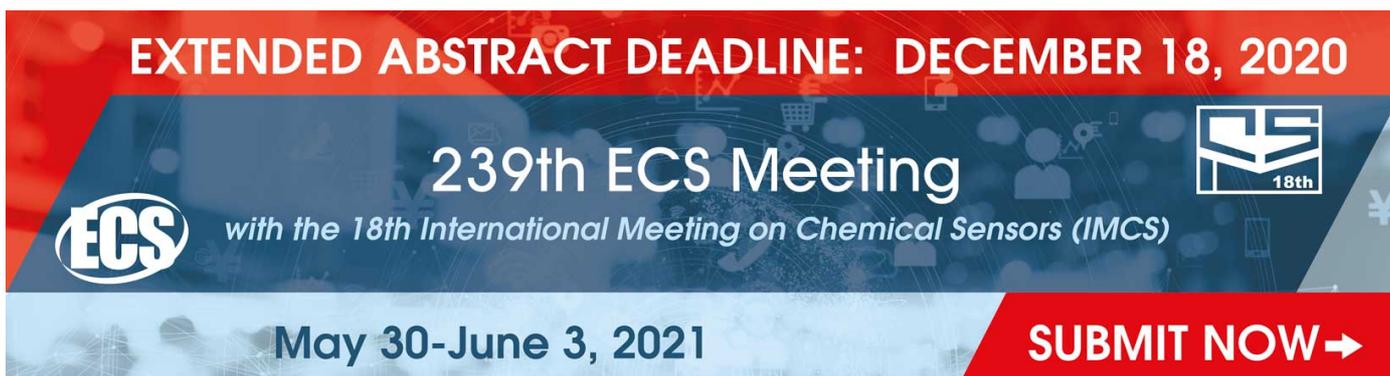


PAPER • OPEN ACCESS

Effects of substrate depth and native plants on green roof thermal performance in South-East Australia

To cite this article: A Pianella *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 022057

View the [article online](#) for updates and enhancements.



EXTENDED ABSTRACT DEADLINE: DECEMBER 18, 2020

239th ECS Meeting
with the 18th International Meeting on Chemical Sensors (IMCS)

May 30-June 3, 2021

SUBMIT NOW →

The banner features a red top section with white text, a dark blue middle section with white text and logos, and a light blue bottom section with white text. The ECS logo is on the left, and the IMCS 18th logo is on the right. The background of the middle section shows a network of nodes and lines.

Effects of substrate depth and native plants on green roof thermal performance in South-East Australia

A Pianella^{1,2,4}, L Aye², Z Chen³ and N S G Williams¹

¹School of Ecosystem and Forest Sciences, The University of Melbourne, Burnley 3121, Australia

²Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, The University of Melbourne, Parkville 3010, Australia

³CSIRO Land and Water, Clayton South 3169, Australia

⁴Melbourne School of Design, The University of Melbourne, Parkville 3010, Australia

Abstract. Three experimental green roofs in Melbourne with depth of 100, 150 and 300 mm have been assessed to quantify their thermal performance. To evaluate the benefit of substrate depth, temperature was recorded every 50 mm along a vertical profile. Green roofs consisted of scoria substrate and a mix of three species of plants: *Lomandra longifolia*, *Dianella admixta* and *Stypandra glauca*. Statistical analyses applying the hierarchical partitioning technique showed that solar radiation is the main driver affecting the green roof surface temperature, air temperature has strong correlations with the variations of the temperatures recorded below the surface, while moisture content has the least influence. Temperature profiles of the green roof show that the first 50 mm do reduce the heat flowing through the green roof substrate regardless the total green roof substrate depth. Differences in thermal performance arise at deeper points, where thicker green roofs are able to delay the change of substrate temperatures. Similar effects were found for the heat fluxes measured at the interface between the green roof and building roof. These results confirmed that green roofs may be used as a sustainable passive technology to reduce building energy consumptions for South-East Australia climate.

