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Evaluating the Thermal Performance of Retrofitted Lightweight Green Roofs and Walls in Sydney and Rio de Janeiro

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Abstract

With increasing densification in urban settlements, environmental issues are a challenge in the sustainable development of all cities globally. Considering that the built environment releases almost half of the total greenhouse gas emissions, an effective solution to mitigating the impacts of increasing temperatures can be the improved performance of existing buildings. Furthermore 87% of the buildings we will have in 2050 are already built. Retrofitting roofs and walls with a living vegetated system such as green roofs and walls could be an upgrade option, increasing sustainable construction. The benefits are improved thermal performance but also improved air quality, stormwater attenuation, increased bio-diversity and lower heating and / or cooling energy consumption. No empirical data exists for Sydney and Rio de Janeiro and the question is; what is the extent of thermal improvement with retrofitted green walls and roof in timber framed and blockwork structures? This study analyses both effects and benefits of the green roofs and walls through an experiment in two countries: one in Sydney, Australia; a timber framed construction, and another one in Rio de Janeiro, Brazil; with blockwork construction. This difference in the material choice was made according to the most common type of construction for housing in each country. In each site, the walls and the roof of one of the prototypes were covered with plants and compared to the performance of an unplanted but otherwise identical prototype. The thermal performance was analysed by observing the temperature variation simultaneously in a non-vegetated and vegetated structure. The initial findings show that the combination of green roof and green walls have a relevant role in temperature attenuation. These results indicate, that this lightweight retrofit green technology could not only represent an important advance on sustainable development, but can that it also lead to more comfortable internal conditions for humans living in dense urban environments.

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1. Introduction

This paper discusses the importance and impact of green retrofitted systems and considers the thermal performance of buildings and the consequences of its effects on people and in the urban environment. The purpose of this paper is to analyse and discuss empirical data collected through an experiment made in Rio de Janeiro (Brazil) and in Sydney (Australia) which simulated a house with lightweight green walls and a green roof. In Brazil, the construction was brickwork whereas in Australia it was timber framed. The paper describes the impact of the green system considering the thermal performance through observation of the temperature difference. This paper commences with a literature review which discusses the consequences of built environment pollution, global temperature increase, and the expansion and densification of urban settlements. Through this analysis, it is apparent that green buildings can mitigate these impacts and conversely, when they are not a good option. The research addresses other potential benefits for green roofs and walls and; in which regions these building types would be more effective. The experiment performed has some limitations that must be considered. Firstly, the experiment is a small scale building that does not have doors, windows or any other feature that allows the air flow and which influences indoor temperature. Secondly, the data collection time is limited and does not cover all seasons. Thirdly, the experiments did not have irrigation systems and watering was not controlled nor measured. Fourthly, the size of the plant holders did not allow deep substrates. Finally, as the experiments were conducted in Sydney and in Rio de Janeiro during the summer period, there is no data for low temperatures.

2. The Literature

2.1 The need for retrofit in the built environment and the relationship to sustainability

Globally populations have been increasing and migrating, as a consequence of development of urban areas, to cities. According to the United Nations, Department of Economic and Social Affairs, Population Division [1], 54 per cent of the world's population was residing in urban areas in 2014, however it is estimated that by 2050, 66 per cent of the world's population will live in cities. As a result, many new buildings are being constructed to accommodate this growing population and, are considered fundamental to the development of urban settlements. However, concentrations of high-density buildings trigger environmental issues, such as the Urban Heat Island (UHI) whereby temperatures increase in higher density locations [2]. The UHI is exacerbated by the loss of green areas in the urban environment [2]. To mitigate the UHI, a number of cities worldwide, such as Toronto Canada, are promoting environmental systems. These systems, called "green" roofs, comprise planting ground cover, shrubs and other flora on a building's roof [3]. As reported by Fishetti [3], by absorbing rainwater, these roofs can reduce storm-water runoff, easing the burden on local sewers and water treatment systems. An additional work performed by Castiglia Feitosa and Wilkinson [4] showed the increasing performance of green roofs in stormwater retention according to its soil depth. It is also reported that the vegetation can keep the roof cooler in summer, lowering interior air-conditioning costs and therefore, peaking demand on area power plants [5].

