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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 10 – Perth: Analysis and Results of the Climatic and Energy Performance of Cool Roofs. Methodology, Global Results and Conclusions.

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Executive summary

This study is performed to assess the energy and environmental benefits as well as the cost-benefit of reflecting or cool roofs in the city of Perth, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Perth, understand the characteristics of the urban overheating, and develop detailed climatic data through advanced mesoscale climatic modelling.
2) To evaluate the magnitude and spatial variation of the mitigation /cooling potential generated by the cool roofs when implemented at the city scale, as well as how its application affects the urban ambient temperature and the other main climatic parameters.
3) To investigate the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Perth.
4) To understand the process of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.
5) To evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones.

The whole study involved the following phases:

Phase 1: Mesoscale simulation of the current climatic conditions. In the first phase, a full mesoscale climatic model for the entire city of Perth using a weather research forecasting model is created to simulate the distribution of the main climatic parameters in the city. Simulations are performed for two representative summer months.

Phase 2: Mesoscale simulation of the climatic conditions when cool roofs are implemented at the city scale. During the second phase, mesoscale climatic simulations are performed considering that cool roofs are implemented at the city scale. The modified climatic parameters are also calculated as in the first phase. The results of the first and second phases are compared to assess the climatic benefits arising from the use of cool roofs in the city. Specifically, the ambient temperatures, surface temperatures, sensible heat flux, latent heat flux, wind, PBL dynamics, and the regional impact on sea breeze circulations in the two scenarios have been compared.

Phase 3: Climatic parameters analysis. In this phase, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 17 weather stations in Perth have been analysed. Firstly, the frequency distribution of hourly air temperatures has been studied. Secondly, cooling degree hours (CDH) base 26 °C, which measures how much, and for how long, outside air temperature, is higher than 26 °C, has been calculated serving as a rough indication of the regional climatic severity. CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 17 weather stations, has been calculated. The frequency and spatial distribution of the calculated CDH are analysed as well.

Phase 4: Assessment of the energy cooling/heating load under various boundary conditions during the summer period. Simulations were performed for seventeen types of buildings and seventeen weather stations across Perth. The cooling load simulations were performed for two summer months of January and February using weather data simulated by WRF as in phases 1 and 2. Three scenarios are simulated a) using the reference climatic data assuming conventional roofs, b) using the reference climatic data but considering roofs are reflecting, and c) using the modified climatic data calculated in Phase 2 considering that the roofs are reflecting.

Phase 5: Assessment of the energy cooling/heating load under various boundary conditions during the whole year. The annual cooling and heating load estimations were also performed to assess the annual cooling load savings of cool roofs against their corresponding annual heating penalty. The annual cooling and heating load simulations were performed using the weather data obtained from the Bureau of Meteorology (BoM).

Phase 6: Assessment of the indoor air temperature under free-floating conditions under three climatic conditions. Additionally, the impact of cool roofs on indoor air temperature was assessed under free-floating conditions in weather stations, presenting the lowest and highest ambient temperatures in Perth during a typical summer and winter period.

Phase 7: Analysis of the impact of building characteristics on the performance of Cool Roofs. Finally, the energy characteristics and mainly the magnitude of thermal losses through the building envelopes and their impact on the performance of cool roofs are assessed in various stations in Perth, and the results have been compared. Specifically, for the seventeen building types, the linear regression has been generated between CDH and the sensible cooling load in a building with a conventional roof, the cooling load reduction when applying a cool roof, and the cooling load reduction for the same building with a cool roof using the climatic data simulated by WRF considering the impact of a cool roof. Focus is put on the slope of the regression line, which indicates the heat loss coefficient of the overall envelope or the effectiveness of a cool roof under different climatic conditions. The heat loss coefficient of buildings with or without insulation, built in older years or recently, and with different heights has been compared, as well as the energy-saving advantage of the cool roof under various climatic conditions.

Phase 8: Life Cycle Cost is used as the base for the assessment to evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones. The feasibility of cool roofs is evaluated by assessing the refurbishment of 17 buildings for Swanbourne and Paerce weather conditions.

To summarise, it is expected that this study can present a comprehensive overview of the existing climatic conditions and the overall climatic effect, as well as the modification in building energy and thermal balance after applying the cool roof in the entire city of Perth.

Collectively, the following conclusions have been drawn:

1) An increase of albedo fraction in Perth city can decrease the peak ambient temperature up to 2.2°C and surface temperature up to 6.5°C.
2) The maximum decrease of sensible heat and latent heat flux were 187.7 W/m^2 and 17.3 W/m^2, respectively.
3) The highest decrease of wind speeds up to 2.9 ms-^{1}. Cool roofs increase the pressure over core urban at a local scale and decrease the wind advection from the adjacent bare surface of desert fetch.
4) In average, compared to the reference scenario, the temperature with the peak distribution in the cool roof scenario is mostly around 1-3 °C lower than that in the reference scenario, indicating the cooling benefits of cool roofs. Around 40%-63% of the ambient temperatures in all stations concentrate in the range of 14-21 °C.
5) Cooling degree hours indicating the climatic severity during the summer period, range from 463.9 to 2613.7, under the existing conditions, increasing from the west of the city to the east.
6) When cool roofs are used in the city, CDH ranges from 309.5 to 2145.8. The percentage of CDH reduction due to the implementation of the cool roof ranges from 17.9% to 39%.
7) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 10.3-13.0 kWh/m^2.

8) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 13.6-16.2 kWh/m^2.
9) In new low-rise buildings with high insulation level, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.9-5.2 kWh/m^2 in a typical new low-rise office building.
10) In new buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be 0.9-1.2 kWh/m^2 and 0.2 kWh/m^2 for new low-rise and high-rise office buildings with insulation, respectively.
11) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.4 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 2.7-3.6 kWh/m^2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
12) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in all types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 17.8-26.8 kWh/m^2, while the corresponding heating penalty is just 1.1-1.2 kWh/m^2.
13) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum and average indoor air temperature of a low-rise office building without roof insulation by 5.1-5.6 ^oC and 1.9-2.1 ^oC, respectively.
14) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum and average indoor air temperature of a low-rise office building without roof insulation by 5.9-6.2 ^oC and 2.8 ^oC, respectively.
15) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and at the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^oC. For instance, the number of hours with an indoor air temperature above 26 ^oC in a typical low-rise office building without insulation is predicted to reduce from 478-498 hours to 361-393 hours and 312-358 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
16) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum and average indoor air temperature reduction by application of cool roofs in both individual building and at the whole

urban area (scenario 2) in a typical new low-rise office building is predicted to be 1.5 ºC and 1.0-1.2 ºC, respectively.

17) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the number of hours with an indoor air temperature above 26 ºC during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ºC in new low-rise office building with insulation is predicted to reduce from 540-556 hours to 471-507 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
18) The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by application cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 5.1-5.6 ºC in a typical summer week, while the average maximum indoor air temperature reduction of the same building is expected to be just 2.5 ºC during a typical winter month. The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ºC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 2.4 ºC occurs when the indoor air temperature is 25.2 ºC.
19) The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ºC especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total number of operational hours with ambient temperature below 19 ºC from 83-95 hours to 98-112 hours in a typical existing low-rise office building with roof insulation.
20) For all 17 buildings, the solution of the coating for the cool roof presents the least Life Cycle Cost and is, in that sense, the most 'thrifty' choice. This is due to the fact that it features a significantly lower initial investment cost compared to cool metal roof, yet achieves comparatively similar savings. This applies both for the low and the high electricity price scenario, albeit as expected for the high electricity price scenario, the results are much more positive.
21) With respect to the 17 buildings considered, it does not come as a surprise that low-rise buildings without thermal insulation of the roof and with high energy requirements are presenting the biggest energy savings potential and consequently the most attractive economic results. For such buildings (like, for example, B02, B15 and B16), the Life Cycle Cost can be reduced by as much as 78%. In such favourable cases, the Payback Period can be as low as 3.0 years.
22) Even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B01, BO5 and B17) and for lower electricity prices, the Life Cycle Cost of the coating cool roof can be reduced compared to the "Do nothing" conventional roof, which is more than enough to justify the cool coating's application, despite comparatively longer Payback Periods.
23) Considering the NPV and IRR results, when the differences between the savings are low, there are some differentiation, i.e. the metal cool roof appears in some cases to be more feasible. This is due to the different impact of the annual saving's value over time compared to the initial investment cost, which affects the NPV and IRR results stronger than the LCC. In any case, the differences are minor and, given the fact that we are considering energy and cost savings, the LCC is the method that produces the most valid results.

Objectives

This study is performed to assess the energy and environmental benefits as well as the cost-benefit of reflecting or cool roofs in the city of Perth, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Perth, understand the characteristics of the urban overheating, and develop detailed climatic data through advanced mesoscale climatic modelling.
2) To evaluate the magnitude and spatial variation of the mitigation /cooling potential generated by the cool roofs when implemented at the city scale, as well as how its application affects the urban ambient temperature and the other main climatic parameters.
3) To investigate the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Perth.
4) To understand the way of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.
5) To evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones

Methodology

The whole study involved the following phases:

Phase 1: Mesoscale simulation of the Current climatic conditions. In the first phase, a full mesoscale climatic model for the entire city of Perth using weather research forecasting model is created to simulate the distribution of the main climatic parameters in the city. Simulations are performed for two representative summer months.

Phase 2: Mesoscale simulation of the climatic conditions when cool roofs are implemented at the city scale. During the second phase, mesoscale climatic simulations are performed considering that cool roofs are implemented at the city scale. The modified climatic parameters are also calculated as in the first phase. The results of the first and second phases are compared to assess the climatic benefits arising from the use of cool roofs at the city. Specifically, the ambient temperatures, surface temperatures, sensible heat flux, latent heat flux, wind, PBL dynamics, and the regional impact on sea breeze circulations in the two scenarios have been compared.

Phase 3: Climatic parameters analysis. In this phase, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 17 weather stations in Perth have been analysed. Firstly, the frequency distribution of hourly air temperatures has been studied. Secondly, cooling degree hours (CDH) base 26 °C, which measures how much, and for how long, outside air temperature, is higher than 26 °C, has been calculated serving as a rough indication of the regional climatic severity. CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 17 weather stations, has been calculated. The frequency and spatial distribution of the calculated CDH are analysed as well.

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Phase 6: Assessment of the Indoor Air Temperature under free-floating conditions under three climatic conditions. Additionally, the impact of cool roofs on indoor air temperature was assessed under free-floating conditions in weather stations presenting the lowest and highest ambient temperatures in Perth during a typical summer and winter period.

Phase 7: Analysis of the Impact of Building Characteristics on the Performance of Cool Roofs. Finally, the energy characteristics and mainly the magnitude of thermal losses through the building envelopes and its impact on the performance of cool roofs are assessed in various stations in Perth and the results have been compared. Specifically, for the seventeen building types, the linear regression has been generated between CDH and the total cooling load in a building with a conventional roof, the cooling load reduction when applying a cool roof, and the cooling load reduction for the same building with a cool roof using the climatic data simulated by WRF considering the impact of a cool roof.

Focus is put on the slope of the regression line, which indicates the heat loss coefficient of the overall envelope or the effectiveness of a cool roof under different climatic conditions. The heat loss coefficient of buildings with or without insulation, built in older years or recently, and with different heights has been compared, as well as the energy-saving advantage of the cool roof under various climatic conditions.

Phase 9: Life Cycle Cost is used as the base for the assessment to evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones. The feasibility of cool roofs is evaluated by assessing the refurbishment of 17 buildings for Swanbourne and Paerce weather conditions.

Specifically, two scenarios, one as the reference case (Solar reflectance_ roof, streets, and walls=0.15; thermal emissivity _ roof, streets, and walls =0.85), the other applied with the cool roof (Solar reflectance _ roof = 0.80; Solar reflectance _ walls and streets=0.15; thermal emissivity _ roof, streets, and walls =0.85) are simulated and analysed in this study. Collectively, it is expected that this study can present a comprehensive overview of the existing climatic conditions and the overall climatic effect, as well as the modification in building energy and thermal balance after applying the cool roof in the entire city of Perth.

1. Report of mesoscale simulations _ simulation of the base case and cool roof scenarios

1.1 Introduction

The mounting urban heat, driven primarily by the burning of fossil fuels, exacerbated extreme events that were reported around the globe and in Australia in 2017 (Bureau of Meteorology, Australia, 2017a, b). Human-induced regional climate change is heating up the urban areas, and urbanization augments the risks associated with extreme events. Climate changes magnify extreme events; cities aren't adapting as quickly enough. Urbanization suppresses the evaporative cooling process from the urban surface and amplifies heatwave intensity with a strong influence on minimum near-surface temperatures. Frequent heat waves are recognized as an abstemious threat to human health worldwide, with urban areas being more exposed due to the urban warming effect. Extreme urban heat, along with regional climate change, can affect the health and wellbeing of humans, the environmental quality, and the socio-economic performance of cities. Higher magnitude of urban temperatures (and for longer periods) is considerably affecting citizens' quality of life and outdoor activities of the citizens. Extreme urban heat is being augmented by local and regional climate change, which leads to an increase in the magnitude, intensity, frequency, and duration of extreme temperature, prolonged thermal distress and heat stress, and increased heat-related mortality and morbidity (Santamouris et al., 2017). To undertake the extreme urban heat and increase the quality and comfort levels of outdoor and indoor environments, it is imperative to investigate and evaluate the feat of cool roof strategies at city-scale during an extreme heat condition.

1.2 Objectives of the study

This study is performed to assess urban heat and mitigation potential of cool materials in the city of Perth, Australia. The magnitude and the characteristics of the extreme urban heat have been assessed in the city of Perth through mesoscale simulations. The purpose of this report is:

- To evaluate the existing climatic conditions (base case) in the city of Perth.
- To evaluate the cooling potential of cool roof technology when they are implemented in the city of Perth.
- To compare the impacts of cool roof strategies at diurnal and monthly scale over urban domain

1.3 Domain and method of simulation

We use a full mesoscale climatic model for the entire city of Perth using weather research forecasting model (WRF v4.3), which is an advanced commonly used numerical climate model. The model is created to simulate the distribution of the main climatic conditions in the city under all climatic, synoptic, and land use conditions. The resolution of the grid in the simulation is 500 x 500 meters (**Table 1** and **Figure 1**). The developed mesoscale model is used to calculate the hourly distribution of the main climatic parameters in Perth under the existing heat wave conditions and one mitigation scenario. The albedo or emissivity as a single fraction was applied uniformly to all urban grid cells. The cool materials were examined by test case of 100% cool surfaces (on the roof only) with changing albedo and emissivity fractions for roofs at the urban scale (**Table 2**). We performed extensive analysis to analyze the performance of cool roof scenario and its cooling potential. One mitigation scenario is evaluated in this report. The mitigation strategy is examined in this study at city-scale.

Table 1 WRF/SLUCM Model configuration

Configuration	Domain 01 (d1)	Domain 02 (d2)	Domain 03 (d3)
Version	ARW-WRF v4.3		
Initial and boundary conditions	ERA-Interim reanalysis		
Run time	31 December 00:00h, 2016 to 1 March 00:00h, 2017 IST		
Time period for analysis	1 January 12:00h, 2017 to 28 February 00:00h, 2017 IST		
Grid distance (m)	4500	1500	500
Grid number	200x200	202x202	202x202
Number of vertical layers	40 layers		
Microphysics	WRF Single-Moment 6-class scheme		
Surface layer model	Noah-LSM+Single layer UCM (Chen &Dudhia, 2001; Kusaka et al., 2001)		
Turbulence	Mellor and Yamada's (1974) TKE scheme		
Short-wave radiation	Dudhia scheme (Dudhia, 1989)		
Long-wave radiation	RRTM scheme (Mlawer et al., 1997)		
Planetary boundary layer	Asymmetrical Convective Model version 2 (ACM2) (Pleim, 2007)		
Cumulus parameterization	Kain-Fritsch (KF) scheme (Kain, 2004)		

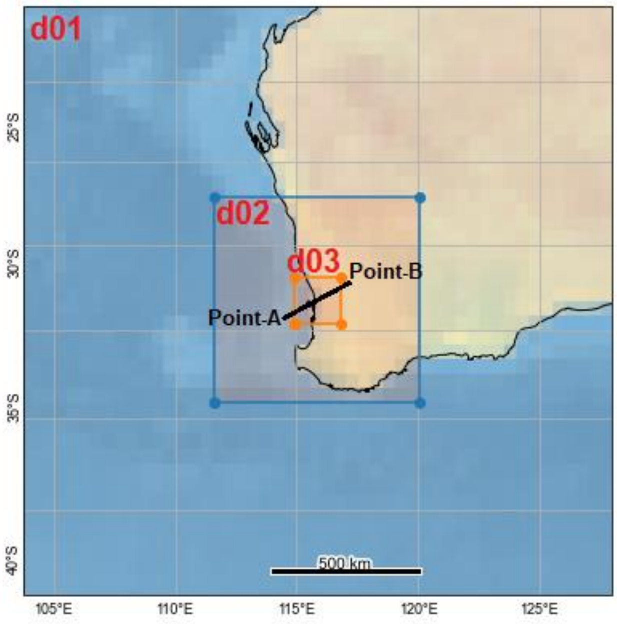


Figure 1 WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500m grid spacing, domain 2 (d02) with 1500m grid spacing and, an innermost domain 3 (d03) with 500m grid spacing; (b) innermost d03 with 500m grid spacing which encompasses the Greater Perth. The Point-A (left) and Point-B (right) are the points used for drawing horizontal-vertical cross-sections to analyze meteorological conditions for **Figure 9.**

Table 2 Numerical design for cool roof for Perth.

Scenarios	Albedo			Emissivity		
	Roof	Wall	Ground	Roof	Wall	Ground
Control	0.15	0.15	0.15	0.85	0.85	0.85
Scenario	0.80	0.15	0.15	0.85	0.85	0.85

1.4 Model evaluation

To evaluate the performance of the WRF-SLUCM system, we compared hourly simulated 2-m ambient air temperature against local measurements for the control case simulation over urban grid cells in the innermost domain. A statistical comparison of the mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r), and the index of agreement (IOA) for hourly 2m air temperature for the 24-hour duration are listed in **Table 3** and **Figure 2**. The model evaluation is based on the correlation between the WRF model and observations for 2m-temperature across the diurnal cycle. The coupled WRF-SLUCM model accurately captures the temperature observed at different stations (mean R=0.950; mean bias=-1.67) for (a) Perth Airport, (b) Perth (c) Gosnells, and (d) Swanbourne. The base case simulation produced urban meteorological conditions well and statistically agreed with local observation ($p<0.05$). The simulated average UHI intensity varied from 2.3°C to5.5°C in the high-density urban residential areas relative to rural (i.e., surrounding) landscapes as a function of the prevailing local weather conditions. The range of MBE and RMSE of air temperature was -1.56°C to -1.73°C and 1.67°C to 1.87°C, respectively. The range of IOA was 0.86 to 0.92, with average values of 0.94 when considering all observation stations. The model slightly overestimated the daily average 2m ambient air temperature, potentially resulting from an overestimate of anthropogenic heating over the urban domain. We also assess impacts on local meteorological stations as it is these stations that are most influenced by the utility of the UCM scheme. The well-simulated daytime warming is balanced by equally well-simulated nighttime cooling, resulting in a diurnal range that is of a similar magnitude to observations. The comfort level of different dew points is >22°C for the stations, representing the uncomfortable situation in the urban environment. The difference is identical when quantifying impacts on local meteorological stations. Although WRF does not display considerable warm (comfort) bias over urban locales, the representation of the 24-h averaged diurnal range of dew point temperature is well captured. In addition, model biases are most likely caused by: (a) lack of proper urban morphological representation and (b) uncertainties in model physical schemes, input data used, and locally meaningful urban biophysical parameters. Nevertheless, our initial evaluation highlights that the model can replicate the urban environment realistically, including a well-simulated evolution of the diurnal cycle of both near-surface temperature and dew-point, and the model framework can be used to predict the regional meteorology and investigate the regional influence of cool roof strategies.

Table 3 Comparison of the simulation results with observation data at an average 24-h scale for 59 days.

Parameters	**Local weather stations**			
	Perth Airport	**Perth**	**Gosnells**	**Swanbour**
Correlation coefficient	0.94	0.96	0.95	0.95
Mean bias error	-1.56	-1.73	-1.68	-1.72
Mean absolute error	-1.551	-1.732	-1.682	-1.724
Root mean square error	1.67	1.83	1.87	1.86
Index of agreement	0.86	0.87	0.92	0.94

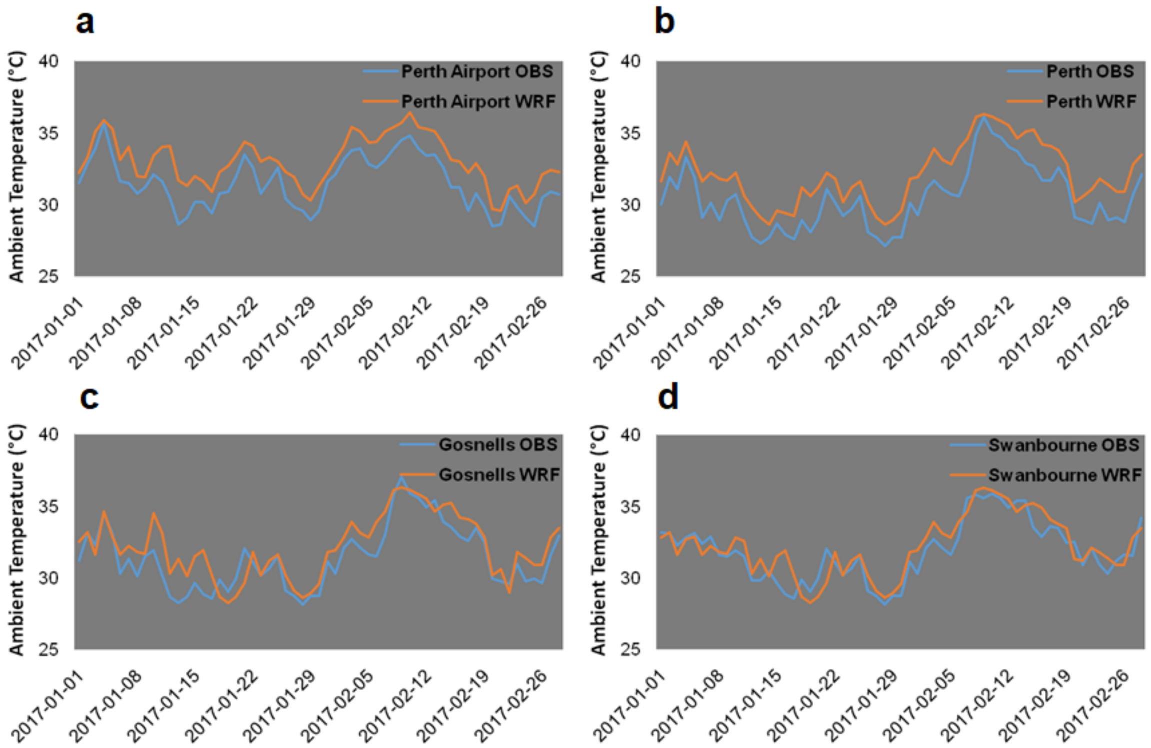


Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: a) Perth Airport, b) Perth, c) Gosnells, and d) Swanbourne.

1.5 Results of the mesoscale simulations

The results of the control scenario (existing condition) are used as a reference to compare with the cool roof scenario. The predictions of the mesoscale model have been compared against the collected data from the main ground climatic stations in Perth to ensure the robustness and accuracy of the model. The results of the base case are presented for two months of summer. The simulated summer period is from January 1st, 2017, to March 2017. The mitigation scenario presented here has been analyzed during the summer period for 59 days of two months (January and February). These two months were warmer than average during 2017 for both daytime and overnight temperatures in Perth. In 2017, Perth was usually warmer than eastern Australia, and it is currently having one of its coldest and wettest summers on record. The mean maximum temperature equalled the record set in 2016 (Bureau of Meteorology, Australia, 2017a, b).

1.5.1 Ambient temperatures

Ambient temperatures can be calculated from the surface energy balance flux partitions in the WRF-SLUCM urban modelling system. Under the cool roof materials scenario, the ambient temperature at 14:00 ranges between 29.2 °C and 39.7 °C. At 06:00 LT, it varies between 24°C and 31.7°C. The results show that the use of cool roof materials maximum reduces the peak ambient temperature ($T_{ambient}$) by 2.2ºC over high-density residential areas and 1.9°C for whole urban average compared to control case. The average ambient temperature reduction at 14:00 over the whole summer is 1.2°C near Fremantle, Osborne Park and the Perth CBD area of the city. The maximum decrease of the ambient temperature during 18:00 LT is 1.6°C near coastal fringe (some parts of Fremantle), and the average decrease of summer months is 1°C **(Figure 3)**.