1. Introduction

The number of green roofs - engineered structures that enable plants to grow on top of buildings - has been increasing in towns and cities as they seek to reduce their environmental impact. Green roofs deliver ecosystem services in dense, urbanised areas (1, 2) and one of the reasons for their adoption in several countries is to reduce energy consumption for cooling and heating of buildings (3, 4). Numerous studies around the world have quantified the energy and thermal benefits of green roofs (5-9). While there is now strong evidence for tropical (10, 11) and temperate (12) climates, this is not the case yet for other climates, such as hot and dry climate. This is mainly due to contrasting results in different regions and across the seasons, likely due to specific selection of plants for green roofs and to changeable vegetation layer over the years. Green roof substrates provide insulation effects and their role in delaying the heat flux through the roof is well understood. In the literature, there are different interpretations on the optimum depth of green roof substrate for maximising the green roof thermal performance. It was reported that in a tropical climate, a 100 mm thick green roof substrate is sufficient to reduce heat penetration into the building (11); in a cold temperate climate, intensive green roofs (i.e. substrate thicker than 300 mm) offer an enhanced thermal performance and insulation effects (13). Direct measurements of temperature variation along the vertical profile is necessary to understand how the temperature increases or decreases during night and day and to suggest the optimal depth for South-East Australia, with a hot and dry climate. This chapter investigates the effect of substrate thickness and vegetation cover on the green roof thermal performance and recommends the appropriate thickness of green roofs in South-East Australia to reduce heating and cooling loads.



2. Materials and methods

2.1. Experimental green roofs

Three experimental green roofs with varying depths (100, 150 and 200 mm) and an area of 15.4 m² were constructed at The University of Melbourne's Burnley Campus, Australia (14). An identical area of the building's original bitumen membrane roof was monitored as a "control". The substrate is comprised of locally sourced scoria mix volcanic rock (15), while the vegetation layer consists of three Australian high-water use plant species, *Stypandra glauca*, *Dianella admixta* and *Lomandra longifolia* (16, 17). In late October 2015 each green roof was planted with 90 tubestock of each specie, giving a density of about 18 plants per m². They were manually irrigated by means of a hose three times a week for about 15 minutes each roof during the summer months following the planting to support plant growth and help establishment. Substrate temperatures were recorded from late March 2016 by means of thermistors (Emerson, model 501-1125, accuracy $\pm 2\%$) placed every 50 mm through the substrate profile. Because the substrate surface is the most challenging part to measure due to exposure to climatic variables, we placed three sets of thermistors at the surface and 50 mm deep, and two sets of thermistors in the other positions. Because of the sparse vegetation of the experimental green roofs, thermistors were placed in the most vegetated patches, approximately between the three species. Heat flux through each green roof was measured by heat flux plate (Hukseflux, model HFP01-L10m) placed in the centre and underneath all the green roof component layers on top of the building's bituminous roof coating. Data were recorded every six minutes and averaged over one hour. With the same time step, substrate moisture content was measured by Aquaflex Soil Moisture Sensors placed in the middle and diagonally on each green roof, following the slope of the green roof runoff. A HOBO U30 weather station measured ambient air temperature, relative humidity, horizontal global radiation, wind speed, wind direction and rainfall every minute. Data were collected and stored in the same datalogger. Plant foliage coverage was quantified through photo pixel counts using Adobe Photoshop CC 2015 program. Photos were taken by a GoPro Hero4 Camera 4 m above the central point of each green roof. Experimental green roof reflectance has been recorded by a CROPSCAN Multispectral Radiometer (MSR) on 21st November 2016 between 12:25 and 12:35.

2.2. Statistical analysis and computer simulations

The contribution of air temperature, solar radiation, relative humidity and substrate moisture content (independent variables) to the variance explained for green roof substrate temperatures measured at the surface and 100 mm below, have been analysed and assessed by analytical hierarchical partitioning statistical technique using R Studio Version 1.1.383 software and 'hier.part' statistical package. The same analysis was undertaken for heat fluxes measured between the green roof and the building roof for all the experimental green roofs.

To evaluate the potential contribution and use of our experimental green roofs, heating and cooling loads of a 120 m² single storey traditional brick building in Melbourne were simulated by using EnergyPlus 8.7.0. The thermostat settings were 21°C for heating and 24°C for cooling. Weather data for 2015 were provided by Weather Analytics from a weather station located at Melbourne International Airport and covering all the required weather inputs for EnergyPlus.

3. Results and discussion

Temperatures for the vegetated green roofs were collected continuously from November 2015 until March 2017. However, as summer shows the most varying thermal performance in terms of amplitude and magnitude, only 2016-2017 summer season results are presented and analysed.

