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Simulation-Based Study on the Effect of Green Roofs on Summer Energy Performance in Melbourne

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Abstract: Green roofs are increasingly recognised as a crucial urban solution, addressing climate change, enhancing energy efficiency, and promoting sustainable architecture in densely populated areas. In this manuscript, the research study delves into the influence of green roofs on energy consumption, focusing on the Treasury Place building in Melbourne, Australia. The utilisation of DesignBuilder and EnergyPlus simulations was explored. Various green roof parameters such as the Leaf Area Index (LAI), plant height, soil moisture, and tree coverage were optimised and compared against base case scenarios. The key findings indicate an optimal LAI of 1.08 for maximum energy savings, with diminishing returns beyond an LAI of 2.5. The soil moisture content was most effective, around 50%, while a plant height of approximately 0.33 m optimised energy reduction. The introduction of 50% canopy tree coverage provided temperature regulation, but increased soil moisture due to trees and their influence on wind flow had an adverse energy impact. These results emphasise the necessity for precise green roof representation and parameter optimisation for maximum energy efficiency. This research offers essential insights for those in urban planning and building design, endorsing green roofs as a pivotal solution for sustainable urban environments.

Keywords: energy performance; EnergyPlus; green roof; Leaf Area Index; urban planning

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1. Introduction

As of 2007, more than half of the global population has become urbanised [1], and this trend is projected to continue, with an estimated 66% [2] of the world's population living in urban areas by 2050 [3]. Such urbanisation poses challenges to public health, as it exacerbates local warming phenomena, including the Urban Heat Island (UHI) effect [4]. This UHI effect amplifies the demand for cooling energy [5,6] and contributes to greenhouse gas (GHG) emissions that further fuel climate change. The UHI effect is the localised increase in temperatures within urban areas compared to their surrounding rural regions. This temperature disparity arises from a combination of factors, including the absorption and retention of heat by buildings and pavements, reduced vegetation cover, and higher energy consumption, creating a microclimate characterised by elevated temperatures. The building sector currently accounts for nearly 120 EJ of global energy usage and approximately 30% of global carbon dioxide (CO_2) emissions [7]. In the European Union (EU28), despite a modest 3.2% decrease in household energy use between 1990 and 2013, significant improvements in the building sector remain crucial to reducing energy consumption and contributing to climate stabilisation [7].

In recent years, nature-based solutions have gained recognition as effective strategies to mitigate the adverse impacts of urbanisation on both the climate and urban dwellers' well-being [8,9]. Green roofs have garnered considerable attention among the various solutions, especially in highly urbanised areas [10,11]. Green roofs offer diverse advantages, acting as natural insulators that mitigate the Urban Heat Island effect by absorbing and dissipating heat, reducing energy consumption in buildings by providing thermal insulation, and improving indoor air quality through the filtration of airborne pollutants and the release of oxygen. With building roofs covering approximately 32% of the horizontal surfaces in urban environments [12], they present an excellent opportunity for retrofitting. Moreover, green roofs offer a range of benefits, including mitigating the UHI effect, reducing energy consumption, and improving indoor air quality [13–16]. The "Green Our Rooftop, Treasury Place" project aligns with the objectives of the City of Melbourne's Green Our City Strategic Action Plan. After careful consideration, the Treasury Place in Melbourne was chosen for the implementation of the green roof. This decision followed an extensive process, including public expression of interest and a thorough site search to find the most suitable location. The Treasury Place is a high-profile site, providing maximum exposure to promote the project and its benefits. It is also well-suited to complement the project's core objectives, including sharing information to inspire others to adopt green roofs. The proposed design for the intensive green roof is innovative and unique, representing the concept of a "Garden of Victorian Landscapes". The design incorporates a novel approach, utilising "topography" and "bioregion" concepts by employing a pixelisation approach and grid morphing algorithm to replicate the topography and bioregions of Victorian regions. In addition, this research serves to utilise the research-by-design method to complement the design process by investigating one of the most essential green roof benefits: their impact on energy performance.

The energy performance of a green roof is influenced by various factors, with the design settings playing a crucial role. Therefore, this study aims to achieve two main objectives: firstly, to quantify the energy-saving benefits of implementing the green roof on the Treasury building on an extremely hot summer day, and secondly, to examine the most optimum design settings for the green roof to maximise the energy performance. Based on the following literature review, the Leaf Area Index (LAI), plant height, soil moisture, and tree coverage were considered essential variables in the design of the green roof.

This study also aims to contribute valuable insights that can further promote the adoption of green roofs as nature-based solutions to tackle the energy challenge in urban areas. The findings of this study will help optimise green roof designs for the optimum level of energy efficiency in urban centre areas.

2. Literature Review

Green roofs offer several benefits depending on the plants and soil used. They are commonly categorised into two main types: intensive and extensive green roofs. Intensive green roofs feature a wide variety of vegetation, including trees and diverse plant species, requiring a minimum soil depth of 12.8 cm [17]. In contrast, extensive green roofs consist of low-growing vegetation like sedum, with a maximum soil depth of 12.8 cm, making them lighter and more suitable for retrofitting existing buildings or constructing green roofs on structures with limited load-bearing capacity [17]. While extensive green roofs may not exhibit the same visual diversity as intensive ones, they offer excellent environmental benefits, with reduced maintenance requirements. It is worth noting that different studies adopt alternative soil depth thresholds when classifying green roofs. Some studies consider a soil depth of 15 cm [18,19], while others use 20 cm [20,21]. These variations in classification can lead to different design approaches and outcomes in green roof construction.

Both intensive and extensive green roofs consist of multiple layers to ensure their functionality and longevity, as illustrated in Figure 1. These layers typically include a waterproofing membrane to prevent water leakage, followed by a root barrier to protect the building structure, a drainage layer to manage excess water, and a filter fabric to prevent soil from clogging the drainage system. The soil layer, with its specific depth, allows for the growth of vegetation, and finally, the vegetation layer completes the green roof ecosystem [22]. Semi-intensive green roofs represent a hybrid approach, combining some features of both intensive and extensive green roofs [23]. They typically feature a diverse mix of plant species, including some taller vegetation, while maintaining a soil depth that falls between that of intensive and extensive roofs. This intermediate approach offers a balance between visual diversity and environmental benefits, providing a unique solution for specific urban contexts [24,25].

