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Concept Paper

Retrofitting Housing with Lightweight Green Roof Technology in Sydney, Australia, and Rio de Janeiro, Brazil

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Abstract: The built environment contributes around half of total greenhouse gas emissions and with 87% of residential buildings that we will have by 2050 already built, it is vital to adopt sustainable retrofitting practices. The question is: what are the viable solutions? One answer may be green roof retrofitting. The environmental benefits include reduced operational carbon emissions, reduced urban heat island effect, increased bio-diversity, housing temperature attenuation and reduced stormwater run-off. The economic benefits are the reduced maintenance costs and lower running costs. The social gain is the creation of spaces where people have access to green areas. However, the barriers to retrofitting include the perceptions of structural adequacy, the risk of water damage, high installation and maintenance costs, as well as access and security issues. Many Australian and Brazilian residential buildings have metal sheet roofs, a lightweight material with poor thermal performance. During the summer, temperatures in Sydney and Rio de Janeiro reach 45 degrees Celsius, and in both cities, rainfall patterns are changing, with more intense downpours. Furthermore, many residential buildings are leased, and currently, tenants are restricted by the modifications that they can perform to reduce running costs and carbon emissions. This research reports on an experiment on two small-scale metal roofs in Sydney and Rio de Janeiro to assess the thermal performance of portable small-scale modules. The findings are that considerable variation in temperature was found in both countries, indicating that green roof retrofitting could lower the cooling energy demand considerably.

Keywords: green roof retrofitting; Sydney; Rio de Janeiro; thermal performance; residential buildings; housing; case studies

1. Introduction

There is a consensus among climate scientists that global weather patterns are changing, with some regions getting hotter and drier, while others will become wetter [1,2]. One of the highest contributors to human-induced climate change is the built environment [2]. Within the built environment, the biggest land use type contributing to greenhouse gas emissions is the residential sector [3]. While efforts are being made globally to improve sustainability in buildings through operational and embodied energy-efficient design, most of the stock that will exist by 2050 is already here. It is estimated that 87% of residential buildings the U.K. will have in 2050 been built already [4]. With many existing residential buildings leased and home ownership rates in decline in many countries, as well as many other residential buildings that could benefit from a low-cost, easily retrofitted means of reducing energy costs and carbon emissions, this exploratory research is a worthwhile undertaking.

In addition, many cities are experiencing rapid urban expansion and/or densification, which contributes to the urban heat island effect, whereby city centres are sometimes up to five degrees warmer than the outer suburbs [5]. In addition, within some cities, urban heat canyons are created, so that heat is trapped between buildings, which can contribute to negative human health impacts and even fatalities during excessively hot days [6,7]. In the recent past, high temperatures have been observed worldwide; Rio de Janeiro experienced historical record high temperatures in February, 2014 [8]. In a four- to five-day period of plus 45 degree Celsius days in January, 2014, in Melbourne, Australia, more than twice the average rate of mortality was experienced. These deaths were attributed to the excessive heat conditions, which were exacerbated in the city centre, where heat was trapped between buildings and under tree cover in an urban canyon [9]. With given predicted climate change impacts and an ageing population, these figures look likely to increase. On this basis, the focus for climate change mitigation is through adaptation and sustainable retrofitting of existing buildings. In addition, the statistics of increasing temperatures and ageing populations are broadly similar across many countries, and retrofitting buildings has universal application. The question is: what are the viable solutions in terms of retrofitting our existing residential buildings? Here, viable is defined as the retrofit measures that are environmentally, economically and socially worthwhile to undertake.

If the aim is to reduce building-related green-house gas emissions, for some regions, the goal will be to keep buildings cool and, therefore, to reduce cooling loads, whilst for other areas, the problem will be one of retaining heat and reducing heat loss through leaky buildings. Whereas in other regions, the problem will be one of accommodating increased frequencies of intense rainfall [5]. One answer, which may suit a number of regions, is to retrofit buildings with green roofs, as there are environmental, economic and social benefits.

The environmental benefits include potential reductions in operational carbon emissions, reductions in the urban heat island, increases in bio-diversity, housing temperature attenuation and reductions in stormwater run-off [10–12]. Air quality is improved as plants remove carbon dioxide and harmful pollutants from the atmosphere, and in addition, green roofs provide habitats for insects, birds and reptiles to shelter and find food and water [13].

Thermally, the mass of the green roof improves the insulating qualities of the building by reducing heat transmission through the roof. Much heat loss occurs through the roof as heat rises and then escapes through inadequately-insulated and poorly-sealed roof structures. Some authors have evaluated the role of green roofs' cooling and warming potential in energy savings and the potential for retrofitting, based either on modelling or experimental data [10]. There is consensus that, in non-insulated buildings, which are common in Rio de Janeiro and Sydney, green roofs can improve the insulation properties and reduce annual energy consumption. According to Castleton [10], over the past 10 years, several studies have shown that green roofs can offer benefits in winter heating reduction, as well as summer cooling. Nichaou *et al.* [14] showed an annual energy saving potential of green roofs on non-insulated buildings for heating of 45%–46% and for cooling of 22%–45%. Wong *et al.* [15] found an annual energy savings of 10.5% for an un-insulated extensive green roof covered in turf, compared with a non-greened un-insulated roof. However, the energy savings are realised only on floors near the roof. Alcazar and Bass [16] state that due to the tall nature of the buildings, roofs comprise around 16% of the total building envelope, and the largest reductions in energy consumption were seen in rooms directly below the green roof. No energy savings were found more than three floors below the roof [16].

Where stormwater or pluvial flooding is an issue, green roofs can reduce the run-off rate and also filter or cleanse the water passing through the roof covering [5]. There are numerous environmental benefits from the installation of green roofs in urban settlements, which are suitable whether the problem is one of excess stormwater or the need to enhance thermal performance. It is the case that the specification of white roofs, roofs that are painted white or with reflective colours, is the most cost-effective means of reducing the heating load in buildings; however, bio-diversity and air quality benefits are absent with this option [17]. The decision to retrofit a green roof has multiple variables and should not be evaluated on one variable alone, but on the multiple benefits that are delivered [18].