3.1. Analytical hierarchical partitioning

Analysis of the green roof surface temperature found that solar radiation is the main driver explaining the temperature variance (Figure 1). There are two reasons for this: the experimental green roofs are fully exposed to solar radiation and had relatively sparse vegetation cover than the green roof modules so solar radiation more directly affected the green roof substrate. Air temperature is the second rank driver of green roof surface temperature but becomes the major driver for green roof substrate temperatures below the surface.

At 100 mm below the surface, air temperature is a significantly greater driver than all the other weather variables (Figure 2). The contribution of substrate volumetric moisture content to explain variance of green roof substrate temperature is very minimal at the surface level, while it slightly increases for temperatures recorded below the surface but remains less important than air temperature or relative humidity. The variation in heat flux is mostly explained by air temperature and relative humidity, which is similar to green roof substrate temperatures recorded below the surface.

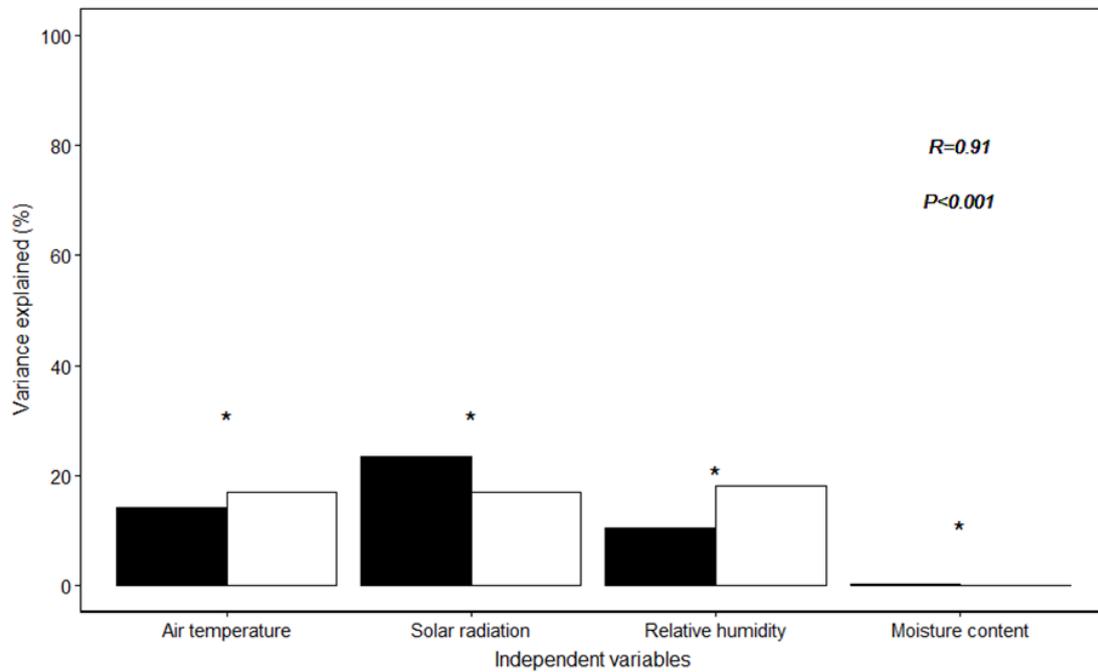


Figure 1. Analytical hierarchical partitioning against surface substrate temperature.

