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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 6 – Brisbane: 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 Brisbane, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Brisbane, 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 Brisbane.
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 investigate the impact of cool roofs on energy efficiency ratio (EER) of air-conditioning (AC) systems and the corresponding cooling load savings.
6) 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 Brisbane 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 at the city scale. 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 31 weather stations in Brisbane 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 31 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 thirty-one weather stations across Brisbane. 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 Brisbane 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 Brisbane, 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: Analysis of the impact of cool roofs on EER of AC systems and the corresponding cooling load savings. The hourly cooling load savings by lower heat gains by application of cool roofs in seventeen types of buildings was computed for the hottest and coldest weather stations in Brisbane. The median ratio of hourly cooling loads for cool roof with modified urban temperature scenario (scenario 2) to reference scenario and its correlation with ambient air temperature for each day was then computed to gain a better understanding of the cooling load reduction potential of cool roofs in different days with different ambient temperatures. Next, the EER (t) for the reference and cool roof with modified urban temperature scenario (scenario 2) was computed using the hourly ambient temperatures for six different AC residential and commercial systems, including split and VAV systems. Then, the two-month cooling loads' savings by application of cool roofs in individual buildings (scenario 1) and cool roof with modified urban temperature scenario (scenario 2) was compared with the corresponding two-month cooling load savings by modified EER for different AC systems for all building types.

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 Amberley and Redland 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 Brisbane.

Collectively, the following conclusions have been drawn:

1) The use of a cool roof at the city scale reduces the maximum peak ambient temperature by 2.5ºC over CBD and eastern Brisbane compared to the existing conditions, reference case.
2) The maximum decrease in the sensible heat flux is 175.0 W/m^2 over the urban domain (Hamilton, Doboy, Morningside and the Central), and the average decrease is 160.0 W/m^2 at 14:00 LT over the central part of the city.
3) Alteration of the urban albedo in Brisbane results in a solemn average reduction up to 735.6 m of the PBL heights over the city and may increase the concentration of pollutants at ground level.
4) On 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 45%-74% of the ambient temperatures in all stations concentrate in the range of 18-25 °C.
5) Cooling degree hours indicating the climatic severity during the summer period range from 956.6 to 4167.1, and about 40% of the data is concentrated in 1800 - 2000. CDH gradually increases from the east of the city to the west.
6) When cool roofs are used in the city, the percentage of CDH reduction due to the implementation of the cool roof ranges from 16% to 62%, with an average value of 34.6%. The percentage of CDH reduction in the original control volume is relatively large in the east of the city and gradually decreases toward the west.
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 11.3-15.6 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 18.7-21.3 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 7.3-9.2 kWh/m^2 in a typical new low-rise office building.
10) In new high-rise 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 1.2-1.6 kWh/m^2 and 0.2-0.3 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 0.4-0.5 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 6.7-9.1 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 34.7-52.7 kWh/m^2, while the corresponding heating penalty is just 0.5-0.9 kWh/m^2.
13) In all building types, the application of cool roofs has a noticeable impact on reduction of hourly cooling loads/peak electricity load. For instance, application of cool roofs is estimated to reduce the cooling load peak

of a low-rise office building without roof insulation-existing building by 36% and 35% in Redland and Amberley stations, 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 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 9.0-10.3 ºC and 3.1-4.0 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 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 9.6-11.1 ºC and 3.8-4.8 ºC, respectively.
16) 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 649-664 hours to 591-629 hours and 558-592 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), 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 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 1.7-2.1 ºC and 1.2-1.4 ºC, respectively.
18) 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 670-672 hours to 662-672 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
19) 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 9-10.3 oC in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 3.4-3.6 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 3.4 ºC occurs when the indoor air temperature is 29.3 ºC.
20) 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 18-29 hours to 26-31 hours in a typical existing low-rise office building with roof insulation.

21) The application of cool roofs in both individual buildings and at the whole urban area is predicted to improve the hourly EER of the six selected AC systems by 0.11-0.31 and 0.12-0.35 in Redland and Amberley stations, respectively.

22) In high-rise buildings with high level of insulation, the cooling load savings by modified EER is significant. For instance, the two-months cooling load savings by modified EER is estimated to range between 1.7 and 3.2 kWh/m^2 for a new high-rise office building with roof insulation-new building in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 0.3 and 1.5 kWh/m^2, respectively.

23) In low-rise buildings with low level of insulation, the cooling load savings by modified EER is noticeable. For instance, the cooling load savings by modified EER is estimated to range between 1.9 and 3.7 kWh/m^2 for an existing office building without roof insulation in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 14.7 and 16.0 kWh/m^2, respectively.

24) In commercial buildings, the cooling load savings by modified EER is quite significant. For instance, the cooling load savings by modified EER is estimated to range between 5.3 and 10.5 kWh/m^2 for a new high-rise shopping mall centre in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 0.6 and 3.2 kWh/m^2, respectively.

25) 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.

26) 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, B01, B13 and B15), the Life Cycle Cost can be reduced by as much as 59%. In such favourable cases, the Payback Period can be as low as 2.0 years.

27) Even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B03 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.

28) Considering the NPV and IRR results, when the differences between the savings are low, there are some differentiations, 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 Brisbane, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Brisbane, 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 Brisbane.
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 investigate the impact of cool roofs on EER of AC systems and the corresponding cooling load savings.
6) 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 Brisbane using the 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 31 weather stations in Brisbane 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 31 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 31 weather stations across Brisbane. 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 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 Brisbane 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 Brisbane, 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 8: Analysis of the impact of cool roofs on EER of AC systems and the corresponding cooling load savings. The hourly cooling load savings by lower heat gains by application of cool roofs in seventeen types of buildings was computed for the hottest and coldest weather stations in Brisbane. The median ratio of hourly cooling loads for cool roof with modified urban temperature scenario (scenario 2) to reference scenario and its correlation with ambient air temperature for each day was then computed to gain a better understanding of the cooling load reduction potential of cool roofs in different days with different ambient temperatures. Next, the EER (t) for the reference and cool roof with modified urban temperature scenario (scenario 2) was computed using the hourly ambient temperatures for six different AC residential and commercial systems, including split and VAV systems. Then, the two-month cooling loads' savings by application of cool roofs in individual buildings (scenario 1) and cool roof with modified urban temperature scenario (scenario 2) was compared with the corresponding two-month cooling load savings by modified EER for different AC systems for all building types.

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 Amberley and Redland weather conditions.

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 Brisbane.

1. Report of mesoscale simulations _ Simulation of the reference case and cool roof scenarios

1.1 Introduction

Urbanization augments the risks associated with extreme events. Urbanization suppresses evaporative cooling from the urban surface and amplifies heatwave intensity with a strong influence on minimum near-surface temperatures. Heat waves are documented as a sober threat to human health worldwide, with urban areas being more vulnerable 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. The higher magnitude of urban temperatures (and for longer periods) is considerably affecting citizens' quality of life and outdoor activities. 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 performance of cool roof strategies at the city scale during an extreme heat condition.

1.2 Objectives of the study

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

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

1.3 Domain and method of simulation

We use a full mesoscale climatic model for the entire city of Brisbane using the 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 **(Figure 1)**. The developed mesoscale model is used to calculate the hourly distribution of the main climatic parameters in Brisbane 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 the cool roof scenario and its cooling potential. One mitigation scenario is evaluated in this report. The mitigation strategy is examined in this study at a city scale.

Table 1 WRF/SLUCM Model configuration

Configuration	Domain 01 (d_1)	Domain 02 (d_2)	Domain 03 (d_3)
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)		

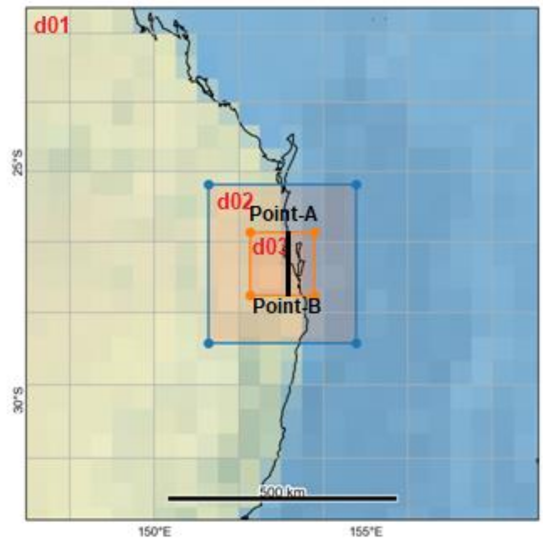


Figure 1 WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500m grid spacing, domain 2 (d02) with 1500m grid spacing and, an innermost domain 3 (d03) with 500m grid spacing; (b)

innermost d03 with 500m grid spacing which encompasses the Greater Brisbane. 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 the cool roof for Brisbane

Scenarios	**Albedo**			**Emissivity**		
	Roof	Wall	Ground	Roof	Wall	Ground
Reference	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=0.902; mean bias=0.96) for Archerfield, Brisbane, Brisbane Airport and Cape Moreton. 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 0.6°C to 1.4°C and 0.8°C to 2.7°C, respectively. The range of IOA was 0.8 to 0.9, with average values of 0.96 when considering all observation stations. The model slightly overestimated the daily average 2m 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 >19°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.

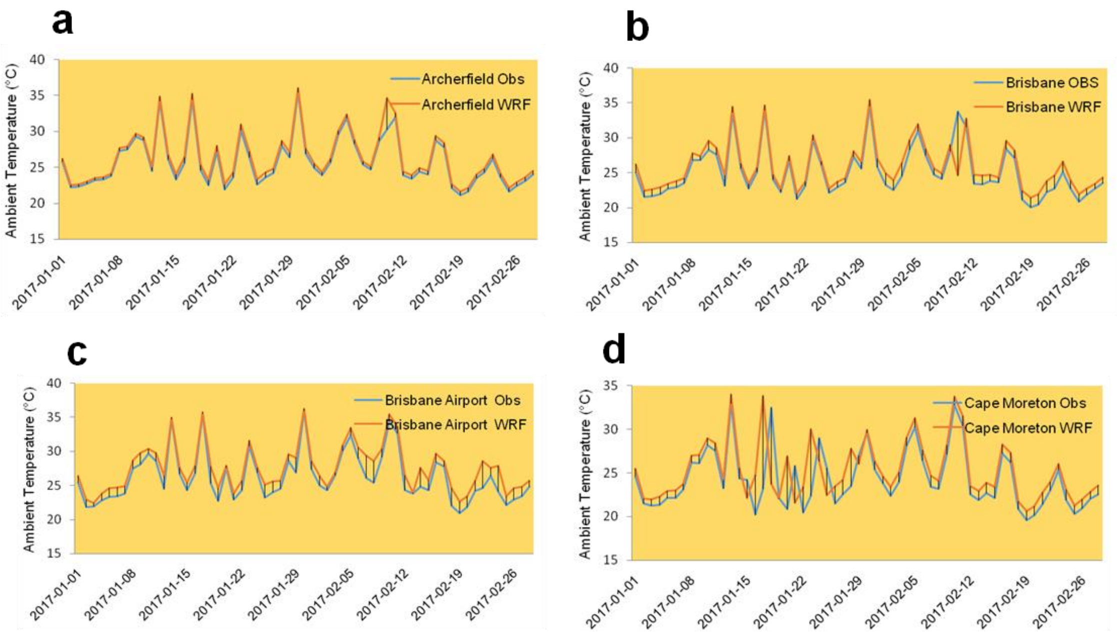


Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Archerfield, (b) Brisbane, (c) Brisbane Airport, and (d) CapeMoreton.

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

Parameters	**Local weather stations**			
	Archerfield	Brisbane	Brisbane Airport	Cape Moreton
Correlation coefficient	0.989	0.922	0.973	0.721
Mean Bias error	-0.63	-0.84	-1.4	-1.0
Mean absolute error	-0.625	-0.825	-1.367	-1.021
Root mean square error	0.809	1.584	1.596	2.667
Index of Agreement	0.986	0.945	0.949	0.829

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 Brisbane 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 Greater Brisbane. Temperatures in Greater Brisbane were very warm overall in 2017, with Brisbane's mean temperature the warmest 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 25.2 °C and 41.4 °C. At 06:00 LT, it varies between 20.7°C and 28.2°C. The results show that the use of cool roof materials maximum reduces the peak ambient temperature ($T_{ambient}$) by 2.5ºC over high-density residential areas and 1.8°C for whole urban average compared to the control case. The average ambient temperature reduction at 14:00 over the whole summer is 1.1°C. The maximum decrease of the ambient temperature during 18:00 LT is 1.3°C near the coastal fringe (Manly Hamilton and Wynnum) and the average decrease of summer months is 0.9°C (**Figure 3**).

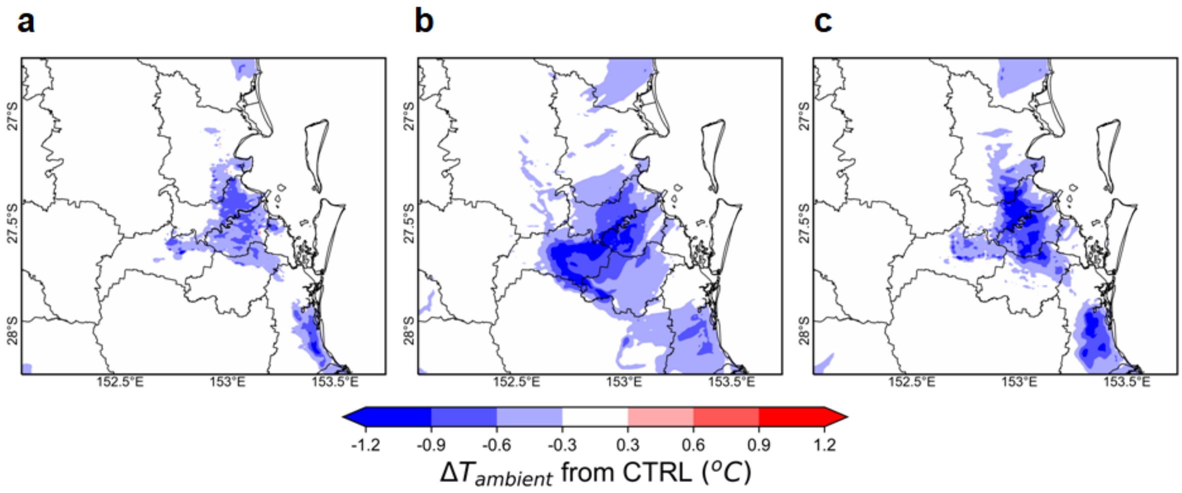


Figure 3 Reduction of ambient temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.2 Surface temperatures

Under the cool roof scenario, the surface temperature ($T_{surface}$) ranges between 27.2°C to 46.8°C at 14:00, 22.7°C to 38.4°C at 18:00 LT and 21.5°C to 33.2°C at 6:00 LT over the city. The maximum decrease of surface temperature during 14:00 LT is 6.1°C over the urban surface, with an average reduction of the whole summer is about 5.6 over the urban domain. But, in the high-density residential urban area, the maximum decrease of surface temperature is about 6.8°C during 14:00 LT of summer months. The maximum surface temperature reduction at 18:00 LT is about 5.0°C near the coastal fringe areas of the city. The average decrease of urban surface temperature is 4.5°C at 18:00 LT, and 1.9°C at 06:00 LT compare to the control case for the whole summer month in the city (**Figure 4**).

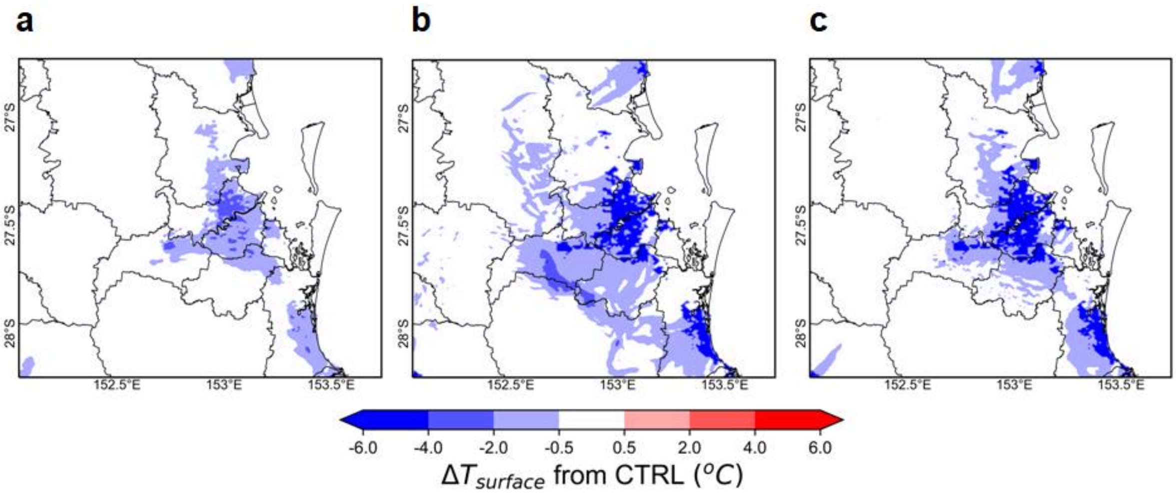


Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

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 the city during 14:00 LT is 474.6 W/m^2 and 412.4 Wm-2. At 18:00LT, the average sensible heat flux is 108.7 W/m^2. The maximum decrease in the sensible heat flux is 175.0 Wm-2over urban domain (Hamilton, Doboy, Morningside and the Central), and the average decrease is 160.0 W/m^2 at 14:00 LT over the central part of the city. In the high density residential urban area, the maximum and average reduction of sensible heat flux are about 184.6 W/m^2 and 169.2 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 69.9 Wm-2and 63.8 Wm-2over the urban domain **(Figure 5)**.

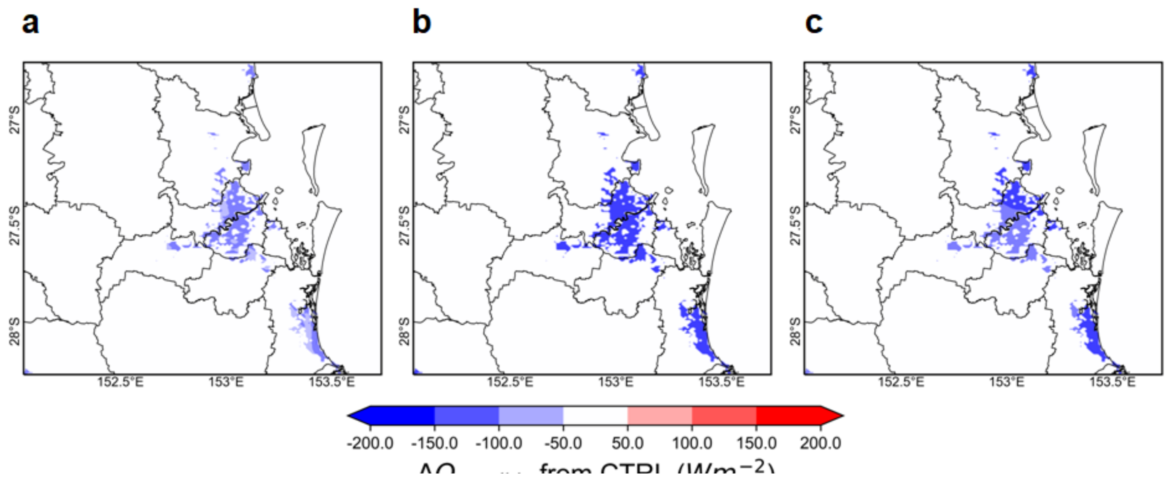


Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

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 26.5 W/m^2 and 22.3Wm-2. At 18:00 LT and 06:00 LT, the average sensible heat flux is 7.8 W/m^2 and 4.9 Wm-2.The maximum decrease the latent heat flux is 15.5 W/m^2 and average decrease is 13.1Wm-2at 14:00 LTnear central and eastern part (Hamilton, Doboy, and Morningside) of the city. But, in the high density residential urban area, the average decrease of latent heat flux is about 15.3 during 14:00LT of summer months. At 18:00 LT, the maximum and average reduction of summer month of latent heat flux is 5.6 Wm-2and 4.3 W/m^2 over eastern Brisbane. At, 06:00 LT, the maximum reduction of latent heat flux is 4.0 Wm-2and average reduction is 3.1Wm-2over urban domain **(Figure 6)**.

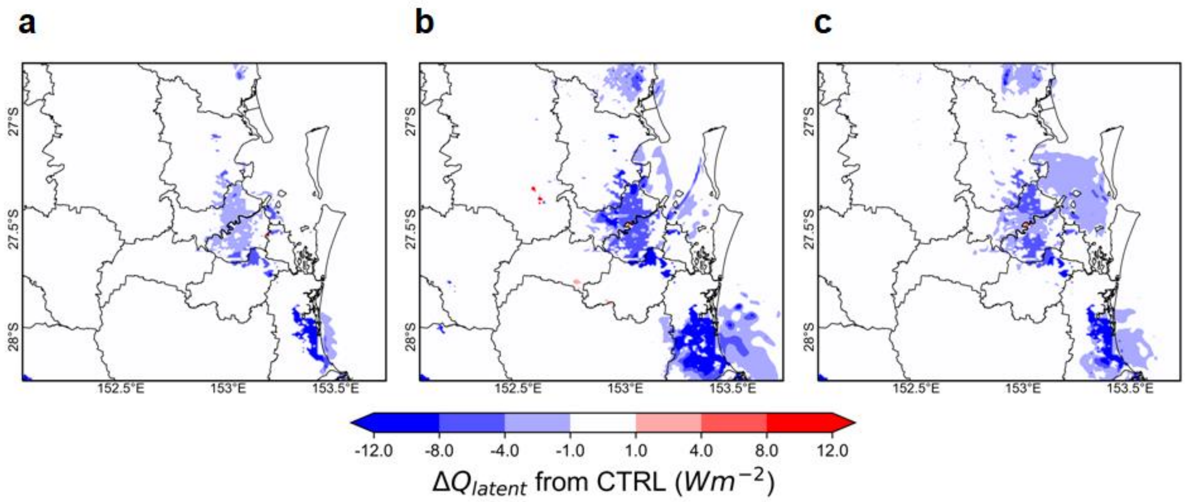


Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.5 Wind

Under the base case simulation, the maximum wind speeds of urban average (W_{speed}) are 3.9 ms-1, 6.7 ms-1 and 6.2 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 the control case is 1.1 ms-1, 2.4 ms-1 and 1.8 ms-1 at 06:00 LT, 14:00 LT and 18:00 LT respectively over inner west (The Gabba and Walter Taylor) south-west (Moorooka, and Tennyson) and near central (high density) part of the city. The average decrease of wind speed of whole summer months is 1.0 ms-1 at 14:00 LT, 0.6 ms-1 at 06:00 LT and 0.7 ms-1 at 18:00 LT over the city **Figure 7.**

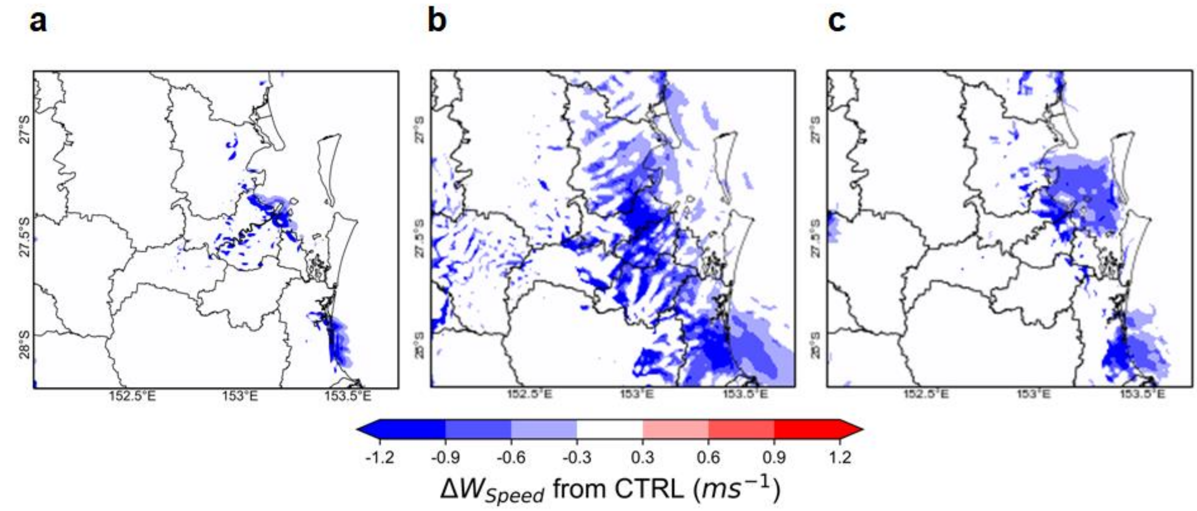


Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

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, 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 145.2 m (over some part of Northgate and Hamilton), 695.5 m (over the Central, The Gobba area, Coorparoo, some part of Holland Park and Moorooka), and 251.1m (near Moorooka, Doboyarea, and some parts of central of the city), for 6:00LT, 14:00LT, 18:00LT, respectively with average value is about 128.3m, 618.0m and 211.3m. The minimum reduction of PBL is 110.2m, 500.6m, and 189.5 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 Brisbane 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.

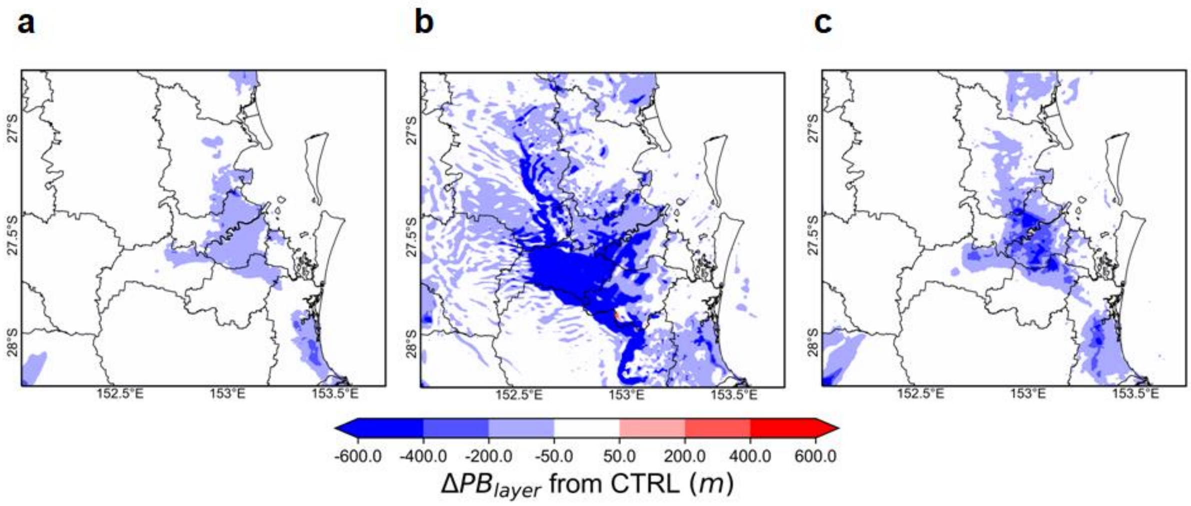


Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.6 Regional impact on sea breeze circulations

The intensification 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 Brisbane is linked closely with the advection of the sea breeze. The circulation can be modified when the cool roof is implemented at the city scale **(Figure 9)**. The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Brisbane. 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, the cool roof for cities has 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 the sea breeze front developed is more prone to the accumulation of secondary pollutants in the back of the front.