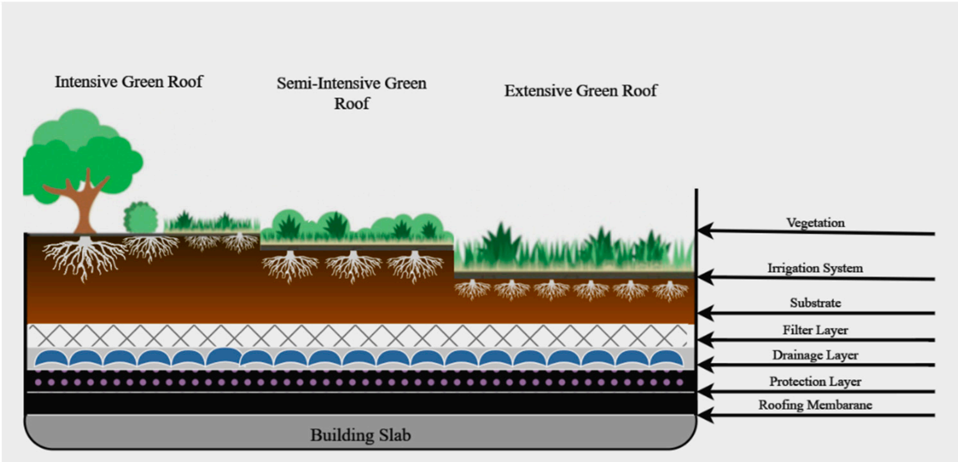


Figure 1. Green roof layers adapted from [22,23].

2.1. Green Roofs and Energy Efficiency

Green roofs play an important role in reducing the energy consumption in buildings. The vegetation and substrate act as excellent insulators by lowering the cooling electric load of buildings and minimising indoor and outdoor temperatures during hot weather [21,26]. Evapotranspiration (ET), the process by which plants release water vapour into the atmosphere, further contributes to cooling the surrounding air and mitigating the UHI effect. Additionally, the type of vegetation and the thickness of the substrate can influence the thermal performance of green roofs. Variations in the LAI and Leaf Area Density (LAD) among different plant species contribute to variations in the cooling capacity of green roofs [27]. As green roofs continue to gain popularity for their environmental and aesthetic benefits, policymakers and legislators must carefully consider design settings when formulating green roof policies. The choice between intensive and extensive green roofs and the specific soil depth requirements should be tailored to suit the plant selection, local climate, building infrastructure, and environmental targets. Effective incorporation of green roof design into urban planning can maximize the potential of these eco-friendly installations, creating greener, more sustainable urban environments [28].

Green roof design relies on two crucial components: the characteristics of the plants, such as LAI and plant height; and the metrics that define the quality of the soil layer, like the type of substrate, soil moisture, etc. LAI is a non-dimensional quantity representing the ratio of the total one-sided leaf area to one unit of ground soil surface area, determined by the vegetation canopy [29]. This parameter is pivotal in the energy performance of green roofs, particularly concerning evaporation rates [30]. Different LAI values lead to diverse temperature profiles and heat flux characteristics [31], influencing the water storage capacity and heat transfer processes [32]. It is important to note that the LAI value can significantly vary over time for different vegetation types due to various factors, such as vegetation species, growth stage, temperature, soil moisture content, humidity, radiation, and soil constituents [33–35]. Therefore, understanding these variations is critical for optimising green roof designs and unlocking their maximum energy-saving potential. Thus, when planning and implementing green roof projects, careful consideration of plant characteristics and the soil layer is essential to effectively harness their environmental benefits.

The issue of water scarcity within the Australian landscape particularly relates to the challenges posed by climate change. Australia, being a continent characterised by climatic extremes, grapples with considerable variability in water resources across its regions. Notably, in the southern temperate zone, where both rural and urban populations, as well as irrigated agriculture, are concentrated, water scarcity is a pressing concern. Australia's storage capacity, approximately 5000 cubic meters (5 mL) per person, ranks among the highest in the world. However, this substantial storage capacity is of paramount importance due to the highly variable water resources and the wide range of climatic conditions experienced in the region. In recent years, the southern part of Australia has faced declining rainfall patterns, a trend attributed to changes in regional climate systems [36]. This decline in rainfall has been particularly evident over the past three decades, with a prolonged drought period extending from 1997 to 2010. It is worth noting that climate change is believed to have exacerbated these drought conditions, leading to reductions in annual irrigation water allocations [37].

Numerous studies have explored the impact of constant LAI values in various green roof simulations [38,39]. For instance, Refahi and Talkhabi conducted research estimating energy savings achieved using a green roof with a constant LAI value in different climatic conditions. They found that energy savings of approximately 8.5% could be achieved in hot–dry climates [40]. Their findings highlighted the significance of selecting appropriate vegetation based on specific climatic conditions to optimise green roof performance. Similarly, Chan and Chow conducted a study simulating the energy performance of a green roof with a specific LAI value of 5, using EnergyPlus. By applying certain parameters to the EcoRoof Model, they projected a decrease in energy consumption for air conditioning by 0.09%, 1.34%, and 2.81% during different future periods (2011 to 2030, 2046 to 2065, and 2080 to 2099) under varying weather conditions [41]. This research underscores the potential energy-saving benefits of green roofs with specific LAI values, supporting the notion that green roofs can effectively improve energy efficiency in buildings. These studies collectively contribute to our understanding of the impact of LAI values on green roof performance and highlight the importance of selecting appropriate vegetation and design parameters for green roofs to achieve optimal energy-saving outcomes.

2.2. Soil and Thermal Properties of Green Roofs

Trees have demonstrated their effectiveness as valuable tools for mitigating the UHI effect and improving thermal comfort in urban areas by providing increased shade and transpiration [42]. When integrated into green roofs, trees can further enhance the thermal efficiency of typical green roof systems and add financial value to buildings [18,43–49]. Their contribution to green roofs extends beyond mere aesthetics, as they play a vital role in enhancing the environmental benefits of such structures. While some studies have investigated the indoor and outdoor thermal effects and energy savings of typical green roofs, both extensive and intensive without trees [50–52], there has been relatively less exploration of the energy-saving potential of intensive green roofs with canopy trees. This research gap presents an opportunity to delve deeper into the benefits of incorporating trees within intensive green roof designs and understanding their impact on energy consumption and thermal performance. Intensive green roofs with canopy trees offer several advantages, including increased shade provision, higher rates of transpiration, and additional cooling effects. These trees can create a microclimate that mitigates the UHI effect and enhances the overall thermal comfort in urban environments [53]. The shading effect of trees reduces direct solar radiation on the roof surface, minimising heat absorption and heat transfer to the building below. Simultaneously, the process of transpiration from the trees releases water vapour, cooling the surrounding air and further contributing to the cooling of the green roof. Investigating the energy-saving potential of intensive green roofs with canopy trees can lead to valuable insights for urban planners, architects, and building owners [54]. Understanding the specific benefits and challenges associated with such green roof designs can inform decisions about implementing green infrastructure in urban areas and contribute to more sustainable and eco-friendly building practices.