Economically, the benefits to occupiers and owners are reduced roof maintenance costs and lower running costs [10]. There are erroneous perceptions, however, among the practitioner community that green roofs lead to higher maintenance costs [18], which is resulting in less application of green roof technology in buildings.

The third aspect, the social gain, is the creation of spaces where people have greater access to nature. The biophilia effect describes the phenomenon in which humans experience positive feelings as a result of the connection to the natural environment [19]. Unfortunately, for many city residents, access to the natural environment is limited and diminishing [12]. In Sydney, for example, it is estimated that there are less than 22 square metres per resident and that only about 15.5% of the city is covered by urban canopy [12]. The city wishes to increase this level of urban greenery for the health and well being of the community [12]. There are initiatives seeking to increase the amount of urban greenery in Sydney by twenty percent before 2020 [20], and the application of green roofs would be a way of contributing to this target. On the contrary, the amount of green spaces in Rio de Janeiro has decreased significantly, mostly due to the lack of space and population growth [21]. No plans have been adopted yet to deal with this problem.

However, there are barriers to the adoption of retrofitted green roofs, which include perceptions of structural adequacy, risk of water damage, high installation and maintenance costs, as well as access and security issues [11].

In some locations, such as Sydney, the intent will be to reduce cooling loads, whereas others locations, such as London, will desire thermal insulation or reduction in stormwater run-off. The ability to meet the demands will depend on the available budget and physical characteristics. Although the technology to design and retrofit green roofs exists, the uptake and the demand have not been high. Overall, the gains have not been deemed sufficient, and in both cities, the existing numbers of residential green roofs confirm this observation. In 2014, the City of Sydney adopted the first green roofs and walls policy for Australia, which sets out a commitment to increase the number of high quality green roofs and walls [22]. The policy includes a three-year implementation plan to ensure that the policy is understood, properly adopted and integrated. There are 59 green roofs in Sydney currently, which serve a variety of purposes, including enhancing thermal performance [12].

Many Australian and Brazilian residential buildings have profiled metal sheet roofing; a lightweight material with poor thermal performance, where the heat transfer is very high. Many buildings have little or no insulation to offset the high heat gains. During summer periods, Sydney and Rio de Janeiro, experience temperatures that can reach 45 degrees Celsius and rainfall patterns that are variable and changing, affected by La Niña and Il Niño weather cycles. This research reports on an experiment on two small-scale profiled metal sheet roofs in both cities to assess thermal performance. Metal roof coverings are fairly typical in Australian housing design and have less load bearing capacity than other coverings, and a lightweight, low-cost, easily-installed module might be a good option for retrofitting; the question that needs addressing is: how do these modules perform? In each city, one roof was left as a control, whilst the second roof was planted with succulent plants in lightweight trays. Data were collected using thermal data loggers over a summer and autumn season. The paper discusses the findings and the potential for retrofitting residential stock with lightweight trays planted with succulents.

2. Methodology

The methodology adopted is predicated on the development of simple technologies to mitigate the problems created by increasing urban densification, which exacerbates urban heat islands and contributes to uncomfortably high internal housing temperatures. There are many technologies and approaches available to execute this research, but in this case, the researchers aimed to use adaptive techniques that minimised initial costs and maintenance costs; in other words technologies that would be affordable and easy to implement. For this reason, this project used lightweight removable modules of vegetation (rectangular containers) of a low thickness. This modular system enables planting, cultivation and maintenance off-site to be undertaken. This is an exploratory study to assess the thermal performance and feasibility of retrofitting with low-cost, lightweight roofing modules for metal sheet roofing.

The researchers sought to evaluate the performance of a green roof retrofit system, which could be widely used in metropolitan areas. At this point, there is an absence of empirical evidence on the performance of green roofs in Australia, with most data coming from the U.S. or Europe, where climatic conditions are very different [23]. Similar conditions exist for South America in terms of empirical data on green roof performance. Previous studies have shown significant variations based on temperatures, evaporation rates and wind conditions, which affect the performance of green roofs, but they have used longer life and more permanent technologies [23].

Two experiments were performed; one in Australia (Sydney) and one in Brazil (Rio de Janeiro). The Australian site is located on the roof of a building at the University of Technology, Sydney, in Ultimo, and the Brazilian location is on the roof of an existing building at the Oswaldo Cruz Foundation (Fiocruz).

Rio de Janeiro (S 23°; W 43°) has a tropical wet and dry or savannah climate with dry winters (Aw), and Sydney (S 33.9°; W 151.2°) has a humid subtropical climate (Cfa). The high and low annual average temperatures in Rio de Janeiro are 27.3 and 21 °C, respectively, whereas for Sydney, these temperatures are 21.7 and 13.9 °C. However, extreme higher temperatures are more commonly observed in Sydney (39.8–48.8 °C), rather than in Rio de Janeiro (37.7–39 °C) [2].

Succulent plants, such as variegated sedum, *Echeveria glauca* and *Kalanchoe* quicksilver, were selected on the basis of their higher drought resistance qualities and a lower risk of fire. Furthermore, these species can develop easily in shallow soils, and therefore, importantly, structural reinforcement of existing roofs is unnecessary. Additionally, due to the modular characteristics of the planting containers, the modules can be applied directly onto the roof covering, be it profiled metal sheeting or tiles.

Rectangular plastic containers were selected according to the availability at the different sites (Rio de Janeiro, 400 mm × 500 mm, and Sydney, 190 mm × 330 mm) where the experiments were performed, as shown in Figure 1.

(**a**) (**b**)

Figure 1. Rectangular plastic containers used in the temperature experiments. (**a**) Brazilian module, provided by Cidade Jardim Institute; (**b**) Australian module.

Both containers have a water storage system, which meets two main objectives. Firstly, it provides water to the soil through evaporation, enhancing the plants survival, even during extended periods of no rainfall. Secondly, it can attenuate temperature fluctuation due to the water layer between the soil and the roof.

