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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 8 – Adelaide: 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 Adelaide, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Adelaide, 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 Adelaide.
4) To understand the process of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.
5) To evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones.
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 Adelaide 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. 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 19 weather stations in Adelaide 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 19 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 nineteenth weather stations across Adelaide. 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 Adelaide during a typical summer and winter period.

Phase 7: Analysis of the impact of building characteristics on the performance of Cool Roofs. Finally, the energy characteristics and mainly the magnitude of thermal losses through the building envelopes and its impact on the performance of cool roofs are assessed in various stations in Adelaide, 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 Sydney (i.e. Kuitpo and Roseworthy stations). 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 Kuitpo and Roseworthy 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 Adelaide.

Collectively, the following conclusions have been drawn:

1) An increase of albedo fraction in Adelaide city can decrease the peak ambient temperature up to 1.9°C and surface temperature up to 6.6°C.
2) The maximum decrease of sensible heat and latent heat flux were 179.5 Wm-^{2} and 15.8 Wm-^{2}, respectively.
3) The highest decrease of wind speeds up to 2.3ms-1. Cool roofs increase the pressure over core urban at local-scale and decrease the wind advection from the adjacent bare surface of desert fetch.
4) 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 58%-95% of the ambient temperatures in all stations concentrate in the range of 12-25 °C.
5) Cooling degree hours indicating the climatic severity during the summer period range from 185.8 to 1328.5, under the existing conditions, increasing from the southeast of the city to the northwest.
6) When cool roofs are used in the city, CDH ranges from 261.5 to 3551.5. The percentage of CDH reduction due to the implementation of the cool roof ranges from 16.2% to 44.3%.
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 9.6-11.3 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 12.5-13.9 kWh/m^2.
9) In new low-rise buildings with high insulation level, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.6-4.3 kWh/m^2 in a typical new low-rise office building.
10) In new buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be 0.9-1.3 kWh/m^2 and 0.2 kWh/m^2 for new low-rise and high-rise office buildings with insulation, respectively.
11) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.3-0.4 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 2.6-3.2 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 11.0-19.2 kWh/m^2, while the corresponding heating penalty is just 1.4-3.6 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 72% and 52% in Kuitpo and Roseworthy 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 7.6-8.4 ^oC and 3.4-3.6 ^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 8.4-10.0 ^oC and 4.3-5.0 ^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 436-457 hours to 326-367 hours and 251-333 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 2.1-3.0 ^oC and 1.4-2.0 ^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 494-510 hours to 388-456 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 7.6-8.4 ^oC in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 0.4-1.8 ^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 3.3 ^oC occurs when the indoor air temperature is 24.0 ^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 176-239 hours to 210-274 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 0.22-0.63 and 0.12-0.41 in Kuitpo and Roseworthy 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 1.2 and 2.3 kWh/m2 for a new high-rise office building with roof insulation-new building in Roseworthy 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 0.2 and 2.2 kWh/m2, 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 1.1 and 2.2 kWh/m2 for an existing office building without roof insulation in Roseworthy 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 11.1 and 12.9 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 4.6 and 8.9 kWh/m^2 for a new high-rise shopping mall centre in Roseworthy 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 4.3 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 and B13), the Life Cycle Cost can be reduced by as much as 42%. In such favourable cases, the Payback Period can be as low as 4.2 years.

27) It must be noted that Adelaide’s weather conditions, and in particular the ones of Kuitpo, are the least feasible ones for cool roof applications, compared to other locations. But even under these conditions and 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 by 10% to 15% compared to the “Do nothing” conventional roof, which is more than enough to justify the cool coating’s application.

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

Objectives

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

1) To evaluate the existing reference climatic conditions in the city of Adelaide, 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 Adelaide.
4) To understand the process of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.
5) To evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones.

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 Adelaide using weather research forecasting model is created to simulate the distribution of the main climatic parameters in the city. Simulations are performed for two representative summer months.

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

Phase 3: Climatic parameters analysis. In this phase, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 19 weather stations in Adelaide 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 19 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 eleven weather stations across Adelaide. 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 Adelaide during a typical summer and winter period.

Phase 7: Analysis of the Impact of Building Characteristics on the Performance of Cool Roofs. Finally, the energy characteristics and mainly the magnitude of thermal losses through the building envelopes and its impact on the performance of cool roofs are assessed in various stations in Adelaide 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 Sydney (i.e. Kuitpo and Roseworthy stations). 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 Kuitpo and Roseworthy weather conditions.

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

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

1.1 Introduction

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

1.2 Objectives of the study

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

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

1.3 Domain and method of simulation

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

Table 1 WRF/SLUCM Model configuration

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

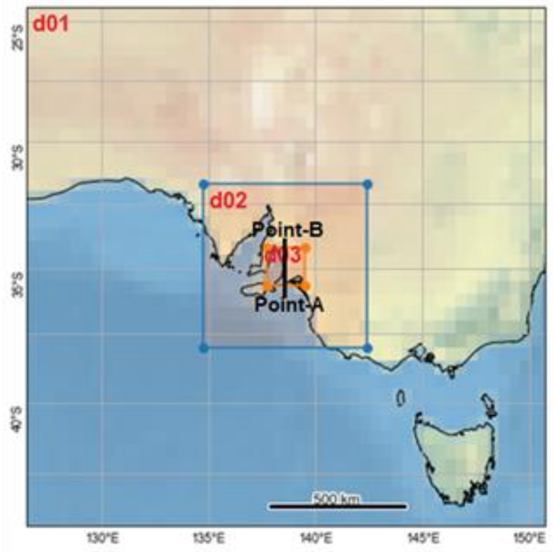


Figure 1 WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500m grid spacing, domain 2 (d02) with 1500m grid spacing and, an innermost domain 3 (d03) with 500m grid spacing; (b) innermost d03 with 500m grid spacing which encompasses the Greater Adelaide.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

Figure 9.

Table 2 Numerical design for cool roof for Adelaide.

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

1.4 Model evaluation

To evaluate the performance of the WRF-SLUCM system, we compared hourly simulated 2-m ambient air temperature against local measurements for the control case simulation over urban grid cells in the innermost domain. A statistical comparison of the mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r), and the index of agreement (IOA) for hourly 2m air temperature for the 24-hour duration are listed in **Table 3** and

Figure 2. The model evaluation is based on the correlation between the WRF model and observations for 2m-temperature across the diurnal cycle. The coupled WRF-SLUCM model accurately captures the temperature observed at different stations (mean R=0.964; mean bias=-1.77) for(a) Adelaide Airport, (b) Parafields Airport, (c) Nourlunga, and (d) Roswarthy. The base case simulation produced urban meteorological conditions well and statistically agreed with local observation ($p<0.05$). The simulated average UHI intensity varied from 2.3°C to5.5°C in the high-density urban residential areas relative to rural (i.e., surrounding) landscapes as a function of the prevailing local weather conditions. The range of MBE and RMSE of air temperature was -1.33°C to -2.28°C and 1.47°C to 2.53°C, respectively. The range of IOA was 0.86 to 0.92, with average values of 0.91 when considering all observation stations. The model slightly overestimated the daily average 2m ambient air temperature, potentially resulting from an overestimate of anthropogenic heating over the urban domain. We also assess impacts on local meteorological stations as it is these stations that are most influenced by 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 similar magnitude to observations. The comfort level of different dew points is >21°C for the stations, representing the uncomfortable situation in urban environment. The difference is identical when quantifying impacts on local meteorological stations. Although WRF does not display considerable warm (comfort) bias over urban locales, the representation of the 24-h averaged diurnal range of dew point temperature is well captured. In addition, model biases are most likely caused by: (a) lack of proper urban morphological representation and (b) uncertainties in model physical schemes, input data used, and locally meaningful urban biophysical parameters. Nevertheless, our initial evaluation highlights that the model can replicate the urban environment realistically, including a well-simulated evolution of the diurnal cycle of both near-surface temperature and dew-point, and the model framework can be used to predict the regional meteorology and investigate the regional influence of cool roof strategies.

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

Parameters	**Local weather stations**			
	Adelaide Airport	Parafields Airport	Nourlunga	Roswarthy
Correlation coefficient	0.96	0.97	0.95	0.97
Mean bias error	-2.28	-1.7	-1.78	-1.33
Mean absolute error	-2.277	-1.703	-1.776	-1.327
Root mean square error	2.53	1.92	1.95	1.47
Index of agreement	0.86	0.92	0.87	0.92
Parameters	0.96	0.97	0.95	0.97

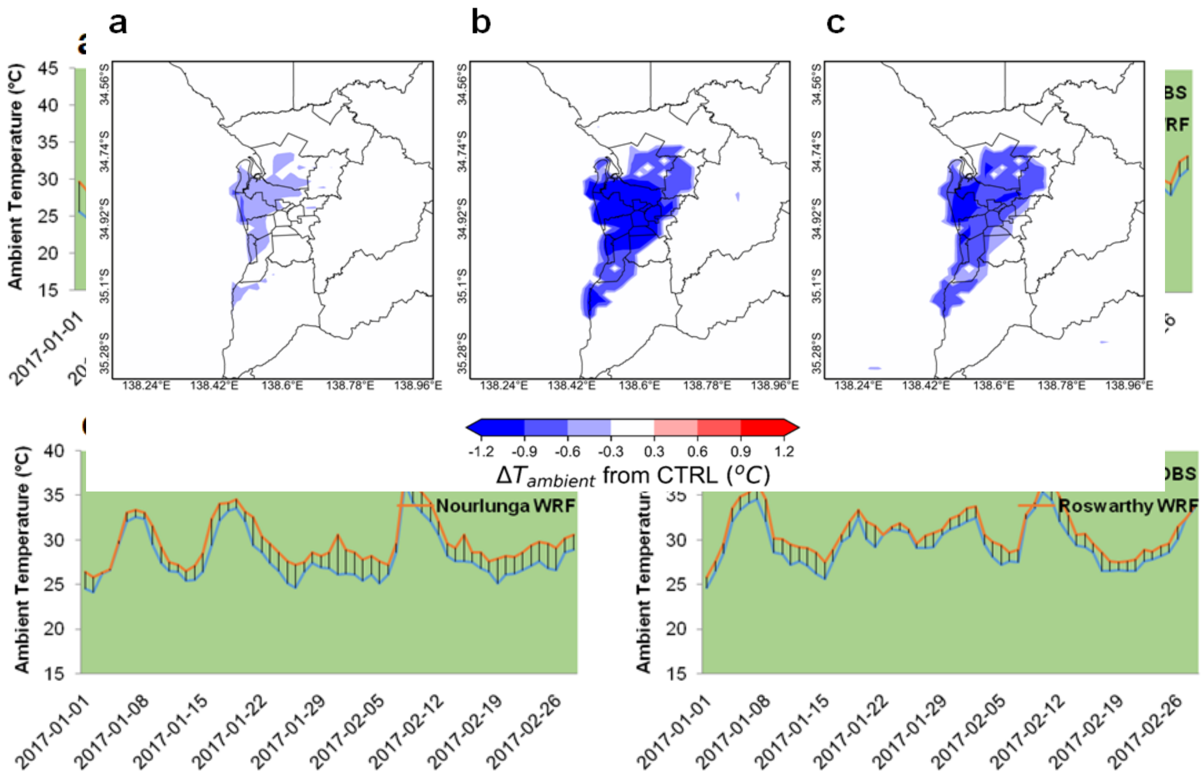


Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Adelaide Airport, (b) Parafields Airport, (c) Nourlunga, and (d) Roswarthy.