The thermal properties of soil are strongly influenced by its water content, which plays a crucial role in regulating heat transfer processes within green roofs. Water enhances soil thermal conductivity and heat capacity, facilitating the downward transmission of heat and providing heat storage capabilities. This feature helps to suppress soil temperature fluctuations, contributing to the overall thermal stability of the green roof ecosystem. Moreover, the moisture content of the soil directly impacts water availability for ET. Additionally, the soil moisture level has implications for the albedo of the green roof. Wetter soil tends to have a dark colour and, as a result, exhibits a lower albedo compared to dry soil [55]. A lower albedo means that the soil surface absorbs more solar radiation, leading to increased net solar energy gains and warmer soil temperatures [56]. Understanding the effects of soil moisture is essential for informing sustainable irrigation and water management strategies that can optimise the ecological functions of green roofs. Proper irrigation practices can ensure that soil moisture levels are maintained at appropriate levels, promoting healthy vegetation and efficient ET [57]. Efficient water management contributes to the cooling effects of green roofs, reducing UHI effects and enhancing the overall thermal comfort in urban environments.

While soil moisture characteristics and their interactions with meteorological conditions like water scarcity have been extensively studied in natural and semi-natural environments, such as forests, croplands, and urban green spaces [58,59], research in constructed green roof ecosystems is relatively scarce. Constructed green roofs involve more human inputs in terms of materials and management, which can influence the soil moisture dynamics differently from natural ecosystems. Bridging this research gap can provide valuable insights for enhancing the performance and sustainability of green roofs in urban environments, promoting more effective urban planning and green infrastructure development.

2.3. Addressing the Knowledge Gap

From the extensive literature review, it is evident that there is a significant progress in understanding the various benefits of green roofs in the context of urban infrastructure. Despite this progress, there remains an underlying gap in our knowledge concerning their integration into urban environments and their specific impact on energy consumption, especially in the context of different climates and building structures. While existing studies has provided some insights on the role of green roofs in reducing energy usage, enhancing thermal comfort, and mitigating urban heat island effects, there is a need for more comprehensive and location-specific research. Factors such as regional climate variations, building types, and diverse vegetation choices necessitate a deeper exploration of how green roofs can be tailored to maximize their energy-saving potential while addressing local environmental and infrastructural challenges. This study represents a first-of-its-kind effort in modelling a complex green roof system featuring diverse plant varieties and various topographical features within a rapidly expanding urban area in Melbourne. Furthermore, the research substantiates the effectiveness of retrofitting buildings with green roofs as a viable means of conserving energy in urban structures. The adoption of green roofs for other buildings in Melbourne's Central Business District (CBD) holds substantial promise for realising significant energy-saving advantages and presents a practical solution for large-scale retrofitting projects, and this study becomes the base case for encouraging this transition. The findings of this study underscore the critical importance of considering key variables, such as the Leaf Area Index (LAI), soil moisture levels, plant height, and vegetation types, when selecting and designing green roofs. By concentrating on the Treasury Place building in Melbourne, Australia, this study provides valuable insights tailored to the specific urban context, while also shedding light on broader implications for the advancement of sustainable urban development.

3. Design Concept—Green Roof

The Treasury Place (Figure 2), also known as the State Government Office in Melbourne, was constructed in the 1960s and currently houses the Department of Treasury and Finance (DTF) and the Victorian Government Department of Premier and Cabinet (DPC) with five levels of office spaces. The proposed green roof for the Treasury Place serves a twofold purpose. Firstly, it aims to demonstrate the successful retrofitting of green roofs on existing buildings, breaking down perceived barriers to green roof retrofits among stakeholders and communities. Secondly, the "Green Our Rooftop" project draws inspiration from the concept of a "Garden of Victorian Landscapes" and seeks to apply research-based design principles to trial and test various conditions, furthering the science of green roofs in Melbourne, Australia. The project also aims to provide a space for learning and promoting green roofs, where people can view, learn, and share information about best practices and the industry.

Figure 2. Treasury Place in Melbourne and the location of the proposed green roof [60].

The design concept of the proposed green roof for the Treasury Place is inspired by the diversity of Victorian plant types or bioregions and the topography of the Victorian plains. Through the use of pixelisation and grid morphing techniques, the design reflects this diversity, creating "bioregions" on the green roof plan (Figure 3) and positioning them at different heights to demonstrate the topography (Figure 4).

