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Green roofs for energy efficiency – a simulation study in Australian climates

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Cover image: Green roof – Kangan Automotive Centre of Excellence by ASPECT Studios (Image: Andrew Lloyd)

Abstract

This paper describes how green roofs influence the energy performance of a hypothetical commercial office building in each of the Australian Building Code Board's eight climate zones of Australia. It presents a dynamic thermal simulation of the energy performance of green roofs, without insulation, as compared with conventional compliant roofs – both concrete and metal deck. A life cycle cost benefit analysis is provided for the modelled roof types.

Simulations were conducted for a single storey office building with a concrete roof, a metal deck roof and for both types with the addition of extensive (i.e. shallow profile, light weight) green roof coverage.

1. Introduction

Roofs that incorporate planting within substrates are called 'green roofs', 'living roofs' or 'roof gardens'. The benefits of green roofs are well documented and include:

- storm water management by reducing peak flows and improving water quality (Berndtsson et al 2006 and Mander et al 2007)
- improved air quality (Li et al 2010, Rowe et al 2011)
- reducing temperatures generally within cities, mitigating the urban heat island effect (Santomouris 2012)
- reducing acoustic impacts (Renterghem and Hotteldooren 2009)
- contributing to biodiversity (Boning and Schrader 2006).

Other potential benefits of green roofs, and greenery more generally include: improvements in visual amenity, and the wellbeing and productivity of people who can see them (Williams et al 2010); increased property values; marketing benefits; food production and food security; and greenhouse gas sequestration (Tomalty 2010).

Research conducted in other parts of the world concludes that green roofs can reduce cooling energy consumption. Table 1 summarises the energy saving potential of green roofs reported in the literature published by researchers in various countries.

This paper presents theoretical work in simulating the role a particular type of extensive green roof can play in reducing energy demand for cooling in the Australian climate zones. Previous research on the thermal performance of green roofs has been conducted outside of Australia, and the authors hope that by providing a simulation in the Australian context, the case can be made for the further research and monitoring that will be required to enable these energy savings to be realised in suitable projects.

The potential energy benefits of green roofs and their influence on building thermal performance have been the subject of previous studies from a general qualitative perspective (Del Barrio 1998, Niachou et al, 2001, Fioretti et al 2010, Castleton et al 2010, Ouldboukhitine et al 2011, Kokogiannakis et al 2011, Tsang and Jim 2011, Jim and Peng 2012, Jim 2012, Jaffal et al 2012, Saadatin et al 2013, Beraddi et al 2014). However a comprehensive assessment in quantitative terms is still a challenge, especially in the Australian context. This is due to the unique qualities of the Australian context including:

- extended hot and dry weather patterns for most of Australia
- native vegetation (which has adapted to local rainfall and soil condition)
- construction methods, codes and standards, particular to Australia.

A detailed description of each climate zone is provided in Table 3.

Despite their potential, energy savings of green roofs have not been studied in detail for Australian climates. Most of the Australian studies such as Williams et al (2010) and Hopkins (2012) report on evaluating the inside and outside surface temperature reductions for summer and winter. The surface temperature of a conventional bitumen roof can reach up to 90°C in parts of Australia (Jaffal et al 2012, Willliams et al 2010). The summer and winter temperatures on a roof exterior surface can be extreme, with a light weight metal deck roof having more extreme temperature fluctuations than a concrete roof deck.

The influence on building energy use and the life cycle cost of the simulated green roofs is the focus of this paper.

Researcher	Country / City / Location	Building description	Method	Results and Comments
A. Niachou (Niachou et al 2001)	Greece/Athens	Hotel building	Simulation/ Measurement	Energy savings varied from 2–44% depending on the area covered by the green roof and varying degree of insulation.
Wong, N. H. (Wong et al 2002)	Singapore	Office building	Simulation	Tested on a five storey commercial office building, which showed a 17–79% reduction in the space load and 1–15% in the annual energy consumption.
Ascione F., (Ascione et al 2013)	Several European cities (Tenerife, Sevilla, Rome, Amsterdam, London, Oslo)	Office building	Simulation	Tenerife, Sevilla: 1–11%; Rome: 1 to 8%. Amsterdam, London: 4–7%; Oslo between 1–6% annual reduction. Warmer climate (Tenerife, Sevilla and Rome) savings are fractionally higher compared to cooler climates (Amsterdam, London and Oslo).
Oliveiri, F., (Olivieri F., et al 2013)	Mediterranean coastal climate	One storey office building	Experimental/ Numerical	With a green roof, incoming thermal gain is 60% lower than when the roof has no vegetation. This is due to shading by the vegetation and thermal mass of the growing media. The model predicted overestimation by about 4.8% for the growing media and about 7.2% for the vegetation.
Sailor D.J., (Sailor D.J., 2008)	US (Chicago and Houston)	Office building	Simulation/ Measurement	This paper reports the total annual energy (electricity and gas) reduction not just cooling and heating. For both Chicago and Houston, the annual electricity consumption was approximately 2% lower. The annual natural gas consumption was also lower by 9% for Chicago and about 11% lower for Houston.

Table 1. Summary of energy saving potential of green roofs in various countries and cities

2. Green roof characteristics

A green roof, in general, consists of six main components (Figure 1):

- vegetation
- gravel ballast / mulch
- growing media and water reservoir
- drainage and filter layers
- waterproof membrane
- roof deck (e.g. concrete slab or roof sheeting).

Green roofs can be categorised into two groups – extensive and intensive. According to the *Growing Green Guide's* (Department of Environment and Primary Industries, 2014) definition, extensive green roofs consist of thin layers of growing medium which are light weight and require relatively low maintenance. Intensive green roofs are relatively heavier with deeper layers of growing media (typically more than 30 cm), and supporting larger vegetation such as trees.

Green roofs exhibit a number of different physical properties and characteristics when compared to conventional roofs. They have very different evaporative, thermal, albedo (reflectivity) and emissivity properties when compared to conventional roofs. Green roofs significantly reduce the surface temperature due to a combination of factors, including:

- shading by foliage
- soil thermal mass
- moisture content
- evaporation of substrate
- evapotranspiration of plants.

In most plant species the leaf emissivity is very high, around 0.9–0.95, which means leaves are better able to radiate energy at the same temperature and wavelength. These values change throughout the day and are further influenced by irrigation applications.

Two examples of green roofs (Figures 2 and 3) are shown on the following page.

Figure 1. Typical extensive green roof build up (Image: ASPECT Studios 2012)

Figure 2. Victorian Desalination Project green roof, Wonthaggi, by ARM Architecture and peckvonhartel with ASPECT Studios. The green roof was designed to ameliorate the visual impacts of the development. (Photo: Aquasure)

Figure 3. Kangan Automotive Centre of Excellence, Melbourne Docklands, by Gray Puksand with ASPECT Studios. This green roof reduces storm water run-off and provides amenity for building users. (Image: Andrew Lloyd)

3. Analysis

The quantification of the thermal properties and energy saving benefits of green roofs is an important part of establishing green roofs as a viable application in Australia. The authors anticipate that green roofs may eventually be included in the National Construction Code (NCC) after further research. This would facilitate a more widespread uptake of green roofs, and foster realisation of the benefits that they can provide.

3.1 Simulation model

The simulation to assess the influence of green roofs on a building's energy consumption involves accounting for several interrelated variables involving heat transfer, mass transfer and plant physiology. Based on the previous research (Table 1) and our findings, the dominant variables that have a major impact on green roof thermal behaviour are:

- shading effects of foliage
- plant physiology
- growing media moisture content, thermal conductivity and specific heat capacity
- solar absorptance, transmittance and reflectance of the leaf surface area and leaf reflectivity and emissivity.

Of these, the more dynamic/time-based variables are: thermal conductivity due to fluctuations throughout the day and night in the soil water content; solar properties due to foliage variability; and the dynamic nature of solar radiation on the roof surfaces over time and throughout the year.

The thermal simulation model and analysis is based on Sailor's theory (Sailor 2008, Moody and Sailor 2013) implemented in EnergyPlus™. The green roof parameters within the model are based on Sailor's data and compare the data from the University of Central Florida and the Florida Solar Energy Center. For further detailed information on EnergyPlus™ integration of green roof thermal simulation refer to EnergyPlus™ Engineering Reference (EnergyPlus™, 2013).

Several simple to detailed models that represent the thermal behaviour of green roofs are available in the literature (Table 1), with specific models studying particular features of green roofs. The model used in this analysis takes into account the radiative exchanges; effects of vegetation; growing media substrate layers and their thickness; and the consideration of the more dynamic variables such as soil thermo-physical properties and moisture content. Refer Table 2 and Figures 7 and 9 for thermal properties and material makeup of the green roofs modelled.

The detailed green roof was modelled in the EnergyPlus™ software and incorporated characteristics based on the NCC requirements for each climate zone for a typical office building. The building model then considers the roof with and without a green roof to analyse the impact on building energy performance. The green roof is analysed with no insulation and 100% soil and plant coverage.