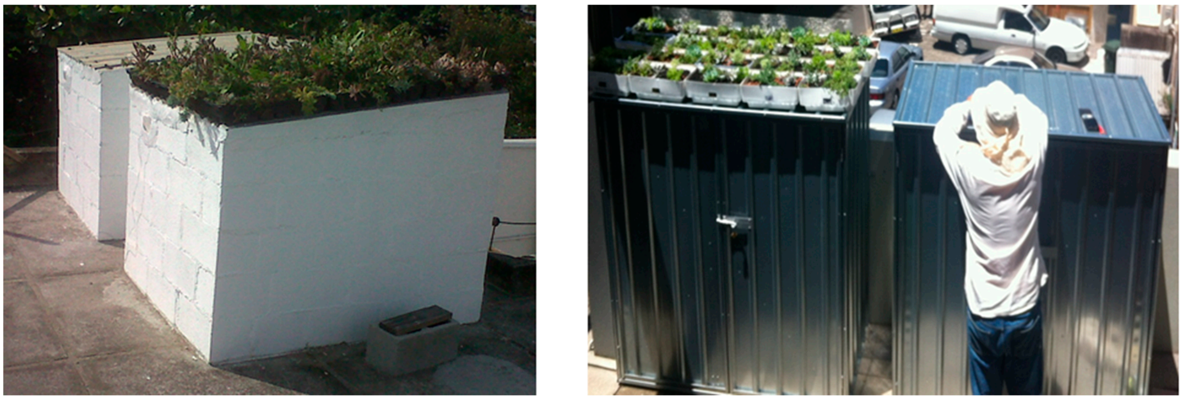
The soil is separated from the drainage system by a permeable fabric (Geotextile), which allows the passage of water, but prevents the soil from leaking into the water chamber. For the plant species used in this research, a soil with good drainage and low organic content was used. A composition of two parts of sand to one part of loam was employed.

The evaluation of the green roofs' cooling potential is performed by the comparison between two housing prototypes with vegetated and non-vegetated roofs. Due to financial limitations and because of the exploratory nature of the research, it was not possible to use full-scale housing for the experiment.

Therefore, small-scale structures are used to demonstrate the thermal performance of a non-green, traditional roof and a green roof. The experimental set-up comprises covering the roof of one of the prototypes with planted soil containers. Different types of housing prototypes are considered in this study. As shown in Figure 2, the Rio de Janeiro tests were carried out using small blockwork houses covered with metal sheeting, whereas in Sydney, metallic sheds were employed. In Australian housing, profiled metal sheet roofs are typically specified, and for this reason, the metal sheds were selected.

A simultaneous comparison between the records of temperature inside the vegetated and non-vegetated structures was made using data loggers that collect continuous temperature records over long periods of time. The temperature measurements were carried out using Extech TH10 Temperature USB Data loggers, using a time sampling of 30 min. The Rio de Janeiro tests were performed over 194 days, from 17 October 2012, to 29 April 2013, whereas the Sydney trial tests comprised a 97-day period from 11 December 2013, to 18 March 2014.

The data loggers were positioned at different heights inside each of the prototypes, according to the experimental site. In Rio de Janeiro and Sydney, they were placed 250 and 50 mm, respectively, below the top of the structure. All of the temperature differences observed are attributed only to the influence of heat incidence on the structures, given that the weather conditions between the vegetated and un-vegetated prototypes are identical.



(**a**) (**b**)

Figure 2. Housing thermal experiments. (**a**) Rio de Janeiro; (**b**) Sydney.

3. Data Analysis and Discussion

The results with regards to the green roof cooling potential for the two experimental sites (Rio de Janeiro and Sydney) are shown in Figures 3 to 5 below. Notwithstanding some basic differences in the structures (that is, blockwork in Rio de Janeiro and metal sheeting in Sydney), the tendency in temperature attenuation is evident. The measurements performed in Rio de Janeiro and in Sydney show that green roofs are able to attenuate daily variations of temperature.

3.1. Rio de Janeiro Data

Figure 3 presents a comparison between the non-green and green roofs' internal temperatures, during the 194-day data collection period, which comprises the whole Brazilian summer period and also part of spring and autumn. Some of this work was partially reported in [24].