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 Adelaide 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 Adelaide. In 2017, Adelaide experienced its hottest Christmas Day since 1941. Temperatures in Greater Adelaide were very warm overall in 2017, with Adelaide'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 23.8 °C and 39.2 °C. At 06:00 LT, it varies between 18.9°C and 31.1°C. The results show that the use of cool roof materials maximum reduces the peak ambient temperature (Tambient) by 1.9ºC over high-density residential areas and 1.6°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 near the Port Adelaide Enfields, Charies and The West Torrens area of the city.. The maximum decrease of the ambient temperature during 18:00 LT is 1.3°C near coastal fringe (some parts of Port Adelaide and the Charies Sturt area), and the average decrease of summer months is 0.8°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 25.3°C to 40.8°C at 14:00, 21.4°C to 36.8°C at 18:00 LT and 21.3°C to 34.8°C at 6:00 LT over 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 5.5 over urban domain. But, in the high-density residential urban area, the maximum decrease of surface temperature is about 6.6°C during 14:00 LT of summer months along the coastal region (Port Adelaide Enfield, Charies, West Torrens and the Holdfast Bay) of the city. The maximum surface temperature reduction at 18:00 LT is about 4.9°C over the Charies Sturt area of the city. The average decrease of urban surface temperature is 4.3°C at 18:00 LT and 1.5°C at 06:00 LT compared to control case for the whole summer month in city **(Figure 4)**

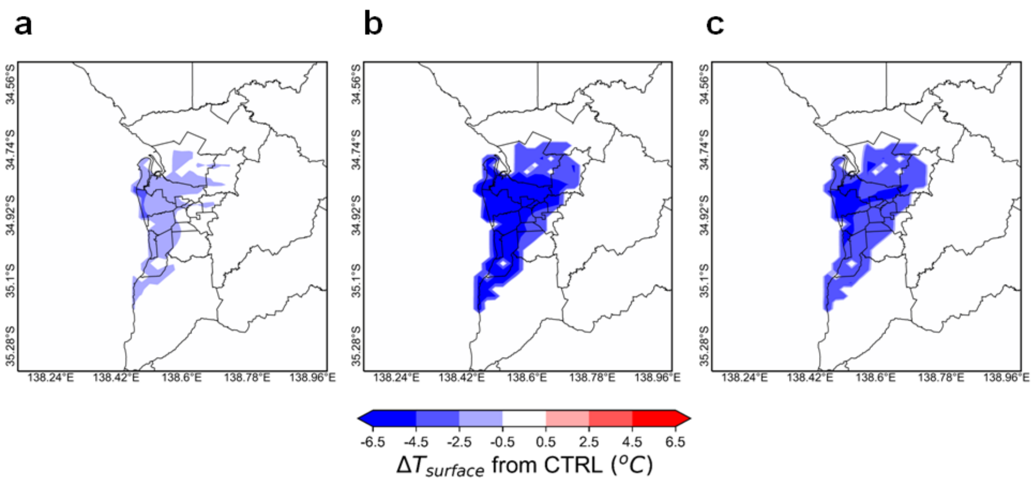


Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.3 Sensible heat flux

The WRF-SLUCM reasonable computed the sensible heat flux from the urban surface. Under the cool roof scenario, the maximum and average sensible heat flux ($Q_{sensible}$) over city during 14:00 LT is 472.3 Wm^{-2} and 336.1 Wm^{-2}; at 18:00LT, the average sensible heat flux is 99.8 Wm^{-2}. The maximum decrease in the sensible heat flux is 171.3 Wm^{-2}, and the average decrease is 145.2 Wm^{-2} at 14:00 LT over the urban domain (Port Adelaide Enfield, Charies Sturt, Prospect, Norwood, Payneham & St Peters, West Torrens and Holdfast Bay). In the high-density residential urban area, the maximum and average reduction of sensible heat flux are about 179.5 Wm^{-2} and 153.0 Wm^{-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 79.4 Wm^{-2} and 64.7 Wm^{-2} over the urban domain **(Figure 5)**.

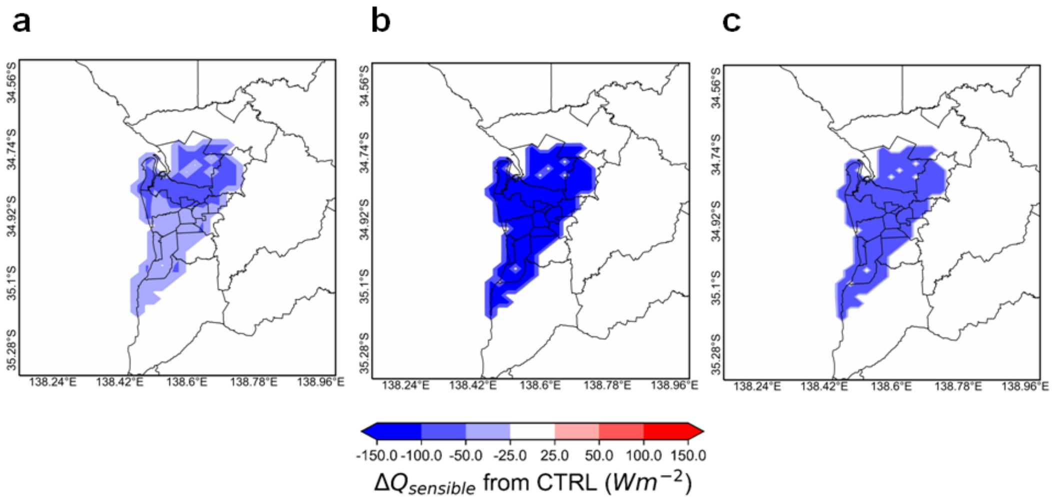


Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.4 Latent heat flux

The maximum and average latent heat flux (Q_{latent}) under cool roof scenario over city during 14:00 LT is 27.4 Wm-^{2} and 20.2 Wm-^{2}. At 18:00 LT and 06:00 LT, the average sensible heat flux is 7.8 Wm-^{2} and 4.8 Wm-^{2}. The maximum decrease in the latent heat flux is 15.0 Wm-^{2}, and the average decrease is 11.9 Wm-^{2} at 14:00 LTnear the coast and central part (Port Adelaide, Charies Sturt and Adelaide, Unley, Burnside) of the city. But, in the high density residential urban area, the average decrease of latent heat flux is about 12.5 during 14:00LT of summer months. At 18:00 LT, the maximum and average reduction of the summer month of latent heat flux is 6.0 Wm-^{2} and 4.3 Wm-^{2} over the urban domain. At 06:00 LT, the maximum reduction of latent heat flux is 4.7 Wm-^{2,} and the average reduction is 3.1 Wm-^{2} over the urban domain **(** **Figure** 6**).**

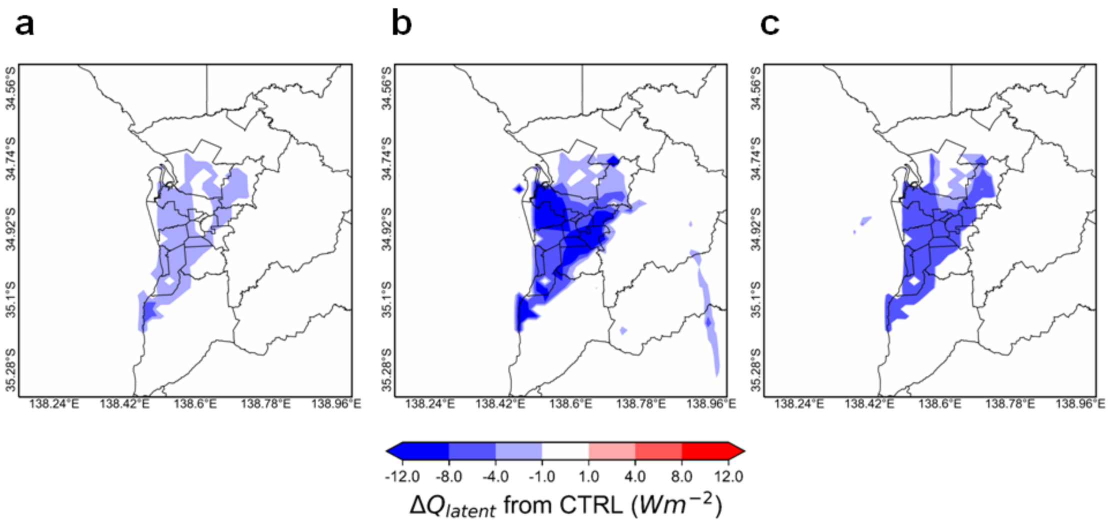


Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.5 Wind

Under the base case simulation, the average wind speed (W_{speed}) are 2.7 ms^{-1}, 6.4 ms^{-1} and 5.2 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 1.4 ms^{-1}, 2.1 ms^{-1} and 2.0 ms^{-1} at 06:00 LT, 14:00 LT (central part of the city, e.g. Adelaide, Walkerville, Burnside, Unley and Mitcham) and 18:00 LT (Port Adelaide Enfield, Charies Sturt, Prospect, Adelaide and West Torrens) respectively over urban domain. The average decrease of wind speed of whole summer months is 1.5 ms^{-1} at 14:00 LT, 0.9 ms^{-1} at 06:00 LT and 1.3 ms^{-1} at 18:00 LT over the city **(Figure 7)**.

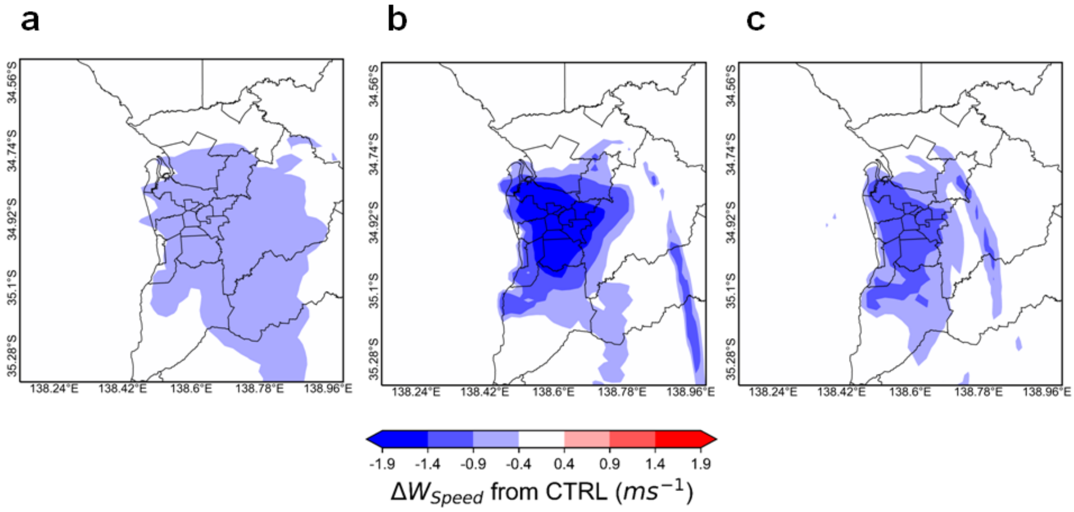


Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

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 at 6:00LT, 14:00LT, 18:00LT. The PBL height distribution and corresponding spatial changes in vertical wind speed. For instance, in core urban areas of the city (central part of the city, e.g. Adelaide, Walkerville, Burnside, Unley, Mitcham, Port Adelaide Enfield, Charies Sturt, Prospect, and West Torrens), 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 176.5 m, 694.0 m (near the coast and central part of the city), and 373.5 m for 6:00LT, 14:00LT, 18:00LT, respectively, with average values, is about 120.9m, 589.0 m and 275.0m. The minimum reduction of PBL is 61.2 m, 417.5 m, and 110.2 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 Adelaide 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.