2.2 The benefits of green roofs and walls

Green roofs and walls can improve the insulation performance of roofs and walls. While the surface of conventional roofs can reach high temperatures when exposed to high solar intensity, green roofs minimise the temperatures because of some effects: foliage shading, soil thermal resistance, evapotranspiration and many others [6]. Building energy demand and indoor thermal conditions can be affected by the heat flux through a green roof [6]. Therefore, the cooling effect of green roofs can be considered an effective solution for the enhancement of thermal comfort and for the reduction of cooling demand. Further, the temperature difference between ambient air and substrate expresses the cooling effect and it is associated with both green coverage and moisture. To maintain and optimise this effect, it is essential to keep a healthy plant cover and provide an adequate watering system [7].

Another reported benefit is potential for storage of water. According to Moisses [8], each 100mm thickness of a green roof can hold a gallon of water per square foot. In this context, considering New York as an example, if all the rooftops in this city were green, they would represent a billion gallons of storage potential. In this way storm-water run off is attenuated and existing systems function without being overwhelmed. The disruption of replacing existing underground pipework with larger pipes to accommodate increased rainwater runoff, either through the increase of hard surfaces or, because changes to climate have resulted in more intense rainfall, is considerable. Green wall as and roofs are an alternative water sensitive urban design option.

Green roofs protect the roof slab from extreme temperatures and high temperature fluctuations, and because of this protection, green roofs can increase the longevity of roofing membranes [6].

The combined benefits are associated with improving local climate conditions and mitigating global climate change. Several experiments have shown that green retrofitted roofs help to mitigate urban heat island effect by reducing the surface temperature of the building as well as the ambient air temperatures. As a consequence of this phenomenon, green roofs can reduce the amount of energy needed to cool the building and subsequently reduced building related greenhouse gas emissions [9]. In addition, the plants sequester carbon dioxide from the atmosphere. In addition, by reducing the concentrations of particulate matter and other air pollutants, green roofs provide better air quality and can attract bio-diversity.

2.3 The challenges of green roofs and walls

However, there are challenges to the adoption of green roofs and walls. It is imperative to determine the structural adequacy of the existing structures and the design parameters, as it may not be possible to retrofit [5]. Many existing buildings were not designed to bear extra loads, however some are overdesigned with generous safety factors incorporated. In further consideration of additional loading, the weight of the new system has to be calculated. Furthermore, this analysis will determine whether an intensive or extensive green roof is possible, and consequently it will influence which plants will be appropriate [10].

In some situations, green roofs are not the best option, for example, if thermal performance is the goal and the building has high levels of thermal insulation, and the roof to floor area ration is small, the thermal impact of a green roof is minimal and would not be cost effective. Niachou et al., [11] simulated the impact of the green roof technology for different types of insulated roofs; and demonstrated that for well-insulated buildings energy saving is less than 2%. Research in Portland, America [9] stated that high initial costs added to annual operational and maintenance costs of green roofs are not offset by the benefits of the technology, considering just the advantages for the building owner, not including the public benefits. Over a five-year period, the investment return is less than 50% of the cost for the period. However, these data relate to Portland`s climate, costs and buildings code and may not be replicated in other locations.

Different buildings, different climates and different types of green roofs and walls around the world make the determination of the design parameters another challenge for green retrofitted systems. The irrigation system, where provided, for instance, has to be monitored and controlled, otherwise an opposite effect may result as the energy to cool the building would be higher compared to a building without green walls and/or a green roof [12]. Challenges exist also with regards to maintenance of green roofs and walls and their viability on tall facades. This study is concerned with low rise housing stock and specifies a low maintenance planting specification. Maintenance issues are acknowledged as important but fall outside the focus of this paper.

2.4 Factors affecting the design of green roofs and walls

Vegetation and local weather are factors to consider when designing an efficient green system. The vegetation is important since the thermal performance of the green roof is directly related to the type, the amount and the health of the plants. In this context, thick dark green plants have a more efficient performance compared to other types. In addition, maximizing the area covered by leaves, reduces the heat loss [7] [11].

Other relevant factor is the local climate; in hot and dry places the effectiveness of green roof and walls will be more intense. In cold climates, green roofs and walls thermal properties reduce the energy needed to increase the indoor temperature [6]. Furthermore, solar radiation influences performance since the more radiation the surface receives, the more the temperature will decrease and therefore, green systems can be very effective in equatorial regions [13].