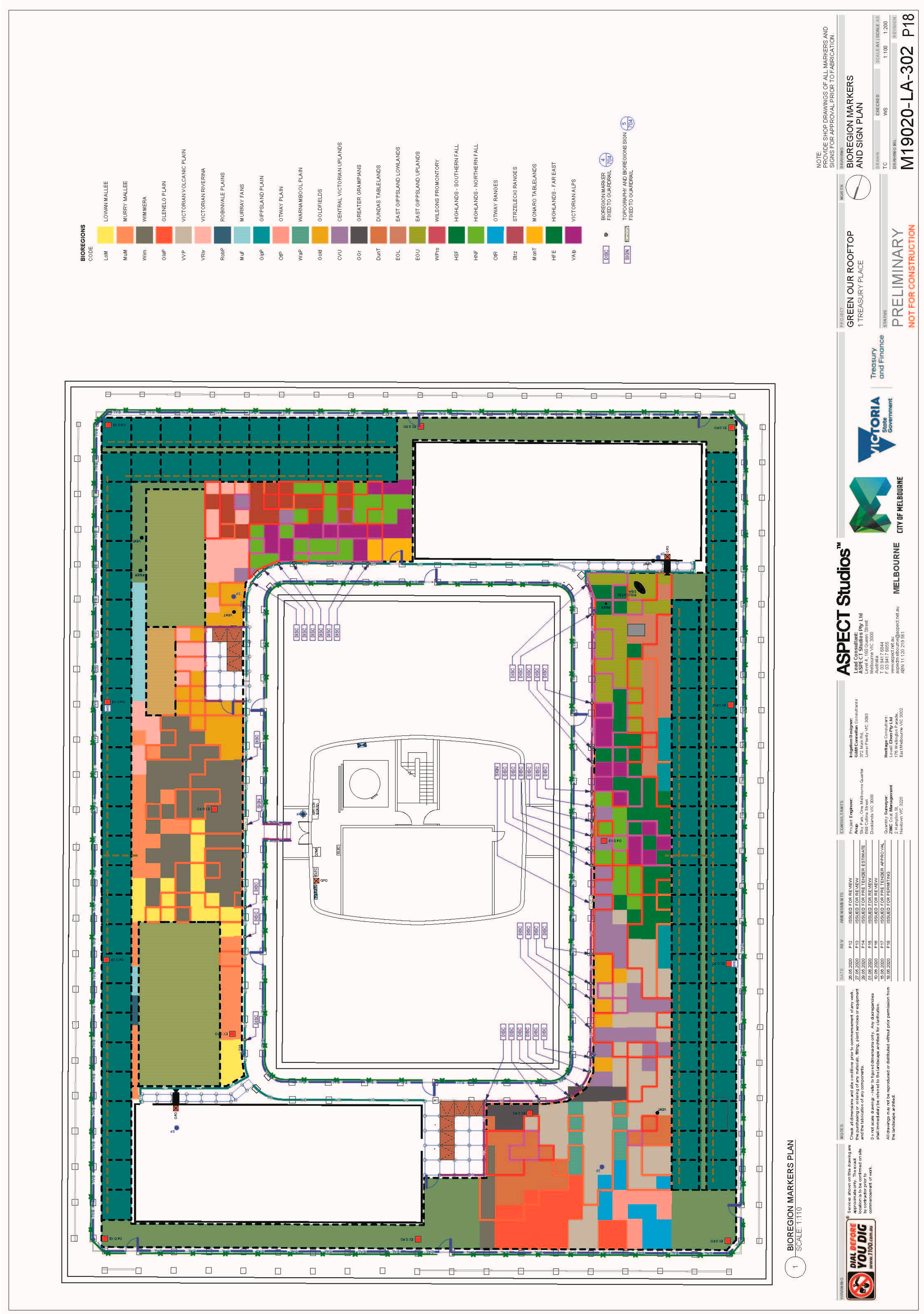
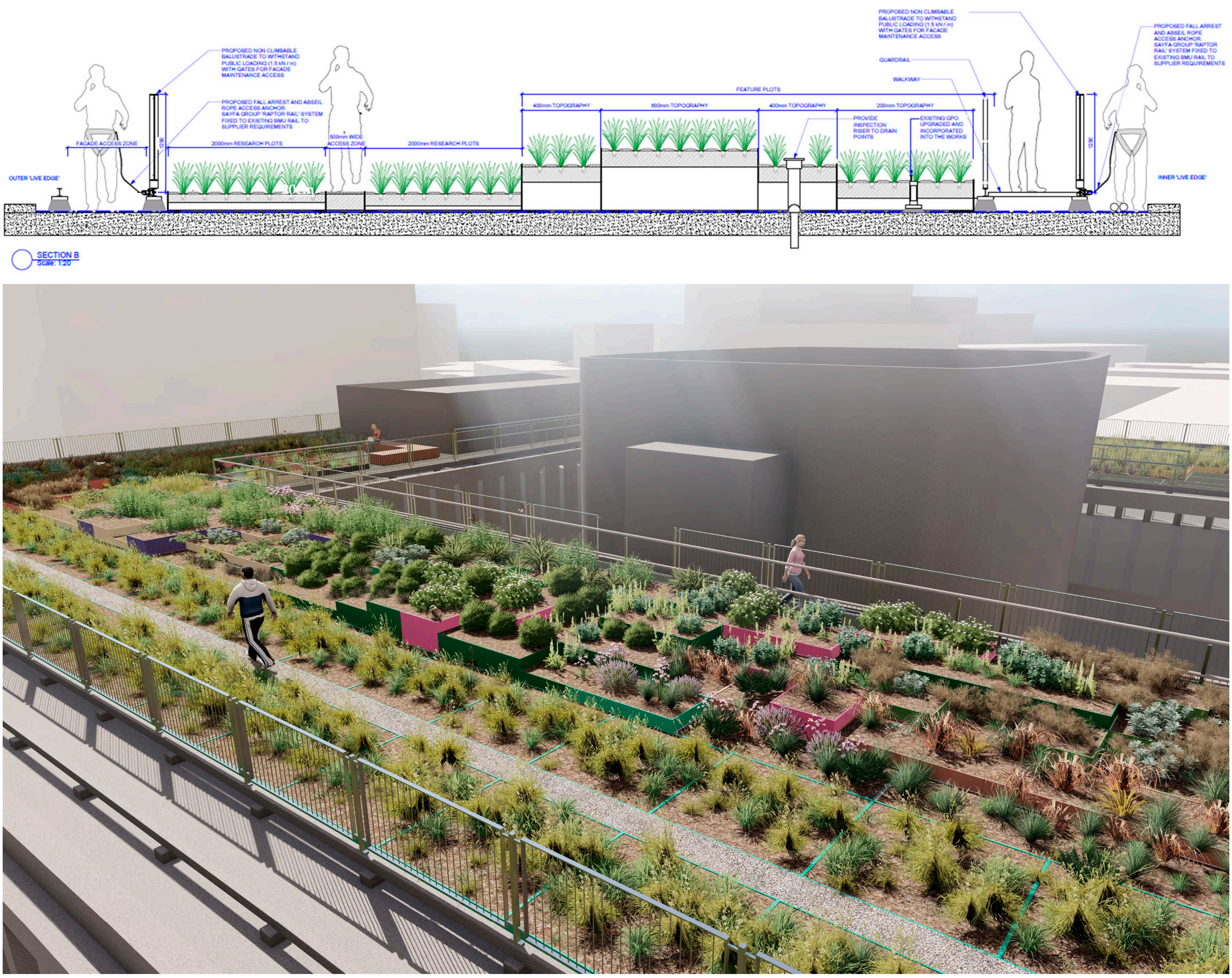


Figure 3. Proposed bioregions for the Treasury Place green roof.

a



b

Figure 4. Proposed topographies for the green roof that is abstracted within four different levels (0, 0.2, 0.4, and 0.6 m) (**a**) Sections, (**b**) Visualization.

To represent Victoria's topography, the designers abstracted it into four different heights from the green roof surface (0, 0.2, 0.4, and 0.6 m), using garden edge restraints and void formers with 200 mm height increments. This abstraction resulted in a green roof that showcases both low and flat bioregions (e.g., the Mallee and the Western Plains) and undulating and high areas (e.g., the Great Dividing Ranges, Gold Field Ranges, Grampians, Otway Ranges, and the Gippsland Highlands).

The concept design of the green roof visually demonstrates the diversity of Victorian plant types through a colour-coded representation of the bioregions (Figure 3). Each 1 m × 1 m plot on the green roof is planted with species that represent a specific bioregion, creating a visual representation of various landscape typologies found within the state. The proposed green roof for the Treasury Place represents a unique and innovative project. It serves as a platform to explore the potential benefits of green roofs, while also acknowledging the importance of considering their limitations. This project not only celebrates the natural diversity of Victorian landscapes but also contributes to sustainable building practices in the urban environment. As we delve into the specific case study of the Treasury Place building in Melbourne, Australia, we explore the rationale behind the chosen parameter values and ranges. This exploration will shed light on the considerations that guided the selection of these parameters and their implications for energy efficiency in urban environments. By examining the validity of parameter choices and their adaptability to various contexts, we aim to contribute to a better understanding of how green roofs can be optimised to enhance their energy-saving capacity and support sustainable urban development.