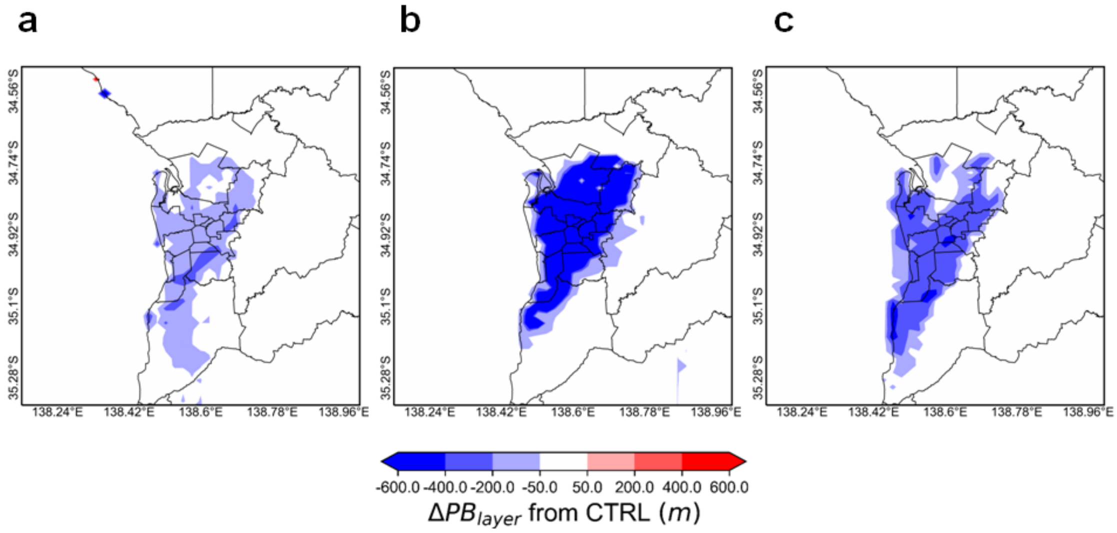


Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.6 Regional impact on sea breeze circulations

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

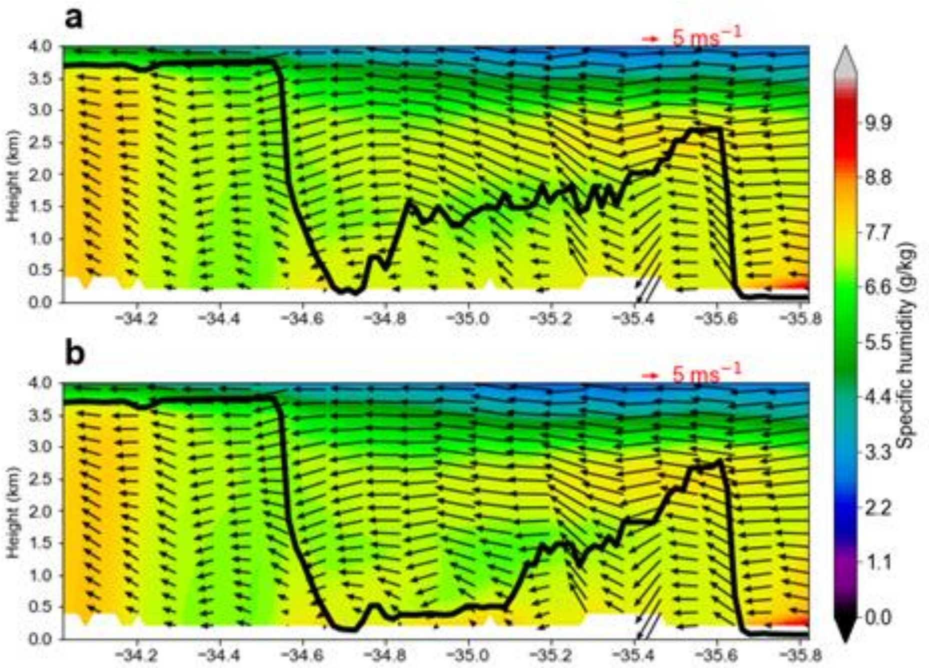


Figure 9 Cross-sectional profile of heat mitigations impacts on sea breeze during peak hour (14:00 LT) over Adelaide (a) control case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere.

The report also shows the implementation of cool roofs over city scale can affect the pressure gradient between city and surrounding surface due to a significant drop in ambient temperature up to 1.9°C and wind speed decrease up to 2.3 ms^{-1}.Thus, changes in roof reflectivity, sensible heating, and wind result in feedback within local climate of the city during peak hour (14:00 LT). The higher urban albedo values decrease the advective flow between 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 city. Consequently, the increase of albedo may prevent the warm airflow from the long fetch desert towards western Adelaide 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.

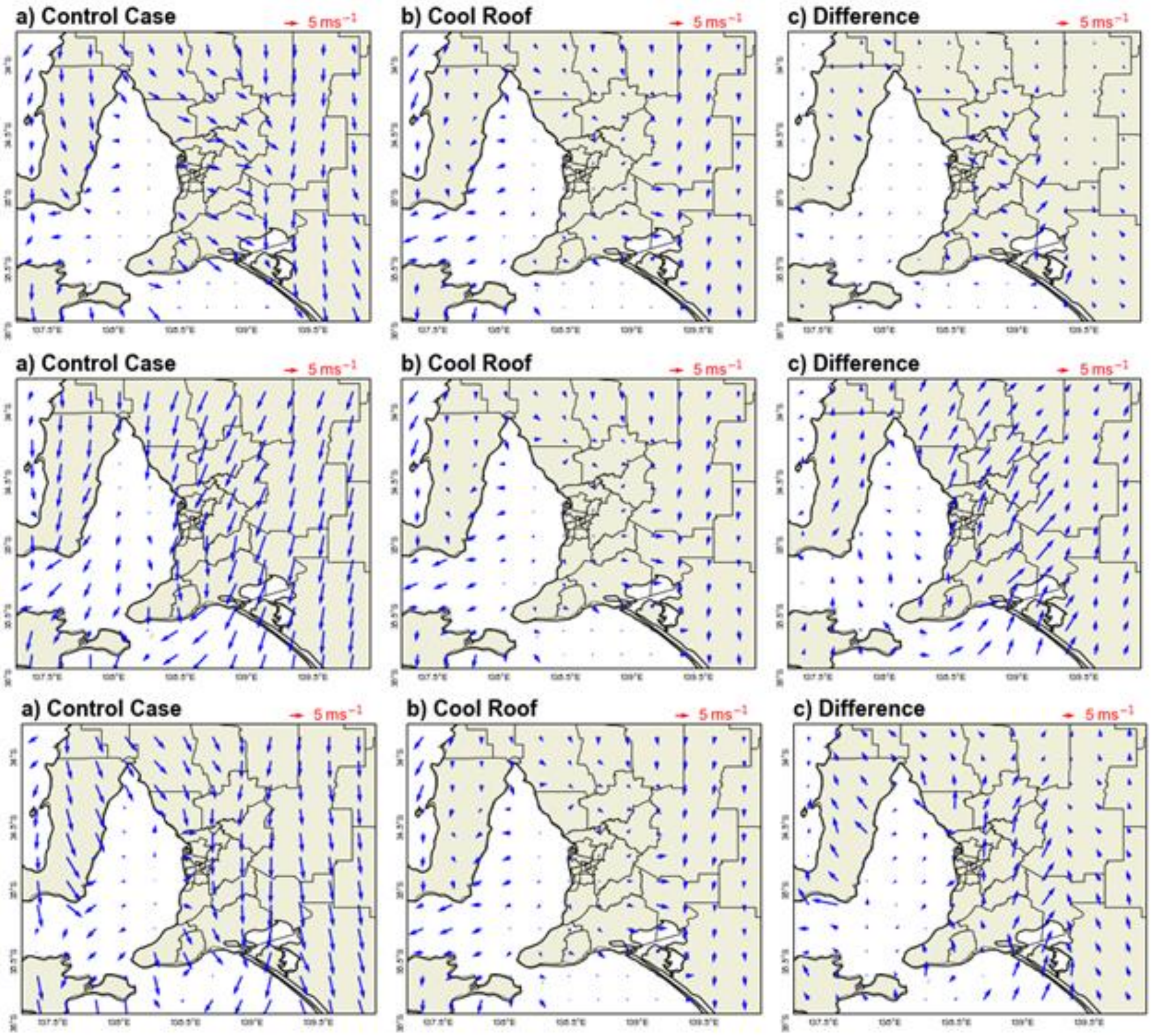


Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) control case (b) cool roof (c) scenarios minus control: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain d03.

1.7 Main conclusions

- The most intense temperature differences occurred between city cores to surroundings. 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 strappingly influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the long fetch desert area. The possible existence of an extra heating mechanism, like the advection of warm air from nearby desert spaces, may intensify the strength of the problem.
- High-density parts of the city exhibit a higher temperature reduction than the urban average. The locations and magnitudes of urban heating in the high-density urban areas vary spatially and diurnally.
- An increase of albedo in Adelaide can decrease the peak summer ambient temperature up to 1.9°C and surface temperature up to 6.6°C. Such cooling improves human comfort levels and could be feasible for reducing cooling energy demand.

- It was found that important temperature differences exist near the coast and core 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 horizontal thermal gradient.
- The city of Adelaide experiences an aggravate UHI at night during extreme urban heatwaves. In the daytime, a pocket of urban heat happens in the northwest part of the high-density urban areas, while at night, a hotspot occurs in the northern part of the city.
- The maximum decrease of sensible heat and latent heat flux were up to 179.5 Wm^{-2} and 15.8 Wm^{-2}, respectively.
- The maximum decrease of wind speeds is up to 2.3 ms^{-1}. Cool roofs increase the pressure over core urban at a local scale and decrease the wind advection from the adjacent bare surface of desert fetch.
- The results show that the increase in albedo fraction leads to a decrease in wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during the heatwave scenario.
- Modification of the urban albedo in Adelaide city results in an average reduction up to 682.1 m of the PBL heights over high density parts of the city and may increase the concentration of bad pollutants at ground level during peak hour (14:00 LT) due to low level urban mixing.
- The sea breeze is significantly affected by cool roof due to higher local pressure over city, which greatly reduces the sea breeze penetration.
- The amplitude of the UHI was linked with the subsistence of the sea breeze in the central parts of the city with a thermal gradient from Adelaide Hills to Western Beach. And it was decreasing the temperature of the coastal zone, combined with wind effects from the inland and nearby surfaces.

2. Climatic Design Parameters _ CDH and air temperature distribution

In this study, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 19 weather stations in Adelaide 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 19 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 Adelaide

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

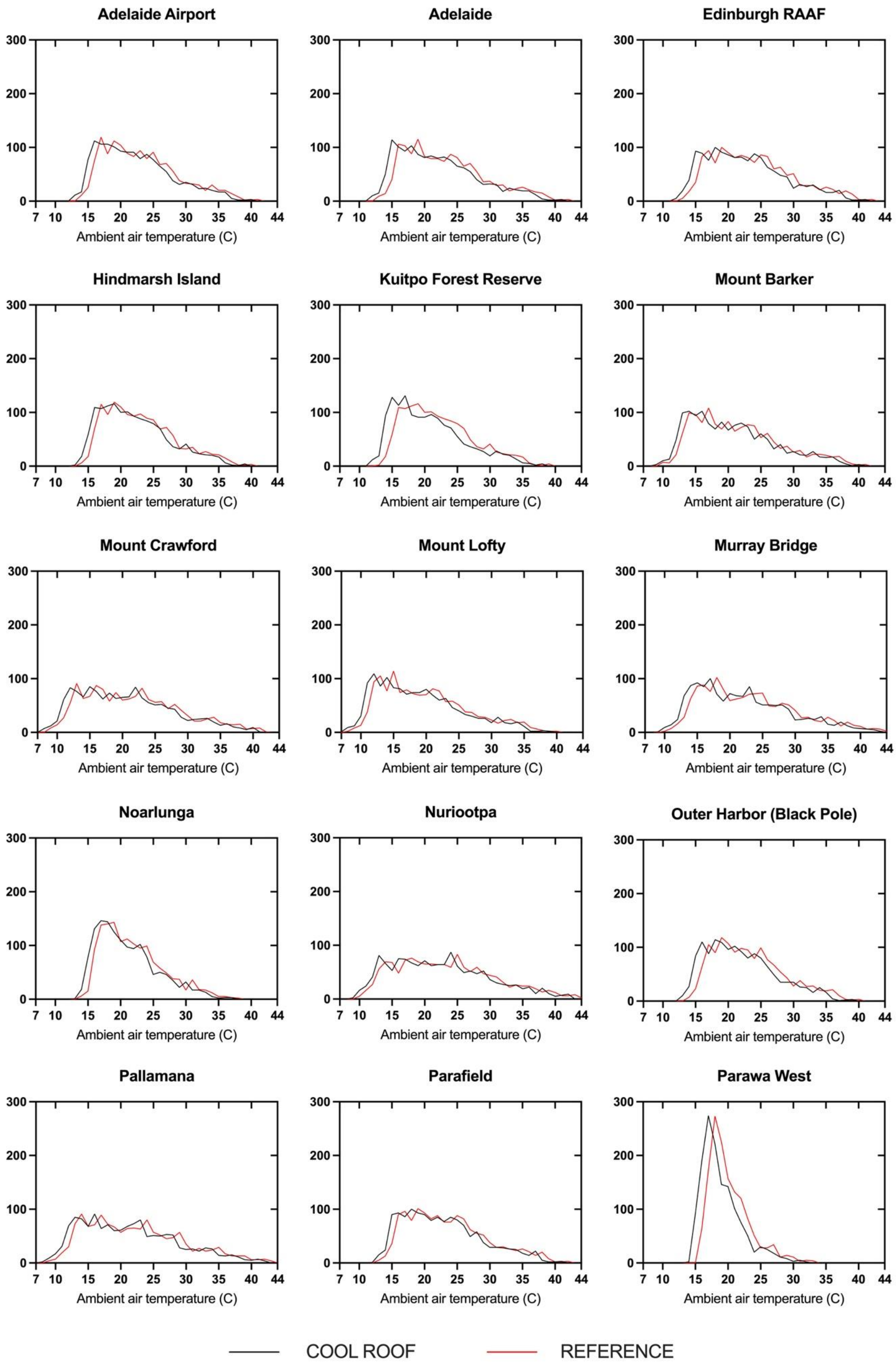
Table 4 Latitude, longitude, and the climate zone of the 19 stations in Adelaide.