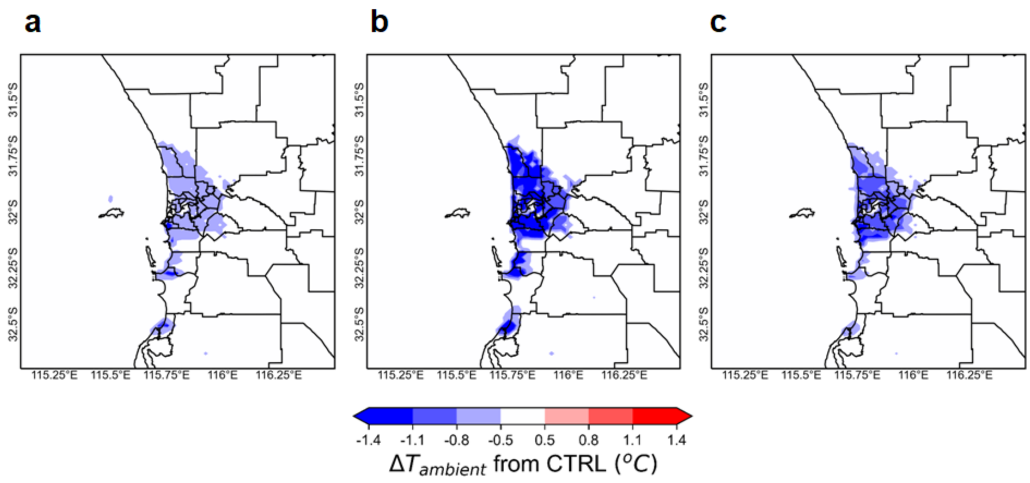


Figure 3 Reduction of ambient temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.2 Surface temperatures

Under the cool roof scenario, the surface temperature ($T_{surface}$) ranges between 30.1°C to 41.1°C at 14:00, 27.4°C to 38.3°C at 18:00 LT and 26.3°C to 37.8°C at 6:00 LT over the city. The maximum decrease of surface temperature during 14:00 LT is 6.2°C over the urban surface with an average reduction of the whole summer is about 5.4 °over urban domain (Fremantle, Rockingham area and some part of Thornlie area of the city). But, in the high-density residential urban area, the maximum decrease of surface temperature is about 6.5°C during 14:00 LT of summer months along the coastal region (Perth CBD, Osborne park and Fremantle area) of the city. The maximum surface temperature reduction at 18:00 LT is about 5.6°C over the central part of the city. The average decrease of urban surface temperature is 4.5°C at 18:00 LT, and 1.7°C at 06:00 LT compare to the control case for the whole summer month in the city **(Figure 4)**.

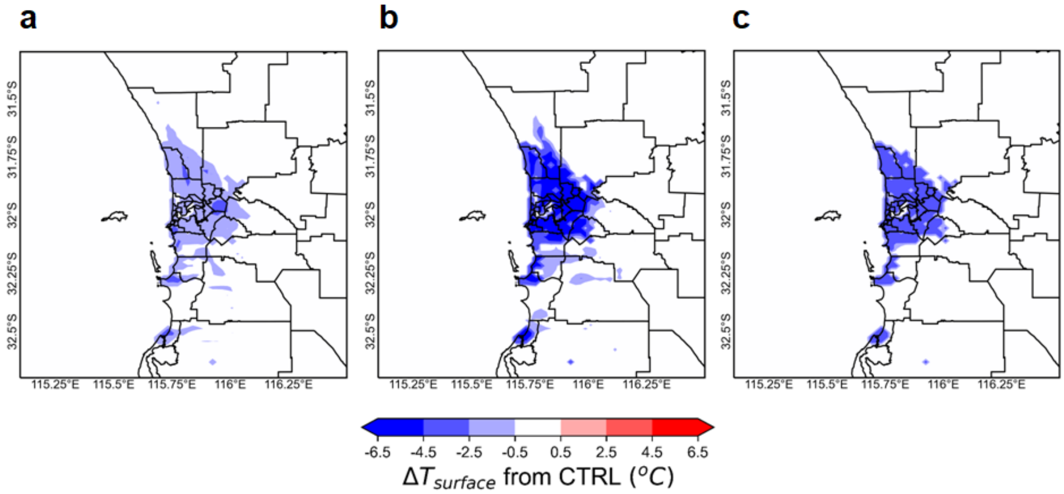


Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.3 Sensible heat flux

The WRF-SLUCM reasonable computed the sensible heat flux from the urban surface. Under the cool roof scenario, the maximum and average sensible heat flux ($Q_{sensible}$) over city during 14:00 LT is 503.3 W/m^2 and 420.9 W/m^2 '. At 18:00LT, the average sensible heat flux is 115.6 W/m^2 . The maximum decrease in the sensible heat flux is 179.6 W/m^2 , and the average decrease is 154.8 W/m^2 at 14:00 LT over the urban domain (Fremantle, Perth CBD, Osborne park, Some parts of Thornlie and Joondalup area). In the high-density residential urban area, the maximum and average reduction of sensible heat flux are about 187.7 W/m^2 and 161.7 W/m^2 during 14:00 LT of summer month compared to the control case. At 18:00LT, the maximum and average reduction of the summer month of sensible heat flux is 91.6 W/m^2 and 72.7 W/m^2 over the urban domain **(Figure 5).**

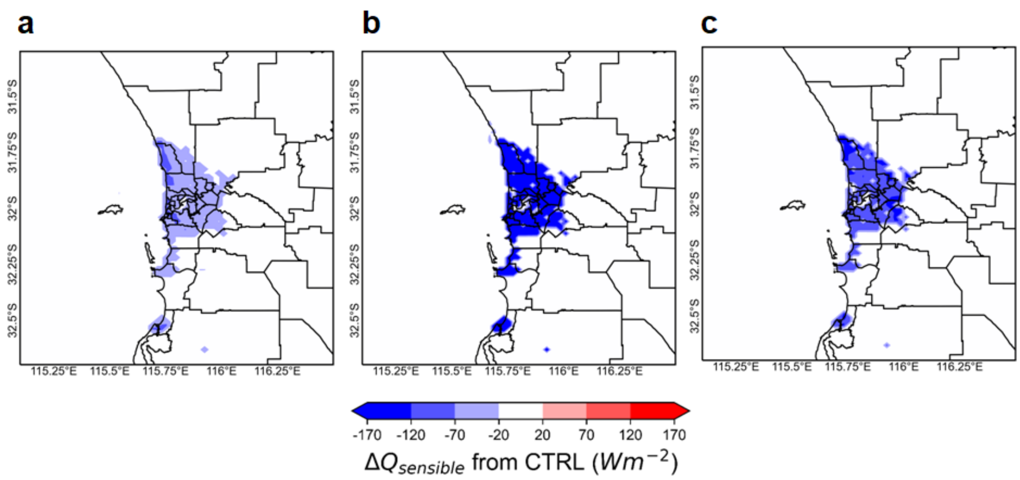


Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.4 Latent heat flux

The maximum and average latent heat flux (Q_{latent}) under cool roof scenario over city during 14:00 LT is 26 W/m^2 and 22.6 W/m^2 . At 18:00 LT and 06:00 LT, the average latent heat flux is 8.1 W/m^2 and 4.2 W/m^2 .The maximum decrease the latent heat flux is 16.6 W/m^2 and average decrease is 13.2 W/m^2 at 14:00 LT near the coast and central part (the Fremantle, some part of Thornlie Joondalup, and Rockingham area) of the city. But, in the high density residential urban area, the average decrease of latent heat flux is about 13.7 during 14:00LT of summer months. At 18:00 LT, the maximum and average reduction of summer month of latent heat flux is 6.4 W/m^2 and 4.8 W/m^2 over urban domain. At, 06:00 LT, the maximum reduction of latent heat flux is 4.6 W/m^2 and average reduction is 3.5 W/m^2 over urban domain **(**

Figure 6**)**.

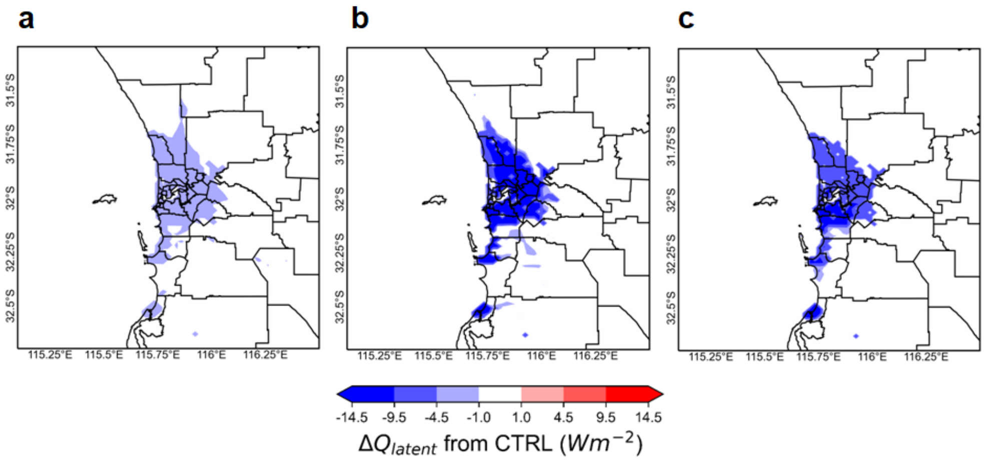


Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.5 Wind

Under the base case simulation, the average wind speed (W$_{speed}$) are 4.4 ms-^{1}, 7.2 ms-1 and 6.1 ms-^{1} during 06:00 LT, 14:00 LT and 18:00 LT respectively over the city. The maximum decrease of wind speed compared to control case is 1.6 ms-^{1}, 2.8 ms-^{1} and 2.3 ms-^{1} at 06:00 LT, 14:00 LT (central part of the city e.g Perth CBD, Osborne, Fremantle, Rockingham and some parts of Thornlie) and 18:00 LT respectively over urban domain. The average decrease of wind speed of whole summer months is 2.0 ms-^{1} at 14:00 LT, 1.2 ms-^{1} at 06:00 LT and 1.7 ms-^{1} at 18:00 LT over the city **(Figure 7)**.

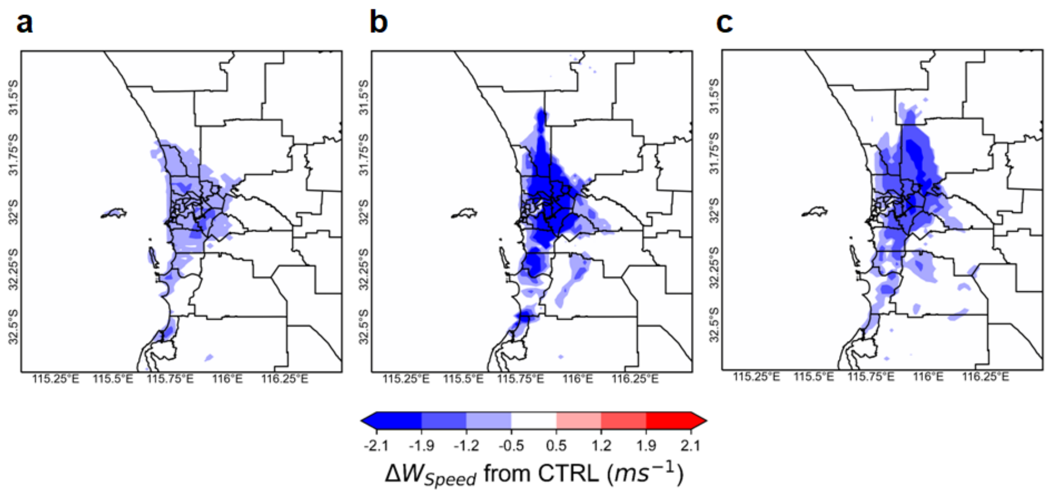


Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.6 Regional Impact of Cool Roof: PBL Dynamics

The high-density urban building environment impacts the lower atmospheric dynamics at the city to regional scale. The diurnal variability of the PBL, resulting from the impacts of cool materials at the city scale, was reported. The magnitude of the PBL height reduction is considerably higher when highly reflective cool materials rather than conventional materials are implemented at the city scale. **Figure 8** shows the spatial distribution of the PBL height in the case of the cool roof implementation at different hours of a summer day at6:00LT, 14:00LT, 18:00LT. The PBL height distribution and corresponding spatial changes in vertical wind speed. For instance, in core urban areas of the city (central part of the city, e.g. Perth CBD, Thornlie, Osborne park area), impacts on PBL depth reduction resulting from the use of highly reflective cool materials appear to extend beyond the scale of the implementation itself. The maximum reduction of PBL is 189.6 m, 710.8 m (near the coast and central part of the city), and 364.2 m for 6:00LT, 14:00LT, 18:00LT, respectively, with average value, is about 162 m, 590.1 m and 272.9 m. The minimum reduction of PBL is 134.6 m, 532.6 m, and 225.6 m, for 6:00LT, 14:00LT, 18:00LT, respectively **(Figure 8).** The maximum reduction is associated with peak hour (14:00 LT) over the central part of Perth city. The prime causes of PBL depth reduction due to cut-off input solar radiation and subsequently decrease in sensible heat and associated turbulence in the lower atmosphere. It is also noted that the increase of the albedo is expected to accelerate the static stability at the diurnal scale of the PBL depth. Modification of the albedo reduces the impacts of urban induced warming and decreases the intensity of the convective mixing, thereby reducing the PBL depth, with potential penalties for air pollutant dilution and dispersion over the city domain. The reduction of moisture transport from the urban surface to the vertical layer caused by the implementation of reflective materials can also be disadvantageous to cloud formation processes, and as a result, reduce the amount of precipitation in urban areas or their downwind environments.

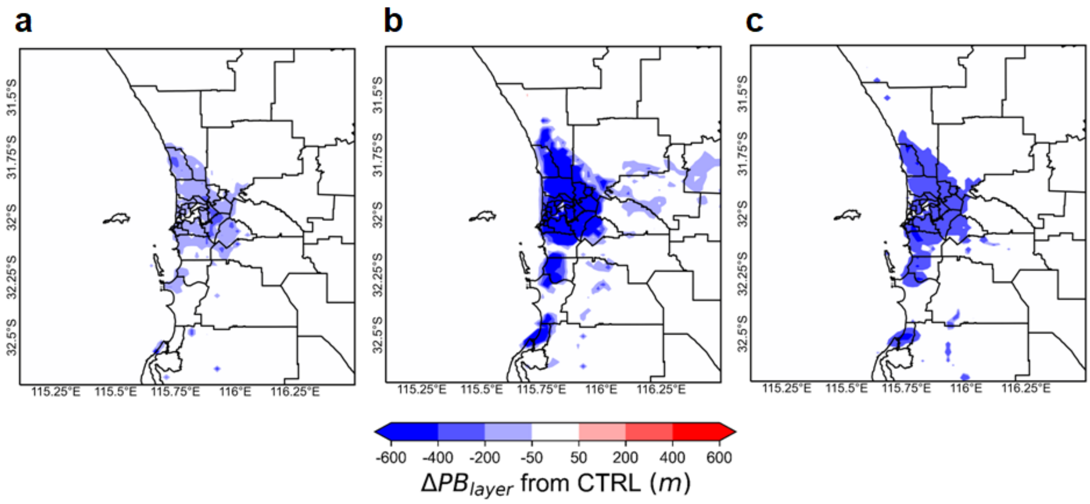


Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.6 Regional impact on sea breeze circulations

The amplification of sea breeze circulation is dependent on the large-scale synoptic background, which plays an important role in modulating the prevailing wind at the near-surface. In the vertical dimension, the report revealed the height of the PBL in Perth is linked closely with the advection of the sea breeze. The circulation can be modified when cool roof is implemented at city-scale **(Figure 9)**. The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Perth. Results also indicate that the onset of the sea breeze was delayed to afternoon (14:00 LT) due to the "regional high" effect within the lower PBL and offshore synoptic wind flow above the PBL. The denser cool air over the urban domain flows towards the suburban area to replenish the buoyant warm air. The cool roof materials can suppress the process of vertical lifting of urban thermals, transport and dispersion of low-level motions due to inversion in hot summer and decelerate the sea breeze front. Therefore, the decrease in the extent of vertical wind speed by 1 to 2 ms-1 induces stronger subsidence over the urban domain where reflective materials are implemented. The surface roughness parameters are painstaking to be useful to pull the cool air of sea breezes down to the surface due to the mixing effects. Besides, the horizontal wind shear and frontal lifting owing to surface roughness parameters could setback the onset of sea breeze front in the urban core. The potency of the sea breeze advection is subjected to the dimension of the city, which persuades the urban heating effect. Thus, cool roofs for cities have greatly modified the thermal and dynamic profile in the urban boundary layer and sea breeze circulation. This synoptic flow prevails in the opposite direction of sea breeze and sea breeze front developed is more prone to the accumulation of secondary pollutants in the back of the front.

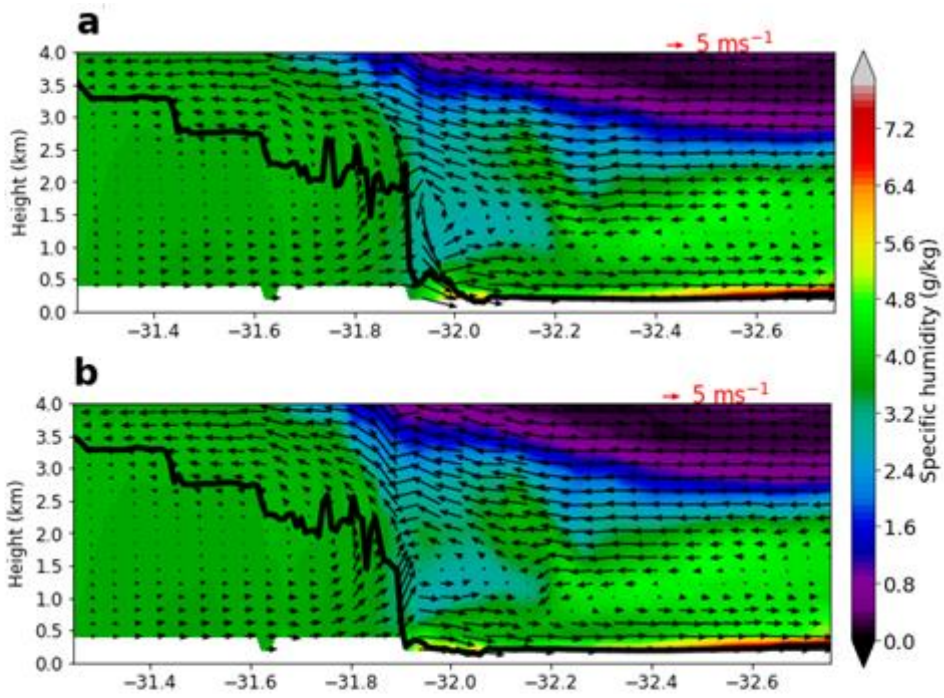


Figure 9 Cross-sectional profile of heat mitigations impacts on sea breeze during peak hour (14:00 LT) over Perth (a) control case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere

The report also shows the implementation of cool roofs over city scale can affect the pressure gradient between the city and surrounding surface due to significant drop ambient temperature up to 2.2°C and wind speed decrease up to 2.9 ms-1. Thus, changes in roof reflectivity, sensible heating, and wind result in feedback within the local climate of the city during peak hour (14:00 LT). The higher urban albedo values decrease the advective flow between the city and its surroundings, improving the cooling potential of reflective materials. It creates a 'regional high', which can reduce both horizontal and vertical wind speed over the city. Consequently, the increase of albedo may prevent the warm air flow from the long fetch desert towards western Perth due to the effect of this regional high over the domain **(Figure 10)**. The sea breeze generated during the day reduced UHI effects by vertically mixing and warming the inland sub-urban area without affecting the urban area with no inversion. In addition, it is clearly proved that the impact of sea breeze considerably reduced over high-density residential areas. This is because, in the extreme heating environment, during the daytime, when the air above the land gets cooled up due to citywide application of cool roof, the air molecules give out the heat and the intermolecular forces between the air molecules become strong and its kinetic energy decrease. The air molecules are stagnant and become high dense, and they become heavier and slow down the Brownian motion. This creates a high-pressure zone over the cityscape and low pressure above the coastal offshore thus, cold air from the sea reduces rush to the city ward.

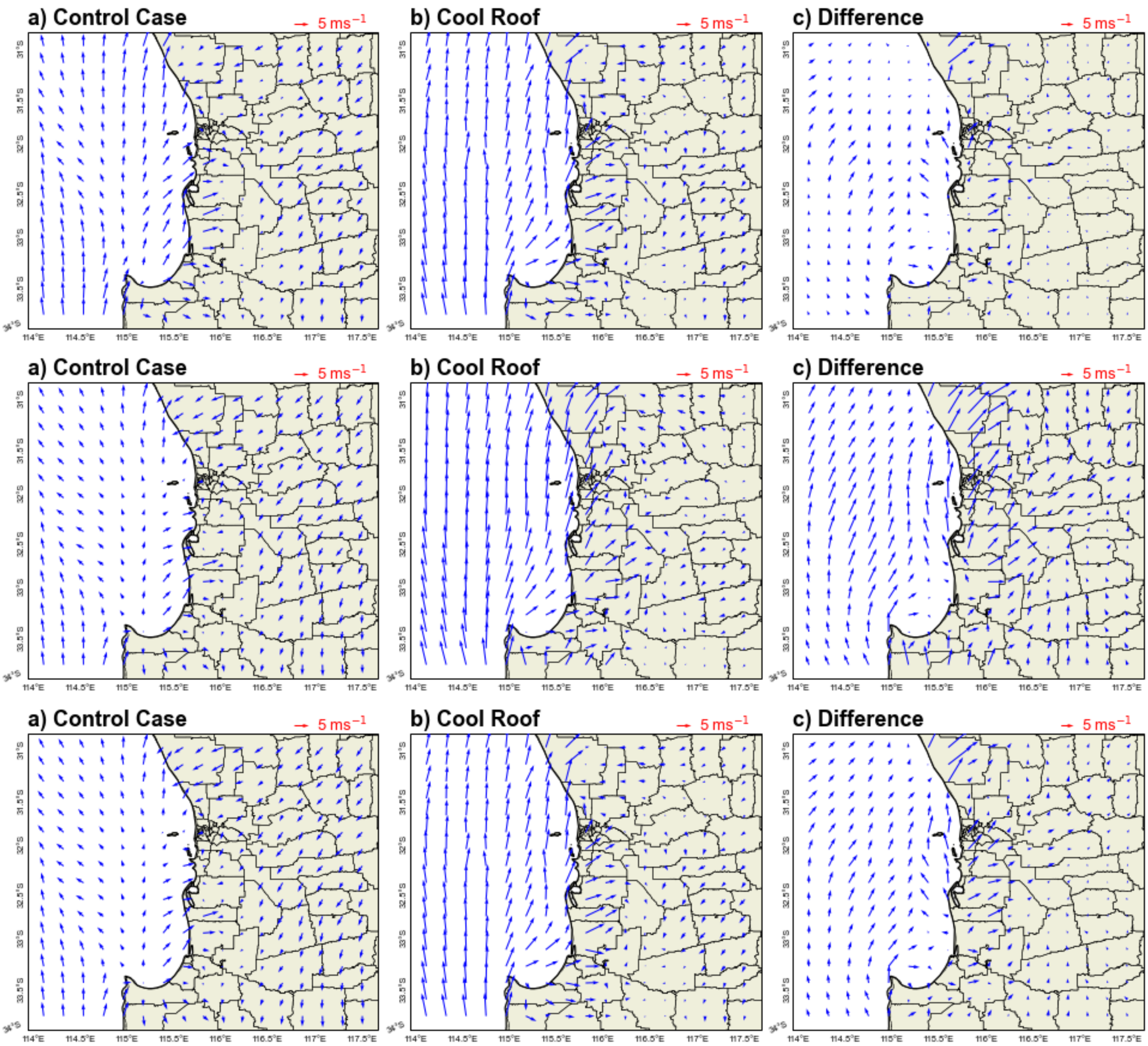


Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) control case (b) cool roof (c) scenarios minus control: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain d03.

