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Green Roof Energy Performance across Cfb/Oceanic Climates: Simulating Climate Change and Future Trends

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Abstract: Green roofs represent a hallmark of sustainable design and provide opportunities for increased recognition and credits within sustainability assessment frameworks. This study examines the thermal performance of green roofs in Auckland, Christchurch, and Wellington, considering two scenarios: present conditions as a "baseline scenario" and future climate change projections for "scenario 2050." Firstly, we simulated green roofs to measure the Total Fuel Consumption (TFC) of a single residential building for heating and cooling purposes with a green roof compared to the same building with a traditional bare roof using Design Builder software. Then, we utilized the Climate Change World Weather File Generator tool to predict future climate change trends in 2050. The findings reveal substantial energy-saving potential in oceanic climates. In the baseline scenario, the green roof could reduce TFC by about 3% (Auckland), 2% (Christchurch), and 1% (Wellington). In scenario 2050, these reductions increase to 3.3%, 2.6%, and 1%, respectively. Notably, green roofs exhibit an impact during summertime, with TFC reductions of approximately 8.5% (2022) and 9% (2050) in Auckland, 4.5% (2022) and 5.6% (2050) in Christchurch, and 1.5% (2022) and 0.2% (2050) in Wellington. Thus, the findings of this research not only contribute to a deeper understanding of promising techniques to combat climate change but also provide valuable insights that can inform decision-making processes regarding sustainable urban development towards Sustainable Development Goal 13.

Keywords: Green roof, energy efficiency, residential buildings, climate change, oceanic climate, design builder, CCWorldWeatherGen.

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1. Introduction

In an era fraught with escalating concerns about environmental sustainability and energy efficiency, the emergence of green roofs has captured the imagination of urban planners, architects, and environmentalists alike (Jaffal et al., 2012). The rapid sprawl of urban landscapes and an insatiable demand for energy in residential buildings pose a daunting challenge for cities worldwide (Madlener & Sunak, 2011). While grappling with the profound effects of climate change, cities stand at a crossroads, urgently requiring innovative strategies to reduce energy consumption and foster ecological balance (Borràs et al., 2022; Mihalakakou et al., 2023). Within this intricate web of environmental concerns, the concept of green roofs has emerged as a beacon of hope, promising not only to mitigate energy demands but also to nurture healthier and more resilient urban communities (Ekmekcioğlu, 2023; Getter & Rowe, 2006; Shafique et al., 2018; Vijayaraghavan, 2016). Once relegated to niche projects, vegetated roof systems, commonly known as green roofs, have been gaining global momentum for their potential to revolutionize urban living (Berardi et al., 2014; Oberndorfer et al., 2007). Green roofs offer benefits by adorning buildings with living vegetation, ranging from counteracting the urban heat island effect to curbing energy consumption in residential structures (Santamouris, 2014). The quest for energy-efficient buildings has evolved into a holistic approach encompassing sustainable design elements, and green roofs have emerged as pivotal components (Niachou et al., 2001). Their insulating properties translate into tangible reductions in heating and cooling demands and significant energy savings. Moreover, they function as natural air purifiers, capturing pollutants and enhancing air quality, positively impacting public health and well-being (Althor et al., 2016).

Beyond their impressive energy-saving potential, green roofs have demonstrated remarkable adaptability across diverse climates worldwide, underscoring their suitability as an energy-efficient solution in various urban settings (Baghaei Daemei & Jamali, 2022). These settings -based on the Köppen climate classification (Arnfield, 2023)- include tropical climates (Jim & Peng, 2012), arid climates (Elnabawi & Saber, 2023), temperate climates (D'Orazio et al., 2012), continental climates (Coma et al., 2016), and polar and alpine climates (Adhikari et al., 2016). Like many other nations, New Zealand (NZ) has been significantly impacted by the effects of climate change (Ministry of Business, 2020; NIWA, n.d.; Royal Society, 2016; Stats, 2020). To date, several studies have investigated the impact of climate change on building energy performance in New Zealand. Jalali et al. (2023), as an example, studied the energy performance of climate change on residential buildings in NZ. They provided significant insightful practices to reduce the risks of climate change. This study's findings indicated that the primary thermal load of Auckland could alter from heating to cooling in the future. In addition, Bui et al. (2021) concluded that the building industry has a dual responsibility to mitigate the impacts of climate change on buildings and decrease greenhouse gas emissions per building. In addition, Cielo and Subiantoro (2021) investigated the challenges and potentials of implementing Net Zero Energy Buildings (NZEB) in New Zealand. They concluded that Stricter and purpose-driven regulations and policies are essential to promote and provide incentives for the broader implementation of the NZEB concept throughout the nation (Daemei et al., 2018). Despite the wealth of research on green roofs, a discernible gap persists in terms of their applicability and performance within the specific climatic conditions found in New Zealand. Surprisingly, the existing literature reveals a conspicuous absence of studies directly assessing green roofs' energy efficiency and performance outcomes within the NZ context.

This absence of research underscores the critical need for a comprehensive investigation into the viability and potential benefits of incorporating green roofs as an energy-saving strategy within NZ's distinct oceanic climate. This research addresses two critical questions to advancing energy efficiency in residential buildings in the three largest cities in NZ (in terms of population): Auckland, Christchurch, and Wellington (New Zealand Guide, 2023). The first question is: does the use of green roofs when compared to conventional bare roofs, result in a substantial decrease in the demand for energy in residential buildings in these three cities? The second question is: what will be energy savings achievable by implementing green roofs in the unique weather patterns characteristic in these three cities in 2050?

2. Material and Methods

2.1. Pinpointing the Study Areas

This study focuses on Auckland, Christchurch, and Wellington as the large cities of NZ and the pilot study areas (population size of 1.657 million, 381,500, and 212,700). Focusing on the integration of green roofs, the research approaches to enhance energy efficiency within residential buildings. By investigating utilizing green roofs in these major cities, the study aims to unveil the potential benefits of these sustainable solutions in mitigating energy consumption and fostering environmental sustainability. The unique climatic conditions and architectural characteristics of Auckland, Christchurch, and Wellington present an intriguing backdrop for exploring how green roofs can be pivotal in promoting more ecologically balanced and energy-efficient buildings. Figure 1 illustrates the research areas on the map. In the following, the climate characteristics of the pilot areas have been discussed.