No.	Station name	Lat	Long	Climate zone
1	ADELAIDE (WEST TERRACE / NGAYIRDAPIRA)	-34.93	138.58	5
2	ADELAIDE AIRPORT	-34.95	138.52	5
3	EDINBURGH RAAF	-34.71	138.62	5
4	HINDMARSH ISLAND AWS	-35.52	138.82	6
5	KUITPO FOREST RESERVE	-35.17	138.68	5
6	MOUNT BARKER	-35.07	138.85	6
7	MOUNT CRAWFORD AWS	-34.73	138.93	6
8	MOUNT LOFTY	-34.98	138.71	6
9	MURRAY BRIDGE	-35.12	139.26	6
10	NOARLUNGA	-35.16	138.51	5
11	NURIOOTPA PIRSA	-34.48	139.01	6
12	BLACK POLE	-34.73	138.47	5
13	PALLAMANA AERODROME	-35.06	139.23	6
14	PARAFIELD AIRPORT	-34.8	138.63	5
15	SECOND VALLEY FOREST AWS	-35.57	138.29	6
16	ROSEWORTHY AWS	-34.51	138.68	6
17	MOUNT TERRIBLE RADAR	-35.33	138.5	5
18	STRATHALBYN RACECOURSE	-35.28	138.89	6
19	ENCOUNTER BAY	-35.55	138.6	6

Figure 11 Location of the 19 weather stations in Adelaide.

2.2 Histogram of WRF simulated ambient temperature in Adelaide

The entire 2-month hourly ambient temperature of 19 stations in Adelaide simulated by WRF has been divided into a series of data with consecutive and non-overlapping interval of 1. The frequency distribution in **Figure 12** shows the quantity of ambient temperatures falling into each interval. The abscissa indicates the starting point of the interval. For example, if the abscissa of a point is 20 and the ordinate is 200, it means that there are 200 ambient temperature data falling within the range of 20-21 °C. At each weather station, the frequency distributions of the reference scenario and cool roof scenario are presented.


Adelaide Airport
Adelaide
Edinburgh RAAF
Hindmarsh Island
Kuitpo Forest Reserve
Mount Barker
Mount Crawford
Mount Lofty
Murray Bridge
Noarlunga
Nuriootpa
Outer Harbor (Black Pole)
Pallamana
Parafield
Parawa West
0
100
200
300
7 10 15 20 25 30 35 40 44
Ambient air temperature (C)
COOL ROOF
REFERENCE

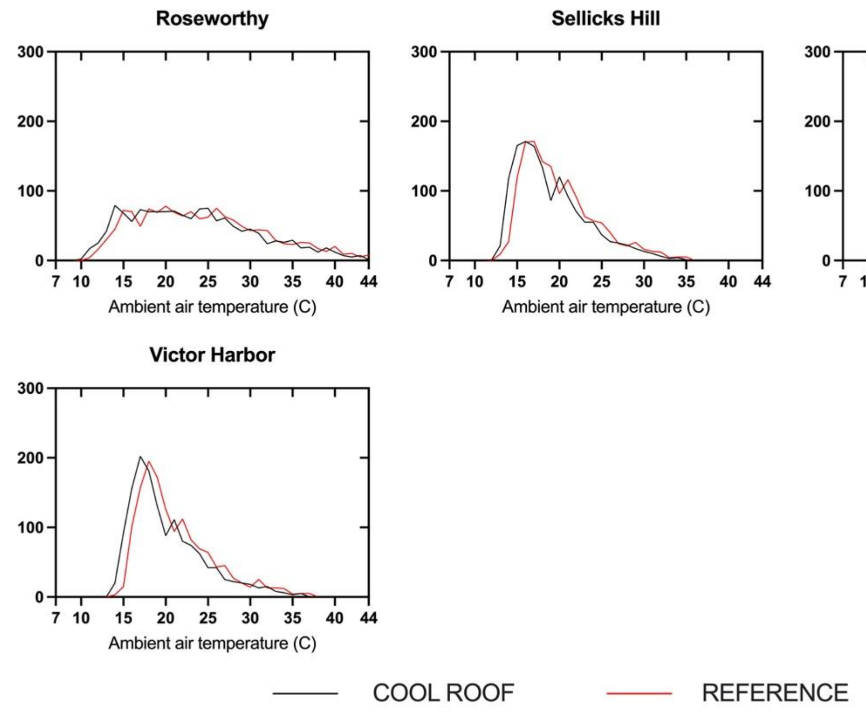


Figure 12 Histogram of WRF simulated ambient temperature in 19 stations in Adelaide.

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 58%-95% of the ambient temperatures in all stations concentrate in the range of 12-25 °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	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Percentage of data concentrated in 12-25 °C (%)
Adelaide Airport COOL ROOF					112										74
Adelaide Airport REFERENCE						119									69
Adelaide COOL ROOF				114											74
Adelaide REFERENCE								115							68
Edinburgh RAAF COOL ROOF							100								71
Edinburgh RAAF REFERENCE								100							64
Hindmarsh Island COOL ROOF								116							75
Hindmarsh Island REFERENCE								119							70
Kuitpo Forest Reserve COOL ROOF						131									82
Kuitpo Forest Reserve REFERENCE								116							75
Mount Barker COOL ROOF					102										76
Mount Barker REFERENCE						108									73
Mount Crawford COOL ROOF				85											68
Mount Crawford REFERENCE		91													68
Mount Lofty COOL ROOF	109														73
Mount Lofty REFERENCE				114											76
Murray Bridge COOL ROOF						100									69
Murray Bridge REFERENCE							102								66
Noarlunga COOL ROOF						146									83
Noarlunga REFERENCE								143							79
Nuriootpa COOL ROOF													87		66
Nuriootpa REFERENCE														83	63
Outer Harbor (Black Pole) COOL ROOF							114								76
Outer Harbor (Black Pole) REFERENCE								118							69
Pallamana COOL ROOF					91										69

Pallamana REFERENCE			91												67
Parafield COOL ROOF							100								70
Parafield REFERENCE								101							65
Parawa West COOL ROOF						274									95
Parawa West REFERENCE							273								92
Roseworthy COOL ROOF			79												63
Roseworthy REFERENCE									78						58
Sellicks Hill COOL ROOF					171										91
Sellicks Hill REFERENCE						171									88
Strathalbyn COOL ROOF					126										81
Strathalbyn REFERENCE							139								76
Victor Harbor COOL ROOF						202									88
Victor Harbor REFERENCE							195								84

2.3 Cooling Degree Hours (CDH) calculation

For all scenarios, Cooling Degree Hours (CDH) Base 26 °C has been calculated for the entire simulation period. It is a rough indication of the cooling load of a building, and it was calculated by firstly subtracting 26 from the hourly dry-bulb air temperature and then adding all the positive differences in the two months. The calculated CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 19 weather stations are shown in **Table 6** and **Figure 13**. Compared with the reference case, the largest percentage reduction is observed in SECOND VALLEY FOREST AWS, and the smallest is found in NURIOOTPA PIRSA, with an average reduction of 23.1%. The mean CDH values of the 19 weather stations for the reference case, cool roof case are 1896.0, 1496.9 respectively, see **Table 7**. It can be observed that in most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions. On the contrary, the percentage reduction is larger in colder regions.

Table 6 The CDH of reference cases, cool roof applied cases, and the difference between these two, as well as the percentage of CDH reduction due to the implementation of the cool roof in 19 weather stations in Adelaide.

Weather Station	CDH_CTRL	CDH_COOL ROOF	CDH_ Difference (CTRL-COOL ROOF)	Percentage of the reduction_% (CDH_Difference/CDH_CTRL)
ADELAIDE (WEST TERRACE / NGAYIRDAPIRA)	2307.4	1762.2	545.2	23.6
ADELAIDE AIRPORT	2073.1	1617.9	455.2	22.0
EDINBURGH RAAF	2568.9	1984.6	584.3	22.7
HINDMARSH ISLAND AWS	1786.9	1417.0	370.0	20.7
KUITPO FOREST RESERVE	1417.0	1053.3	363.7	25.7
MOUNT BARKER	1846.2	1504.8	341.4	18.5
MOUNT CRAWFORD AWS	2174.6	1754.1	420.5	19.3
MOUNT LOFTY	1342.7	1052.3	290.4	21.6
MURRAY BRIDGE	2786.2	2249.7	536.5	19.3
NOARLUNGA	1085.4	823.2	262.2	24.2
NURIOOTPA PIRSA	3014.6	2526.0	488.6	16.2
BLACK POLE	1909.3	1364.1	545.2	28.6
PALLAMANA AERODROME	2514.7	2053.8	460.9	18.3
PARAFIELD AIRPORT	2441.7	1983.3	458.4	18.8
SECOND VALLEY FOREST AWS	261.5	145.7	115.8	44.3
ROSEWORTHY AWS	3551.5	2945.5	606.0	17.1

MOUNT TERRIBLE RADAR	527.3	377.6	149.7	28.4
STRATHALBYN RACECOURSE	1570.9	1205.2	365.7	23.3
ENCOUNTER BAY	844.4	620.1	224.3	26.6

Table 7 Mean and SD of the CDH of the 19 weather stations in reference cases and cool roof cases respectively.

	Mean	SD	Sample No.
CDH_CTRL	1896.0	855.0	19
CDH_COOL ROOF	1496.9	725.1	19
CDH_DIFFERENCE (CTRL-COOL ROOF)	399.2	142.9	19

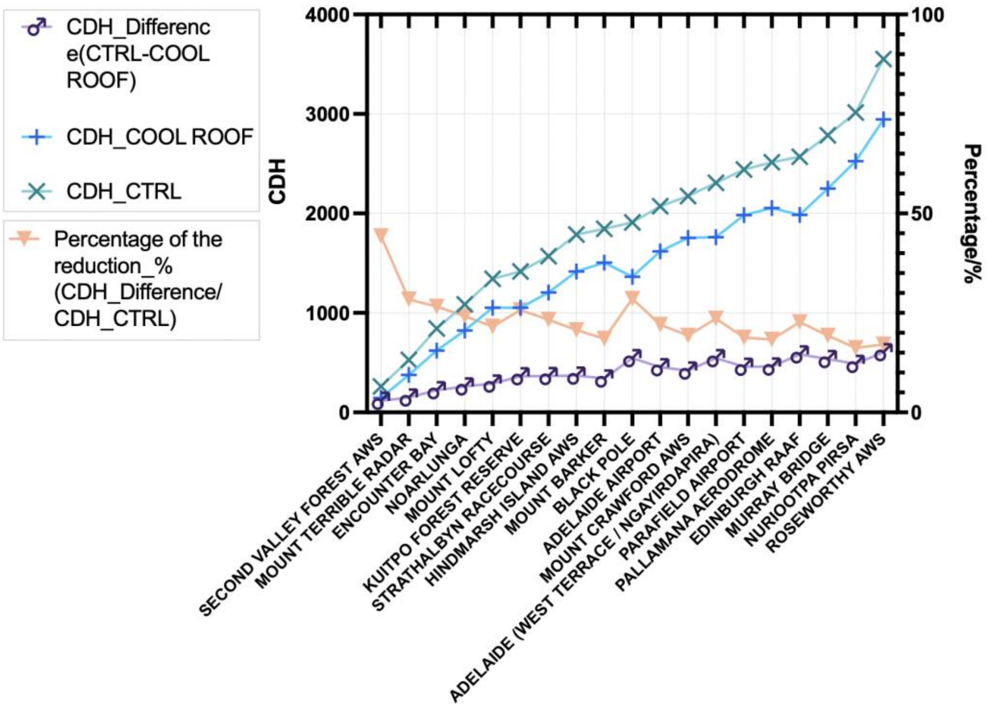


Figure 13 The CDH of reference cases, cool roof applied cases, the difference between these two, and the percentage of the CDH reduction due to the implementation of the cool roof in 19 weather stations in Adelaide.