1.7 Main conclusions

- It is reported that the temperature differences exist near the coast and core part of the city, and the magnitude of the phenomena may vary between 4-5°C. The intensity and the characteristics of the phenomena are sturdily influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the long fetch open area. The potential existence of an extra heating mechanism, like the advection of warm air from desert spaces, could make stronger the strength of the urban heating.
- The city of Perth incidents an exacerbate UHI is evident at night during the heat wave. In the daytime, a pocket of extreme urban heat turns out in the eastern region of the high density urban, while at night, a hotspot takes place in the northeastern part of the city.
- Increase in albedo in Perth, the highest decrease of sensible heat and latent heat flux were up to 187.7 W/m2 and 17.3 W/m^2 , respectively. Thus, it can decrease the peak summer ambient temperature up to 2.2°C and surface temperature up to 6.5°C. Such cooling improves human comfort levels and could be feasible for reducing cooling energy demand. The pattern of the ambient temperature distribution and its reduction in the

city was found to depend highly on the local climate, urban density and the magnitude of the horizontal thermal gradient over the city.

- Perth is an isolated urban centre experiencing significant urban growth. High-density parts of the city display a higher temperature drop than the whole urban average. The locations and magnitudes of urban heating in the high-density urban areas vary spatially and diurnally.
- The maximum decrease of wind speeds is up to 2.9 ms^{-1}. Cool roofs augment the high pressure over core urban at a local scale and diminish the wind advection from the contiguous bare surface of desert fetch. The results show that the increase in albedo fraction leads to decrease wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during heat wave scenario.
- Alteration of the urban albedo in Perth city results in an average reduction up to 742.7 m of the PBL heights over high density parts of the city and may increase the concentration of bad pollutants at ground level during peak hour (14:00 LT) due to low level urban mixing.
- The sea breeze considerably affected by cool roof due to regional high effects over city, which significantly reduces the sea breeze incursion. In the extreme heating environment, in the daytime, when the air above the land gets cooled up due to citywide application of cool roof, the air molecules give out the heat, and the intermolecular forces between the air molecules become strong and its kinetic energy decrease.
- The UHI is being linked with the continuation of the sea breeze in the central parts of the city with a thermal gradient from Perth's eastern region to the western Beach. It can lessen the temperature of the coastal zone, combined with wind effects from the urban and nearby surfaces.

2. Climatic Design Parameters _ CDH and air temperature distribution

In this study, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 17 weather stations in Perth have been analysed. Firstly, the frequency distribution of hourly air temperatures has been studied. Secondly, cooling degree hours (CDH) base 26 °C, which measures how much, and for how long, outside air temperature is higher than 26 °C, has been calculated serving as a rough indication of the regional climatic severity. Two scenarios: reference scenario (Solar reflectance_ roof, streets, and walls=0.15; thermal emissivity _ roof, streets, and walls =0.85) and cool roof scenario (Solar reflectance _ roof = 0.80; Solar reflectance _ walls and streets=0.15; thermal emissivity _ roof, streets, and walls =0.85) are simulated and analysed. CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 17 weather stations, has been calculated. The frequency and spatial distribution of the calculated CDH are analysed as well.

2.1 Overview of the weather stations in Perth

Seventeen stations in Perth, as shown in **Table 4** and **Figure 11**, have been simulated for two months: January and February, and the dry bulb temperatures generated by Weather Research Forecasting Model have been used in subsequent calculations.

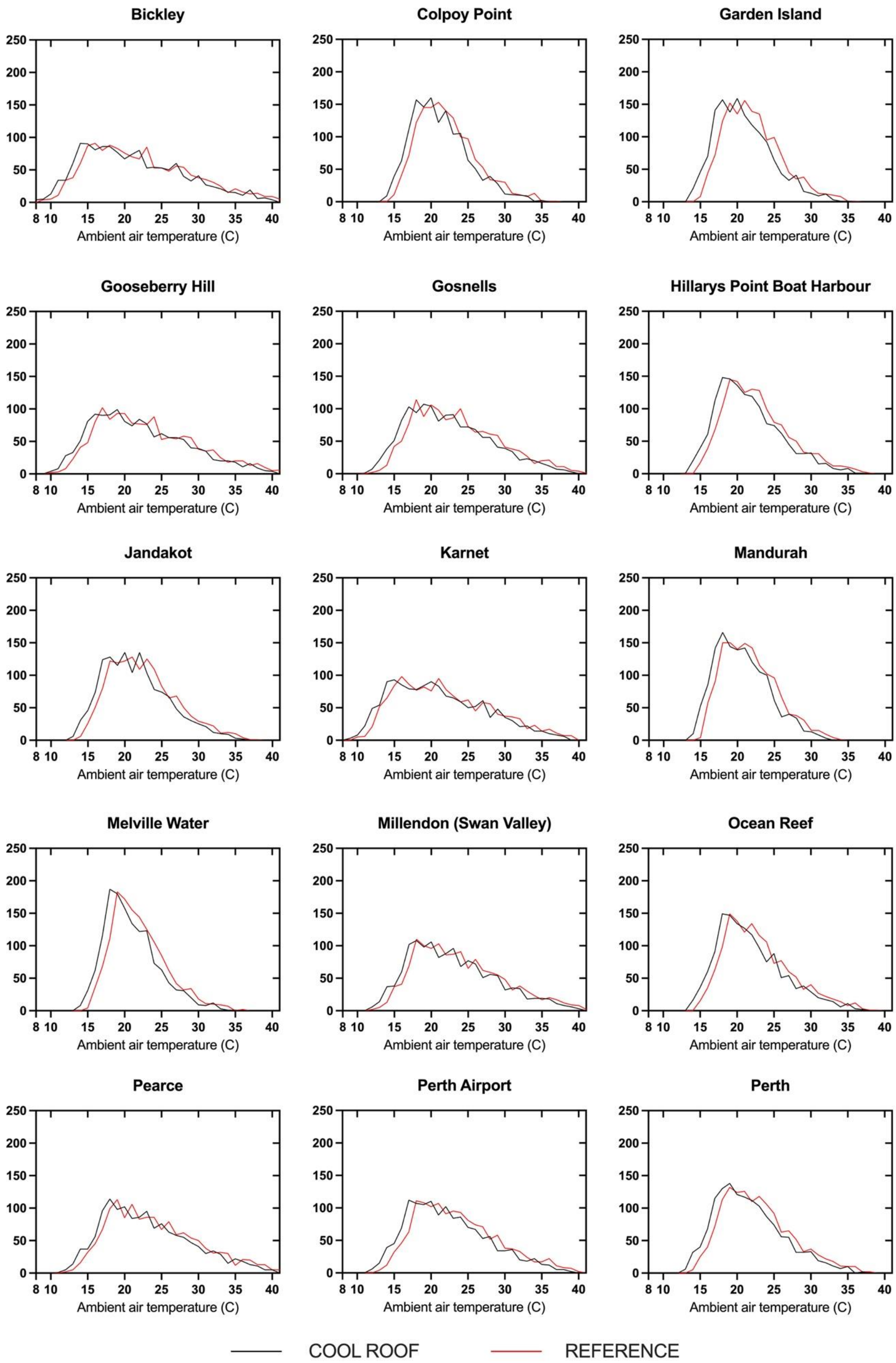
Table 4 Latitude, longitude, and the climate zone of the 17 stations in Perth.

No.	Station name	Lat	Long	Climate zone
1	PERTH METRO	-31.92	115.87	5
2	PERTH AIRPORT	-31.93	115.98	5
3	BICKLEY	-32.01	116.14	5
4	COLPOYS POINT	-32.23	115.70	5
5	GARDEN ISLAND HSF	-32.24	115.68	5
6	GOOSEBERRY HILL	-31.94	116.05	5
7	GOSNELLS CITY	-32.05	115.98	5
8	HILLARYS BOAT HARBOUR NTC AWS	-31.83	115.74	5
9	JANDAKOT AERO	-32.1	115.88	5
10	KARNET	-32.44	116.08	5
11	MANDURAH	-32.52	115.71	5
12	INNER DOLPHIN PYLON	-31.99	115.83	5
13	MILLENDON (SWAN VALLEY)	-31.81	116.02	5
14	OCEAN REEF	-31.76	115.73	5
15	PEARCE RAAF	-31.67	116.02	5
16	ROTTNEST ISLAND	-32.01	115.5	5
17	SWANBOURNE	-31.96	115.76	5

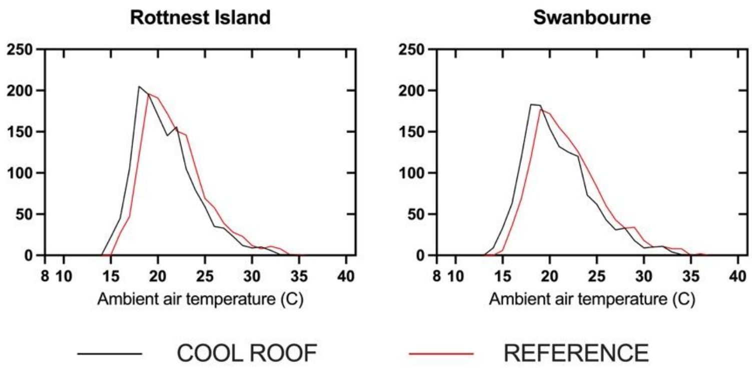
Figure 11 Location of the 17 weather stations in Perth.

2.2 Histogram of WRF simulated ambient temperature in Perth

The entire 2-month hourly ambient temperature of 17 stations in Perth simulated by WRF has been divided into a series of data with a consecutive and non-overlapping interval of 1. The frequency distribution in **Figure 12** shows the quantity of ambient temperatures falling into each interval. The abscissa indicates the starting point of the interval. For example, if the abscissa of a point is 20 and the ordinate is 200, it means that there are 200 ambient temperature data falling within the range of 20-21 °C. At each weather station, the frequency distributions of the reference scenario and cool roof scenario are presented.


Bickley
Colpoy Point
Garden Island
Gooseberry Hill
Gosnells
Hillarys Point Boat Harbour
Jandakot
Karnet
Mandurah
Melville Water
Millendon (Swan Valley)
Ocean Reef
Pearce
Perth Airport
Perth
250
200
150
100
50
0
8 10 15 20 25 30 35 40
Ambient air temperature (C)
COOL ROOF
REFERENCE

(a)



(b)

Figure 12 Histogram of WRF simulated ambient temperature in 17 stations in Perth.

In average, compared to the reference scenario, most of the peaks in the curve of the cool roof scenario is shifted to the left by around 1-3 °C, indicating the cooling benefits of cool roof, as shown in **Table 5**. Around 40%-63% of the ambient temperatures in all stations concentrate in the range of 14-21 °C.

Table 5 The temperature range with the most data at each weather station, including both the reference and cool roof scenarios.

Ambient air temperature starts from	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**Percentage of data concentrated in 14-21 °C (%)**
Bickley COOL ROOF	91								46
Bickley REFERENCE			91						45
Colpoy Point COOL ROOF							160		57
Colpoy Point REFERENCE								153	49
Garden Island COOL ROOF							159		61
Garden Island REFERENCE								156	49
Gooseberry Hill COOL ROOF						99			47
Gooseberry Hill REFERENCE				102					44
Gosnells COOL ROOF						107			47
Gosnells REFERENCE					114				42
Hillarys Point Boat Harbour COOL ROOF					148				56
Hillarys Point Boat Harbour REFERENCE						145			45
Jandakot COOL ROOF							135		53
Jandakot REFERENCE								128	46
Karnet COOL ROOF		93							48
Karnet REFERENCE			98						47
Mandurah COOL ROOF					166				62
Mandurah REFERENCE						150			52
Melville Water COOL ROOF					187				62
Melville Water REFERENCE						183			51

Millendon (Swan Valley) COOL ROOF					108				45
Millendon (Swan Valley) REFERENCE					110				40
Ocean Reef COOL ROOF					149				54
Ocean Reef REFERENCE						149			44
Pearce COOL ROOF					114				44
Pearce REFERENCE						113			40
Perth Airport COOL ROOF				112					48
Perth Airport REFERENCE					111				41
Perth COOL ROOF						138			54
Perth REFERENCE						132			45
Rottnest Island COOL ROOF					205				63
Rottnest Island REFERENCE						196			53
Swanbourne COOL ROOF					183				62
Swanbourne REFERENCE						177			52

2.3 Cooling Degree Hours (CDH) calculation

For all scenarios, Cooling Degree Hours (CDH) Base 26 °C has been calculated for the entire simulation period. It is a rough indication of the cooling load of a building, and it was calculated by firstly subtracting 26 from the hourly dry-bulb air temperature and then adding all the positive differences in the two months. The calculated CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 17 weather stations are shown in **Table 6** and **Figure 13**. Compared with the reference case, the largest percentage reduction is observed in MANDURAH, and the smallest is found in PEARCE RAAF, with an average reduction of 28.1%. The mean CDH values of the 17 weather stations for the reference case, cool roof case are 1453.7, 1091.4, respectively; see **Table 7**. It can be observed that in most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions. On the contrary, the percentage reduction is larger in colder regions.

Table 6 The CDH of reference cases, cool roof applied cases, and the difference between these two, as well as the percentage of CDH reduction due to the implementation of the cool roof in 17 weather stations in Perth.

Weather Station	**CDH_CTRL**	**CDH_COOL ROOF**	**CDH_ Difference (CTRL-COOL ROOF)**	**Percentage of the reduction_% (CDH_Difference/CDH_CTRL)**
PERTH METRO	1296.5	906.2	390.3	30.1
PERTH AIRPORT	2114.4	1554.4	560.0	26.5
BICKLEY	2271.0	1807.1	463.9	20.4
COLPOYS POINT	768.1	530.7	237.4	30.9
GARDEN ISLAND HSF	727.2	443.8	283.5	39.0
GOOSEBERRY HILL	2400.5	1906.6	493.9	20.6
GOSNELLS CITY	2237.1	1716.2	520.9	23.3
HILLARYS BOAT HARBOUR NTC AWS	1179.7	816.5	363.2	30.8
JANDAKOT AERO	1134.8	791.9	342.9	30.2
KARNET	1890.6	1491.6	399.0	21.1
MANDURAH	530.7	333.3	197.4	37.2
INNER DOLPHIN PYLON	629.3	411.5	217.8	34.6
MILLENDON (SWAN VALLEY)	2481.0	2000.5	480.5	19.4
OCEAN REEF	1341.1	974.4	366.7	27.3
PEARCE RAAF	2613.7	2145.8	467.9	17.9
ROTTNEST ISLAND	463.9	309.5	154.4	33.3
SWANBOURNE	632.8	414.4	218.4	34.5

Table 7 Mean and SD of the CDH of the 17 weather stations in reference cases and cool roof cases respectively.

	Mean	SD	Sample No.
CDH_CTRL	1453.7	774.7	17
CDH_COOL ROOF	1091.4	658.3	17
CDH_DIFFERENCE (CTRL-COOL ROOF)	362.2	125.8	17

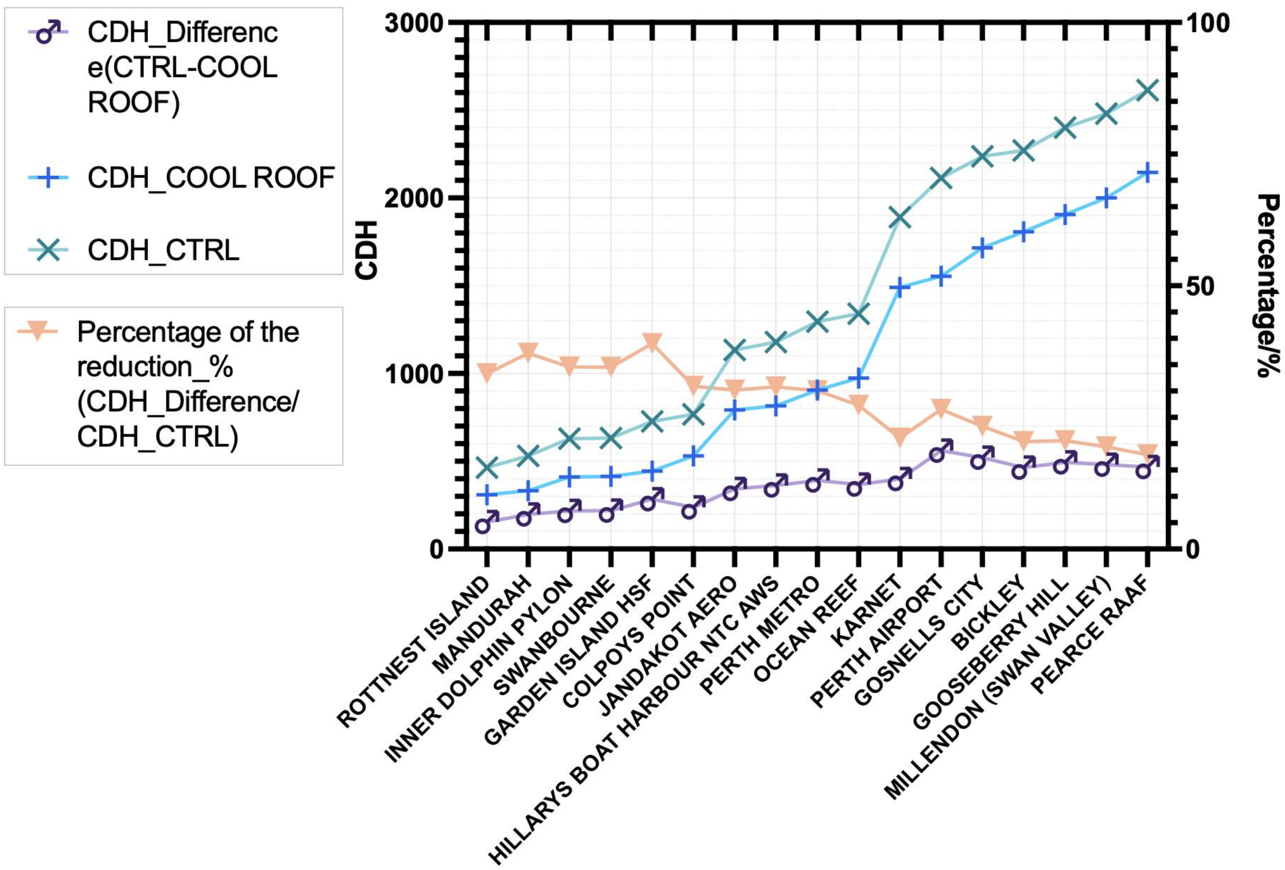


Figure 13 The CDH of reference cases, cool roof applied cases, the difference between these two, and the percentage of the CDH reduction due to the implementation of the cool roof in 17 weather stations in Perth.

2.3.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 17 weather stations in both the reference cases and the cool roof cases is shown in **Figure 14**. In the reference case, the CDH distribution of the 17 stations is relatively uniform with even distribution in small, medium and large values' ranges. This means that the CDH variations among most weather stations are relatively uniform. In the cool roof case, around 30% of the data is centered around 400, with the rest evenly distributed.

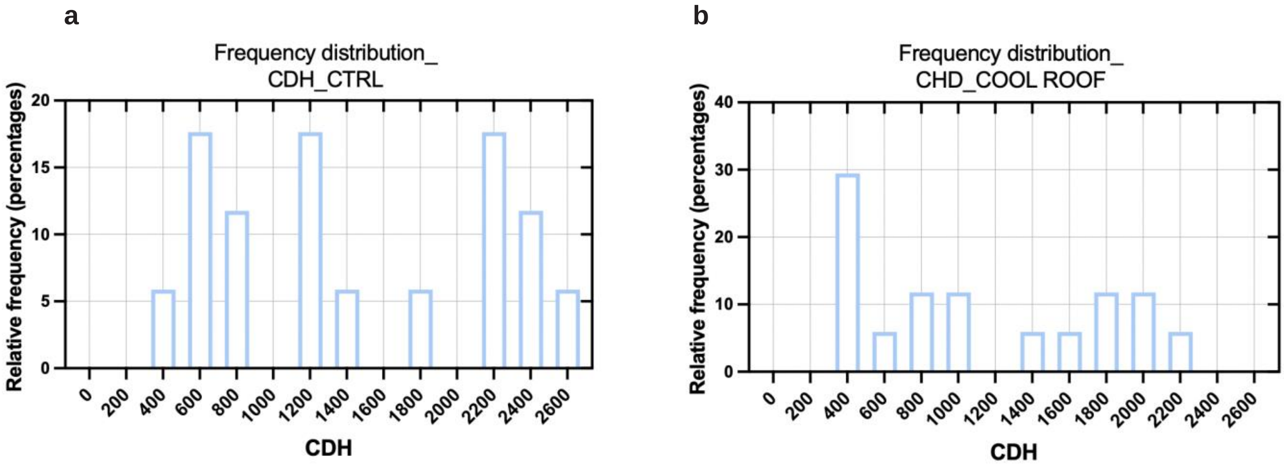


Figure 14 Frequency distribution of the CDH values for the 17 weather stations in reference cases (a) and cool roof cases (b).

2.3.2 Spatial distribution of the results

- **CDH_Reference scenario: (Figure 15)**
  The highest CDH of 3997.7 is observed in PEARCE RAAF, and ROTTNEST ISLAND has the lowest number. CDH gradually increases from west to east.

- **CDH_Cool roof scenario: (Figure 16)**
  When applied with a cool roof, the decrease of CDH is observed at every station. CDH still increases from west to east.

- **CDH_Reference scenario – cool roof scenario: (Figure 17)**
  The maximum decrease occurs in PERTH AIRPORT, while the smallest is observed in ROTTNEST ISLAND. The average decrease after applying cool roof is 362.2 **(Table 6)**.

- **CDH_(Reference scenario – cool roof scenario)/Reference scenario: (Figure 18)**
  The proportion of CDH reduction in the original reference volume is relatively large in the west and gradually decreases toward the east, as shown in **Figure 18**.

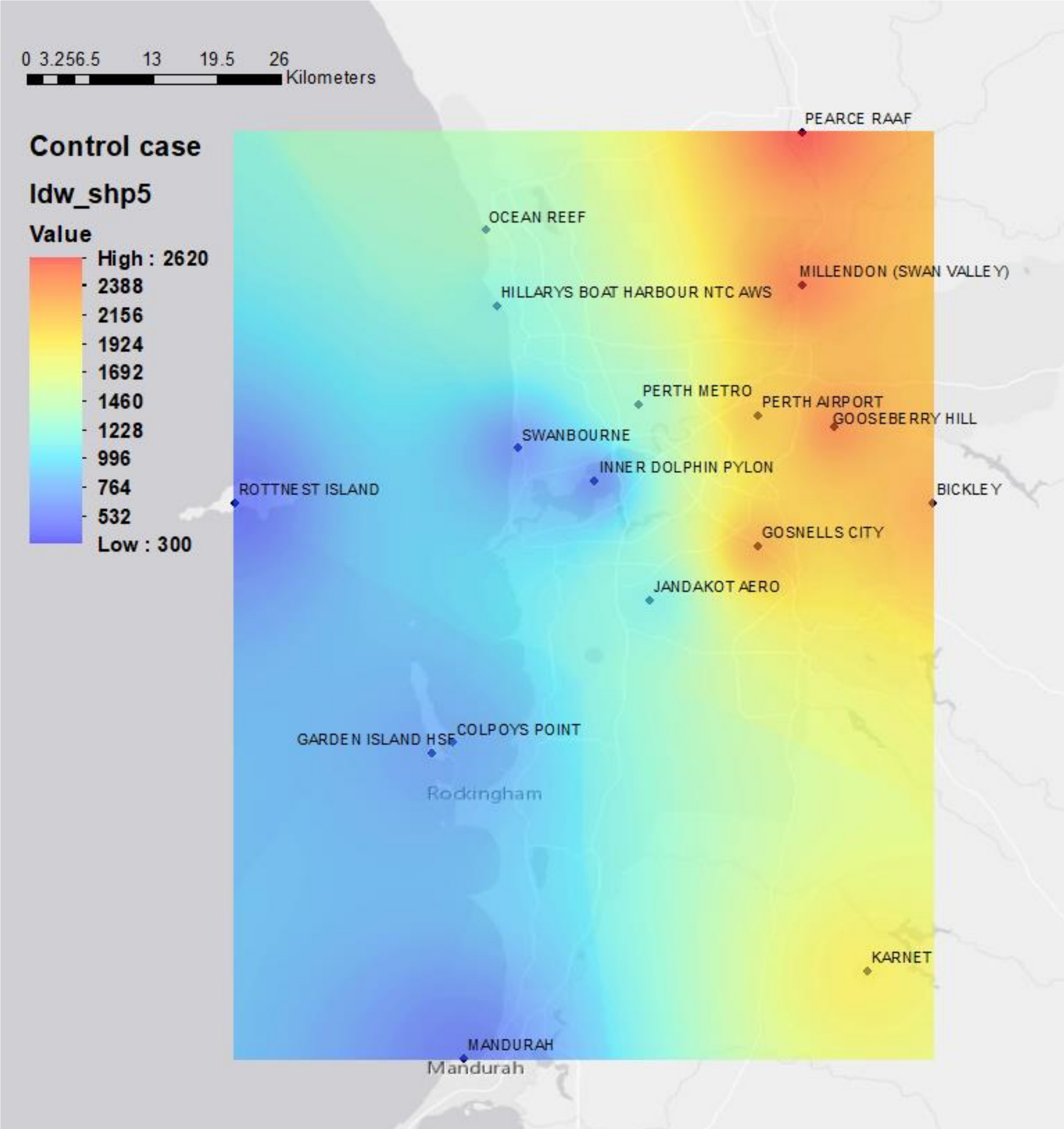


Figure 15 The sum of Cooling degree hours in Jan and Feb of the reference cases in the 17 stations in Perth.