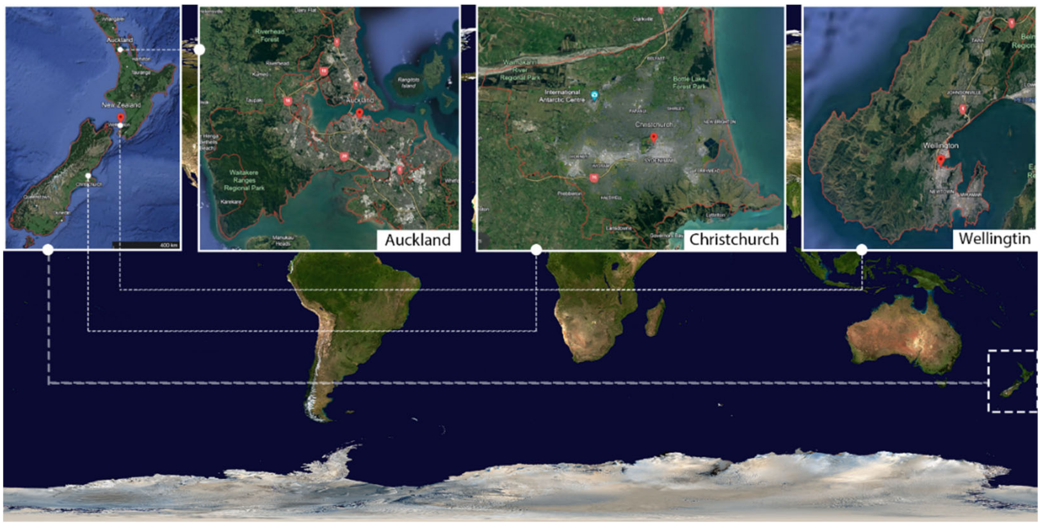

Figure 1. Location of pilot areas on the map

2.2. Climatic Features of the Pilot Climates

Auckland enjoys a subtropical climate, benefiting from its position around 13° south of the Tropic of Capricorn. This location allows tropical plants to thrive during protected winters, flowering and bearing fruit in the summer. Similarly, cold-climate vegetables sown in autumn mature in early spring, given proper drainage (P. R. Chappell, 2014). Effective optimization of factors like radiation, shelter, drainage, and irrigation supports diverse plant growth. Summers are warm and humid, while winters remain mild, with infrequent frosts. Rainfall is consistent throughout the year, occasionally heavy. Auckland receives about 2000 hours of annual bright sunshine. Extreme events sometimes lead to flooding and wind damage, though generally less severe than in other regions (Newnham et al., 2007). The climate is characterized by comfortable summers, cold and wet winters, and a persistently windy, partly cloudy atmosphere. Temperature ranges from 8°C to 23°C, rarely going below four °C or above 26°C—warm months span December 22 to March 22, with average daily highs exceeding 21°C. The hottest month is February, averaging 23°C highs and 17°C lows. From May 31 to September 16, the cool season sees average highs below 16°C. July is the coldest month, averaging lows of 9°C and highs of 14°C. Auckland experiences muggy conditions from December 11 to March 27, with about 4% discomfort due to humidity. February sees the muggiest days, around 3.5. Wind speed varies seasonally. Windy periods extend from May 11 to December 5, with average speeds exceeding 22.5 kilometers per hour. October is windiest, with an average speed of 24.3 kilometers per hour (Gosai et al., 2009).

Christchurch, the South Island's largest city and the seat of the Canterbury Region, experiences a climate defined by comfortable summers and cold, windy winters with partial cloud cover. Temperatures range from 3°C to 22°C annually, rarely dropping below -1°C or exceeding 27°C. The warm season spans 3.4 months, from December 4th to March 16th, with an average daily high above 19°C (McGann, 1983). January, the hottest month, averages 21°C high and 13°C low. The cool season lasts 3.0 months, from May 29th to August 30th, with an average high below 13°C. July is the coldest month, averaging a low of 3°C and a high of 11°C. Rainfall patterns are depicted through cumulative 31-day sliding intervals around each day of the year. Perceived humidity levels, discomforted by muggy to oppressive conditions, remain steady at 0% throughout the year. Average hourly wind speeds exhibit mild seasonal variation. The windier period lasts 6.1 months, from September 16th to March 18th, with December as the windiest month at 17.6 km/h. Calm conditions extend 5.9 months, from March 18th to September 16th, with April recording the lowest wind speed at 15.3 km/h (Gosai et al., 2009).

Wellington, NZ's capital city, is nestled at the southwestern tip of the North Island, between Cook Strait and the Remutaka Range. Its climate features temperate summers, cold and wet winters, and consistent winds, resulting in partly cloudy skies year-round. Temperature ranges from 7°C to 20°C, with rare extremes beyond 4 °C and 23°C (R. P. Chappell, 2014). During the warm season (December 15 - March 20), daily highs surpass 18°C, with February being the warmest (20°C high, 15°C low). In the cool season (June 2 - September 10), highs stay below 13°C, with the coldest month in July (12°C high, 7°C low). Humidity comfort levels remain relatively constant, and dew points influence perceived humidity. The wind pattern sees windier months (September 3 - January 11) with speeds above 21.9 km/h, notably in October (23.5 km/h average). Calm months (January 11 - September 3) observe an average wind speed of 20.1 km/h, with April being the most favorable (Wikipedia contributors, 2023). The comparison of climatic data and geographical details is provided in Figure 2.

