The potential for cool roofs to improve the energy efficiency of single storey warehouse-type retail buildings in Australia: a simulation case study

Abstract

Australia's commercial building stock exceeds 134 million m^2 of net lettable area, with retail buildings contributing 35% to this sector's energy use. The energy intensity of retail buildings in hotter climates is higher than the national average, as is the energy intensity of smaller buildings (under 1500m^2) that are not considered 'high-end' commercial properties. Little attention has been paid to improving the energy efficiency of these types of buildings through regulation (for new buildings) or through market mechanisms (for retrofitting). As many of these buildings are single storey 'warehouse' type buildings, their predominant heat load comes through the roof, and thus are well suited to benefit from cool roof technology. Despite this, there remains a deficiency in quantifying the benefit of such technology in the context of single-storey retail buildings in Australia. This paper reports on an experimentally validated numerical study aimed at addressing this deficiency. Results show that application of cool roof technology to a warehouse type building in a subtropical environment increases the energy efficiency by shifting space temperature towards the design set point (21-23°C), and thus reducing cooling energy demand. This study also indicates an energy saving every month with the application of cool roof, with the largest saving in hotter months and no heating penalty in cooler months. Application of cool roof technology on warehouse style buildings across Australia buildings indicates energy savings can be achieved in all broad Australian climatic zones, with the greatest energy reduction associated with tropical, subtropical and desert environments.

Keywords: building simulation, cool roof, energy efficiency, CO2 emissions reduction, retail building

1. Introduction

1.1 Need for energy efficiency in commercial buildings

Urbanisation, natural resource and infrastructure constraints, and the reality and future threats of climate change, are forcing many world governments to quantify the impact our built environment has on these challenges, and introduce measures to reduce this impact. Signatories to the Paris Climate Change Agreement have committed to a global transition to zero net emissions, inevitably involving a move to net zero energy or net zero carbon buildings. For example, buildings account for 23% of Australia's greenhouse gas emissions: this means that it is essential to reduce the carbon intensity of Australia's building stock in order to meet international obligations.

Australia's commercial building stock in 2009 was 134 million m^2 of net lettable area [1]. According to this report, retail buildings and office buildings were the largest contributors to this sector's energy use: 35% and 25% respectively (Figure 1). The energy intensity of these buildings varies between building type, building size and climate zone. For example, the energy intensity of retail buildings in warmer climates (e.g. Queensland) is higher than the national average for these buildings; fast food outlets are more energy intensive than other retail tenancies; and small office buildings (<1,500m^2) are more energy intensive than larger office buildings [1]. Heating, ventilation and air conditioning (HVAC) represent 43% of electricity consumption for retail and office buildings, predominantly relying on electricity for their energy service needs. Whilst energy efficiency measures have been taken up by some sectors, especially in high-end commercial properties, the energy intensity of the commercial sector as a whole has only improved 2% [2].

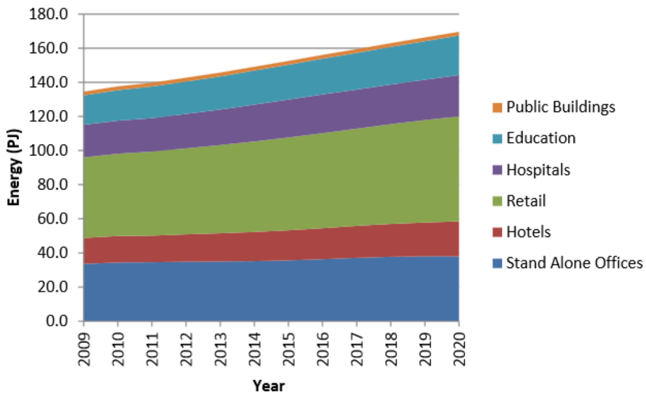


Fig. 1 Sector share of commercial building energy consumption in Australia [1]

The internal heat load of commercial and industrial buildings in warm and hot climates is predominantly driven by solar heat gain through the roof, walls and floors [3, 4], rather than by internal loads from equipment and occupants. Whilst both internal and external heat loads are now addressed to some extent through the energy efficiency requirements for new buildings through the Australian Construction Code, there remains significant commercial building stock in need of energy efficiency retrofits. Cost effective mechanisms for improving the thermal efficiency of existing commercial building stock have the potential to reduce the cooling loads of these buildings, conceivably providing financial benefit to both building operators and electricity networks. For single storey or low rise constructions, typical in suburban and regional retail shopping strips and small office buildings, it would seem logical that addressing heat gain through the roof should be the first priority, given the large roof surface area to internal volume ratio and high solar radiation in Australia.

1.2 Effectiveness of cool roof coatings

A 'cool roof' is defined as a roof that, because of the surface coating with specifically designed optical and infra-red properties, remains at or near ambient temperature under sunny conditions. These coatings are typically identified by their *high solar reflectance*, *high thermal emittance* and/or *solar reflectance index* [5] *(*a combination of the two). Cool roof coatings are typically white with a high albedo and either a single ply membrane or liquid applied coating. Typical single ply coatings involve EPDM (Ethylene-Propylene diene-Tetrolymer Membrane), PVC (Polyvinyl Chloride), CPE (Chlorinated Polyethylene) and TPO (Thermoplastic Polyolefin) while typical liquid coatings include paints or elastomeric, polyurethane or acrylic coatings. Cool Roofs are reported to have multiple benefits including reductions in energy consumption and peak demand, monetary savings, increased thermal comfort in and around buildings, and extended roof life. The extent of these benefits, however, is reported to vary with climate and season, building type and materials, actual change in solar reflectance values, electricity pricing, heating and cooling equipment and operational efficiency, and building occupancy [6-15]. They are also reported to potentially enhance urban environmental quality by increasing urban albedo [8, 10, 16].