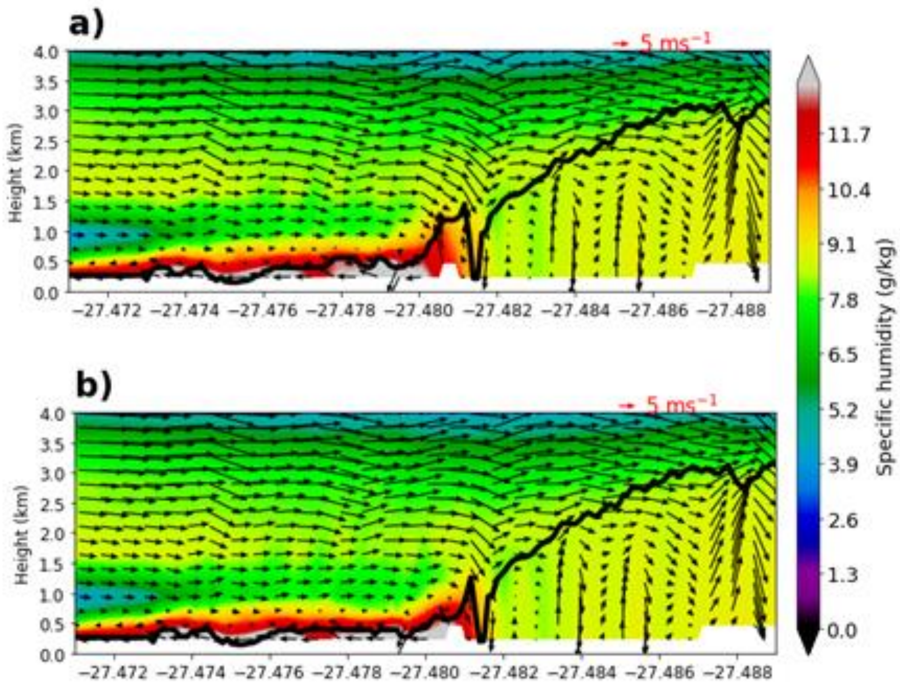


Figure 9 Cross-sectional profile of heat mitigations impacts on sea breeze during peak hour (14:00 LT) over Brisbane (a) control case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere.

The report also shows the implementation of the cool roof over the city scale can affect the pressure gradient between the city and surrounding surface due to a significant drop in ambient temperature up to 2.5°C and wind speed decrease up to 2.5 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 airflow from the adjacent desert towards western Brisbane 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.

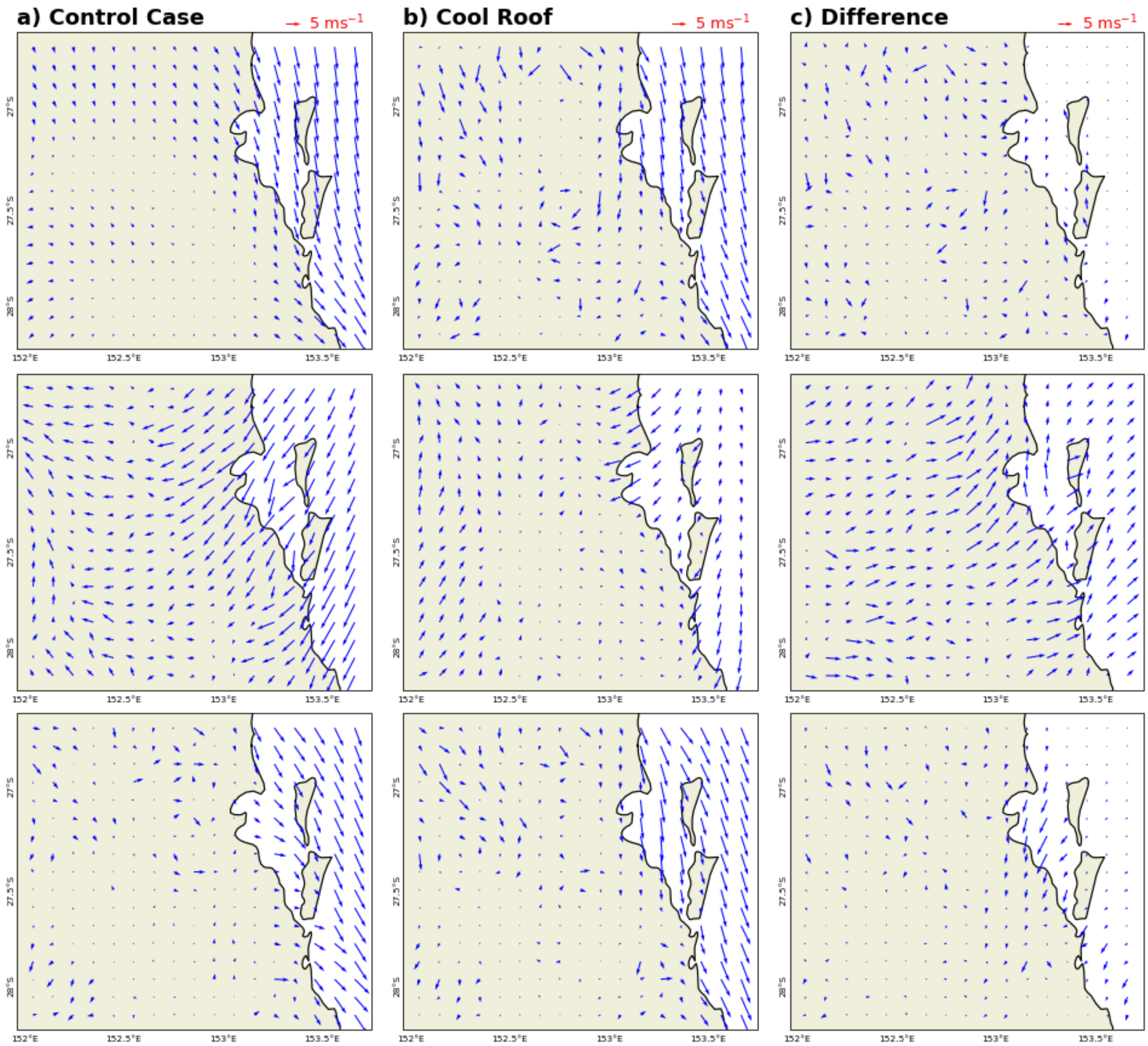


Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) reference case (b) cool roof (c) reference minus scenarios: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain 03.

1.7 Impact of cool materials on the urban thermal gradient

The impact of cool materials on the open-air surface and ambient temperature, which is associated with urban heating and thermal flow condition, has been well reported **(Figure 11)**. Under the low wind speed, an additional thermal gradient was observed over Brisbane city. The thermal wind describes the vertical change in the geostrophic wind in a baroclinic atmosphere at a synoptic scale. But, under the low inflow circumstance, the wind velocity was simply prejudiced by the geometry of buildings, thermal difference, and buoyancy flow. After heating the rooftop and pavements, the wind velocity increased while turbulent concentration decreased due small scale thermal gradient. This strength could make pollutant transporting more rapidly but withdraw pollutants from mixing. The situations also occur over some parts of Brisbane city (Marchant, Central, The Gabba, Paddington, Walter Taylor, Coorparoo, Holland Park, Tennyson, Jamboree, and Moorooka) when the wind speed is low and the ambient and surface temperature is very high. Under these conditions, there is a substantial temperature difference between the cool roofs and the warm pavements that generate some small local thermal winds at the neighbourhood scale. It is assumed this could designate the influence of solar radiation alteration by cool materials on wind flow, and thus when the wind velocity is small; the effect of the roof and surface material is noticeably shown in the thermal wind environment at the vicinity of the roof surface to warm pavements with an increase of the wind velocity and decrease of the turbulent energy.

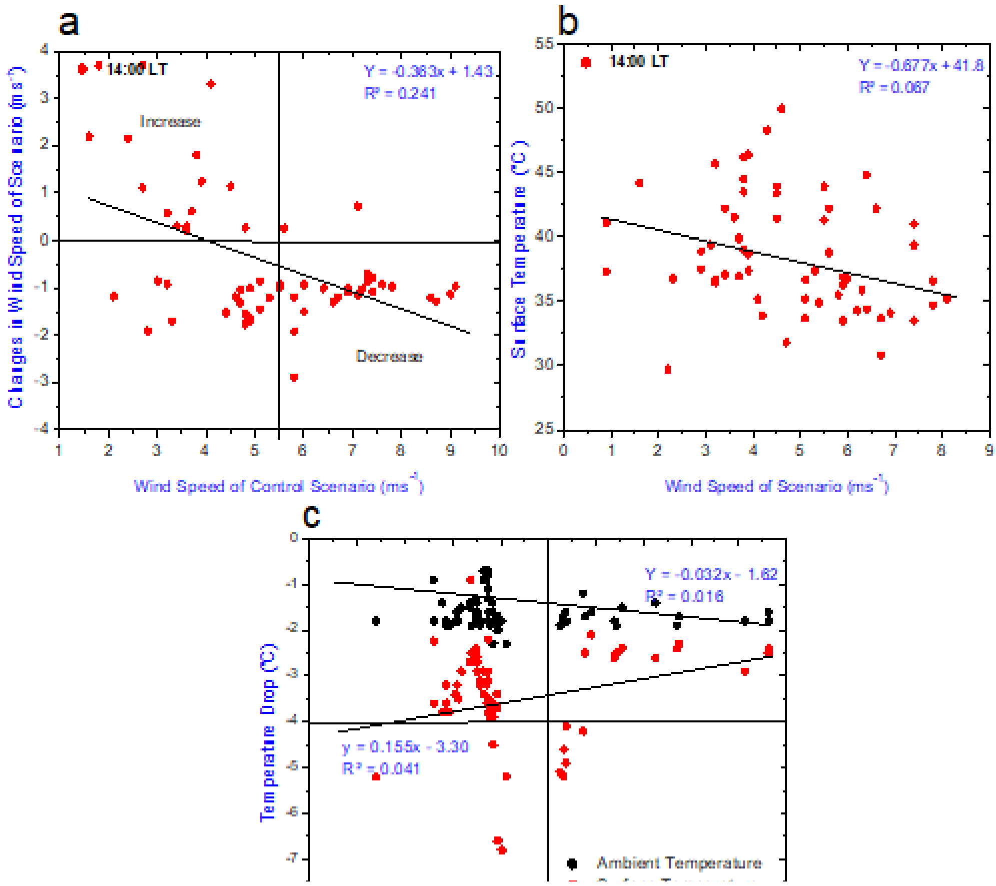


Figure 11 (a) Variability of the average wind speed in the simulated area as a function of the average control wind speeds for the albedo scenario at 14:00 LT, (b) Association of the wind speed and surface temperature at peak hour (14:00 LT), and (c) Association

1.8 Main conclusions

- It is found that a strong urban heat island (UHI) phenomenon is developed. The maximum magnitude of the phenomena may exceed 5°C. The UHI effect would be added evenhandedly balanced spatially under the urban expansion. The intensity and the characteristics of the phenomena are strongly influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the desert area. The possible existence of an additional heating mechanism, like the advection of warm air from nearby spaces, may intensify the strength of the problem.
- High-density parts of the city exhibit a much higher temperature drop than the urban average. An increase of albedo in Brisbane can decrease the peak summer ambient temperature up to 2.5°C and surface temperature up to 6.8°C. It was found that important temperature differences exist near the coast and central part of the city. The patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the magnitude of the surface thermal gradient.
- The maximum decrease of sensible heat and latent heat flux was up to 184.6 W/m^2 and 17.4 Wm-2, respectively.

- The maximum decrease of wind speeds is up to 2.5 ms-1. Cool roofs increase the pressure at the local scale and decrease the wind advection from the bare surface.
- The results of numerical experiments 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 heatwave scenarios. Under the low wind speed, an additional thermal gradient was observed over Brisbane city. When the wind speed is low, and the ambient and surface temperature is very high. Under these conditions, there is a substantial temperature difference between the cool roofs and the warm pavements that generate some small local thermal winds at the neighbourhood scale.
- Alteration of the urban albedo in Brisbane results in a solemn average reduction up to 735.6 m of the PBL heights over the city and may increase the concentration of pollutants at ground level,
- The urban–sea temperature difference approaches to sea-breeze effects. The cool roof reduced daytime ambient temperatures, but higher winds over cool roof implemented city greatly reduced the sea breeze penetration.
- The magnitudes of the UHI phenomenon were associated with the existence of a sea breeze in the eastern parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that heat up the western zones of the city.

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 31 weather stations in Brisbane 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 31 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 Brisbane

Thirty-one stations in Brisbane, as shown in **Table 4** and **Figure 12,** have been simulated for two months: Jan and Feb, by Weather Research Forecasting Model.

Table 4 Latitude, longitude, and the climate zone of the 31 stations in Brisbane.

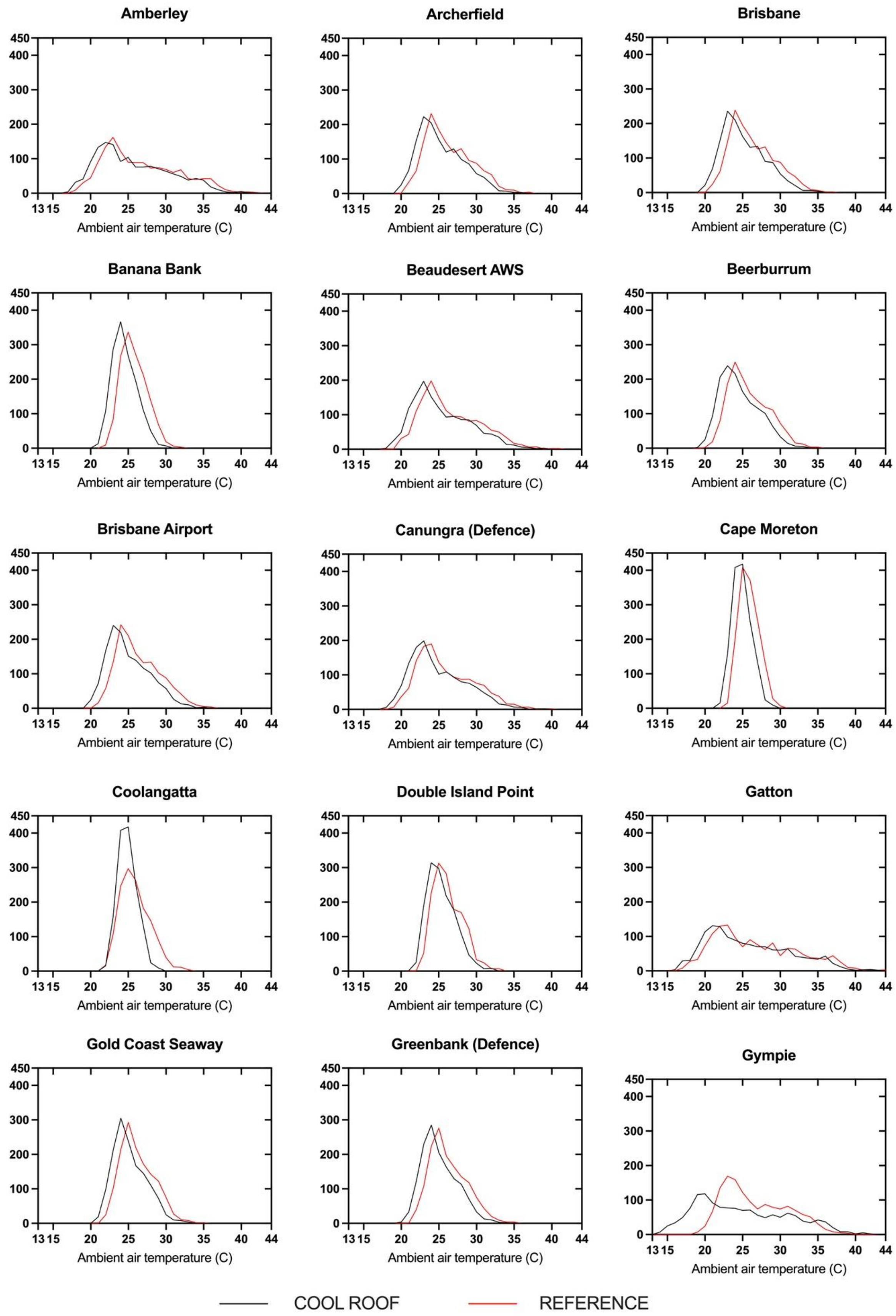
No.	Station name	Lat	Long	Climate zone
1	BRISBANE	-27.48	153.04	2
2	BRISBANE AERO	-27.39	153.13	2
3	AMBERLEY AMO	-27.63	152.71	2
4	ARCHERFIELD AIRPORT	-27.57	153.01	2
5	BANANA BANK NORTH BEACON	-27.53	153.33	2
6	BEERBURRUM FOREST STATION	-26.96	152.96	2
7	BEAUDESERT DRUMLEY STREET	-27.97	152.99	2
8	CANUNGRA (DEFENCE)	-28.04	153.19	2
9	CAPE MORETON LIGHTHOUSE	-27.03	153.47	2
10	COOLANGATTA	-28.17	153.51	2
11	DOUBLE ISLAND POINT LIGHTHOUSE	-25.93	153.19	2
12	UNIVERSITY OF QUEENSLAND GATTON	-27.54	152.34	2
13	GOLD COAST SEAWAY	-27.94	153.43	2
14	GREENBANK (DEFENCE)	-27.69	152.99	2
15	GYMPIE	-26.18	152.64	2
16	HOPE BANKS BEACON	-27.43	153.29	2
17	INNER RECIPROCAL MARKER	-27.26	153.24	2
18	KINGAROY AIRPORT	-26.57	151.84	5
19	LOGAN CITY WATER TREATMENT PLANT	-27.68	153.19	2
20	NAMBOUR DAFF - HILLSIDE	-26.64	152.94	2
21	NORTH WEST 10 BEACON	-27	153.24	2

22	OAKEY AERO	-27.4	151.74	5
23	RAINBOW BEACH	-25.9	153.09	2
24	REDCLIFFE	-27.22	153.09	2
25	REDLAND (ALEXANDRA HILLS)	-27.54	153.24	2
26	SUNSHINE COAST AIRPORT	-26.6	153.09	2
27	TEWANTIN RSL PARK	-26.39	153.04	2
28	TIN CAN BAY (DEFENCE)	-25.94	152.96	2
29	TOOWOOMBA AIRPORT	-27.54	151.91	5
30	WARWICK	-28.21	152.1	5
31	WELLCAMP AIRPORT	-27.55	151.78	5

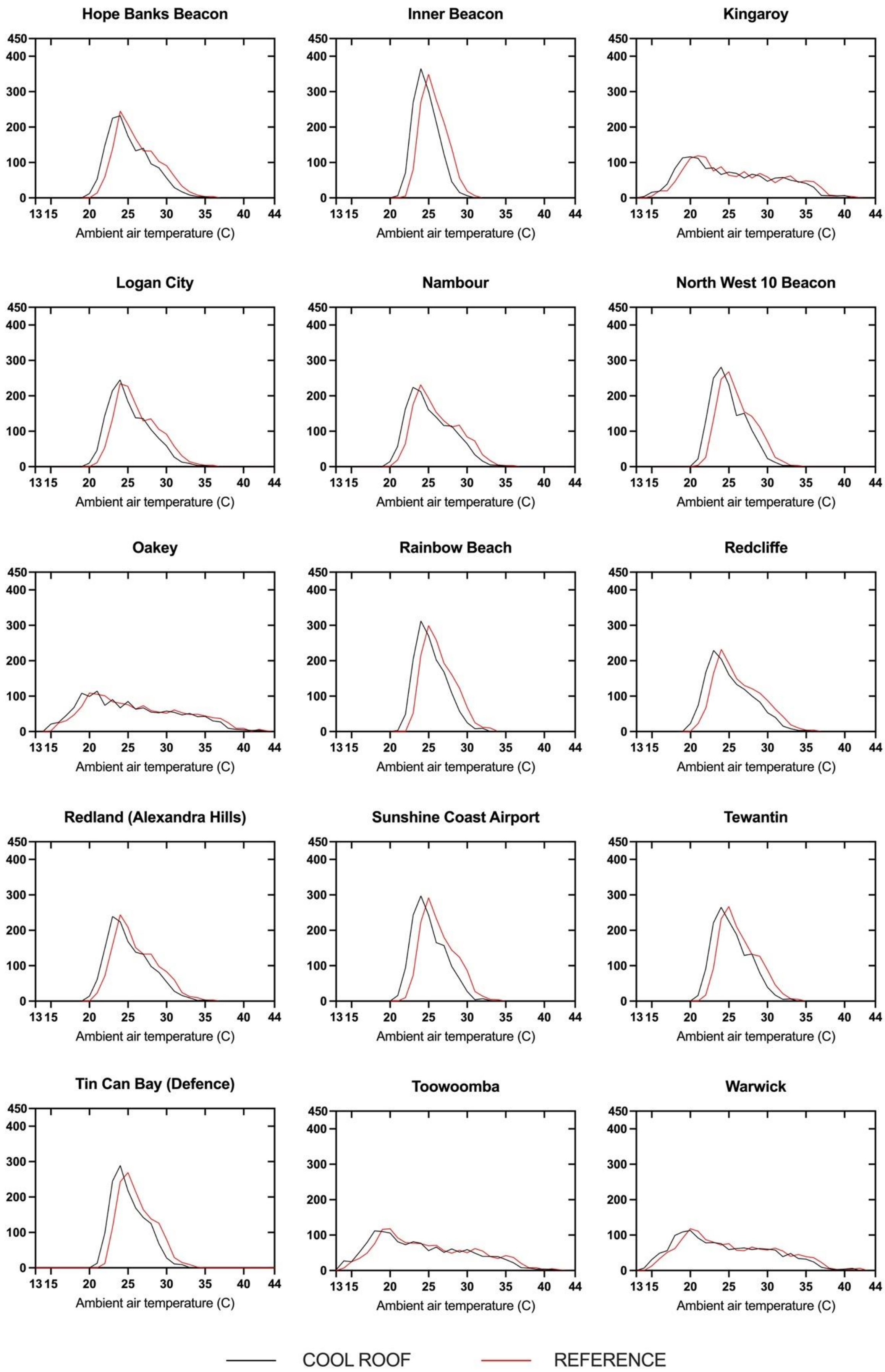
Figure 12 Location of the 31 weather stations in Brisbane.

2.2 Histogram of WRF simulated ambient temperature in Brisbane

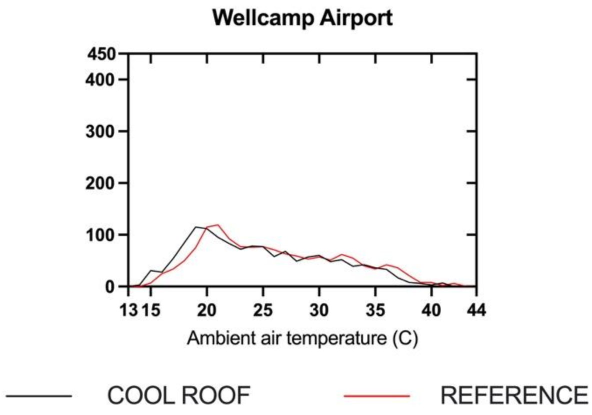
The entire 2-month hourly ambient temperature of 31 stations in Brisbane simulated by WRF has been divided into a series of data with consecutive and non-overlapping intervals of 1. The frequency distribution in **Figure 13** shows the quantity of ambient temperatures falling into each interval. The 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.


Amberley
Archerfield
Brisbane
Banana Bank
Beaudesert AWS
Beerburrum
Brisbane Airport
Canungra (Defence)
Cape Moreton
Coolangatta
Double Island Point
Gatton
Gold Coast Seaway
Greenbank (Defence)
Gympie
Ambient air temperature (C)
COOL ROOF
REFERENCE

(a)


Hope Banks Beacon
Inner Beacon
Kingaroy
Logan City
Nambour
North West 10 Beacon
Oakey
Rainbow Beach
Redcliffe
Redland (Alexandra Hills)
Sunshine Coast Airport
Tewantin
Tin Can Bay (Defence)
Toowoomba
Warwick
Ambient air temperature (C)
COOL ROOF
REFERENCE

(b)



(c)

Figure 13 Histogram of WRF simulated ambient temperature in 31 stations in Brisbane.

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 45%-74% of the ambient temperatures in all stations concentrate in the range of 18-25 °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	18	19	20	21	22	23	24	25	Percentage of data concentrated in 18-25 °C (%)
Amberley COOL ROOF					147				55
Amberley REFERENCE						162			48
Archerfield COOL ROOF						223			58
Archerfield REFERENCE							232		47
BRISBANE COOL ROOF						236			60
BRISBANE REFERENCE							239		47
Banana Bank COOL ROOF							367		74
Banana Bank REFERENCE								337	49
Beaudesert AWS COOL ROOF						197			58
Beaudesert AWS REFERENCE							198		49
Beerburrum COOL ROOF						239			67
Beerburrum REFERENCE							250		52
Brisbane Airport COOL ROOF						240			62
Brisbane Airport REFERENCE							242		47
Canungra (Defence) COOL ROOF						199			61
Canungra (Defence) REFERENCE							190		53
Cape Moreton COOL ROOF								418	70
Cape Moreton REFERENCE								409	44
Coolangatta COOL ROOF								418	70
Coolangatta REFERENCE								297	47
Double Island Point COOL ROOF							314		58
Double Island Point REFERENCE								313	42
Gatton COOL ROOF				131					52
Gatton REFERENCE						133			47

Gold Coast Seaway COOL ROOF							305		62
Gold Coast Seaway REFERENCE								293	45
Greenbank (Defence) COOL ROOF							285		62
Greenbank (Defence) REFERENCE								276	46
Gympie COOL ROOF			118						50
Gympie REFERENCE						169			48
Hope Banks Beacon COOL ROOF							232		60
Hope Banks Beacon REFERENCE							245		47
Inner Beacon COOL ROOF							365		72
Inner Beacon REFERENCE								349	50
Kingaroy COOL ROOF			116						52
Kingaroy REFERENCE				119					49
Logan City COOL ROOF							245		60
Logan City REFERENCE							234		46
Nambour COOL ROOF						224			59
Nambour REFERENCE							231		48
North West 10 Beacon COOL ROOF							281		65
North West 10 Beacon REFERENCE								268	48
Oakey COOL ROOF				114					50
Oakey REFERENCE			109						48
Rainbow Beach COOL ROOF							312		59
Rainbow Beach REFERENCE								299	40
Redcliffe COOL ROOF						229			61
Redcliffe REFERENCE							232		48
Redland (Alexandra Hills) COOL ROOF						239			60
Redland (Alexandra Hills) REFERENCE							244		50
Sunshine Coast Airport COOL ROOF							297		63
Sunshine Coast Airport REFERENCE								292	42

Tewantin COOL ROOF							265		58
Tewantin REFERENCE								267	43
Tin Can Bay (Defence) COOL ROOF							289		61
Tin Can Bay (Defence) REFERENCE								269	45
Toowoomba COOL ROOF	112								49
Toowoomba REFERENCE			118						50
Warwick COOL ROOF			113						50
Warwick REFERENCE			118						49
Wellcamp Airport COOL ROOF		115							51
Wellcamp Airport REFERENCE				119					48

2.3 Cooling Degree Hours (CDH) calculation

For all scenarios, Cooling Degree Hours (CDH) Base 26 °C, which measures how much (in degrees), and for how long (in hours), outside air temperature is higher than 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 control 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 31 weather stations are shown in **Table 6** and **Figure 14**. Compared with the control case, the largest percentage reduction (62%) is observed in BANANA BANK NORTH BEACON, and the smallest (16%) is found in OAKEY AERO, with an average reduction of 34.6%. The mean CDH values of the 31 weather stations for the control case cool roof case are 2363.7, 1653.7, respectively, with standard deviations of 932.7 and 934.3 sequentially, see **Table 7**.