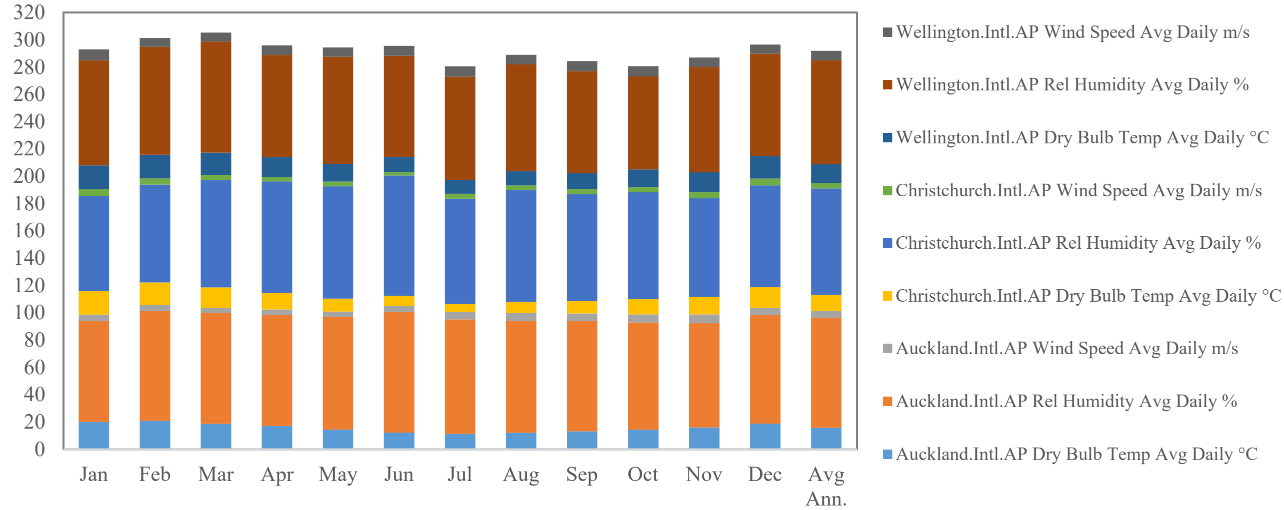

Fig. 2. Climatic features of the pilot areas. From up to bottom: Auckland, Christchurch, and Wellington (achieved from EPW Weather Data File, plotted by DView)

2.3. Specification of the Pilot Model

To systematically evaluate the performance of green roofs across diverse urban contexts, a comparative methodology will be employed, utilizing a pilot house design that maintains consistent specifications across three distinct cities. This approach isolates the effects of varying climatic conditions while ensuring a controlled simulation setup. The pilot house design will adhere to a standardized set of parameters, encompassing building dimensions, orientation, envelope materials, and interior layouts. By maintaining these specifications, any variations in the subsequent simulations can be attributed primarily to the impact of the chosen green roof system and the specific climate of each city. Figure 3 shows a typical single-story architectural plan with an area of 182.58 m2 over the foundation, 174.98 m2 over the frame, and 203.76 m2 over the roof. This plan specifically was issued for educational purposes for the first author of the present research by Fine Design & Architecture Limited, or FDAL, on 11 August 2023. Figure 3 shows an architectural plan and main elevation. We opted to study a single-story residential building due to the prevailing trend in New Zealand, where a significant proportion of buildings are one story, as indicated by BRANZ (2022).

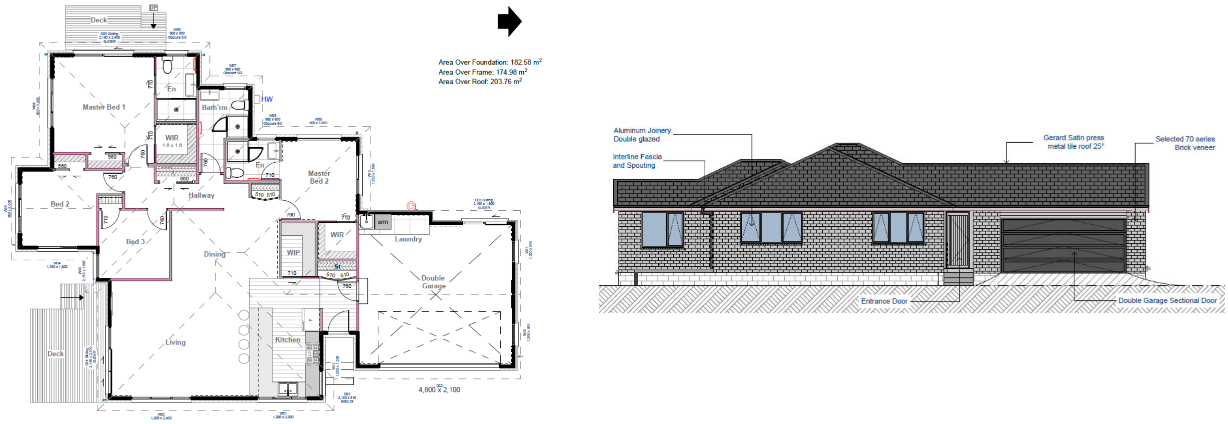

Fig. 3. The architectural plan of the pilot single-story house (left) and east elevation (right)

In the following, the selection of the pilot house as the focal point of this research is driven by a specific and strategic rationale. Notably, the pilot house lacks an attic or roof cavity, a unique characteristic that provides a distinct advantage in directly measuring the thermal performance of the green roof system and its consequent impact on energy conservation. The potential confounding effects of additional insulation or thermal buffering are effectively minimized by opting for a house devoid of an attic or roof cavity. This deliberate design choice ensures that the observed changes in energy consumption can be more directly attributed to the presence and effectiveness of the green roof system itself. This focused approach allows for a more precise and unambiguous assessment of the energy-saving potential afforded by the green roof, enhancing the reliability and applicability of the study's findings. Furthermore, this methodology aligns with the overarching objective of the research, which is to investigate the tangible benefits of green roofs in real-world scenarios. The absence of an attic or roof cavity in the pilot house aligns with this goal, as it enables a more accurate evaluation of the thermal impact of the green roof on the building's energy performance, thereby providing insights that can be directly applied to practical architectural and environmental considerations.

2.4. DesignBuilder Set-up to Model Green Roofs

The DesignBuilder Software has been selected as the primary tool for executing the methodologies outlined in this paper. This advanced software offers a robust platform that facilitates the detailed analysis and simulation of building energy performance (Samuelson & Reinhart, 2009). By utilizing the DesignBuilder Software, a comprehensive assessment of the energy-saving potential, thermal behavior, and overall performance of a building can be accurately modeled and analyzed, contributing to a thorough and insightful exploration of its implications for sustainable building practices (Monisha & Balasubramanian, 2023). This Software specializes in creating user-friendly, top-tier simulation software designed to expedite the evaluation of environmental efficacy in both fresh and standing structures. Using advanced simulation tools, DesignBuilder substantially reduces modeling durations while enhancing overall efficiency (Cardinale et al., 2013). It's important to note that DesignBuilder's prowess is rooted in its utilization of the EnergyPlus Simulation, enabling users to tap into its extensive capabilities for accurate and insightful building performance evaluations. With a global distribution network and a collaboration of international partners, DesignBuilder software remains an invaluable tool in pursuing sustainable and efficient building simulation and operation (Feng & Hewage, 2014).