4. Climate Condition

Melbourne's climate is classified as a temperate oceanic climate according to the Köppen climate classification. The city experiences hot summers, typically from December to February, with a mean monthly maximum temperature of 25.3 °C. During summer, Melbourne's maximum temperatures reach up to 40 °C [61]. On average, the city has nine extremely hot days with temperatures exceeding 35 °C each year. However, climate change modelling by the Bureau of Meteorology (BOM) and CSIRO predicts an increase in the number of extremely hot days in Melbourne. By 2030, it is forecasted to have 11 such days annually, and by 2070, this number is expected to rise to 20 days per year. These projections indicate a trend towards more frequent and intense heatwaves in Melbourne due to climate change. It underscores the importance of implementing effective strategies, such as green roofs, to mitigate the impacts of urban heat and improve thermal comfort in the city.

Figure 5 displays the mean maximum temperature distribution for the year 2020, recorded at the Melbourne Olympic Park station (Location: 086338). As shown in Figure 5, January is the hottest month in Melbourne, and thus, it was selected as the preferred date for conducting simulations and field measurements. This decision allows us to consider the worst-case scenario with the highest level of urban air temperature, thermal distress, and the highest level of energy consumption for cooling.

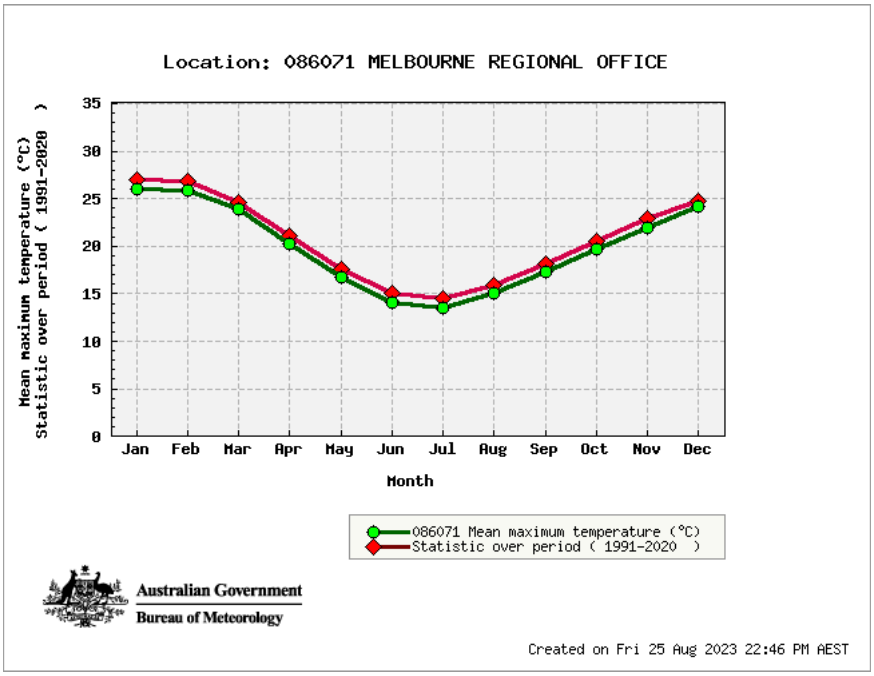


Figure 5. Mean monthly maximum temperature in Melbourne (Olympic Park, Station number: 086338) (2013–present) (Source: BOM, "Melbourne (Olympic Park), Victoria Weather observation", 2020).

The wind speed in Melbourne varies depending on the time of day and the season. Typically, wind speeds are lowest at night and early morning before sunrise. As the surface heats up during the day, turbulence induced by the surface heat increases wind speed. Weather phenomena, such as showers and thunderstorms, can also impact wind speed.

Additionally, early spring and late winter often experience extremely windy days. On 3 September 1982, a strong wind gust of 120 km/h was recorded in the area [62]. Figure 6 illustrates the wind direction and speed at the Olympic Park in Melbourne at 3 pm during summer. This information is valuable for understanding the local wind conditions, which is crucial in the energy performance and thermal comfort of green roofs and buildings in urban environments.

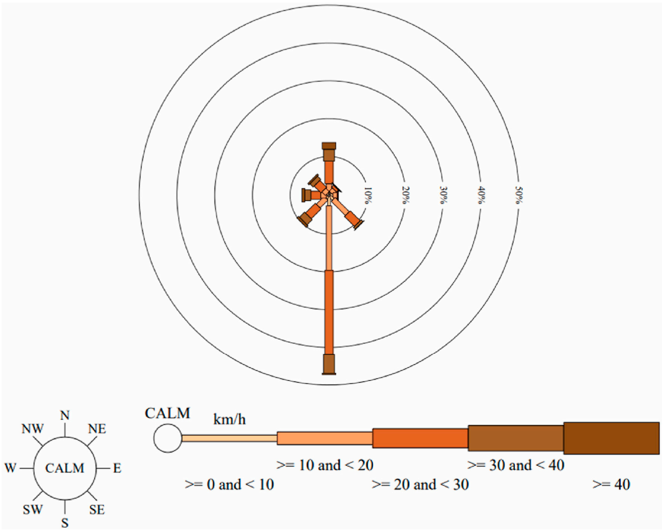


Figure 6. Wind speed and Wind direction in Melbourne (Olympic Park, Station number: 086282) at 3 p.m. in summer (1 July 1970 to 9 August 2019) [63].

In this study, the climatic data were obtained from two main sources. Firstly, data were derived from the nearest Bureau of Meteorology (BOM) weather station to the Treasury Place building; the BOM provides regional climatic parameters such as air temperature (°C), relative humidity (%), solar radiation (W/m^2), and wind speed (m/s) for the broader area of Melbourne. These regional data served as a basis for understanding the general climatic conditions in the vicinity of the Treasury Place. Secondly, a weather station was installed on the top of the building to capture the local-scale climatic conditions specific to the Treasury Place and its green roof. This station continuously monitored the relevant climatic parameters, including air temperature, relative humidity, solar radiation, and wind speed at the immediate site. The recorded data from this local weather station were then used as inputs for the simulation model of this study, which also helped validate the existing scenarios and the used simulation model, ensuring the accuracy and reliability of the findings. This comprehensive approach allows for a deeper understanding of the energy impact and electrical energy conservation performance of the applied green roof scenarios in the specific context of the Treasury Place in Melbourne.

5. Methodology

5.1. Tools (DesignBuilder and EnergyPlus)

In this study, DesignBuilder [64] version 6 was used to build the energy model, and EnergyPlus was used to assess the energy-saving capacity of the proposed green roof on the Treasury Place building. Coupling these tools facilitates building the model and further investigates the green roofs.

DesignBuilder is a building simulation software that allows users to model, analyse, and optimise the energy performance of buildings. It offers a user-friendly interface, making it accessible to both experts and non-experts in building energy simulation. The software is capable of integrating various building components, such as walls, windows, roofs, and HVAC systems, to create a detailed virtual model of the building. Users can input specific building materials, construction details, occupancy schedules, and HVAC settings to accurately represent the building's characteristics.