Evidence suggests that the effectiveness of a cool roof is inversely proportional to the level of insulation [14]. Thus, the use of cool roof technology is best suited to building with low- to no-insulation in a number of climates [17, 18] as an effective measure to reduce cooling load [18-20]. The residential demand side management potential of cool roof technology for Australian tropics has been reported in [21], highlighting the impact of building characteristics (e.g. roof colour and level and type of roof and ceiling insulation) and occupant behaviour (e.g. cooling set point) on expected outcomes. Indicative energy benefits reported for commercial buildings in warm/hot climates are shown in Table 1.

Table 1 Reported benefits for commercial/retail buildings in warm/hot climates in the US [22] and India [11]

Location	Building Type	Reduction in cooling energy (kWh)	Reduction in peak demand
Florida, California, Texas, Sacramento	Retail	2-52% (A California estimate of 6-15 kWh/m^2 of conditioned area/year; for a particular retail building type)	0.65W – $3.8W/m^2$ (A California estimate, for particular retail building type, of 2.9-5.8 W/m^2 (12:00 – 17:00))
California	Cold storage facility (group of 4 buildings)	3-4% (summer) 4.5 – 7.4 kWh/m^2 of conditioned area/year	3.9- 6.6 W/m^2 (12:00 – 17:00)
California, Mississippi	Commercial (offices)	12-26%	
Metropolitan Hyderabad	Commercial	10 - 26% 13-22 kWh/m^2 (depending on initial roof reflectance)	

Analysis of the economic and energy benefits associated with retrofitting cool roof technology on commercial buildings indicates significant potential for saving [23, 24]. In North America, an annual cooling energy saving of 10.4 TWh, and an annual heating energy penalty of about 3.9 TWh was estimated to be achieved if 80% of commercial building roofs were retrofitted with reflective white roof coatings (solar reflectance 0.55). This translated to 6.23Mt reduction in CO_2 and an annual cost saving of US$735 million [23]. The Lawrence Berkley Laboratory (LBL) cites energy density reductions of $3.2kWh/m^2$ and $2.1W/m^2$ in electricity use for cooling and cooling power demand respectively, with the installation of cool roofs with a minimum solar reflectance of 0.70 and a minimum thermal emittance of 0.75 [24]. Additionally, cool roof technology has been shown to provide broader societal benefits such as lower ambient air temperature (i.e. reduced heat-island effect) resulting in increased comfort levels [24]. Experimental field and computational studies such as the aforementioned have helped provide evidence for the inclusion of cool roofs in energy efficiency standards for buildings or in building maintenance and operations. For example, cool roof requirements began to enter into regulatory codes in California in 2001. A similar regulatory standard is yet to be proposed in Australia.

1.3 This research

The purpose of this research is to assess the impact of cool roof technology on a common commercial building typology in Australia: single-storey warehouse type buildings. The aim is to provide validated data analysis from which conclusions and recommendations can be used to contribute to the development of industry guidelines and/or regulations to enhance the energy efficiency of the commercial building stock in Australia.

2. Methodology

Experimental data and building simulation using a case study building were utilised in this research, as described in the following sections.

2.1 Case study building

The case study building is a 1002 m^2 single-storey 'warehouse' style retail building in sub-tropical south-east Queensland (27.4679°S). The store was constructed in the 1990s and has two retail tenancies: a clothing store and an appliance store, as well as a general storage area and bathrooms (Figure 2). The building is situated within a larger retail complex that has large areas of dark pavement (roads or car parking) and is cooled by two roof mounted air conditioners, as seen in an aerial view (Figure 2(b)). The building's main glass façade and shop entrances face north-west (refer to elevations shown in Figure 3). The average monthly daytime temperatures (during store operating times) for this climate are shown in Figure 4. Table 2 summarise the main building characteristics.

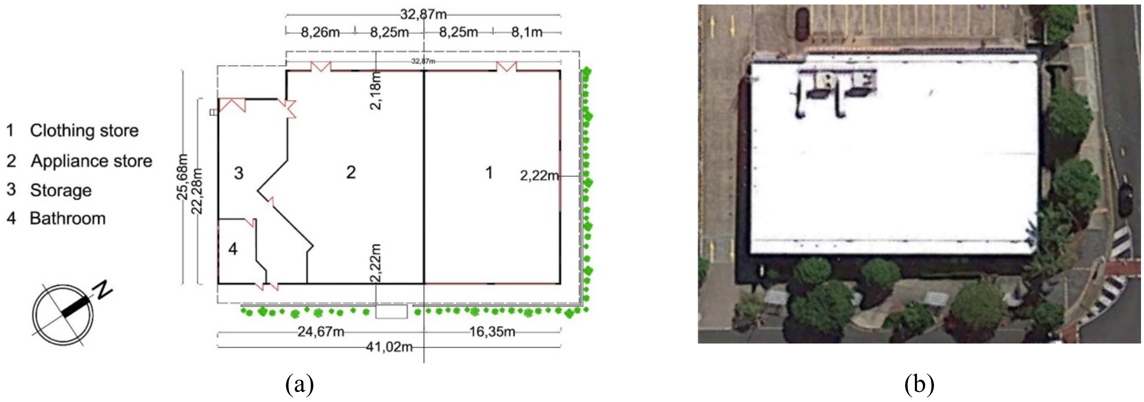


Fig. 2. (a) Case study floor plan (dimensions in meters, not to scale) and (b) aerial view

Fig. 3. Elevations of case study building: (a) NW, (b) NE, (c) SW and (d) SE.