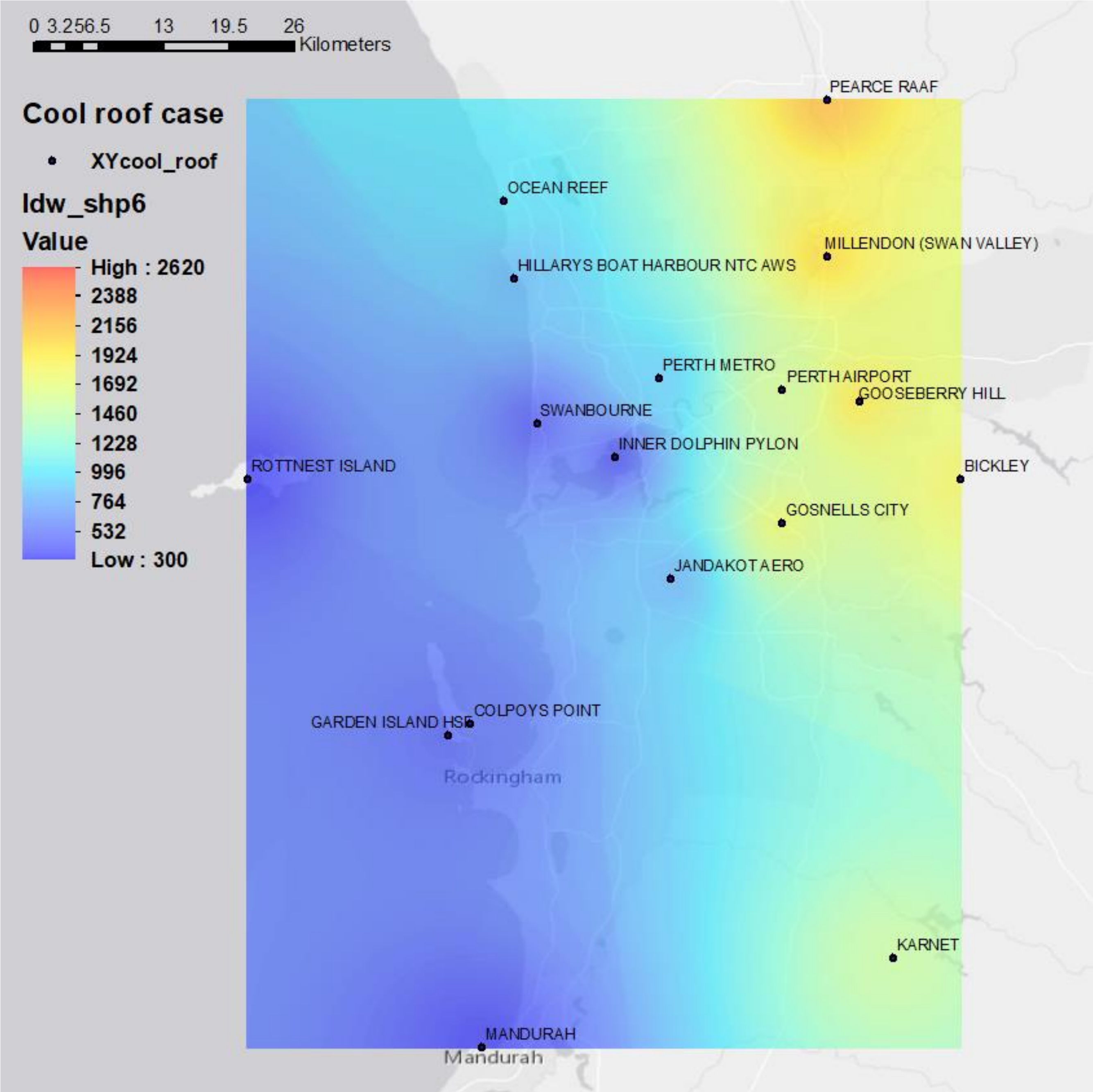


Figure 16 The sum of Cooling degree hours in Jan and Feb of the cool roof cases in the 17 stations in Perth.

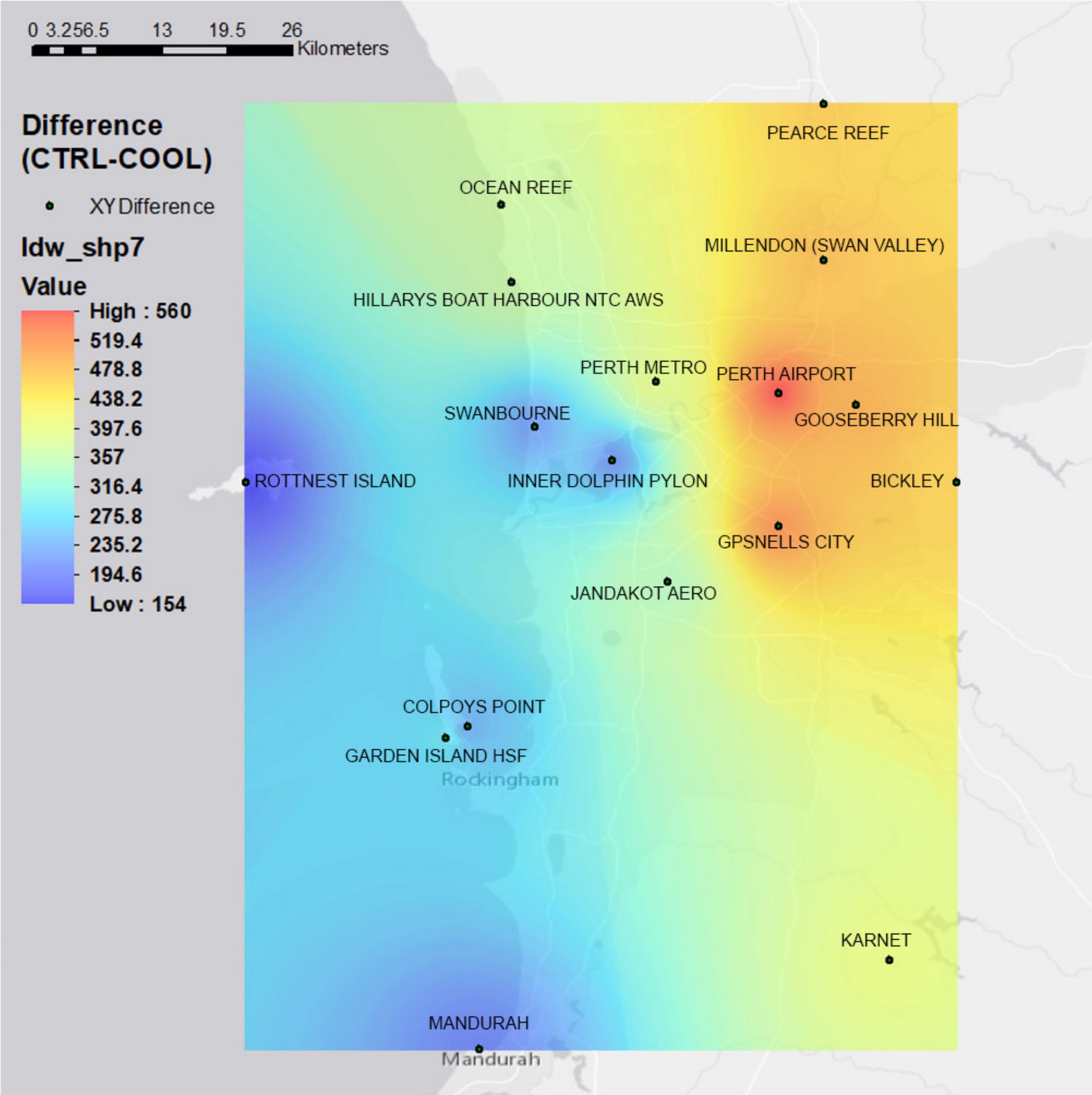


Figure 17 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and reference ones in the 17 stations in Perth.

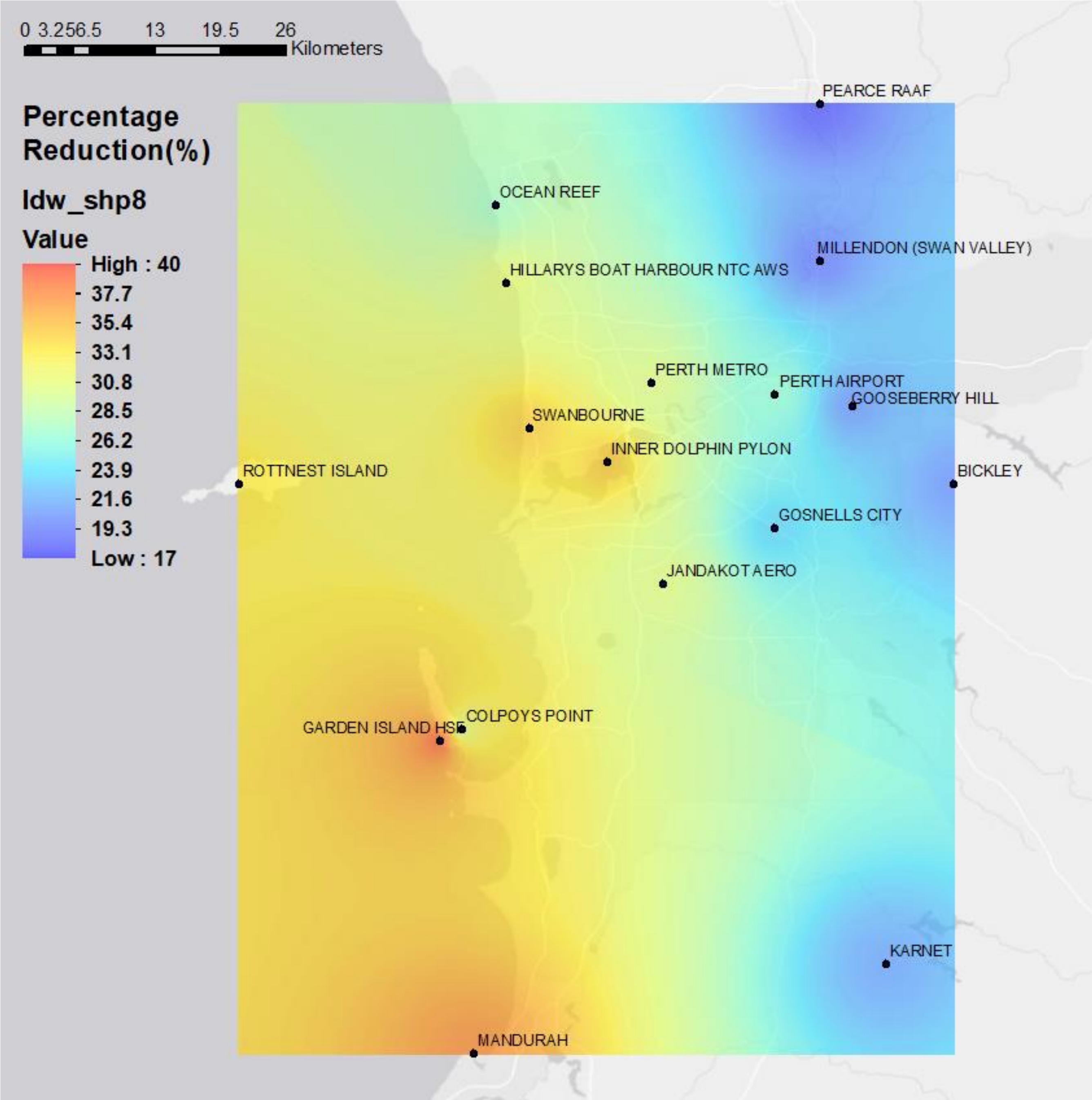


Figure 18 The percentage of CDH reduction due to the implementation of the cool roof in the 17 stations in Perth.

2.4 Conclusion

- In average, compared to the reference scenario, the temperature with the peak distribution in the cool roof scenario is mostly around 1-3 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Around 40%-63% of the ambient temperatures in all stations concentrate in the range of 14-21 °C.
- In reference cases, CDH ranges from 463.9 to 2613.7, and the frequency distribution of CDH values is close to uniform in the ranges of small, medium and large values. CDH gradually increases from the west of the city to the east.
- When applied with a cool roof, the decrease of CDH is observed at every station, with an average decrease of 362.2. CDH also increases from the west to the east.
- In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions.

- The percentage of CDH reduction due to the implementation of the cool roof ranges from 17.9% to 39%, with an average value of 28.1%. The percentage is smaller in the hotter regions.

3. Impact of cool roofs on the cooling/heating load and indoor air temperature of buildings

3.1 Introduction

This chapter investigates the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Perth. The cooling load simulations were performed for two summer months of January and February using weather data simulated by WRF. The annual cooling and heating load estimations were also performed to assess the annual cooling load savings of cool roofs against their corresponding annual heating penalty. The annual cooling and heating load simulations were then performed using the weather data obtained from the BoM. Additionally, the impact of cool roofs on indoor air temperature was assessed under free-floating mode in weather stations presenting the lowest and highest ambient temperatures in Perth during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and five weather stations across Perth (in climate zone 5). The seventeen typical buildings modelled in this study include the following, and their characteristics are listed in **Appendix: Building characteristic**s:

1) A low-rise office building without roof insulation-existing building,
2) A high-rise office building without roof insulation-existing building,
3) A low-rise office building with roof insulation-new building,
4) A high-rise office building with roof insulation-new building,
5) A low-rise shopping mall centre- new building,
6) A mid-rise shopping mall centre- new building,
7) A high-rise shopping mall centre-new building,
8) A low-rise apartment building-new building,
9) A mid-rise apartment building-new building,
10) A high-rise apartment building-new building,
11) A typical stand-alone house-existing building,
12) A typical school building-existing building,
13) A low-rise office building with roof insulation-existing building,
14) A high-rise office building with roof insulation-existing building,
15) A low-rise shopping mall centre-existing building,
16) A high-rise shopping mall centre-existing building,

17) A stand-alone house-new building.

The five weather stations modelled in Perth include (See **Figure 19**):

1) Jandakot Aero, Climate zone 5
2) Pearce Raaf, Climate zone 5
3) Perth Airport, Climate zone 5
4) Perth Metro, Climate zone 5
5) Swanburne, Climate zone 5.

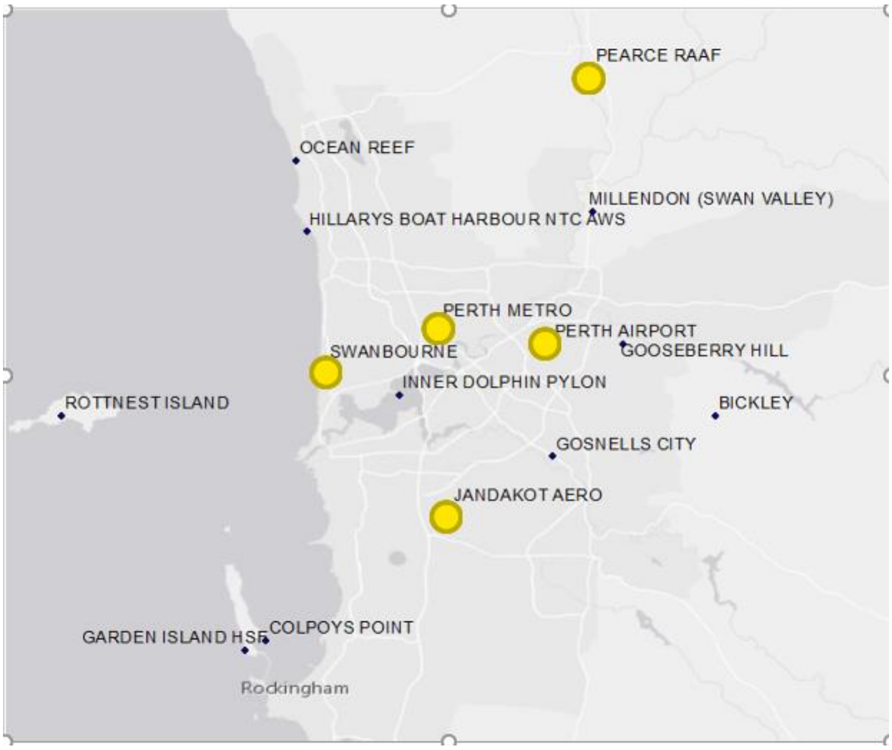


Figure 19 Weather stations in Perth, including 5 weather stations in climate zone 5 (including Jandakot Aero, 2) Pearce Raaf, Perth Airport, Perth Metro, and Swanburne.

The corresponding building specifications for the buildings in climate zones 5. Three sets of simulations were performed in this study:

1) Cooling load simulations for two summer months:

The cooling load simulations were performed for two summer months of January and February. Two sets of weather data were used for the simulations, including one climatic data for the current condition and one climatic data considering an extensive use of cool roofs in the city. The reference and cool weather data, including hourly values of all climatic variables, were generated from the results of WRF simulations for the two summer months of January and February in Perth. The simulations were performed under three scenarios:

- **Reference scenario:** A reference building with a conventional roof using the climatic data simulated by WRF for the current condition.

- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition.

- **Scenario 2 (Cool roof with modified urban temperature scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city.

The cooling load saving for the two summer months was then computed for the two cool roof scenarios (i.e. scenarios 1 and 2) against the reference scenario. The spatial distribution maps of cooling loads for the three scenarios were presented to compare the impact of cool roofs on the cooling loads of each building type in different weather stations. The spatial distribution of the cooling load for two summer months was generated using ArcMap 10.6.

2) Annual cooling and heating load simulations

The annual cooling and heating load estimations were performed to assess the annual cooling load savings of cool roofs against their corresponding annual heating penalty. The annual cooling and heating load simulations were performed using the measured annual weather data obtained from the BoM. The simulations were performed under two scenarios:

- **Reference scenario:** A reference building with a conventional roof using the BoM annual measured climatic data.

- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the BoM annual measured climatic data.

3) Indoor air temperature simulations under free-floating mode

The impact of cool roofs on indoor air temperature was assessed under free-floating mode in weather stations presenting the lower and higher ambient temperatures in Perth (Swanbourne [coldest] and Pearce Raaf [hottest]) during a typical summer and winter period. The indoor air temperature simulations for the summer period were performed under three scenarios:

- **Reference scenario:** A reference building with a conventional roof using the climatic data simulated by WRF for the current condition.

- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition.

- **Scenario 2 (Cool roof with modified urban temperature scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city.

The indoor air temperature reduction of the cool roof scenarios (i.e. scenarios 1 and 2) against the reference scenario was computed. In addition, the number of hours above 26 ºC for the three scenarios was computed to assess the impact of cool roofs on the number of hours the buildings can be functional without an air-conditioning system.

In parallel, the indoor air temperature estimations for the typical winter period were performed under two scenarios:

- **Reference scenario:** A reference building with a conventional roof using the BoM measured weather data.

- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the BoM measured weather data.

The indoor air temperature difference between the cool roof scenario and the reference scenario was then computed. The indoor air temperature reduction in scenario 1 vs reference scenario was plotted against the indoor air temperature in the reference scenario to determine the periods when the undesired temperature reduction occurs. In addition, the number of hours below 19 ºC during occupational/total (i.e. non-occupational and occupational) periods for the two scenarios were computed to assess the impact of cool roofs on the number of hours the buildings can be functional without an air-conditioning system.

3.2 Impact of cool roofs on the cooling/heating load and indoor air temperature of individual buildings

The impact of cool roofs on the cooling/heating load and indoor air temperature of the individual buildings is presented in detail in ***Volume 8***.

3.3 Summary of results

This report investigated the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Perth. In this chapter, a summary of the simulation results and detailed discussions are presented. A summary table of the impact of application of cool roofs in individual buildings (scenario 1) or both individual buildings and at the whole urban area (scenario 2) on total cooling load of different types of buildings in two summer months is given in **Table 8**.

Table 8 Total cooling load under reference scenario and cooling load reductions by building-scale and combined building-scale and urban scale application of cool roofs for all building types for two summer months (i.e. Jan and Feb) with weather data simulated by WRF for COP=1 for heating and cooling

Building Type	Cooling load-reference	Reference with cool roof scenario (scenario 1) vs reference scenario		Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario	
	kWh/m^2	kWh/m^2	%	kWh/m^2	%
A low-rise office building without roof insulation-existing building	21.7-32.3	10.3-13.0	40.4-47.7	13.6-16.2	47.5-62.6
A high-rise office building without roof insulation-existing building	13.2-22.1	1.8-2.3	10.5-13.6	4.9-6.2	22.3-40.5
A low-rise office building with roof insulation-new building	12.4-21.1	0.9-1.2	5.8-7.6	3.9-5.2	18.3-36.3
A high-rise office building with roof insulation-new building	11.7-20.3	0.2	1.0-1.4	2.9-4.4	14.3-32.5

A low-rise shopping mall centre-new building	58.3-69.1	1.6	2.4-2.7	8.4-11.3	12.2-19.3
A mid-rise shopping mall centre-new building	56.9-67.6	0.7-0.8	1.1-1.3	7.5-10.5	11.1-18.4
A high-rise shopping mall centre-new building	56.3-67.0	0.5	0.7-0.8	7.3-10.2	10.9-18.1
A low-rise apartment building-new building,	7.5-13.2	1.1	8.6-14.3	3.4-4.3	26.7-45.2
A mid-rise apartment building-new building	7.1-12.8	0.6-0.7	5.1-8.8	3.0-3.8	24.1-42.0
A high-rise apartment building-new building	6.8-12.5	0.4	3.1-5.4	2.7-3.6	22.6-40.1
A typical stand-alone house-existing building,	11.4-16.4	6.1-6.6	39.9-53.5	7.7-8.7	50.3-67.9
A typical school building-new building	16.0-27.9	0.9-1.0	3.5-6.2	5.1-6.5	18.4-32.7
A low-rise office building with roof insulation-existing building	16.0-25.5	4.8-6.1	24.0-29.8	8.2-9.7	33.7-50.8
A high-rise office building with roof insulation-existing building	12.3-21.0	0.9-1.1	5.2-6.9	3.7-5.1	17.8-36.2
A low-rise shopping mall centre-existing building	62.1-73.6	7.9-8.2	11.1-12.8	14.9-17.4	20.2-28.0
A high-rise shopping mall centre-existing building	57.2-68.2	2.3-2.4	3.6-4.1	9.2-12.0	13.5-21.0
A stand-alone house-new building.	8.7-13.2	3.4-3.6	27.2-39.0	5.2-5.9	40.8-60.3

Table 9 Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference with cool roof scenario (scenario 1) vs reference scenario for all building types using annual measured weather data for COP=1 for heating and cooling

Building Type	Annual cooling load saving		Annual heating load penalty	Annual total cooling & heating load saving	
	kWh/m^2	%	kWh/m^2	kWh/m^2	%
A low-rise office building without roof insulation-existing building	17.8-26.8	42.1-48.2	1.1-1.2	16.6-25.5	35.8-41.2
A high-rise office building without roof insulation-existing building	2.9-4.6	10.3-13.1	0.3-0.4	2.6-4.2	8.6-11.3
A low-rise office building with roof insulation-new building	1.5-2.4	5.9-7.1	0.1-0.2	1.4-2.2	5.0-6.1
A high-rise office building with roof insulation-new building	0.3-0.4	1.0-1.3	0	0.2-0.4	0.9-1.2
A low-rise shopping mall centre-new building	5.2-6.7	2.9-3.5	0.1	5.1-6.6	2.8-3.4
A mid-rise shopping mall centre-new building	2.4-3.1	1.4-1.7	0-0.1	2.3-3.1	1.3-1.7
A high-rise shopping mall centre-new building	1.5-2.0	0.9-1.1	0	1.5-1.9	0.9-1.1
A low-rise apartment building-new building,	1.7-2.3	8.8-13.1	0.8-0.9	0.8-1.4	1.9-3.6
A mid-rise apartment building-new building	0.9-1.3	5.1-7.9	0.4-0.5	0.4-0.8	1.1-2.1
A high-rise apartment building-new building	0.5-0.8	3.1-4.7	0.3	0.2-0.5	0.6-1.2
A typical stand-alone house-existing building,	11.3-15.0	43.1-55.5	4.5-5.2	6.2-10.0	12.0-18.6
A typical school building-new building	1.6-2.1	3.5-5.5	0.3	1.2-1.7	2.0-3.4
A low-rise office building with roof insulation-existing building	7.9-12.2	24.8-29.0	0.5-0.7	7.4-11.4	21.0-24.9
A high-rise office building with roof insulation-existing building	1.3-2.1	5.0-6.4	0.1	1.2-2.0	4.4-5.7