Table 6 The CDH of control 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 31 weather stations in Brisbane.

Weather Station	CDH_CTRL	CDH_COOL ROOF	CDH_ Difference (CTRL-COOL ROOF)	Percentage of the reduction_% (CDH_Difference/CDH_CTRL)
BRISBANE	2243.8	1451.4	792.4	35
BRISBANE AERO	2225	1319.9	905.2	41
AMBERLEY AMO	3754.5	2988.1	766.4	20
ARCHERFIELD AIRPORT	2380	1641.2	738.8	31
BANANA BANK NORTH BEACON	1119.1	428.3	690.8	62
BEERBURRUM FOREST STATION	1736.4	1010.8	725.6	42
BEAUDESERT DRUMLEY STREET	2993.7	2223.4	770.3	26
CANUNGRA (DEFENCE)	2507.5	1831.1	676.4	27
CAPE MORETON LIGHTHOUSE	956.6	377.7	578.9	61
COOLANGATTA	1380.3	727.4	652.9	47

DOUBLE ISLAND POINT LIGHTHOUSE	1584.1	958.4	625.7	39
UNIVERSITY OF QUEENSLAND GATTON	4167.1	3446.5	720.7	17
GOLD COAST SEAWAY	1760.5	1038	722.5	41
GREENBANK (DEFENCE)	1872.7	1091.8	780.9	42
GYMPIE	3369.8	2665.4	704.4	21
HOPE BANKS BEACON	2146.8	1419.2	727.6	34
INNER RECIPROCAL MARKER	1052	460	592	56
KINGAROY AIRPORT	3821.1	3168.4	652.7	17
LOGAN CITY WATER TREATMENT PLANT	2131.8	1399.5	732.3	34
NAMBOUR DAFF - HILLSIDE	2135.2	1467.2	668	31
NORTH WEST 10 BEACON	1634.8	950.2	684.6	42
OAKEY AERO	4096.4	3431.3	665.1	16
RAINBOW BEACH	1764.7	998.3	766.4	43
REDCLIFFE	2207.1	1424.1	783	35
REDLAND (ALEXANDRA HILLS)	2016.8	1390.8	626	31
SUNSHINE COAST AIRPORT	1809.4	943.8	865.6	48
TEWANTIN RSL PARK	1962	1200.4	761.6	39
TIN CAN BAY (DEFENCE)	1773.6	1053.9	719.7	41
TOOWOOMBA AIRPORT	3280.2	2706.2	574	17

WARWICK	3462.7	2855.7	607	18
WELLCAMP AIRPORT	3927.6	3196	731.6	19

Table 7 Mean and SD of the CDH of the 31 weather stations in control cases and cool roof cases, respectively.

	Mean	**SD**	**Sample No.**
CDH_CTRL	2363.7	932.7	31
CDH_COOL ROOF	1653.7	934.3	31
CDH_DIFFERENCE (CTRL-COOL ROOF)	710.0	77.8	31
PERCENTAGE OF THE REDUCTION (%) (CDH_DIFFERENCE/CDH_CTRL)	34.6	12.9	31

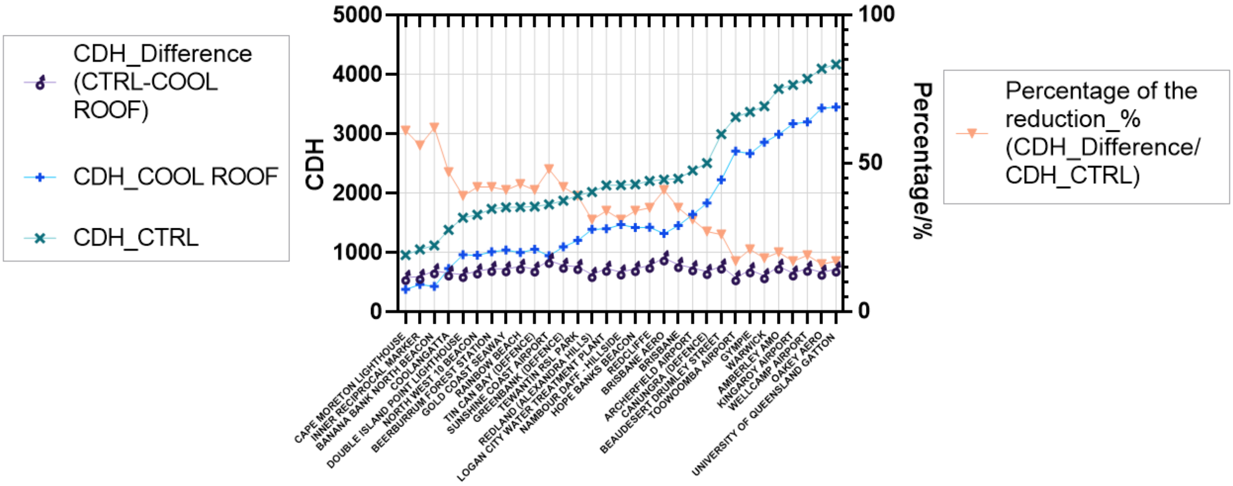


Figure 14 The CDH of control cases, cool roof applied cases, the difference between these two and the percentage of the CDH reduction due to the implementation of the cool roof in 31 weather stations in Brisbane.

2.3.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 31 weather stations in both the control cases and the cool roof cases is shown in **Figure 15**. In control cases, the CDH centred around 1800 and 2000 has the largest proportion: each accounting for 19.4 % of the total, while all the remaining intervals have proportions of less than 10%. In cool roof cases, the CDH centred around 1000 and 1400 has the two largest proportions of 25.8% and 22.6%, respectively. The data of all remaining intervals account for less than 10%.

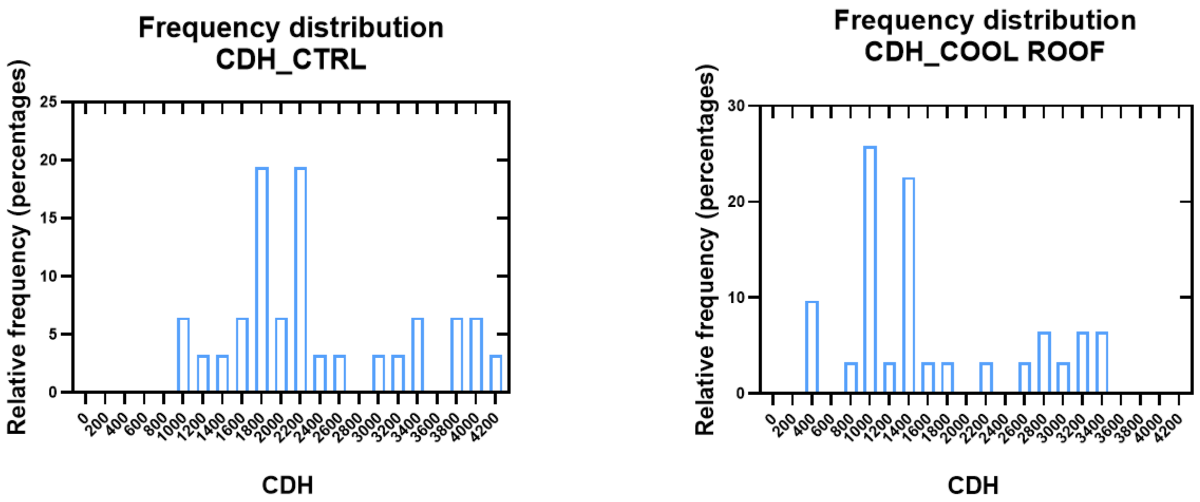


Figure 15 Frequency distribution of the CDH values for the 31 weather stations in control cases (a) and cool roof cases (b).

2.3.2 Spatial distribution of the results

- **CDH_Reference scenario: (Figure 16)**
  The highest CDH of 4167.1 is observed in University of Queensland Gatton, and Cape Moreton Lighthouse has the lowest number. CDH gradually increases from east to west.

- **CDH_Cool roof scenario**: **(Figure 17)**
  When applied with a cool roof, the decrease of CDH is observed at every station. The highest CDH of 3446.5 is still observed in University of Queensland Gatton, and Cape Moreton Lighthouse again has the lowest number **(Figure 16).** The spatial distribution pattern is very similar to that of the control cases: CDH increases from east to west.

- **CDH_Reference scenario – cool roof scenario: (Figure 18)**
  The maximum decrease occurs along the coastline (BRISBANE AERO:905.2) of the city. The smallest decrease is observed in the western part of the city (TOOWOOMBA AIRPORT: 574). The average decrease due to the implementation of a cool roof is 710.0 (**Table 7**) across the 31 stations.

- **CDH_(Reference scenario – cool roof scenario)/Reference scenario: (Figure 19)**
  The proportion of CDH reduction in the original control volume is relatively large in the east region of the city and gradually decreases toward the west, as shown in **Figure 19**.

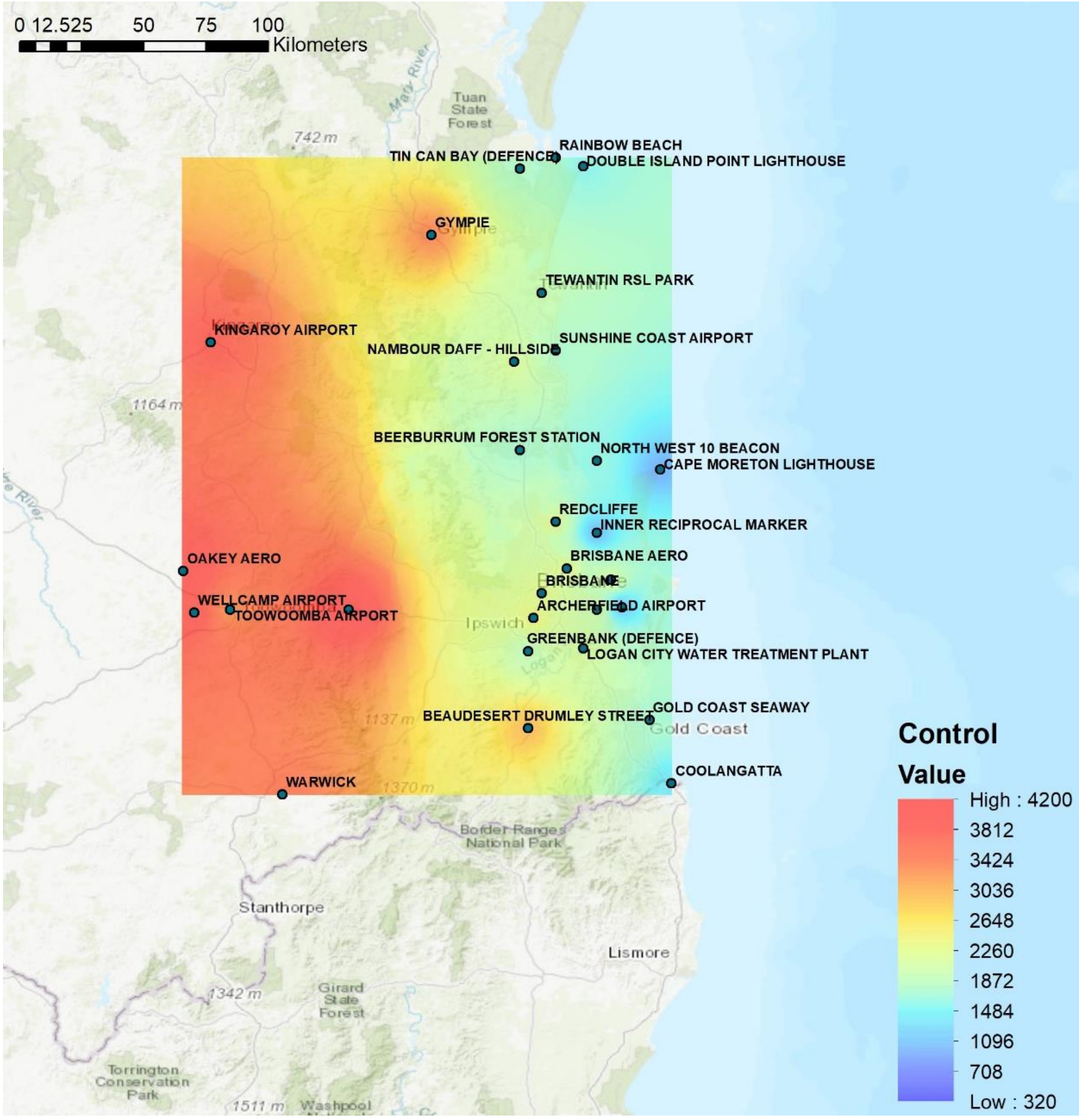


Figure 16 The sum of Cooling degree hours in Jan and Feb of the control cases in the 31 stations in Brisbane.

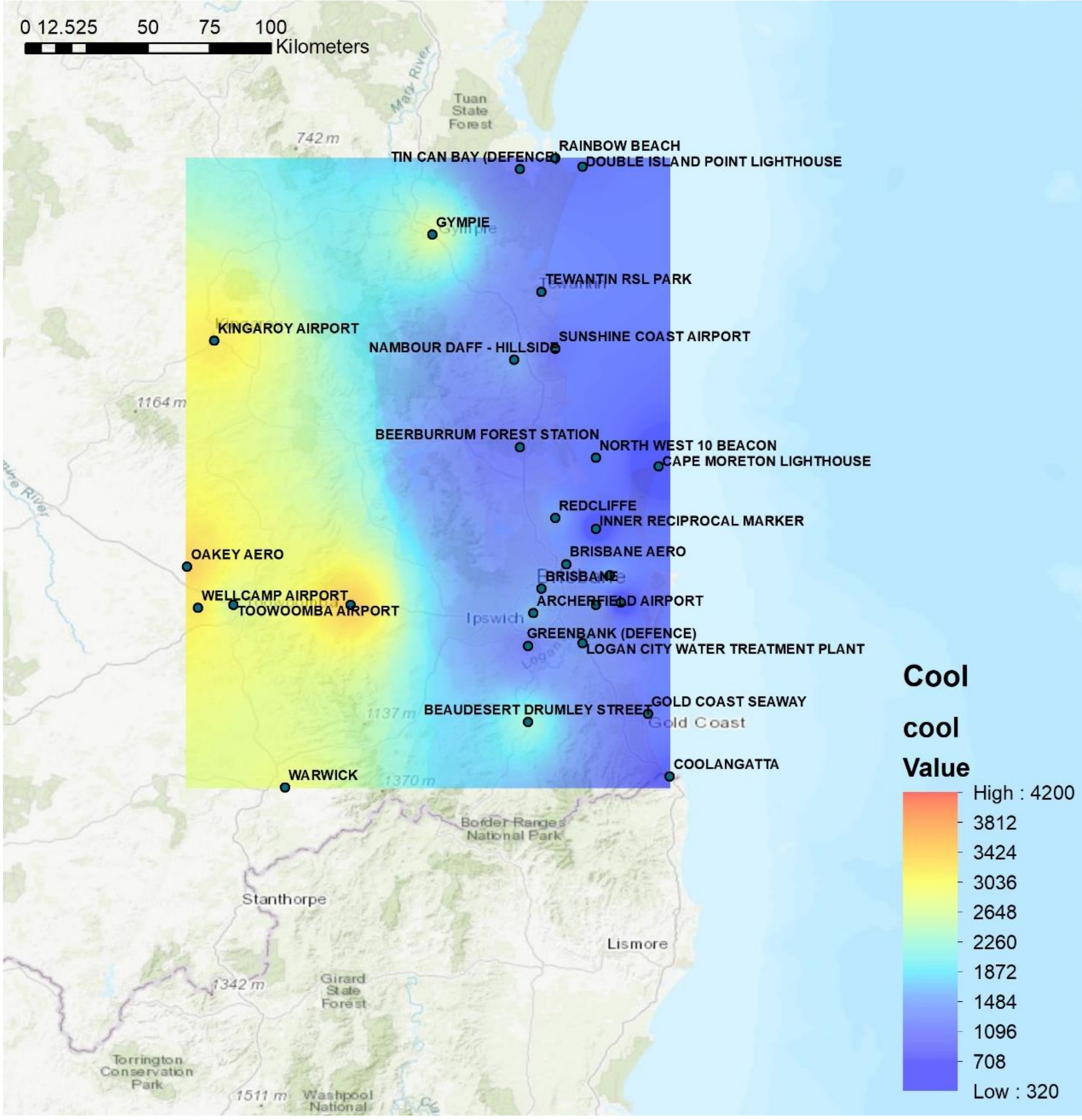


Figure 17 The sum of Cooling degree hours in Jan and Feb of the cool roof cases in the 31 stations in Brisbane.

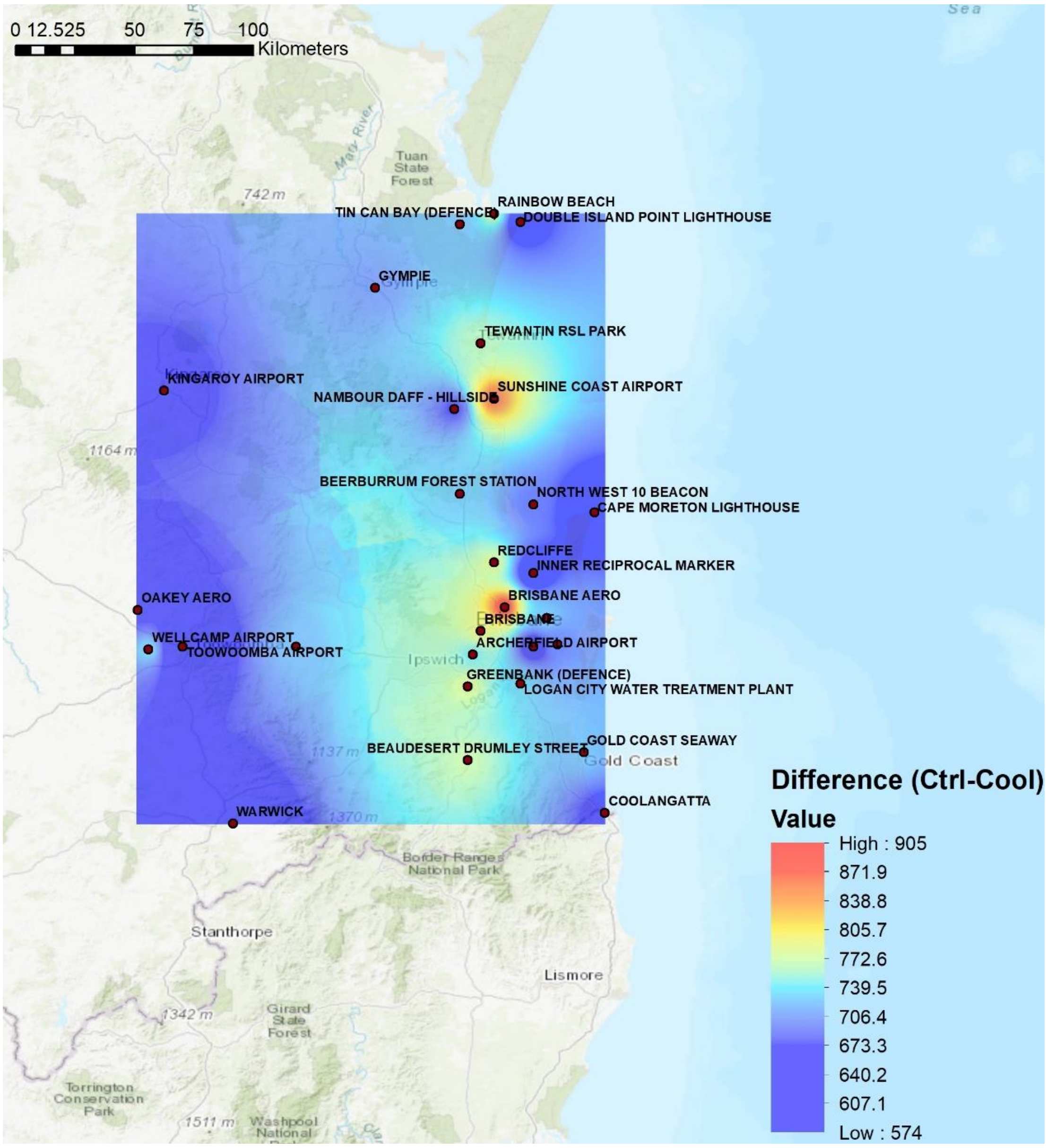


Figure 18 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and control ones in the 31 stations in Brisbane.

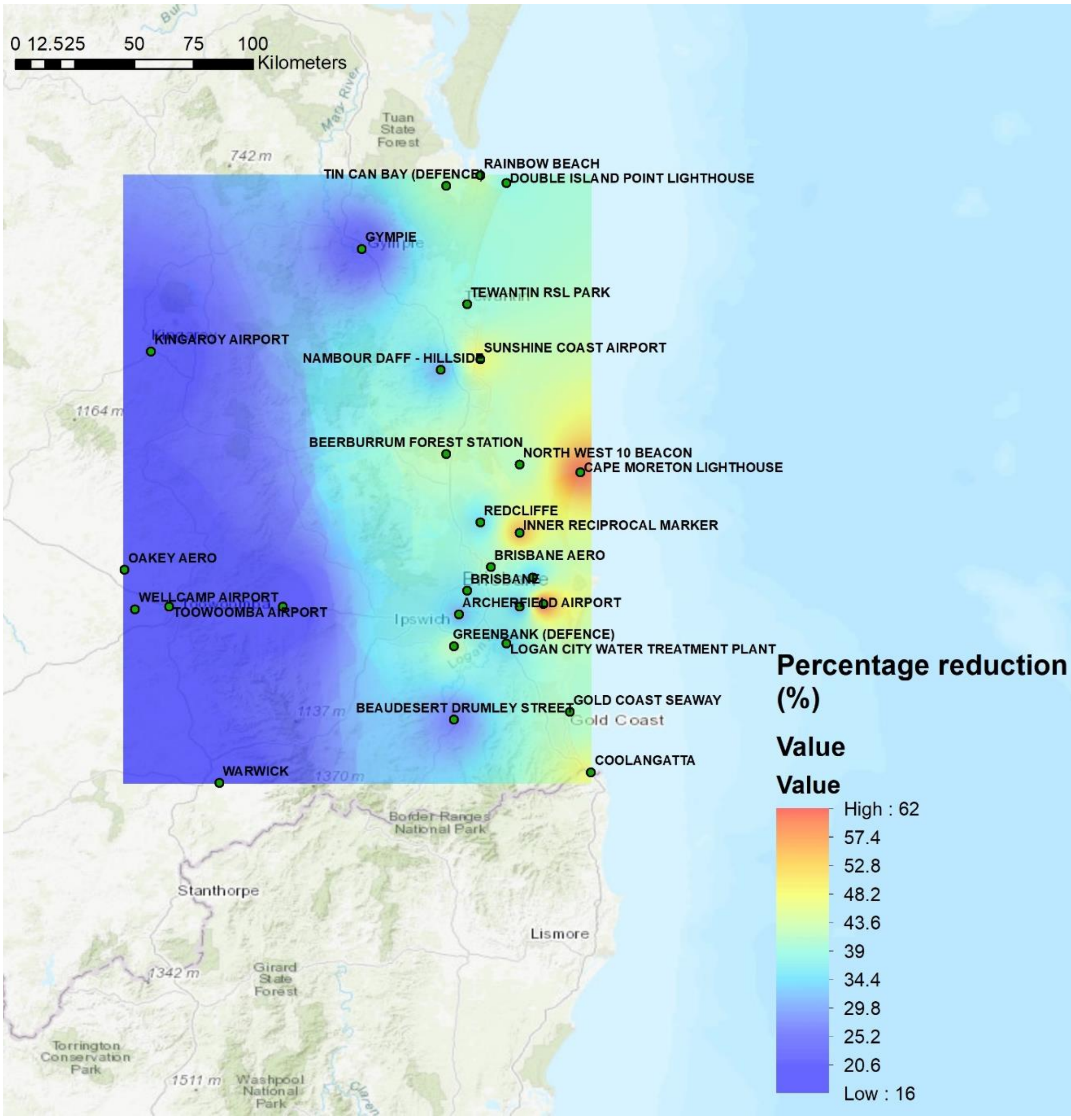


Figure 19 The percentage of CDH reduction due to the implementation of the cool roof in the 31 stations in Brisbane.

2.4 Conclusions

- In average, compared to the reference scenario, 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 45%-74% of the ambient temperatures in all stations concentrate in the range of 18-25 °C.
- In control cases, CDH ranges from 956.6 to 4167.1, and about 40% of the data is concentrated in 1800 - 2000. CDH gradually increases from the east of the city to the west.
- In cool roof cases, CDH ranges from 377.7 to 3446.5, and about 50% of the data is concentrated in 1000 - 1400. Its spatial distribution is also similar to that of the control case.
- The percentage of CDH reduction due to the implementation of the cool roof ranges from 16% to 62%, with an average value of 34.6%. The percentage of CDH reduction in the original control volume is relatively large in the east of the city and gradually decreases toward the west.

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

3.1 Introduction

This report investigated the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Brisbane. 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 Brisbane during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and seven weather stations across Brisbane (in climate zone 2). 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 seven weather stations modelled in Brisbane include (See **Figure 20**):

1) Brisbane Airport -Climate zone 2,

2) Amberley-Climate zone 2,

3) Archerfield-Climate zone 2,

4) Gold Coast Seaway- Climate zone 2,

5) Greenbank (Defence)-Climate zone 2,

6) Redcliffe-Climate zone 2,

7) Redland (Alexandra Hills)-Climate zone 2,

Figure 20 Weather stations in Brisbane

The corresponding building specifications for the buildings in climate zones 2 was considered. 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 Brisbane. 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 Brisbane (i.e. Redland and Amberley) 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 6***.