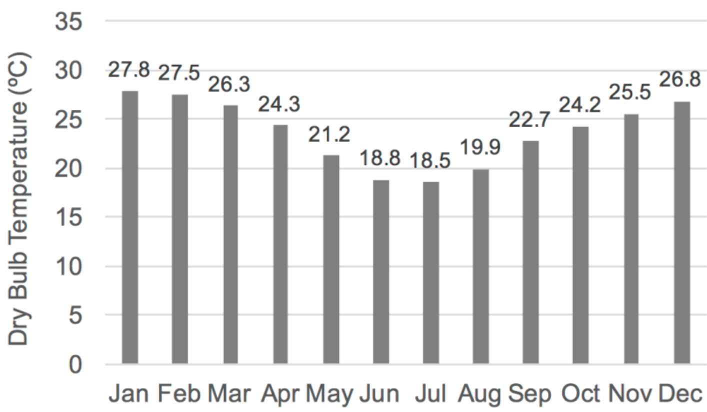


Fig. 4. Average monthly daytime dry-bulb temperatures for Brisbane (8am-5pm)

Table 2 Case study building characteristics and Model input parameters

Building size, type and context	Single storey warehouse style retail building. Outside dimension $(L \times W \times H)$ $41.02m \times 25.68m \times 5.39m$. Total floor area of 1001.8 m^2, roof area of 1004m^2 Roof slope of 3.5% Total volume of 5198.6 m^3. External wall surface area to volume ratio of 13%. Conditioned area: 411.6 m^2. Conditioned volume of 1234.8 m^3 Building surrounded by significant high absorptance areas
External walls	Concrete and breeze block construction on SW with metal sheeting on gable end (total wall U value:1.78 (W/m^2K) Metal and glass façade NW and SE (total wall U value: 2.39 (W/m^2K). Glazing Total U: 5.7(W/m^2K); g-value (EN 410): 0.83 No insulation
Roof	Low pitched metal roof (3.5%) Reflective foil-backed bulk insulation blanket under roof sheeting (R1.3)

	U-value 1.97 (W/m^{2}K) Solar reflectance (Before): 0.2, (After): 0.875 Emissivity: (Before): 0.25, (After): 0.9
Ceiling	Suspended ceiling and partial mezzanine floor; no insulation
Floor	Concrete slab
Fire wall	Retail spaces separated by full fire wall (floor to roof), so the two zones are separate thermally
Space cooling	Two roof-mounted air conditioning (AC) units, one for each tenancy: Temperzone Model#OPA96RKTBH; Rated electrical output 31.4kW; Rated COP 2.8. AC operates in the tenanted store at all times when the store is open for business. Set point 22°C, +/- 1°C
Occupancy during experimental study (Aug 2013 - Sept 2014)	One tenancy (the appliance store shown as zone 2 in Figure 1) was not occupied Aug 2013 - April 2014. This provided an opportunity to measure the impact of the roof coating on temperature (in the unoccupied zone) and electricity (in the occupied zone) under the same conditions simultaneously.
Business operating hours	7 days 8:00 - 17:00 (Zone 1 only; Zone 2 was not tenanted)

2.2 Applied Cool Roof Coating

The cool roof coating used on the case study building was a water based acrylic coating, specifically Shieldcoats Thermobond HRC (Artic White). This coating as a solar reflectance (R_{sol}) value of 0.878 when tested to ASTM C1549. The coating is a non-hazardous liquid glaze consisting of acrylate block copolymer resin (>50%), water (<30%) and Ethylene Glycol Monobutyl Ether (<2%) with mould inhibitors and surfactants. The cost of the cool roof coating, excluding labour and any necessary safety features required for installation, was an additional AUD 2-3 per m^2 above standard roof paint (2017 currency).

2.3 Case Study Experimental Data and Results

Onsite measurements were obtained from the case study building before and after the application of a cool roof coating. Building performance was monitored for approximately two months (31/08/2013 – 18/11/2-13) before the application of the cool roof coating, after which it was monitored for approximately nine months (21/11/2013 – 06/08/2014). No detailed material specifications were available for the original roof coating, however, energy and temperature results from the validated numerical model indicated that the roof likely had a total U-value, emissivity and absorptance of 1.9660 W/m^{2}K, 0.25 and 0.8 respectively. The underside of the roof and internal (suspended ceiling) surface temperature was recorded with Maxim ibuttons (DS1922/3). Locations of these sensors are shown in Figure 5. Temperature measurements were taken every 30 minutes within an accuracy of ±0.5°C. Daily temperature profiles at the examined locations where generated from this data. Due to the nature of the building occupancy, temperature sensors could not be reliably or safely placed within the main store zone.

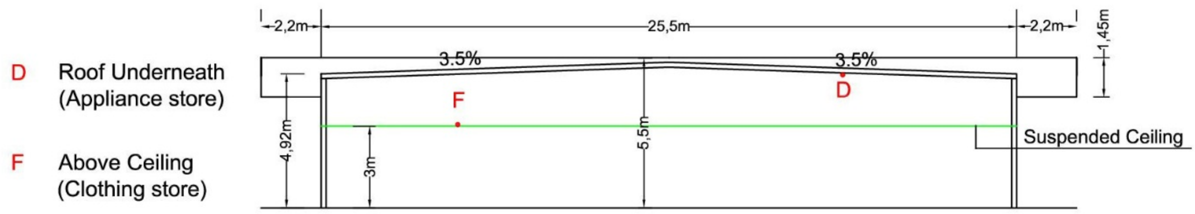


Fig. 5. Location of internal temperature sensors

The electrical cooling load of the building was measured in 30 minute intervals by an energy (kW) meter (Dent ElitePro SC) connected to the air-conditioning (AC) circuit relating to the occupied tenancy. The usage profile of the tenancy was determined manually by looking at daily internal temperature and electricity profiles, excluding periods where air conditioning was not operational (for example weekends and public holidays). The impact of the cool roof coating on the roof surface temperature was directly measured, and the impact on internal temperatures was seen by analysing the temperatures of the unoccupied tenancy (Figure 6).