2.3.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 19 weather stations in both the reference cases and the cool roof cases is shown in **Figure 14**. In the reference case, the CDH of the 19 stations in reference cases and cool roof cases are concentrated mainly in 1400-2600 and 1000-2000 respectively. The CDH distribution of reference case and cool roof cases share similar patterns, with the former of around 400 (the average decrease of CDH after applying cool roof) higher than the latter.

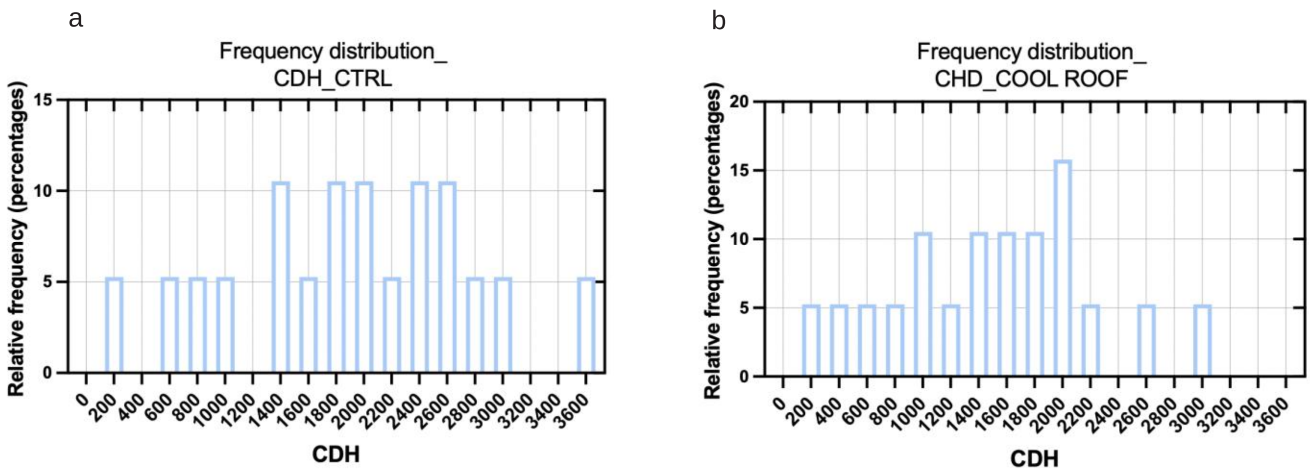


Figure 14 Frequency distribution of the CDH values for the 19 weather stations in reference cases (a) and cool roof cases (b).

2.3.2 Spatial distribution of the results

- **CHD_Reference scenario: (Figure 15)**
  The highest CDH of 3551.5 is observed in ROSEWORTHY AWS and SECOND VALLEY FOREST AWS has the lowest number. CDH gradually increases from southwest to northeast.
- **CDH_Cool roof scenario: (Figure 16)**
  When applied with a cool roof, the decrease of CDH is observed at every station. CDH still increases from southwest to northeast.
- **CDH_Reference scenario – cool roof scenario: (Figure 17)**
  The maximum decrease occurs in the northern regions of the city while the smallest is observed in the southweat. The average decrease after applying cool roof is 399.2 **(Table 7)**.
- **CDH_(Reference scenario – cool roof scenario)/Reference scenario: (Figure 18)**
  The proportion of CDH reduction in the original reference volume is relatively large in southwest and gradually decreases toward the northeast, as shown in **Figure 18**. Its spatial distribution is the opposite compared with that of the other three parameters.

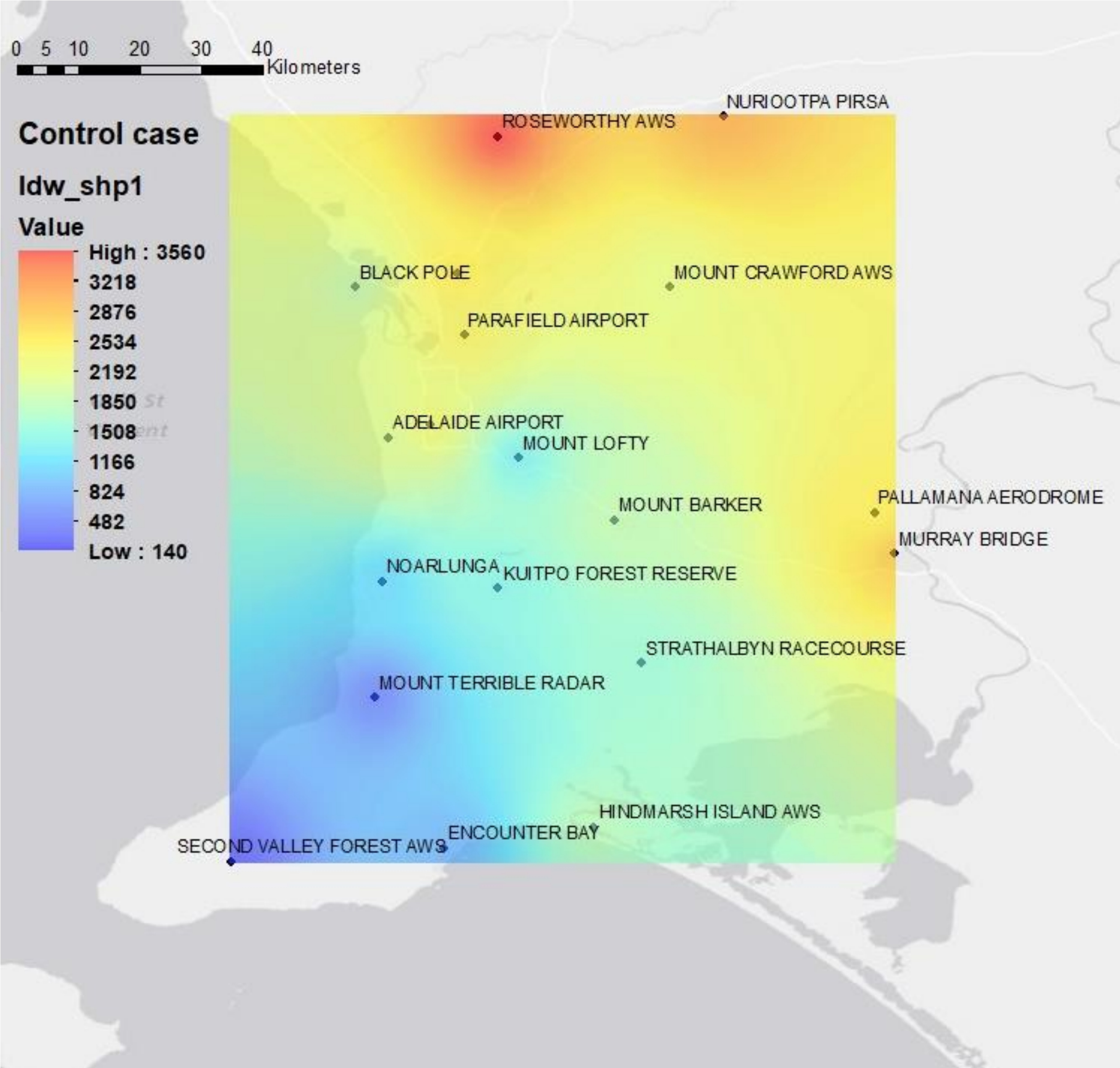


Figure 15 The sum of Cooling degree hours in Jan and Feb of the reference cases in the 19 stations in Adelaide.

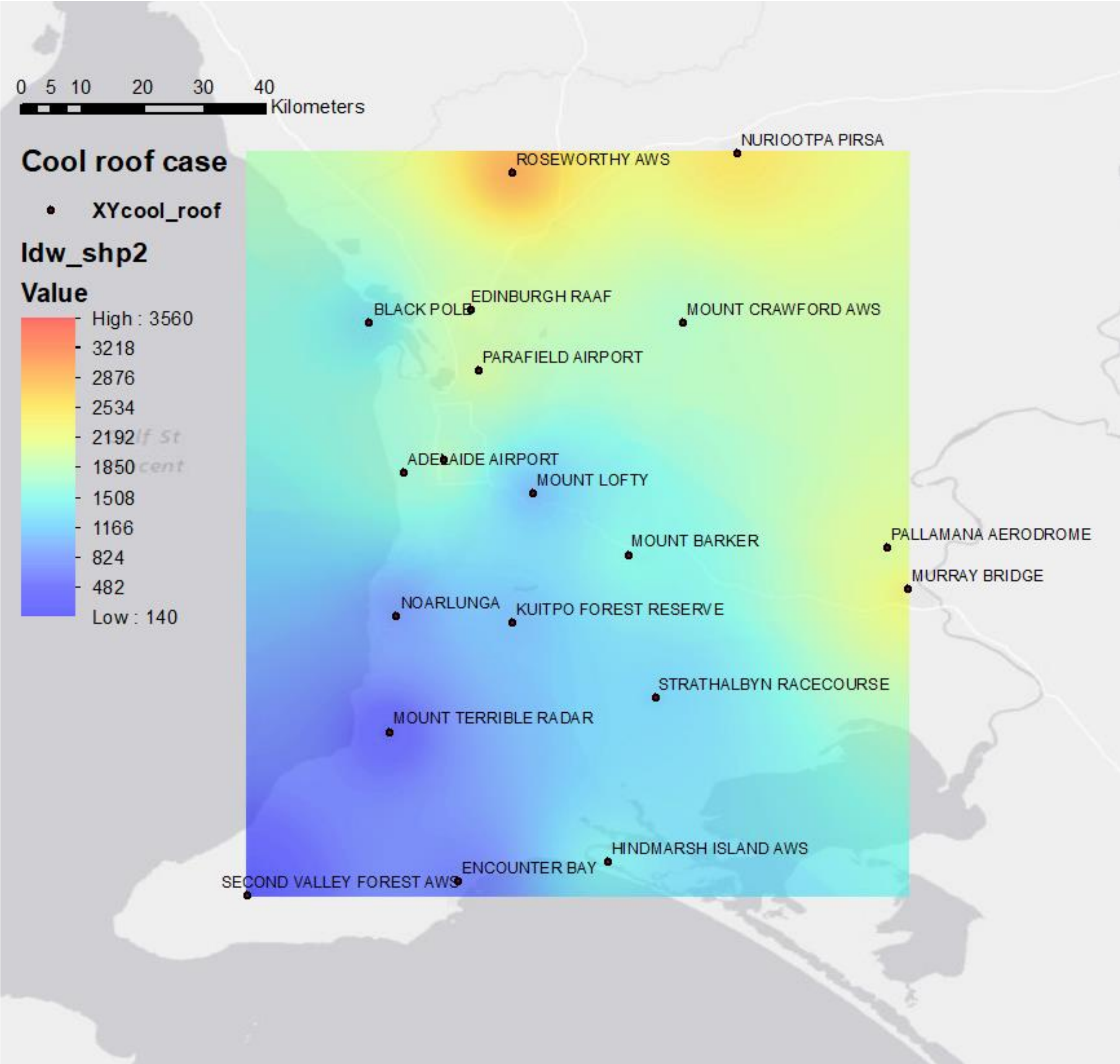


Figure 16 The sum of Cooling degree hours in Jan and Feb of the cool roof cases in the 19 stations in Adelaide.