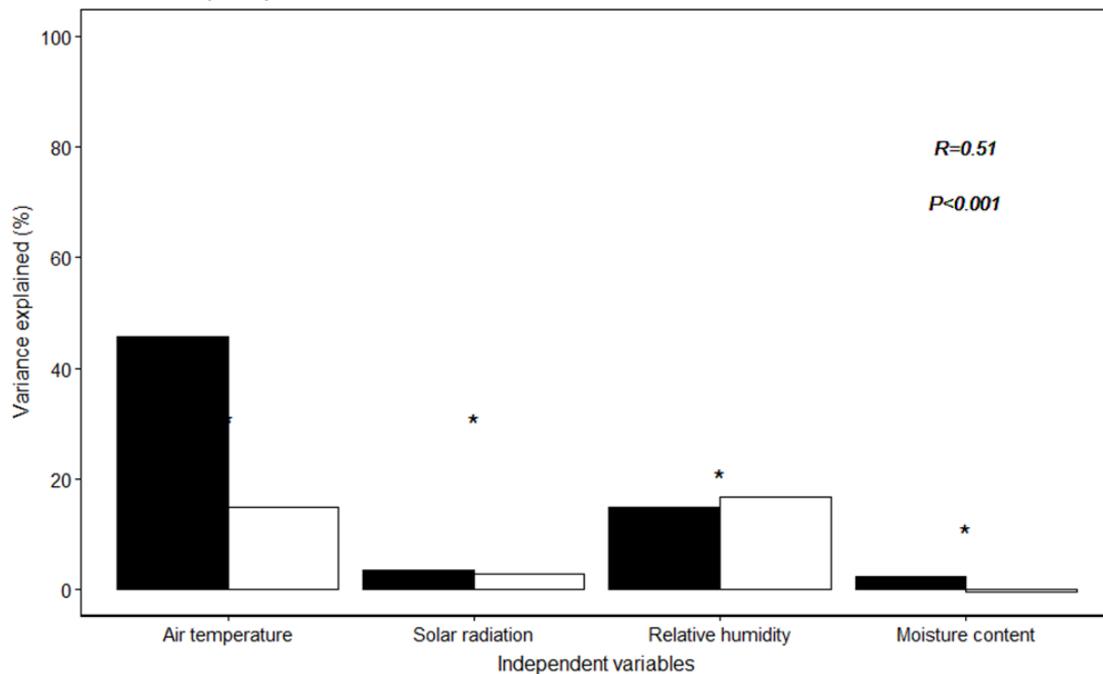


Figure 2. Analytical hierarchical partitioning against substrate temperature at the depth of 100 mm.

3.2. Temperature profiles

Substrate temperatures are only presented for three typical summer days in Melbourne (December 1st-3rd, 2016; Figure 3) to help readability and to avoid the influence of irrigation on surface temperature. In general, there is minimal difference in substrate surface temperatures between the 100 and 150 mm thick green roof. In hour 14, the 100 mm green roof has a comparable surface temperature to the 150 mm green roof (53.3°C and 53.1°C), while it is lower the following day (e.g. in hour 36, 53.8°C and 55.1°C). However, for summer 2016-2017, the daily peak surface temperature of the thickest green roof is consistently lower than the other two green roofs (difference between 2.5 and 4°C). This is explained by the higher thermal mass, although it is the least rank variable, by moisture content, which was up to 11% more on the days selected. Likely due exposure to longer sunny hours (North faced), the 150 mm green roof is the driest, explaining why its surface temperature is the highest. It should be noted that surface temperatures give no direct information on the insulative properties of green roofs - this is deducible through temperatures recorded below the surface. However, the lower the surface temperature, the less the amount of heat emitted back to surrounding areas. This phenomenon triggers the increase of ambient air temperature and it is at the basis of the urban heat island effect (18, 19).

For all the three experimental green roofs, temperatures measured below the surface consistently have greater differences with increasing depth of measurement point. Temperatures recorded 50 mm below the surface have the smallest differences as the daily peak temperature of the 100 mm green roof is 0.9-1.2°C higher than the 150 and 200 mm thick green roofs, while nightly minimums are 0.7-0.8°C lower. In contrast, at 100 mm below the surface, the 100 mm thick green roof has temperature up to 3°C higher than the 200 mm green roof (e.g. hour 65). In conclusion, although temperatures were recorded at the same depth (i.e. 100 mm below the surface), the diurnal swings vary according to the depth of the green roof, with the 200 mm green roof always having the lowest amplitude diurnal temperature swings. As expected, temperatures fluctuations decrease at deeper locations (150 and 200 mm below the surface), with the lowest being the bottom temperature recorded in the thickest green roofs.