3.2 The office building model

The baseline building is a typical new single story office building (Figure 4). The building fabric, glazing and building services (lighting, power and air conditioning) comply with the current NCC Volume One minimum regulatory requirements. These regulatory requirements vary for each climate zone. The NCC compliant concrete and metal deck roofs are modelled with and without a green roof. Note in the case of the green roof, insulation is not included in all simulation scenarios.

The building is modelled with the following criteria:

- A heating and cooling system operating during office hours (7am-6 pm on weekdays) but not operational on weekends.
- The temperature set points are static between 21 °C to 24 °C. That is, the heating is activated when the interior temperature is less than 21 °C, while the mechanical cooling is activated when the interior temperature exceeds 24 °C.
- The assumed ventilation rate is equal to 10 L/s/person as per NCC requirements and satisfactory indoor air quality, with an occupancy rate of 1 person per 10 m2.
- The lighting level is 9 W/m2 as per NCC Volume One, Section J requirements, with a typical office equipment power density of 15 W/m2 (ABCB, 2016).

The typical zoning layout is shown in Figure 5. The building is rectangular in shape with a fully exposed longer northern facade with minimum shading projection. The exposure on shorter east and west elevations is minimised. The facility is predominantly an open plan flexible working office with visual amenity and access to daylight. The service spaces are located at the central core of the building. Overall dimensions:

- floor dimensions: 50 x 20 m
- gross floor area: 1000 m2
- overall floor-to-ceiling height: 3.5 m
- net volume: 3700 m3.

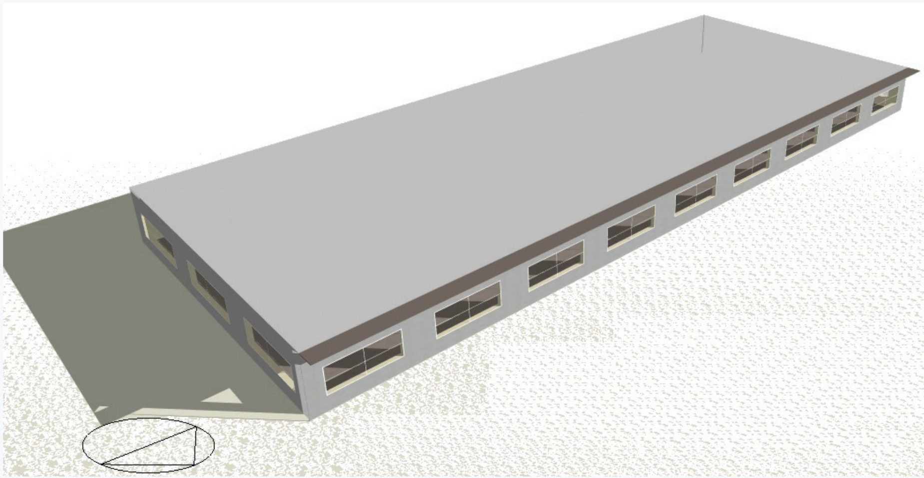


Figure 4. 3D Model of the simulated building (Source: Authors)

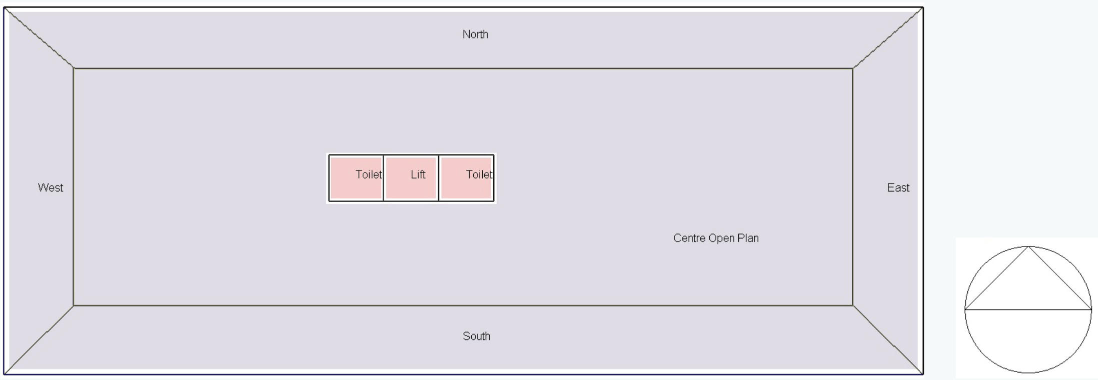


Figure 5. Office layout and thermal zones (Source: Authors)

The green roof is an extensive type and has been modelled in comparison with a traditional NCC Section J compliant conventional roof for the given climate zone. Figures 6–9 show the modelled NCC Section J roofs and green roofs respectively.

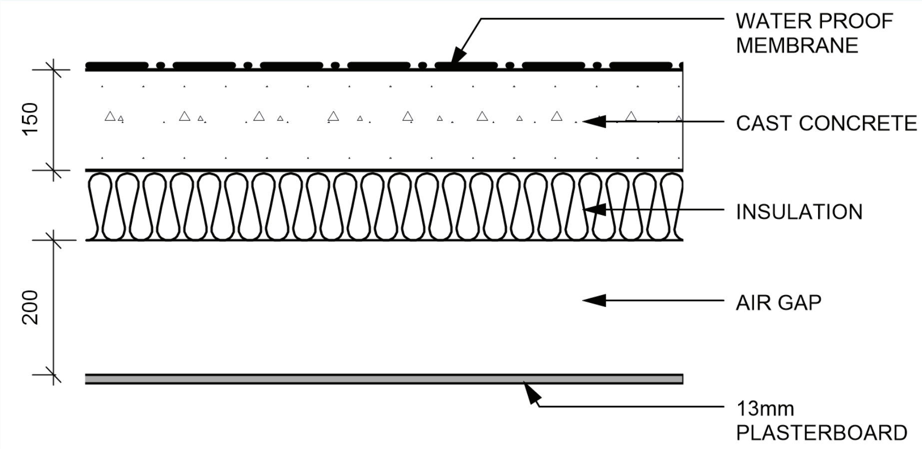


Figure 6. NCC concrete roof build up used in modelling (Source: Authors)

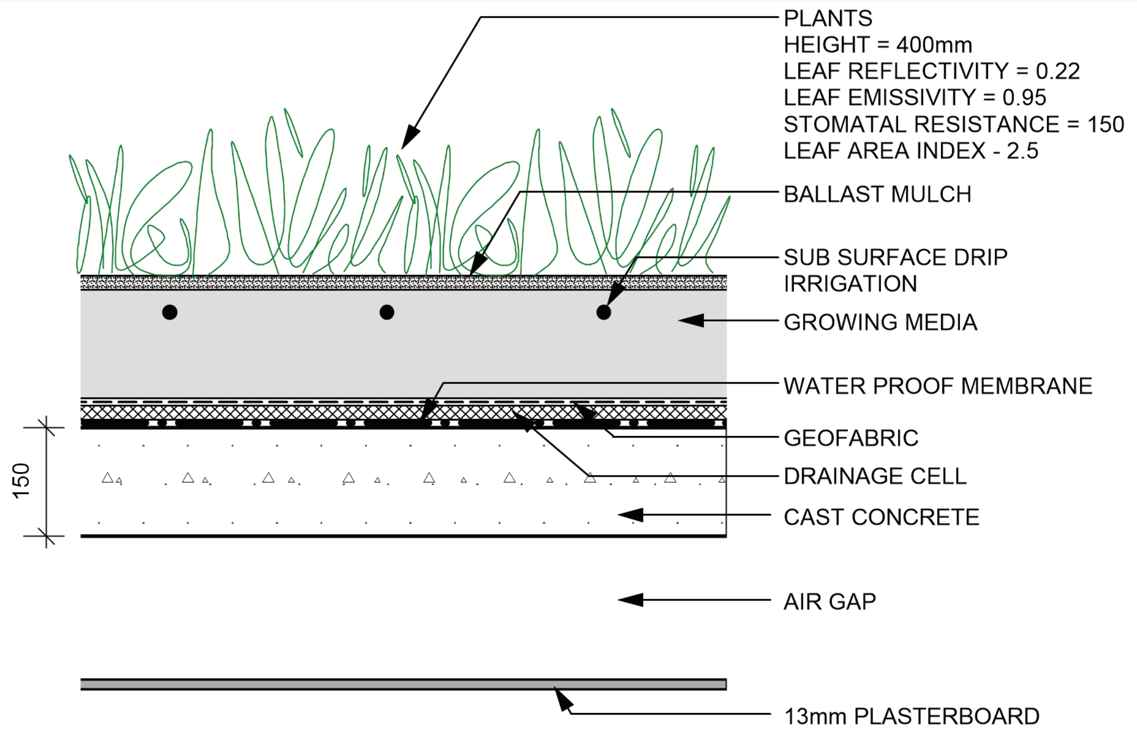


Figure 7. Green roof build up on concrete deck used in modelling (Source: Authors)

Definitions for Figure 7 and 9 terms

Leaf Area Index (LAI) is the projected leaf area per unit area of soil surface (The LAI of 2.5 noted refers to a non-deciduous coverage).