3 Research design

The methodology adopted is developed from simple and adaptive technologies that aim to mitigate the problems caused by increasing urban expansion. Besides heat island effects, housing temperature attenuation is an important question to be addressed. This research focuses on low cost techniques that enable planting, cultivation and maintenance off site to be undertaken. It adopts lightweight removable modules of vegetation (rectangular containers) of low thickness are used as green roof and green walling systems. It is important to highlight that in urban areas, composed mostly of high buildings where facade areas are substantially higher than rooftop areas, is expected a major role of green walls in temperature attenuation. In order to evaluate the combined influence of green roof and green walls, two sets of experiments were carried out in Australia (Sydney) and in Brazil (Rio de Janeiro). The experimental sites are located at the University of Technology, Sydney (Australia) and at the Oswaldo Cruz Foundation - Fiocruz (Brazil).

Succulent plants were selected considering their drought resistance, low risk of fire and capability of development in shallow substrates, which allows setting up the system with no structural reinforcement and at low cost. Furthermore these plants require minimal ongoing maintenance and tending. With this system being intended for low-rise buildings access for maintenance is fairly straightforward either from the ground or a ladder.

In the green roof system, previously planted modules are applied directly onto the structural roof slabs or roof covering comprising tiles metal sheeting or tiles. In this case, for both sites (Sydney and Rio de Janeiro), within the planting modules, the substrate is separated from the drainage system by a permeable geotextile fabric which is responsible for blocking soil particles, but not the water flow to the storage system. The water stored then is able to retro feed, via evaporation, the substrate with accumulated water. More details about this modules and the methodology are found in Wilkinson and Castiglia Feitosa [14].

The green wall system adopted was originally developed at Fiocruz (Brazil) and consists of a two-part box made with alveolar plastic. Firstly the substrate is placed in the container, and then covered by the geotextile fabric before being sealed by the cover of the container box. Six square shaped openings were drilled into the lids, in a three row and two column array. Fig. 1 shows the experimental set ups used in Rio de Janeiro and Sydney for the study. Following this, small cuts are made in the fabric and the plants are planted. When fully planted, the vegetated boxes are placed one by one in a "U" shaped metal profile fixed to the wall. The Australian experimental setup followed the same procedure performed in Brazil, where the soil thicknesses were approximately 50 mm. However in Sydney, the plastic containers had circular shaped openings for planting.

Fig. 1. Experimental setup (Left side – Rio de Janeiro, right side – Sydney).

The evaluation of the combined effect of green roofs and green walls in terms of cooling potential is performed by comparing the temperature between two identical housing prototypes, in each of the experimental sites (Rio de Janeiro and Sydney), where one prototype has its walls and roof covered with vegetation and the other does not. Both prototypes used profiled metal sheet roofs, a commonly used roofing material in both countries. One slight difference was that the Rio de Janeiro tests were carried out using small painted brick houses, whereas in Sydney timber frame prototypes were used.

Inside the vegetated and non-vegetated prototypes, temperature data were collected every 30 minutes via data loggers (Extech TH10). The Rio de Janeiro records comprise a 96-day period from July 7th 2015 to October 13th 2015, and Sydney tests were performed over 92 days, from January 19th 2016 to April 20th 2016. In both sites the data loggers were placed about 300 mm below the top of the structure.

4 Results and discussion

The cooling potential of the combined effect of green roofs and green walls (vegetated house) performed in two experimental sites (Rio de Janeiro and Sydney) is shown in Figures 2, 3, 4, and 5 below. Independently of the differences in prototypes structures materials, the following results show that the temperature attenuation is even more evident than that observed in previous work carried out by Wilkinson and Castiglia Feitosa [14], which considered green roof systems only and not green walls.

4.1 Rio de Janeiro results

Fig. 2 presents a comparison between the inner temperature from non-vegetated and vegetated house over a 96-day period that covers a winter to mid-autumn seasonal period.

From this data set, the maximum, minimum and average temperatures observed in non-vegetated house were 40.2°C, 17.7°C and 26.1°C, respectively. Correspondingly, the vegetated house presented for these values 36.6°C, 18.3°C and 26.0°C.