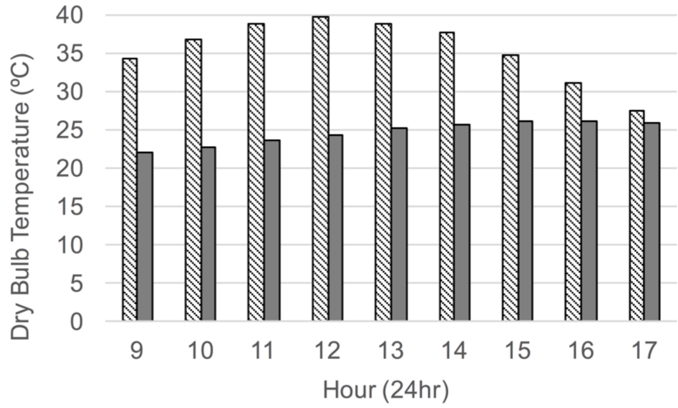


Fig. 6. Comparison of average internal temperatures before (cross-hatched) and after (grey bar) cool roof application

Measured electricity data was filtered for the occupancy hours of the occupied tenancy (i.e. periods when the air conditioner would be operating). To account for weather variations before and after cool roof coating, air conditioning demand from the measured data was analysed for all half hour periods with the same outdoor ambient dry bulb temperature. This analysis gave an indication of the cooling demand for each Celsius degree, enabling a comparison of the 'before' and 'after' cooling loads associated with the cool roof, and accounted for the different frequency distribution of ambient air temperature on different days. A summary of the analysed data for the experimental study is shown in Table 3. The measured impact of the cool roof on temperature was evaluated from experimentally collected data before and after the application the cool roof for days with comparable ambient conditions.

Table 3 Impact of cool roof coating on the case study commercial building

Criteria	**Measured impact**
Reduction in underside roof surface temperature (Sensor D in Fig 5)	9°C
Reduction in internal temperature (Sensor F in Fig 5)	8°C
Cooling load (W) reduction (relative to occupancy)	3.1W/m^2
Cooling energy (kWh) reduction	3.9kWh/m^2/year
Annual average load reduction for network peak time 12:00 - 14:00	2.2 kW (18%)
Annual average kWh reduction	1,628 kWh

2.4 Building simulation software

Building energy simulation has been used to extend the data from the field study. Utilising a commercial software (IES-VE) package an analysis was performed on the benefit of cool roof technology beyond the experimental data collection period and location. Experimental data (temperature and energy usage) was used to validate the building energy model, ensuring a high fidelity computational model. IES-VE (a virtual environment software by Integrated Environmental Solutions) was selected for this study because its accuracy and validity has been confirmed in literature [32,33].

2.5 Simulation model development and validation

Site visits were the primary method available to inform the architectural construction and layout of the building due to a lack of detailed as-built architectural drawings. A 3D model of the building, with four distinct zones (as shown in Figure 2), was developed based on these site visits (Figure 7). For simplicity, the smaller zones (3 and 4) were not considered in the computational model as they are unconditioned spaces, and thus do not significantly contribute to the cooling load demand. Zone 2 in Figure 2 was unoccupied and unconditioned in the case study building during the experimental data collection period. As such, this zone was simulated to be unoccupied with no internal heat gains and the associated HVAC unit turned off in the model,). Internal heat gains were applied to zone 1 to account for lighting and equipment according to the store's operational hours. Details on equipment, lighting and operating procedures in Zone 1 were determined during site visits and interviews with store employees. Due to a lack of actual relative humidity measurements, and for modelling simplicity, a relative humidity 'set point' of 30-60% was used (ASHRAE Standard 55-2004). Infiltration rates during the store's opening hours and out of hours were independently determined and applied the model. As there are no regulatory requirements of air tightness in Australian buildings, the out-of-hours infiltration rates were set to 2 ACH_{50} broadly reflecting the little data that exists on Australia's leaky buildings [34] and generating a cooling demand that matched experimental data. Infiltration rates during store opening hours were to between 8-20 ACH_{50} to capture standard store operational procedures. In particular, the site visit and interview indicated that the main shop door was permanently open during working hours which led to greater infiltration over this period. The impact of this operational procedure has been included in the model.

Detailed HVAC modelling (Chillers, AHU's dampers, controls etc.) was not carried out in this project. Instead, a fixed set-points of 22°C +/- 1°C and 19-22°C +/- 1°C was applied for cooling and heating respectively and the COP of the HVAC system included in the model. These temperature set-points define the desired conditioned space temperature to be maintained by the mechanical system. Actual annual weather data for 2013 from the closest site as measured by the Australian Bureau of Meteorology was used in the simulation, rather than a test-reference year.

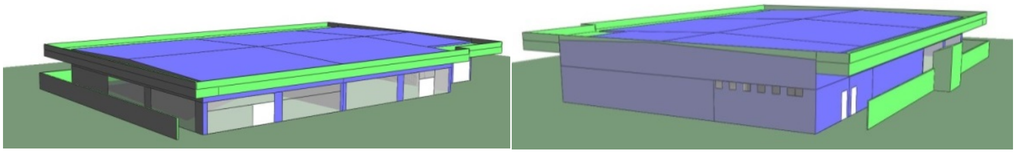
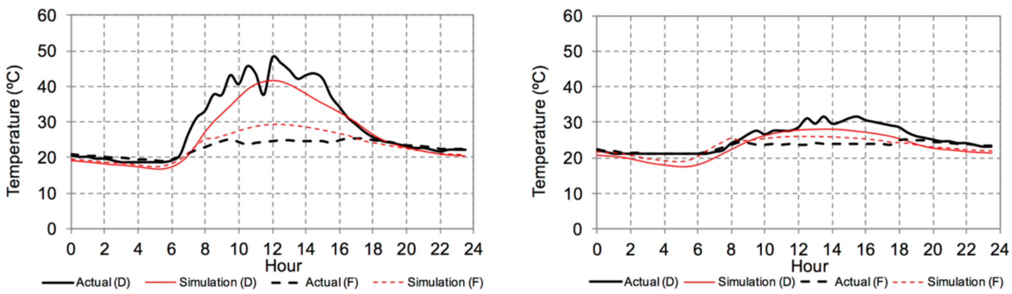


Fig. 7. 3D model in IES-VE from different views

The model was validated against the experimental data (temperature and energy consumption) from the field study. Figure 8 shows the actual and simulated temperatures (for sensor placements D and F) of the building for selected days before and after cool roof coating.



(a) (b)

Fig. 8. Actual and simulated temperatures at sensor placements D and F (a) before (20/10/2013) and (b) after (20/12/2013) cool roof coatings

The differences between the modelled and actual temperatures are tabulated in Table 4. The variation is around 10% which is within the 5-15% acceptable agreement between simulated and measured quantities as reported in the literature [28,35-37].