Growing media is a substrate to support the plant growth on the roof garden. It is comprised of a majority of inorganic material with high air filled porosity, good water holding capability, and low organic matter content (less than 20%), irrigated and free draining.

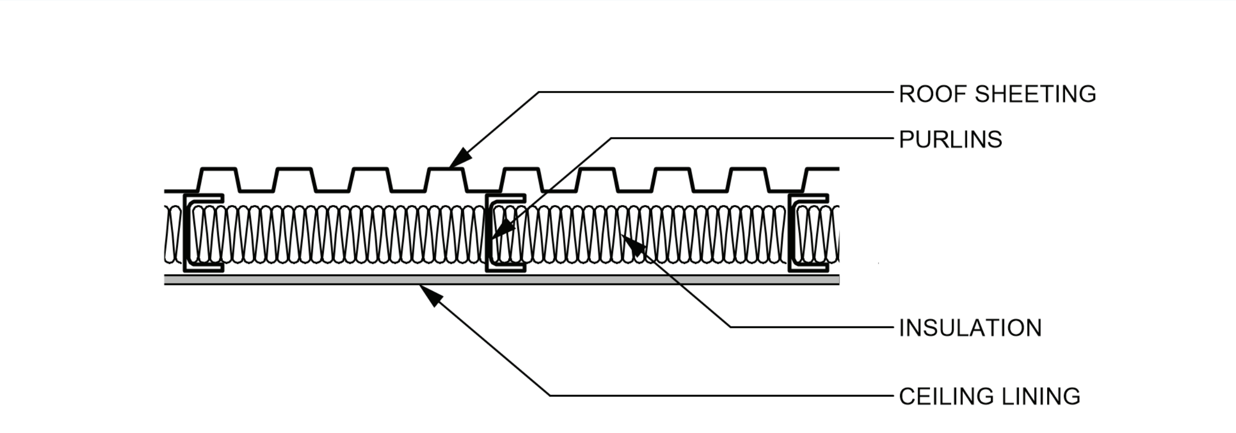


Figure 8. NCC metal deck roof build up used in modelling (Source: Authors)

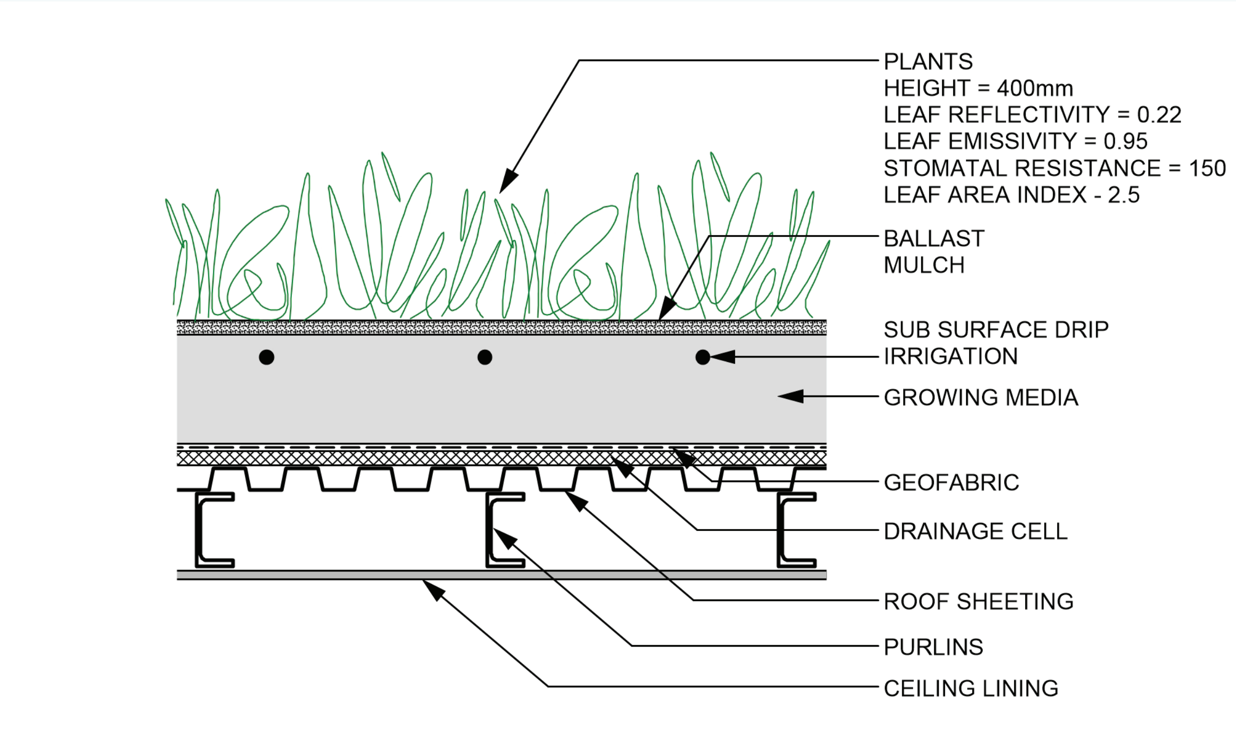


Figure 9. Green roof build up on metal deck used in modelling (Source: Authors)

Table 2 on the next page summarises the thermal properties of both the NCC Volume One compliant conventional roof and the green roof in the buildings modelled. The main characteristics of the modelled building's envelope and services make reference to the current version of the NCC Volume One (ABCB, 2016)

Characteristics	Parameters – NCC Volume One roof		Green roof	
Orientation	Due North (0°)			
Dimensions	50 m length, 20 m width and 3.5 m height (floor to ceiling)			
Net Lettable Area (NLA)	937 m2			
Walls	200 mm precast concrete walls with insulation, which varies by climate zone as follows: Climate Zones 1, 2 and 3: Total R-value 3.3 m2K/W Climate Zones 4, 5, 6 and 7: Total R-value 2.8 m2K/W Climate zone 8: Total R-value 3.8 m2K/W			
Floor	Slab on ground (no insulation)			
Roof and ceiling construction	Concrete deck roof, comprised of: 200 mm concrete/ insulation/ air cavity/ 13 mm plasterboard (Figure 6)	Metal deck roof, comprised of: metal deck/ insulation/ air cavity/ 13 mm plasterboard (Figure 8)	Green roof on concrete deck, comprised of: vegetation/ 200 mm growing media/ 200 mm concrete slab (Figure 7)	Green roof on metal deck, comprised of: vegetation/ 200 mm growing media/ metal decking/ structural joists (Figure 9)
Roof Solar absorptance (colour medium)	0.60	0.60	0.60	0.60
Roof insulation product (R-value)	Concrete deck roof • R2.71 for the NCC minimum R-value R3.20 • R3.21 for the NCC minimum R-value R3.70 • R4.31 for the NCC minimum R-value R4.80	Metal deck roof • R2.80 for the NCC minimum R-value R3.20 • R3.30 for the NCC minimum R-value R3.70 • R4.40 for the NCC minimum R-value R4.80	No added insulation	No added insulation
Thermal properties of roof assembly	Roof insulation varies with climate zone. Overall thermal resistance (R-values) are as follows: Climate zones 1–6 3.2 m2K/W Climate zone 7 3.7 m2K/W Climate Zone 8 4.8 m2K/W		Overall thermal resistance for all climates: 0.80 to 1.20 m2K/W Thermal properties of green roof: • Conductivity: 0.3 W/m K • Specific heat: 1333 J/kg K • Density: 850 kg/m3 • Irrigation: summer and shoulder seasons three days/week, 20 minutes a cycle for two hours • Initial volumetric moisture content: 15% • Maximum volumetric moisture content: 50% • Plant height: 400 mm • Leaf area index (LAI): 2.5 • Leaf reflectivity: 0.22 • Leaf emissivity: 0.95 • Stomatal resistance: 150 sec/m Green roof includes the growing media (substrate). Note: other layers such as drainage cell, waterproofing and plants are not considered in the total thermal resistance calculation.	

Glazing (Facade to glazing ratio ≈25%) and sill height of 0.8 m	Glazing performance properties (for all climates) North: U-value = 4.0; SHGC = 0.52; fixed shading of 1 m projection and at 2.7 m above window sill. East: U-value = 4.0; SHGC = 0.52 South: U-value = 5.8; SHGC = 0.9 West: U-value = 4.0; SHGC = 0.61
Lighting power density (office)	9 W/m2
Lighting power density (amenities)	6 W/m2
Equipment power density (office)	15 W/m2
Air conditioning plant	Reverse cycle packaged system
HVAC plant efficiency or COP (heating and cooling)	2.7
Temperature set points	Cooling 24 °C and heating 21 °C

Table 2. Characteristics of case study building with and without green roof

Various Australian climates have been considered. Figure 8 shows the climate zones of Australia and the major cities within the climate zone for green roof thermal simulation and comparison with the local code.