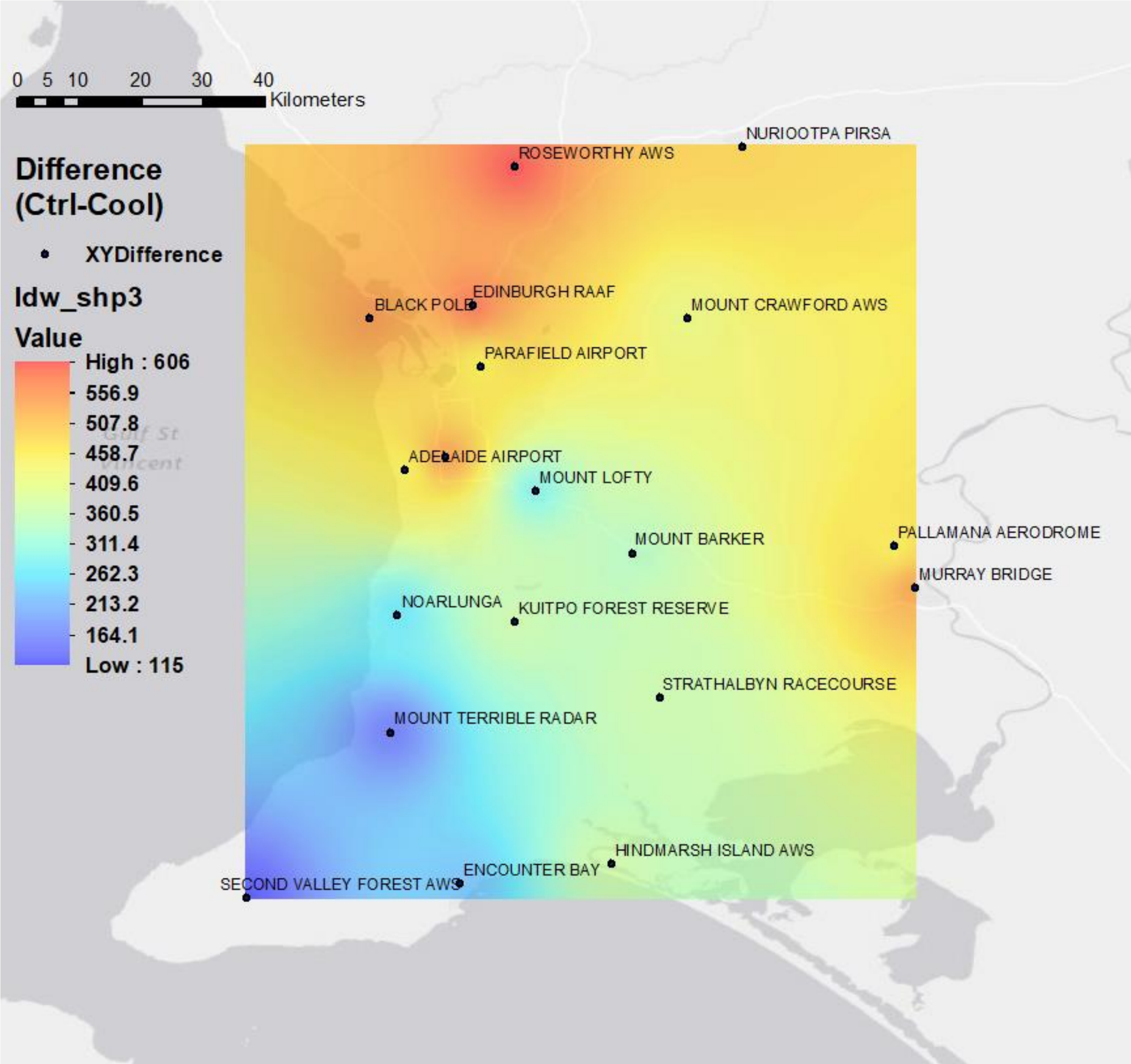


Figure 17 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and reference ones in the 19 stations in Adelaide.

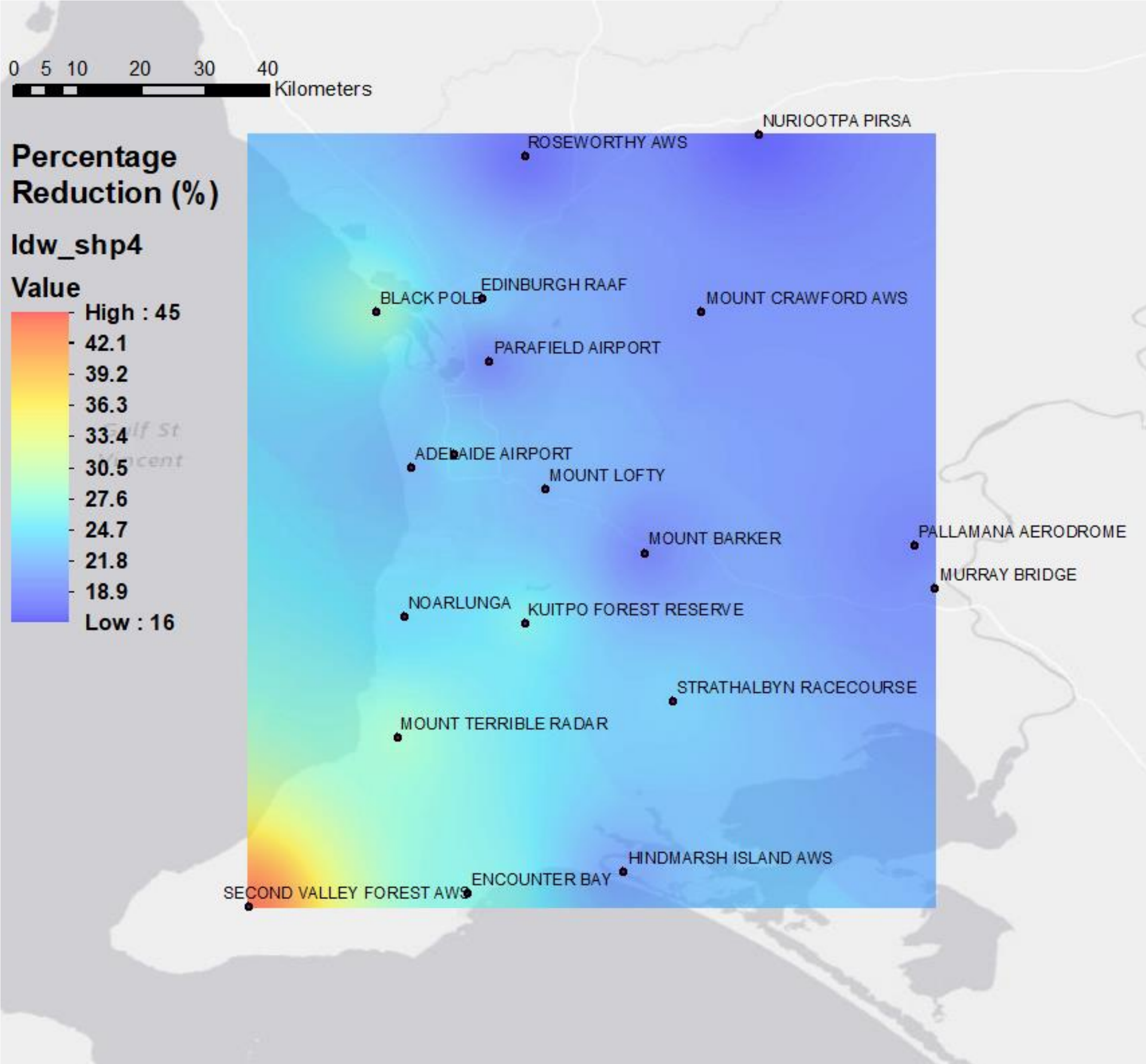


Figure 18 The percentage of CDH reduction due to the implementation of the cool roof in the 19 stations in Adelaide.

2.4 Conclusion

- 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 58%-95% of the ambient temperatures in all stations concentrate in the range of 12-25 °C.
- In reference cases, CDH ranges from 261.5 to 3551.5, and the CDH values are mainly concentrated in 1400-2600. CDH gradually increases from southwest to northeast.
- When applied with a cool roof, the decrease of CDH is observed at every station. The average decrease is 399.2 in all stations. CDH still increases from southwest to northeast.
- In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions.
- The percentage of CDH reduction due to the implementation of the cool roof ranges from 16.2% to 44.3%, with an average value of 23.1%. The percentage is smaller in the hotter regions.

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

3.1 Introduction

This chapter investigates the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Adelaide. 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 Adelaide during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and five weather stations across Adelaide (in climate zone 5 and 6). The seventeen typical buildings modeled in this study include the following, and their characteristics are listed in **Appendix: Building characteristic**s:

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

17) A stand-alone house-new building.

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

1) Adelaide Airport, Climate zone 5
2) Edinburgh Raaf, Climate zone 5
3) Kuitpo, Climate zone 5
4) Parafield Airport, Climate zone 5
5) Roseworthy, Climate zone 6.

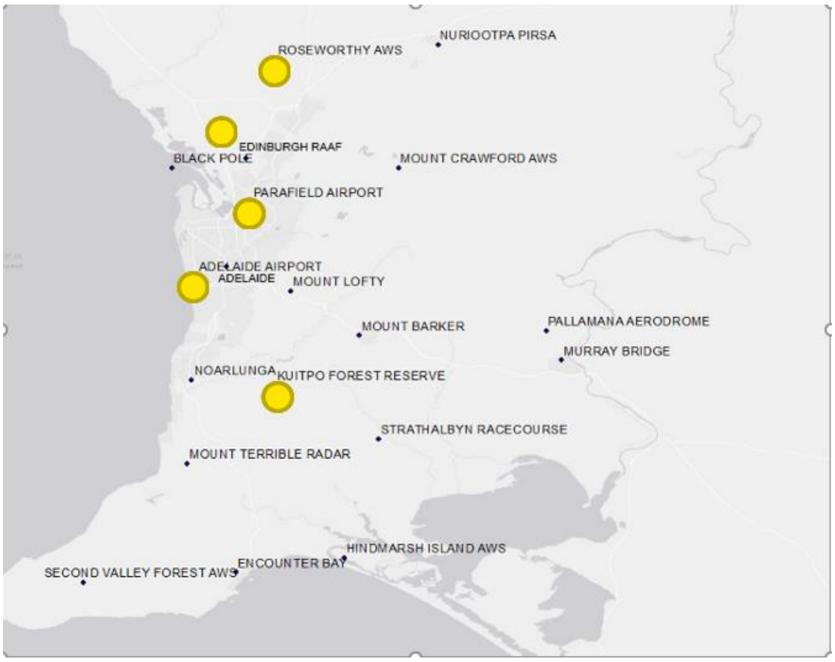


Figure 19 Weather stations in Adelaide including four weather stations in climate zone 5 (including Adelaide Airport, Edinburgh Raaf, Kuitpo, and Parafield Airport) and one weather stations in climate zone 6 (Roseworthy).

The corresponding building specifications for the buildings in climate zones 5 and 6 were 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 Adelaide. 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. scenario 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 Adelaide (Kuitpo [coldest] and Roseworthy [hottest]) during a typical summer and winter period. The indoor air temperature simulations for the summer period were performed under three scenarios:

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

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

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

The indoor air temperature reduction of the cool roof scenarios (i.e. scenarios 1 and 2) against the reference scenario was computed. In addition, the number of hours above 26 ^{o}C 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 °C during occupational/total (i.e. non-occupational and occupational) periods for the two scenarios were computed to assess the impact of cool roofs on the number of hours the buildings can be functional without an air-conditioning system.