3.3 Summary of results

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	43.6-46.3	11.3-15.6	25.6-33.7	18.7-21.3	42.9-46.2
A high-rise office building without roof insulation-existing building	34.2-35.2	2.0-3.0	5.7-8.8	8.6-10.4	24.9-29.6
A low-rise office building with roof insulation-new building	32.1-33.7	1.2-1.6	3.6-5.0	7.3-9.2	22.3-27.5
A high-rise office building with roof insulation-new building	31.6-33.8	0.2-0.3	0.6-0.9	6.3-8.5	19.9-25.4
A low-rise shopping mall centre-new building	96.4-99.4	1.3-1.9	1.3-2.0	15.4-19.4	15.8-19.6
A mid-rise shopping mall centre-new building	95.3-98.5	0.7-0.8	0.7-0.8	14.6-18.7	15.1-19.0
A high-rise shopping mall centre-new building	94.8-98.1	0.4-0.6	0.4-0.6	14.4-18.4	15.0-18.8
A low-rise apartment building-new building,	25.5-27	1.3-1.6	4.8-6.3	7.7-9.9	30.2-37.1
A mid-rise apartment building-new building	25.2-26.9	0.7-0.9	2.6-3.6	7.1-9.4	28.2-35.5
A high-rise apartment building-new building	24.9-26.7	0.4-0.5	1.5-2.0	6.7-9.1	26.9-34.6
A typical stand-alone house-existing building,	21.8-22.6	3.9-4.2	17.3-18.8	8.6-10.1	38.8-44.9
A typical school building-existing building	44.4-46	1.5-1.7	3.3-3.8	12.6-17.5	27.9-38.0
A low-rise office building with roof insulation-existing building	37.1-37.8	6.0-7.5	15.9-19.8	12.2-14.0	32.9-37.0
A high-rise office building with roof insulation-existing building	32.6-34.3	0.9-1.4	2.6-4.3	7.4-9.3	22.4-27.3
A low-rise shopping mall centre-existing building	102.1-103.6	7.4-9.6	7.2-9.3	21.6-25.6	21.2-24.7
A high-rise shopping mall centre-existing building	96.6-99.1	2.1-2.9	2.1-3.0	16.2-20.2	16.6-20.4
A stand-alone house-new building.	22.5-23.5	4.1-4.4	17.4-19.3	8.8-10.4	39.1-44.6

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/m²	**%**	**kWh/m²**	**kWh/m²**	**%**
A low-rise office building without roof insulation-existing building	34.7-52.7	34.6-40.0	0.5-0.9	34.2-52.2	33.8-39.4
A high-rise office building without roof insulation-existing building	5.7-9.7	7.5-10.6	0-0.2	5.6-9.7	7.4-10.6
A low-rise office building with roof insulation-new building	3.5-5.2	4.8-6.0	0-0.1	3.4-5.2	4.6-6.0
A high-rise office building with roof insulation-new building	0.6-1.0	0.8-1.2	0-0.1	0.6-1.0	0.8-1.2
A low-rise shopping mall centre-new building	6.6-9.2	1.9-2.5	0-0.1	6.6-9.2	1.9-2.5
A mid-rise shopping mall centre-new building	3.0-4.4	0.9-1.2	0	3.0-4.4	0.9-1.2
A high-rise shopping mall centre-new building	2.0-2.8	0.6-0.8	0	2.0-2.8	0.6-0.8
A low-rise apartment building-new building,	3.8-5.6	7.4-9.5	0.2-0.4	3.6-5.4	6.4-8.6
A mid-rise apartment building-new building	2.2-3.3	4.3-5.6	0.1-0.2	2.1-3.2	3.7-5.1
A high-rise apartment building-new building	1.2-2.0	2.4-3.4	0.1	1.1-1.9	2.1-3.0
A typical stand-alone house-existing building,	11.5-13.6	21.7-29.3	0.4-0.6	11.1-13.1	19.4-25.3
A typical school building-existing building	4.1-5.8	4.0-5.3	0-0.1	4.1-5.7	3.8-5.0
A low-rise office building with roof insulation-existing building	16.6-25.1	19.8-24.1	0.1-0.4	16.5-24.9	19.6-23.8
A high-rise office building with roof insulation-existing building	2.8-4.6	3.8-5.3	0-0.1	2.8-4.6	3.8-5.3
A low-rise shopping mall centre-existing building	30.8-44.2	8.8-11.5	0-0.2	30.8-44.1	8.8-11.4
A high-rise shopping mall centre-existing building	8.7-13.5	2.6-3.7	0-0.1	8.7-13.5	2.6-3.7
A stand-alone house-new building.	12.3-16.4	24.6-30.2	0.4-0.7	11.9-15.9	20.3-26.2

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 the 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	46.4-53.3	9.0-10.3	9.6-11.1	649-664	591-629	558-592
A high-rise office building without roof insulation-existing building	41.5-46.3	1.6-2.0	2.4-2.8	672	672	668-672
A low-rise office building with roof insulation-new building	41.8-46.4	1.0-1.2	1.7-2.1	670-672	668-672	662-672
A high-rise office building with roof insulation-new building	41.0-45.1	0.2-0.3	1.2-1.3	672	672	672
A low-rise shopping mall centre-new building	45.9-51.7	0.5-0.7	1.6-1.8	672	671-672	666-672

A mid-rise shopping mall centre-new building	45.3-50.9	0.4	1.4-1.8	672	672	672
A high-rise shopping mall centre-new building	45.1-50.7	0.3-0.4	1.3-1.8	672	672	672
A low-rise apartment building-new building,	34.9-38.9	0.6-0.8	1.4-1.7	635-656	624-651	581-614
A mid-rise apartment building-new building	34.6-38.4	0.4-0.5	1.2-1.4	639-664	637-660	598-631
A high-rise apartment building-new building	34.4-38.1	0.2-0.3	1.1-1.2	642-665	640-664	606-637
A typical stand-alone house-existing building	37.0-41.6	2.4-2.8	3.1-3.6	573-592	530-565	463-490
A typical school building-existing building	36.7-42.1	0.6-0.7	1.4-1.6	623-650	616-645	569-607
A low-rise office building with roof insulation-existing building	43.7-49.4	4.6-5.6	5.3-6.4	664-672	644-666	617-657
A high-rise office building with roof insulation-existing building	41.2-45.6	0.8-1.1	1.7-2.0	672	672	672
A low-rise shopping mall centre-existing building	46.7-53.2	2.5-2.8	3.3-3.7	664-672	662-672	648-672
A high-rise shopping mall centre-existing building	45.3-51.1	0.9-1.0	1.7-1.9	672	672	672

A stand-alone house-new building.	36.9-41.1	2.5-2.9	3.2-3.7	558-618	552-583	485-566

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	11.7-15.5	3.4-3.6	30-37	158-229	42-56	221-294
A high-rise office building without roof insulation-existing building	16.7-19.5	0.6	0-15	6-80	4-16	10-91
A low-rise office building with roof insulation-new building	15.5-18.9	0.6	7-24	21-109	15-27	24-116
A high-rise office building with roof insulation-new building	17.6-20.3	0.1-0.2	0-10	1-57	0-14	1-59
A low-rise shopping mall	14.0-18.5	0.4	15-31	43-116	17-31	44-121

centre-new building						
A mid-rise shopping mall centre-new building	15.2-19.5	0.2	8-25	15-87	9-26	16-89
A high-rise shopping mall centre-new building	15.5-19.8	0.2	5-25	9-83	5-25	9-84
A low-rise apartment building-new building,	14.4-17.5	0.4	N/A	120-240	N/A	129-248
A mid-rise apartment building-new building	14.8-17.8	0.2	N/A	108-236	N/A	112-242
A high-rise apartment building-new building	15.0-17.9	0.2	N/A	102-234	N/A	107-238
A typical stand-alone house-existing building,	11.8-15.6	1.3.1.4	N/A	235-330	N/A	270-360
A typical school building-existingbuilding	11.2-15.5	0.2	35-50	156-248	37-52	165-253
A low-rise office building with roof insulation-existing building	13.4-17.1	1.9-2.0	18-29	85-173	26-31	119-207
A high-rise office building with roof insulation-existing building	17.1-19.9	0.4	1-14	3-71	2-19	5-75
A low-rise shopping mall centre-existing building	12.6-17.3	1.1-1.2	20-42	79-171	25-45	91-182

A high-rise shopping mall centre-existing building	15.0-19.3	0.4	9-29	19-95	11-30	20-97
A stand-alone house-new building.	12.4-16.1	1.4-1.5	N/A	189-296	N/A	234-333

3.4 Conclusion

The conclusions drawn from this study are:

- 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 11.3-15.6 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 buildings and in the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 18.7-21.3 kWh/m^2.
- In existing buildings without insulation/with low insulation level, the cooling load reduction of the cool roofs is remarkable even for the high-rise buildings. For instance, the application of cool roofs on the individual building (scenario 1) and both individual buildings and at the whole urban area (scenario 2) is expected to decrease the cooling loads of a high-rise office building without roof insulation by 2.0-3.0 kWh/m^2 and 8.6-10.4 kWh/m^2, respectively.
- 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 in the whole urban area (scenario 2) is predicted to be 7.3-9.2 kWh/m^2 in a typical new low-rise office building.
- In new high-rise buildings with high insulation level, 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 0.2-0.3 kWh/m^2 for new high-rise office buildings with insulation.
- In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and in 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 just 0.4-0.5 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 6.7-9.1 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 types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 34.7-52.7 kWh/m^2, while the corresponding heating penalty is just 0.5-0.9 kWh/m^2.

- 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 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 9.0-10.3 ^{o}C.
- 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 in 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 in 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 9.6-11.1 ^{o}C.
- In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, the application of cool roofs in both individual buildings and in the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum indoor air temperature reduction by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 1.7-2.1 ^{o}C in a typical new low-rise office building.
- In residential buildings and under free-floating conditions in a typical summer period, the application of cool roofs in individual buildings (scenario 1) or both individual building and in the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^{o}C. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in a typical existing stand-alone house is predicted to reduce from 573-592 hours to 530-565 hours and 463-490 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 non-residential buildings and under free-floating conditions in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual buildings and at the whole urban area (scenario 2) has low or no impact on reducing the number of hours with an indoor air temperature above 26 ^{o}C during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in a mid-rise shopping mall centre is predicted to remain unchanged after the application of cool roofs.
- 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 9-10.3 ^{o}C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 3.4-3.6 ^{o}C 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 ^{o}C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.4 ^{o}C occurs when the indoor air temperature is 29.3 ^{o}C.
- The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ^{o}C, 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 ^{o}C from 18-29 hours to 26-31 hours in a typical existing low-rise office building with roof insulation.

4. Energy loss through building envelopes in various stations in Brisbane_ 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 Brisbane 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 7 weather stations in Brisbane 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 21** 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, all office building types present an increased cooling load reduction with the increase of cooling degree hours. Similar to scenario 1, 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.

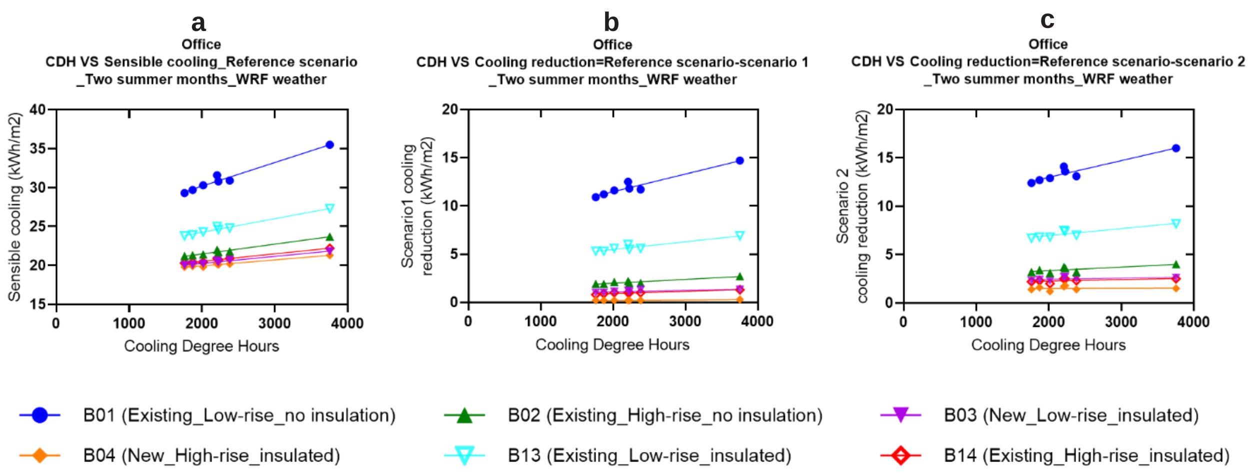


Figure 21 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 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)	0.003031	24.13	Y = 0.003031*X + 24.13
B02 (Existing_High-rise_no insulation)	0.001263	18.95	Y = 0.001263*X + 18.95
B03 (New_Low-rise_insulated)	0.0009024	18.45	Y = 0.0009024*X + 18.45
B04 (New_High-rise_insulated)	0.0007687	18.40	Y = 0.0007687*X + 18.40
B13 (Existing_Low-rise_insulated)	0.001747	20.77	Y = 0.001747*X + 20.77
B14 (Existing_High-rise_insulated)	0.0009647	18.59	Y = 0.0009647*X + 18.59

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.001828	7.823	Y = 0.001828*X + 7.823
B02 (Existing_High-rise_no insulation)	0.0003923	1.205	Y = 0.0003923*X + 1.205
B03 (New_Low-rise_insulated)	0.0001448	0.8074	Y = 0.0001448*X + 0.8074
B04 (New_High-rise_insulated)	0.00005349	0.09037	Y = 0.00005349*X + 0.09037
B13 (Existing_Low-rise_insulated)	0.0007941	3.903	Y = 0.0007941*X + 3.903
B14 (Existing_High-rise_insulated)	0.0002184	0.4941	Y = 0.0002184*X + 0.4941

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.001727	9.543	Y = 0.001727*X + 9.543
B02 (Existing_High-rise_no insulation)	0.0003720	2.595	Y = 0.0003720*X + 2.595
B03 (New_Low-rise_insulated)	0.0001187	2.225	Y = 0.0001187*X + 2.225
B04 (New_High-rise_insulated)	0.00001690	1.475	Y = 1.690e-005*X + 1.475
B13 (Existing_Low-rise_insulated)	0.0007253	5.520	Y = 0.0007253*X + 5.520
B14 (Existing_High-rise_insulated)	0.0001462	1.990	Y = 0.0001462*X + 1.990

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 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 center 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, 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 B06 and B07 presenting a decreased cooling load reduction with the increase of cooling degree hours, all other buildings show an increased cooling load reduction with the increase of cooling degree hours. A higher increase rate is observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.

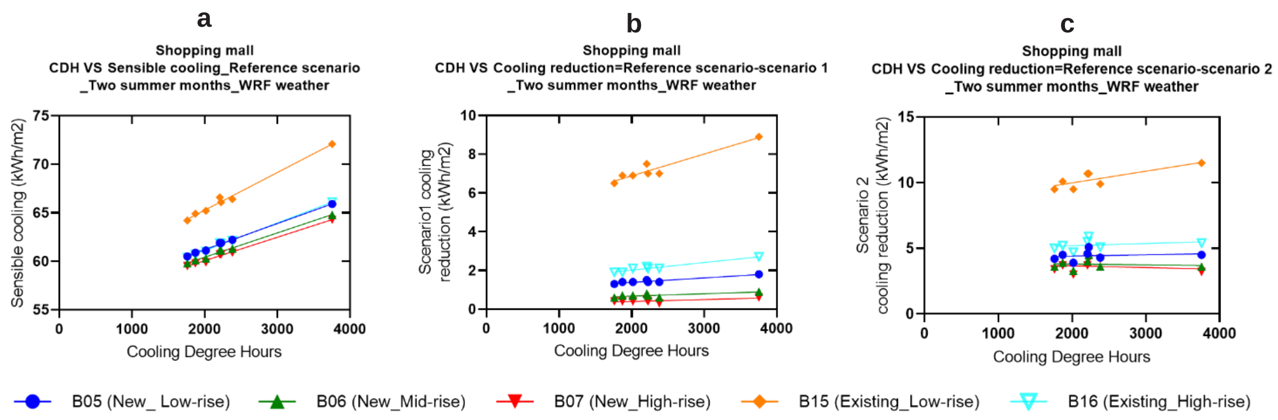


Figure 22 For shopping mall center a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.002691	55.82	Y = 0.002691*X + 55.82
B06 (New_Mid-rise)	0.002507	55.41	Y = 0.002507*X + 55.41
B07 (New_High-rise)	0.002416	55.23	Y = 0.002416*X + 55.23
B15 (Existing_Low-rise)	0.003888	57.49	Y = 0.003888*X + 57.49
B16 (Existing_High-rise)	0.002864	55.37	Y = 0.002864*X + 55.37

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.0002306	0.9230	Y = 0.0002306*X + 0.9230
B06 (New_Mid-rise)	0.0001212	0.4334	Y = 0.0001212*X + 0.4334
B07 (New_High-rise)	0.0001005	0.1956	Y = 0.0001005*X + 0.1956
B15 (Existing_Low-rise)	0.001127	4.632	Y = 0.001127*X + 4.632
B16 (Existing_High-rise)	0.0003913	1.236	Y = 0.0003913*X + 1.236

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.00009975	4.212	Y = 0.00009975*X + 4.212

B06 (New_Mid-rise)	-0.00006307	3.932	Y = -0.00006307*X + 3.932
B07 (New_High-rise)	-0.0001326	3.936	Y = -0.0001326*X + 3.936
B15 (Existing_Low-rise)	0.0008903	8.209	Y = 0.0008903*X + 8.209
B16 (Existing_High-rise)	0.0001657	4.873	Y = 0.0001657*X + 4.873

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 23** 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.

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 under unmodified climatic conditions, a cool roof is more effective in 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, except B11 and B17 which present 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.

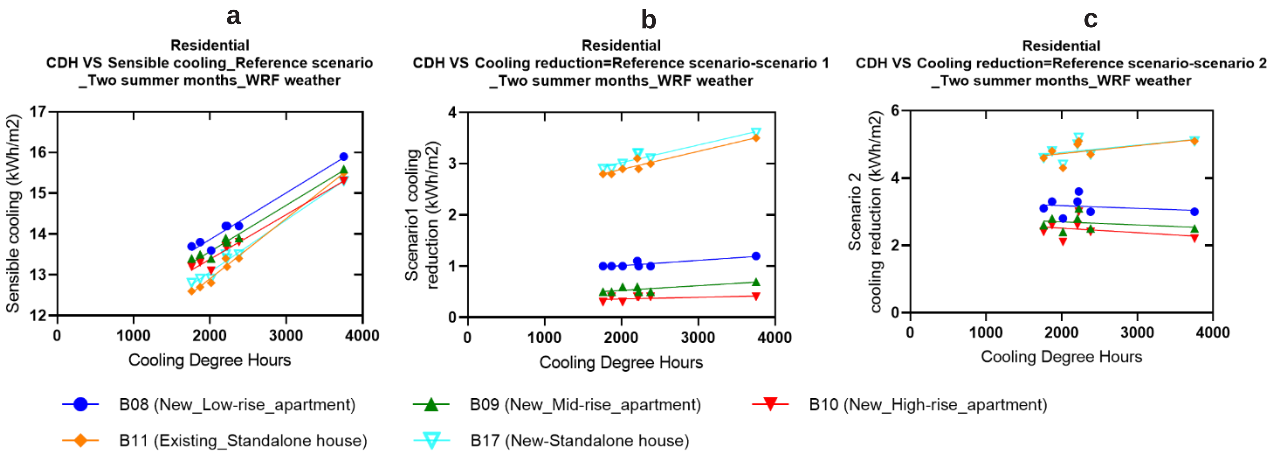


Figure 23 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.001146	11.57	Y = 0.001146*X + 11.57
B09 (New_Mid-rise_apartment)	0.001138	11.29	Y = 0.001138*X + 11.29
B10 (New_High-rise_apartment)	0.001095	11.19	Y = 0.001095*X + 11.19
B11 (Existing_Standalone house)	0.001478	9.947	Y = 0.001478*X + 9.947
B17 (New-Standalone house)	0.001277	10.51	Y = 0.001277*X + 10.51

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B08 (New_Low-rise_apartment)	0.0001029	0.8045	Y = 0.0001029*X + 0.8045
B09 (New_Mid-rise_apartment)	0.00009175	0.3446	Y = 9.175e-005*X + 0.3446
B10 (New_High-rise_apartment)	0.00003184	0.2977	Y = 3.184e-005*X + 0.2977
B11 (Existing_Standalone house)	0.0003523	2.184	Y = 0.0003523*X + 2.184
B17 (New-Standalone house)	0.0003455	2.328	Y = 0.0003455*X + 2.328

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B08 (New_Low-rise_apartment)	-0.00008061	3.344	Y = -0.00008061*X + 3.344
B09 (New_Mid-rise_apartment)	-0.00009177	2.884	Y = -0.00009177*X + 2.884
B10 (New_High-rise_apartment)	-0.0001352	2.785	Y = -0.0001352*X + 2.785
B11 (Existing_Standalone house)	0.0002369	4.251	Y = 0.0002369*X + 4.251
B17 (New-Standalone house)	0.0002223	4.314	Y = 0.0002223*X + 4.314

4.5 School

School load reduction in scenario 1 and scenario 2 for the one building type (B12_Existing) is shown in **Figure 24** 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 an increased cooling load reduction with the increase of cooling degree hours.

a b c

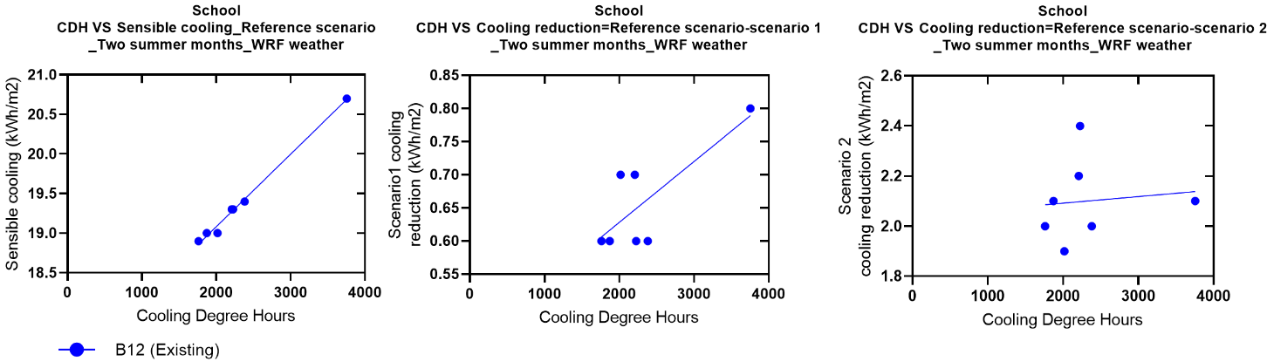


Figure 24 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared 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)	0.0009170	17.25	Y = 0.0009170*X + 17.25

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.00009175	0.4446	Y = 0.00009175*X + 0.4446

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.00002634	2.039	Y = 0.00002634*X + 2.039

4.6 Conclusion

- Regarding the sensible 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 an increasing 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 hotter areas for all buildings except for three residential buildings and two shopping centres.

- A general ranking of the heat loss coefficients of these buildings from low to high is office, school, residential buildings 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
B04 (Office_New_High-rise_insulated)	0.0007687
B03 (Office_New_Low-rise_insulated)	0.0009024
B12 (School_Existing)	0.000917
B14 (Office_Existing_High-rise_insulated)	0.0009647
B10 (Apartment_New_High-rise)	0.001095
B09 (Apartment_New_Mid-rise)	0.001138
B08 (Apartment_New_Low-rise)	0.001146
B02 (Office_Existing_High-rise_no insulation)	0.001263
B17 (Standalone house_New)	0.001277
B11 (Standalone house_Existing)	0.001478
B13 (Office_Existing_Low-rise_insulated)	0.001747
B07 (Shopping mall_New_High-rise)	0.002416
B06 (Shopping mall_New_Mid-rise)	0.002507
B05 (Shopping mall_New_ Low-rise)	0.002691
B16 (Shopping mall_Existing_High-rise)	0.002864
B01 (Office_Existing_Low-rise_no insulation)	0.003031
B15 (Shopping mall_Existing_Low-rise)	0.003888

5. Impact of cool roofs on energy efficiency ratio (EER) of air-conditioning (AC) systems

Cool roofs can reduce the cooling loads of buildings due to their impact on solar heat gains and local urban climate. The application of cool roofs can also increase the energy efficiency ratio (EER) of air-conditioning (AC) systems resulting in an extra cooling load saving. This study evaluated the impact of cool roofs on EER of six different AC systems and the corresponding cooling load savings in seventeen types of buildings in two-summer months of January and February in Brisbane. As estimated, the application of cool roofs can improve the hourly EER of the six selected AC systems by 0.11-0.31 in Redland station in Brisbane. This is equivalent to a noticeable EER-related cooling load saving of around 7-16% in a new high-rise shopping mall centre in Redland station. For the same building and weather station, the corresponding primary cooling load saving by lower heat gains and improved local urban climate by the application of cool roofs in individual buildings and in the whole urban area is estimated to be 5%.

5.1 Introduction

In this study, the impact of cool roofs on energy efficiency ratio (EER) of air-conditioning (AC) systems and the corresponding cooling load saving is estimated. The EER of an AC system is a ratio of useful cooling provided to work (energy) required and is highly dependent on ambient air temperature. A study on the impact of local urban climate on the performance of cooling systems shows that rooftop AC systems may experience up to 17% lower EER in urban areas compared to rural areas (Gracik *et al.*, 2015). Another study showed that the average operation time and energy of AC systems increase linearly with outdoor temperatures up to 25 ^{o}C, and remain constant at higher temperatures (Perez *et al.*, 2014).

In this context, this study aims to evaluate the impact of cool roofs on EER of AC systems and the corresponding cooling load savings. The cooling load saving by modified EER is in addition to the primary cooling load savings by lower heat gains and improved urban climate by implementing cool roofs in individual buildings and in the whole urban area. The methodology and results of the study are discussed in detail in the following.

5.2 Methodology

This study investigates the impact of cool roofs on EER of AC systems and the corresponding cooling load savings in Brisbane. First, the hourly cooling load savings by lower heat gains by application of cool roofs in seventeen types of buildings was computed for the hottest and coldest weather stations in Brisbane (i.e. Amberley and Redland stations). 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 Brisbane. 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 seventeen typical buildings modelled in this study include:

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-existing building-new building,
6. A mid-rise shopping mall centre-existing building-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 median ratio of hourly cooling loads for cool roof with modified urban temperature scenario (scenario 2) to reference scenario for each day was then computed to gain a better understanding on the hourly cooling load/peak electricity load reduction potential of cool roofs. Next, the EER (t) for the reference and cool roof with modified urban temperature scenario (scenario 2) was computed using the hourly ambient temperatures for different AC residential and commercial systems including split and VAV systems. The considered equations for calculation of EER (t) for different AC systems are as follow (Gracik *et al.*, 2015):

Residential systems-Split:

$$EER\ (t) = 4.825 - 0.0687\ To\ (t) \quad (1)$$
$$EER\ (t) = 5.153 - 0.0738\ To\ (t) \quad (2)$$
$$EER\ (t) = 5.241 - 0.0742\ To\ (t) \quad (3)$$
$$EER\ (t) = 9.459 - 0.3323\ To\ (t)^{0.7654} \quad (4)$$

Commercial systems-Split:

$$EER\ (t) = 12 - 0.35\ To\ (t) + 0.0034\ To\ (t)^2 \quad (5)$$

Commercial systems-VAV system:

$$EER\ (t) = 0.0011\ To\ (t)^{\ 2}\ - 0.1392\ To\ (t) + 6.4115 \quad (6)$$

Where To (t) is the hourly ambient air temperature at a given time. The additional energy gain by modified EER was estimated using the following equation:

$$EG = \Sigma((EER\ CR\ (t) - EER\ REF\ (t)) \times Cooling\ load\ CR\ (t)) \quad (7)$$

At last, the two-month cooling loads savings by application of cool roofs in individual buildings (scenario 1) and cool roof with modified urban temperature scenario (scenario 2) was compared with the corresponding two-month cooling load savings by modified EER for different AC systems for all building types.