The International Weather Data for Energy Calculation (IWEC) hourly date for major capital cities has been used for this analysis. The IWEC data files are compiled from no less than 18 years of weather records and are considered to be equivalent to Test Reference Year (TRY) weather data. Where IWEC data is not available for a location, Reference Meteorological Year (RMY) data has been used.

The summary of the climate for each location considered is described in Table 3.

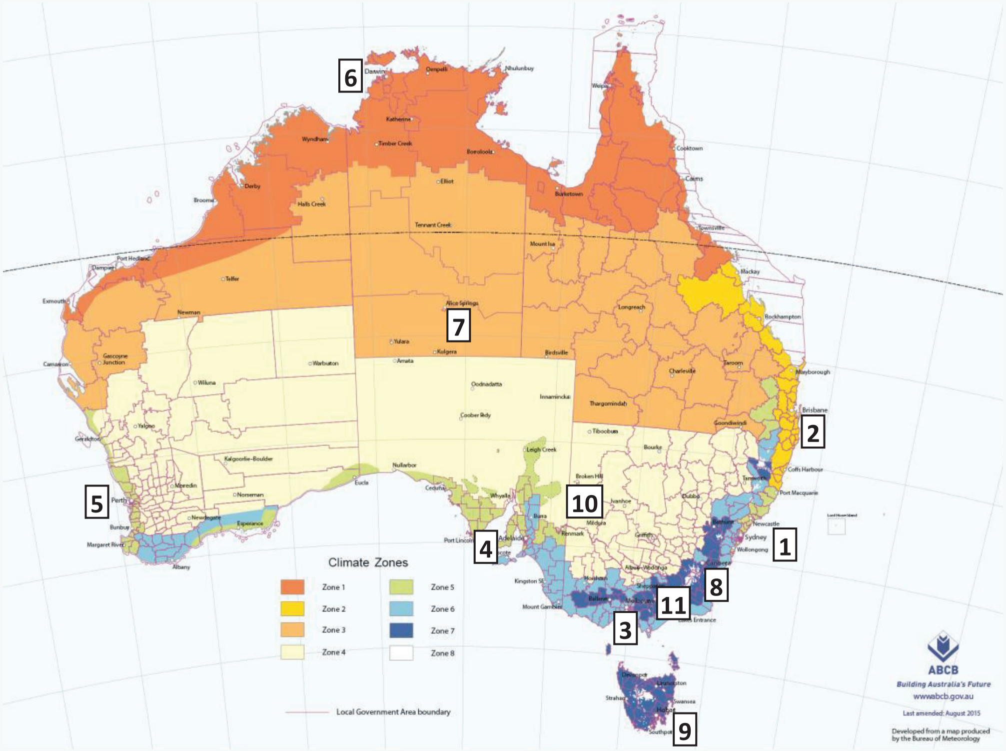


Figure 10. Climate Zone Map of Australia. Information sourced from the Australian Building Codes Board (ABCB, 2016) www.abcb.gov.au (Note: Location numbers 1–10 added by authors).

Australian Climate Zone	**Location (refer Figure 10) and Weather Data**	**Characteristics of the location**
Climate Zone 1	Darwin (6) IWEC Weather Data	Tropical – hot humid summer and warm winter. High outdoor temperatures year round and minimal seasonal temperature variation.
Climate Zone 2	Brisbane (2) IWEC Weather Data	Sub-tropical – warm humid summer and mild winter. Hot to very hot summers with mild winters.
Climate Zone 3	Alice Springs (7) RMY Weather Data	Hot and arid – hot dry summer and warm winter. Very hot summers with mild winters and very low humidity.
Climate Zone 4	Broken Hill (10) RMY Weather Data	Cold semi-arid – hot dry summer and cool winter. Very hot summers with mild winters and low humidity.
Climate Zone 5	Sydney (1), Adelaide (4) and Perth (5) IWEC Weather Data for all locations	Warm temperate – warm summer and cool winter. Four distinct seasons.
Climate Zone 6	Melbourne (3) IWEC Weather Data	Mild temperate – mild to warm summer, cool winter. High diurnal temperature range and four distinct seasons, cold winter with low humidity.
Climate Zone 7	Canberra (8) and Hobart (9) IWEC Weather Data for Canberra and RMY Weather Data for Hobart	Cool temperate – mild to warm summer and cold winter. Hot summer and cold winter with low humidity.
Climate Zone 8	Thredbo (11) RMY Weather Data	Alpine – warm summer and cold to very cold winter.

Table 3. Climate zone and typical characteristics

3.3 Energy performance of green roofs

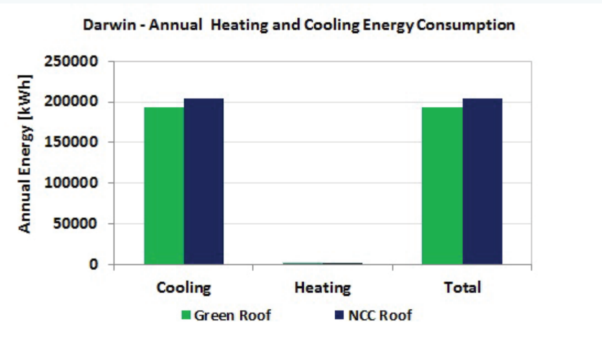
A green roof influences the thermal performance of the building envelope which in turn means that its influence on energy consumption is limited to heating and cooling energy only. A green roof will not influence lighting or equipment energy consumption.

Overall heating and cooling energy consumption levels were compared with and without a green roof for the office building described in section 3.2. This analysis focused on a new commercial office building, but a similar analysis could be extended to other facilities such as schools, airports, aged care facilities, data centres and various other community facilities such as recreation centres.

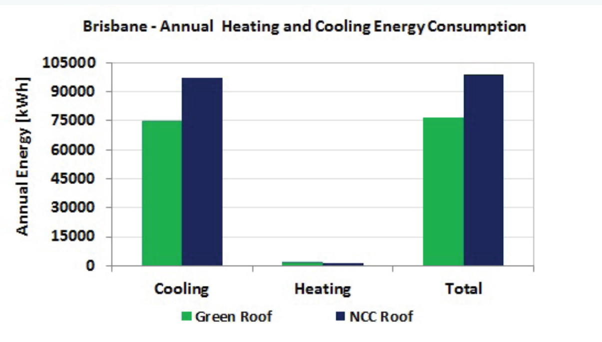
Non-residential buildings have large internal heat loads that come from higher densities of occupants, electric lighting and heat-generating equipment and appliances. Non-residential buildings also typically have higher lighting requirements for work-related visual tasks than residential buildings. These higher internal loads mean that non-residential buildings like offices typically use more energy in cooling annually for a given floor area than residential buildings (EDG 86 MS, Shaw, 2016).

Table 4 shows the overall heating and cooling energy consumption of the modelled office building in various climate zones for both concrete and metal deck with and without a green roof. The data tables that inform the graphs can be found in Appendix A (Tables 8 and 9).