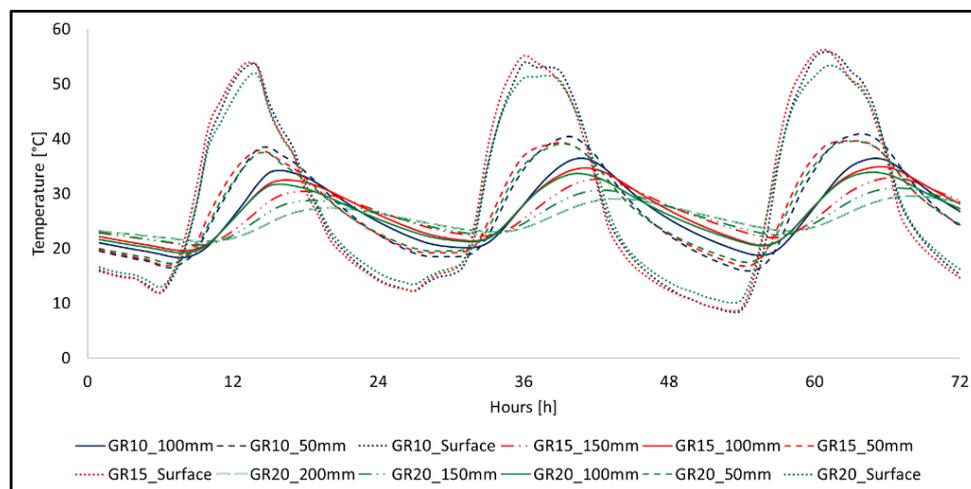


Figure 3. Green roof substrate temperature profiles (1-3 Dec 2016).

3.3. Heat fluxes

Heat fluxes decreased with increasing thickness of the green roof. The period investigated in Figure 4 represents the three hottest days during Summer 2016-2017 (16th-18th January 2017), when ambient air temperature was closer to 40°C and solar radiation approached 1,200 W m⁻². As expected, the diurnal heat flux variation of the 100 mm green roof has greater amplitude (maximum 35 W m⁻² and minimum -20 W m⁻²) than the thicker 150 mm and 200 mm green roofs, which recorded maximums 17 and 12 W m⁻² and minimums -8 and -5 W m⁻² respectively. The substrate thickness not only affected the amplitude and magnitude of the heat flux, but also the time lag of the heat transmitted. In

fact, the peak heat flux in the thinnest green roof occurred about 3.5 hours after the peak solar radiation, while it was delayed 5 and 7 hours for the 150 and 200 mm thick green roofs. The second day shows a trough of the solar radiation during early afternoon (hours 39-40) when solar radiation decreased from 1,181 to 411 W m^{-2} in 40 minutes, between 14:40 and 15:20. The decrease in solar radiation is reflected in the heat flux of the thinner green roof which slightly decreased from 33 to 32 W m^{-2} before rising up again to about 34 W m^{-2} . This result illustrates that the heat flux through the 100 mm green roof is more sensitive to solar radiation changes than the 150 and 200 mm green roofs. The analysis also confirms that green roofs can consistently reduce and delay heat transfer into the building and increasing substrate thickness lengthens these delays due to increased thermal mass of the substrate, and increased heat capacity provided by greater water retention – due to higher porosity - in thicker substrates (7).

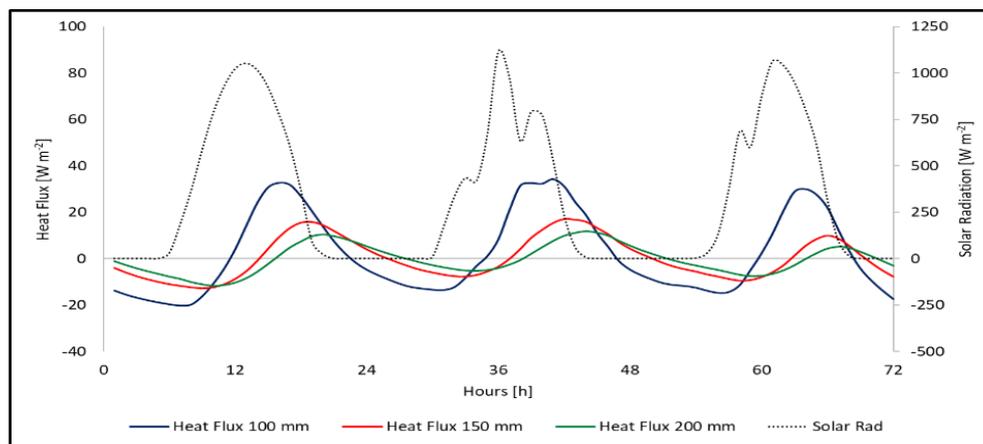


Figure 4. Solar radiation and heat flux through green roofs (16-18 Jan 2017).