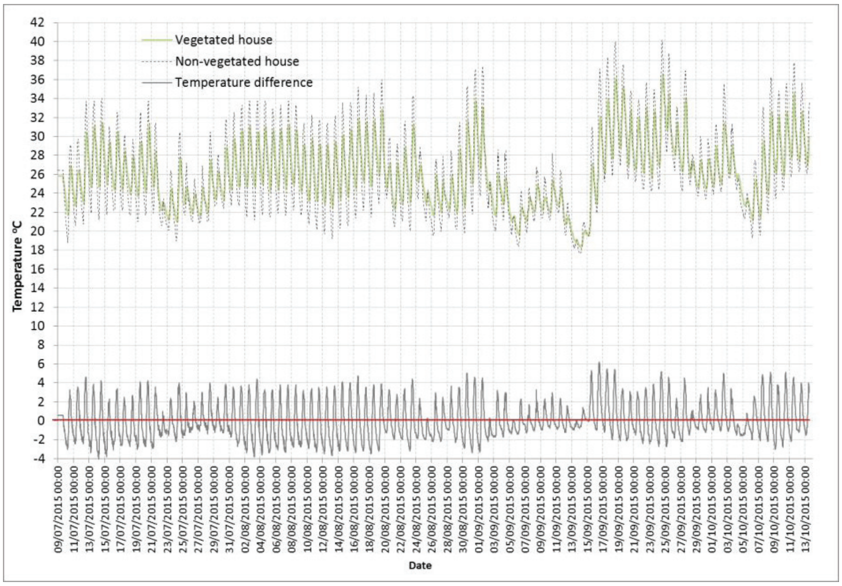

Fig. 2. Non-vegetated and vegetated houses inner temperature comparison, Rio de Janeiro, Brazil.

During the daytime the temperatures in the non-vegetated and vegetated houses varied from 18.2°C to 40.2°C and 18.4°C to 36.6°C, respectively. The lowest temperatures observed in this period occurred in the first hours of early morning and the highest around mid-afternoon. The night-time temperatures ranged from 17.7°C to 36.3°C and from 18.3°C to 36 °C, respectively for non-vegetated and vegetated houses. Similar to the daytime period, the lowest temperatures were observed also in the early morning. The highest records occurred in the beginning of the night. Compared to non-vegetated houses, it is important to consider that the temperature attenuation of the vegetated houses is not directly related to the differences observed in the temperature ranges aforementioned presented, due to the existing time lag between the non-vegetated and vegetated houses temperature peaks.

The temperature attenuation is related to the temperature differences observed simultaneously in non-vegetated and vegetated houses. According to Fig. 2 the temperature differences varied from -4.1°C to 6.2°C, where positive values mean higher temperatures in non-vegetated house and negative values indicate higher temperatures in vegetated house. In all data sets presented, non-vegetated house temperatures were higher during the daytime (positive values) and lower along the night-time. The highest positive values occurred slightly after noon-time, while the highest negative values were observed in the early morning, indicating the capability of vegetation in heat exchange attenuation and adding some thermal mass.