Concrete deck with and without green roof

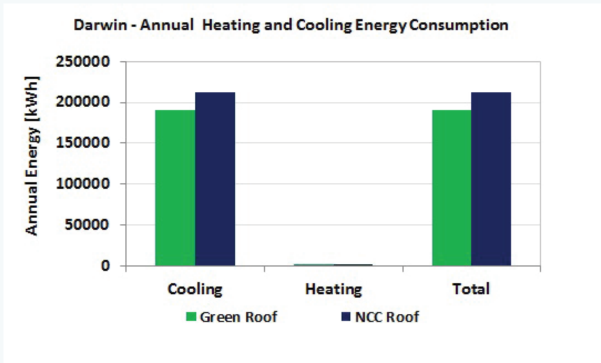


Climate Zone 1

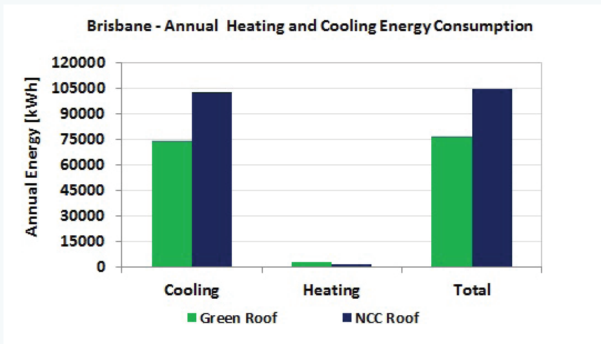


Climate Zone 2

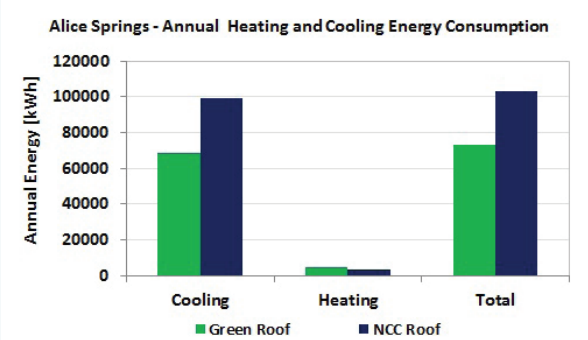
Metal deck with and without green roof



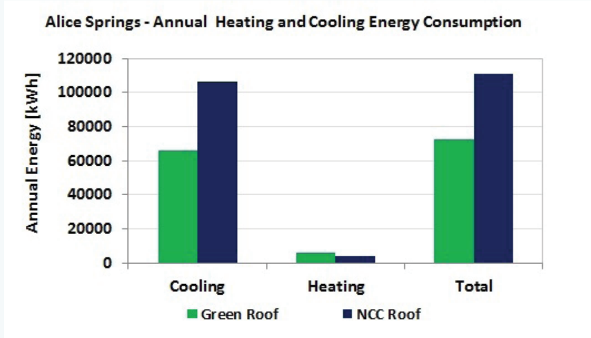
Climate Zone 1



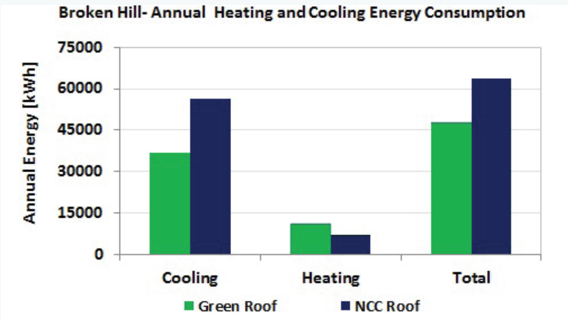
Climate Zone 2



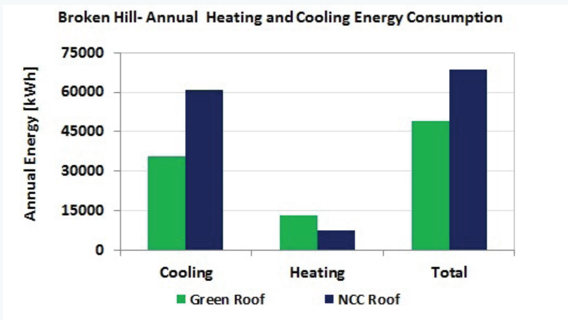
Climate Zone 3



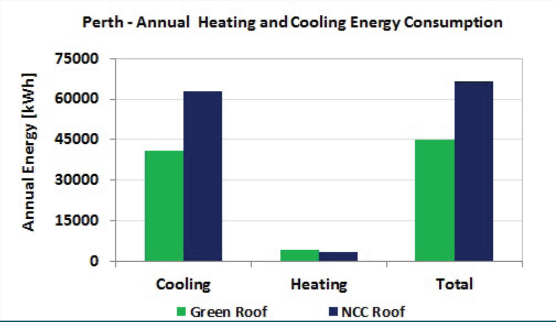
Climate Zone 3



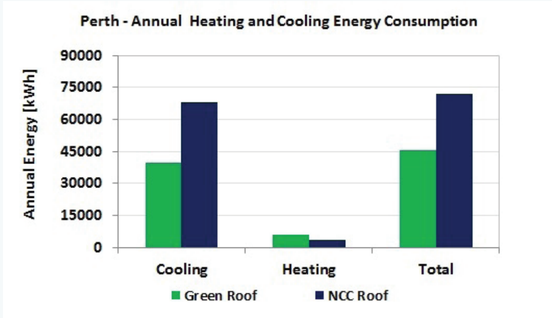
Climate Zone 4



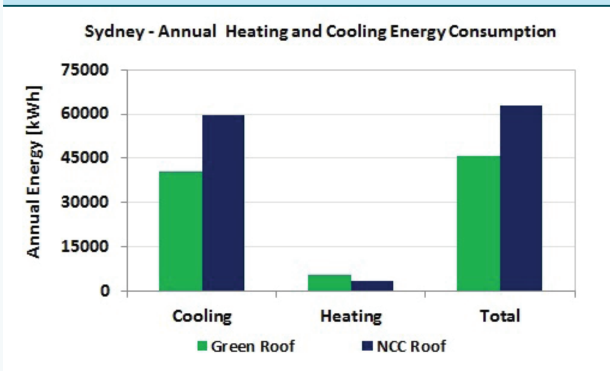
Climate Zone 4



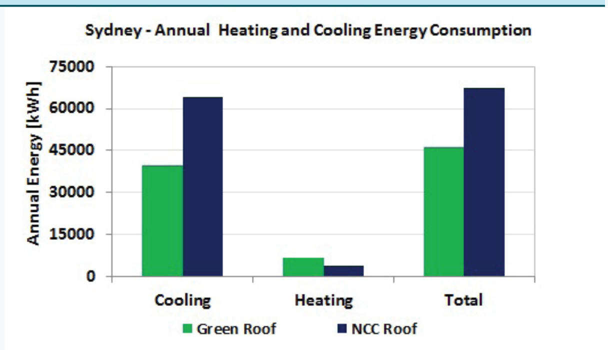
Climate Zone 5



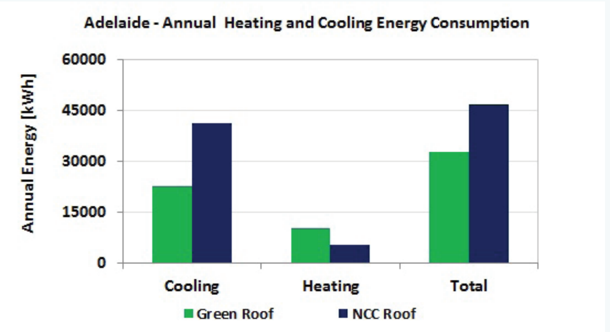
Climate Zone 5



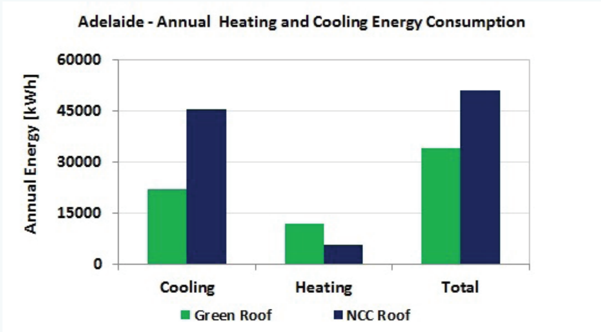
Climate Zone 6



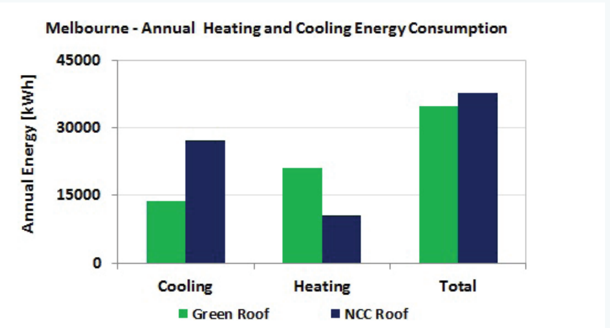
Climate Zone 6



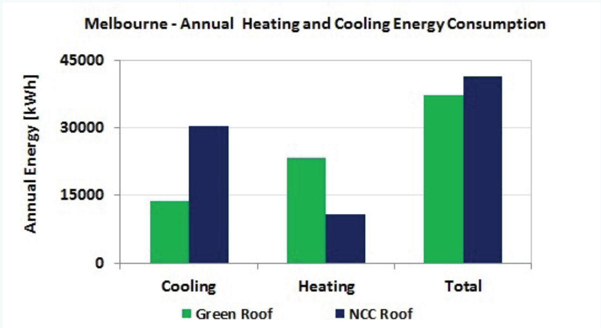
Climate Zone 5



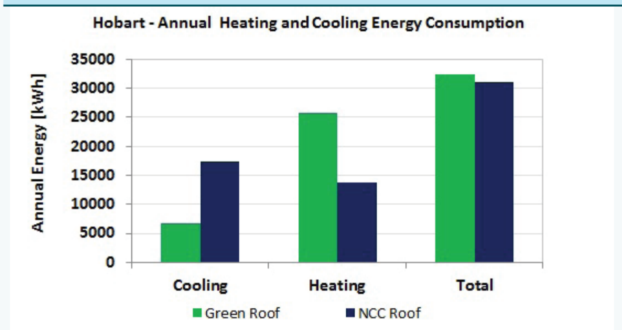
Climate Zone 5



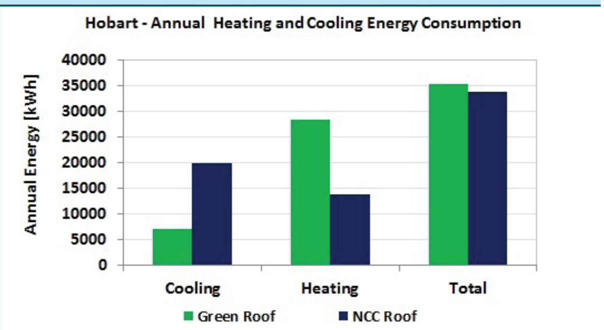
Climate Zone 6



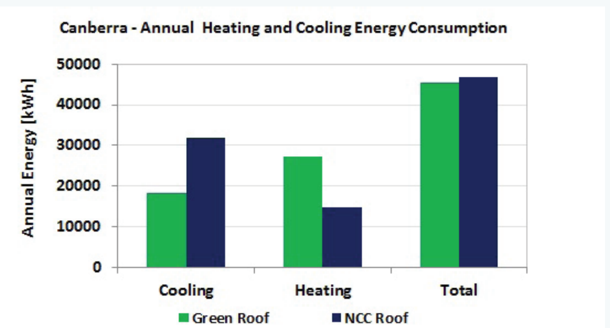
Climate Zone 6



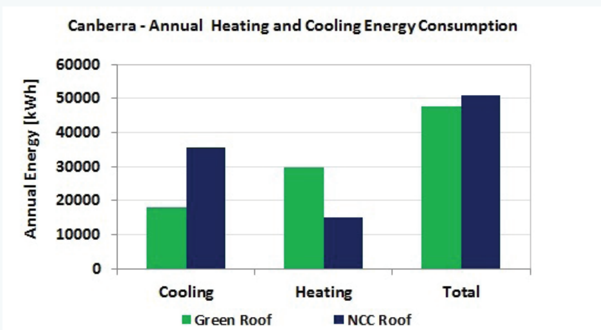
Climate Zone 7



Climate Zone 7



Climate Zone 7



Climate Zone 7

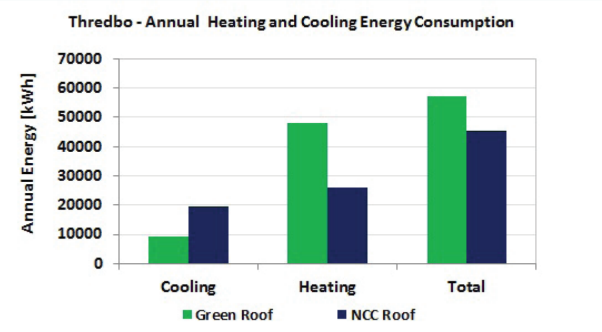
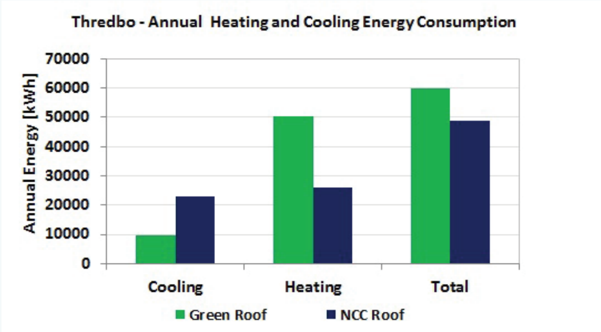
	
Climate Zone 8	Climate Zone 8

Table 4. Comparison of energy performance of roof types with and without green roof

The result of the annual energy simulation shows that for all climate zones, green roofs decrease cooling energy consumption. In some instances with a metal deck roof, heating is also seen to decrease. Generally, the green roof (modelled without insulation) increased heating energy consumption in most climates.
The decreased cooling load is seen to be of more significance, which consequently reduces the overall energy consumption in all but two of the climate zones.

The cooling energy reduction is due to the thermal mass and the shading provided by the foliage. The calculated thermal resistance of the green roof is significantly less compared to a code compliant roof. As a result, the green roof is more conductive and loses heat more readily. This heat loss is more comparable to an uninsulated roof.

The summary of energy savings for each climate is provided in Table 5.

<table>
<tr><th>Location</th><th>Climate Zone</th><th>Annual heating and cooling energy savings: green roof on concrete deck</th><th>Annual heating and cooling energy savings: green roof on metal deck</th><th>Comments</th></tr>
<tr><td>Darwin</td><td>1</td><td>5%</td><td>11%</td><td>No heating required.</td></tr>
<tr><td>Brisbane</td><td>2</td><td>22%</td><td>27%</td><td>Reduction in both heating and cooling with the exception of concrete roof for heating only.</td></tr>
<tr><td>Alice Springs</td><td>3</td><td>29%</td><td>34%</td><td>Reduction in both heating and cooling with the exception of concrete roof for heating only.</td></tr>
<tr><td>Broken Hill</td><td>4</td><td>25%</td><td>29%</td><td>Reduction in cooling but increases the heating energy consumption therefore a low level of insulation may be recommended.</td></tr>
<tr><td>Sydney</td><td rowspan="3">5</td><td>27%</td><td>31%</td><td rowspan="3">Reduces both cooling and heating, with the exception that the concrete deck roof increases the heating energy consumption for each city and heating increases for both roof types in Adelaide.</td></tr>
<tr><td>Adelaide</td><td>30%</td><td>34%</td></tr>
<tr><td>Perth</td><td>32%</td><td>37%</td></tr>
<tr><td>Melbourne</td><td>6</td><td>8%</td><td>10%</td><td>Reduces the cooling but heating increases significantly, therefore low to moderate level of insulation may be required.</td></tr>
<tr><td>Canberra</td><td rowspan="2">7</td><td>2%</td><td>6%</td><td rowspan="2">Reduces the cooling but heating increases significantly. As a result, a moderate to high level of insulation may be required.</td></tr>