5.3 Calculation of the hourly cooling demand

The hourly cooling demand results for the seventeen building types for the reference and cool roof with modified urban temperature scenario (scenario 2) in Redland and Amberley stations during the two summer months are presented in the following section.

The hourly cooling demand results show a noticeable cooling load reduction in cool roof with modified urban temperature scenario (scenario 2) compared to reference scenario for all building types in Redland stations. As estimated, the average median ratio of cooling load ratio in cool roof with modified urban temperature scenario (scenario 2) compared to reference scenario is estimated to range between 0.17-1.04 and 0.18-1.02 in Redland and Amberley stations, respectively (See **Table 17** and **Figures 25-58**).

Table 17 Two-months sensible cooling load in reference scenario and average median average ratio of hourly sensible cooling load in cool roof with modified urban temperature scenario (Scenario 2) to reference scenario for seventeen building types in Redland and Amberley stations.

Buildings	Station	Two-months sensible cooling loads-Reference scenario (kWh/m^2)	Average median ratio of hourly sensible cooling load in cool roof with modified urban temperature scenario (Scenario 2) to reference scenario
B01- low-rise office building without roof insulation-existing building	Redland	30.3	0.64
	Amberley	35.5	0.65
B02- high-rise office building without roof insulation-existing building	Redland	21.4	0.88
	Amberley	23.7	0.86
B03- low-rise office building with roof insulation-new building	Redland	20.2	0.91
	Amberley	21.8	0.9
B04- high-rise office building with roof insulation-new building	Redland	19.8	0.97
	Amberley	21.3	0.95
B05- low-rise shopping mall centre-existing building-new building	Redland	61.1	0.96
	Amberley	65.9	0.96
B06- mid-rise shopping mall centre-existing building-new building	Redland	60.3	0.97
	Amberley	64.8	0.97
B07- high-rise shopping mall centre-new building	Redland	59.9	0.98
	Amberley	64.3	0.98
B08- low-rise apartment building-new building	Redland	13.6	0.75
	Amberley	15.9	0.75
B09- mid-rise apartment building-new building	Redland	13.4	0.78
	Amberley	15.6	0.78
B10- high-rise apartment building-new building	Redland	13.1	0.8
	Amberley	15.3	0.8
B11- typical stand-alone house-existing building	Redland	12.8	0.17
	Amberley	15.5	0.18

B12- typical school building-existing building	Redland	19	1.00
	Amberley	20.7	1.00
B13- low-rise office building with roof insulation-existing building	Redland	24.3	0.76
	Amberley	27.3	0.72
B14- high-rise office building with roof insulation-existing building	Redland	20.4	0.93
	Amberley	22.2	0.9
B15- low-rise shopping mall centre-existing building	Redland	65.2	0.87
	Amberley	72.1	0.87
B16- high-rise shopping mall centre-existing building	Redland	61	0.95
	Amberley	66.1	0.87
B17- stand-alone house-new building	Redland	12.9	0.64
	Amberley	15.3	0.64

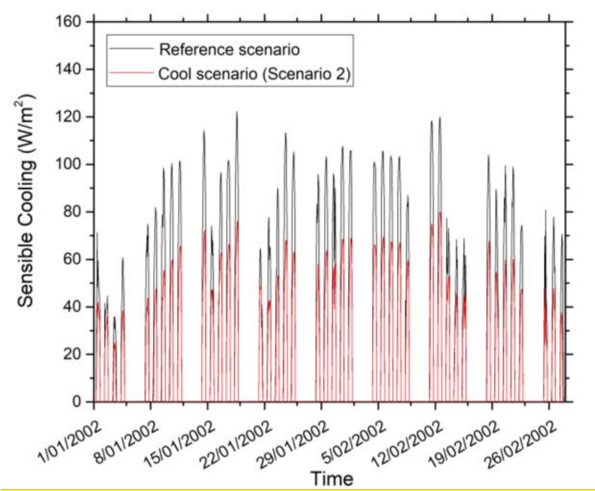


Figure 25 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-existing building in Redland station

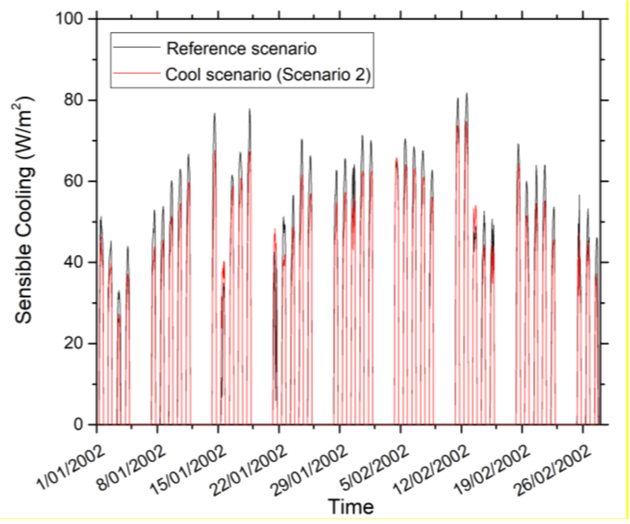


Figure 26 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-existing building in Redland station

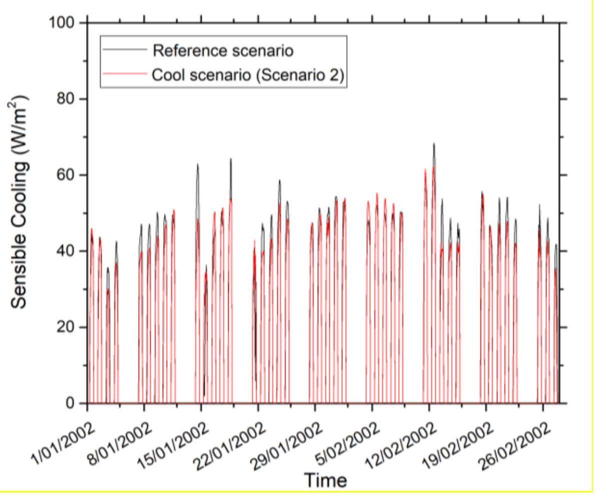


Figure 27 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-new building in Redland station

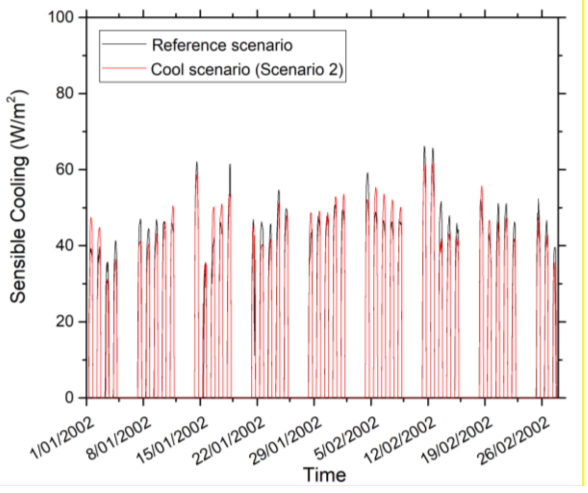


Figure 28 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-new building in Redland station

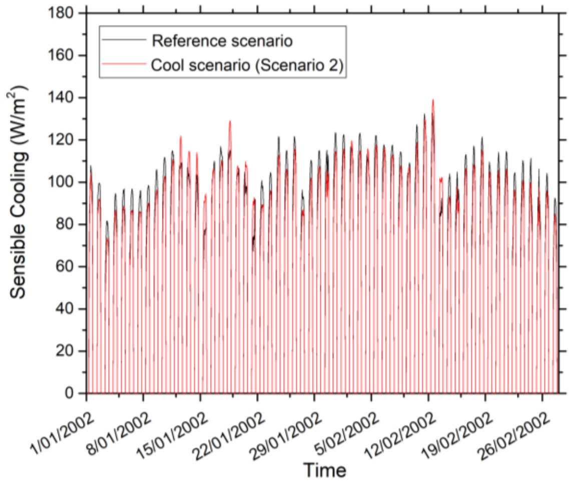


Figure 29 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise shopping mall centre-new building in Redland station

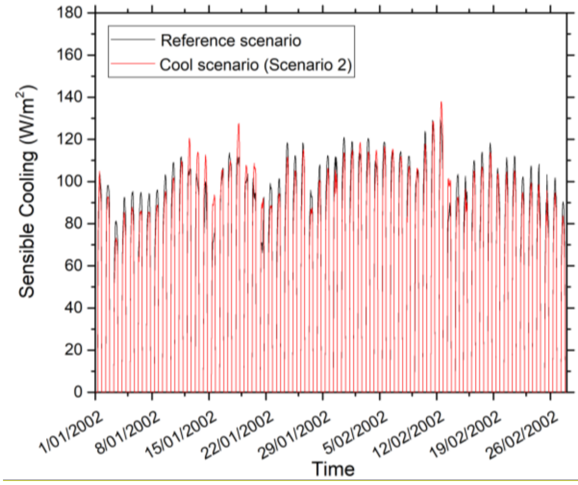


Figure 30 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise shopping mall centre-new building in Redland station

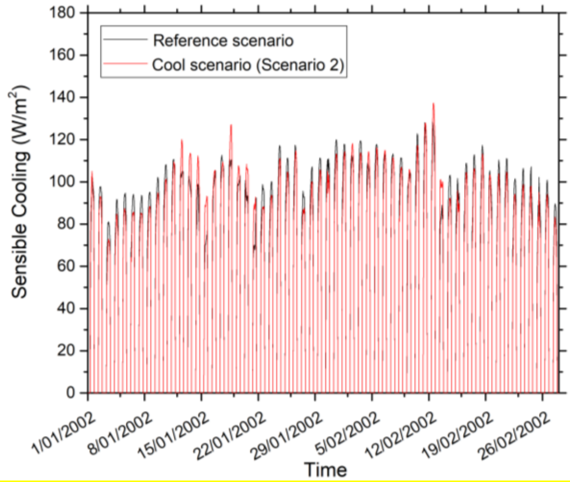


Figure 31 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise shopping mall centre-new building in Redland station

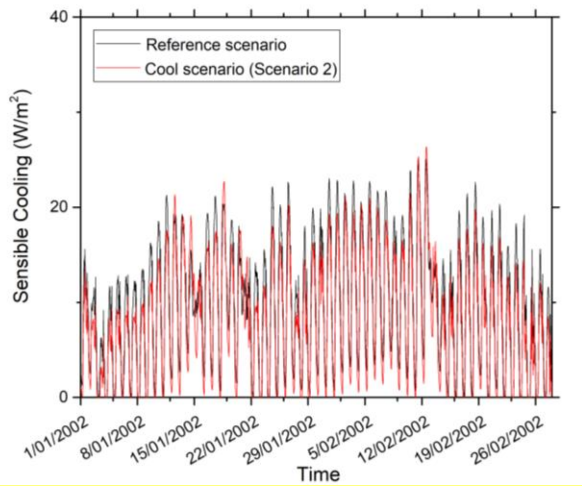


Figure 32 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise apartment-new building in Redland station.

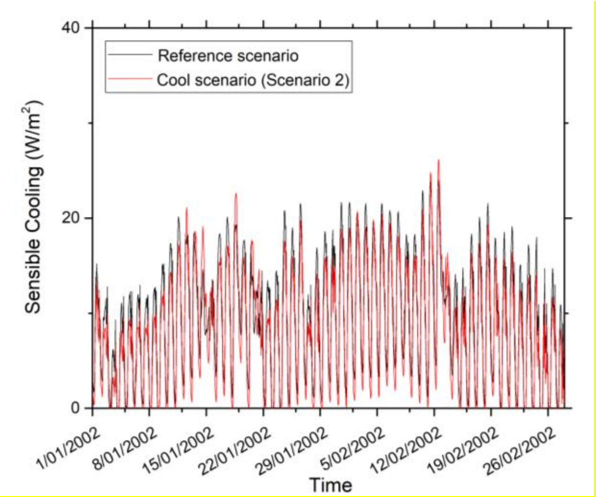


Figure 33 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise apartment-new building in Redland station

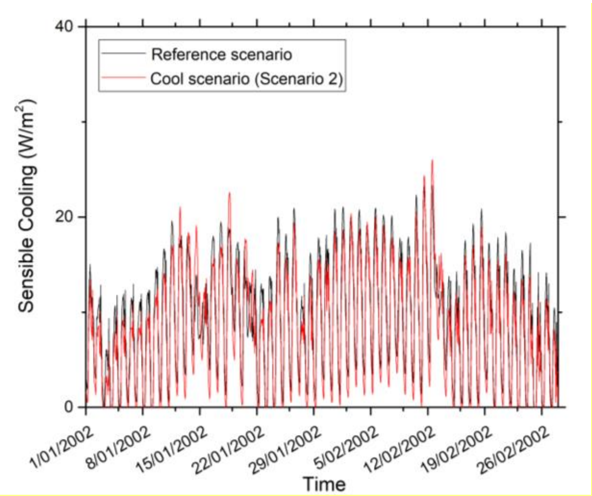


Figure 34 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise apartment-new building in Redland station

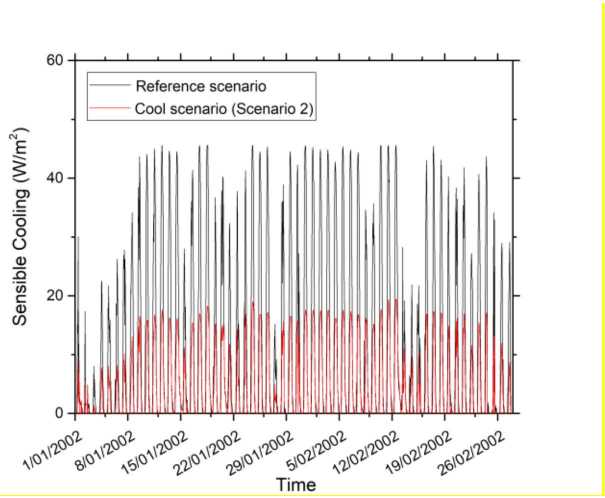


Figure 35 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical stand-alone house-existing building in Redland station

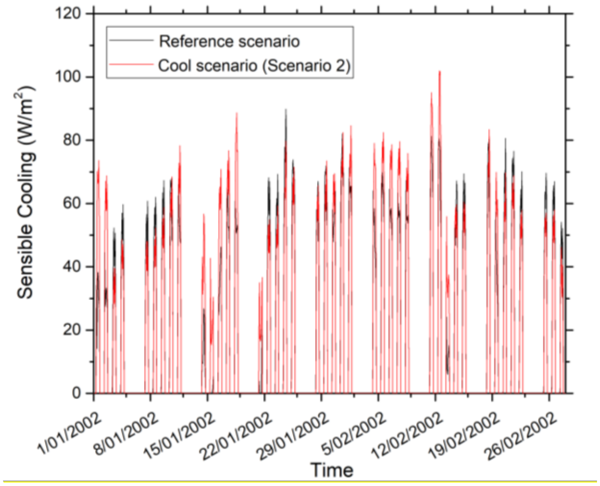


Figure 36 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical school building-existing building in Redland station

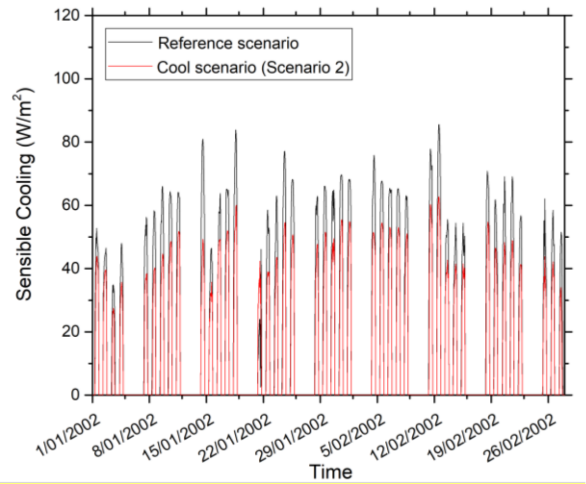


Figure 37 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise office-existing building in Redland station

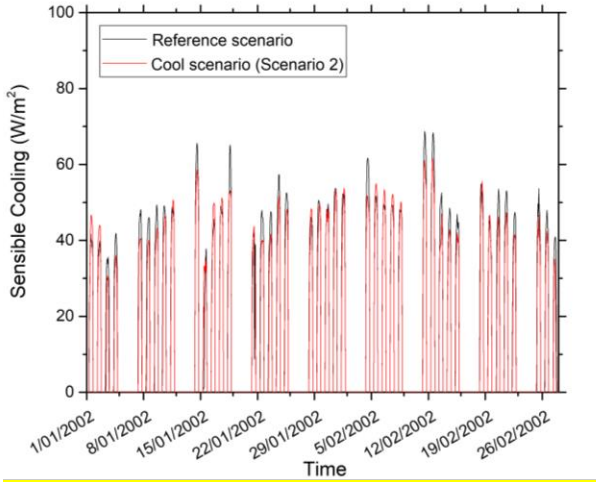


Figure 38 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise office-existing building in Redland station

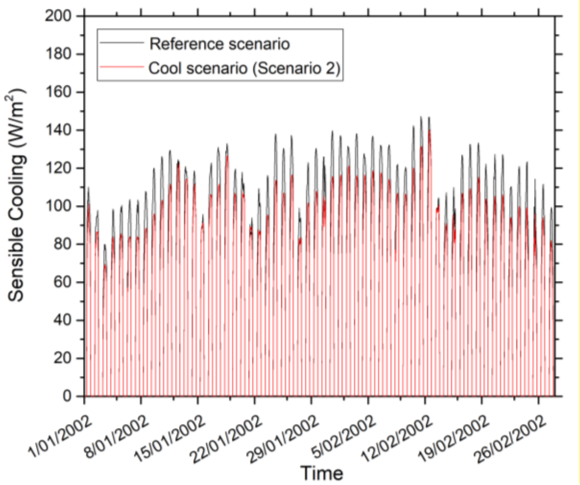


Figure 39 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise shopping mall centre-existing building in Redland station

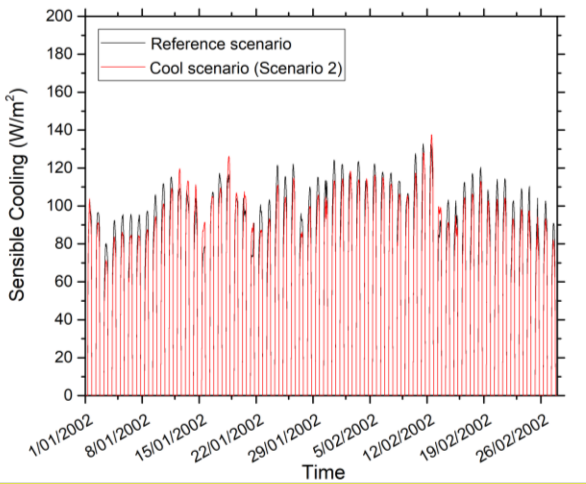


Figure 40 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise shopping mall centre-existing building in Redland station

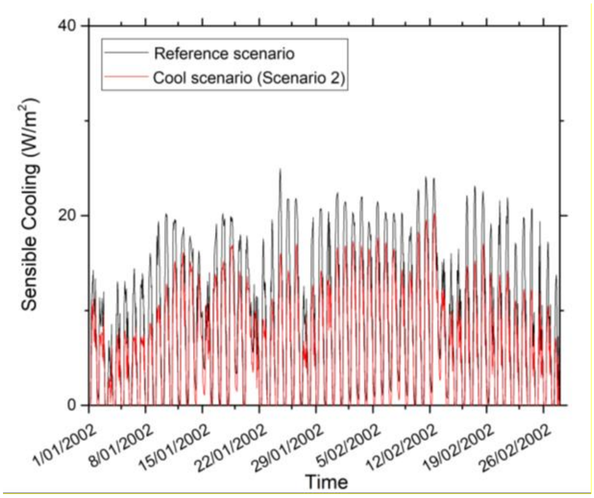


Figure 41 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a stand-alone house-new building in Redland station

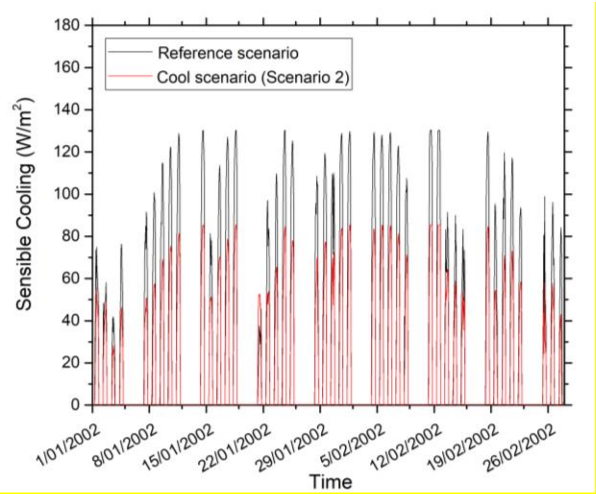


Figure 42 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-existing building in Amberley station

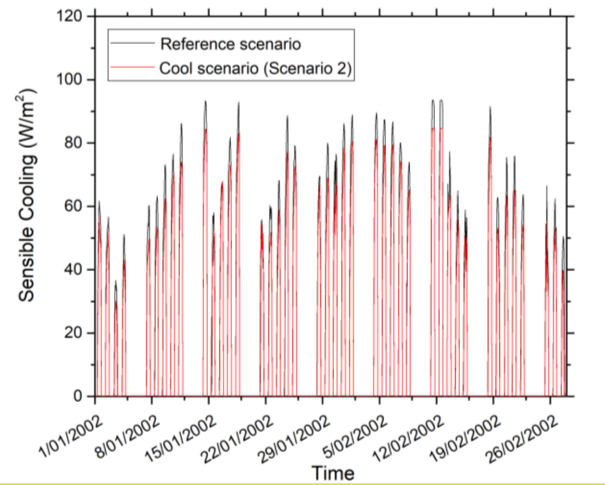


Figure 43 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-existing building in Amberley station

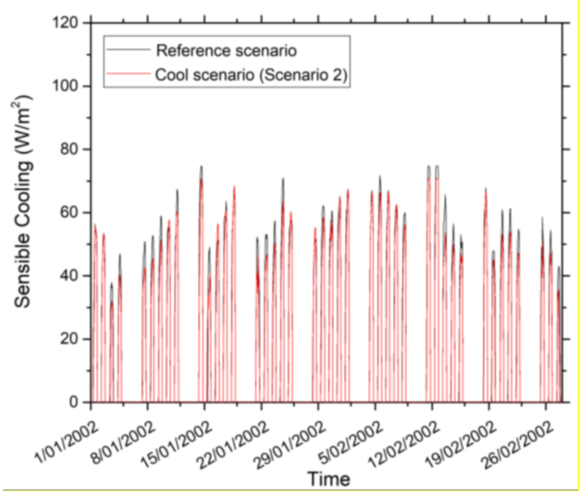


Figure 44 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-new building in Amberley station

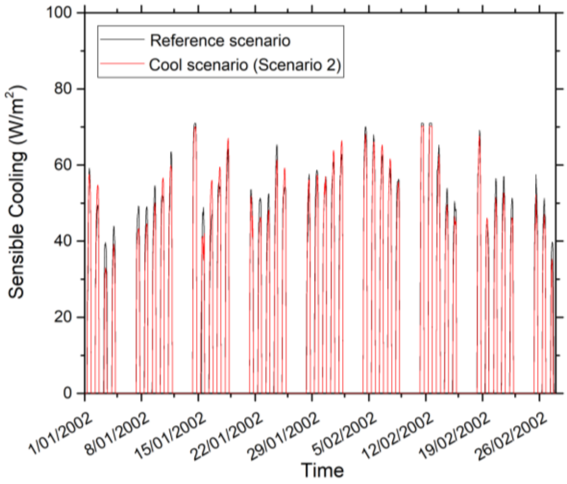


Figure 45 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-new building in Amberley station

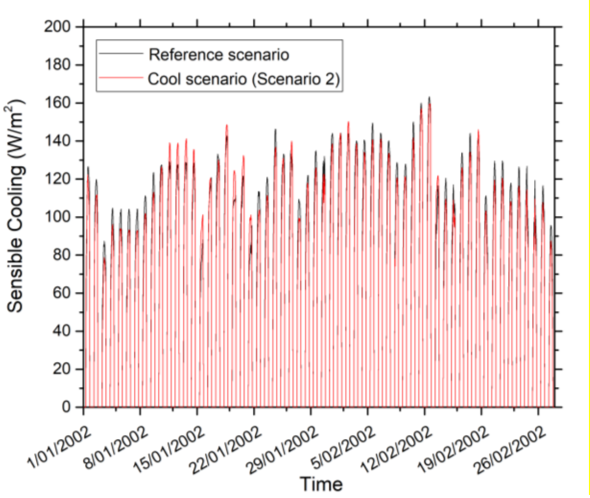


Figure 46 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise shopping mall centre-new building in Amberley station.