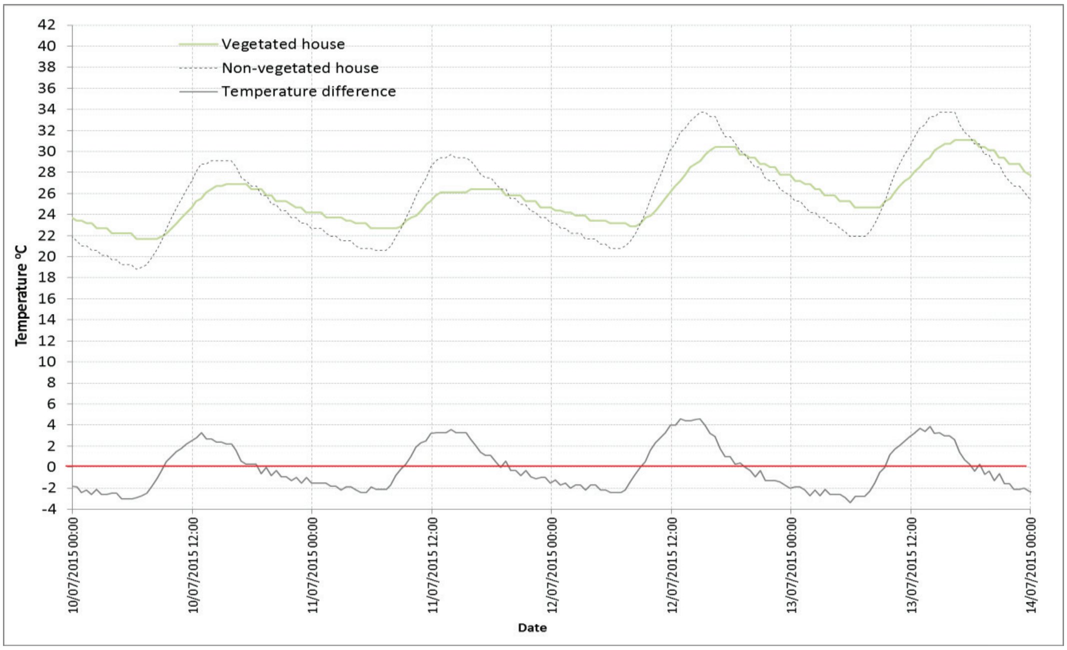

Fig. 3. Typical detail of the temperature records between non-vegetated and vegetated houses. Rio de Janeiro.

Compared to previous work performed by Wilkinson and Castiglia Feitosa [14] where only green roof effect in temperature attenuation was analysed, it is important to highlight that the combination of green roof and green walls pronounces even more the temperature differences between non-vegetated and vegetated houses. Considering that in the former work the differences observed varied from -1.5°C to 5.6°C, it can be observed that the new positive limit of 6.2°C is not so significant as the negative limit herein presented of -4.1°C. Fig. 3 shows a typical detail of four out of the 96-day in temperature comparison between non-vegetated and vegetated houses. Comparing the temperature fluctuations, it can be observed for vegetated house that the rate of heat gain is lower during the daytime. However along the night-time the green walls dampen the heat loss, and thus keep the vegetated house warmer. Additionally, in relation to the green roof experimental setup, it could be observed, besides the increase in insulation, inertia against temperature fluctuation, resulting in a temperature peak reduction and delay, meaning an increase in thermal mass properties.

4.2 Sydney results

Besides the date difference, compared to Rio de Janeiro dataset, the Sydney experiments showed better performance in heat attenuation. Fig. 4 presents a comparison between the inner temperature from non-vegetated and vegetated house during a 92-day period that covers mostly the summer time and a small part of autumn.

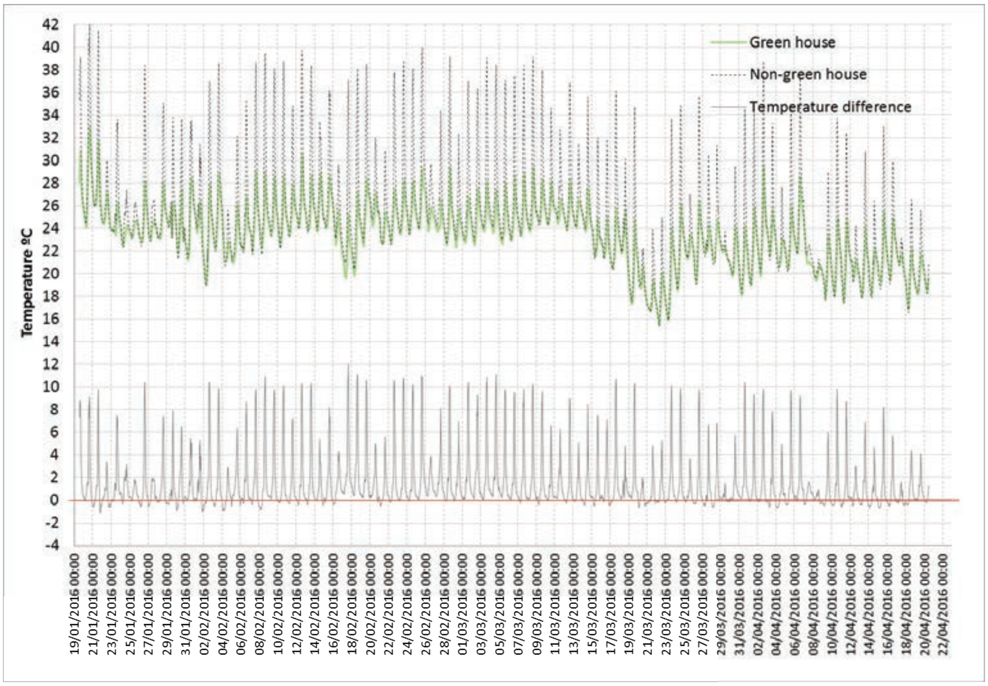

Fig. 4. Non-vegetated and vegetated houses inner temperature comparison, Sydney, Australia.