DesignBuilder enables users to intricately model and simulate the performance of green roofs within diverse architectural contexts. This capability allows for detailed assessments of the energy-saving potential, thermal behavior, and overall environmental impact of green roof implementations (Khotbehsara et al., 2019). Extensive green roofs encompass a configuration where drought-resistant vegetation thrives within a thin layer (50–150 mm). They possess a delicate constitution, rendering them unsuitable for public access. The primary purpose of these particular green roofs is the mitigation of stormwater, encompassing reduction, retention, and filtration, alongside tempering the urban heat island effect (Ignatieva et al., 2008). A desirable green roof operates autonomously, necessitating minimal upkeep, and encompasses irrigation (Butler & Orians, 2011; Snodgrass & McIntyre, 2010). Typical extensive green roof components and the layers' parameters were based on work by Khotbehsara et al. (2019), who defined seven green roof layers. Layer properties and plant thermal properties can be accessed in Table 1 and Figure 4.

According to Fig. 4, it can be said that Sample 1 has five layers, including gravel, bitumen, slab (concrete), cement mortar, and plaster from outside to inside, and Sample 2 has seven layers, including the vegetation layer, mud, natural rubber, bitumen, cement mortar, slab (concrete) and plaster from the surface to the inside, respectively. Furthermore, the Leaf Area Index (LAI) and the other critical green roof parameters used in the building models were based on the CIBSE Guide A (CIBSE, 2015) presented in Table 5. In the following, heat transfer data of the roofs was extracted in the Design Builder software's Heating design and Fabric and Ventilation output. According to BRANZ (2022): "Sheet metal is the dominant roof cladding material with its market share trending upwards since 2012. It experienced a noticeable increase in 2018, which has been maintained in 2019." As a result of this report, metal roof claddings have increased from 50% (since 2010) to 70% (in 2019). The properties of bare and green roofs are standard metal roof tiles 12º, metal tile roofing, roof underlay, rafter, and interior plaster, and also plant and substrate.

Table 1. Plant and soil specifications

Inner surface	
Convective heat transfer coefficient (W/m2-k)	4.460
Radiative heat transfer coefficient (W/m2-k)	5.540
Surface resistance (m2-k/W)	0.100
Outer surface	
Convective heat transfer coefficient (W/m2-k)	19.870
Radiative heat transfer coefficient (W/m2-k)	5.130
Surface resistance (m2-k/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-k)	0.522
R-Value (m2-k/W)	2.057
U-Value (W/m2-k)	**0.486**
With Bridging (BS EN ISO 6946)	
Thickness (s)	0.4000
Km-Internal heat capacity (KJ/m2-K)	42.0000
Upper resistance limit (m2-k/W)	2.057
Lower resistance limit (m2-k/W)	2.057
U-Value surface to surface (W/m2-k)	0.522
R-Value (m2-k/W)	2.057
U-Value (W/m2-k)	**0.486**
Green roof plant	
Grass/straw materials – straw thatch (m)	0.100
Thermal bulk properties	
Conductivity (W/m-K)	0.400
Specific heat (J/kg-K)	11.00
Density (kg/m3)	641.0
Height of plants (m)	0.10
Green roof thermal parameters	
Leaf Area Index (LAI)	2.700
Leaf reflectivity	0.220
Leaf emissivity	0.950
Minimum stomatal resistance (s/m)	100.0
Max volumetric moisture content at saturation	0.500
Min residual volumetric moisture content	0.010
Initial volumetric moisture content	0.150
Surface properties	
Thermal absorptance (emissivity)	0.780
Solar absorptance	0.600
Visible absorptance	0.600

In the present research, we used EPW (EnergyPlus Weather) files to simulate the thermal performance of green roofs. These EPW files were obtained from the Design Builder library, a resource that facilitates accurate and comprehensive building energy simulations. EPW files contain a comprehensive meteorological data set, including temperature, humidity, solar radiation, wind speed, and more. These files are instrumental in characterizing the climatic conditions of specific locations, enabling us to conduct simulations that closely mirror real-world scenarios and enhance the reliability of our findings (CCWorldWeatherGen, n.d.; Jentsch et al., 2013). For the scope of our study, we deliberately focused on occupied zones that offer a controlled environment, namely MB1, MB2, Bed2, Bed3, and living area (see Fig. 6). This approach allows us to manage and manipulate the conditions within these spaces closely, ensuring a more targeted and insightful analysis of the green roof's thermal performance.

Furthermore, our simulation methodology adopted an adiabatic assumption around the building envelope. This deliberate choice enabled us to isolate and precisely analyze the impact of the green roof on energy conservation, thermal attributes, and heat transfer only through the control roofs. By treating the exterior boundary as adiabatic, we could effectively investigate the energy-saving potential, and the intricate thermal behavior exhibited by the roofs under varying conditions. The HVAC system employed in our simulation consisted of a Split system coupled with Separate Mechanical Ventilation. The simulation timeframe spanned from January 1st to December 31st, encompassing a complete annual cycle of weather conditions. Notably, our simulation assumed the absence of airflow within the roof cavity, thus allowing us to focus on the specific thermal characteristics of the green roof without the influence of convective processes. The specifications and proportions of windows are marked from a to k in the plan (see Fig. 4). The total height of the building is 350 cm. Also, the windows have two layers with 30% glazing (from inside to outside: Generic PYR B Clear 3 mm+Air 13 mm+Generic Clear 3mm).

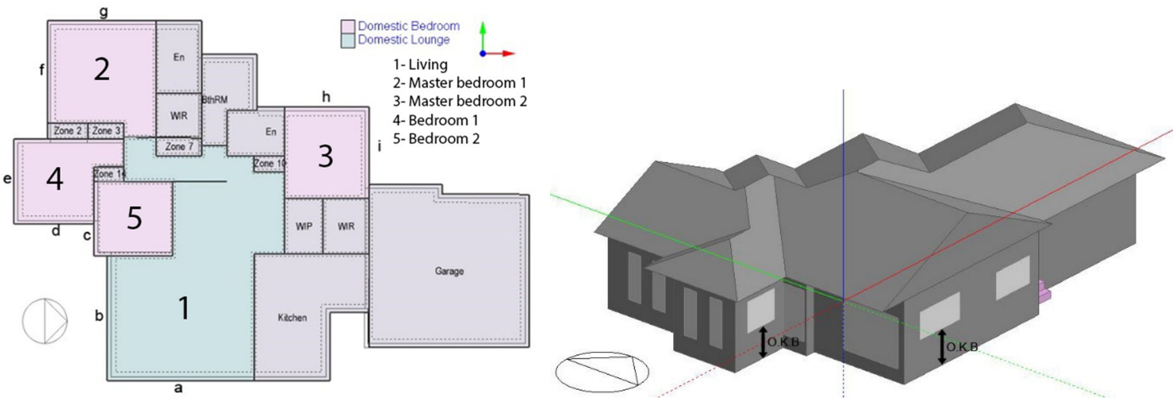

Fig. 4. Architectural plan (left) and 3D of the pilot model (right)