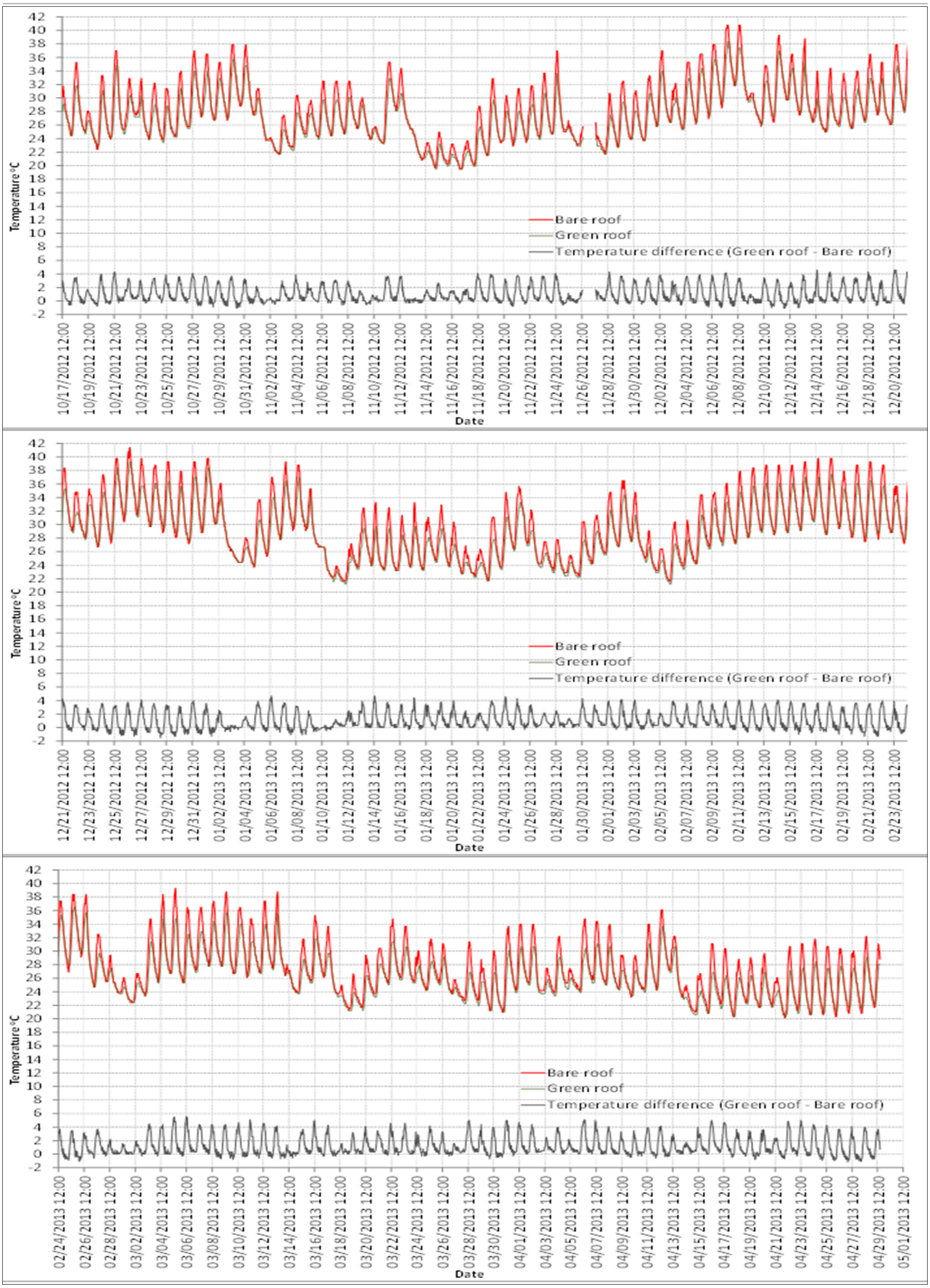


Figure 3. Comparison between the inner temperature of the non-green and green roofs, Rio de Janeiro, Brazil.

Figure 4 presents the typical detail of three out of the 194-day temperature comparison, where it mostly can be observed that the highest temperature differences are between 12:00 and 15:00.

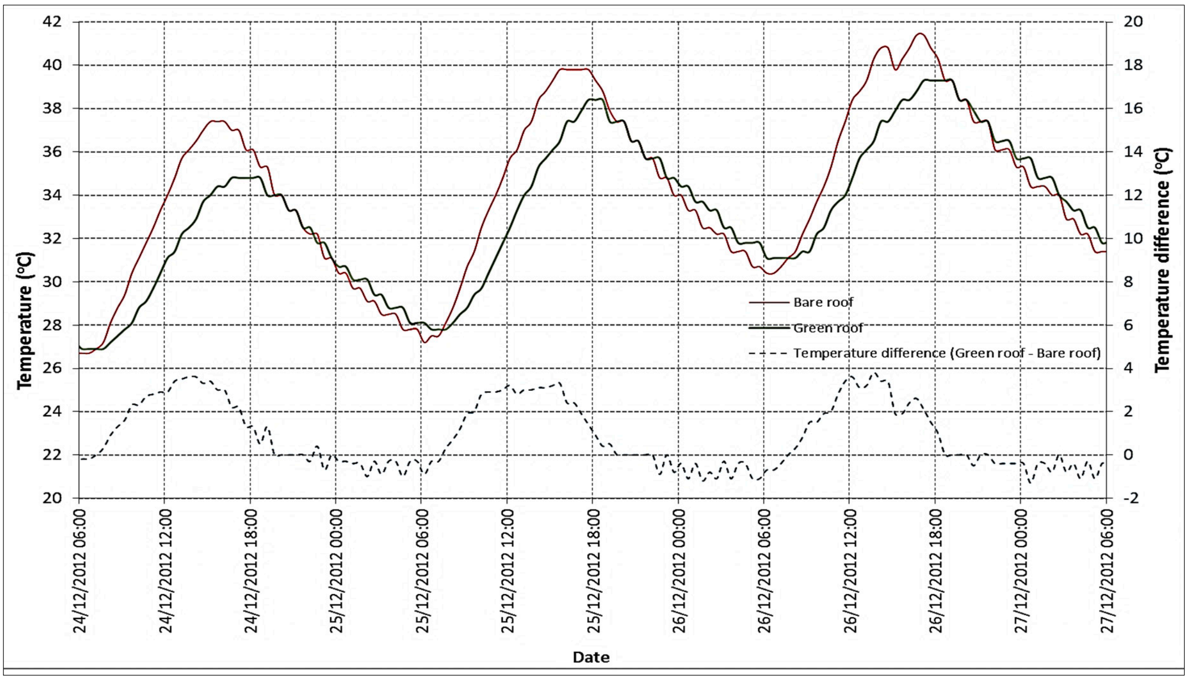


Figure 4. Typical detail of the temperature records between green and non-green (bare) roofs. Rio de Janeiro site.

During the whole period of investigation (194 days), the non-green roof presented maximum, minimum and average temperatures equal to 41.1 °C, 20.1 °C and 28.8 °C, respectively. Correspondingly, the values observed in the green roof case were 39.3 °C, 20.3 °C and 27.7 °C.

Based on daily variations of temperature, the maximum values observed during the daytime for non-green and green roofs varied from 23.9 °C to 41.4 °C and 23.2 to 39.3 °C, respectively. The minimum values that occurred during the nighttime varied from 20.1 °C to 31.8 °C for the non-green roof and 20.3 °C to 31.8 °C for the green roof. It is important to highlight that the green roof cooling potential, in attenuating high temperatures, is not directly related to the differences observed between those limits presented, due to the existing time lag between the non-green and green roof temperature peaks.

Comparing the simultaneous temperature differences between green and non-green roofs (Figure 1), it was observed that these values vary from –1.5 °C to 5.6 °C. The temperature differences were dependent of the temperature background. That is to say, that past temperature influences the present ones, showing that green roofs tend to buffer thermal exchanges. If, for example, a warm day increases the inner temperature, this internal heat will influence the following temperature. Positive values mean higher non-green roof temperature. The lowest positive temperature differences between non-green and green roofs (≤2 °C) were observed when the internal non-green roof temperatures were below 30 °C. The highest positive temperature differences (≥5 °C) were registered at the end of the summer period, when during the previous nighttime period, the green roofs' temperatures were cooler than the non-green roofs. However, higher green roof nocturnal temperatures contribute to weakening the following daytime temperature differences (<5 °C). The delay observed between the temperature peaks of non-green and green roofs results in slightly warmer green roof temperatures (negative differences) during the nighttime and early morning periods, which contributes to diminishing the temperature differences the following day.