EnergyPlus is a sophisticated building energy simulation software that combines building load analysis, system thermodynamics, and DOE-2 programs to accurately model and simulate hourly building energy consumption under various parameters, including loads, schedules, and weather conditions [16]. The EcoRoof model, also known as the integrated Green Roof Model within EnergyPlus, is a commonly employed tool for examining how green roofs impact a building's thermal efficiency and offering insights into the attributes of the building's thermal envelope. This model, referred to as EcoRoof, was initially introduced and validated by Sailor et al. [16]. The full description of the EcoRoof model and its integration with EnergyPlus can be found in the published research of Sailor et al. [16]

Through the integration of DesignBuilder, EnergyPlus, and the EcoRoof model, this study was able to leverage the powerful capabilities of these tools to analyse the proposed green roof's energy performance comprehensively. The simulation considered various design settings and optimisation scenarios to determine the most effective configuration for maximising energy efficiency and sustainability in the Treasury Place building in Melbourne.

However, previous categorisations of green roofs (intensive, semi-intensive, and extensive) do not provide sufficient detail for partitioned green roofs with multiple plant species and varying soil layers. Zheng et al. [65] and Kumar et al. [66] highlighted the importance of accurately representing green roofs down to the plant/biome level, as parameters such as LAI, soil depth, and leaf reflectivity can significantly affect energy savings.

5.2. Simulation Scenarios

The following scenarios were evaluated to understand the impact of the various parameters of the green roof on the electricity load for colling: the base case (no green roof), the proposed green roof (by the designer), and various optimisation scenarios for LAI, plant height, soil moisture, and also adding 50% extra tree coverage.

The base case involved modelling the existing building without any green roof intervention. Figure 7 shows the model of the base case scenario considered for the case study on optimisation of different parameter of the green roof. This scenario allowed us to establish a baseline for the building's energy consumption and thermal performance under typical climatic conditions in Melbourne. The green roof design, including two plant types (low canopy and trees), three LAI parameters, four plant height values, and four soil moisture levels, was integrated into the proposed green roof scenario. These 14 scenarios aimed to evaluate the potential energy-saving benefits and thermal comfort improvements associated with implementing the green roof on the Treasury Place building and were tested separately. In addition, a series of optimised scenarios were examined to assess the capability of the green roof further and determine the most optimum design settings for the green roof. These scenarios involved varying combinations of plant types (Table 1), LAI values, plant heights, soil moisture levels, and tree coverage to analyse their individual and combined effects on energy consumption and thermal performance. The goal was to identify the optimal configuration that maximises energy efficiency and sustainability for the proposed green roof. Through the comprehensive analysis of these scenarios, this study provides valuable insights into the potential energy-saving capacity of the green roof on the Treasury Place building, supporting informed decision making for sustainable building design and green roof implementation in urban environments.

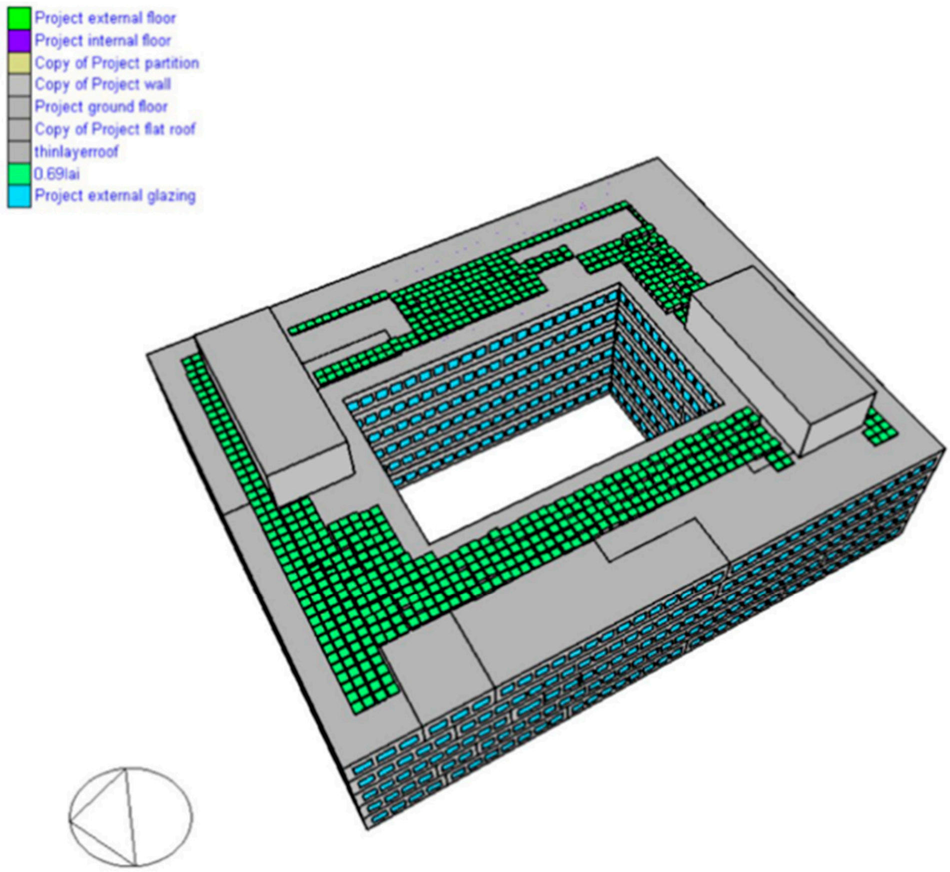


Figure 7. Base case model in DesignBuilder for the case study.

Table 1. Simulation Parameters.

Parameter	Optimised Value
LAI (m^2/m^2)	0.69 (Average LAI of the proposed green roof)
	1.08
	2.5
Plant height (m)	0.2
	0.33 (Average plant height of the proposed green roof)
	0.4
	0.6
Soil Moisture [0.1] (bars)	0.1
	0.3
	0.5 (Default soil moisture of the proposed green roof)
	0.6
Increase tree coverage (%)	+50%

6. Results

The impact of green roof parameters on the performance of green roof settings in terms of cooling electric loads was evaluated. The evaluation includes changing the plant LAI and height and the soil moisture content and adding a 50% canopy tree coverage percentage.

6.1. Impact of LAI

The results of the different scenarios were compared and analysed to evaluate the changes in energy consumption. The baseline scenario, which represents a bare roof, was compared to the actual green roof-settings scenario. Furthermore, the LAI was increased to 1.08 and then further increased to 2.5, and the corresponding effects on cooling electricity loads were examined. The results, presented in Figure 8A, demonstrate the energy consumption for each scenario over 24 h.