All windows are 'Generic PYR B Clear 3mm+Air 13mm+Generic Clear 3mm.' The properties of width, height, and the vertical distance from the ground level to the bottom of the windows for the windows highlighted by characters 'a,' 'b,' 'c,' 'd,' 'e×2,' 'f×2,' 'g,' and 'h' are as follows: (240-140-150), (270-215-55), (110-215-55), (160-135-135), (60-200-80), (60-200-80), (160-215-55), and (260-60-210) in centimeters (cm). DesignBuilder employs a dynamic simulation approach to calculate the thermal performance of a building and its components, including the roof, about the zones. While I can't provide the exact equations used by DesignBuilder due to its proprietary nature, I can give you a general overview of the concepts and equations commonly used in building energy simulation software, which might be similar to what DesignBuilder employs. Heat Transfer Equation: The fundamental equation governing heat transfer through building elements like the roof is the heat conduction equation, which calculates the heat flow (Q) through a material based on its thermal conductivity (k), area (A), temperature difference (ΔT), and thickness (d):

$$Q = k * A * \Delta T / d \tag{1}$$

Zone Temperature Calculation: DesignBuilder uses a simplified energy balance equation to calculate the zone temperature changes over time. The equation takes into account various heat gains and losses within a zone, including solar radiation, internal heat gains, ventilation, and thermal mass effects:

$$Q\_net = Q\_solar - Q\_internal - Q\_ventilation - Q\_conduction - Q\_radiation \tag{2}$$

Where:

Q_net: Net heat gain or loss in the zone

Q_solar: Solar heat gain

Q_internal: Internal heat gains (from occupants, equipment, lighting, etc.)

Q_ventilation: Heat loss or gain due to ventilation

Q_conduction: Heat conduction through walls, roofs, and other building elements

Q_radiation: Radiative heat exchange with surrounding surfaces

Roof Insulation Effect: The design Builder considers the insulation properties of the roof, typically represented by its U-value, to calculate heat transfer through the roof. The U-value represents the overall thermal conductance of a building element and is the inverse of its thermal resistance (R-value). The heat conduction equation uses the U-value to calculate heat transfer through the roof.

$$U = 1 / R \tag{3}$$

Solar Radiation Absorption: The solar radiation incident on the roof is absorbed and converted into heat, which affects the zone's temperature. The absorbed solar radiation depends on factors like solar absorptance, roof area, and solar radiation intensity. Thermal Mass Effects: DesignBuilder also considers the thermal mass of the building elements, including the roof.

Thermal mass affects the rate at which a zone's temperature changes in response to heat gains and losses. Equations involving specific heat capacity and mass of the materials are used to model this behavior.

2.5. CCWorldWeatherGen: Possible Climate Change

In this section, the research team predicts possible climate change in Auckland. For this purpose, CCWorldWeatherGen has been utilized, a tool designed for generating weather files specifically for building performance simulation programs. It can generate Climate Change Weather Files (CCWF) for various locations globally. The tool utilizes summary data of the HadCM3 A2 experiment ensemble from the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report model, which can be acquired from the IPCC Data Distribution Centre (IPCC DDC). The program is Excel-based and can transform existing EPW weather files into either climate change EPW or TMY2 weather files. These converted files are compatible with most Building Performance Simulation Programs (BPSP), making them a convenient and efficient tool for energy management in buildings (Yassaghi et al., 2019). This tool was developed by Jentsch et al. (2013), who applied the morphing method using HadCM3 (Hadley Centre Coupled Model, version 3) forced with IPCC A2 emission scenario to generate EnergyPlus Weather (EPW) file (Jafarpur & Berardi, 2019).

The HadCM3 model, which couples different climate models, has been widely used to predict future climate scenarios, detect and attribute climate change, and examine the climate system's sensitivity to various factors (Pope et al., 2000). CCWorldWeatherGen is a weather generator software used to generate future climate data. It is designed to inform users about possible changes in the weather and aid in decision-making related to climate change and weather-related issues. The software uses climate change scenarios and statistical models to generate weather data. The user inputs data such as latitude, longitude, and elevation to generate weather data specific to the location. The software can also consider topography and vegetation cover factors to create more accurate weather data (Triana et al., 2018).

3. Results and Findings

3.1. Baseline Scenario of Green Roof Thermal Performance

In this section, aligning with our research aims, we conduct an extensive year-long simulation of green roofs' thermal performance and compare it with traditional (bare) roofs within residential buildings across our pilot study areas. Our investigation aims to comprehensively understand how green roofs impact energy consumption and thermal efficiency throughout all seasons and, separately, summertime (in Auckland: December through February), offering valuable insights into their suitability as a sustainable solution for urban environments in various oceanic climates. In the following, Figure 5 compares the results of total fuel consumption (TFC) between bare and green roofs during a year for each area.