The plants (Table 1) also helped reduce the magnitude of heat fluxes, even if green roofs were not fully vegetated (20). During the 2014-2015 summer, when green roofs were non-vegetated, the 100 mm deep green roof had heat fluxes between -22 and 50 W m^{-2} , the 150 mm green roof between -17 and 30 W m^{-2} , while the 200 mm green roof between -15 and 25 W m^{-2} . Daily peaks and troughs were both respectively higher and lower than those reported in Figure 4. Heat flux daily peaks of summer 2015-2016 (14) lie in between the other two summers investigated, while troughs were comparable to summer 2014-2015 and this is explained by a lower foliage coverage (about 20%) compared to summer 2016-2017 (about 45%). However, distinct summer seasons and different irrigation schedules did not enable a further analysis of the influence of the vegetation coverage alone, as both temperatures and heat fluxes were influenced by varying moisture content and weather conditions (i.e. air temperature, direct solar radiation, etc.). Monitoring the three experimental green roofs over three summers showed that increasing vegetation cover reduced heat fluxes, most likely due to greater shade and higher albedo (8, 21).

Table 1. Foliage coverage and reflectance for three green roofs with different substrate depth

Thickness	Summer 2016-2017 Coverage [%]	Reflectance of solar radiation at different wavelengths [%]					
		530	570	650	855	1240	1640
100 mm	48.1 ± 6.1	6.5 ± 0.04	7.8 ± 0.05	8.6 ± 0.04	18.8 ± 0.42	22.5 ± 0.57	19.7 ± 0.38
150 mm	41.5 ± 10.3	7.2 ± 0.03	8.7 ± 0.03	9.3 ± 0.11	20.2 ± 0.51	23.6 ± 0.69	20.7 ± 0.22
200 mm	46.2 ± 10.8	7.4 ± 0.02	8.9 ± 0.04	9.6 ± 0.07	20.7 ± 0.34	23.8 ± 0.75	21.3 ± 0.41

3.4. Building energy simulation: a practical application

Building simulation of thermal performance of green roofs provided information on their insulation benefit. This information can be used to quantify building cooling and heating loads to estimate the potential energy savings of installing a green roof to a new or existing building as a passive strategy technique. Building energy performance simulations for Melbourne's climate are shown in Figure 5 and compared with the baseline building without a green roof. Green roof thickness selected for the simulations were based on the thickness of the green roofs we experimentally investigated. Increasing substrate thickness has a positive effect on heating load as its value decreases compared to the baseline due to increased insulation. This finding agrees well with results reported from cold climate regions (22, 23) where it was found that reduction of heating load is achieved by increasing substrate thickness and associated insulation. In contrast, cooling loads slightly increase due to greater thermal mass which reduces the cooling effect of the green roof occurring near the green roof surface was observed by La Roche and Berardi (24).

The plant layer (increased LAI in EnergyPlus which corresponds to increased vegetation coverage, has a positive effect on cooling due to larger evaporative cooling effect and higher albedo. This confirms Wong et al's (9) finding, that the largest reduction of heat gain (up to 60%) was found in green roofs well covered by plants. However, fully-vegetated green roofs have a negative impact on heating load due to cooling effect from the plants. This has also been reported in studies from Greece (25, 26), Singapore (10) and Hong Kong (27). However Bevilacqua et al. (5) calculated that green roofs in Italy reduced heat lost (outgoing heat flux) in winter between 30% and 37%, showing an energy benefit also for winter, although less significant than summer, where green roofs achieved 100% reduction on heat gain (ingoing heat flux). Similar findings were also reported by Niachou et al (28) and Foustalieraki et al (19). Summer cooling effect of green roof in hot and dry regions, such as Mediterranean region and South-East Australia, does not only depend on vegetation coverage as in tropical climates but also on plant type. Ferrante et al. (29) found that cooling load reduced between 8 and 20% depending on the plant used, while Huang et al. (6) ranked the thermal performance of perennial herb, shrub, vine and groundcover plants in reducing green roof substrate temperature. Results from building energy simulations showed that substrate improves thermal performance in winter, while in summer plants do. As such, the most suitable green roof set-up would be balancing between substrate thickness and plants' LAI to maximise the year-round thermal performance, reduce energy use and improve comfort.