<tr><td>Hobart</td><td>No savings – overall energy increased by 4%</td><td>No savings – overall energy increased by 5%</td></tr>
<tr><td>Thredbo</td><td>8</td><td>No savings – overall energy increased by 18%</td><td>No savings – overall energy increased by 23%</td><td>The increase in heating energy outstrips any cooling benefit, therefore the application of a green roof should be analysed for the building type and its internal heat loads.</td></tr>
</table>

Table 5. Summary of energy savings in each climate zone

Table 5 indicates that temperate climate zones 2, 3, 4 and 5 benefit the most from green roofs, where the energy savings are between 22–37% of overall heating and cooling energy consumption. In these climates cooling can represent a significant portion of the annual energy consumption and heating typically represents a small portion. Therefore the increase in heating energy consumption does not impact on an overall energy reduction with the installation of a green roof. An extensive green roof with 200 mm depth may be sufficient in most cases to reduce cooling energy consumption, however the growing media or soil depth needs to be optimised for each building and for each climate.

In Canberra, Melbourne and Hobart (climate zones 6 and 7) which are typically characterised by a hot to very hot summer and a cold winter with low humidity, the energy saving benefit of a green roof without insulation is more moderate at around 2–8%. This is because heating energy typically represents a significant portion of the total (heating and cooling) energy consumption and the addition of a green roof increases heating by about 65%. Therefore a green roof reduces the overall savings.

In tropical (hot and humid) climates such as Darwin (climate zone 1) the savings are around 4%. This is because Darwin is hot and humid and an extensive roof with 200 mm depth is not sufficient enough to reduce heat gain to achieve a cooling energy reduction. In such climates, an intensive roof with a higher depth will result in a reduction in cooling energy consumption. Also note that in Darwin's climate, no heating energy was required for the model.

In cooler climates such as Thredbo (climate zone 8) both heating and cooling energy consumption are more or less equal and there are no net savings. While cooling energy consumption is significantly reduced, the heating energy consumption increases with equal proportion. In such climates the use of insulation is recommended. However, it should be noted that the use of insulation can reduce the cooling benefit, therefore the amount of insulation needs to be optimised for the location and the building type considered.

If heating demand is considerable, the amount of insulation must be optimised, as too much insulation placed between the occupied space and green roof will disconnect the space from the benefits of thermal mass, therefore negating the cooling benefit a green roof can offer. In this case, savings in heating usage will be outweighed by increased cooling and may not result in an overall reduction in the building's energy consumption. This optimised outcome will result in less R value of insulation than required under Section J of the NCC when a green roof is included. A thermal simulation will be required in this case to demonstrate performance solution based compliance with NCC Section J 'JV3' rather than the 'Deemed to Satisfy' requirements.

The heating energy savings are less significant in a majority of the commercial office buildings in all climates analysed except the alpine climate, where the heating energy required is significant. Accordingly, from an overall energy reduction point of view, green roofs can present a good passive cooling strategy for offices and potentially other building types in many Australian climate zones.

