accurate design recommendations.

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