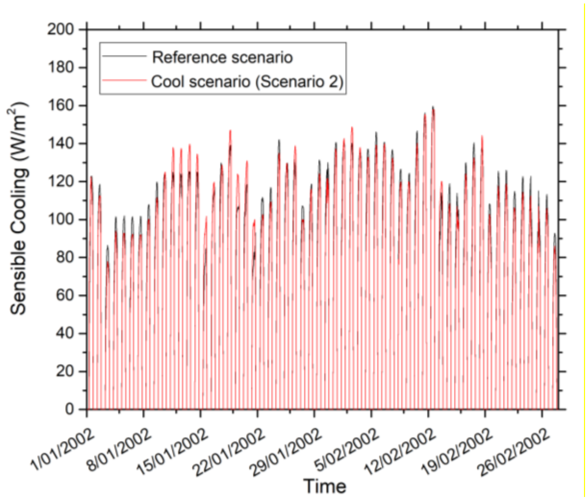


Figure 47 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise shopping mall centre-new building in Amberley station

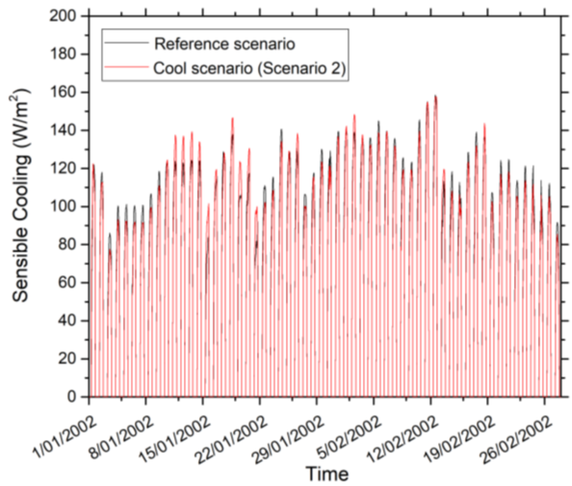


Figure 48 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise shopping mall centre-new building in Amberley station

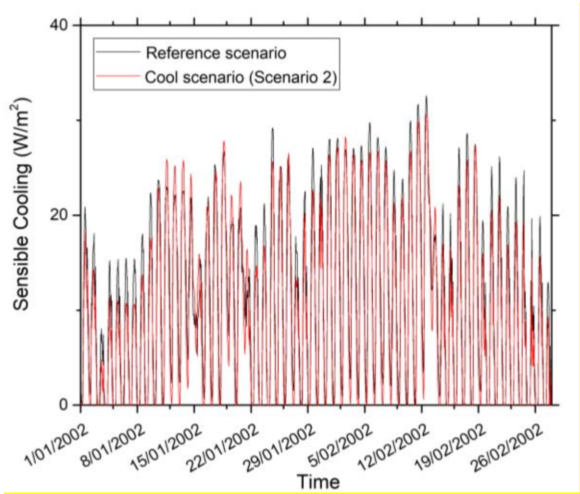


Figure 49 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise apartment-new building in Amberley station

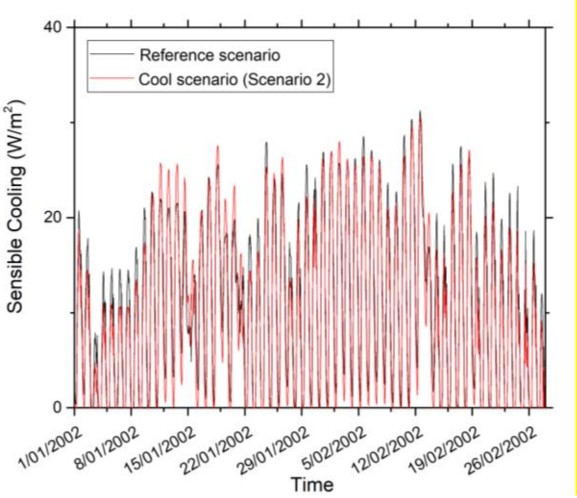


Figure 50 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise apartment-new building in Amberley station

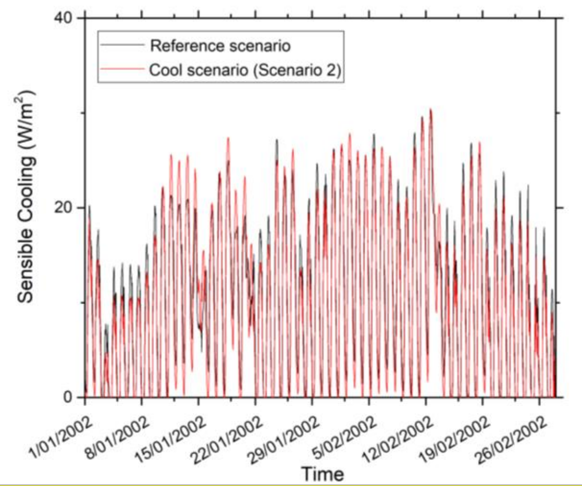


Figure 51 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise apartment-new building in Amberley station

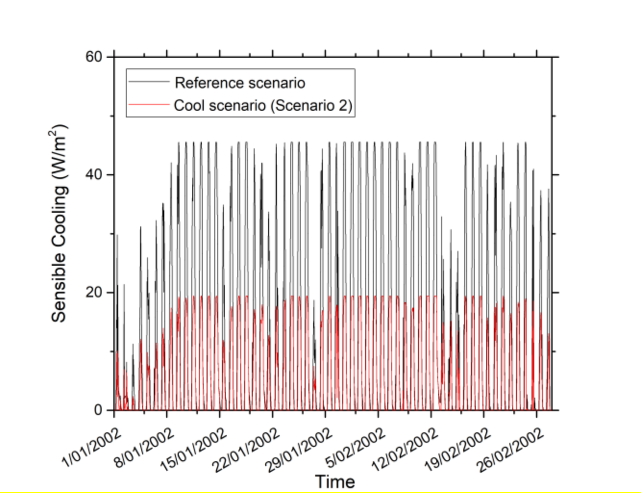


Figure 52 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical stand-alone house-existing building in Amberley station

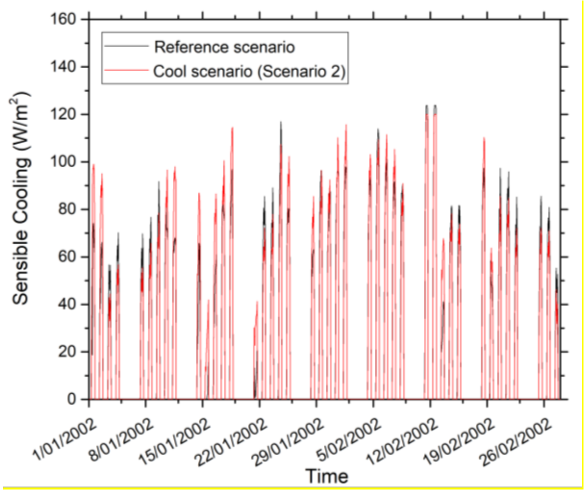


Figure 53 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical school building-existing building in Amberley station

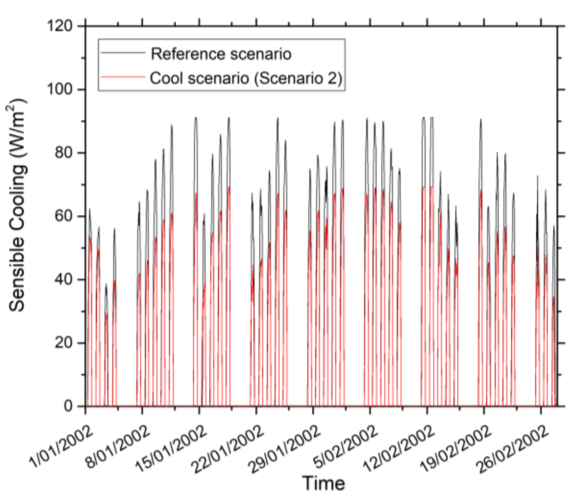


Figure 54 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise office-existing building in Amberley station

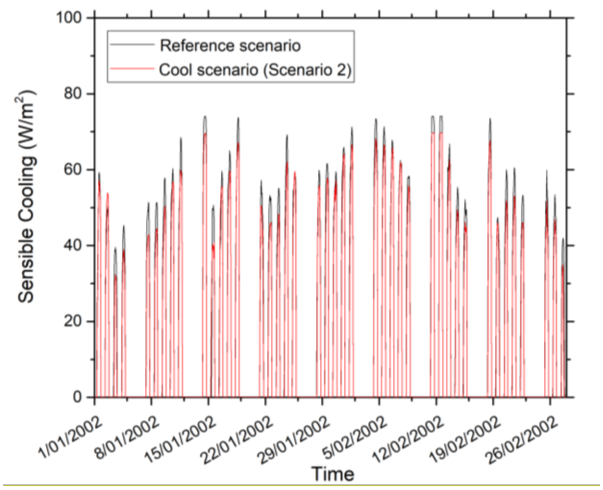


Figure 55 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise office-existing building in Amberley station

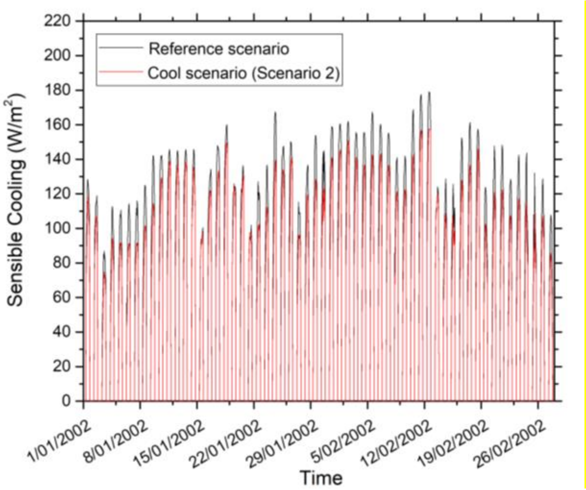


Figure 56 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise shopping mall centre-existing building in Amberley station

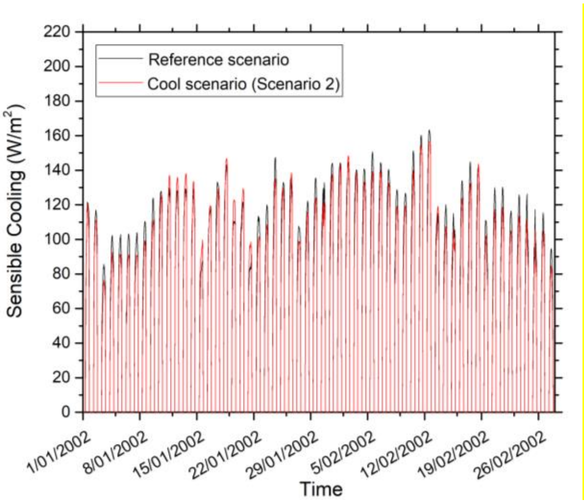


Figure 57 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise shopping mall centre-existing building in Amberley station

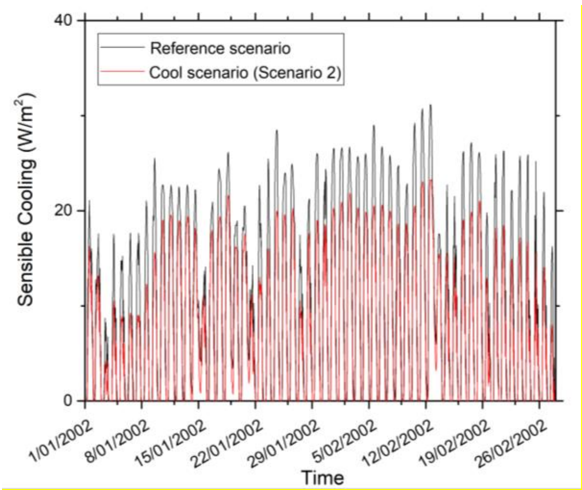


Figure 58 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a stand-alone house-new building in Amberley station

5.4 Impact of cool roofs on EER and its corresponding cooling load savings

5.4.1. Impact of cool roofs on EER

In this part, the EER of the six different AC systems under the reference scenario and cool roof with modified urban temperature scenario (Scenario 2) is computed. The estimations illustrate a noticeable improvement in the EER of all cooling systems due to lower temperatures in cool roof with modified urban temperature scenario (Scenario 2) compared to the reference scenario. **Table 18** shows the minimum, average, and maximum ambient temperature variations in cool roof with modified urban temperature scenario (Scenario 2) compared to reference scenario in Redland and Amberley stations. **Table 19** and 4 illustrate the average, minimum, and maximum variations of the EER in cool roof with modified urban temperature scenario (Scenario 2) compared to reference scenario for the different AC systems in Redland and Amberley stations, respectively. **Figure 59** shows the relation between EER and ambient temperature for the cool roof scenario.

Table 18 Average, minimum, and maximum ambient temperature variations in cool roof scenario compared to reference scenario in Redland and Amberley stations.

Station	Average ambient temperature variation (cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario) (ºC)	Minimum ambient temperature variation (cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario) (ºC)	Maximum ambient temperature variation (cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario) (ºC)
Redland	0.91	0.45	1.58
Amberley	1.04	0.55	1.68

Table 19 Average, minimum, and maximum hourly EER variations for six different AC systems in cool roof scenario compared to reference scenario in two-summer months in Redland station

AC systems	Average hourly EER variation (Cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario)	Minimum hourly EER variation (Cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario)	Maximum hourly EER variation (Cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario)
Residential-Split system-Eq 1	0.06	0.03	0.11
Residential-Split system-Eq 2	0.07	0.03	0.12
Residential-Split system-Eq 3	0.07	0.03	0.12

Residential-Split system-Eq 4	0.11	0.05	0.19
Residential-Split system-Eq 5	0.16	0.06	0.31
Residential-Split system-Eq 6	0.07	0.03	0.14

Table 20 Average, minimum, and maximum hourly EER variations for six different AC systems in cool roof scenario compared to reference scenario in two-summer months in Amberley station

AC systems	**Average hourly EER variation (Cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario)**	**Minimum hourly EER variation (Cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario)**	**Maximum hourly EER variation (Cool roof with modified urban temperature scenario (Scenario 2) vs reference scenario)**
Residential-Split system-Eq 1	0.07	0.04	0.12
Residential-Split system-Eq 2	0.08	0.04	0.12
Residential-Split system-Eq 3	0.08	0.04	0.12
Residential-Split system-Eq 4	0.12	0.07	0.21
Residential-Split system-Eq 5	0.17	0.06	0.35
Residential-Split system-Eq 6	0.08	0.04	0.16

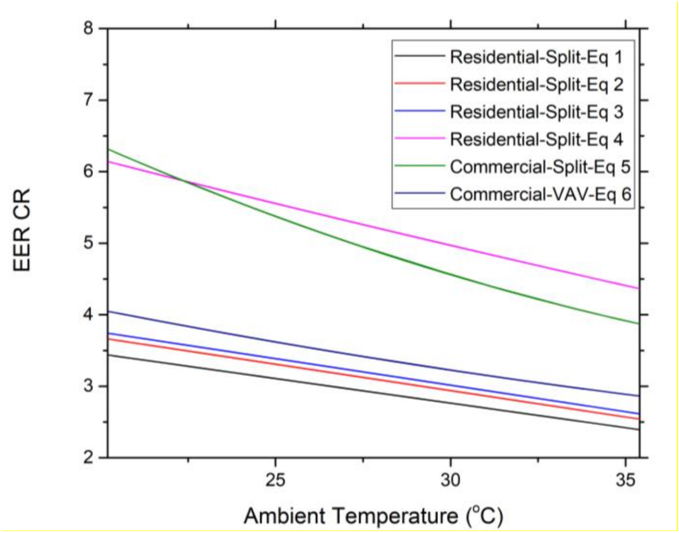


Figure 59 EER for cool roof scenario for six different AC systems.

5.4.1. Cooling load impacts by modified EER

This section analyses the impact of higher EER values on the cooling loads in the cool roof with modified urban temperature scenario (Scenario 2) compared to the reference scenario in the two summer months in Redland and Amberley stations. The corresponding cooling load savings by application of cool roofs in individual buildings (scenario 1) and both individual buildings and at the whole urban area (scenario 2) for the same period was also estimated for the comparison purpose. **Table 21** and **Table 22** show the cooling load savings by application of cool roofs in individual buildings (scenario 1), implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2), and modified EER for the six different AC systems in Redland and Amberley stations, respectively.

Table 21 Sensible cooling load saving of cool roofs by scenario 1, scenario 2 , and additional sensible cooling load due to modified EER using equation 1-6 for B01-B017 (B01: A low-rise office building without roof insulation-existing building, B02-A high-rise office building without roof insulation-existing building, B03-A low-rise office building with roof insulation-new building, B04-A high-rise office building with roof insulation-new building, B05-A low-rise shopping mall centre-new building, B06-A mid-rise shopping mall centre-new building, B07-A high-rise shopping mall centre-new building, B08-A low-rise apartment building-new building, B09-A mid-rise apartment building-new building, B10-A high-rise apartment building-new building, B11-A typical stand-alone house-existing building, B12-A typical school building-existing building, B13-A low-rise office building with roof insulation-existing building, B14-A high-rise office building with roof insulation-existing building, B15-A low-rise shopping mall centre-existing building, B16-A high-rise shopping mall centre-existing building, B17-A stand-alone house-new building) in Redland station.

Building	Cooling load-Reference	EG-Scenario 1		EG-Scenario 2		EG-EER-Equation 1		EG-EER-Equation 2		EG-EER-Equation 3		EG-EER-Equation 4		EG-EER-Equation 5		EG-EER-Equation 6	
		kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
B01	30.3	11.6	38	12.9	43	1.5	5	1.6	5	1.6	5	2.5	8	3.2	11	1.6	5
B02	21.4	2.1	10	3.1	14	1.4	7	1.6	7	1.6	7	2.4	11	3.2	15	1.6	7
B03	20.2	1.1	5	2.3	11	1.3	6	1.4	7	1.4	7	2.2	11	2.9	14	1.4	7
B04	19.8	0.2	1	1.2	6	1.3	7	1.4	7	1.4	7	2.2	11	3.0	15	1.5	7
B05	61.1	1.4	2	3.9	6	4.3	7	4.6	8	4.6	8	7.2	12	9.7	16	4.7	8
B06	60.3	0.7	1	3.3	5	4.3	7	4.6	8	4.6	8	7.2	12	9.6	16	4.7	8
B07	59.9	0.4	1	3.0	5	4.3	7	4.6	8	4.6	8	7.2	12	9.6	16	4.7	8
B08	13.6	1.0	7	2.8	21	0.7	5	0.8	6	0.8	6	1.3	9	1.7	13	0.8	6
B09	13.4	0.6	4	2.4	18	0.8	6	0.8	6	0.8	6	1.3	9	1.7	13	0.8	6
B10	13.1	0.3	2	2.1	16	0.8	6	0.8	6	0.8	6	1.3	10	1.7	13	0.8	6
B11	12.8	2.9	23	4.3	34	1.1	9	1.2	10	1.2	10	1.9	15	2.5	19	1.2	10
B12	19	0.7	4	1.9	10	1.5	8	1.7	9	1.7	9	2.6	14	3.4	18	1.7	9
B13	24.3	5.6	23	6.8	28	1.3	5	1.4	6	1.4	6	2.1	9	2.8	12	1.4	6

B14	20.4	1.0	5	2.0	10	1.3	6	1.4	7	1.4	7	2.2	11	3.0	14	1.5	7
B15	65.2	6.9	11	9.5	15	4.2	6	4.5	7	4.5	7	7.1	11	9.4	14	4.6	7
B16	61	2.1	3	4.7	8	4.2	7	4.5	7	4.6	7	7.1	12	9.5	16	4.7	8
B17	12.9	3.0	23	4.4	34	0.6	5	0.6	5	0.6	5	1.0	8	1.3	10	0.6	5

Table 22 Sensible cooling load saving of cool roofs by scenario 1, scenario 2 , and additional sensible cooling load due to modified EER using equation 1-6 for B01-B017 (B01: A low-rise office building without roof insulation-existing building, B02-A high-rise office building without roof insulation-existing building, B03-A low-rise office building with roof insulation-new building, B04-A high-rise office building with roof insulation-new building, B05-A low-rise shopping mall centre-existing building-new building, B06-A mid-rise shopping mall centre- new building, B07-A high-rise shopping mall centre-new building, B08-A low-rise apartment building-new building, B09-A mid-rise apartment building-new building, B10-A high-rise apartment building-new building, B11-A typical stand-alone house-existing building, B12-A typical school building-existing building, B13-A low-rise office building with roof insulation-existing building, B14-A high-rise office building with roof insulation-existing building, B15-A low-rise shopping mall centre-existing building, B16-A high-rise shopping mall centre-existing building, B17-A stand-alone house-new building) in Amberley station.

Building	Cooling load-Reference	EG-Scenario 1		EG-Scenario 2		EG-EER-Equation 1		EG-EER-Equation 2		EG-EER-Equation 3		EG-EER-Equation 4		EG-EER-Equation 5		EG-EER-Equation 6	
		kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
B01	35.5	14.7	41	16.0	45	1.9	5	2.0	6	2.1	6	3.1	9	3.7	10	1.9	5
B02	23.7	2.7	11	4.0	17	1.9	8	2.0	9	2.0	9	3.1	13	3.6	15	1.9	8
B03	21.8	1.3	6	2.6	12	1.6	7	1.7	8	1.7	8	2.7	12	3.1	14	1.6	7
B04	21.3	0.3	1	1.5	7	1.7	8	1.8	8	1.8	8	2.7	13	3.2	15	1.7	8
B05	65.9	1.8	3	4.5	7	5.3	8	5.7	9	5.7	9	8.8	13	10.5	16	5.4	8
B06	64.8	0.9	1	3.6	6	5.3	8	5.7	9	5.7	9	8.8	14	10.5	16	5.4	8
B07	64.3	0.6	1	3.2	5	5.3	8	5.7	9	5.7	9	8.7	14	10.5	16	5.4	8
B08	15.9	1.2	8	3.0	19	1.0	6	1.1	7	1.1	7	1.7	11	2.1	13	1.0	7
B09	15.6	0.7	4	2.5	16	1.0	7	1.1	7	1.1	7	1.7	11	2.1	13	1.1	7
B10	15.3	0.4	3	2.2	14	1.0	7	1.1	7	1.1	7	1.7	11	2.1	14	1.1	7
B11	15.5	3.5	23	5.1	33	1.5	10	1.6	11	1.6	11	2.5	16	2.9	19	1.5	10
B12	20.7	0.8	4	2.1	10	2.2	10	2.3	11	2.3	11	3.6	17	4.1	20	2.1	10
B13	27.3	6.9	25	8.2	30	1.6	6	1.7	6	1.7	6	2.6	10	3.1	11	1.6	6
B14	22.2	1.3	6	2.5	11	1.7	7	1.8	8	1.8	8	2.7	12	3.2	14	1.7	7

B15	72.1	8.9	12	11.5	16	5.2	7	5.6	8	5.7	8	8.7	12	10.3	14	5.3	7
B16	66.1	2.7	4	5.4	8	5.3	8	5.6	9	5.7	9	8.7	13	10.4	16	5.3	8
B17	15.3	3.6	24	5.1	33	0.8	5	0.8	6	0.9	6	1.3	9	1.6	10	0.8	5

5.5 Conclusions

This study investigated the impact of cool roofs on EER of different AC systems and the corresponding cooling load saving in seventeen types of buildings in Brisbane. The AC systems considered in this study include AC residential and commercial split and VAV systems. To estimate the energy saving by modified EER, the hourly cooling load simulation was first performed for reference scenario and cool roof with modified urban temperature scenario (scenario 2). Then, the energy gains by modified EER was calculated using the hourly cooling loads for different AC systems. At last, a detailed analysis on the impact of cool roofs on cooling loads savings by implementation of cool roofs in individual buildings (scenario 1), application of cool roofs in both individual buildings and at the whole urban area (scenario 2), and modified EER for different AC systems was provided. A summary on the cooling load savings by application of cool roofs in individual buildings (scenario 1), implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2), and modified EER for different types of buildings in two summer months is given in **Table 23**.

Table 23 Average median ratio of hourly cooling load in cool roof with modified urban temperature (scenario 2) to reference scenario, two-month cooling load-Reference scenario, two-month cooling load saving by reference with cool roof scenario (Scenario 1), two-month cooling load saving- cool roof with modified urban temperature (Scenario 2), and two-month cooling load saving by modified EER using equations 1-6 for seventeen different types of buildings for the coldest and hottest weather stations (i.e. Redland and Amberley) in Brisbane.

Buildings	Stations	Average median ratio of hourly cooling load in cool roof with modified urban temperature (scenario 2) to reference scenario	Two-month cooling load-Reference scenario (kWh/m^2)	Two-month cooling load saving by reference with cool roof scenario (Scenario 1)		Two-month cooling load saving by cool roof with modified urban temperature (Scenario 2)		Two-month cooling load saving by modified EER-Equation 1-6	
				kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
B01- low-rise office building without roof insulation-existing building	Redland	0.64	30.3	11.6	38	12.9	43	1.5-3.2	5-11
	Amberley	0.65	35.5	14.7	41	16.0	45	1.9-3.7	5-10
B02- high-rise office building without roof	Redland	0.88	21.4	2.1	10	3.1	14	1.4-3.2	7-15
	Amberley	0.86	23.7	2.7	11	4.0	17	1.9-3.6	8-15

insulation-existing building									
B03- low-rise office building with roof insulation-new building	Redland	0.91	20.2	1.1	5	2.3	11	1.3-2.9	6-14
	Amberley	0.9	21.8	1.3	6	2.6	12	1.6-3.1	7-14
B04- high-rise office building with roof insulation-new building	Redland	0.97	19.8	0.2	1	1.2	6	1.3-3.0	7-15
	Amberley	0.95	21.3	0.3	1	1.5	7	1.7-3.2	8-15
B05- low-rise shopping mall centre-existing building-new building	Redland	0.96	61.1	1.4	2	3.9	6	4.3-9.7	7-16
	Amberley	0.96	65.9	1.8	3	4.5	7	5.3-10.5	8-16
B06- mid-rise shopping mall centre-existing building-new building	Redland	0.97	60.3	0.7	1	3.3	5	4.3-9.6	7-16
	Amberley	0.97	64.8	0.9	1	3.6	6	5.3-10.5	8-16
B07- high-rise shopping mall centre-new building	Redland	0.98	59.9	0.4	1	3.0	5	4.3-9.6	7-16
	Amberley	0.98	64.3	0.6	1	3.2	5	5.3-10.5	8-16
B08- low-rise apartment building-new building	Redland	0.75	13.6	1.0	7	2.8	21	0.7-1.7	5-13
	Amberley	0.75	15.9	1.2	8	3.0	19	1.0-2.1	6-13
B09- mid-rise apartment	Redland	0.78	13.4	0.6	4	2.4	18	0.8-1.7	6-13
	Amberley	0.78	15.6	0.7	4	2.5	16	1.0-2.1	7-13

building-new building									
B10- high-rise apartment building-new building	Redland	0.8	13.1	0.3	2	2.1	16	0.8-1.7	6-13
	Amberley	0.8	15.3	0.4	3	2.2	14	1.0-2.1	7-14
B11- typical stand-alone house-existing building	Redland	0.17	12.8	2.9	23	4.3	34	1.1-2.5	9-19
	Amberley	0.18	15.5	3.5	23	5.1	33	1.5-2.9	10-19
B12- typical school building-existing building	Redland	1.00	19	0.7	4	1.9	10	1.5-3.4	8-18
	Amberley	1.00	20.7	0.8	4	2.1	10	2.2-4.1	10-20
B13- low-rise office building with roof insulation-existing building	Redland	0.76	24.3	5.6	23	6.8	28	1.3-2.8	5-12
	Amberley	0.72	27.3	6.9	25	8.2	30	1.6-3.1	6-11
B14- high-rise office building with roof insulation-existing building	Redland	0.93	20.4	1.0	5	2.0	10	1.3-3.0	6-14
	Amberley	0.9	22.2	1.3	6	2.5	11	1.7-3.2	7-14
B15- low-rise shopping mall centre-existing building	Redland	0.87	65.2	6.9	11	9.5	15	4.2-9.4	6-14
	Amberley	0.87	72.1	8.9	12	11.5	16	5.2-10.3	7-14
B16- high-rise shopping mall centre-existing building	Redland	0.95	61	2.1	3	4.7	8	4.2-9.5	7-16
	Amberley	0.87	66.1	2.7	4	5.4	8	5.3-10.4	8-16

B17- stand-alone house-new building	Redland	0.64	12.9	3.0	23	4.4	34	0.6-1.3	5-10
	Amberley	0.64	15.3	3.6	24	5.1	33	0.8-1.6	5-10

The conclusions drawn from this study are:

- In low-rise buildings without roof insulation/with low level of insulation, the application of cool roofs in both individual buildings and at the whole urban area can significantly reduce the hourly cooling loads. For instance, the average median ratio of cooling load in cool roof with modified urban temperature scenario (scenario 2) to reference scenario is estimated to be 0.64-0.65 and 0.72-0.76 for a low-rise office building without roof insulation-existing building (b01) and low-rise office building with roof insulation-existing building (b13), respectively.
- In high-rise buildings with high level of insulation, the cooling load savings by modified EER is significant. For instance, the two-months cooling load savings by modified EER is estimated to range between 1.7 and 3.2 kWh/m2 for a new high-rise office building with roof insulation-new building in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 0.3 and 1.5 kWh/m2, respectively.
- The application of cool roofs in both individual buildings and at the whole urban area is predicted to improve the hourly EER of the six selected AC systems by 0.11-0.31 and 0.12-0.35 and in Redland and Amberley stations, respectively.
- In low-rise buildings with low level of insulation, the cooling load savings by modified EER is noticeable. For instance, the cooling load savings by modified EER is estimated to range between 1.9 and 3.7 kWh/m2 for an existing office building without roof insulation in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 14.7 and 16.0 kWh/m2, respectively.
- In commercial buildings, the cooling load savings by modified EER is quite significant. For instance, the cooling load savings by modified EER is estimated to range between 5.3 and 10.5 kWh/m^2 for a new high-rise shopping mall centre in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 0.6 and 3.2 kWh/m2, respectively.