A low-rise shopping mall centre-existing building	23.5-31.1	13.0-15.7	0.2-0.4	23.1-30.7	12.4-15.1
A high-rise shopping mall centre-existing building	6.6-9.0	4.0-5.0	0.1	6.5-8.9	3.8-4.9
A stand-alone house-new building.	5.9-7.8	29.2-39.5	1.3-1.7	4.4-6.2	11.4-17.2

Table 10 Maximum indoor air temperature in reference scenario, maximum indoor air temperature reduction between reference scenario vs reference with cool roof scenario (scenario 1) and reference scenario vs cool roof with modified urban temperature scenario (scenario 2) for all building types under free floating conditions during a typical summer week using weather data simulated by WRF, and number of hours with indoor air temperature above 26 ºC in free-floating mode during a typical summer month using weather data simulated by WRF

Building type	**Maximum Indoor air temp in a typical summer week**	**Maximum indoor air temp reduction in a typical summer week**		**Number of hours above 26 ºC in a typical summer month**		
	Reference scenario (ºC)	**Reference with cool roof scenario (scenario 1) vs reference scenario (ºC)**	**Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario (ºC)**	**Reference scenario (hours)**	**Reference with cool roof scenario (scenario 1) (hours)**	**Cool roof with modified urban temperature scenario (scenario 2) (hours)**
A low-rise office building without roof insulation-existing building	38.4-40.8	5.1-5.6	5.9-6.2	478-498	361-393	312-358
A high-rise office building without roof insulation-existing building	34.7-37.2	0.9-1.0	1.8	587-596	568-583	515-545
A low-rise office building	35.0-37.3	0.6-0.7	1.5	540-556	520-543	471-507

with roof insulation-new building						
A high-rise office building with roof insulation-new building	34.3-36.8	0.1-0.2	1.1-1.3	606-612	600-609	555-583
A low-rise shopping mall centre-new building	39.9-42.1	0.4	1.3-1.5	594-595	586-593	551-564
A mid-rise shopping mall centre-new building	39.5-41.6	0.2-0.3	1.1-1.4	618-623	616-623	586-592
A high-rise shopping mall centre-new building	39.3-41.4	0.2-0.3	1.1-1.3	625-627	625	594-603
A low-rise apartment building-new building,	29.2-30.9	0.5	1.2-1.3	328-408	289-388	210-328
A mid-rise apartment building-new building	29.0-30.8	0.3	1.1-1.2	329-412	304-403	219-346
A high-rise apartment building-new building	28.9-30.6	0.2	1.1-1.2	327-412	314-408	216-350
A typical stand-alone house-existing building	31.7-34.0	3.6	4.2-4.3	332-371	226-300	170-268
A typical school building-new building	30.9-33.0	0.2-0.3	1.2-1.3	345-409	325-402	251-347
A low-rise office building with roof	36.4-38.8	2.6-2.9	3.5-3.7	517-534	445-468	387-429

insulation-existing building						
A high-rise office building with roof insulation-existing building	34.5-36.9	0.5	1.3-1.4	592-604	587-596	534-567
A low-rise shopping mall centre-existing building	39.9-42.2	1.8	2.6-2.7	557-558	539-545	501-511
A high-rise shopping mall centre-existing building	39.2-41.3	0.6	1.3-1.4	615-618	612-615	577-588
A stand-alone house-new building.	30.3-32.2	2.0	2.7-2.8	330-376	256-327	192-288

Table 11 Minimum indoor air temperature in reference scenario during a typical winter week, average maximum indoor air temperature reduction between reference scenario vs reference with cool roof scenario (scenario 1) for all building types under free floating conditions during a typical winter month using annual measured weather data, and number of hours with indoor air temperature below 19 ºC in free-floating mode during a typical winter month using annual measured weather data

Building type	Minimum Indoor air temp in a typical winter week	Average maximum indoor air temp reduction in a typical winter month	Number of hours below 19 ºC in a typical winter month			
	Reference scenario (ºC)	Reference with cool roof scenario (scenario 1) vs reference scenario (ºC)	Reference scenario (hours)		Reference with cool roof scenario (scenario 1) (hours)	
			Operational hours	Total	Operational hours	Total
A low-rise office building without roof insulation-existing building	9.6-10.3	2.5	98-112	361-402	138-158	439-479
A high-rise office building without roof						

insulation-existing building						
A low-rise office building with roof insulation-new building	15.1-15.6	0.4	49-67	149-218	54-75	160-232
A high-rise office building with roof insulation-new building	14.3-14.7	0.5	56-66	177-230	59-75	186-246
A low-rise shopping mall centre-new building	16.1-16.5	0.1	34-51	100-157	34-51	100-159
A mid-rise shopping mall centre-new building	11.2-12.3	0.3	28-38	172-217	29-40	176-221
A high-rise shopping mall centre-new building	12.3-13.2	0.2	23-32	132-181	23-34	132-183
A low-rise apartment building-new building,	12.6-13.4	0.1	19-31	117-165	20-35	118-174
A mid-rise apartment building-new building	11.2-12.0	0.3	N/A	442-524	N/A	465-540
A high-rise apartment building-new building	11.5-12.3	0.2	N/A	449-532	N/A	459-546
A typical stand-alone house-existing building,	11.7-12.4	0.1	N/A	456-540	N/A	465-550
A typical school building-new building	8.1-9.6	1.8	N/A	496-532	N/A	576-607
A low-rise office building with	11.3-11.7	0.2	142-155	421-463	147-161	427-472

roof insulation-existing building						
A high-rise office building with roof insulation-existing building	11.9-12.4	1.4	83-95	273-336	98-112	323-374
A low-rise shopping mall centre-existing building	15.6-16.0	0.3	40-58	121-187	44-59	131-194
A high-rise shopping mall centre-existing building	9.8-11.0	0.8-0.9	43-50	223-272	46-54	232-282
A stand-alone house-new building.	12.1-13.0	0.3	28-39	144-196	29-39	153-199

3.4 Conclusion

The conclusions drawn from this chapter are:

- In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, the application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 10.3-13.0 kWh/m^2.
- In existing buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in both individual buildings and in the whole urban area (scenario 2) is quite significant. For instance, the application of cool roofs in both individual building and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 13.6-16.2 kWh/m^2.
- In new low-rise buildings with high insulation level, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.9-5.2 kWh/m^2 in a typical new low-rise office building.
- In high-rise buildings, the application of cool roofs in individual buildings (scenario 1) is predicted to have a relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2 kWh/m^2 for a new high-rise office building with insulation.
- In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by the implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be 2.3-2.4 kWh/m^2 in an existing high-

rise shopping mall centre, which is expected to increase to 9.2-12 kWh/m^2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).

- The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in all building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 17.8-26.8 kWh/m^2, while the corresponding heating penalty is just 1.1-1.2 kWh/m^2.
- In existing low-rise buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, the application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 5.1-5.6 ^oC.
- In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, the application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 5.9-6.2 ^oC.
- In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and at the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^oC. For instance, the number of hours with an indoor air temperature above 26 ^oC in a typical low-rise office building without insulation is predicted to reduce from 478-498 hours to 361-393 hours and 312-358 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
- In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the number of hours with an indoor air temperature above 26 ^oC during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ^oC in new low-rise office building with insulation is predicted to reduce from 540-556 hours to 471-507 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
- The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by applying cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 5.1-5.6 ^oC in a typical summer week, while the average maximum indoor air temperature reduction of the same building is expected to be just 2.5 ^oC during a typical winter month.
- The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ^oC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 2.4^oC occurs when the indoor air temperature is 25.2 ^oC.
- The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ^oC, especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total number of operational hours with ambient temperature below 19 ^oC from 83-95 hours to 98-112 hours in a typical existing low-rise office building with roof insulation.

4. Energy loss through building envelopes in various stations in Perth _ The correlation between cooling load (reduction) and CDH

4.1 Introduction

In this report, the impact of building characteristics and, in particular of the energy loss through building envelopes on the performance of cool roofs in various stations in Perth has been investigated. Specifically, for the 17 building types, the correlation between cooling degree hours (Base 26) and the sensible cooling load in **reference scenarios** (A reference building with conventional roof using the climatic data simulated by WRF for the current condition), and the cooling load reduction in **scenario 1** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition) and **scenario 2** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city) has been plotted using the simulated data in 5 weather stations in Perth for two summer months. For each plot, the linear regression line has been generated in the format of

$$Y=a X + b$$

Y is the cooling load (reduction) (kWh/m^2);

X is the cooling degree hours (K);

<u>For reference scenarios:</u>

a is the slope of the regression line, indicating the approximate heat loss magnitude of the overall envelope, including ventilation

b is the Y-intercept of the regression line, indicating the approximate cooling load caused by miscellaneous heat gain when the cooling degree hour is zero (K).

<u>For the cooling load reduction in scenarios 1 and 2:</u>

a is the slope of the regression line, indicating the rate of variation in cooling load reduction when cooling degree hours change, indirectly expressing the effectiveness of cool roofs under different climatic conditions.

b is the Y-intercept of the regression line, indicating the cooling load reduction when cooling degrees hour is zero.

4.2 Office buildings

The correlation between cooling degree hours and the sensible cooling load in reference scenarios and the cooling load reduction in scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is shown in **Figure 20** and **Table 12**.

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B03 VS B13; or B04 VS B14) have a lower heat loss coefficient of the overall envelope; the envelope of an insulated building loses less heat (B01 VS B13 or B02 VS B14).

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all office building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, no insulation, and older construction years, which often have higher heat loss coefficients in envelopes.

3) For the cooling load reduction in scenario 2 compared with the reference scenario, except B01 and B13, which presents an increased cooling load reduction with the increase of cooling degree hours, all other building types have an opposite trend. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for most of the buildings.

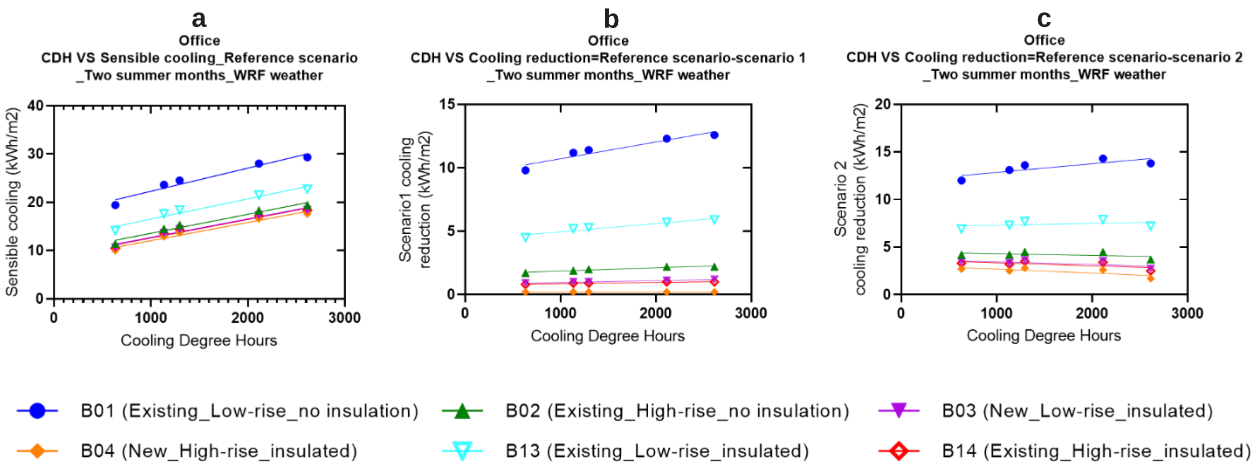


Figure 20 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 12 Slope, Y-intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.004792	17.49	Y = 0.004792*X + 17.49
B02 (Existing_High-rise_no insulation)	0.003934	9.65	Y = 0.003934*X + 9.65
B03 (New_Low-rise_insulated)	0.003834	8.89	Y = 0.003834*X + 8.89
B04 (New_High-rise_insulated)	0.003755	8.31	Y = 0.003755*X + 8.31
B13 (Existing_Low-rise_insulated)	0.004186	12.34	Y = 0.004186*X + 12.34
B14 (Existing_High-rise_insulated)	0.003834	8.79	Y = 0.003834*X + 8.79

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.001318	9.40	Y = 0.001318*X + 9.40
B02 (Existing_High-rise_no insulation)	0.0002541	1.60	Y = 0.0002541*X + 1.60
B03 (New_Low-rise_insulated)	0.0001421	0.81	Y = 0.0001421*X + 0.81
B04 (New_High-rise_insulated)	0	0.2	Y = 0.2000
B13 (Existing_Low-rise_insulated)	0.0006482	4.31	Y = 0.0006482*X + 4.310
B14 (Existing_High-rise_insulated)	0.0001004	0.76	Y = 0.0001004*X + 0.76

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.0009072	11.95	Y = 0.0009072*X + 11.95
B02 (Existing_High-rise_no insulation)	-0.0001739	4.49	Y = -0.0001739*X + 4.49
B03 (New_Low-rise_insulated)	-0.0002742	3.73	Y = -0.0002742*X + 3.73
B04 (New_High-rise_insulated)	-0.0004163	3.11	Y = -0.0004163*X + 3.11
B13 (Existing_Low-rise_insulated)	0.0001953	7.10	Y = 0.0001953*X + 7.10
B14 (Existing_High-rise_insulated)	-0.000316	3.67	Y = -0.0003160*X + 3.67

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 21**.

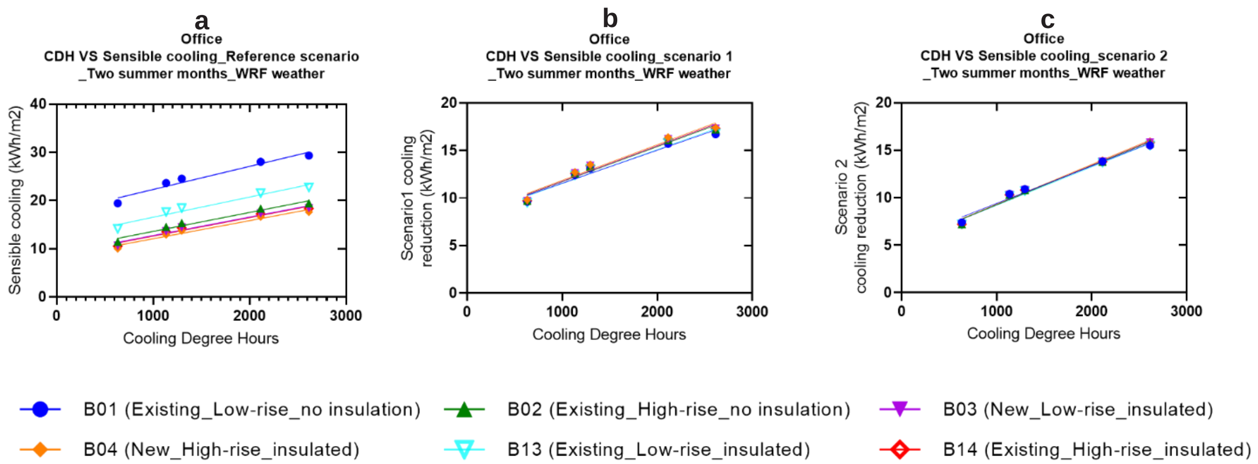


Figure 21 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.3 Shopping mall centres

The correlation between cooling degree hours and the sensible cooling load in reference scenarios and the cooling load reduction in scenario 1 and scenario 2 for the 5 shopping mall centre building types (B05_New_Low-rise; B06_New_Mid-rise; B07_New_High-rise; B15_Existing_Low-rise; B16_Existing_High-rise) is shown in **Figure 22** and **Table 13**.

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B05 VS B15; or B07 VS B16) have a lower heat loss coefficient of the overall envelope.

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all shopping mall centre building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions.

3) For the cooling load reduction in scenario 2 compared with the reference scenario, all buildings present a decreasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for all buildings.

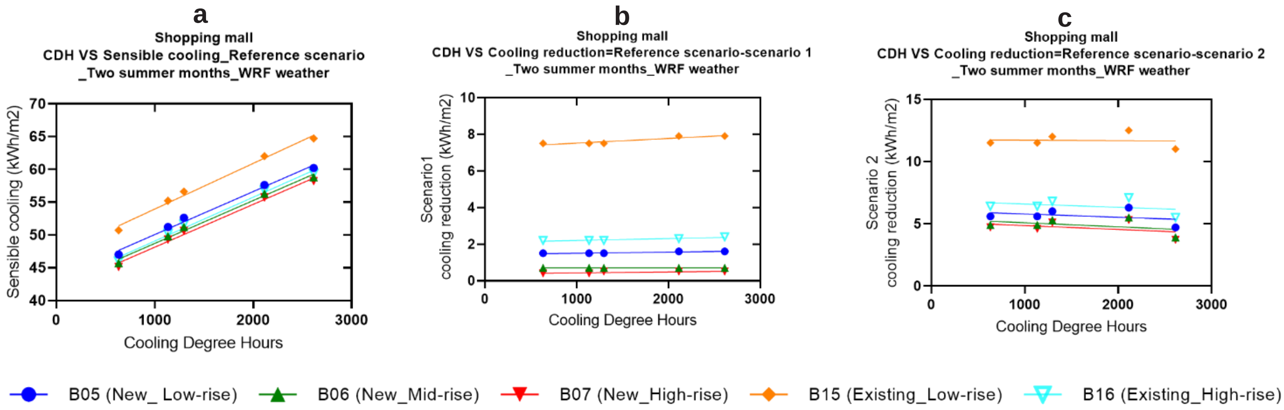


Figure 22 For shopping mall centre a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 13 Slope, Y-intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.006558	43.5	Y = 0.006558*X + 43.50
B06 (New_Mid-rise)	0.006544	42.16	Y = 0.006544*X + 42.16
B07 (New_High-rise)	0.006527	41.61	Y = 0.006527*X + 41.61
B15 (Existing_Low-rise)	0.006965	46.99	Y = 0.006965*X + 46.99
B16 (Existing_High-rise)	0.006686	42.38	Y = 0.006686*X + 42.38

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.0000638	1.44	Y = 0.0000638*X + 1.44
B06 (New_Mid-rise)	0	0.70	Y = 0.7000
B07 (New_High-rise)	0.0000534	0.38	Y = 0.0000534*X + 0.38
B15 (Existing_Low-rise)	0.000255	7.26	Y = 0.0002550*X + 7.26
B16 (Existing_High-rise)	0.0001055	2.10	Y = 0.0001055*X + 2.10

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	-0.0002632	6.05	Y = -0.0002632*X + 6.050
B06 (New_Mid-rise)	-0.000327	5.41	Y = -0.0003270*X + 5.410
B07 (New_High-rise)	-0.0003102	5.16	Y = -0.0003102*X + 5.163
B15 (Existing_Low-rise)	-0.0000406	11.76	Y = -0.0000406*X + 11.76
B16 (Existing_High-rise)	-0.0002632	6.85	Y = -0.0002632*X + 6.850

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 23**.

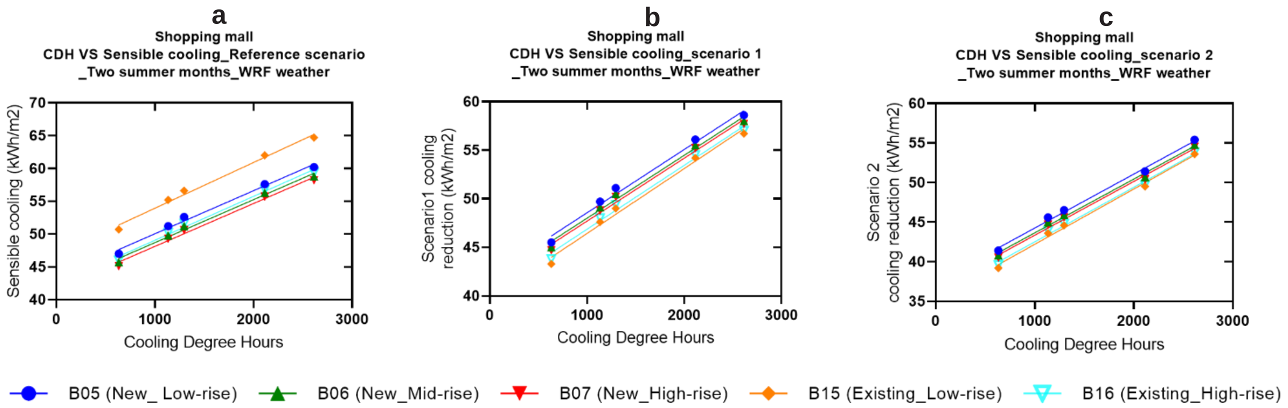


Figure 23 For shopping mall centre a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.4 Residential building

The correlation between cooling degree hours and the sensible cooling load in reference scenarios and the cooling load reduction in scenario 1 and scenario 2 for the 5 residential building types (B08_Existing_Low-rise_apartment; B09_New_Mid-rise_apartment; B10_New_High-rise_apartment; B11_Existing_Standalone house; B17_New_Standalone house) is shown in **Figure 24** and **Table 14**.

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B11 VS B17) have a lower heat loss coefficient of the overall envelope. As a one-story new standalone house, B17 has the lowest heat loss coefficient among all 5 building types, being the most stable one when the external environment changes.

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all residential building types, indicating that in all cases, under unmodified climatic conditions, a cool roof is more effective reducing cooling load in hotter regions. Moreover, a higher increase rate is mostly observed in buildings with fewer floors and older construction years, which often have higher heat loss coefficients in envelopes.

3) For the cooling load reduction in scenario 2 compared with the reference scenario, all residential building types present an increased cooling load reduction with the increase of cooling degree hours. Moreover, a higher increase rate is mostly observed in buildings with fewer floors and older construction years, which often have higher heat loss coefficients in envelopes.

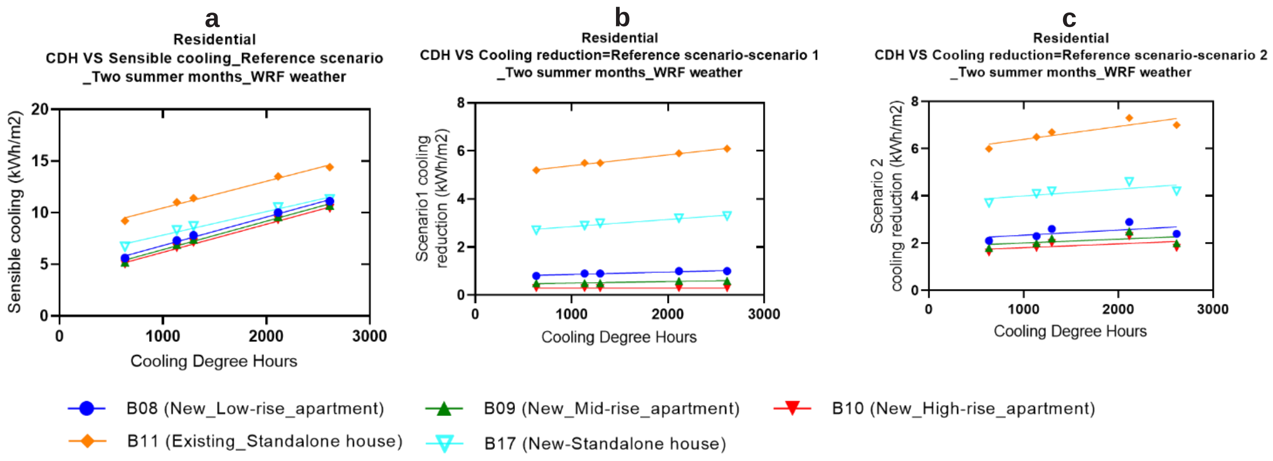


Figure 24 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 14 Slope, Y-intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.002751	4.07	Y = 0.002751*X + 4.07
B09 (New_Mid-rise_apartment)	0.002751	3.67	Y = 0.002751*X + 3.67
B10 (New_High-rise_apartment)	0.002715	3.45	Y = 0.002715*X + 3.45
B11 (Existing_Standalone house)	0.002587	7.87	Y = 0.002587*X + 7.87
B17 (New-Standalone house)	0.002281	5.55	Y = 0.002281*X + 5.55

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0001004	0.76	Y = 0.0001004*X + 0.7636
B09 (New_Mid-rise_apartment)	0.0000638	0.44	Y = 0.0000638*X + 0.4407
B10 (New_High-rise_apartment)	0	0.30	Y = 0.3000
B11 (Existing_Standalone house)	0.0004484	4.94	Y = 0.0004484*X + 4.941
B17 (New-Standalone house)	0.0002959	2.56	Y = 0.0002959*X + 2.559

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B08 (New_Low-rise_apartment)	0.0002159	2.12	Y = 0.0002159*X + 2.12
B09 (New_Mid-rise_apartment)	0.0001625	1.85	Y = 0.0001625*X + 1.85
B10 (New_High-rise_apartment)	0.0001625	1.65	Y = 0.0001625*X + 1.65
B11 (Existing_Standalone house)	0.0005471	5.85	Y = 0.0005471*X + 5.85
B17 (New-Standalone house)	0.0002879	3.71	Y = 0.0002879*X + 3.71

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 25**.