The maximum, minimum and average temperatures observed in vegetated house were 33°C, 15.5°C and 23.4°C, respectively. Correspondingly, the non-vegetated house presented for these values 42°C, 15.4°C and 26.1°C. The temperatures during the daytime in the non-vegetated house varied from 15.4°C to 42°C, whereas in the vegetated house these limits corresponded to 15.5°C and 33°C. Similarly to the observations in the Rio de Janeiro dataset, the highest temperatures were recorded in the midafternoon and the lowest temperatures occurred during the early morning. During the night-time the temperatures varied from 15.6°C to 31.6°C and from 15.7°C to 30.3°C in the non-vegetated and vegetated houses, respectively. Regarding to the daytime period, the highest temperatures were recorded in the beginning of the night and the lowest in the early morning. Fig. 5 shows a typical detail of four out of the 92-day in temperature comparison between non-vegetated and vegetated houses.

The temperature differences observed simultaneously in non-vegetated and vegetated houses varied from -1.1°C to 12°C. Non-vegetated house temperatures were higher during the daytime (positive values) and lower during the night-time. The highest positive differences occurred in the mid-afternoon. Negative values of temperature differences were not so common and did not follow a similar pattern. So to speak, the lowest and negative differences occurred during the night-time and during the early morning periods. It is important to highlight there is no considerable time lag between the non-vegetated and vegetated houses temperature peaks. However compared to the non-vegetated house, there is considerable temperature attenuation in the vegetated house, indicating a good insulating property of the system adopted in the experimental setup.

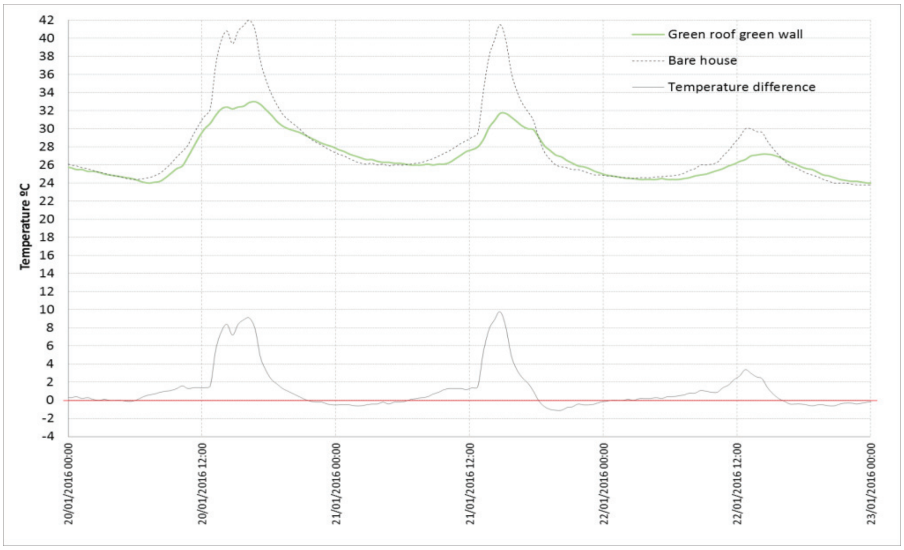

Fig. 5. Typical detail of the temperature records between non-vegetated and vegetated houses. Sydney.

4.3 Evaluation of Rio de Janeiro and Sydney results

Compared to previous work carried out by Wilkinson and Castiglia Feitosa [14], for Rio de Janeiro experiments the addition of green walls to the existing green roof prototype, improved the temperature attenuation previously observed. Based on that work, in relation to a bare structure, a green roof promoted differences between its maximum, minimum and average temperatures respectively equal to 2.1°C, -0.2°C and 1.1°C. According to results presented above, the combination of green walls with previously vegetated rooftop altered the aforementioned differences to 3.6°C, -0.6°C and 0.1°C, respectively, increasing even more the insulating characteristics of the system. In addition to the insulating effect, the combination of green roof and green walls added thermal mass to the system. In the former work [14], the time delay observed between green and non-green roof temperatures peaks were on average, about 60 minutes. According to the current experiments, this delay increased to approximately 150 minutes. It is important to highlight that the average of the differences between non-vegetated and vegetated prototypes close to zero does not mean that the vegetation is inefficient in temperature attenuation in Rio de Janeiro experiments. This is explained by the occurrence of negative differences during the night time that offsets the positive differences observed during the day. This tendency was not observed for Sydney experiments since these negative differences were insignificant. Table 1 shows a compilation of the results presented.