4. Financial analysis

A financial assessment is presented here to compare the costs between green roofs and conventional roofs in terms of the energy saving they provide due to the cooling effects they contribute to the thermal performance of a building. Whole of life (WOL) and return on investment (ROI) analyses are used as tools to facilitate this comparison. The WOL approach considers the initial cost and ongoing yearly maintenance and operation costs. The financial benefit is presented by incorporating energy costs into WOL costs in the modelled office-type facility, as described in section 4.1.

The non-thermal performance and energy saving benefits of green roofs such as their contribution to stormwater management (in meeting water sensitive urban design best practice); their reduction of the urban heat island effect (by cooling cities); their contribution to air quality, and amelioration of noise impacts (through air absorption); their contribution to biodiversity (by providing habitat for animals and plants); and the social benefits that accrue (such as improvements to human wellbeing that manifest from proximity to living systems and natural processes) were not considered in this study.

Once these benefits are factored in, it is the authors' belief that the overall business case for the increased adoption of extensive green roofs in the urban context will be convincing.

4.1 Whole of life, payback and internal rate of return

The Whole of Life (WOL) cost analysis includes the cumulative total of initial capital costs (CAPEX) and the operating expenditure (OPEX) for maintenance, utilities and upkeep. The total costs are then discounted over the life of the system and displayed as operational capital expenditure, service and maintenance as a total combined WOL cost at the end of the analysis period. The analysis period is taken to be 30 years.
The assumptions used are shown in Table 6.

Variables considered	Green roofs	Typical NCC compliant conventional roofs
Economic life	30 years	30 years
Capital cost	$250/m2 of roof area	$180/m2 of roof area
Maintenance cost	Initial $5000 for three years and after three years $750/year. It is expected to keep pace with inflation which averages 2.5% annually over the study period.	$250/year. It is expected to keep pace with inflation which averages 2.5% annually over the study period.
Electricity cost	$0.25/kWh	$0.25/kWh
Gas cost	$0.05/MJ	$0.05/MJ
Electricity price escalation	12%	12%
Gas price escalation	5%	5%
Interest rate	7%	7%

Table 6. WOL inputs and assumptions for a new build

Based on the above inputs and assumptions, the 30 years WOL is compared with and without green roofs for the major cities of Australia taking into account the energy consumption figures presented in Appendix A. Table 6 assumptions are applied consistently for all the locations investigated in this paper.

Table 7 summarises the payback and internal rate of return (IRR) or effective interest rate for all the cases investigated. The IRR is presented to evaluate the desirability of green roof projects and to demonstrate whether green roofs are an acceptable investment. Generally, if a project's IRR is greater than an established minimum rate of return (usually bank interest rate) then it is considered a good investment from the point of view of most economists.

In the case of Darwin, the annual cooling energy is almost twice that of Brisbane, which reflects the fact that on a WOL basis, the office building in Darwin is almost twice as expensive to operate (refer Appendix A) when compared with a similar building in Brisbane. Similar reasoning is also valid for other locations.

Location	Concrete deck roof				Metal deck roof			
	WOL cost ($)		Payback period (years)	IRR (%)	WOL cost ($)		Payback period (years)	IRR (%)
	Green roof	NCC roof			Green roof	NCC roof		
Darwin	$3,108,269	$3,183,693	21	5%	$3,068,863	$3,308,564	13	11%
Brisbane	$1,377,795	$1,614,751	13	11%	$1,365,817	$1,696,186	11	13%
Alice Springs	$1,300,626	$1,660,053	10	14%	$1,270,838	$1,763,339	8	17%
Broken Hill	$855,884	$1,040,820	15	8%	$848,043	$1,108,245	13	10%
Adelaide	$643,883	$811,488	16	7%	$641,622	$871,175	14	9%
Sydney	$889,288	$1,071,355	15	9%	$879,771	$1,136,396	13	11%
Perth	$887,906	$1,122,325	13	10%	$877,861	$1,200,389	11	13%
Melbourne	$555,513	$624,262	23	5%	$565,054	$673,131	20	5%
Canberra	$648,191	$709,140	24	0%	$654,595	$768,344	20	2%
Hobart	$470,581	$492,271	28	N/A	$486,318	$529,442	26	N/A
Thredbo	$596,697	$573,123	-	N/A	$610,850	$622,328	-	N/A

Table 7. Summary of WOL, payback and IRR for the modelled office building

5. Limitations

In these simulations, it has been assumed that no insulation is provided for the green roofs in all climates. This has been done to make a fair comparison with and without a green roof, and also to understand the impact of a green roof only for both cooling and heating loads.

It is recognised that there are limitations in the paper's methodology that reflect the complexity and diversity of green roof design and construction in Australia. This is due to the many variations that could eventuate in practice as outlined below.

Variation in the proportion of green roof coverage, as well as the quantity of HVAC plant and equipment, coverage of access walkways, paved areas, solar panels, shade structures and other elements, will influence the thermal performance outputs and assumptions in the simulations undertaken for this paper. The diversity of these potentially variable factors has not been included in the simulations.

The composition, depth, water holding capacity, air-filled porosity, organic content, drainage configuration and irrigation regimes of the various potential green roof configurations will also have a bearing on the results, and these too have not been factored into the simulations.

Similarly, the variety of plant species included in potential green roof designs will have a bearing on the cooling effects due to the variety of shading coefficients from foliage, as well as the seasonal variability of the plants.

It is recognised that the simulation method explored in this paper is not a definitive description of the benefits, but an attempt to highlight how these benefits could be realised in a value proposition for the inclusion of green roofs into more projects in Australia.

Further validation of these findings will be required in the form of monitoring data from built green roofs, in benchmarked trials and research projects which can compare green roofs to conventional roofs for each climate zone with actual energy consumption data to verify the implications of the simulations provided in this paper.

6. Conclusion

This paper describes the contribution of a 200 mm deep growing media green roof on building energy performance with respect to both heating and cooling energy consumption. A typical new office building with and without a green roof was modelled in all climate zones of Australia. The heat transfer, peak cooling load and energy performance were analysed.

The results show that green roofs reduce external heat flux through the roof surface and therefore the heat transfer through the roof surface is minimised. It was observed that the heat gain profile is more or less constant compared with a typical NCC compliant concrete roof which helps to reduce peak energy demand. This not only reduces the size of air conditioning plant required but also helps the air conditioning plant to operate more efficiently with resultant energy cost savings.

The passive cooling effect of a green roof was observed due to a reduction in peak cooling load. This reduction can be attributed to shading by foliage, the effect of thermal mass, moisture content and irrigation cycles. The green roof operates like a phase change material on the roof surface, absorbing heat from the conditioned space, thus helping to reduce cooling energy consumption.

In all scenarios modelled the effect of insulation was not considered for the green roof in contrast to the NCC compliant conventional roof that has insulation.

An analysis of the simulation results indicates that green roofs perform at their best in cooling mode in cases where the inclusion of thermal resistance insulation is not beneficial. If heating energy demand is significant, such as in the climates of Melbourne, Canberra and Hobart, then some thermal resistance insulation is advisable, but the level of this insulation needs to be optimised otherwise the cooling benefit of the green roof will be reduced.

Based on these simulations, the annual energy consumption and resultant financial analysis, it can be concluded that a green roof performs better in hot and moderately humid or dry climates such as Alice Springs, Darwin, Sydney, Adelaide, Perth and Brisbane. In these climates, the payback is between 8–14 years. In tropical climates such as Darwin, deeper growing media may be required for better savings. In an alpine climate such as Thredbo, a green roof may not be advisable, depending on the internal heat loads for the building.

This simulation suggests that further research is required by way of demonstration projects where these findings can be verified through the monitoring of the actual thermal performance of green roof installations.

The thermal performance and contribution to energy savings of a green roof, when combined with other benefits such as storm water management; improvements in air quality; sound attenuation; improvements in the wellbeing and productivity of people; increased property values; marketing benefits; food production and food security; and greenhouse gas mitigation, could provide a meaningful incentive for their inclusion in many Australian projects. It is hoped by the authors that with further research and development, green roofs may one day be included in the National Construction Code as an acceptable measure for achieving the requirements under Section J.

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Arjun Adhikari, BE (Mech), ME (Studies), ME (Research), is the Director of Thermal Environmental Engineering and a Sustainability Consultant. Over the last 12 years, he has developed unique technical and multi-disciplinary project management and coordination skills to deliver sustainable outcomes in the built environment.