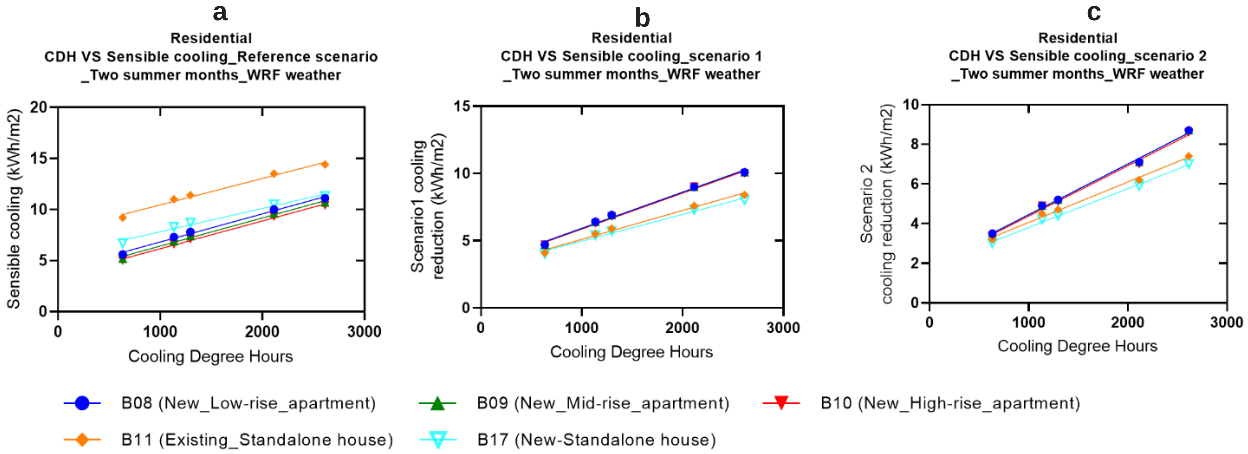


Figure 25 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.5 School

School load reduction in scenario 1 and scenario 2 for the one building type (B12_Existing) is shown in **Figure 26** and **Table 15**. As only one building type is simulated under the category of school, no conclusions can be drawn from internal comparisons like other building categories. For this existing school alone, its sensible cooling load increases with the increase of cooling degree hours. Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree, indicating that in most cases, under unmodified climatic conditions, a cool roof is more effective reducing the cooling load in hotter regions. For the cooling load reduction in scenario 2 compared with the reference scenario, B12 presents a decreasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas.

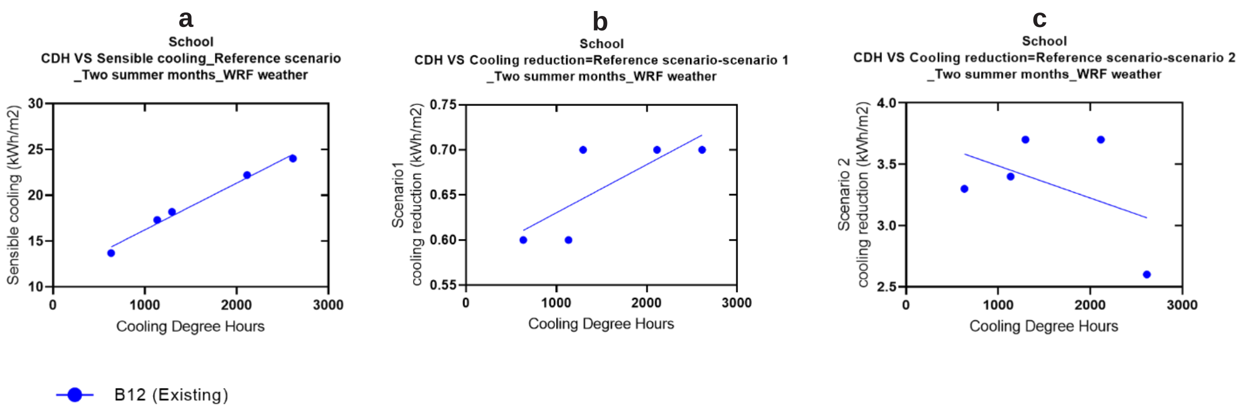


Figure 26 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 15 Slope, Y intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.0051	11.13	Y = 0.005100*X + 11.13

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.0000534	0.58	Y = 0.0000534*X + 0.58

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	-0.0002625	3.75	Y = -0.0002625*X + 3.75

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 27**.

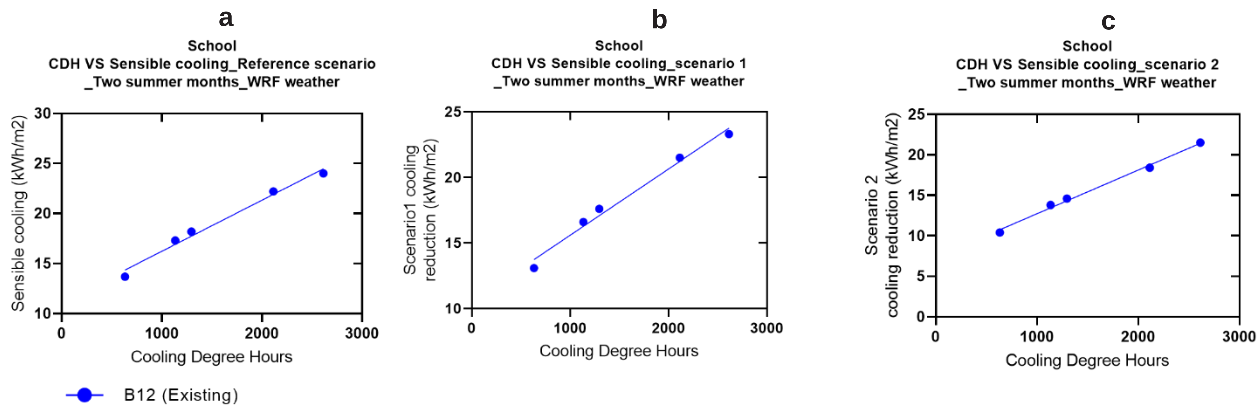


Figure 27 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2

4.6 Conclusion

- Regarding the total cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.
- Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors and older construction years, which often have higher heat loss coefficients in envelopes.
- For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present a decreasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for all buildings.
- A general ranking of the heat loss coefficients of these buildings from low to high is residential buildings, office buildings, school and shopping mall centres (Table 16).

Table 16 A general ranking of the heat loss coefficients of these buildings from low to high.

Building No.	Heat loss coefficient
B17 (Standalone house_New)	0.002281
B11 (Standalone house_Existing)	0.002587
B10 (Apartment_New_High-rise)	0.002715
B08 (Apartment_New_Low-rise)	0.002751
B09 (Apartment_New_Mid-rise)	0.002751
B04 (Office_New_High-rise_insulated)	0.003755

B03 (Office_New_Low-rise_insulated)	0.003834
B14 (Office_Existing_High-rise_insulated)	0.003834
B02 (Office_Existing_High-rise_no insulation)	0.003934
B13 (Office_Existing_Low-rise_insulated)	0.004186
B01 (Office_Existing_Low-rise_no insulation)	0.004792
B12 (School_Existing)	0.0051
B07 (Shopping mall_New_High-rise)	0.006527
B06 (Shopping mall_New_Mid-rise)	0.006544
B05 (Shopping mall_New_ Low-rise)	0.006558
B16 (Shopping mall_Existing_High-rise)	0.006686
B15 (Shopping mall_Existing_Low-rise)	0.006965

5. Feasibility of cool roofs: Evaluation of refurbishment of 17 buildings for Swanbourne and Pearce weather conditions

5.1 Methodological approach

A series of investment appraisal methods can be applied to evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones. The most widely used methods are the following:

1) Net Present Value

Net present value is obtained by discounting all cash outflows and inflows attributable to a capital investment project by a given rate, e.g., the investor’s weighted average cost of capital.

The method discounts the net cash flows from the investment by the minimum required rate of return and deducts the initial investment to give the yield from the capital invested. If the yield is positive, the project is acceptable. If it is negative, the project is unable to pay for itself and is thus unacceptable.

Merits:

(a) It recognizes the time value of money.

(b) It considers the total benefits arising out of proposals over its lifetime.

(c) This method is particularly useful for the selection of mutually exclusive projects, which is the case in the evaluation of the cool roofs’ technologies.

(d) This method is an absolute measure. When two projects are being considered, this method will favour the project which has a higher NPV.

Demerits:

(a) Capital cost is the basis of determining the desired rate. The calculation of capital cost is itself complicated. Moreover, desired rates of return can vary from year to year due to inflation and other parameters.

(b) This method may not give satisfactory results where two projects having different effective lives are being compared. Normally, the project with shorter economic life is preferred if other things are equal. This method does not attach importance to the shorter economic life of the project.

(c) This method emphasizes the comparison of net present value and disregards the initial investment involved. It is hence more difficult to assess investments with significantly different initial investment requirements.

2) Internal Rate of Return Method

Internal rate of return (IRR) is a percentage discount rate used in capital investment appraisals which brings the cost of a project and its future cash inflows into equality. It is the rate of return which equates the present value of anticipated net cash flows with the initial outlay. The IRR is also defined as the rate at which the net present value is zero. The rate for computing IRR depends on bank lending rate or opportunity cost of funds to invest. The test of profitability of a project is the relationship between the IRR (96) of the project and the minimum acceptable rate of return. The IRR is to be obtained by trial-and-error to ascertain the discount rate at which the present values of total cash inflows will be equal to the present values of total cash outflows.

In appraising the investment proposals, IRR is compared with the desired rate of return or a weighted average cost of capital to ascertain whether the project can be accepted or not. IRR is also called as 'cut off rate' for accepting the investment proposals.

Merits:

(a) It considers the time value of money.

(b) It considers the total cash inflows and cash outflows.

(c) It is easier to compare than NPV. For example, if told that IRR of an investment is 10% as against the desired return on an investment is 8%.

Demerits:

(a) Projects selected based on higher IRR may not yield the highest total cash inflows.

(e) Unless the life of the project can be accurately estimated, assessment of cash flows cannot be correctly made.

(f) Single discount rate ignores the varying future interest rates.

3) Depreciated Payback Period Method

The simple payback period is expressed in years, which takes the cash inflows from a capital investment project to equal the cash outflows. It hence specifies the recovery time by accumulation of the cash inflows (inclusive of depreciation) year by year until the cash inflows are equal to the amount of the original investment. However, the simple Payback Period does not fully allow for the evaluation of the impact on time over the value of the cashflows.

Hence the Depreciated Payback Period is used, which is calculated in much the same way as the simple payback, but the cashflows accumulated are being discounted at the discount rate used in the NPV method (i.e., the required return on investment).

Thus, in addition to the recovery of cash investment, the cost of financing the investment during the time that part of the investment remains unrecovered is also considered. It, therefore, ensures the achievement of at least the minimum required return.

Merits:

(a) This method has the advantage of the cash inflows being reinvested once they are received.

(b) It is easier to understand than all other methods.

(c) It is better suited to cash budgeting requirements.

Demerits:

(a) Projecting the future rates of interest at which the cash inflows will be reinvested is difficult.

4) Life Cycle Cost Analysis

Life cycle cost analysis (LCC or LCCA) is an approach used to assess the total cost of owning a facility or running a project. LCCA considers all the costs associated with obtaining, owning, and disposing of an investment. It is especially useful where a project comes with multiple alternatives, and all of them meet performance necessities, but they differ with regards to the initial as well as the operating cost. In this case, the alternatives are compared to find one that can maximize savings.

In that sense, it is ideally suited to energy-saving measures, and project-related costs are classified into initial costs, fuel costs, replacement costs, operation and maintenance costs, finance charges, and residual values. Replacement costs are incurred every cycle based on the predefined age of replacement for different assets and the manufacturer's preference. Another important element of LCCA is disposal cost. When the disposal cost is incorporated, it is possible to offset any additional cost incurred during a particular year. All the costs involved are treated as base year values equivalent to present-day monetary amounts; LCCA transforms all dollar values into future year occurrence equivalents and then discounts all the values to their base dates. In such a way, it's easy to find their present value.

Merits:

(a) This method provides a clear statement on the total costs occurring to the asset's operation.

(b) It is ideally suited for measures (i.e. investments) that do not generate a profit but reduce expenses.

Demerits:

a) Projecting the future rates of interest at which the cash inflows will be reinvested is difficult.

b) It is not well suited to cash budgeting requirements.

5) Synopsis:

Choices among energy-savings measures can be made either by estimating for each alternative measure all the related life-cycle costs and savings relative to a 'base case' and computing the net present value (NPV) of that monetary values looking (a) for the maximum NPV or IRR or (b) by calculating the present value of each project's life-cycle cost and choosing the alternative (including the 'do nothing' alternative) that yields the minimum present-value life-cycle cost (LCCA). The DPB can be used as an additional criterion to provide an indication of the time needed to recover the capital investment.

5.2 Input data and information

In order to evaluate the cool roof's feasibility, data and information are needed on the building and its energy performance, on the cost of energy and on macroeconomic parameters. In detail:

- About the building:
  - Roof area
  - Building's energy consumption before and after the refurbishment

  - Installation cost of the cool roof (Metal roof – MR, and Coating – Coat)
  - Lifetime expectancy of the cool roofs
- On the cost of energy and economic parameters
  - Electricity retail price (Business as usual and high price scenario)
  - Increase rate of electricity price (incl. inflation)
  - Capital cost rate (incl. inflation)

An example of how these data are included in the analysis is presented in the form of **Table 17** and **Table 18**.

Table 17 Building Features

Building features	B01 Swanbourne	B01 Pearce
Energy consumption prior cool roof (MWh)	66,40	86
Energy consumption after cool roof (MWh)	40,10	54,00
Energy savings (MWh)	26,30	31,90
Energy savings (%)	39,61%	37,14%
Area (m^2)	2.400	2.400
Roof costs - Metal roof (AU$/$m^2$)	38,00	38,00
Roof costs - Coating (AU$/$m^2$)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/$m^2$)	15,0	15,0

Table 18 Energy cost and economics

Energy cost and economics	
Electricity cost - Low (AU$/MWh)	150
Electricity cost - High (AU$/MWh)	290
Increase rate of electricity	0,030
Capital cost	0,030

5.3 Assumptions

In order to be able to comparatively evaluate the feasibility of the ‘do nothing’, the metallic cool roof and the cool roof paint, following assumptions are made:

The refurbishment of the roof is taking place in ‘Year 0’, e.g., in the present time, whilst the energy savings are occurring after the 6th month of year 0.

In the ‘do nothing’ scenario, maintenance costs are considered in the year 14, at the cost of 15 AU$/$m^2$.

No salvage value or costs are considered at the end of the roof’s lifetime.

5.4 Selection of most suitable methods

Given the differences in the economic approach that is the background of the four methods applied, the results of the analysis can be understood as follows:

Since the implementation of cool roofs techniques is not a revenue-generating investment but one that reduces operational expenses of the buildings' function, it is not always possible to achieve positive Net Present Values or Internal Rates of Return. These two indices can only be used in a comparative and not in an absolute way, i.e. the solution with the biggest value is better, even if the value is a negative one.

Similarly, it is not always possible to achieve a meaningful Payback Period since the investment in the building's roof has to be implemented anyway, either as a conventional roof or as a cool one.

The determining factor is, therefore, the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost but is only considering the incremental cost of the two variations of the cool roof.

Therefore, the Life Cycle Cost is used as the base for the assessment.

5.5 Presentation of results

The results of the analysis of the 17 buildings are presented as follows:

In four tables are depicted the respective results of the four methods (NPV, IRR, LCC, PB) initially for the 17 buildings. Part I refers to Swanbourne weather conditions, whilst Part 2 to Pearce ones. In each table, there is a set of results for the lower and one for the higher initial electricity price. Coloured cells depict the solution that achieves the best economic performance.

6.5.1 Part 1. Results for Swanbourne weather conditions

Table 19 Net Present Value for Swanbourne weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	21.904	25.709	83.668	74.441
2	7.753	14.543	56.309	52.855
3	-38.445	-21.907	-33.007	-17.617
4	-38.445	-21.907	-33.007	-17.617
5	-7.482	-522	455	8.083
6	-21.437	-9.190	-3.569	4.908
7	-21.854	-9.519	-4.373	4.273
8	-19.692	-11.155	-16.584	-8.703
9	-19.692	-11.155	-16.584	-8.703
10	-20.524	-11.812	-18.193	-9.973
11	-6.015	-3.046	-3.296	-901
12	-32.259	-17.728	-24.490	-11.599
13	-14.306	-2.861	13.663	19.207

14	-18.468	-6.145	5.616	12.858
15	55.559	51.561	155.400	128.609
16	40.992	40.068	117.129	100.140
17	-6.847	-3.703	-4.905	-2.171

Table 20 Internal Rate of Return for Swanbourne weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	6,18%	10,36%	13,21%	21,52%
2	4,21%	7,44%	10,28%	16,74%
3	-8,08%	-9,30%	-5,02%	-5,32%
4	-8,08%	-9,30%	-5,02%	-5,32%
5	-1,18%	-0,17%	3,08%	5,81%
6	-1,77%	-0,97%	2,35%	4,75%
7	-1,90%	-1,14%	2,19%	4,54%
8	-7,66%	-8,76%	-4,55%	-4,70%
9	-7,66%	-8,76%	-4,55%	-4,70%
10	-8,92%	-10,38%	-5,95%	-6,54%
11	-3,76%	-3,65%	-0,06%	1,37%
12	-6,06%	-6,68%	-2,73%	-2,27%
13	0,38%	1,98%	5,06%	8,69%
14	-0,54%	0,71%	3,88%	6,97%
15	10,76%	17,50%	21,20%	35,27%
16	8,97%	14,66%	17,69%	29,24%
17	-5,45%	-5,88%	-2,03%	-1,32%

Table 21 Life Cycle Cost for Swanbourne weather data

LCC	Low Electricity Price			High Electricity Price		
Building	**As built**	**Metal Roof**	**Coating**	**As built**	**Metal Roof**	**Coating**
1	177.617	141.254	102.412	332.609	231.771	173.259
2	501.003	473.134	363.076	957.823	873.404	677.209
3	106.447	131.678	95.119	195.014	213.257	159.160
4	448.978	468.217	359.389	857.241	863.899	670.080
5	1.081.028	1.060.145	748.739	1.283.548	1.250.232	974.027
6	1.263.349	1.252.278	975.716	2.432.589	2.383.193	1.863.707
7	1.852.270	1.831.312	1.430.407	3.571.170	3.502.659	2.742.778
8	97.155	109.245	81.477	182.226	189.720	144.659
9	150.429	161.586	122.579	285.222	290.913	224.122
10	229.506	240.113	184.245	438.105	442.731	343.344
11	19.394	22.780	16.212	35.321	35.709	26.354

12	257.813	275.155	208.465	488.553	494.090	380.355
13	133.500	134.118	96.945	247.316	217.975	111.706
14	468.956	467.867	359.039	895.865	863.223	669.404
15	683.584	605.660	467.665	1.382.472	1.193.717	918.961
16	1.848.940	1.765.194	1.378.252	3.534.714	3.374.832	2.641.944
17	13.984	18.297	12.694	24.860	27.041	19.553

Table 22 Payback Period for Swanbourne weather data

PB	**Low Electricity Price**		**High Electricity Price**	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	24,9	16,8	8,2	5,0
2	17,8	11,6	10,2	6,3
3	-	-	-	-
4	-	-	-	-
5	-	-	20,0	13,2
6	-	-	21,6	14,4
7	-	-	22,0	14,7
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	19,4
12	-	-	-	-
13	26,85	18,35	16,33	10,54
14	-	20,60	18,40	12,03
15	9,81	6,04	5,17	3,02
16	11,36	7,09	6,15	3,64
17	-	-	-	-

In order to comparatively illustrate the results for the 17 buildings, in the following **Figure 29** and **Figure 30** are depicted their Internal Rate of Return and their Life Cycle Cost values.

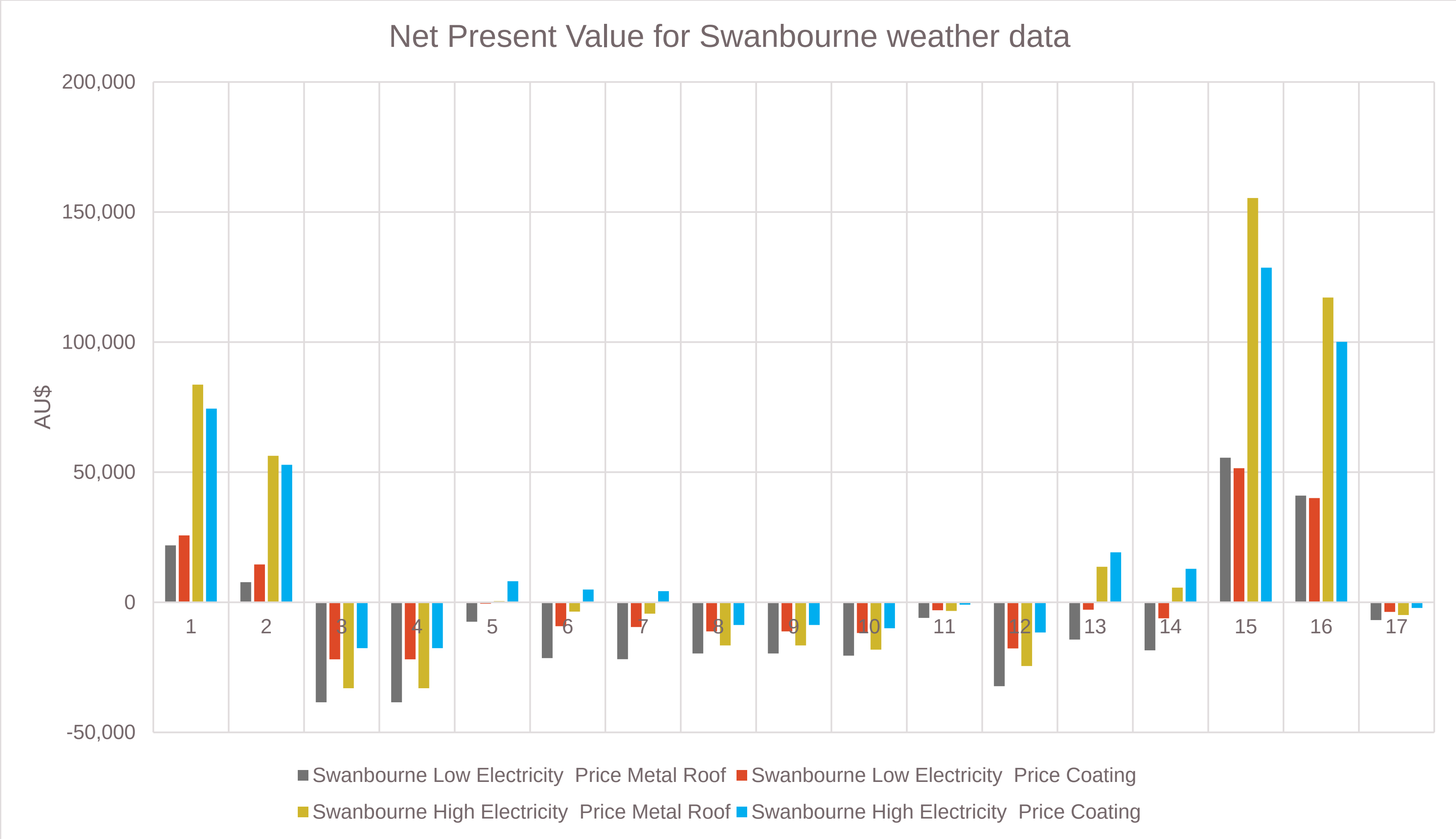


Figure 28 Net Present Value for the buildings for Swanbourne weather conditions

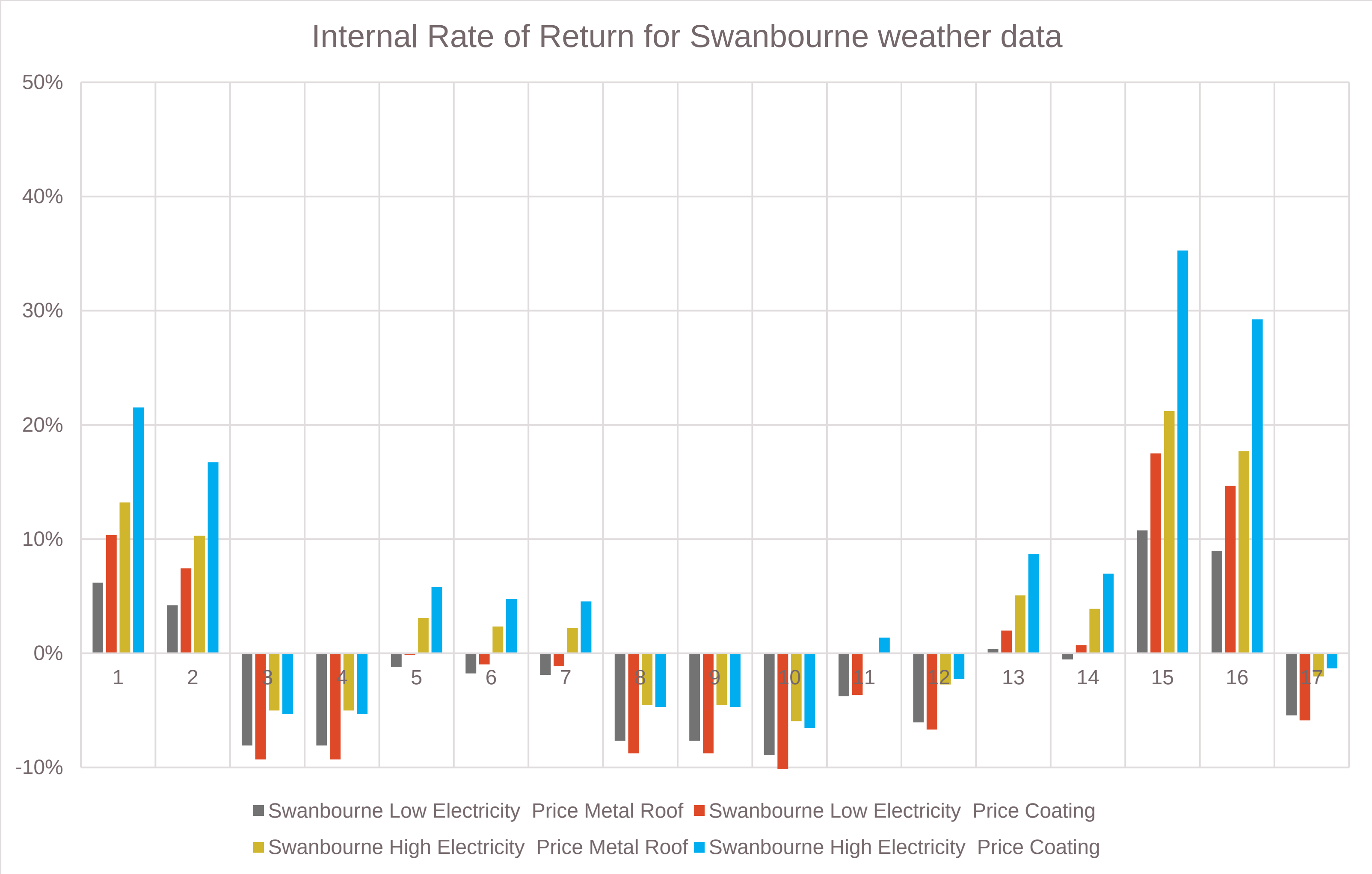


Figure 29 Internal Rate of Return for the buildings for Swanbourne weather conditions