Table 4 Percentage variation between IES-VE and actual results of D and F sensor placements.

Parameter	**Thermometer D**		**Thermometer F**	
	Oct 20th	Dec 20th	Oct 20th	Dec 20th
Root Mean Squared Variation (RMSE)	3.64	2.37	2.33	2.22
Average percentage variation	12.51	9.34	10.19	9.56

The agreement between the computational model and the experimental data is considered good given the number of simplifying assumptions and professional engineering judgements made. In particular, detailed information on operating profiles and energy density of internal lighting and equipment were not available and neither was accurate data on relative humidity and infiltration rates. The simulated model, using a combination of measured, observed and approximated building parameters, was validated against experimental temperature data with the agreement given in Table 2 achieved. The model was further validated by comparing monthly energy consumption of the simulated model with field study data (Figure 9). The total difference in annual energy consumption was 1.12MWh, an error margin of 2.4%.

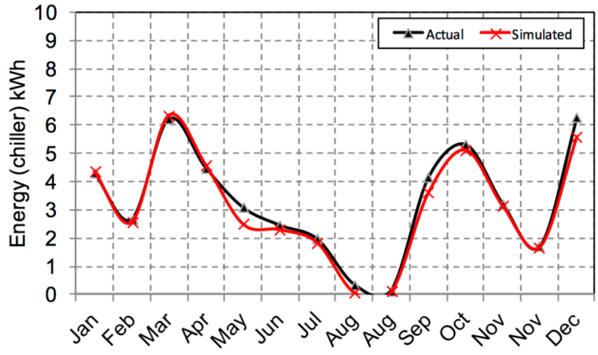


Fig. 9. Comparison of simulated and actual energy consumption over 1 year

2.6 Model extrapolation to other climate zones

The energy efficiency potential of cool roof technology applied to similar retail buildings across Australia was extrapolated from the model through the examination of seven different locations, or climate zones. Locations examined, as shown in Figure 10 and Table 5, are considered major urban areas within their respective climate zones and therefore likely to have significant numbers of. Single storey warehouse-type retail buildings.

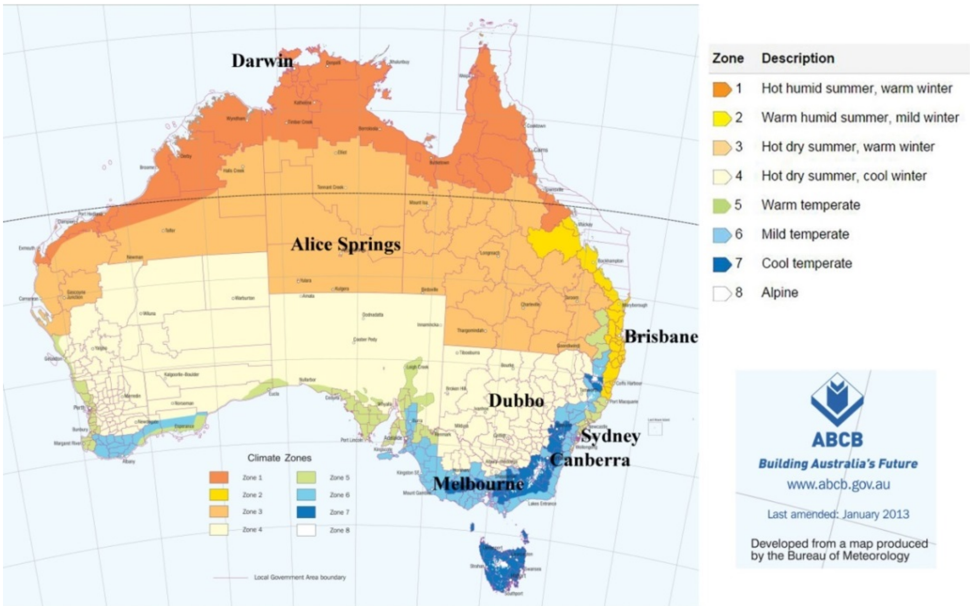


Fig. 10. Australia climate zones [42]

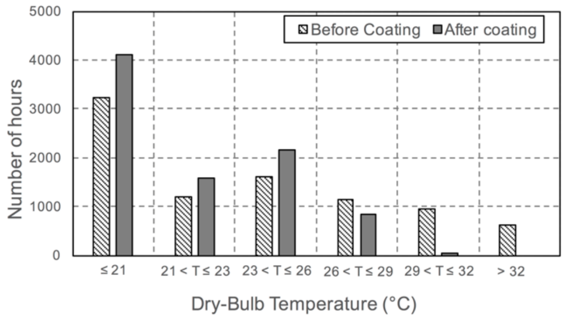
Table 5 Description of selected weather files

Climate Zone	Selected city	Latitude/Longitude	Climate
1	Darwin	12.4624°S, 130.8456°E	Hot humid summer, warm winter
2	Brisbane	27.4698°C, 153.0251°E	Warm humid summer, mild winter
3	Alice Springs	23.6980°S, 133.8807°E	Hot dry summer, warm winter
4	Dubbo	32.2315°S, 148.6330°E	Hot dry summer, cool winter
5	Sydney	33.8688°S, 151.2093°E	Warm temperate
6	Melbourne	37.8136°S, 144.9631°E	Mild temperate
7	Canberra	35.2809°S, 149.1300°E	Cool temperate