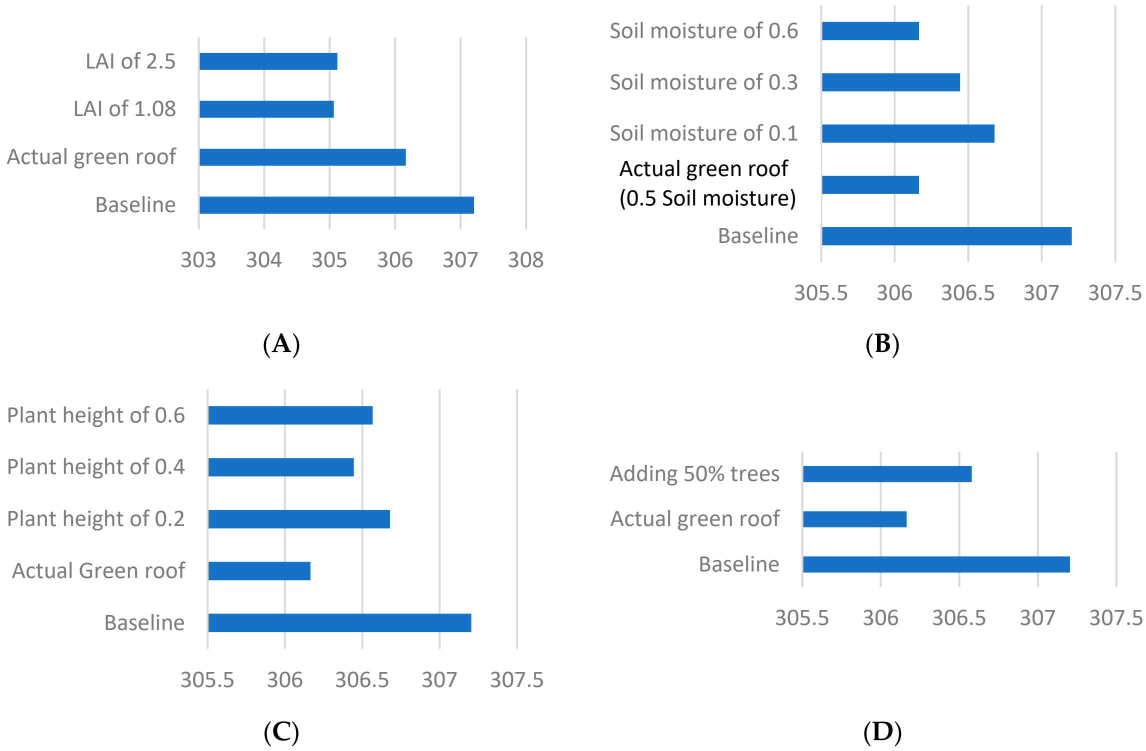


Figure 8. The HVAC system electric consumption of the various investigated green roof settings in MJ for 24 h under different optimisation scenarios (**A**) LAI, (**B**) Soil Moisture, (**C**) Plant height, (**D**) Increase tree coverage (%).

When comparing the green roof scenarios with the bare roof (baseline), it is evident that the actual green roof settings resulted in a slight reduction in the cooling electric load of 0.34%. This outcome suggests that green roof settings can save energy and reduce the cooling load. Moreover, the LAI was increased to 1.08, and a further decrease in cooling electricity loads was observed. The energy consumption dropped 0.36% compared to the actual green roof settings, leading to a total reduction of 0.70% compared to the bare roof. Interestingly, increasing the LAI to 2.5 resulted in less of an effect than 1.08 of 0.02%. Therefore, out of the various investigated values of the LAI, 1.08 had the highest impact on reducing the HVAC system electric loads.

6.2. Impact of Soil Moisture

Various changes in the soil moisture levels were examined. The scenarios with reduced soil moisture levels of 0.1 and 0.3 and increased soil moisture of 0.6 were evaluated. The results are presented in Figure 8B. When the soil moisture was reduced to 0.1, a slight increase in cooling electricity loads was observed compared to the actual green roof settings of 0.17% relative to the actual scenario. Similarly, when the soil moisture was reduced to 0.3, a marginal increase of 0.09% occurred in cooling electricity loads compared to the actual green roof settings. In contrast, increasing the soil moisture to 0.6 resulted in a return to a similar cooling electric load as the actual green roof settings, increasing the soil moisture above 50% and having no impact on energy reduction. In comparison, 50% of soil moisture is optimal for reducing the HVAC system's electric consumption while implementing this type of green roof.

6.3. Impact of Plant Height

The impact of changing the plant height was also investigated. The scenarios with a reduced plant height of 0.2 m and increased plant height of 0.4 m and 0.6 m were evaluated. The results are presented in Figure 8C. Interestingly, both reducing and increasing the plant heights had a negative effect on energy reduction. When the plant height was reduced to 0.2 m, a slight increase in cooling electricity loads was observed compared to the actual green roof settings of 0.17% compared to the actual green roof. In addition, increasing the plant height to 0.4 m and 0.6 m increased the energy demand by 0.09% and 0.13%, respectively. Therefore, a plant with an average height of 0.33 m is ideal for this type of green roof.

6.4. Impact of Adding Trees

The impact of adding 50% canopy tree coverage on the green roof was evaluated. The results are presented in Figure 8D. When 50% canopy tree coverage was added to the green roof, a slight increase in cooling electricity loads was observed compared to the actual green roof settings of 0.14%. Although there was a reduction in the temperature on the roof level by adding the trees, the increase in the soil level due to adding the trees had a negative effect on energy reduction. This finding highlights the complexity of green roof design settings and their potential influence on energy performance, suggesting that careful consideration is needed when incorporating canopy trees into green roof projects. Further investigations are warranted to optimise the integration of canopy trees on green roofs to achieve the desired energy-saving benefits while maintaining overall environmental and climatic advantages.

7. Discussion

The results obtained from the simulation scenarios provide valuable insights into the significance of different green roof parameters on energy consumption and cooling load reduction. Increasing the LAI to 1.08 led to a further decrease in cooling electricity loads. These results suggest that increasing the vegetation density on green roofs can enhance their energy-saving potential. Similar findings have been reported in previous studies, emphasising the role of vegetation density in improving thermal performance and reducing energy consumption [67,68]. However, increasing the LAI to 2.5 showed less of an impact on energy reduction than 1.08, with only a marginal decrease of 0.02%. This finding suggests that there might be a threshold beyond which increasing the LAI does not significantly contribute to further energy savings. Thus, carefully investigating the LAI of the selected plants is highly important, where green roofs are needed for reducing HVAC system electric loads as the main benefit.

Another parameter investigated in this study was soil moisture content. It was found that reducing the soil moisture to 0.1 and 0.3 led to slight increases in cooling electricity loads compared to the actual green roof settings. This implies that maintaining adequate soil moisture levels is crucial for achieving energy reduction through green roofs. In contrast, increasing the soil moisture to 0.6 resulted in a return to similar cooling electricity loads as the actual green roof settings. These results suggest that a soil moisture content of around 50% is optimal for reducing HVAC system electric consumption while implementing green roofs. These findings are consistent with previous research highlighting the importance of proper irrigation and soil moisture management in optimising the cooling performance of green roofs [57,69]

The impact of plant height on energy reduction was also examined. Both reducing and increasing the plant heights had a negative effect on energy consumption. Reducing the plant height to 0.2 m resulted in a slight increase in cooling electric load, while increasing the plant height to 0.4 m and 0.6 m led to further energy demand increases. These findings suggest that a plant height of approximately 0.33 m is ideal for reducing energy in this green roof setting. Previous studies have also emphasised the importance of appropriate plant height selection to optimise green roofs' thermal performance and energy efficiency and maintain this height to insure the best outcomes [70]. It should be considered that different weather conditions, site orientations, and adjacent elements could have an impact on the simulated parameters, and, therefore, the use of a simulation could advance the design process and enhance the outcome quality.