3.2. Sydney Data

Despite the shorter period, when compared to Rio de Janeiro data, it was observed that a significant green roof cooling occurs. However, according to the characteristics of the site where the experiments were undertaken, a particular pattern in temperature registers can be observed. As shown in Figure 5, a sudden reduction in temperature occurs both for non-green and green roofs around 3 pm, due to the shading created by adjacent buildings. This figure shows an attenuation in temperature variation for green roofs, which is consistent with their insulating properties.

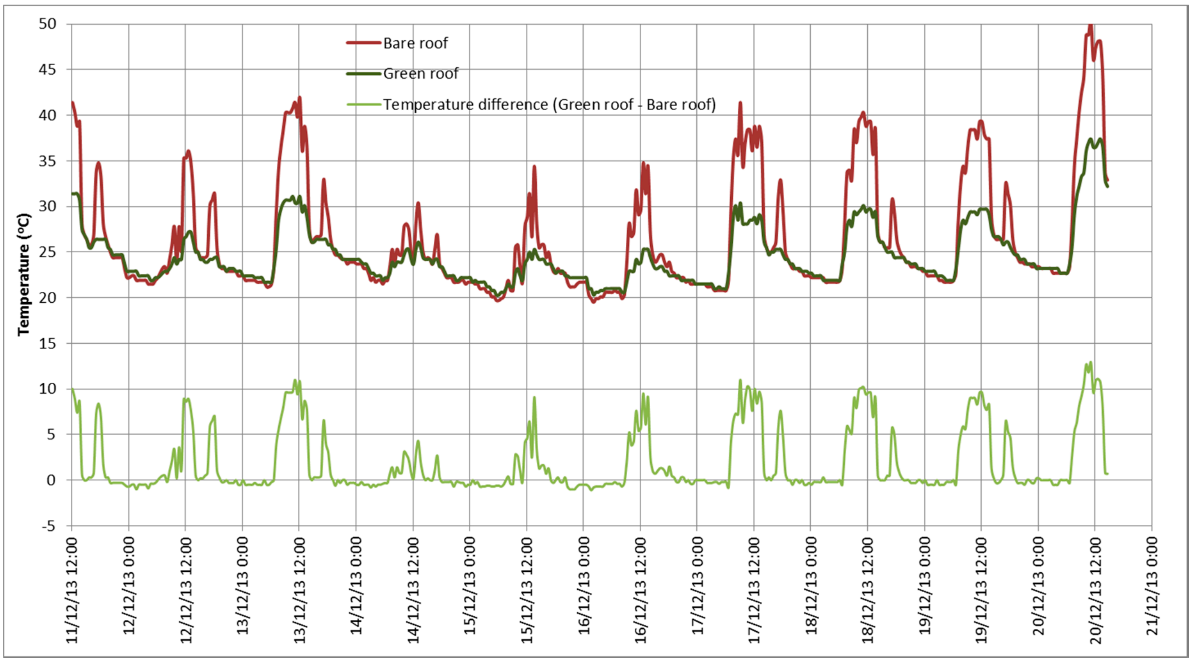


Figure 5. Influence of shadows on temperature caused by adjacent buildings for Sydney experimental roofs.

Figure 6 presents a comparison between non-green and green roof inner temperatures, for 133 days, during the summer period. The Sydney non-green roofs presented maximum, minimal and average temperatures equal to 50.3 °C, 17.2 °C and 25.2 °C, respectively. The values observed in the green roof case were 37.4 °C, 17.6 °C and 23.9 °C.

The temperature differences between green and non-green roofs varied from −1.6 °C to 14.8 °C. The lowest positive temperature differences between the non-green and green roofs (≤4 °C) were observed for the non-green roofs' inner temperature being under 30 °C. The highest positive differences (≥10 °C) occurred at non-green roof temperature peaks higher than 42 °C.