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

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

3.3 Summary of results

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

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

Building Type	Cooling load-reference	Reference with cool roof scenario (scenario 1) vs reference scenario		Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario	
	kWh/m^2	kWh/m^2	%	kWh/m^2	%
A low-rise office building without roof insulation-existing building	20.9-28.5	9.6-11.3	39.6-45.9	12.5-13.9	47.7-59.8
A high-rise office building without roof insulation-existing building	13.5-19.9	1.7-2.0	10.3-12.6	4.5-5.0	22.8-37.4

A low-rise office building with roof insulation-new building	12.8-19.3	0.9-1.3	6.1-6.9	3.6-4.3	19.6-33.5
A high-rise office building with roof insulation-new building	12.2-18.4	0.2	1.2-1.3	2.8-3.6	15.1-29.7
A low-rise shopping mall centre-new building	56.3-66.3	1.6-1.8	2.5-2.9	7.3-10.2	11.0-18.1
A mid-rise shopping mall centre-new building	54.8-64.6	0.7-0.9	1.2-1.4	6.3-9.4	9.8-17.2
A high-rise shopping mall centre-new building	54.2-64.0	0.5-0.6	0.8-0.9	6.0-9.2	9.4-16.9
A low-rise apartment building-new building,	8.7-13.4	1.0-1.2	8.6-11.0	3.2-3.8	25.7-41.5
A mid-rise apartment building-new building	8.3-12.9	0.5-0.7	5.1-6.6	2.8-3.4	22.9-39.4
A high-rise apartment building-new building	8.1-12.6	0.3-0.4	3.1-4.0	2.6-3.2	21.3-38.2
A typical stand-alone house-existing building,	11.8-15.8	5.7-6.0	38.1-48.1	7.3-7.9	48.1-62.2
A typical school building-new building	17.0-26.5	0.7-0.9	3.4-4.2	4.4-5.2	17.1-29.1
A low-rise office building with roof insulation-existing building	16.0-23.0	4.5-5.5	24.1-28.3	7.7-8.3	34.6-48.0
A high-rise office building with roof insulation-existing building	12.7-19.0	0.8-1.0	5.3-6.3	3.5-4.2	18.5-33.2

A low-rise shopping mall centre-existing building	60.3-70.5	8.0-8.2	11.4-13.3	13.4-16.3	19.1-27.0
A high-rise shopping mall centre-existing building	55.2-65.1	2.4-2.5	3.7-4.3	7.9-11.0	12.1-19.9
A stand-alone house-new building.	9.0-12.3	2.9-3.3	23.7-33.9	4.6-5.2	37.1-54.9

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

Building Type	**Annual cooling load saving**		**Annual heating load penalty**	**Annual total cooling & heating load saving**	
	kWh/m^2	**%**	**kWh/m^2**	**kWh/m^2**	**%**
A low-rise office building without roof insulation-existing building	11.0-19.2	39.3-46.9	1.4-3.6	7.4-17.7	21.3-32.5
A high-rise office building without roof insulation-existing building	1.8-3.2	9.6-12.9	0-0.9	0.9-2.9	4.6-9.7
A low-rise office building with roof insulation-new building	1.0-2.1	5.5-7.5	0-0.3	0.6-1.9	3.2-6.2
A high-rise office building with roof insulation-new building	0.2-0.3	1.0-1.3	0-0.1	0.1-0.3	0.6-1.1
A low-rise shopping mall centre-new building	4.1-5.0	2.9-3.9	0.1-0.2	3.9-4.8	2.7-3.5
A mid-rise shopping mall centre-new building	1.9-2.3	1.4-1.9	0-0.1	1.8-2.2	1.3-1.7
A high-rise shopping mall centre-new building	1.2-1.4	0.9-1.2	0-0.1	1.1-1.4	0.8-1.1

A low-rise apartment building-new building,	0.9-1.8	8.5-13.0	0.8-1.5	-0.6-0.9	-1.2-1.8
A mid-rise apartment building-new building	0.5-1.0	5.0-7.8	0.5-0.9	-0.4-0.5	-0.7-1.0
A high-rise apartment building-new building	0.3-0.6	3.0-4.8	0.3-0.5	-0.2-0.3	-0.5-0.6
A typical stand-alone house-existing building,	6.9-11.4	41.3-55.4	5.1-8.7	-1.8-5.9	-3.3-10.6
A typical school building-new building	0.8-1.5	3.3-4.3	0.3-0.8	0-1.1	0-1.8
A low-rise office building with roof insulation-existing building	4.9-9.0	23.1-28.5	0.6-1.6	3.3-8.3	13.2-19.5
A high-rise office building with roof insulation-existing building	0.8-1.5	4.8-6.3	0.1-0.3	0.5-1.4	2.9-4.2
A low-rise shopping mall centre-existing building	18.2-22.0	12.3-16.9	0.3-0.8	17.4-21.6	11.4-14.9
A high-rise shopping mall centre-existing building	5.1-6.3	3.8-5.4	0.1-0.2	4.9-6.2	3.5-4.8
A stand-alone house-new building.	3.3-5.9	25.8-40.0	1.4-2.7	0.6-4.3	1.7-10.5

Table 10 Maximum indoor air temperature in reference scenario, maximum indoor air temperature reduction between reference scenario vs reference with cool roof scenario (scenario 1) and reference scenario vs cool roof with modified urban temperature scenario (scenario 2) for all building types under free floating conditions during a typical summer week using weather data simulated by WRF, and number of hours with indoor air temperature above 26 °C 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 °C in a typical summer month		
	Reference scenario (°C)	Reference with cool roof scenario (scenario 1) vs reference scenario (°C)	Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario (°C)	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	47.5-49.8	7.6-8.4	8.4-10.0	436-457	326-367	251-333
A high-rise office building without roof insulation-existing building	42.1-44.7	1.5-1.6	2.4-3.3	510-542	485-521	462-477
A low-rise office building with roof insulation-new building	42.8-45.8	1.0	2.1-3.0	494-510	471-493	388-456

A high-rise office building with roof insulation-new building	41.4-44.2	0.2	1.5-2.5	529-560	523-556	436-511
A low-rise shopping mall centre-new building	48.4-52.6	0.6	1.6-2.9	520-533	518-530	467-506
A mid-rise shopping mall centre-new building	47.6-52.1	0.4-0.6	1.7-2.7	543-552	542-549	493-532
A high-rise shopping mall centre-new building	47.4-51.9	0.4-0.5	1.6-2.7	548-556	547-555	498-536
A low-rise apartment building-new building,	35.3-39.5	0.7	1.6-2.7	556-593	555-593	532-536
A mid-rise apartment building-new building	34.9-39.4	0.4-0.5	1.3-2.5	328-421	311-409	219-355
A high-rise apartment building-new building	34.7-39.3	0.3-0.4	1.2-2.4	245-349	241-343	150-295
A typical stand-alone	38.9-42.4	4.4-4.5	5.1-5.5	297-354	185-282	136-248

house-existing building						
A typical school building-new building	38.7-42.6	0.6	1.6-2.6	285-371	275-358	200-316
A low-rise office building with roof insulation-existing building	44.9-47.4	3.9-4.5	4.8-6.1	459-493	373-428	308-385
A high-rise office building with roof insulation-existing building	41.7-44.4	0.8-0.9	1.7-2.9	518-552	501-541	412-495
A low-rise shopping mall centre-existing building	49.1-53.0	2.3-2.6	3.6-4.2	498-513	478-496	424-467
A high-rise shopping mall centre-existing building	47.5-51.9	0.8	1.8-3.0	538-546	538-541	485-525
A stand-alone house-new building.	36.9-40.2	2.2-2.4	3.1-4.0	284-356	203-300	139-264

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 ^{o}C in free-floating mode during a typical winter month using annual measured weather data

Building type	Minimum Indoor air temp in a typical winter week	Average maximum indoor air temp reduction in a typical winter month	Number of hours below 19 ºC in a typical winter month			
	Reference scenario (ºC)	Reference with cool roof scenario (scenario 1) vs reference scenario (ºC)	Reference scenario (hours)		Reference with cool roof scenario (scenario 1) (hours)	
			Operational hours	Total	Operational hours	Total
A low-rise office building without roof insulation-existing building	9.2-9.6	0.4-1.8	215-272	574-635	261-317	622-681
A high-rise office building without roof insulation-existing building	12.5-12.7	0.1-0.3	156-221	460-551	165-234	473-569
A low-rise office building with roof insulation-new building	12.0-12.5	0.4-1.3	135-195	437-525	165-205	472-541
A high-rise office building with roof insulation-new building	13.1-13.4	0.1	136-199	416-505	137-202	417-510
A low-rise shopping mall centre-new building	12.0-12.1	0.2-0.3	64-79	345-388	65-81	348-392
A mid-rise shopping mall centre-new building	12.5-12.8	0.1-0.2	62-81	325-369	63-82	327-372
A high-rise shopping mall centre-new building	12.6-13.0	0.1	62-81	316-365	62-85	318-370
A low-rise apartment	10.2-11.1	0.2	N/A	316-365	N/A	318-370

building-new building,						
A mid-rise apartment building-new building	10.3-11.3	0.1	N/A	714-732	N/A	718-732
A high-rise apartment building-new building	10.3-11.3	0.1	N/A	721-732	N/A	721-732
A typical stand-alone house-existing building,	9.1-9.4	1.2-1.3	N/A	691-721	N/A	720-732
A typical school building-new building	8.1-8.9	0.1-0.2	257-313	642-707	262-316	647-712
A low-rise office building with roof insulation-existing building	10.6-10.9	1.0	176-239	516-595	210-274	560-636
A high-rise office building with roof insulation-existing building	12.8-13.0	0.2	143-212	435-531	146-216	442-540
A low-rise shopping mall centre-existing building	10.9-11.1	0.6	84-112	392-452	86-116	398-457
A high-rise shopping mall centre-existing building	12.3-12.6	0.2	70-104	340-404	71-104	342-405
A stand-alone house-new building.	10.2-10.4	0.7-0.8	N/A	680-718	N/A	703-727

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 9.6-11.3 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 at the whole urban area (scenario 2) is quite significant. For instance, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 12.5-13.9 kWh/m^2.
- In new low-rise buildings with high insulation level, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.6-4.3 kWh/m^2 in a typical new low-rise office building.
- In high-rise buildings, the application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2 kWh/m^2 for a new high-rise office building with insulation.
- In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by the implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.5-0.6 kWh/m^2 in an existing high-rise shopping mall centre, which is expected to increase to 6.0-9.2 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 a majority of building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 11.0-19.2 kWh/m^2, while the corresponding heating penalty is just 1.4-3.6 kWh/m^2.
- The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Adelaide. For instance, the heating penalty can be up to 6.9-11.4 kWh/m^2 compared to the equivalent 5.1-8.7 kWh/m^2 in an existing stand-alone house.
- In existing low-rise buildings without insulation/with low level of insulation and under free-floating condition 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 7.6-8.4 ^{o}C.
- In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, the application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 8.4-10.0 ^{o}C.
- 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 ^{o}C. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in a typical low-rise office building without insulation is predicted to reduce from 436-457 hours to 326-367 hours and 251-333 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.

- In new low-rise buildings with high insulation level and under free-floating 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 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 2.1-3.0 ^{o}C in a typical new low-rise office building.
- 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 ^{o}C during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in new low-rise office building with insulation is predicted to reduce from 494-510 hours to 388-456 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
- The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by applying cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 7.6-8.4 ^{o}C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 0.4-1.8 ^{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 3.3 ^{o}C occurs when the indoor air temperature is 24.0 ^{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 176-239 hours to 210-274 hours in a typical existing low-rise office building with roof insulation.

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

$$Y=a X + b$$

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

X is the cooling degree hours (K);

<u>For reference scenarios:</u>

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

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

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

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

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

4.2 Office buildings

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

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B03 VS B13; or B04 VS B14) have a lower heat loss coefficient of the overall envelope; the envelope of an insulated building loses less heat (B01 VS B13 or B02 VS B14).
2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all office building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, no insulation, and older construction years, which often have higher heat loss coefficients in envelopes.
3) For the cooling load reduction in scenario 2 compared with the reference scenario, except B01 and B13, which presents an increased cooling load reduction with the increase of cooling degree hours, all other building types have an opposite trend. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for most of the buildings.