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Appendix A

Australian Climate Zone	Roof Type	Concrete Deck Roof			
		Cooling (kWh)	% Difference (NCC roof and green roof)	Heating (kWh)	% Difference (NCC roof and green roof)
Climate Zone 1 (Darwin)	NCC roof	204,355	-5%	-	N/A
	Green roof	193,170		-	
Climate Zone 2 (Brisbane)	NCC roof	97,059	-23%	1,550	14%
	Green roof	74,813		1,761	
Climate Zone 3 (Alice Springs)	NCC roof	99,616	-31%	3,547	32%
	Green roof	68,787		4,664	
Climate Zone 4 (Broken Hill)	NCC roof	56,468	-35%	7,178	57%
	Green roof	36,745		11,241	
Climate Zone 5 (Sydney)	NCC roof	59,593	-32%	3,233	67%
	Green roof	40,586		5,338	
Climate Zone 5 (Adelaide)	NCC roof	41,318	-45%	5,392	88%
	Green roof	22,595		10,140	
Climate Zone 5 (Perth)	NCC roof	63,021	-35%	3,400	25%
	Green roof	40,784		4,234	
Climate Zone 6 (Melbourne)	NCC roof	27,184	-50%	10,592	98%
	Green roof	13,698		20,994	
Climate Zone 7 (Canberra)	NCC roof	31,846	-42%	14,819	83%
	Green roof	18,385		27,130	
Climate Zone 7 (Hobart)	NCC roof	17,366	-62%	13,711	88%
	Green roof	6,643		25,783	
Climate Zone 8 (Thredbo)	NCC roof	19,662	-52%	25,829	85%
	Green roof	9,385		47,856	

Table 8. Cooling and heating energy on concrete deck with and without green roof

Australian Climate Zone	Roof type	Metal deck roof			
		Cooling (kWh)	% Difference (NCC roof and green roof)	Heating (kWh)	% Difference (NCC roof and green roof)
Climate Zone 1 (Darwin)	NCC roof	218,133	-4%	-	N/A
	Green roof	208,718		-	
Climate Zone 2 (Brisbane)	NCC roof	105,674	-21%	1,578	-33%
	Green roof	83,188		1,054	
Climate Zone 3 (Alice Springs)	NCC roof	108,518	-15%	3,768	-52%
	Green roof	92,781		1,804	
Climate Zone 4 (Broken Hill)	NCC roof	63,522	-29%	7,378	20%
	Green roof	45,132		8,835	
Climate Zone 5 (Sydney)	NCC roof	66,276	-29%	3,376	-7%
	Green roof	46,737		3,130	
Climate Zone 5 (Adelaide)	NCC roof	47,274	-39%	5,484	19%
	Green roof	28,899		6,516	
Climate Zone 5 (Perth)	NCC roof	70,730	-31%	3,537	-21%
	Green roof	49,052		2,787	
Climate Zone 6 (Melbourne)	NCC roof	31,880	-42%	10,527	35%
	Green roof	18,451		14,190	
Climate Zone 7 (Canberra)	NCC roof	36,989	-42%	14,465	63%
	Green roof	21,279		23,528	
Climate Zone 7 (Hobart)	NCC roof	20,614	-61%	13,109	65%
	Green roof	8,036		21,655	
Climate Zone 8 (Thredbo)	NCC roof	23,035	-53%	23,095	89%
	Green roof	10,762		43,684	

Table 9. Cooling and heating energy on metal deck with and without green roof

References

Ascione, F., Bianco, N., de Rossi, F., Turni, G., Vanoli G.P., 2013, 'Green Roofs in European Climates. Are effective solutions for the energy savings in air-conditioning?', *Applied Energy*, Elsevier, pp 845-859.

Australian Building Code Board (ABCB), 2016 *National Construction Code Series*, Volume One.

Berardi U., GhaffarianHoseini A. and GhaffarianHoseini A. 2014, 'State of the art analysis of the environmental benefits of green roofs', *Applied Energy*, Elsevier, pp. 411–428.

Berndtsson J. C., Emilsson T. and Bengtsson L., 2006, 'The Influence of extensive vegetated roofs on runoff water quality', *Science of the Total Environment*, Elsevier Sweden, pp. 48–63.

Boning M. and Schrader S., 2006, 'Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans', *Pedobiologia*, Elsevier Germany, pp. 347–356.

Castleton H. F., Stovin V., Beck S. B. M. and Davidson J. B. 2010, 'Green roofs; building energy savings and potential for retrofit', *Energy and Buildings*, Elsevier United Kingdom, pp. 1582–1591.

Del Barrio, E 1998, 'Analysis of the green roofs cooling potential in Buildings', *Energy and Buildings,* Elsevier Science France, pp. 179–193.

Department of Environment and Primary Industries, 2014, *Growing Green Guide – A guide to green roofs, walls and facades in Melbourne and Victoria, Australia,* February 2014, http://www.growinggreenguide.org/

ENERGYPLUS™, 2013, *EnergyPlus Engineering Reference*, US Department of Energy (DOE).

Fioretti R., Palla A., Lanza L., G. and Principi P. 2010, 'Green roof energy and water related performance in the Mediterranean climate', *Building and Environment*, Elsevier Italy, pp. 1890–1904.

Hopkins, G. (Fifth Creek Studio), 2012, *Green Roof Trials Monitoring Report*, SA Government's Building Innovation Fund and Aspen Development Fund No.1.

Jaffal I., Ouldboukhitine S. and Belarbi R., 2012, 'A comprehensive study of the impact of green roofs in building energy performance', *Renewable Energy*, Elsevier France, pp. 157–164.

Jim C. Y. and Peng L. L. H. 2012, 'Weather effects on thermal and energy performance of an extensive tropical green roof', *Urban Forestry and Urban Greening*, Elsevier Hong Kong, pp. 73–85.

Jim C. Y. 2012, 'Effects of vegetation biomass structure on thermal performance of tropical green roof', *Landscape Ecological Engineering*, pp. 173–187.

Kokogiannakis G., Tietje A. and Darkwa J. 2011, 'The role of green roofs on reducing heating and cooling loads: a database across Chinese climates', *Procedia Environmental Sciences*, Elsevier China, pp. 604–610.

Li, J., Wai, O. W. H., Li, Y. S., Zhan, J., Ho, Y. A., Li, J. and Lam E., 2010, 'Effect of green roof on ambient CO2 concentration', *Building and Environment*, Elsevier, pp. 2644–2651.

Mander, U. and Teemusk A., 2007, 'Rainwater runoff quantity and quality performance from a green roof: The effects of short-term events', *Ecological Engineering*, Elsevier Estonia, pp. 271–277.

Moody S., S. and Sailor D., J., 2013, 'Development and application of a building energy performance metric for green roof systems', *Energy and Buildings*, Elsevier USA, pp. 262–269.

Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A and Mihalakakou G. 2001, 'Analysis of the green roof thermal properties and investigation of its energy performance', *Energy and Buildings*, Elsevier Science Greece, pp. 719–729.

Olivieri, F., Di Perna,C., D'Orazio, M., Olivieri, L., Neila, J., 2013, 'Experimental measurements and numerical assessment of extensive green roofs in a Mediterranean coastal climate', *Energy and Buildings*, Elsevier, pp 1-14.

Ouldboukhitine S., Belarbi R., Jaffal I. and Trabelsi A. 2011, 'Assessment of green roof thermal behaviour: A coupled heat and mass transfer model', *Building and Environment*, Elsevier France, pp. 2624–2631.

Renterghem T. V. and Botteldooren D., 2009, 'Reducing the acoustical façade load from road traffic with green roofs', *Building and Environment*, Elsevier Belgium, pp. 1081–1087.

Rowe D, B., 2011, 'Green roof as a means of pollution abatement', *Environmental Pollution*, Elsevier, pp. 2100–2110.

Saadatin O., Sopian K., Salleh E., Lim C. H., Riffat S., Saddatian E., Toudeshki A. and Sulaiman M. Y., 2013, 'A review of energy aspects of green roofs', *Renewable and Sustainable Energy Reviews*, Elsevier, pp. 155–168.

Sailor, D. J., 2008, 'A green roof model for building energy simulation programs', *Energy and Buildings*, Elsevier USA, pp. 1466–1478.

Santomouris, M. 2012, 'Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments', *Solar Energy*, Elsevier Greece.

Shaw, M. 2016, 'NCC Section J and commercial building facade design – 2016 update', *Environment Design Guide*, EDG 86 MS, May.

Tomalty, R., Komorowski, B., Doiron, D. 2010 *The Monetary Value of the Soft Benefits of Green Roofs*, Smart Cities Research Services, Montreal.

Tsang S. W. and Jim C. Y., 2011, 'Theoretical evaluation of thermal and energy performance of tropical green roofs', *Energy*, Elsevier Hong Kong, pp. 3590–3598.

Williams N. S. G., Rayner J. P, and Raynor K. J., 2010, 'Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia', *Urban Forestry and Urban Greening*, Elsevier Australia, pp. 245–251.

Wong, N.H., Cheong, D.K.W., Yan H., Soh, J., Ong, C.L., Sia, A., 2003, 'The effects of rooftop garden on energy consumption of a commercial building in Singapore', *Energy and Buildings*, Elsevier Science, pp 353–364.

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