3. Results

3.1 Simulated impact of cool roof coating on temperature (Brisbane climate)

Data was analysed in three main temperature ranges: under 21°C, 21-23°C (the operating range of the AC with a set point of 22°C), and greater than 23°C. The impact of the cool roof coating is quantified by measuring the actual change in number of hours within the defined temperature bands (Figure 11) for all hours (not just store operating hours) for each of the zones (refer to Figure 2a). The full annual operation, rather than the operating hours have been examined as heat entering the building is stored internally (building envelope, furnishings etc.) and must be rejected either through thermal lag overnight when temperatures are appropriate or once the HVAC system is turned on. As such, any reduction in the number of hours above 23°C results in reduced thermal storage (and associated thermal lag) and a reduction in energy use for the HVAC system. The percentage changes are shown in Table 6. Results show that there is, on average a 4% increase in the number of hours spent within the design set point range (21-23°C) with the application of cool roof technology. Importantly, this increase is due to a significant reduction in hours at elevated temperatures (> 26°C), where on average a 1%, 7.5% and 9% reduction was found in the temperature ranges $26 < T \leq 29$, $29 < T \leq 32$ and $T > 32$ respectively. Reduction of periods at elevated temperatures will directly impact (reduce) the cooling energy demand and usage by reducing the thermal storage within the conditioned space as well as the space temperature cooling load demand. Further, the results demonstrate that through the reduction of hours at elevated temperatures, the cool roof coating has been successful in limiting heat transfer by approximately 60%, 70%, 92% and 99% in the temperature ranges $23 < T \leq 26$, $26 < T \leq 29$, $29 < T \leq 32$ and $T > 32$, through the roof into the building, resulting in reduced internal temperatures.



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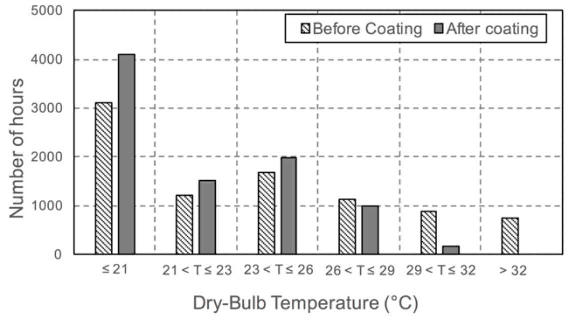

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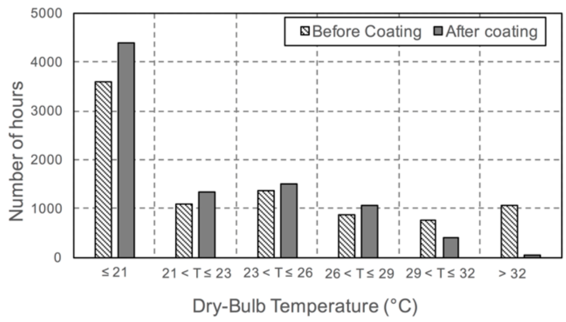


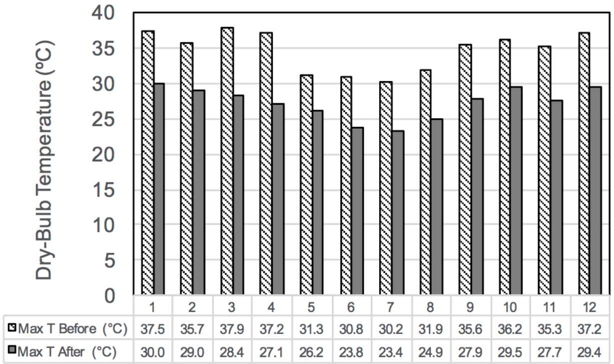
(c)

Fig. 11. Comparison of number of hours (24-hr operation) in different temperature bands in (a) ceiling void 1, (b) ceiling void 2, (c) and ceiling void 3 before and after cool roof application during the year.

Table 6 Percentage change in hours within defined internal temperature range for ceiling voids 1, 2 and 3 after cool roof coating.

Temperature range	CV1	CV2	CV3	Average
< 21°C	9.9%	11.0%	8.9%	10%
21- 23°C	4.6%	3.6%	2.8%	4%
23.01 - 26 °C	6.3%	3.6%	1.7%	4%
26.01 - 29 °C	-3.7%	-1.3%	2.1%	-1%
29.01 - 32 °C	-10.1%	-8.4%	-4.0%	-7.5%
> 32 °C	-7.0%	-8.5%	-11.5%	-9%

The change in ceiling void 1 temperature due to the application of the cool roof coating is shown in Figure 12. Temperature within this space provides a strong indicator of the effectiveness of the cool roof coating as the space is both directly adjacent to the cool roof and the unconditioned (unoccupied) tenancy. Thus, any temperature change observed can be related directly to the application of the cool roof coating. As seen in Figure 12, the maximum (a), mean (b) and minimum (c) temperatures all decreased, by 22%, 10% and 6% respectively. Further, this reduction is observed, year round, indicating that there may not be any winter penalty for cool roof applications in a subtropical climate zone. Further, Figure 12 illustrates that there is a greater reduction over the summer months, indicating that the greatest benefit of cool roof technology is likely to be in climate zones with the high maximum temperatures.



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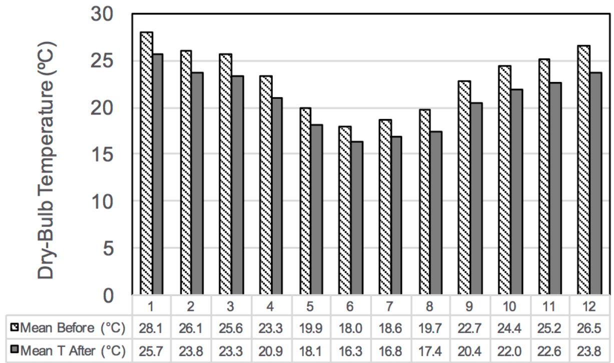

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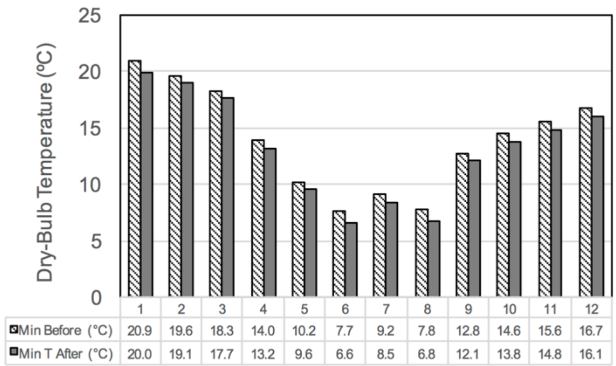

(c)

Fig. 12. Monthly (a) Maximum, (b) Mean, and (c) Minimum air temperatures before and after cool roof coating for ceiling void1 (clothing store) in computational model.