Lastly, the impact of adding 50% canopy tree coverage on the green roof was evaluated. It was observed that, although adding trees resulted in a temperature reduction at the roof level, the increase in soil depth due to tree presence had a negative effect on energy reduction. This finding implies that, while trees can provide shading and improve microclimate conditions, careful consideration should be given to their integration within green roof settings to minimise potential energy trade-offs. Similar conclusions have been drawn in previous studies, highlighting the need for balanced tree integration to achieve optimal energy-saving outcomes [53]. In addition, and as highlighted in the above paragraph, the use of simulation during the design could have better influence on the decision-making process, which will also help in creating a balance between the energy performance and aesthetics aspects of green roofs. This can ensure that the performance of the designed green roof is closer to reality instead of relying on general research studies that might not lead to the desired outcomes or might provide negative impacts.

While our study has provided valuable insights into the energy-saving potential of green roofs on the Treasury Place building in Melbourne, Australia, we recognize several limitations that require attention. Firstly, the results presented in this manuscript are specific to the local climate and building characteristics of our study site, and their applicability to other regions with different climatic conditions may vary. Additionally, our findings are based on simulation models with assumptions about building usage, occupancy, and maintenance practices, which may not fully capture real-world variations. To address these limitations and advance the field of green roof research, future studies should explore multi-objective optimisation techniques to balance energy savings with ecological benefits and integrating IoT-based monitoring systems in a co-simulation environment where you model and verify the system using real-world data. Moreover, conducting urban-wide impact assessments will provide a broader understanding of the implications of widespread green roof adoption on urban heat island mitigation. Long-term performance analyses, incorporating plant health and maintenance considerations, are essential for ensuring sustained benefits. Furthermore, exploring the integration of emerging green roof technologies and investigating socioeconomic aspects, such as cost–benefit analyses and public perception, will contribute to more comprehensive and sustainable green infrastructure solutions, which are considered future directions of research.

Significance of the Case Study

This study represents a significant advancement in the field of green roof research, offering several novel contributions and innovative approaches:

1. Complex modelling of intensive green roof systems: One of the primary innovations of this research presented in this manuscript is in its comprehensive modelling of a complex green roof added to the urban building. Unlike previous studies that often focused on simplified scenarios, this research delves into the intricate dynamics of green roofs with diverse plant types and topographical variations. This approach provides a more accurate representation of real-world green roof installations, enhancing the reliability of the findings.
2. Location-specific insights: The study's focus on the Treasury Place building in Melbourne, Australia, contributes location-specific insights into green roof performance. By considering the unique climatic conditions, building characteristics, and sustainability goals of this urban context, the research offers practical recommendations that

can be tailored to similar environments, ensuring the relevance and applicability of the findings.
3. Validation of retrofitting for energy savings: This research confirms the effectiveness of retrofitting buildings through green roofs as a viable method for energy conservation in urban buildings. By quantifying energy savings and examining the feasibility of large-scale retrofits, the study addresses a critical gap in the literature and provides valuable guidance for urban planners and building owners seeking sustainable retrofit solutions.
4. Parameter optimisation: The study explores the rationale behind the chosen parameter values and ranges, shedding light on the considerations that guided their selection. This approach not only validates the parameter choices but also encourages future research to refine and standardize these values for improved green roof design and assessment.
5. Interdisciplinary perspective: By bridging the gap between environmental science, urban planning, and architecture, this research offers an interdisciplinary perspective on the integration of green roofs into urban environments. It underscores the importance of collaboration across these fields to achieve sustainable urban development goals.

The findings of this study have practical implications for sustainable urban planning, building design, and retrofitting strategies, thus making this study a valuable addition to the existing body of knowledge in the field.

8. Conclusions

This study comprehensively investigated the energy-saving potential of green roofs on the Treasury Place building in Melbourne, Australia, using the research-by-design approach to help in the design process. Using DesignBuilder and EnergyPlus tools, 14 scenarios were analysed, including the base case, proposed green roof, and optimised scenarios, considering different green roof parameters, such as the LAI, plant height, soil moisture, and tree coverage. The results provide valuable insights into the significance of these green roof parameters on energy consumption and cooling load reduction. Increasing the LAI to 1.08 demonstrated a further decrease in cooling electricity loads, highlighting the importance of higher vegetation density for enhancing energy-saving potential. However, increasing the LAI to 2.5 showed a lesser impact on energy reduction, suggesting the existence of a threshold for LAI beyond which further energy savings are limited. Proper soil moisture content proved crucial for achieving energy reduction through green roofs, as reducing or increasing soil moisture levels led to slight increases in cooling electricity loads. An optimal soil moisture content of around 50% was identified as ideal for reducing an HVAC system's electric consumption while implementing green roofs. Plant height was found to significantly influence energy consumption, with an approximate height of 0.33 m identified as ideal for reducing energy in this green roof setting. Careful plant height selection is vital for optimising thermal performance and energy efficiency. Additionally, the integration of 50% canopy tree coverage on the green roof reduced the outdoor temperature due to shading and improved microclimate conditions. However, the increase in soil depth caused by tree presence had a negative impact on energy reduction. This emphasises the importance of balanced tree integration in green roof settings to minimise potential energy trade-offs. Lastly, this study underscores the importance of accurately representing green roofs down to the plant/biome level and carefully considering green roof parameters to maximise energy-saving potential.

While our study offers valuable insights into a specific urban environment, the findings may not be directly transferable to all regions due to varying climatic conditions and building characteristics. Additionally, the modelling and simulation approaches employed in this study, while robust, involve certain assumptions that may introduce uncertainties. Further empirical research and long-term monitoring are needed to validate our findings in real-world scenarios. Moreover, our study primarily focuses on the energy-saving aspects of green roofs, and future research should consider a broader spectrum of environmental and socioeconomic factors to provide a comprehensive assessment of their overall impact. When green roofs are being properly designed and optimised using site-specific scientific evidence, green roofs can contribute significantly to energy efficiency and climate mitigation efforts in the built environment. The results of this study can serve as a valuable resource for policymakers, building designers, and urban planners seeking to promote green infrastructure solutions for sustainable and resilient cities and emphasise the use of the research-by-design method as a powerful method to maximize the green roofs benefits.

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