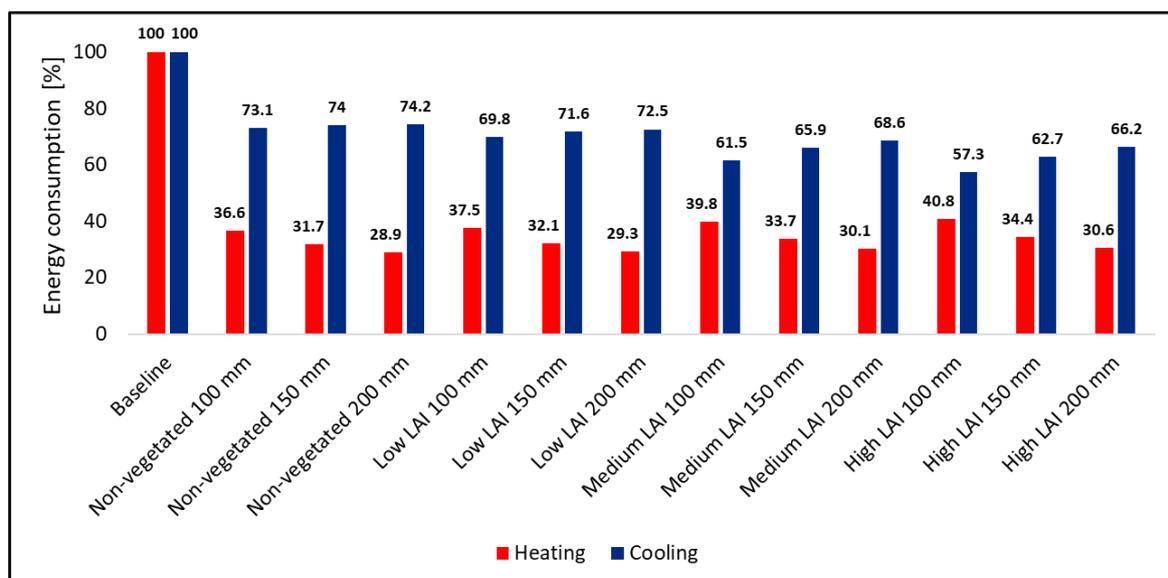


Figure 5. Annual heating and cooling loads simulated for 1-storey brick building in Melbourne.

4. Conclusions

Three experimental green roofs with distinct substrate thicknesses have been assessed to quantify their thermal performance. Statistical analyses showed that solar radiation is the main driver affecting the surface temperature of green roof substrate, air temperature has strong correlations with the variations of the temperatures recorded below the surface while moisture content had the least influence.

Temperature profiles of green roof substrates showed that the 200 mm green roof was able to delay the occurrence of peak measured at the same depth across the three experimental green roofs. It proved that the effect of increased substrate thickness in reducing heat gain occurred consistently across the substrate and not only at the deepest points we measured. Similar conclusion can be drawn for the heat fluxes measured between the green roof and building roof.

The detailed contribution of the plants could not be fully assessed due to overall sparse vegetation, with coverage of about 40%. The recorded heat fluxes of the three experimental green roofs with different plant coverage (non-vegetated, 20% and 40-45%) for three summers from 2014-2015 until 2016-2017, showed that they can reduce the daily peak heat fluxes. As such, we can confidentially infer that increasing vegetation cover would ultimately improve the thermal performance of green roofs due to greater shade, evaporative cooling effect and albedo.

Acknowledgments

This research was funded by Australian Research Council Linkage grant LP130100731 supported by Melbourne Water and Inner Melbourne Action Plan (IMAP) municipal councils.

References

- [1] Berardi U, GhaffarianHoseini A, GhaffarianHoseini A. State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy*. 2014;115:411-28.
- [2] Oberndorfer E, Lundholm J, Bass B, Coffman RR, Doshi H, Dunnett N, et al. Green roofs as urban ecosystems: Ecological structures, functions, and services. *BioScience*. 2007;57(10):823-33.
- [3] Santamouris M. Cooling the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*. 2014;103:682-703.
- [4] Santamouris M. Cooling the buildings – past, present and future. *Energy and Buildings*. 2016;128:617-38.
- [5] Bevilacqua P, Mazzeo D, Bruno R, Arcuri N. Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area. *Energy and Buildings*. 2016;122:63-79.
- [6] Huang YY, Chen CT, Liu WT. Thermal performance of extensive green roofs in a subtropical metropolitan area. *Energy and Buildings*. 2018;159:39-53.
- [7] Lin YJ, Lin HT. Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries. *Building and Environment*. 2011;46(2):345-55.
- [8] Olivieri F, Di Perna C, D'Orazio M, Olivieri L, Neila J. Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a Mediterranean coastal climate. *Energy and Buildings*. 2013;63:1-14.
- [9] Wong NH, Tan PY, Chen Y. Study of thermal performance of extensive rooftop greenery systems in the tropical climate. *Building and Environment*. 2007;42(1):25-54.
- [10] Wong NH, Chen Y, Ong CL, Sia A. Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment*. 2003;38(2):261-70.
- [11] Jim CY, Tsang SW. Biophysical properties and thermal performance of an intensive green roof. *Building and Environment*. 2011;46(6):1263-74.
- [12] Eksi M, Rowe DB, Wichman IS, Andresen JA. Effect of substrate depth, vegetation type, and season on green roof thermal properties. *Energy and Buildings*. 2017;145:174-87.