Table 1 – Summary results of Rio de Janeiro and Sydney experiments.

	Rio de Janeiro				Sydney			
Temperatures (°C)	Non Vegetated (NV)	Vegetated (V)	Difference (NV) – (V)	Simultaneous temperature difference	Non Vegetated (NV)	Vegetated (V)	Difference (NV) – (V)	Simultaneous temperature difference
Maximum	40.2	36.6	3.6	6.2	42	33	9	12
Minimum	17.7	18.3	-0.6	-4.1	15.4	15.5	-0.1	-1.1
Average	26.1	26.0	0.1	-	26.1	23.4	2.7	-

(Source: Authors).

The Sydney experimental conditions comprise a new setup, even if compared to the previous one as detailed in Wilkinson and Castiglia Feitosa [14], where sheet metal sheds were used in the evaluation of thermal performance with a green roof only. Therefore, a comparison between the Sydney ‘green roof only’ and the combination of

Sydney 'green roof and green walls' data presented above is not reasonable, due to the differences in the materials used, the position of data loggers, as well as the experimental site location. However, even highlighted such differences the current experiment showed a good capability in temperature attenuation using vegetation in both roof and walls. In comparison to the Rio Janeiro results, it was observed in the Sydney experiments, that there are higher differences between the non-vegetated and vegetated houses that indicate a higher thermal insulation characteristic very likely due to the existing air layer, trapped inside the timber frame structure used in the Sydney experiments. In addition to this, it is also important to highlight that the colour of the prototypes may exert a significant influence in the differences observed. Compared to white wall prototypes in Rio de Janeiro, the dark blue colour of the Sydney prototypes may increase substantially the non-vegetated wall temperature in contrast the shaded walls of vegetated surfaces.

5. Conclusions

Both the Rio de Janeiro and Sydney experimental setups have demonstrated the potential for lightweight, portable vegetated modules to be retrofitted on roofing and walls as a means of cooling existing buildings. Considering that in urban environment, buildings have more perimeter than roof area, it is expected in a city scale that facades have a major role in temperature attenuation in buildings.

In the Rio de Janeiro experimental setup, green walls were added to former prototype, which already had its rooftop covered with succulent plants. The results show an increase of insulation properties and thermal mass characteristics by the combined effect of green roof and green walls. Besides the insulating effect, the combination of green roof and green walls added thermal mass to the system as well. The combination of green roof and green walls pronounced the negative differences in temperatures between non-vegetated and vegetated houses during the night-time and early morning. This fact can be attributed simultaneously to an increase in insulation and thermal mass properties. Djedjiga et al. [15] reported similar results under experimental conditions quite similar to Rio de Janeiro, where white facades were compared to vegetated facades. From this work, it is also evident periods when vegetated structure temperatures are higher than the bare, or non-vegetated ones due to the simultaneous effect of thermal mass and insulation.

The Sydney site comprised a new experimental setup and, compared to the Rio de Janeiro data set, showed higher temperature attenuation. This is attributed mostly to the structure type and its surface colour. The timber frame structures adopted in the Sydney experiments are shown to have more insulation properties than the blockwork strcutures used in Rio de Janeiro, because timber frame structures are not good heat conductors, and also because the air layer trapped inside the walls increases its insulation characteristics. Additionally, in opposition to the white walls of the Rio de Janeiro experiment, the dark blue colour used in the Sydney experiment contributes more to internal heating of the bare prototypes, in contrast to vegetated prototypes that besides the air insulation layer, have its walls protected from direct sunlight by the vegetation.

The green walls in the Rio de Janeiro experiments contributed to more pronounced thermal mass properties than the Sydney site, mostly due to the type of materials used in prototypes setup.

According to Castleton [10], in addition to insulation, green roofs add thermal mass and provide inertia against temperature fluctuation. Thus is believed that the combination of green roof and walls increase even more these properties, depending on the materials used and the experimental setup adopted.

It is important to highlight that even in the experimental scale adopted in this work, green walls showed an important role in temperature attenuation, and thus the relationship between rooftop and façade areas must be taken into account. It is expected that green walls have a much higher relevance in thermal comfort in building, since even for low building's façade areas are significantly greater than rooftop areas. Other areas of further investigation include on-going maintenance requirements and performance over the long term.

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