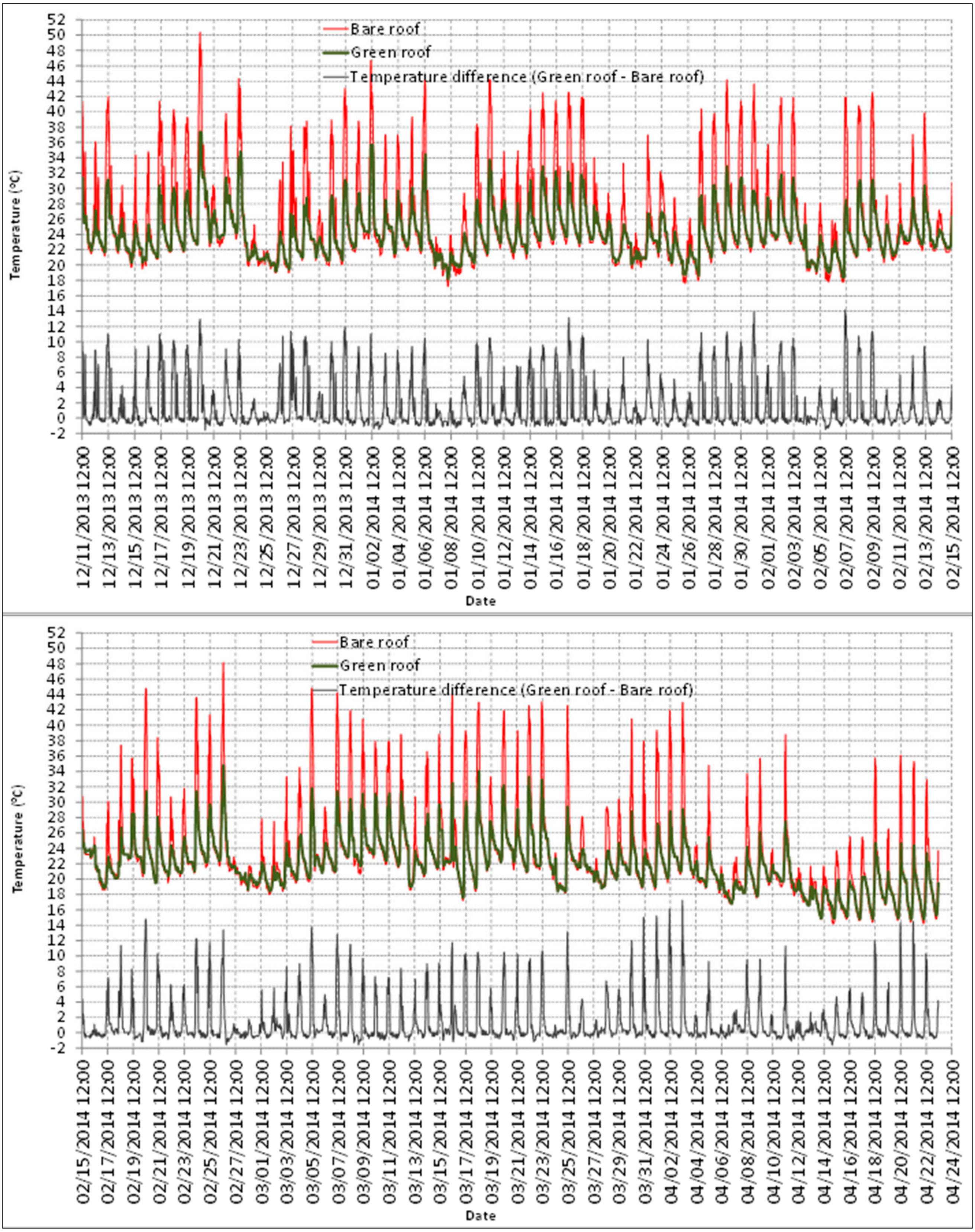


Figure 6. Non-green and green roofs' inner temperature comparison, Sydney, Australia.

Figure 7 depicts a two-day detail of the whole set of data presented in Figure 6. Similarly to what was observed at the Rio de Janeiro site, the highest differences in the temperatures between green and non-green roofs also were detected around noon. Negative differences were evident practically along all nighttime periods, additionally corroborating the efficiency of the green roof in attenuating high and relatively low temperatures.

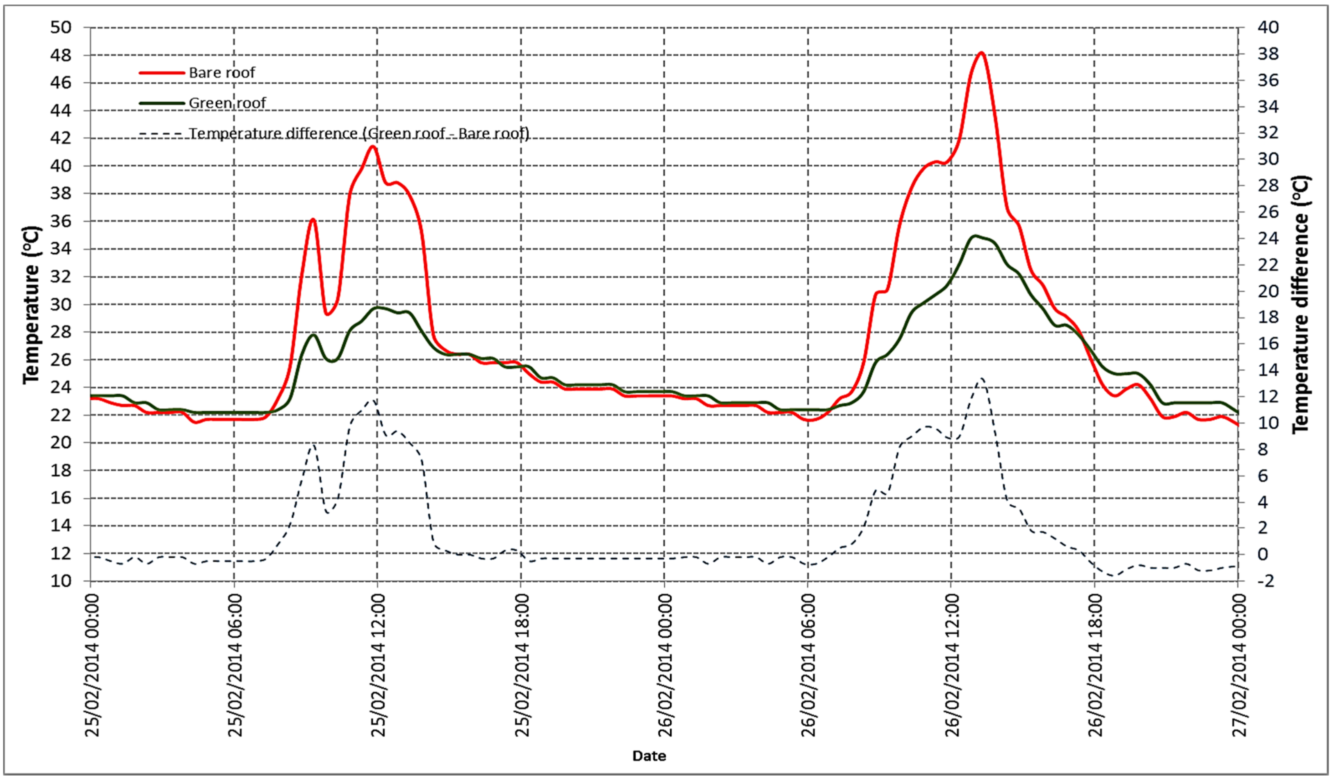


Figure 7. Typical detail of the temperature records between green and non-green roofs, Sydney site.

3.3. Evaluation of Rio de Janeiro and Sydney Data

This work does not solely intend to perform a comparison between the Sydney and Rio de Janeiro experiments, but it aims to evaluate the potential of the green roofs to attenuate housing temperature.