3.2 Simulated impact of cool roof coating on energy (Brisbane climate)

Annual space cooling energy consumption of the model, before and after cool roof coating, is shown in Table 7. It reveals a 13%, or 2.84MWh reduction in energy due to the application of the cool roof coating. Further, it shows an energy reduction every month, confirming that the cool roof does not introduce a heating penalty [17, 30, 31] in the cooler winter months associated with subtropical environments. Although this result is consistent with literature that shows that cool roofs may or may not result in a heating penalty, depending on the specific climate, the observed consistent monthly reduction of energy use has not previously been reported. It should be noted that the model depicts the case study store as operated, that is, with the main shop entrance always open during retail hours. This poor but common practice in Australia would exacerbate high energy use. Building energy efficiency could be enhanced by retrofitting alternative door entrance mechanisms.

3.3 Simulated impact of cool roof coatings for seven Australian climates

Seven different climates, corresponding to the locations in Figure 11, were analysed to extrapolate and generalise the impact that cool roof coatings could have on similar building types in major urban areas in Australia. The results, shown in Table 8, however, need to be interpreted with caution. While they indicate that the *percentage* of cooling energy difference is greater in cooler climates, the *actual reduction* in energy consumption (in MWh), and hence energy cost, is higher for hotter climates. For example, the mild and cool temperature climates of Melbourne and Canberra show the highest percentage reductions, but the tropical (Darwin), desert (Alice Springs) and subtropical (Brisbane) climates show greater energy consumption reductions. This is due to the higher annual cooling load for these climates and the absence of a winter heating penalty. These hotter climates also exhibit the greatest savings per m^2 of floor space.

Table 7 Energy use predicted in IES-VE before and after cool roof coating for a leaky commercial building in Brisbane.

Energy use/Date	Jan 01^{st}-31^{st}	Feb 01^{st}-28^{th}	Mar 01^{st}-31^{st}	Apr 01^{st}-30^{th}	May 01^{st}-31^{st}	Jun 01^{st}-30^{th}	Jul 01^{st}-31^{st}	Aug 01^{st}-31^{st}	Sep 01^{st}-30^{th}	Oct 01^{st}-31^{st}	Nov 01^{st}-30^{th}	Dec 01^{st}-31^{st}	**Summed total**
Before cool coating (MWh)	3.52	2.48	2.7	1.82	0.87	0.47	0.52	0.88	1.5	1.92	2.1	2.61	**21.39**
After cool coating (MWh)	3.24	2.24	2.43	1.56	0.7	0.37	0.38	0.65	1.25	1.64	1.80	2.28	**18.55**

Table 8 Modelled annual cooling energy use for warehouse type buildings in seven Australian climate zones

City	**Zone**	**Before coating (MWh/year)**	**After coating (MWh/year)**	**Difference (MWh/year)**	**Difference (%)**	**Saving (kWh/year/m^2)**
Darwin	1	47.83	44.38	-3.44	-7.20	8.36
Brisbane	2	19.78	17.12	-2.67	-13.48	6.47
Alice Springs	3	22.82	19.42	-3.40	-14.90	8.25
Dubbo	4	12.86	10.92	-1.93	-15.02	4.69
Sydney	5	10.69	8.78	-1.91	-17.84	4.63
Melbourne	6	5.62	4.48	-1.14	-20.31	2.77
Canberra	7	6.95	4.93	-2.02	-29.10	4.91

3.4 CO_2 emissions

Energy efficiency measures are often driven by environmental and sustainable development goals that call for a reduction in carbon dioxide (CO_2) emissions [38,39]. Whilst IES-VE can directly report the CO_2 emissions of all simulations, the calculations in the software are based on the national calculation methodology (NCM) of CO_2 emissions factors in the UK [40], and are therefore not applicable for the Australian market. The carbon intensity of Australia's electricity supply depends on the specific mix of electricity generation plant within each state / territory and is reported by the Australian government annually. The emissions factor for each state for 2014 (Table 9) were applied to the appropriate model simulations to determine the CO_2 reductions for each climate zone (Table 10). The results show that the highest emission reductions are attributed to Darwin and Alice Springs (Northern Territory) and Brisbane (Queensland), the same three locations where the highest energy savings were realised.

Table 9 CO_2 emission factors-consumption of purchased electricity by end users in Australia-2014 [41]

State	New South Wales	Australian Capital Territory	Victoria	Queens-land	South Australia	Western Australia	Tasmania	Northern Territory
Emission factor (kg CO2-e/kWh)	0.99	0.99	1.34	0.93	0.72	0.83	0.23	0.78

Table 10 Annual CO_2 emission reduction for the model in different cities in climatic zones of Australia.

City	Climate Zone	Emissions Factor Coefficient	Annual Energy Saving	Annual Emissions Reduction	
		($kgCO_2/kWh$)	**(kWh)**	**(kg CO_2)**	**(kg CO_2/year/m^2)**
Darwin	1	0.78	3444.6	2686.8	6.52
Brisbane	2	0.93	2666.2	2479.6	6.02
Alice Springs	3	0.78	3401.1	2652.9	6.44
Dubbo	4	0.99	1931.4	1912.1	4.64
Sydney	5	0.99	1906.6	1887.5	4.58
Melbourne	6	1.34	1142	1530.3	3.71
Canberra	7	0.99	2023.8	2003.6	4.86

4. Discussion

These simulation results show that Cool Roof coatings can have a significant positive impact on reducing internal temperatures, energy consumption and carbon emissions, in all climate zones examined in this study. The range of the energy reductions (2.77 - 8.36 kWh/m^2/yr) is comparable with the ranges of other reported reductions, as mentioned previously in Table 1. It should be noted that the savings accrued, despite a relatively modest change to the roof which resulted in a significant increase in the roof reflectance (i.e. 0.2 - 0.875).