- [13] Liu KB, B. Thermal performance of green roofs through field evaluation. Proceedings for the First North American Green Roof Infrastructure Conference, Awards and Trade Showm Chicago IL. 2003.
- [14] Pianella A, Aye L, Chen Z, Williams NSG. Substrate Depth, Vegetation and Irrigation Affect Green Roof Thermal Performance in a Mediterranean Type Climate. *Sustainability*. 2017;9(8):1451.
- [15] Pianella A, Clarke RE, Williams NSG, Chen Z, Aye L. Steady-state and transient thermal measurements of green roof substrates. *Energy and Buildings*. 2016;131:123-31.
- [16] Farrell C, Szota C, Williams NSG, Arndt SK. High water users can be drought tolerant: Using physiological traits for green roof plant selection. *Plant Soil*. 2013;372(1-2):177-93.
- [17] Zhang Z, Szota C, Fletcher TD, Williams NSG, Werdin J, Farrell C. Influence of plant composition and water use strategies on green roof stormwater retention. *Science of The Total Environment*. 2018;625:775-81.
- [18] Bevilacqua P, Mazzeo D, Bruno R, Arcuri N. Surface temperature analysis of an extensive green roof for the mitigation of urban heat island in southern mediterranean climate. *Energy and Buildings*. 2017;150:318-27.
- [19] Foustalieraki M, Assimakopoulos MN, Santamouris M, Pangalou H. Energy performance of a medium scale green roof system installed on a commercial building using numerical and experimental data recorded during the cold period of the year. *Energy and Buildings*. 2017;135:33-8.
- [20] Liu K, Minor J. Performance evaluation of an extensive green roof. *Greening Rooftops for Sustainable Communities*; May 5-6, 2005; Washington, D.C., United States of America 2005. p. 1-11.
- [21] D'Souza U. The thermal performance of green roofs in a hot, humid microclimate. *WIT Transactions on Ecology and the Environment*. 2013;173:475-86.
- [22] Berardi U. The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy and Buildings*. 2016;121:217-29.
- [23] Zhao M, Srebric J. Assessment of green roof performance for sustainable buildings under winter weather conditions. *Journal of Central South University of Technology (English Edition)*. 2012;19(3):639-44.
- [24] La Roche P, Berardi U. Comfort and energy savings with active green roofs. *Energy and Buildings*. 2014;82:492-504.
- [25] Santamouris M, Pavlou C, Doukas P, Mihalakakou G, Synnefa A, Hatzibiros A, et al. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. *Energy*. 2007;32(9):1781-8.
- [26] Sfakianaki A, Pagalou E, Pavou K, Santamouris M, Assimakopoulos MN. Theoretical and experimental analysis of the thermal behaviour of a green roof system installed in two residential buildings in Athens, Greece. *International Journal of Energy Research*. 2009;33(12):1059-69.
- [27] Jim CY, Peng LLH. Weather effect on thermal and energy performance of an extensive tropical green roof. *Urban Forestry and Urban Greening*. 2012;11(1):73-85.
- [28] Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings*. 2001;33(7):719-29.
- [29] Ferrante P, La Gennusa M, Peri G, Rizzo G, Scaccianoce G. Vegetation growth parameters and leaf temperature: Experimental results from a six plots green roofs' system. *Energy*. 2016;115(P3):1723-32.



Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Pianella, A;Aye, L;Chen, Z;Williams, N

Title:

Effects of substrate depth and native plants on green roof thermal performance in South-East Australia

Date:

2020-11-20

Citation:

Pianella, A., Aye, L., Chen, Z. & Williams, N. (2020). Effects of substrate depth and native plants on green roof thermal performance in South-East Australia. IOP Conference Series: Earth and Environmental Science, Volume 588, 1.01 – 1.05, 588, (2), pp.022057-022057. IOP Publishing. <https://doi.org/10.1088/1755-1315/588/2/022057>.

Persistent Link:

<http://hdl.handle.net/11343/252702>

License:

[CC BY](#)