6. Feasibility of cool roofs: Evaluation of refurbishment of 17 buildings for Amberley and Redland weather conditions

6.1 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 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, a 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 that 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 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 away, 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.

6.2 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)
  - Life time 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 24** and

Table 25.

Table 24 Building Features

Building features	B01 Amberley	BO1 Redland
Energy consumption prior cool roof (MWh)	111.90	99.9
Energy consumption after cool roof (MWh)	71.30	61.00
Energy savings (MWh)	40.60	38.90
Energy savings (%)	36.28%	38.94%
Area (m2)	1,200	1,200
Roof costs - Metal roof (AU$/m2)	38.00	38.00
Roof costs - Coating (AU$/m2)	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$/m2)	15.0	15.0

Table 25 Energy cost and economics

Energy cost and economics	
Electricity cost - Low (AU$/MWh)	150
Electricity cost - High (AU$/MWh)	290
Increase rate of electricity	0,034
Capital cost	0,030

6.3 Assumptions

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

The refurbishment of the roof is taking place in 'Year 0', e.g. in present time, whilst the energy savings are occurring after the 6^{th} 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.

6.4 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.

6.5 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 1 refers to Amberley weather conditions, whilst Part 2 to Redland 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 Amberley weather conditions

Table 26 Net Present Value for Amberley weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	108,467	96,567	206,751	184,929
2	89,280	81,107	213,929	181,545
3	-29,224	-14,380	-15,179	-3,063
4	-31,481	-16,198	-19,543	-6,579
5	-15,001	-3,683	8,876	15,556
6	-16,505	-4,896	5,966	13,211
7	-18,010	-6,108	10,322	15,419
8	-12,111	-4,992	-1,929	3,213
9	-12,864	-5,598	-3,384	2,041
10	-13,240	-5,901	-4,111	1,455
11	-4,790	-2,011	-928	1,101
12	-19,139	-7,018	875	9,109
13	28,712	32,303	96,830	87,190
14	18,930	24,421	77,919	71,952
15	80,179	73,009	192,889	163,827
16	67,764	63,006	168,888	144,488
17	-4,414	-1,708	-200	1,688

Table 27 Internal Rate of Return for Amberley weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	16.54%	27.77%	15.98%	26.78%
2	14.42%	24.07%	28.26%	49.80%
3	-3.71%	-3.36%	0.11%	1.87%
4	-4.56%	-4.49%	-0.90%	0.47%
5	-0.16%	1.51%	4.55%	8.27%
6	-0.54%	0.98%	4.06%	7.55%
7	-0.93%	0.43%	4.69%	7.97%
8	-1.88%	-0.87%	2.36%	5.07%
9	-2.28%	-1.42%	1.85%	4.34%
10	-2.50%	-1.71%	1.59%	3.97%
11	-2.00%	-1.04%	2.20%	4.84%
12	-1.24%	0.01%	3.16%	6.23%
13	7.22%	12.33%	15.25%	25.52%
14	5.89%	10.30%	13.14%	21.90%
15	14.21%	23.72%	27.86%	49.01%
16	12.69%	21.14%	24.90%	43.23%
17	-1.50%	-0.35%	2.83%	5.75%

Table 28 Life Cycle Cost for Amberley weather data

LCC	Low Electricity Price			High Electricity Price		
Building	**As built**	**Metal Roof**	**Coating**	**As built**	**Metal Roof**	**Coating**
1	432,525	304,357	234,490	836,986	591,375	455,114
2	1,476,115	1,346,933	1,070,638	2,843,038	2,562,751	2,045,162
3	294,082	306,284	236,563	557,776	550,829	432,617
4	1,367,768	1,361,445	1,082,738	2,633,568	2,590,807	2,068,556
5	1,104,591	1,087,826	864,016	2,125,658	2,065,254	1,647,754
6	2,136,142	2,100,916	1,676,449	4,119,989	4,023,893	3,218,459
7	3,162,802	3,109,209	2,485,037	7,119,428	6,980,559	5,412,896
8	174,171	177,020	137,237	331,123	320,751	252,461
9	274,993	276,643	217,131	526,047	513,357	406,923
10	425,099	424,219	335,478	816,250	798,671	635,728
11	23,397	25,450	18,578	43,060	40,870	30,929
12	554,957	552,969	435,113	1,063,033	1,031,197	818,542
13	349,761	302,949	233,667	665,421	544,382	427,018
14	1,409,150	1,351,615	1,074,662	2,713,574	2,571,803	2,052,943
15	1,153,874	1,040,976	826,080	2,220,938	1,974,676	1,574,411
16	3,193,650	3,053,686	2,440,183	6,107,004	5,865,916	4,695,011
17	24,150	25,811	18,867	44,515	41,569	31,487

Table 29 Payback Period for Amberley weather data

PB	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	12.5	7.8	6.6	3.9
2	7.3	4.4	3.7	2.1
3	-	-	27.6	18.4
4	-	-	-	21.0
5	-	19.0	16.8	10.7
6	-	20.0	17.7	11.3
7	-	21.1	17.1	11.2
8	-	-	21.3	13.8
9	-	-	22.6	14.7
10	-	-	23.3	15.2
11	-	-	21.7	14.1
12	-	22.0	19.5	12.5
13	12.9	8.0	6.9	4.1
14	14.7	9.2	8.0	4.8
15	7.4	4.4	3.8	2.1
16	8.3	4.9	4.2	2.4
17	-	-	20.2	13.0

In order to comparatively illustrate the results for the 17 buildings, in the following **Figure 61** and **Figure 62** are depicted their Internal Rate of Return and their Life Cycle Cost values

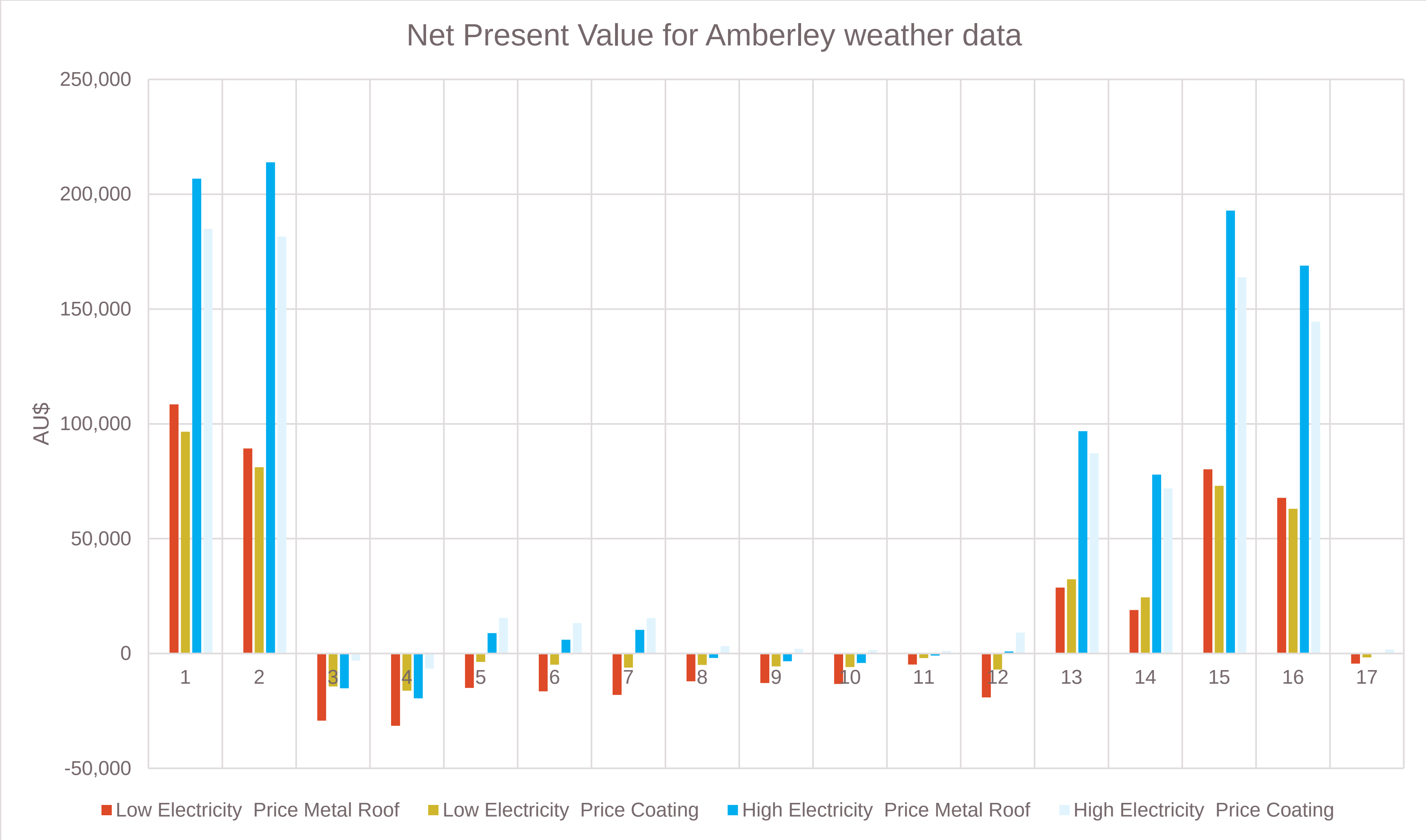


Figure 60 Net Present Value for the buildings for Amberley weather conditions

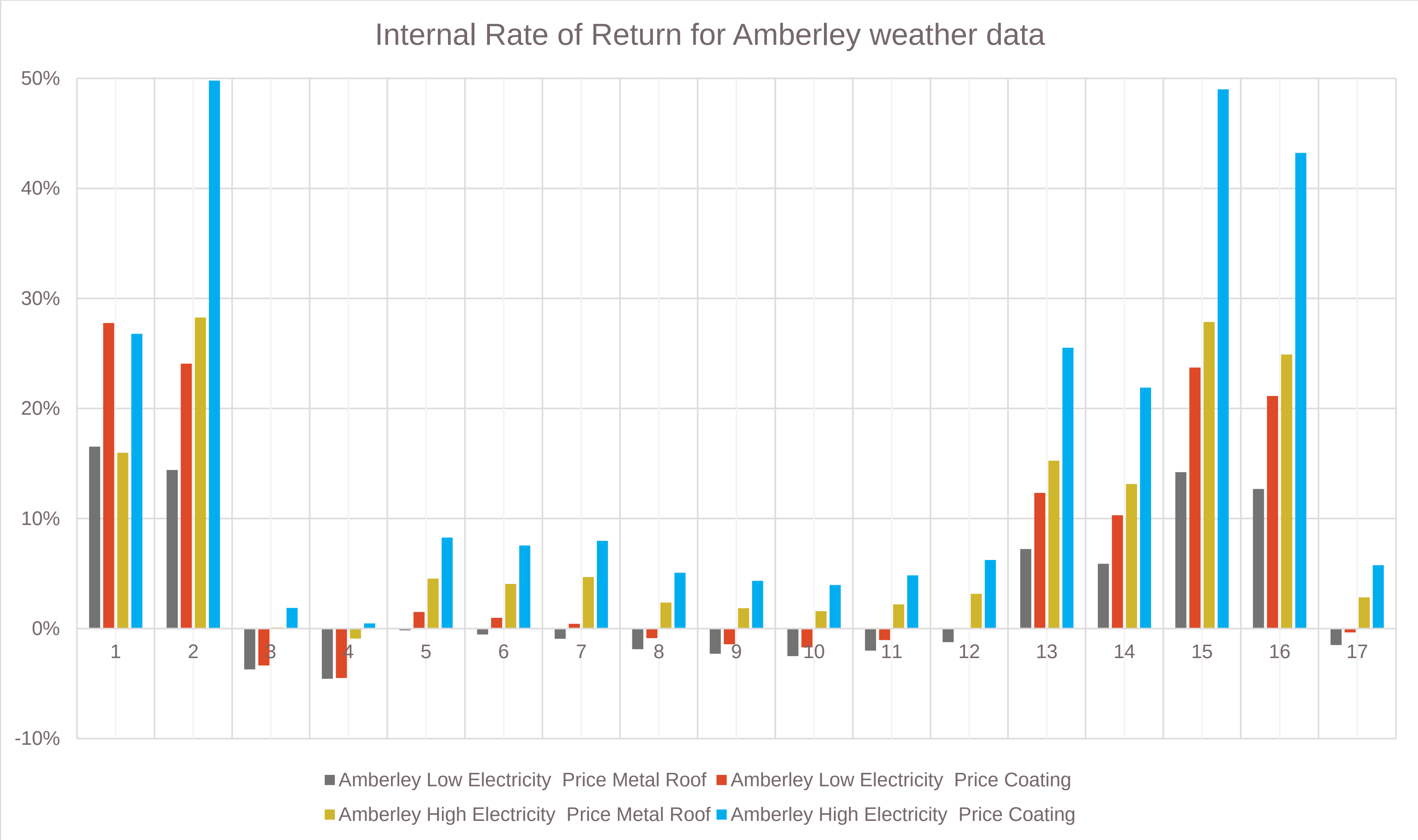


Figure 61 Internal Rate of Return for the buildings for Amberley weather conditions

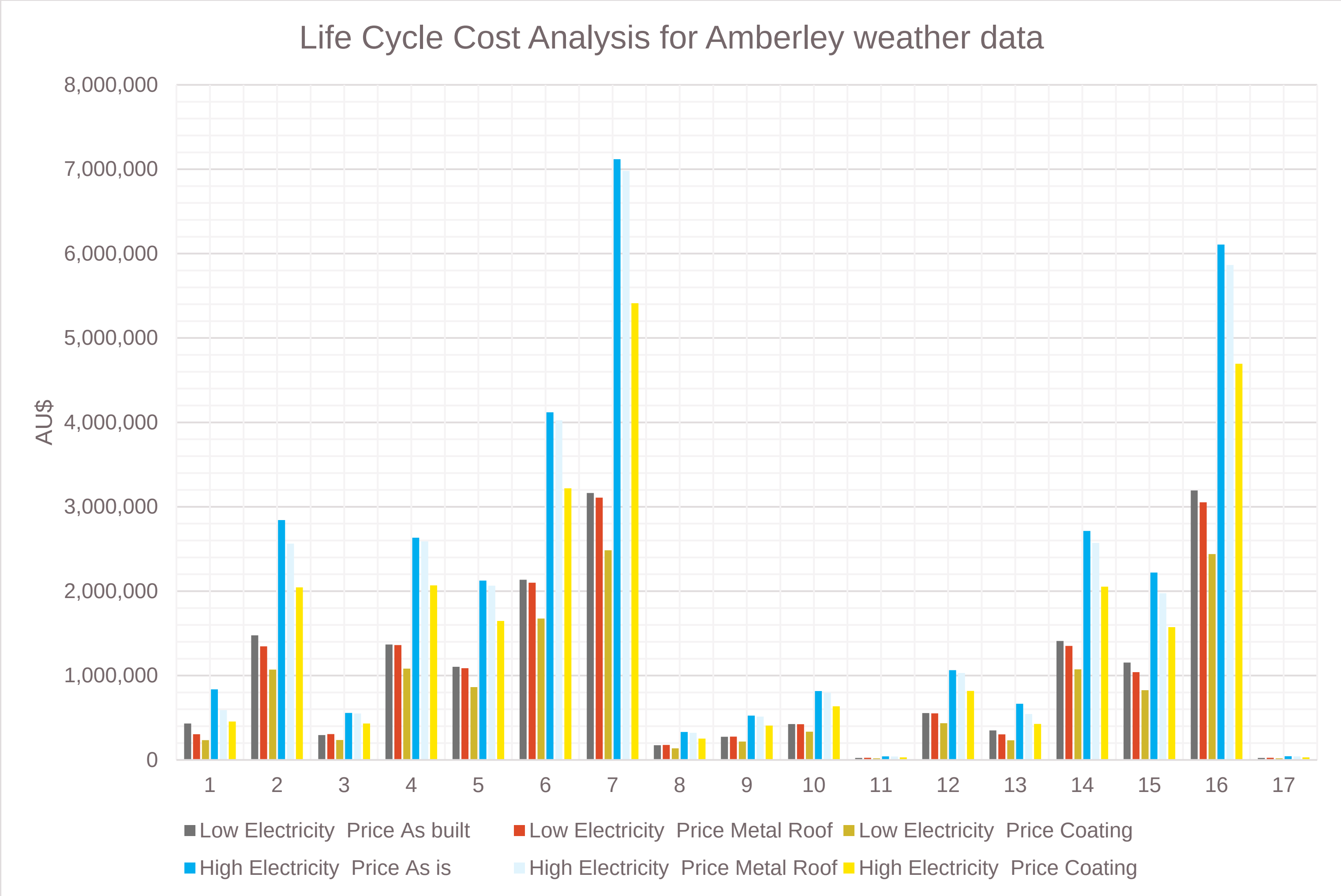


Figure 62 Life Cycle Cost for the buildings for Amberley weather conditions

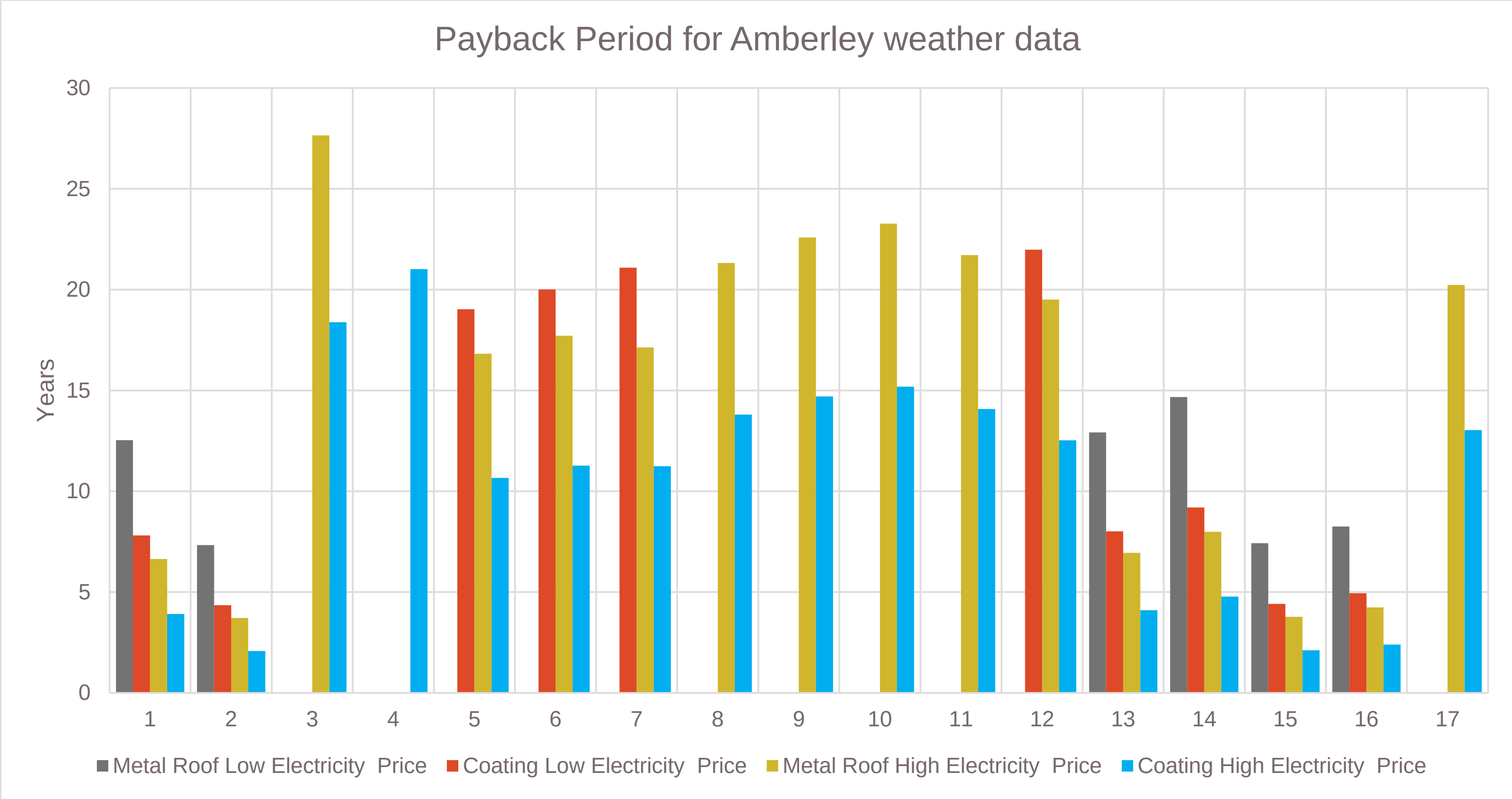


Figure 63 Payback Period for the buildings for Amberley weather conditions

6.5.2 Part 2. Results for Redland weather conditions

Table 30 Net Present Value for Redland weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	102,071	91,413	194,387	174,966
2	82,133	75,347	200,110	170,410
3	-29,976	-14,986	-16,633	-4,235
4	-31,857	-16,502	-20,270	-7,165
5	-14,248	-3,077	10,330	16,728
6	-15,377	-3,986	8,148	14,970
7	-16,882	-5,199	12,867	17,405
8	-10,230	-3,476	1,708	6,143
9	-10,983	-4,082	253	4,971
10	-11,735	-4,689	-1,202	3,799
11	-4,038	-1,404	527	2,274
12	-16,129	-4,593	6,694	13,797
13	26,454	30,484	92,466	83,673
14	17,049	22,906	74,282	69,022
15	85,822	77,556	203,799	172,618
16	70,774	65,431	174,706	149,176
17	-3,661	-1,101	1,254	2,860

Table 31 Internal Rate of Return for Redland weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	15.83%	26.53%	15.29%	25.59%
2	13.62%	22.70%	26.69%	46.70%
3	-3.98%	-3.72%	-0.22%	1.42%
4	-4.71%	-4.69%	-1.08%	0.22%
5	0.03%	1.76%	4.79%	8.63%
6	-0.25%	1.38%	4.43%	8.09%
7	-0.63%	0.85%	5.07%	8.54%
8	-0.94%	0.43%	3.54%	6.79%
9	-1.30%	-0.08%	3.08%	6.12%
10	-1.68%	-0.60%	2.60%	5.43%
11	-1.02%	0.31%	3.43%	6.63%
12	-0.44%	1.11%	4.18%	7.73%
13	6.92%	11.87%	14.77%	24.68%
14	5.63%	9.89%	12.73%	21.21%
15	14.90%	24.90%	29.23%	51.72%
16	13.06%	21.76%	25.61%	44.61%
17	-0.57%	0.93%	4.01%	7.48%

Table 32 Life Cycle Cost for Redland weather data

LCC	Low Electricity Price			High Electricity Price		
Building	**As built**	**Metal Roof**	**Coating**	**As built**	**Metal Roof**	**Coating**
1	387,381	266,482	204,141	749,707	518,150	396,440
2	1,313,595	1,194,707	948,590	2,528,833	2,268,446	1,809,203
3	260,224	273,834	210,543	492,317	488,091	382,312
4	1,217,663	1,214,622	964,997	2,343,364	2,306,948	1,840,924
5	1,147,102	1,128,762	896,840	2,207,846	2,144,396	1,711,215
6	2,227,935	2,189,804	1,747,728	4,297,457	4,195,744	3,356,263
7	3,301,997	3,244,582	2,593,592	7,433,340	7,286,717	5,650,614
8	154,232	155,586	120,041	292,575	279,313	219,216
9	243,392	243,773	190,764	464,951	449,807	355,946
10	376,192	374,755	295,805	721,698	703,039	559,026
11	21,140	22,484	16,197	38,696	35,135	26,325
12	496,270	492,408	386,535	949,570	834,776	724,625
13	311,388	267,577	205,309	591,233	475,994	372,192
14	1,253,778	1,201,132	953,992	2,413,188	2,280,867	1,819,646
15	1,189,237	1,070,011	849,343	2,289,307	2,030,811	1,619,386
16	3,324,945	3,179,430	2,541,010	3,324,945	3,177,419	2,538,998
17	21,893	22,845	16,486	40,151	35,835	26,883

Table 33 Payback Period for Redland weather data

PB	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	13.0	8.1	6.9	4.1
2	7.7	4.6	4.0	2.2
3	-	-	-	19.2
4	-	-	-	21.5
5	27.9	18.6	16.4	10.4
6	-	19.3	17.0	10.8
7	-	20.3	16.5	10.8
8	-	21.1	18.7	12.0
9	-	-	19.7	12.6
10	-	-	20.7	13.4
11	-	21.3	18.9	12.1
12	-	19.8	17.5	11.1
13	13.3	8.3	7.2	4.2
14	15.1	9.5	8.2	4.9
15	7.1	4.2	3.6	2.0
16	8.0	4.8	4.1	2.3
17	-	20.1	17.8	11.3

In order to comparatively illustrate the results for the 17 buildings, in the following **Figure 65** and **Figure 66** are depicted their Internal Rate of Return and their Life Cycle Cost values.