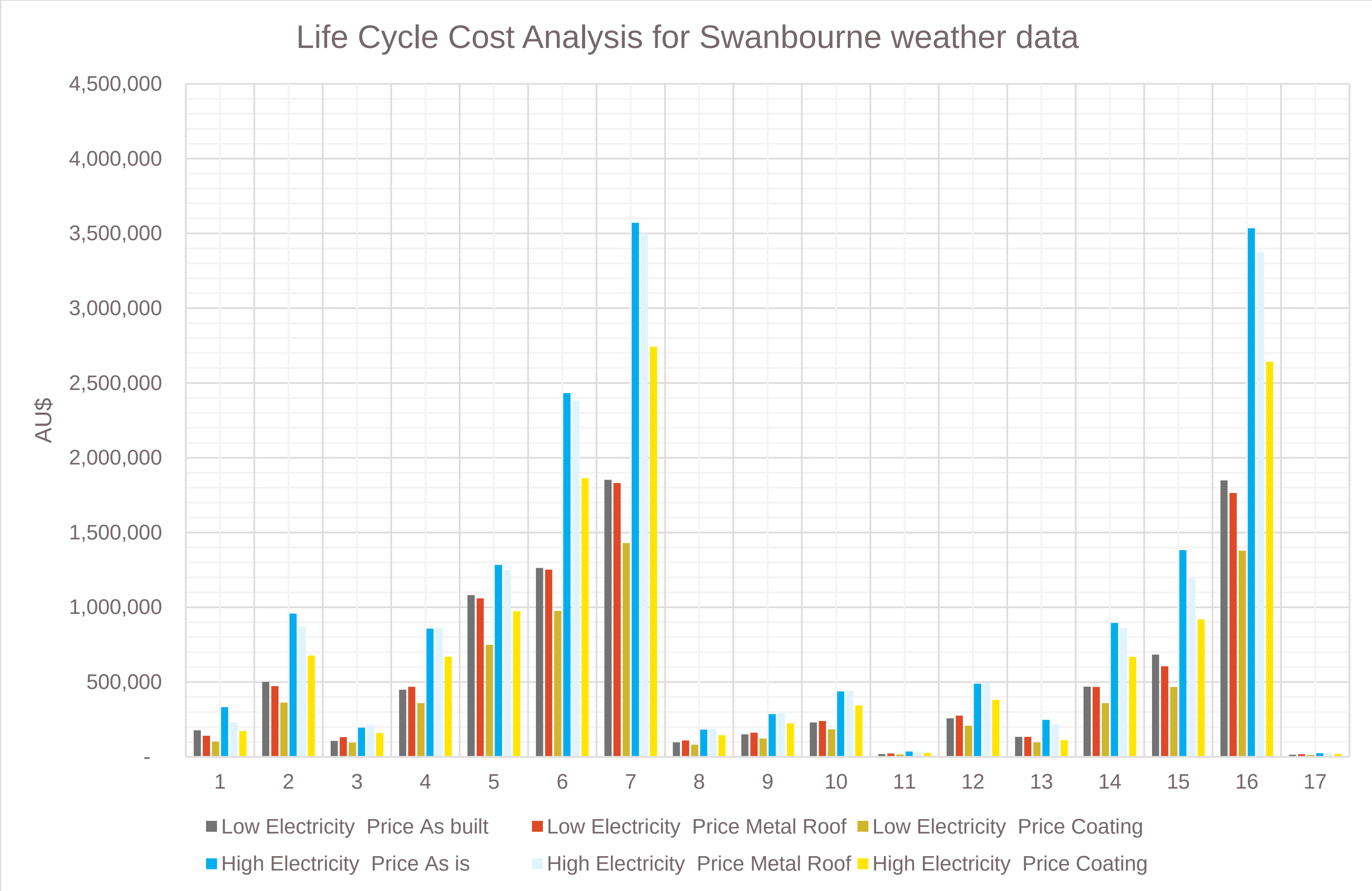


Figure 30 Life Cycle Cost for the buildings for Swanbourne weather conditions

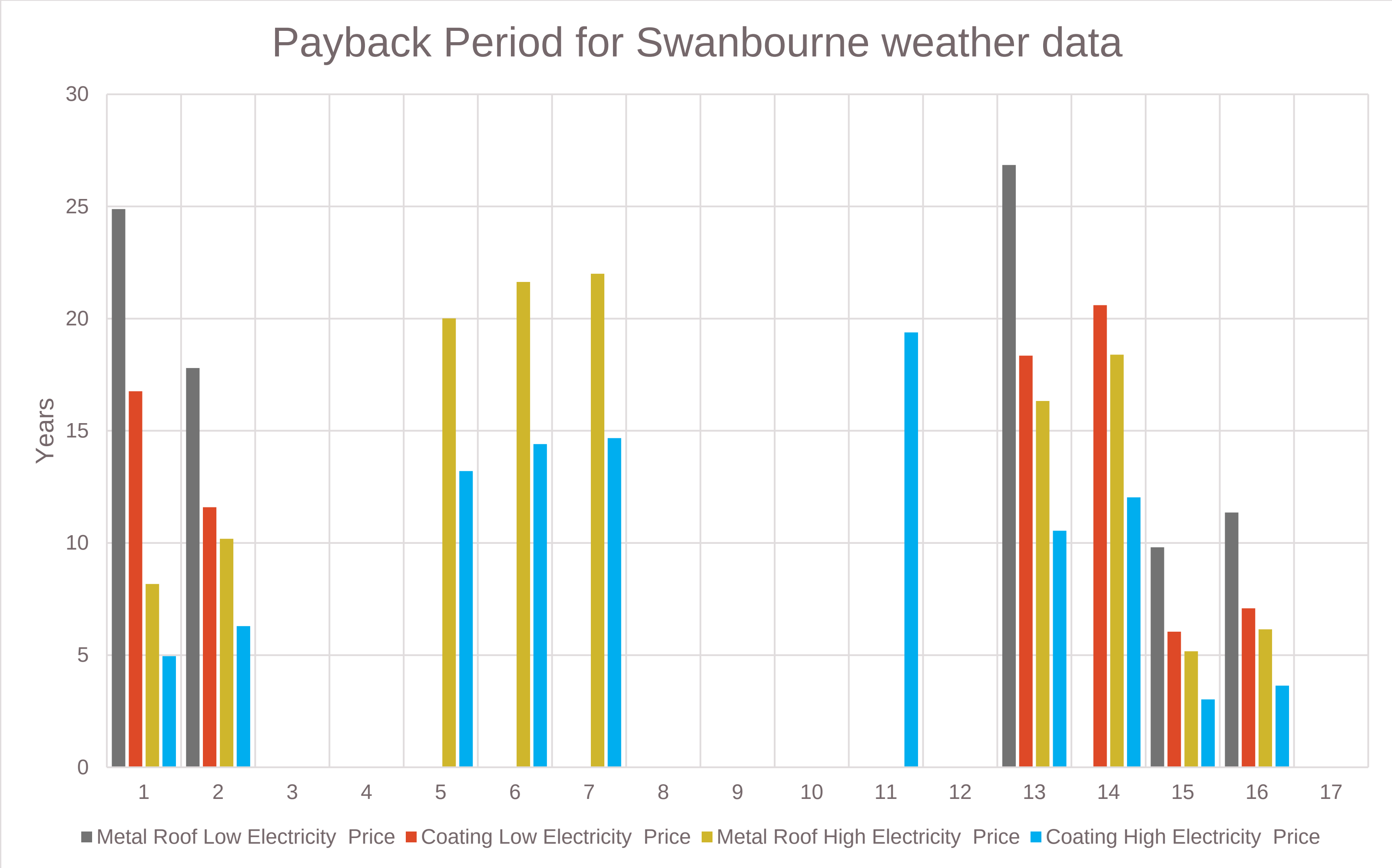


Figure 31 Payback Period for the buildings for Swanbourne weather condition

6.5.2 Part 2. Results for Pearce weather conditions

Table 23 Net Present Value for Pearce weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	50.205	48.039	138.384	117.613
2	33.557	34.903	106.198	92.218
3	-35.115	-19.280	-26.570	-12.537
4	-38.029	-21.579	-32.202	-16.982
5	-8.828	-1.483	-1.155	6.813
6	-21.437	-9.190	-3.569	4.908
7	-21.854	-9.519	-4.373	4.273
8	-19.692	-11.155	-16.584	-8.703
9	-20.108	-11.484	-17.389	-9.338
10	-19.692	-11.155	-16.584	-8.703
11	-6.015	-3.046	-3.296	-901
12	-32.675	-18.057	-25.294	-12.233
13	-571	7.976	40.216	40.158
14	-8.063	2.065	25.733	28.730
15	52.646	49.262	149.462	123.975
16	39.328	38.754	113.910	97.601
17	-6.847	-3.703	-4.905	-2.171

Table 24 Internal Rate of Return for Pearce weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	9,60%	15,65%	18,75%	31,13%
2	7,65%	12,60%	15,52%	25,44%
3	-6,02%	-6,63%	-2,69%	-2,21%
4	-7,78%	-8,91%	-4,68%	-4,87%
5	-1,41%	-0,48%	2,79%	5,39%
6	-1,77%	-0,97%	2,35%	4,75%
7	-1,90%	-1,14%	2,19%	4,54%
8	-7,66%	-8,76%	-4,55%	-4,70%
9	-8,25%	-9,52%	-5,21%	-5,57%
10	-7,66%	-8,76%	-4,55%	-4,70%
11	-3,76%	-3,65%	-0,06%	1,37%
12	-6,30%	-7,00%	-3,01%	-2,64%
13	2,91%	5,55%	8,45%	13,84%
14	1,60%	3,70%	6,67%	11,11%
15	10,41%	16,93%	20,59%	34,14%
16	8,76%	14,33%	17,34%	28,62%
17	-5,45%	-5,88%	-2,03%	-1,32%

Table 25 Life Cycle Cost for Pearce weather data

LCC	Low Electricity Price			High Electricity Price		
Building	**As built**	**Metal Roof**	**Coating**	**As built**	**Metal Roof**	**Coating**
1	271.261	204.959	152.331	513.656	354.934	269.768
2	848.529	788.775	610.838	1.629.706	1.483.645	1.156.216
3	176.368	197.047	146.438	330.195	339.636	258.375
4	774.862	787.983	610.485	1.487.283	1.482.113	1.155.533
5	1.171.869	1.151.319	813.549	1.392.176	1.358.569	1.059.105
6	1.370.312	1.357.369	1.058.240	2.639.385	2.586.371	2.023.253
7	2.012.506	1.988.745	1.554.033	3.880.961	3.807.029	2.981.787
8	143.770	155.043	117.441	272.347	278.264	214.189
9	225.345	235.607	180.706	430.059	434.021	336.501
10	349.372	357.048	276.067	669.845	668.807	520.866
11	24.805	28.096	20.386	45.781	45.987	34.424
12	388.915	404.380	309.941	742.018	663.295	576.543
13	212.577	198.078	147.118	400.200	341.630	259.690
14	802.747	785.414	608.355	1.541.194	1.477.147	1.151.416
15	747.262	671.137	519.093	1.512.279	1.327.309	1.022.715
16	2.017.917	1.932.879	1.509.934	2.017.917	1.931.575	1.508.629
17	18.978	23.204	16.547	34.516	36.528	27.003

Table 26 Payback Period for Pearce weather data

PB	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	19,1	12,5	5,8	3,4
2	12,8	8,0	7,0	4,2
3	-	-	-	-
4	-	-	-	-
5	-	-	20,6	13,7
6	-	-	21,6	14,4
7	-	-	22,0	14,7
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	19,4
12	-	-	-	-
13	20,38	13,48	11,89	7,45
14	23,46	15,76	13,97	8,88
15	10,09	6,23	5,33	3,13
16	11,56	7,23	6,28	3,72
17	-	-	-	-

In order to comparatively illustrate the results for the 17 buildings, in the following **Figure 33** and **Figure 34** are depicted their Internal Rate of Return and their Life Cycle Cost values.

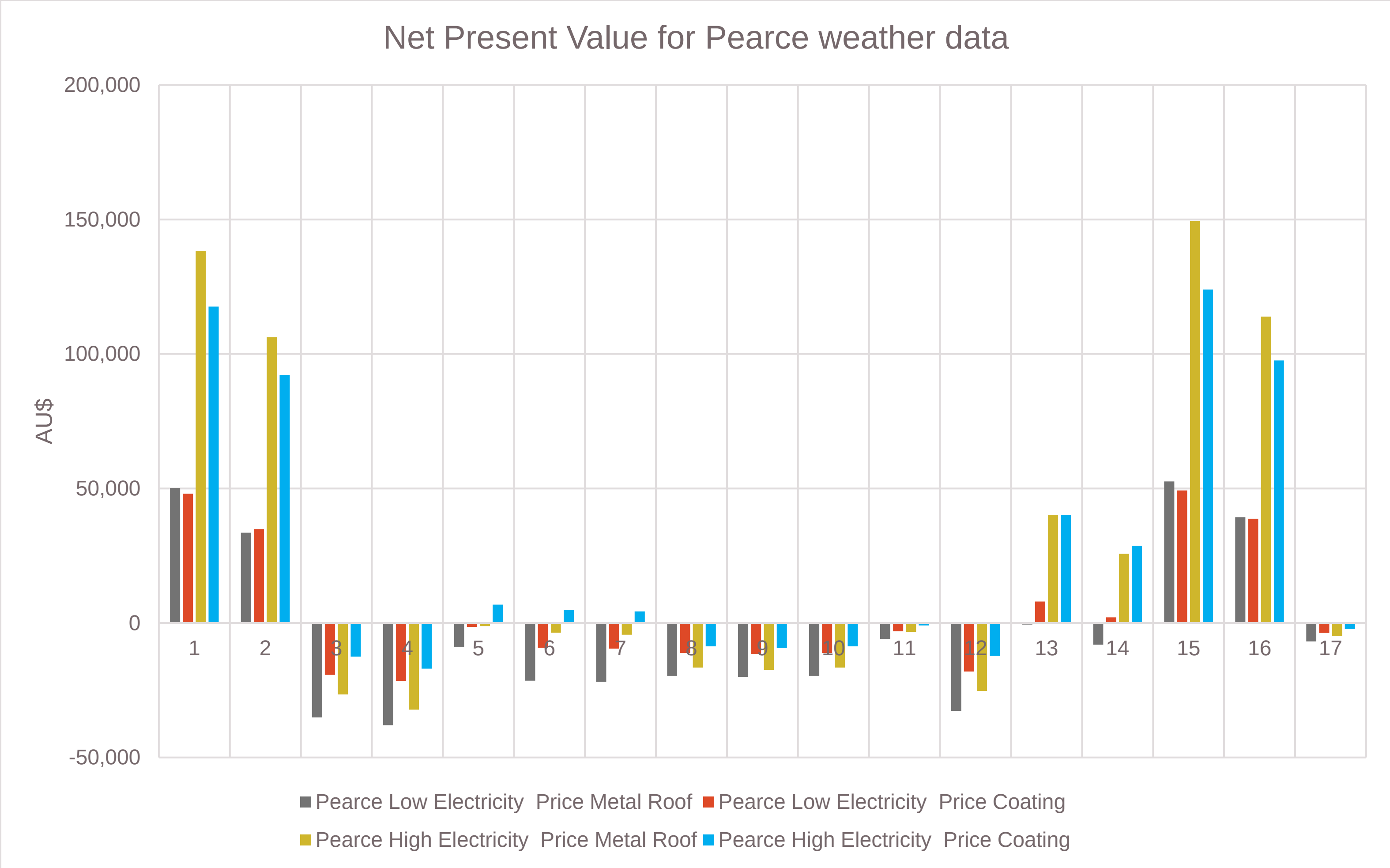


Figure 32 Net Present Value for the buildings for Pearce weather conditions

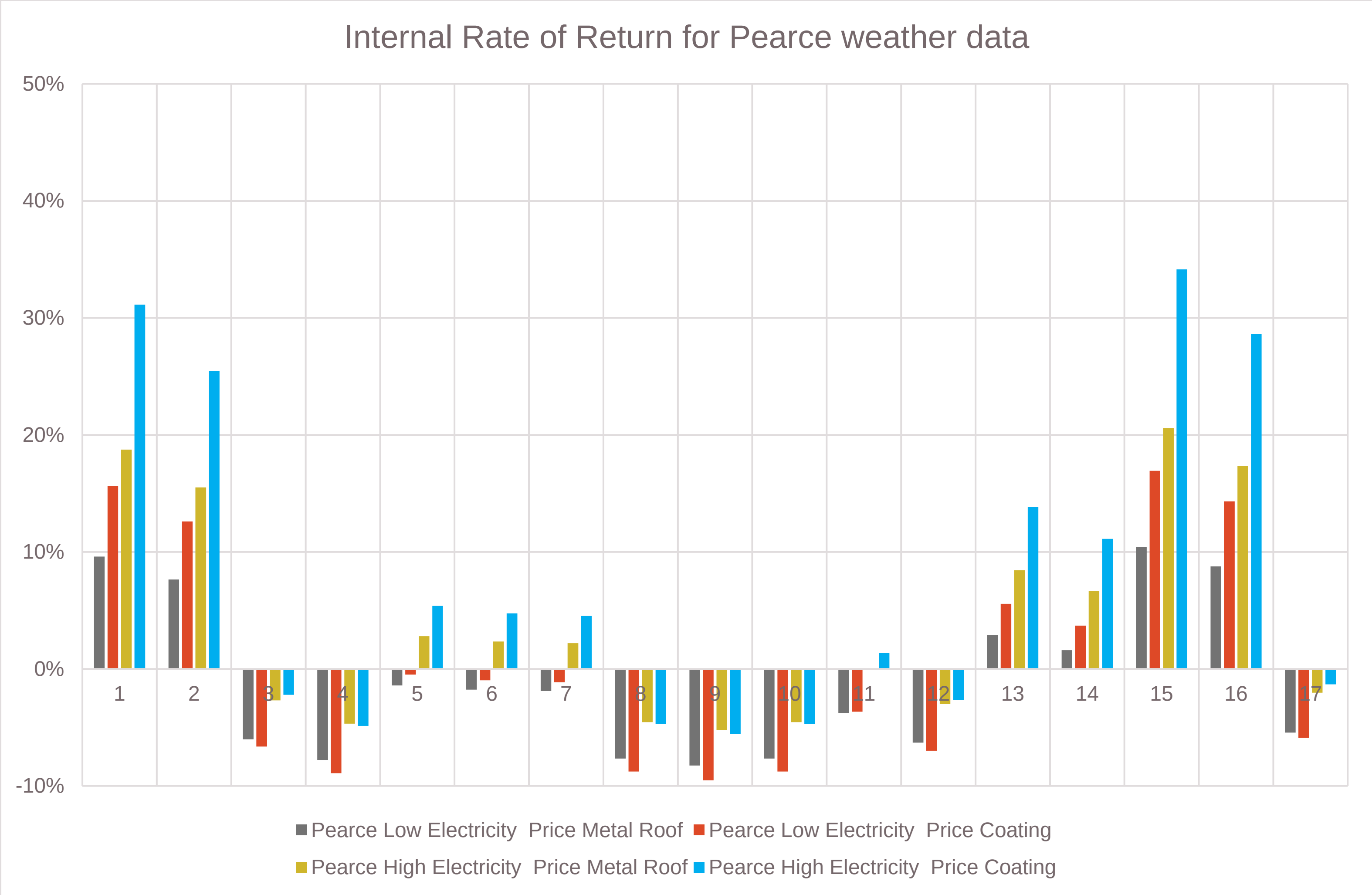


Figure 33 Internal Rate of Return for the buildings for Pearce weather conditions