In both the Rio de Janeiro and Sydney cases, it could be seen that the green roof's capabilities lie in improving the insulation properties of the roof, due to the reduction of heat gain in the housing prototypes and, consequently, the temperature reduction, when compared to the non-green roof. In other words, the vegetation increases the thermal performance of the roof, which is quantified by the *U*-value parameter. This parameter quantifies the heat gain or loss through a surface and is also known as the overall heat transfer coefficient. A decrease in this parameter means that there is an improvement in thermal performance due to the attenuation of heat transfer into the buildings. According to work presented by Wong *et al.* [15], in a non-thermal insulating building, a green roof coverage with turf reduces the *U*-value from 2.39 to 1.19 W/m^2K.

Table 1 depicts the non-green and green roofs' maximum, minimum and average temperatures, as well as their higher and lower differences for the Sydney and Rio de Janeiro sites. It was observed that the green roof cooling potential in Sydney was greater than that in Rio de Janeiro, which was most likely due to the existing differences in both experiments. This may be attributed basically to the positioning of the temperature data loggers. In Sydney, they were located about 50 mm below the roof, whereas in Rio de Janeiro, they were 250 mm below the roof. As mentioned previously, the goal of this work is not the comparison between the two sites. Surrounding buildings for parts of the day overshadowed the Sydney site, and the amount and duration of overshadowing changes over time as the Sun's height increases or decreases. The study sought to evaluate the insulating properties of green roofs in different scenarios and under different criteria. This can be corroborated by temperature differences (up to 14.8 °C) observed in the Sydney experiments, taken so close to the inner roof surface, composed of a good thermal conductor (metal sheet).

Table 1. Experimental temperature comparison between Sydney and Rio de Janeiro.

Temperatures (°C)	Rio de Janeiro			Sydney		
	Non-green roof	Green roof	Simultaneous temperature difference	Non-green roof	Green roof	Simultaneous temperature difference
Maximum	41.4	39.3	5.6	50.3	37.4	14.8
Minimum	20.1	20.3	–1.5	17.2	17.6	–1.6
Average	28.8	27.7	-	25.2	23.9	-

According to Castleton [10], in addition to insulation, green roofs also add thermal mass, which is the material capacity to absorb and store energy, and thus, they provide inertia against temperature fluctuation, resulting in a temperature peak delay. However, analogous to Castleton [10], the green roof internal temperature peak delay observed is not relevant when compared to the non-green roof. In the present work, according to Figures 4 and 7, a slight time delay between green and non-green roof temperatures in both Sydney and Rio de Janeiro sites can be seen. The higher observed delays mostly ranged from 30 to 90 min, showing a more insulating, rather than a thermal mass insulating, property of the green roofs.

Besides the insulation properties of the green roofs, it is believed that their relevance in temperature attenuation and, consequently, energy savings in urban environments may be affected by neighbourhood shading conditions and different roof side conditions.

Another aspect to consider is related to the water and/or its levels in the soil and in the storage systems. Due to the high specific heat, water is supposed to provide inertia against temperature fluctuations. Although water levels have not been monitored in the current study, previous works have evaluated this effect [10,15,16,25,26].

Regarding the soil moisture content, studies performed by Alcazar and Bass [16] revealed that the thermal performance decreases for wetter soils, since water is a better conductor than air. However, Del Barrio [25] indicates the opposite, that is water promotes insulation. The results presented by Wong *et al.* [15] concur with Nichaou *et al.*, Alcazar and Bass [16] and Castleton *et al.* [10]: higher U-values (heat gain) being observed for higher water soil content.

Lazzarin *et al.* [26] presented an evaluation of passive cooling and the role of evapotranspiration, considering the wet and dry soil conditions of the green roofs. According to these authors, compared to a traditional roof, even under dry conditions, green roofs reduce the incoming heat flux by 60%. However, in a wet green roof, the additional evapotranspiration not only avoids heat entry, but also removes it from the building. The water effect in the green roofs' cooling potential seems to be dependent simultaneously on the soil water content and the evapotranspiration process. According to

Castleton [10], the moisture levels of the soil influence the heat loss through evapotranspiration. Wet soils can promote heat removal from the building when evapotranspiration effects are considerable.

Different studies have assessed the evapotranspiration effect of succulents in extensive green roofs. According to Berghage *et al.* [27], it has been previously hypothesized that transpiration from succulents is not significant when compared to evaporation from bare substrate. However, these authors stated that the transpiration has a relevant role in the evapotranspiration process under well-watered soil conditions; and during dry conditions, these plants stop transpiring, leading to similar levels of evapotranspiration and evaporation [28].

Based on studies presented by Rezaei and Jarret [29], depending on the seasonal condition, respectively for winter and summer, planted plots with succulents transferred to the atmosphere 34% and 51% more water due to the evapotranspiration process when compared to bare soil. According to experiments performed by Voyde *et al.* [30], the observed results challenge the hypothesis that succulent plants hold water all the time. Furthermore, using a lightweight modular system, their results indicated that when the water supply is not limited, transpiration contributes approximately 48% of the evapotranspiration.

Regarding the influence of the water in the storage systems, Alcazar and Bass's [16] studies revealed that water storage can improve the thermal performance of green roofs. Even though the water levels have not been monitored, their results show a reduction in *U*-values compared to systems without water storage. Furthermore, no monitoring has been carried out in the present work, and the water levels do not seem to have an important role in green roof thermal performance.

Due to water's thermal mass, a delay would be expected in the Sydney and Rio de Janeiro results between temperature peaks considerably greater than the observed ones. Additionally, the modular system adopted herein is simply supported on top of the roof, and thus, it promotes the passage of air, which is believed to enhance the thermal insulation more so. It should be pointed out also that only temperature, and not solar radiation levels, were collected in the two exploratory studies presented. Thus, it is posited that the temperature attenuation provided by the green roofs must be directly related to high solar radiation levels and that during cloudy days, this effect tends to be less pronounced.