4.1 Implications for industry and regulation

That this type of building would produce such results should also not be surprising, as previous research on cool roof applications for demand management in housing has shown that benefits would accrue to single storey buildings (a high roof area to volume ratio), and buildings with solar reflectance less than 0.7, low levels of ceiling insulation and, high air conditioning use [21].

The study suggests several important issues that should be considered by industry and regulators. First, it highlights that, even given the leaky nature of such buildings as constructed in Australia, the potential savings are significant. This suggests that building regulations could be improved by stipulating specific minimum solar reflectance and emissivity requirements for the roofs of such buildings, as occurs in California. Second, it reveals the Australian regulatory failure to set a more stringent airtightness requirement for new buildings. This is consistent with recommendations contained in [2] .

From an industry perspective this study suggests that there is a need for a guideline that encourages building owners, operators and tenants to consider Cool Roof applications in their retrofit or maintenance regimes. The results of this study provide a few indicators that could be included in such a guideline (i.e. the types of buildings and indicative energy and carbon reductions). A comprehensive guideline, however, would also need to include further evidence of possible benefits such as the:

(i) Impact on power demand (i.e. reductions in kW, as most retail customers pay demand charges as well as consumption charges);
(ii) Impact on roof surface temperature, and hence impact on the energy efficiency and sizing of roof mounted air conditioners;
(iii) Impact on roof life (as some literature suggests that Cool Roof coatings can extend roof life) [24,43]; and
(iv) Impact on Urban Heat Island effect (e.g. to what extent does it enhance the local ambient environment).

Of equal importance may be the need for such a guideline to include a benefit:cost analysis formulae that enables input of such variables as building roof area, volume, building thermal rating, infiltration rate, existing roof solar reflectance, energy and power costs and the marginal cost of Cool Roof coatings (i.e. the cost difference between standard roof coatings and Cool Roof coatings).

There is also a need for such data to feed into national plans relating to electricity market reform and the changing climate. The summer of 2016-17 has seen significant extended and severe heat waves across much of Australia, with temperature records being broken in many regions (in terms of maximum temperatures and the number of days above 35°C). The heat waves have revealed significant weaknesses in Australia's national electricity grid (e.g. forced load shedding) and with the National Electricity Market (e.g. extremely high spot prices on the wholesale market). Heat events decrease the efficiency of the electricity network (generation, transmission and distribution), decrease the efficiency of electrical appliances (e.g. air conditioners), as well as apply heat stress to our buildings and population. The electricity market typically responds either by investing in a significantly bigger system to cope with such spikes, or heavily inflating electricity prices during such events. Both of these responses lead to higher electricity prices. One possible alternate solution is to improve the standard of our built environment to add to building and occupant resilience. Cool Roofs are one such strategy that could be deployed as it is equally applicable to the existing building stock and new building stock, and appears beneficial in all climate zones examined.

4.2 Limitations of the study and areas for further research

This study was limited to the development of a single building model (a warehouse-type retail store). To further realise the potential benefits of Cool Roofs for such buildings, a mesoscale analysis of this building typology is required (e.g. for each region, what is the net lettable area of this type of building; what is the predominant roof material and reflectance; what are the typical store operating parameters). More work is required to establish the parameters for determining the benefit:cost effectiveness and Return on Investment, such as those mentioned in the previous section. The same process needs to be implemented for other commercial building typologies such as grocery retail stores (i.e. stores with a high internal refrigeration load) and single storey and low rise industrial buildings (e.g. small manufacturers, trades and offices).

A further area of research on Cool Roofs in general, without recourse to a specific building typology, would be its role on all building types in a changing climate, and the impact of the changing climate on the effectiveness of Cool Roof coatings.

5. Conclusion

An experimental and computational study has been performed to quantify the benefit of retro-fitting cool roof technology to 'warehouse' style buildings in Australia. This benefit was examined in terms of energy efficiency, CO_2 emissions, and space temperatures (as an indication of heat conduction) within the ceiling void adjacent to the conditioned zone. Simulated space temperatures within this zone were within 9-12% of the experimentally measured values on the case-study building located in sub-tropical Brisbane. The computational analysis confirms a significant reduction in ceiling void temperature after the application of cool roof technology. Results indicate an average 4% increase in hours within the ceiling void at temperature in the design set point range of (21-23°C) accompanied by a 7.5% and 9% reduction of hours where the ceiling void space temperature exceeds the ranges $29° < T \leq 32°C$ and $\geq 32°C$ respectively. Both of these act to reduce heat conducted into the space, and thus reduce cooling demand, as reflected in the cooling energy savings predicted by the computational model. Cool roof technology was shown to reduce cooling energy demand across all climatic zones studied. Further, the results indicate that a cooling energy saving every month is achievable in 'warehouse' style buildings thus indicating no heating penalty. The greatest cooling energy reduction was found to occur in tropical, subtropical and dessert environments where an energy saving of 6.5-8.4 kWh/year/m^2 is predicted. When adjusted for Australian state and territory CO_2 emission factors, the computational models predict an annual CO_2 emissions saving between 1530 – 2680 kg CO_2 per warehouse style building, further highlighting the potential of cool-roof technology on both energy and GHG emissions savings.

Acknowledgements

The experimental field study was conducted as part of the Cool Roof Trial in Queensland funded by the Guided Innovation Alliance and results were made available for this research.

Author Contributions

Author 1: Development and validation of the computational model. Simulation, analysis and interpretation of results, preparation of figures and tables, drafting of initial manuscript.

Author 2: Drafting, editing and reviewing of manuscript including preparation of figures and data analysis. Technical expertise on simulation and analysis procedure.

Author 3: Drafting, editing of manuscript. Technical expertise and analysis on energy use with cool roofs.

Author 4: Technical expertise and analysis on building energy use and simulation analysis. Editing and reviewing of manuscript.

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