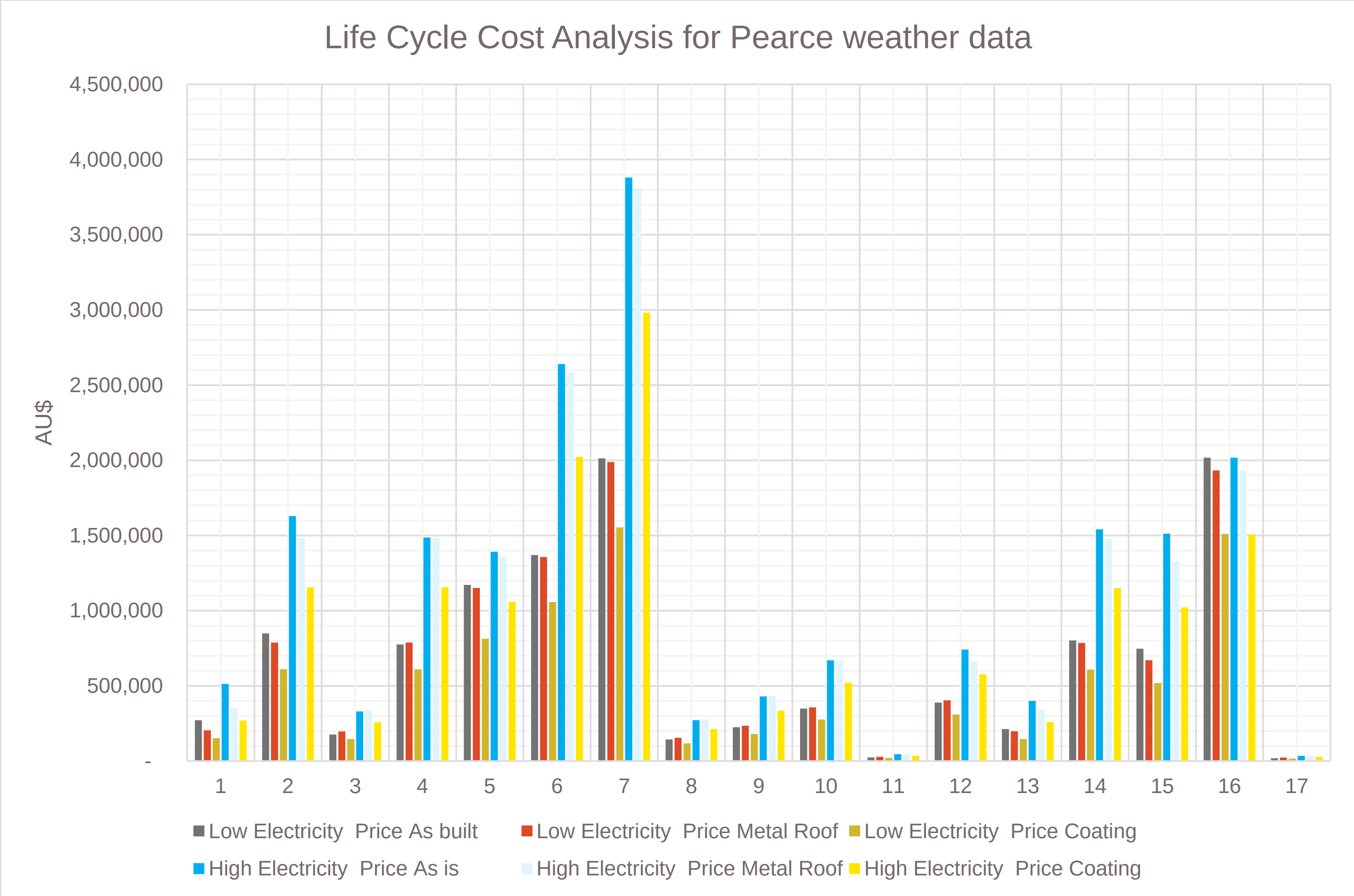


Figure 34 Life Cycle Cost for the buildings for Pearce weather conditions

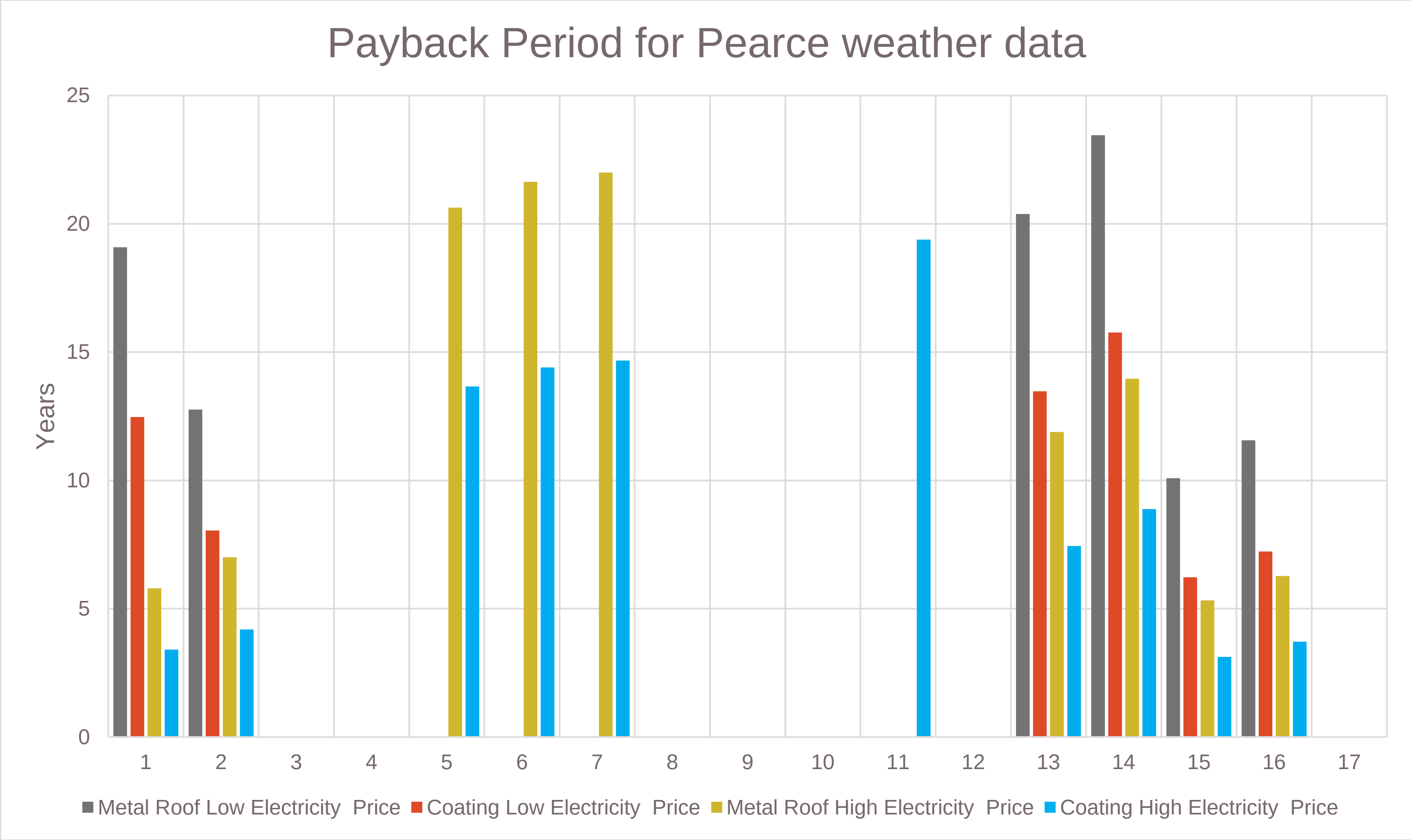


Figure 35 Payback Period for the buildings for Pearce weather conditions

5.6 Discussion of the results

A series of interesting conclusions can be drawn from the results presented:

For all 17 buildings, the solution of the coating for the cool roof presents the least Life Cycle Cost and is, in that sense, the most ‘thrifty’ choice. This is due to the fact that it features a significantly lower initial investment cost compared to cool metal roof, yet achieves comparatively similar savings.

This applies both for the low and the high electricity price scenario, albeit as expected for the high electricity price scenario, the results are much more positive.

Also, for all 17 buildings, the “Do nothing” scenario presents the highest Life Cycle Cost and by a great margin. This becomes dramatic for the high electricity price scenario.

Considering the NPV and IRR results, when the differences between the savings are flow, there is some differentiation, i.e. the metal cool roof appears in some cases to be more feasible. This is due to the different impact of the annual saving’s value over time, which affects the NPV and IRR results stronger than the LCC. In any case, the differences are minor and, given the fact that we are considering energy and cost savings, the LCC is the method that produces the most valid results.

With respect to the 17 buildings considered, it does not come as a surprise that low-rise buildings without thermal insulation of the roof and with high energy requirements are presenting the biggest energy savings potential and consequently the most attractive economic results. For such buildings (like, for example, B02, B15 and B16), the Life Cycle Cost can be reduced by as much as 78%. In such favourable cases, the Payback Period can be as low as 3.0 years.

But even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B01, BO5 and B17) and for lower electricity prices, the Life Cycle Cost of the coating cool roof can be reduced compared to the “Do nothing” conventional roof, which is more than enough to justify the cool coating’s application, despite comparatively longer Payback Periods.

Finally, the impact of electricity prices is, as expected, a big one: it leads to drastically higher Life Cycle Costs for the ‘Do Nothing’ solution, and consequently to shortened Payback Periods for the application of cool roofs. The currently prevailing volatility in the energy markets is a good reminder that energy conservation measures pay off, especially when implemented on time and not after having been hit by an energy crisis.

6. Conclusions

This study is performed to assess the extreme urban heat and cooling potential of cool materials in the city of Perth, Australia. Specifically, it has

1) Evaluated the existing climatic conditions (reference case) in the city of Perth.

2) Assessed the magnitude and spatial variation of cooling potential generated by the cool roof, as well as how its application affects the climate in multiple ways when it is implemented in the city of Perth.
3) Compared the impacts of cool roof strategies at diurnal and monthly scales over the urban domain.
4) Investigated the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Perth.
5) Compared the energy loss through building envelopes in various building types and the advantages applying cool roof in various stations.
6) Evaluated the feasibility of cool roofs by assessing the refurbishment of 17 buildings for Swanbourne and Pearce weather conditions.

Specifically, the following conclusions have been drawn:

1) It is reported that the temperature differences exist near the coast and core part of the city, and the magnitude of the phenomena may vary between 4-5°C. The intensity and the characteristics of the phenomena are sturdily influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the long fetch open area. The potential existence of an extra heating mechanism, like the advection of warm air from desert spaces, could make stronger the strength of the urban heating.
2) The city of Perth incidents an exacerbate UHI is evident at night during heatwaves. In the daytime, a pocket of extreme urban heat turn out in the eastern region of the high density urban, while in the night, a hotspot takes place in the northeastern part of the city.
3) Increase of albedo in Perth, the highest decrease of sensible heat and latent heat flux were up to 187.7 W/m^2 and 17.3 W/m^2 , respectively. Thus, it can decrease the peak summer ambient temperature up to 2.2°C and surface temperature up to 6.5°C. Such cooling improves human comfort levels, and could be feasible for reducing cooling energy demand. The pattern of the ambient temperature distribution and its reduction in the city was found to depend highly on the local climate, urban density and the magnitude of the horizontal thermal gradient over the city.
4) Perth is an isolated urban centre experiencing significant urban growth. High-density parts of the city display a higher temperature drop than the whole urban average. The locations and magnitudes of urban heating in the high-density urban areas vary spatially and diurnally.
5) The maximum decrease of wind speeds is up to 2.9 ms^{-1}. Cool roofs augment the high pressure over core urban at a local scale and diminish the wind advection from the contiguous bare surface of desert fetch. The results show that the increase in albedo fraction leads to a decrease in wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during the heatwave scenario.
6) In average, compared to the reference scenario, the temperature with the peak distribution in the cool roof scenario is mostly around 1-3 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Around 40%-63% of the ambient temperatures in all stations concentrate in the range of 14-21 °C.

7) Alteration of the urban albedo in Perth city results in an average reduction up to 742.7 m of the PBL heights over high-density parts of the city and may increase the concentration of bad pollutants at ground level during peak hour (14:00 LT) due to low level urban mixing.
8) The sea breeze considerably affected by cool roof due to regional high effects over city, which significantly reduces the sea breeze incursion. In the extreme heating environment, in the daytime, when the air above the land gets cooled up due to citywide application of cool roof, the air molecules give out the heat, and the intermolecular forces between the air molecules become strong and its kinetic energy decrease.
9) The UHI is being linked with the continuation of the sea breeze in the central parts of the city with a thermal gradient from Perth's eastern region to the western Beach. It can lessen the temperature of the coastal zone, combined with wind effects from the urban and nearby surfaces.
10) In reference cases, CDH ranges from 463.9 to 2613.7, and the frequency distribution of CDH values is close to uniform in the ranges of small, medium and large values. CDH gradually increases from the west of the city to the east.
11) When applied with a cool roof, the decrease of CDH is observed at every station, with an average decrease of 362.2. CDH also increases from the west to the east.
12) In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions.
13) The percentage of CDH reduction due to the implementation of the cool roof ranges from 17.9% to 39%, with an average value of 28.1%. The percentage is smaller in the hotter regions.
14) In existing buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, the application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 10.3-13.0 kWh/m^2.
15) In existing buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 13.6-16.2 kWh/m^2.
16) In new low-rise buildings with high insulation level, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.9-5.2 kWh/m^2 in a typical new low-rise office building.
17) In high-rise buildings, the application of cool roofs in individual buildings (scenario 1) is predicted to have a relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2 kWh/m^2 for a new high-rise office building with insulation.
18) In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be 2.3-2.4 kWh/m^2 in an existing high-rise shopping mall centre, which is expected to increase to 9.2-12 kWh/m^2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).

19) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in all building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 17.8-26.8 kWh/m^2, while the corresponding heating penalty is just 1.1-1.2 kWh/m^2.
20) In existing low-rise buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, the application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 5.1-5.6 ^oC.
21) In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 5.9-6.2 ^oC.
22) In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and at the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^oC. For instance, the number of hours with an indoor air temperature above 26 ^oC in a typical low-rise office building without insulation is predicted to reduce from 478-498 hours to 361-393 hours and 312-358 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
23) In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the number of hours with an indoor air temperature above 26 ^oC during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ^oC in new low-rise office building with insulation is predicted to reduce from 540-556 hours to 471-507 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
24) The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by applying cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 5.1-5.6 ^oC in a typical summer week, while the average maximum indoor air temperature reduction of the same building is expected to be just 2.5 ^oC during a typical winter month.
25) The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ^oC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 2.4^oC occurs when the indoor air temperature is 25.2 ^oC.
26) The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ^oC, especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total number of operational hours with ambient temperature below 19 ^oC from 83-95 hours to 98-112 hours in a typical existing low-rise office building with roof insulation.
27) Regarding the total cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.

28) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors and older construction years, which often have higher heat loss coefficients in envelopes.
29) For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present a decreasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for all buildings.
30) A general ranking of the heat loss coefficients of these buildings from low to high is residential buildings, office buildings, school and shopping mall centres.
31) For all 17 buildings, the solution of the coating for the cool roof presents the least Life Cycle Cost and is, in that sense, the most ‘thrifty’ choice. This is due to the fact that it features a significantly lower initial investment cost compared to cool metal roof, yet achieves comparatively similar savings.
32) The low-rise buildings without thermal insulation of the roof and with high energy requirements are presenting the biggest energy savings potential and consequently the most attractive economic results. For such buildings, the Life Cycle Cost can be reduced by as much as 78%. In such favourable cases, the Payback Period can be as low as 3.0 years.
33) But even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B01, BO5 and B17) and for lower electricity prices, the Life Cycle Cost of the coating cool roof can be reduced compared to the “Do nothing” conventional roof, which is more than enough to justify the cool coating’s application, despite comparatively longer Payback Periods.
34) Finally, the impact of electricity prices is, as expected, a big one, it leads to drastically higher Life Cycle Costs for the ‘Do Nothing’ solution, and consequently to shortened Payback Periods for the application of cool roofs. The currently prevailing volatility in the energy markets is a good reminder that energy conservation measures pay off, especially when implemented on time and not after having been hit by an energy crisis.

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8. Appendix: Meso-scale simulation results

Table 27 Reduction of ambient temperature: cool roof minus control scenario

Parameters	Ambient Temperature at 2m (°C)			
	06:00 LT	14:00 LT	18:00 LT	24-h avg.
Maximum	-1.4	-1.9	-1.6	-1.7
Minimum	-0.4	-0.7	-0.6	-0.5
Average of January	-0.7	-1.1	-0.9	-0.9
Average of February	-0.9	-1.4	-1.2	-1.2

Table 28 Reduction of surface temperature: cool roof minus control scenario

Parameters	Surface Temperature (°C)			
	06:00 LT	14:00 LT	18:00 LT	24-h avg.
Maximum	-2.3	-6.2	-5.6	-5.4
Minimum	-1.2	-4.7	-3.9	-3.6
Average of January	-1.6	-5.3	-4.3	-4.2
Average of February	-1.7	-5.6	-4.6	-4.6

Table 29 Reduction of sensible heat flux: cool roof minus control scenario

Parameters	Sensible Heat Flux (W/m^2)			
	06:00 LT	14:00 LT	18:00 LT	24-h avg.
Maximum	-49.6	-179.6	-91.6	-106.5
Minimum	-19.6	-110.9	-58.4	-60.5
Average of January	-30.4	-149.6	-69.7	-70.9
Average of February	-39.3	-160.6	-76.0	-81.2

Table 30 Reduction of latent heat flux: cool roof minus control scenario

Parameters	Latent Heat Flux (W/m^2)			
	06:00 LT	14:00 LT	18:00 LT	24-h avg.
Maximum	-4.6	-16.6	-6.4	-6.9
Minimum	-2.4	-10.6	-3.6	-3.9
Average of January	-3.2	-12.4	-4.4	-4.8
Average of February	-3.9	-14.0	-5.3	-5.7

Table 31 Reduction of wind speed: cool roof minus control scenario

Parameters	Wind Speed (ms^{-1})

	06:00 LT	14:00 LT	18:00 LT	24-h avg.
Maximum	-1.6	-2.8	-2.3	-2.5
Minimum	-0.7	-1.2	-1.0	-1.1
Average of January	-1.1	-1.9	-1.5	-1.6
Average of February	-1.2	-2.2	-2.0	-2.0

Table 32 Reduction of PBL height: cool roof minus control scenario

Parameters	**PBL Height (m)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-189.6	-710.8	-364.2	-372.6
Minimum	-134.6	-532.6	-225.6	-220.1
Average of January	-156.6	-571.9	-265.1	-270.6
Average of February	-167.9	-610.3	-281.5	-287.0

9. Appendix: Building characteristics_ Cool roofs project simulations inputs _ Climate zone 5

The following **Table 33** to **Table 36** have presented the general building parameters, internal gains, and ventilation; operation schedules; ventilation, HVAC, and setpoints parameters and building envelope parameters employed in the simulations in **Chapter 3**.

Table 33 General building parameters, internal gains, and ventilation.

		Office			Shopping mall		School	Standalone House		Apartment
Building ID		**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type		Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Floor area (m2)		1200			1100		1100	242		624
Aspect ratio		1:1			2:1		2:1	1:2		1:4.3
Window to Wall Ratio (WWR)		0.6			0.3		0.32	0.14	0.15	0.24
Year Built		1990		2018	1990	2018	1990	1990	2018	1990
Number of stories *__Low rise (L), mid-rise (M), high-rise (H)__*		2 (L)			2 (L)	2 (L)	3	1		3 (L)
		-			4 (M)	-				5 (M)
		10 (H)			6 (H)	4 (H)				8 (H)
Building height (m) *__Low rise (L), mid-rise (M), high-rise (H)__*		7.2 (L)			13.8 (L)	13.8 (L)	12.6	2.8		8.4 (L)
					27.6 (M)					14 (M)
		36 (H)			41.4 (H)	41.4 (H)				22.4 (H)
Lighting power density (W/m^2) **(before operation profile and radiant fraction)**		4.5			14		4.5	4.5		
Lighting internal gains (W/m^2) *__(radiant fraction 0.42)__*	Hourly Max	2.61			8.12		2.76	2.5		
	Hourly Mean	1.45			4.77		1.13	0.6		
	Hourly Min	0.39			0.81		0.15	0		
Equipment gains *__(before operation profile)__*		11			5		5	6.88		
Equipment internal gains (W/m^2)	Hourly Max	11			3.5		4.75	6.88		
	Hourly Mean	6.16			2.31		1.86	1.1		
	Hourly Min	2.75			0.5		0.25	0.6		
Occupancy density (person/m2)		0.1			0.2		0.5	0.02	0.025	0.04

Continues

Table 34 Operation schedules

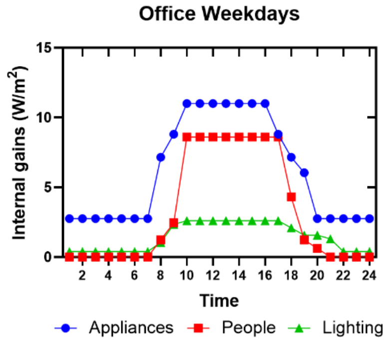
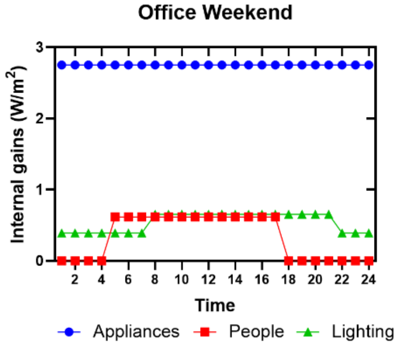
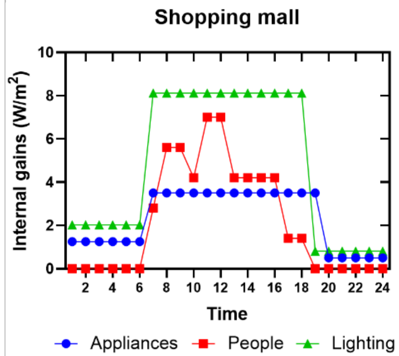
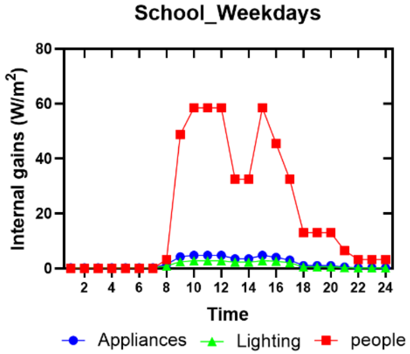
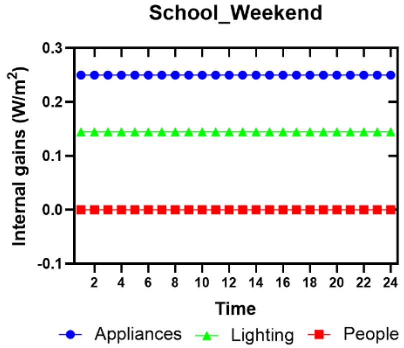
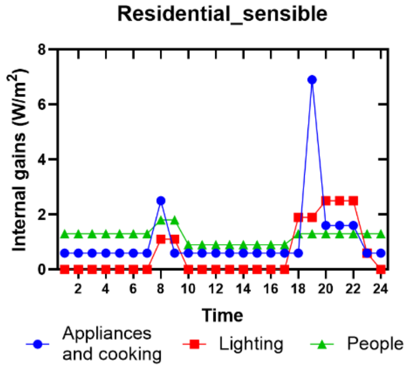
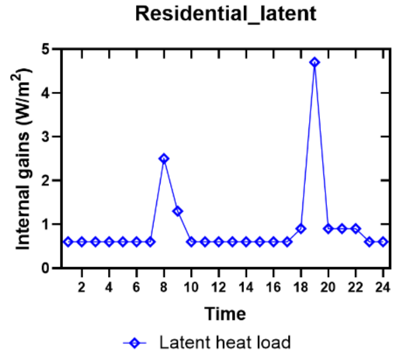
	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Intensity of internal heat gains (W/m²) **(from NatHERS and NCC 2019)**	  			 		  	  		

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Table 35 Ventilation, HVAC, and setpoints parameters

	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Ventilation op. hours (l/s. p)	7.5 (same for all buildings)								
Infiltration (op. hours) (ac/h)	1 (same for all buildings)								
Infiltration (non-op. hours) (ac/h)	1.5								
HVAC system type	VAV, AHU, Central plant			Heat pump air-cooled reverse cycle PAC		Non-ducted reverse cycle split units	Split-system central AC		Split-system central AC
HVAC cooling COP	1								
HVAC heating COP	1								
HVAC fan efficiency	1								
Heating setpoint (°C)	20 (same for all buildings)								
Heating setback (°C)	NA (system off out of working ours for commercial buildings, following NCC)								
Cooling setpoint (°C)	25 (same for all buildings)								
Cooling setback (°C)	NA (system off out of working ours for commercial buildings, following NCC)								

Continues

In the study by Delta Q (the one provided by Kavya for the archetypes) they used 22.5 °C setpoint, which is considering the current worst practice used in the industry, as pointed out by AIRAH (https://www.airah.org.au/Content_Files/HVACRNation/2015/08-15-HVACR-003.pdf).

Table 36 Building envelope parameters

	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Roof R-value (m2·K/W)	0	3.7 in climate zone 5 and 3.2 in climate zone 6	0.5	3.7 in climate zone 5 and 3.2 in climate zone 6	0.5	3.7 in climate zone 5 and 3.2 in climate zone 6	2	4.1 in climate zone 5 and 4.6 in climate zone 6	3.7 in climate zone 5 and 3.2 in climate zone 6
Roof solar reflectance	0.15_CTRL								
	0.80_COOL								
Roof thermal emittance	0.85								
Wall R-value (m2·K/W)	0	1	1	1		1	2.8		1
Wall solar reflectance	0.15								
Wall thermal emittance	0.85								
Window U-value (W/m²K)	2.4			4.2		2.4	5.6	2.5	5.6
Window SHGC (summer)	0.25 (same for all buildings)								
Window SHGC (winter)	0.70 (same for all buildings)								

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