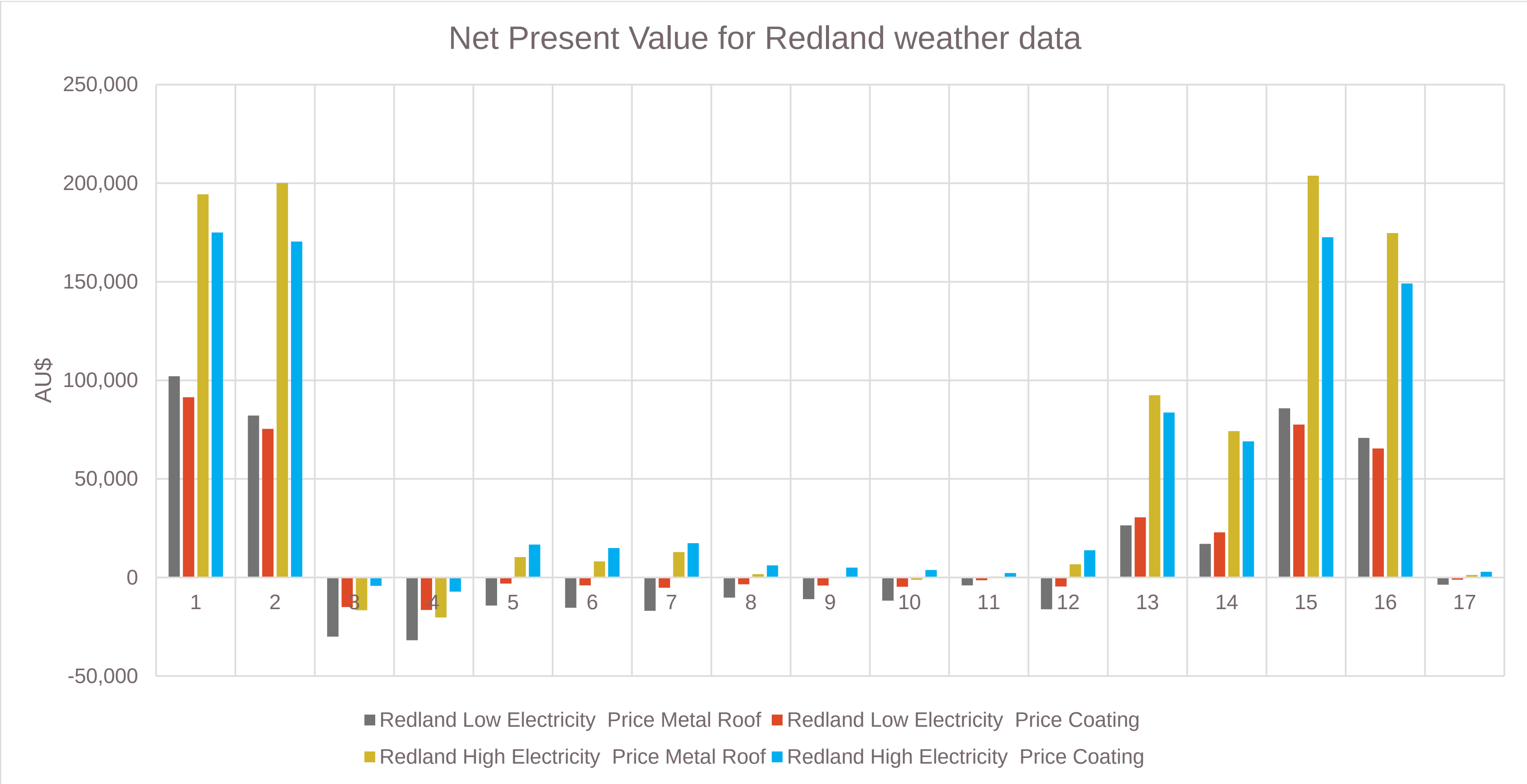


Figure 64 Net Present Value for the buildings for Redland weather conditions

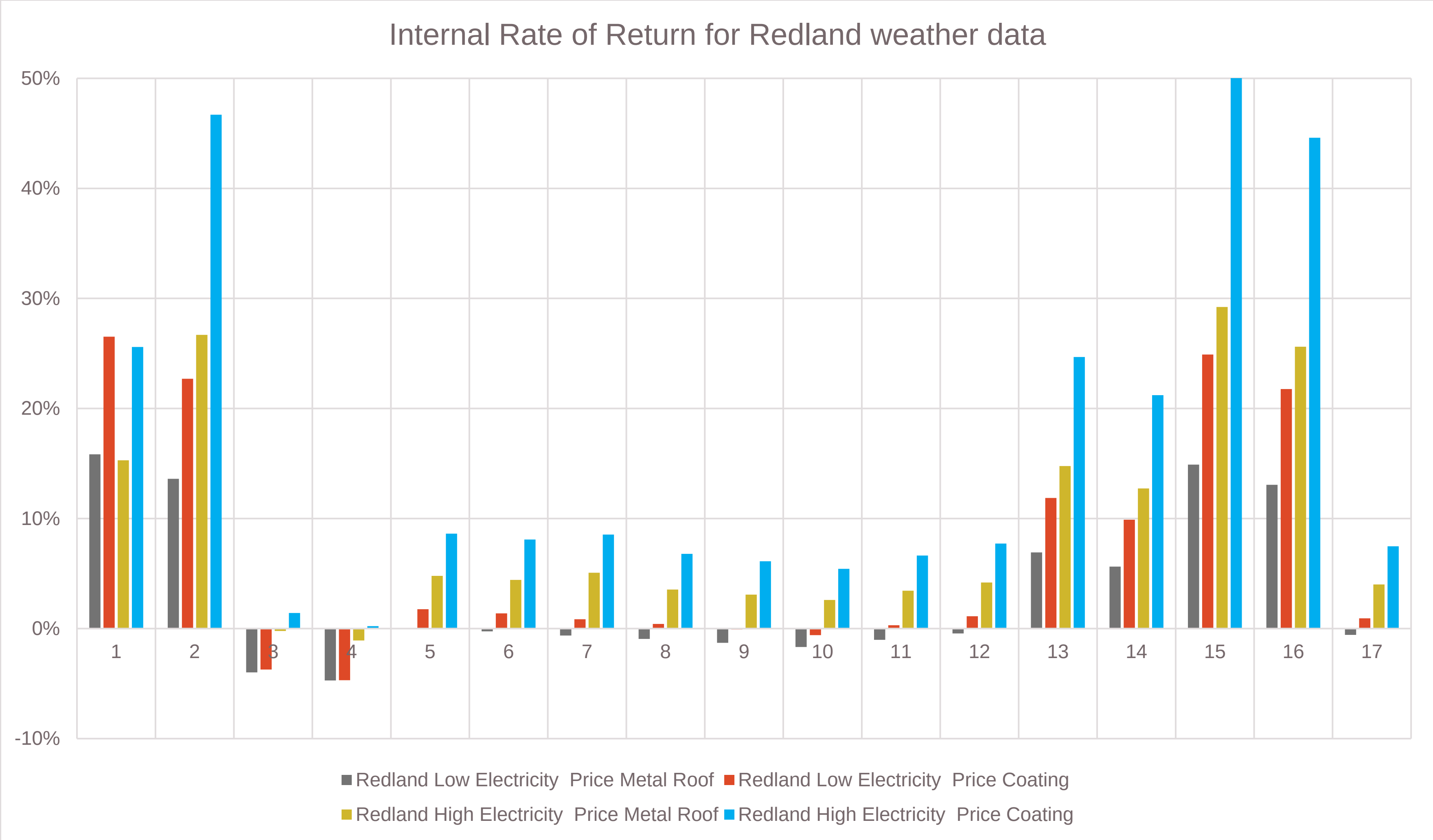


Figure 65 Internal Rate of Return for the buildings for Redland weather conditions

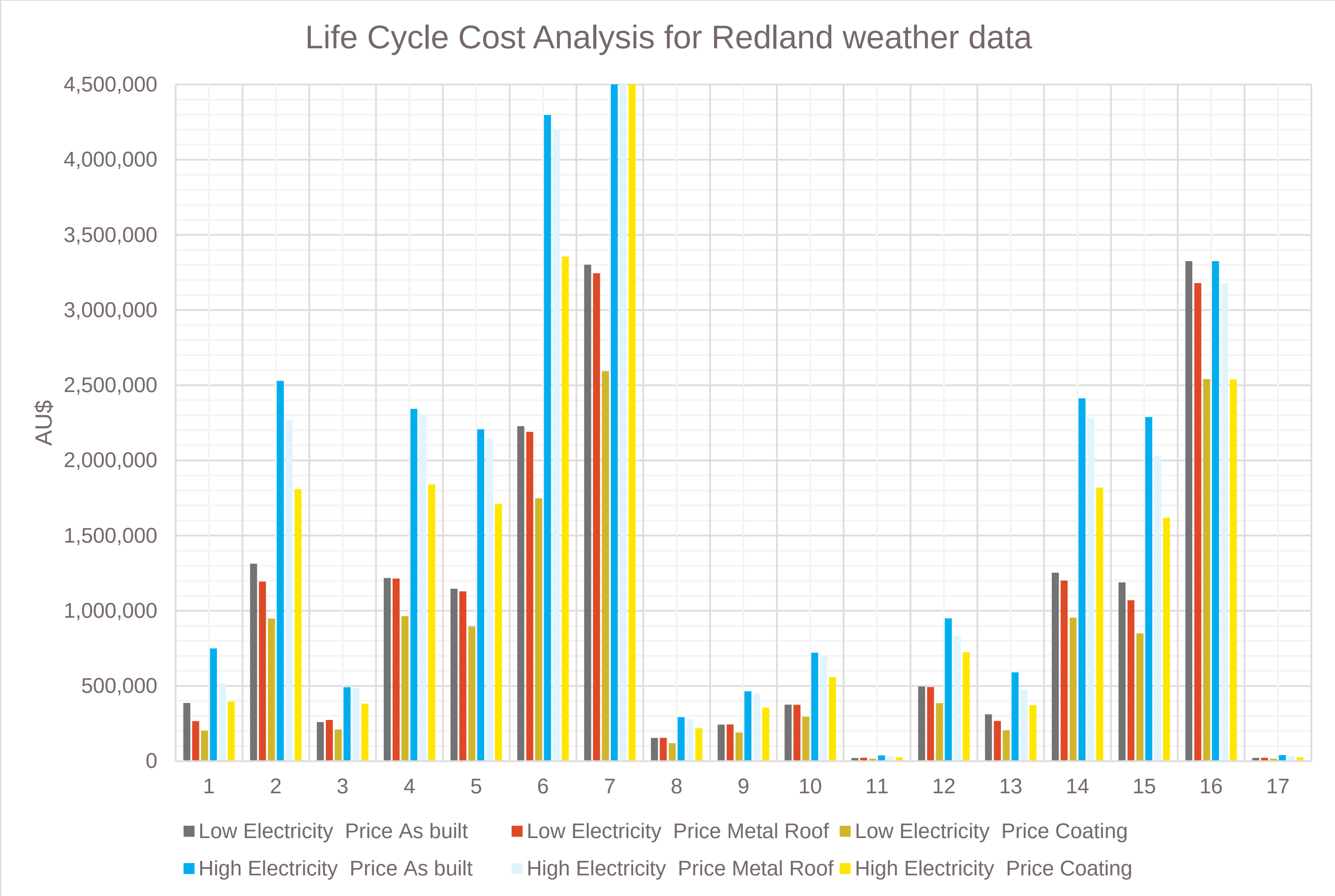


Figure 66 Life Cycle Cost for the buildings for Redland weather conditions

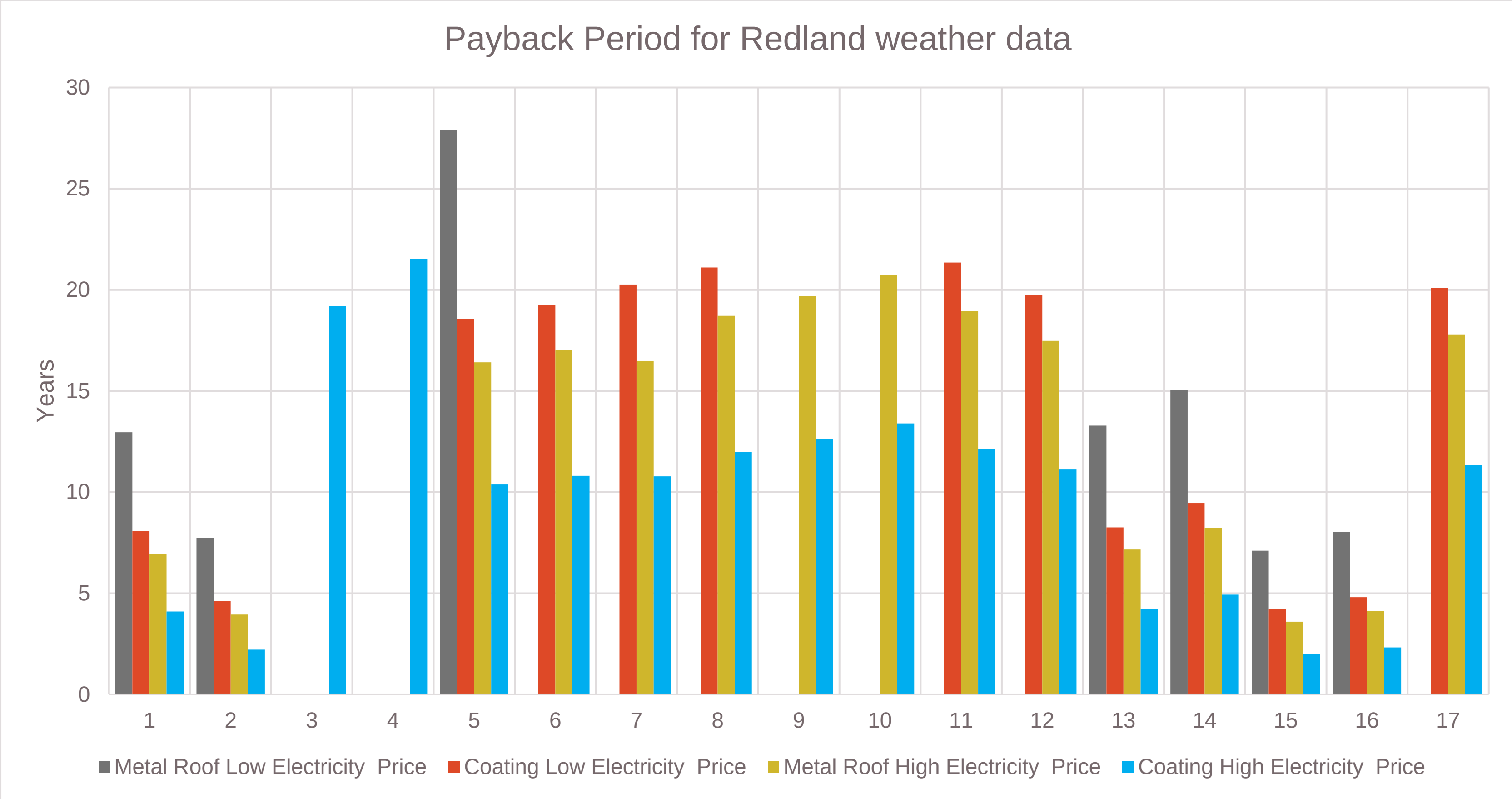


Figure 67 Payback Period for the buildings for Redland weather conditions

6.6 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, B01, B13 and B15), the Life Cycle Cost can be reduced by as much as 59%. In such favourable cases, the Payback Period can be as low as 2.0 years.

But even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B03 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.

7. Conclusions

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

1) Evaluated the existing climatic conditions (reference case) in the city of Brisbane.
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 Brisbane.
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 Brisbane.
5) Compared the energy loss through building envelopes in various building types and the advantages of applying cool roofs in various stations.
6) Evaluated the feasibility of cool roofs by assessing the refurbishment of 17 buildings for Amberley and Redland weather conditions.

Specifically, the following conclusions have been drawn:

1) It is found that a strong urban heat island (UHI) phenomenon is developed. The maximum magnitude of the phenomena may exceed 5°C. The UHI effect would be added evenhandedly balanced spatially under the urban expansion. The intensity and the characteristics of the phenomena are strongly influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the desert area. The possible existence of an additional heating mechanism, like the advection of warm air from nearby spaces, may intensify the strength of the problem.
2) High-density parts of the city exhibit a much higher temperature drop than the urban average. An increase of albedo in Brisbane can decrease the peak summer ambient temperature up to 2.5°C and surface temperature up to 6.8°C. It was found that important temperature differences exist near the coast and central part of the city. The patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the magnitude of the surface thermal gradient.
3) The maximum decrease of sensible heat and latent heat flux were up to 184.6 W/m^2 and 17.4 Wm-2, respectively.
4) The maximum decrease of wind speeds is up to 2.5 ms-1. Cool roofs increase the pressure at the local scale and decrease the wind advection from the bare surface.
5) The results of numerical experiments 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. Under the low wind speed, an additional thermal gradient was observed over Brisbane city. When the wind speed is low, and the ambient and surface temperature is very high. Under these conditions, there is a substantial temperature difference between the cool roofs and the warm pavements that generate some small local thermal winds at the neighbourhood scale.
6) In average, compared to the reference scenario, 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 45%-74% of the ambient temperatures in all stations concentrate in the range of 18-25 °C.
7) Alteration of the urban albedo in Brisbane results in a solemn average reduction up to 735.6 m of the PBL heights over the city and may increase the concentration of pollutants at ground level,

8) The urban–sea temperature difference approaches to sea-breeze effects. The cool roof reduced daytime ambient temperatures, but higher winds over cool roof implemented city greatly reduced the sea breeze penetration.
9) The magnitudes of the UHI phenomenon were associated with the existence of a sea breeze in the eastern parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that heat up the western zones of the city.
10) In control cases, CDH ranges from 956.6 to 4167.1, and about 40% of the data is concentrated in 1800 - 2000. CDH gradually increases from the east of the city to the west.
11) In cool roof cases, CDH ranges from 377.7 to 3446.5, and about 50% of the data is concentrated in 1000 - 1400. Its spatial distribution is also similar to that of the control case.
12) The percentage of CDH reduction due to the implementation of the cool roof ranges from 16% to 62%, with an average value of 34.6%. The percentage of CDH reduction in the original control volume is relatively large in the east of the city and gradually decreases toward the west.
13) 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 11.3-15.6 kWh/m2.
14) 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 in the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 18.7-21.3 kWh/m2.
15) In existing buildings without insulation/with low insulation level, the cooling load reduction of the cool roofs is remarkable even for the high-rise buildings. For instance, the application of cool roofs on the individual building (scenario 1) and both individual buildings and at the whole urban area (scenario 2) is expected to decrease the cooling loads of a high-rise office building without roof insulation by 2.0-3.0 kWh/m2 and 8.6-10.4 kWh/m2, respectively.
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 in the whole urban area (scenario 2) is predicted to be 7.3-9.2 kWh/m2 in a typical new low-rise office building.
17) In new high-rise buildings with high insulation level, 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 0.2-0.3 kWh/m2 for new high-rise office buildings with insulation.
18) In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and in 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 just 0.4-0.5 kWh/m2 in a new high-rise apartment building, which is expected to increase to 6.7-9.1 kWh/m2 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 types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 34.7-52.7 kWh/m2, while the corresponding heating penalty is just 0.5-0.9 kWh/m2.

20) 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 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 9.0-10.3 ^oC.
21) 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 buildings and in 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 in 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 9.6-11.1 ^oC.
22) In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, the application of cool roofs in both individual buildings and in the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum indoor air temperature reduction by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 1.7-2.1 ^oC in a typical new low-rise office building.
23) In residential buildings and under free-floating conditions in a typical summer period, the application of cool roofs in individual buildings (scenario 1) or both individual building and in 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 existing stand-alone house is predicted to reduce from 573-592 hours to 530-565 hours and 463-490 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
24) In non-residential buildings and under free-floating conditions in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual buildings and at the whole urban area (scenario 2) has low or no impact on reducing 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 mid-rise shopping mall centres is predicted to remain unchanged after the application of cool roofs.
25) 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 9-10.3 ^oC in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 3.4-3.6 ^oC during a typical winter month.
26) 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 3.4 ^oC occurs when the indoor air temperature is 29.3 ^oC.
27) 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 18-29 hours to 26-31 hours in a typical existing low-rise office building with roof insulation.
28) Regarding the sensible 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.

29) 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.
30) For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present an increasing 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 hotter areas for all buildings except for three residential buildings and two shopping centres.
31) A general ranking of the heat loss coefficients of these buildings from low to high is office, school, residential buildings and shopping mall centres.
32) In low-rise buildings without roof insulation/with low level of insulation, the application of cool roofs in both individual buildings and at the whole urban area can significantly reduce the hourly cooling loads. For instance, the average median ratio of cooling load in cool roof with modified urban temperature scenario (scenario 2) to reference scenario is estimated to be 0.64-0.65 and 0.72-0.76 for a low-rise office building without roof insulation-existing building (b01) and low-rise office building with roof insulation-existing building (b13), respectively.
33) In high-rise buildings with high level of insulation, the cooling load savings by modified EER is significant. For instance, the two-months cooling load savings by modified EER is estimated to range between 1.7 and 3.2 kWh/m2 for a new high-rise office building with roof insulation-new building in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 0.3 and 1.5 kWh/m2, respectively.
34) The application of cool roofs in both individual buildings and at the whole urban area is predicted to improve the hourly EER of the six selected AC systems by 0.11-0.31 and 0.12-0.35 and in Redland and Amberley stations, respectively.
35) In low-rise buildings with low level of insulation, the cooling load savings by modified EER is noticeable. For instance, the cooling load savings by modified EER is estimated to range between 1.9 and 3.7 kWh/m2 for an existing office building without roof insulation in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 14.7 and 16.0 kWh/m2, respectively.
36) In commercial buildings, the cooling load savings by modified EER is quite significant. For instance, the cooling load savings by modified EER is estimated to range between 5.3 and 10.5 kWh/m^2 for a new high-rise shopping mall centre in Amberley station. The corresponding cooling load saving by application of cool roofs in individual building (scenario 1) and application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building/weather station is predicted to be 0.6 and 3.2 kWh/m2, respectively.
37) 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, B01, B13 and B15), the Life Cycle Cost can be reduced by as much as 59%. In such favourable cases, the Payback Period can be as low as 2.0 years.
38) But even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B03 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.

39) 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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9. Appendix: Meso-scale simulation results

Table 34 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	-0.6	-1.8	-1.3	-1.2
Minimum	-0.1	-0.9	-0.6	-0.5
Average of January	-0.4	-1.1	-0.9	-0.8
Average of February	-0.4	-1.2	-1.9	-0.9

Table 35 Reduction of surface temperature: cool roof minus reference scenario

Parameters	**Surface Temperature (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-2.2	-6.1	-5.0	-4.5
Minimum	-1.3	-5.1	-3.9	-3.7
Average of January	-1.9	-5.6	-4.5	-4.1
Average of February	-1.9	-5.6	-4.5	-4.0

Table 36 Reduction of sensible heat flux: cool roof minus reference scenario

Parameters	**Sensible Heat Flux (W/m^2)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-59.7	-175.0	-69.9	-80.1
Minimum	-42.1	-135.4	-56.4	-66.6

Average of January	-51.6	-158.0	-63.4	-74.0
Average of February	-53.2	-162.3	-64.3	-74.5

Table 37 Reduction of latent heat flux: cool roof minus control scenario

Parameters	**Latent Heat Flux (W/m²)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-4.0	-15.1	-5.6	-7.6
Minimum	-2.0	-9.9	-2.4	-5.2
Average of January	-2.8	-12.9	-4.0	-6.1
Average of February	-3.4	-13.4	-4.6	-6.9

Table 38 Reduction of wind speed: cool roof minus reference scenario

Parameters	**Wind Speed (m/s)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-1.1	-2.4	-1.8	-1.9
Minimum	-0.1	-0.2	-0.1	-0.2
Average of January	-0.7	-1.1	-0.8	-0.9
Average of February	-0.8	-1.0	-0.6	-0.7

Table 39 Reduction of PBL height: cool roof minus reference scenario

Parameters	**PBL Height (m)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-145.2	-695.5	-251.1	-264.0
Minimum	-110.2	-500.6	-189.5	-199.4

Average of January	-131.1	-615.4	-212.6	-226.1
Average of February	-125.2	-621.0	-209.9	-230.0

10. Appendix: Building characteristics_ Cool roofs project simulations inputs _ Climate zone 2

The following **Table 40** to **Table 43** 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 40 General building parameters, internal gains, and ventilation.

		Office			Shopping mall		School	Standalone House		Apartment
Building ID		**B01 (L), B02 (H)**	**B03 (L), B04 (H)**	**B13 (L), B14 (H)**	**B05 (L), B06 (M), B07 (H)**	**B15 (L), B16 (H)**	**B12**	**B11**	**B17**	**B08 (L), B09 (M), B10 (H)**
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

Table 41 Operation schedules

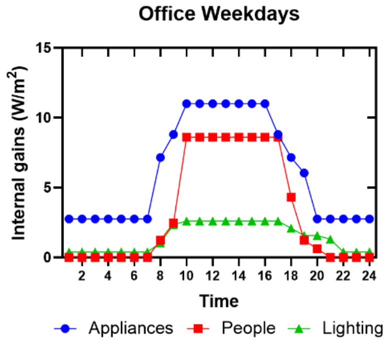
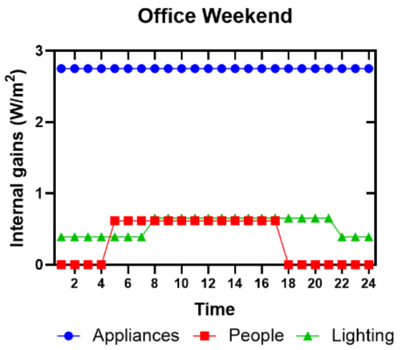
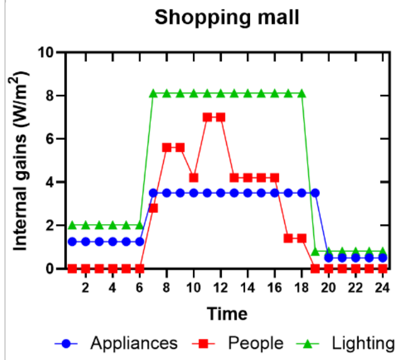
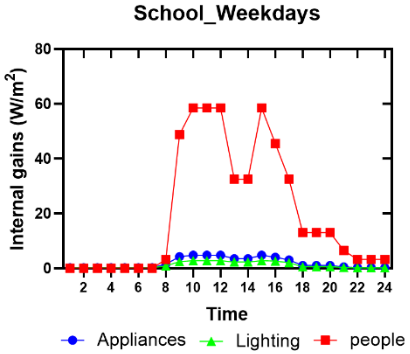
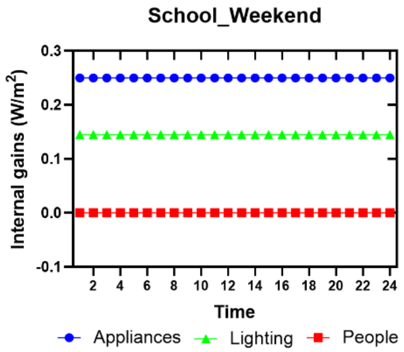
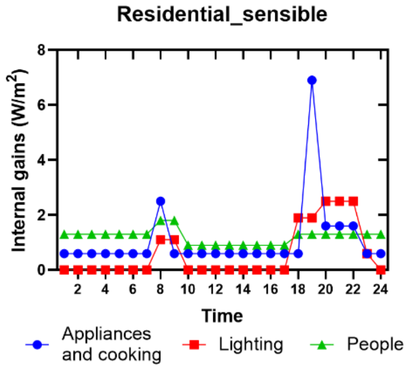
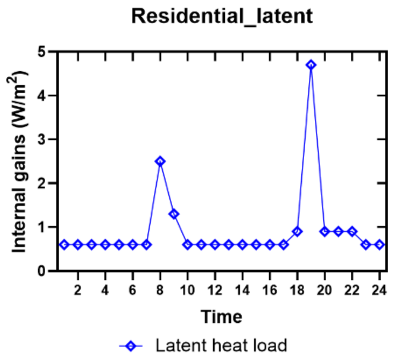
	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Intensity of internal heat gains (W/m^2) **(from NatHERS and NCC 2019)**	 					 	 		

Table 42 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 43 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)-calculated	0.26	3.84	0.64	3.84	0.64	3.84	0.26	4.24	3.84
Roof solar reflectance	0.15_CTRL								
	0.80_COOL								
Roof thermal emittance	0.85								
Wall R-value (m2·K/W)-calculated	1.17	1.17	1.17	1.17		1.17	2.97		1.17
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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