4. Conclusions

Both experimental setups in Rio de Janeiro and Sydney have demonstrated the potential for lightweight, portable green roof modules to be retrofitted on metal sheet roofing as a means of cooling buildings, reducing carbon emissions and contributing towards zero carbon targets. However, the exploratory experiments carried out in Sydney presented a potentially better green roof performance in temperature attenuation, which may be attributed to the closer positioning of the data loggers in relation to the roof.

There are different typologies regarding green roof technologies. At different scales, from extensive to intensive systems, it is expected that different soil depths, substrate composition, water retention layers, types of plants, soil moisture content, *etc.*, have a particular role in heat transmission, thermal inertia and evapotranspiration. The low cost, modular, portable, lightweight green roof adopted here comprises an extensive system, where all the components are gathered in a single module. The only difference between the experimental systems explored here and the conventional ones is that there is no full contact between the modules and the underlying roof, which provides some air circulation (and some extra insulating effect). However, considering that there is partial contact between the modules and the roof, it was, in fact, observed that there was some effect on inertia and the time shift when the inner temperatures of the bare and green roofs are compared. Similar results from experiments where modular systems were employed [27] show the same trend observed in the present exploratory study.

The U-value parameter has been used to quantify the heat gain or loss through a surface according to different works presented in the literature so far. In addition to Wong *et al.* [15], who evaluated this parameter from exposed roofs to covered roofs with different types of vegetation and soil substrates, Nichaou *et al.* [14], Alcazar and Bass [16] and Castleton [10] presented an evaluation of this parameter, especially for lightweight green roofs with depths of 75–100 mm and 50 mm, respectively. These works not only corroborate the role of the green roofs in reducing *U*-values substantially when compared to exposed roofs, but also noted the effects of evapotranspiration, thermal inertia, soil moisture content and water storage. According to Castleton [10], in addition to insulation, green roofs add thermal mass and provide inertia against temperature fluctuation. A green roof may work as a passive cooler. In the case of high external temperatures, not only the entering heat flux is cancelled, but also a slight outgoing flux is produced due to the cooling effect of the evapotranspiration.

The water levels in the soils are shown to affect the extent of heat loss due to the evapotranspiration process. The thermal conductivity of the soil is proportional to the water content, as drier soil conditions offer better thermal insulation.

An alternative to a green roof; known as a cool roof, is to paint the roof surface white, and this is common practice in the Mediterranean. This approach lowers the air and surface temperature, and less heat energy propagates into the building. According to Diep [31], cool or white roofs have an extreme capacity to reflect sunlight and heat. Green roofs do not reflect as well as white roofs. However, both roofs manage to cool buildings on hot days. During summer periods, green roofs have a major role in energy savings, due to the cooling effect of evapotranspiration, while in the winter, they are able to reduce heat loss, because of their more pronounced insulation properties.

Water levels were not monitored in this feasibility study. However, it is noted that due to the delay between the temperature peaks observed, the water levels do not seem to have a predominant role in green roof thermal performance. Furthermore, the passage of air is allowed in the modular system adopted, due to the existing space between the planted trays and the underside of the roof. This characteristic seems to enhance the insulating properties of the system and/or mitigate the effects of the water storage.

Even though no low temperatures (that is <16 °C) were measured, the negative differences observed (the green roof temperature was higher than the non-green roof) may indicate the potential for green roofs to attenuate extremes of temperature, due to their insulation properties. It is probable that different substrates would provide different results, and this should be investigated.

The temperature differences showed a relationship to the temperature background. The slight delay between temperature peaks of non-green and green roofs results in slightly warmer green roof temperatures (negative differences) during the nighttime and in the early morning periods, which contribute to weakening the temperature differences during the following day.

Considerable differences of temperature between city centres and suburban urban areas have been reported in the literature. Green roofs promote thermal comfort improvement, attenuating heat exchanges between the internal and external environments of buildings. Additionally, as these results suggest, attenuation of the urban heat island effect in large cities can be achieved, if green roofs are adopted for new building and as retrofitting for existing buildings on a city scale. For example, a modelling study for Toronto, Canada, predicted that adding green roofs to 50% of the available surfaces downtown would cool the entire city by 0.1 to 0.8 °C. Irrigating these roofs could further reduce temperatures by about 2 °C and extend a 0.5–1 °C cooled area over a larger geographic region [32]. The research has demonstrated that roof structures planted with succulent plants are viable, as the plants survived well and could provide a low-cost, drought-tolerant, lightweight option to reduce heat gain and heat loss through roof structures in some regions of NSW and Australia.

However, as far as the thermal effect is concerned, the adoption of green roofs in urban centres is a partial solution, due to the contribution of the building facades in the overall heating. Thus, a combination of green walls and green roofs could be an optimum solution for this problem. Furthermore, with regard to energy saving issues, considering that buildings comprise the most part of big cities, the use of green roofs would only bring an effect to top floors, which reinforces the combination of these systems (green roof and green walls) in the urban environments.

Additional experiments with structures that more closely emulate typical Australian housing specifications in terms of wall construction would be very useful to consolidate the preliminary results found here. One of the limitations of this exploratory research is that the walls of the shed are profile metal sheeting, which is not typically specified in housing, although it does exist. In the Rio de Janeiro experiments, brick walls comprise a common type of solution adopted in the majority of housing. However, additional procedures, such as green walls, should be evaluated in order to mitigate the existing thermal exchanges through the walls.

The lightweight modular green roof system adopted in our prototypes in Rio have been in testing for approximately 2.5 years, during which time, no maintenance has been required. The succulent plants have shown extreme resistance to intense heat, drought periods and atmospheric pollutants. The Sydney experiment has been underway for a year, and no maintenance of the plants has been required.

This study, as performed to date, used a modular system that has enabled new adaptive techniques to be adopted, where the green roof set-up costs have been substantially reduced using reusable materials. This novel approach is being tested at the Fiocruz campus using cellular plastic boxes, which are commercially available at a low cost. Additionally, these boxes are also being adopted as a new green wall system, arranged side by side in “U” metal profiles bolted on the walls. This new modular system has been shown to be applicable to roofs and walls and comprises a portable green patch solution that is intended for widespread use at a large scale in urban environments, which will lead to better environmental outcomes for the inhabitants.

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Author Contributions

Both authors contributed equally to this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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