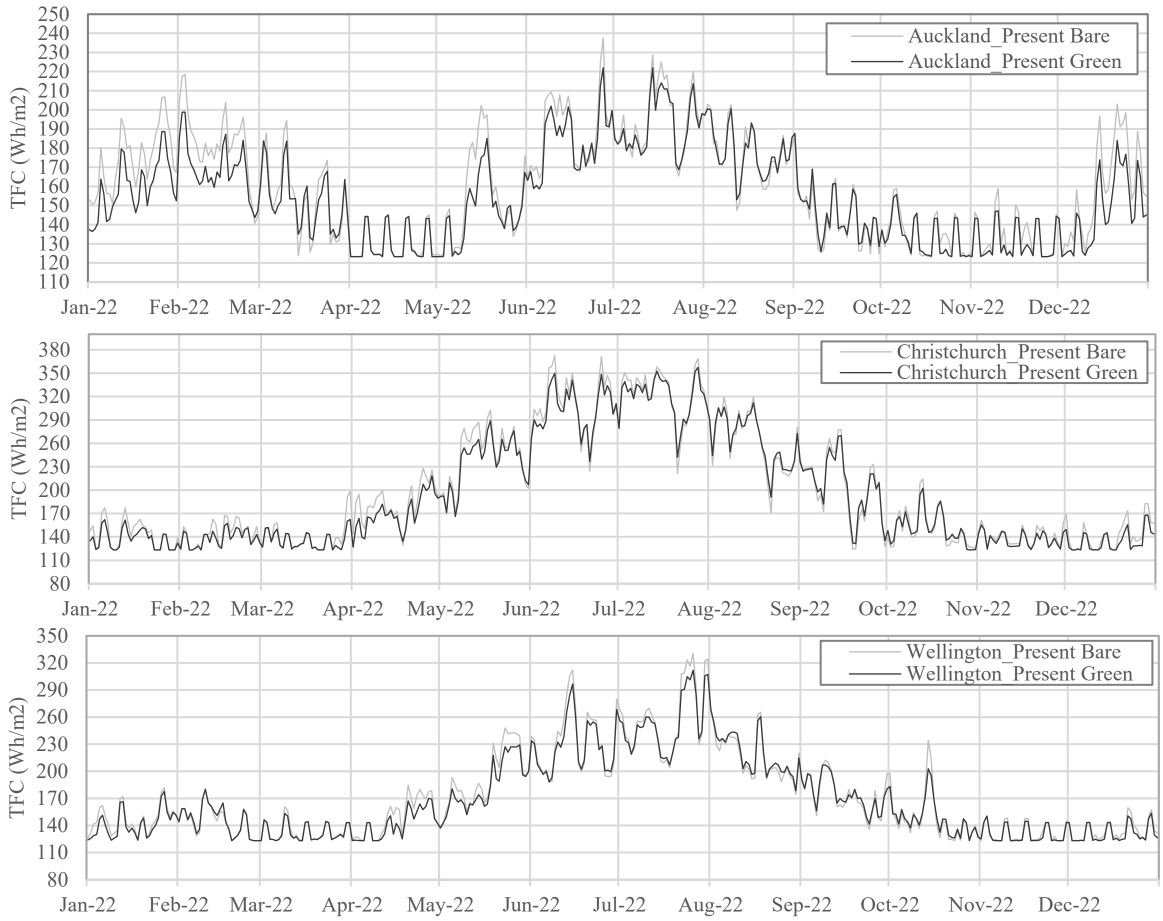

Fig. 5. Comparison between bare and green roofs' thermal performance per annum for each climate

Figure 5 provides data relevant to the impact of green roofs on the TFC of electricity for heating and cooling purposes. In the context of TFC, lower values typically indicate reduced energy consumption, which is often desirable for environmental and cost-saving reasons. This suggests that the green roof results in a relatively lower TFC than the bare roof for the first scenario. Importantly, this reduction in TFC due to green roofs appears most prominent during summertime. This is a critical detail as summertime typically brings higher temperatures and increased demand for cooling, making it a crucial period for assessing the effectiveness of green roofs in reducing energy consumption. To further understand and visualize this reduction in TFC during summertime, Figure 6 provides additional data specifically during the summer season for each climate.

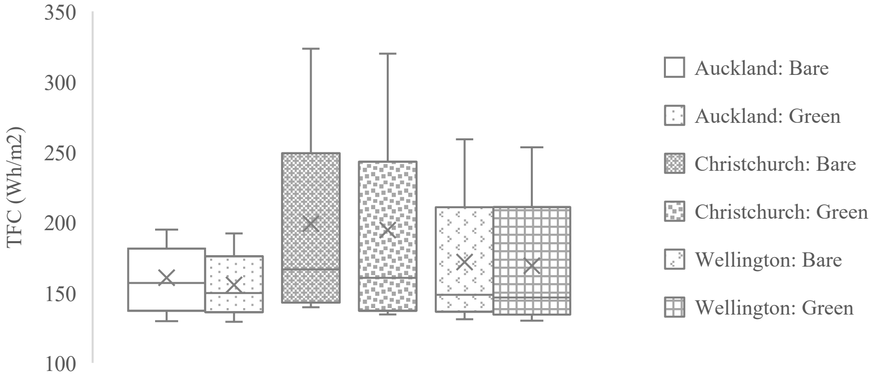

Fig. 6. Comparison of bare and green roofs Total Fuel Consumption Total Fuel Consumption (TFC) during summertime

Figure 6 presents simulation results related to the summertime thermal performance of the green roof compared to the bare roof in the present scenario. The results show a decrease in the average values of TFC.

3.2. Preparing Future Weather Data

In this part of the study, we used the EPW file generated by CCWorldWeatherGen to measure the effectiveness of green roofs in 2050 for the possibility of climate change for the three study areas. To do so, the research team created new climate models in the Design Builder library and ran the simulation module with the exact setting with the baseline scenario. Figure 7 depicts the climate features of 2050.

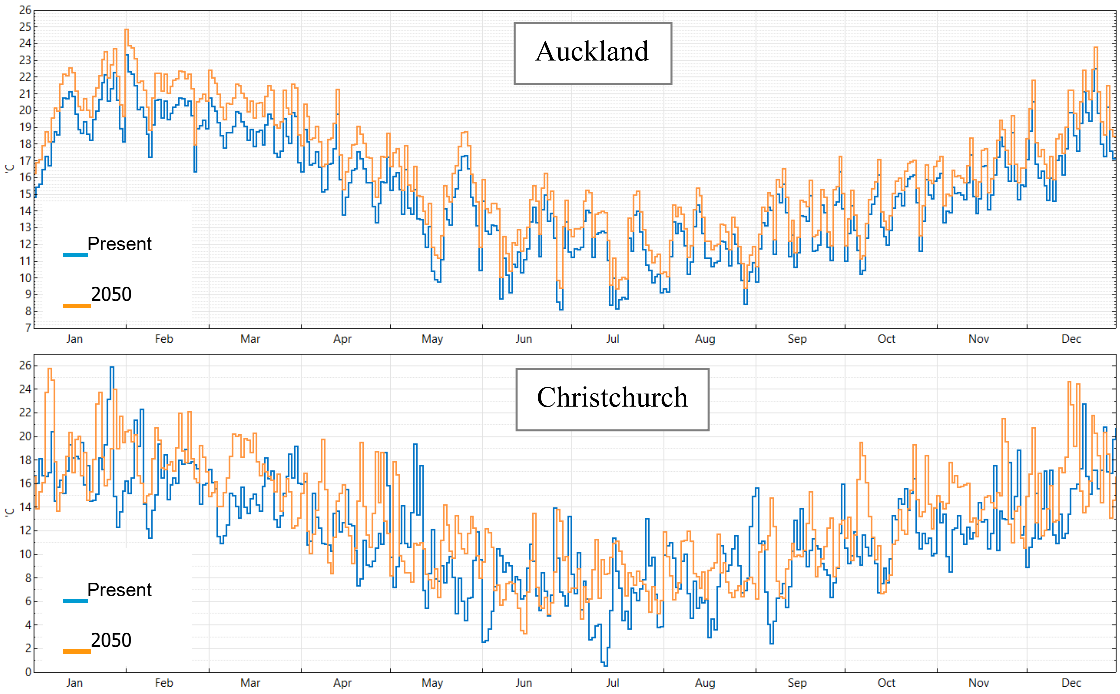

Fig. 7. Comparing the current and future scenarios (2050) of possible climate change

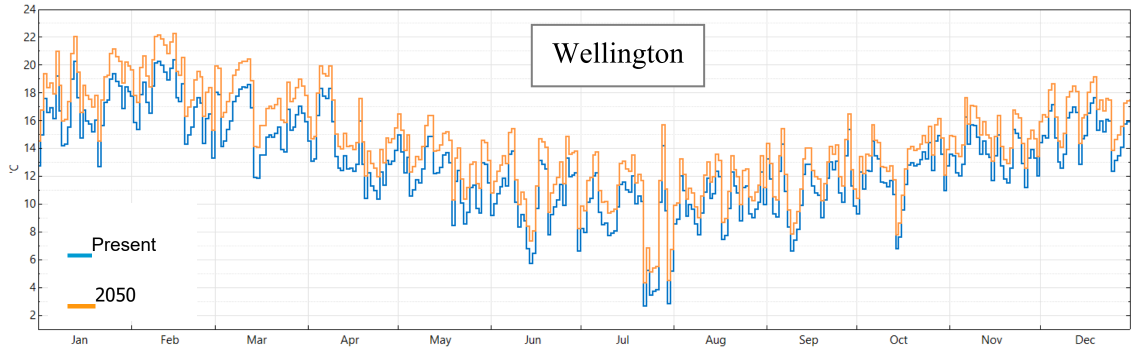

Fig. 7. Comparing the current and future scenarios (2050) of possible climate change (continued)

Figure 7 displays temperature differences and fluctuations focused on the year 2050, providing insights into how temperatures are expected to change and vary during that period. Three key temperature parameters are being analyzed: the mean dry bulb temperature, the minimum temperature, and the maximum temperature. These parameters are evaluated for both a baseline scenario (typically representing present or recent conditions) and the 2050 scenario, which offers projections for the future (2050). In the following, Figures 8 and 9 represent simulation results based on the EPW 2050 scenario generated by the CCWorldWeatherGen tool. We used that EPW file and simulated both scenarios again to visualize the future possible climate change and highlight the impact of green roofs for each climate zone.

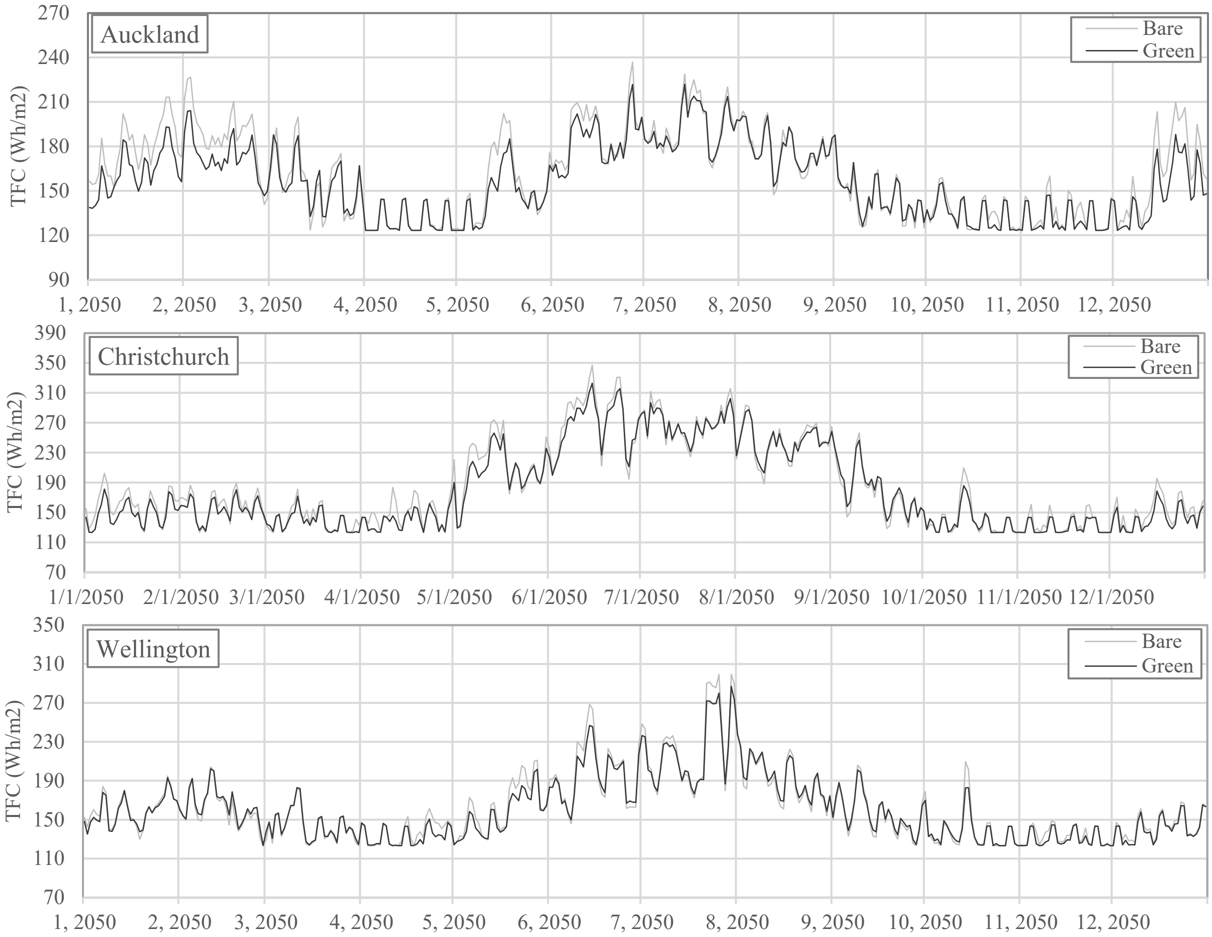

Fig. 8. Comparison between the thermal performance of bare roofs and green roofs projected for the year 2050 in Auckland, Christchurch, and Wellington

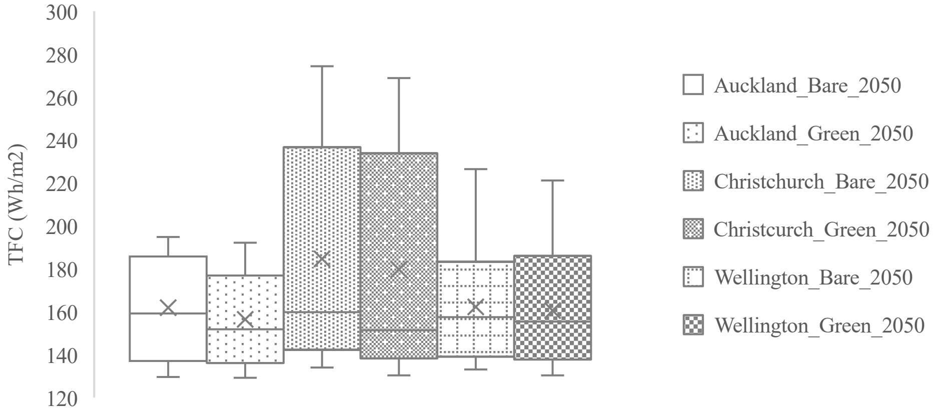

Fig. 9. Average Total Fuel Consumption (TFC) of green roofs for the baseline and 2050 scenarios per annum (a) and during summertime (b)

Figure 9 presents simulation results related to the summertime thermal performance of the green roof compared to the bare roof in the 2050 scenario. The results show a decrease in the average values of TFC in 2050.

4. Discussion

Based on the findings obtained through simulation, it is evident that the green roof holds partial promise in mitigating energy consumption in residential buildings in the oceanic climate. This finding is based on the architectural plan proposed in Figure 3. According to the data, the TFC for bare roof in Auckland, Christchurch, and Wellington is recorded as 58599 Wh/m2, 72787 Wh/m2, and 62794 Wh/m2, respectively, while the TFC for green roof is relatively lower at 56757 Wh/m2, 71125 Wh/m2, and 61825 Wh/m2 per annum for each area in the baseline scenario (see Fig. 6). In addition to this, for the baseline scenario, the results indicate a noteworthy reduction in TFC per annum when compared to conventional bare roofs: approximately 3% in Auckland, 2% in Christchurch, and 1% in Wellington (see Fig. 7). Looking ahead to the 2050 scenario, the TFC for bare roof in Auckland, Christchurch, and Wellington is recorded as 59074 Wh/m2, 67481 Wh/m2, and 59273 Wh/m2, respectively, while the TFC for green roof is relatively lower at 57121 Wh/m2, 65704 Wh/m2, and 58634 Wh/m2 per annum for each area in the baseline scenario (see Fig. 9). In addition to this, for the baseline scenario, the results indicate a noteworthy reduction in TFC per annum when compared to conventional bare roofs: approximately 3% in Auckland, 2% in Christchurch, and 1% in Wellington. The potential for TFC reduction becomes even more pronounced, with estimated reductions of 3.3% in Auckland, 2.6% in Christchurch, and 1% in Wellington annually (see Fig. 10).

Our extensive year-long simulation of green roofs' thermal performance and subsequent comparison with traditional (bare) roofs within residential buildings across our pilot study areas aligns precisely with our research objectives. This investigation aimed to provide a comprehensive understanding of how green roofs impact energy consumption and thermal efficiency across all seasons, focusing on summertime (in Auckland: December through February). We sought to offer valuable insights into the suitability of green roofs as a sustainable solution for urban environments in various oceanic climates. In terms of future recommendations, this study emphasizes the importance of widespread green roof adoption for sustainable urban development. Efforts should be made to encourage the integration of green roofs in both Auckland and other urban areas, supported by appropriate policies and incentives. Regarding the alignment with Sustainable Development Goal 13 (SDG 13) - Climate Action, it is essential to highlight that this paper contributes to the relative achievement of its targets.

The reason for selecting green roofs as the focus of this study stems from our introduction section, where we highlighted various studies emphasizing the positive aspects of green roofs. However, it is worth noting that no prior research had undertaken the measurement of thermal performance within this system. By demonstrating the potential of energy-saving of green roof technology in oceanic climate, our research supports the global agenda of combating climate change and promoting sustainability. In addition, we provided a link in the Supplementary Materials to access the dataset discussed in this paper. Despite the promising results obtained in this paper through year-round simulations, it's essential to acknowledge that our research team exclusively evaluated a single residential building. Additionally, our measurements pertained to gable/pitched roofs, the most prevalent roof type in oceanic climates. Therefore, the applicability of our findings to flat roofs remains uncertain.

It's crucial to acknowledge the limitations we encountered during our research. One main constraint was the focus on a specific residential building layout, specifically investigating the impact of green roofs on energy efficiency. While this allowed us to delve deeply into the effects of this particular eco-friendly feature, it raises concerns about the generalizability of our results to other building layouts and functions like office or commercial buildings. Individual houses' uniqueness and architectural characteristics pose a challenge in extrapolating our findings to a broader context.

5. Conclusion

This study aims to simulate the energy efficiency of green roofs compared to bare roofs in the oceanic clime in the largest cities of NZ, such as Auckland, Christchurch, and Wellington, annually and during summertime. Moreover, the possible climate change and effectiveness of the green roof have been evaluated and discussed. There is a pressing need to delve deeper into climate-responsive green roof designs tailored to oceanic climate. Research should emphasize plant selection and irrigation systems to optimize cooling and energy-saving potential through experimental measurements. Collaborative research efforts with fellow academics, institutions, and local governments are essential to expand our knowledge of green roofs' performance in oceanic climates for energy consumption and cooling performance for ambient temperature. Collecting experimental data and insights can improve our understanding and lead to more effective, context-specific strategies. Furthermore, for future studies, we highly recommend measuring plant performance, such as green roofs and walls, to mitigate ambient temperature increases in response to potential future climate change.

Supplementary Materials

Impact of Climate Change on Green Roof Energy Performance in Oceanic Climates: A Simulation Dataset (2022-2050) (Original data) (Mendeley Data).

Author Contributions

Abdollah Baghaei Daemei contributes to conceptualization, methodology, software, validation, analysis, investigation, data collection, draft preparation, manuscript editing, and visualization. Ruggiero Lovreglio, Zhenan Feng, and Daniel Paes contribute to supervision, manuscript editing, preparing the final manuscript draft, resources, and review & editing. All authors have read and agreed with the manuscript before its submission and publication.

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