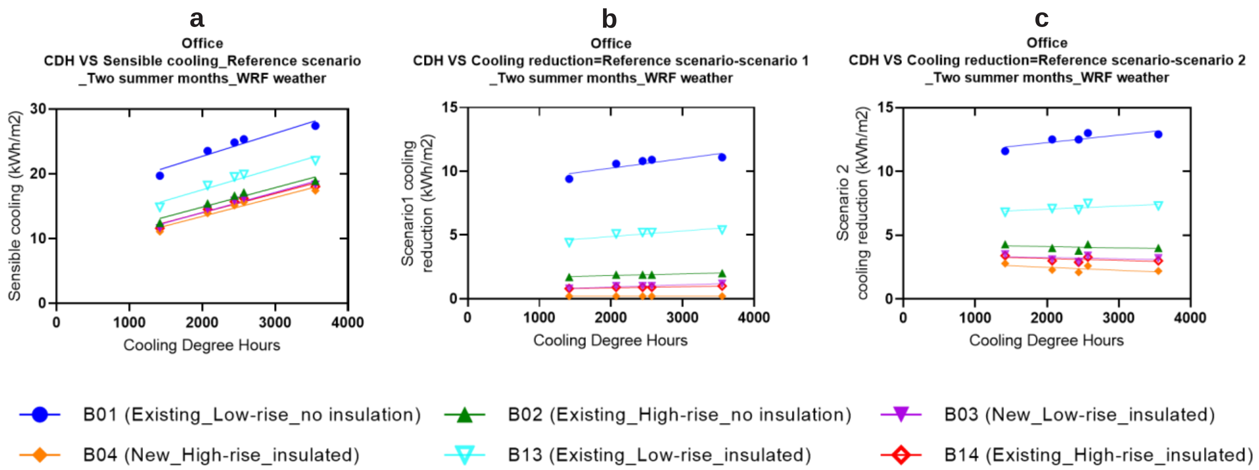


Figure 20 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2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

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

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.003521	15.65	Y = 0.003521*X + 15.65
B02 (Existing_High-rise_no insulation)	0.002998	8.85	Y = 0.002998*X + 8.85
B03 (New_Low-rise_insulated)	0.003099	7.81	Y = 0.003099*X + 7.81
B04 (New_High-rise_insulated)	0.002916	7.59	Y = 0.002916*X + 7.59
B13 (Existing_Low-rise_insulated)	0.003304	10.92	Y = 0.003304*X + 10.92
B14 (Existing_High-rise_insulated)	0.002957	8.07	Y = 0.002957*X + 8.07

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.0007479	8.76	Y = 0.0007479*X + 8.756
B02 (Existing_High-rise_no insulation)	0.0001288	1.57	Y = 0.0001288*X + 1.57
B03 (New_Low-rise_insulated)	0.0001758	0.58	Y = 0.0001758*X + 0.58
B04 (New_High-rise_insulated)	0.000	0.20	Y = 0.20
B13 (Existing_Low-rise_insulated)	0.0004351	4.01	Y = 0.0004351*X + 4.01
B14 (Existing_High-rise_insulated)	0.00008788	0.69	Y = 0.00008788*X + 0.69

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.0005887	11.08	Y = 0.0005887*X + 11.08
B02 (Existing_High-rise_no insulation)	-0.0001057	4.34	Y = -0.0001057*X + 4.34
B03 (New_Low-rise_insulated)	-0.0000996	3.46	Y = -0.0000996*X + 3.46
B04 (New_High-rise_insulated)	-0.0002345	2.97	Y = -0.0002345*X + 2.97
B13 (Existing_Low-rise_insulated)	0.0002415	6.56	Y = 0.0002415*X + 6.56
B14 (Existing_High-rise_insulated)	-0.0001453	3.47	Y = -0.0001453*X + 3.47

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

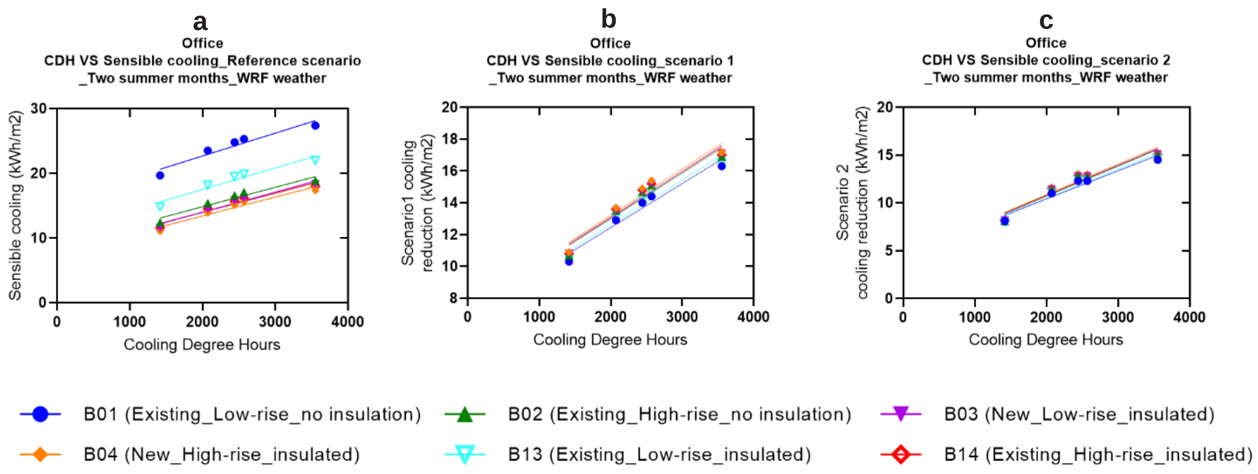


Figure 21 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.3 Shopping mall centres

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

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

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

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

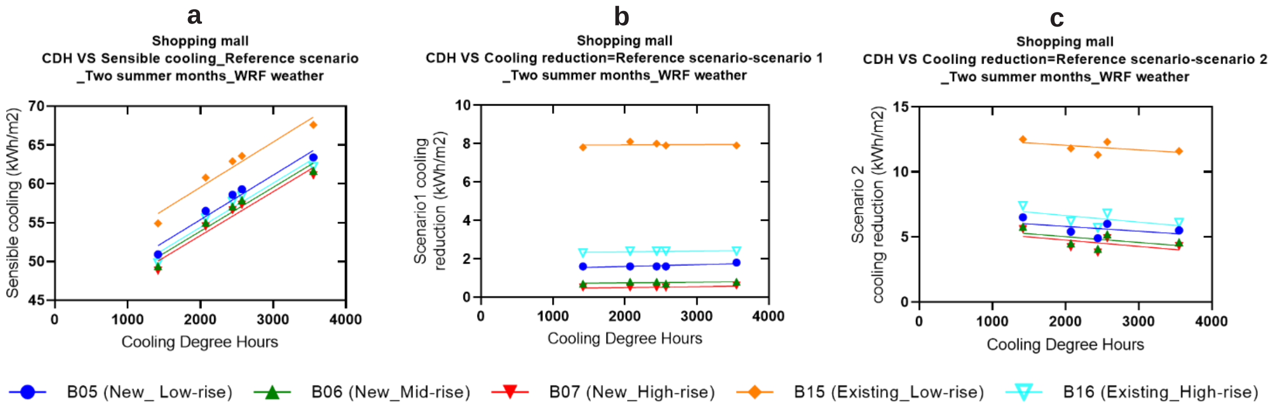


Figure 22 For shopping mall centre a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario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

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

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.005742	43.9	Y = 0.005742*X + 43.90
B06 (New_Mid-rise)	0.005654	42.59	Y = 0.005654*X + 42.59
B07 (New_High-rise)	0.005642	42.06	Y = 0.005642*X + 42.06
B15 (Existing_Low-rise)	0.005818	47.94	Y = 0.005818*X + 47.94
B16 (Existing_High-rise)	0.005683	43.04	Y = 0.005683*X + 43.04

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.00009396	1.41	Y = 0.00009396*X + 1.41
B06 (New_Mid-rise)	0.00003438	0.68	Y = = 0.00003438*X + 0.68
B07 (New_High-rise)	0.00004698	0.41	Y = 0.00004698*X + 0.41
B15 (Existing_Low-rise)	0.00001441	7.91	Y = 0.00001441*X + 7.91
B16 (Existing_High-rise)	0.00004090	2.28	Y = 0.00004090*X + 2.28
c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**

B05 (New_ Low-rise)	-0.0003702	6.55	Y = -0.0003702*X + 6.55
B06 (New_Mid-rise)	-0.0004442	5.91	Y = -0.0004442*X + 5.91
B07 (New_High-rise)	-0.0004851	5.73	Y = -0.0004851*X + 5.73
B15 (Existing_Low-rise)	-0.0003541	12.75	Y = -0.0003541*X + 12.75
B16 (Existing_High-rise)	-0.0005051	7.66	Y = -0.0005051*X + 7.66

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

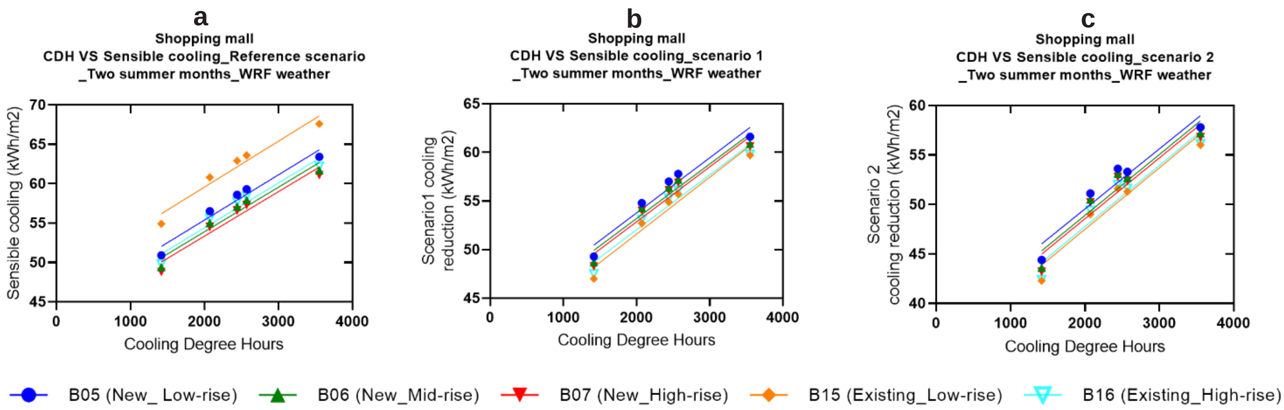


Figure 23 For shopping mall centre a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.4 Residential building

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

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

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all residential building types except for B17, indicating that in most cases, under unmodified climatic conditions, a cool roof is more effective reducing cooling load in hotter regions. Moreover, a higher increase rate is mostly observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.

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

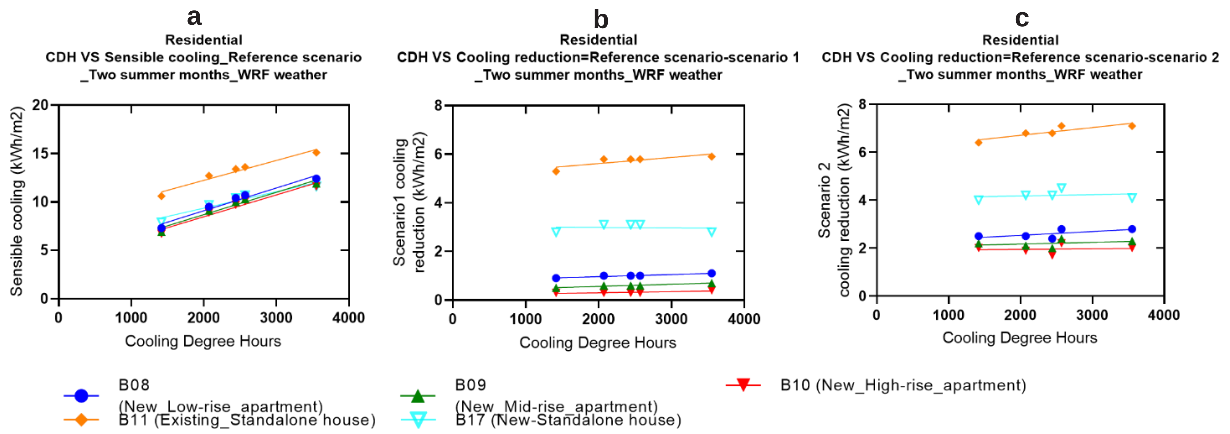


Figure 24 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario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

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

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.002352	4.39	Y = 0.002352*X + 4.39
B09 (New_Mid-rise_apartment)	0.002305	4.08	Y = 0.002305*X + 4.08
B10 (New_High-rise_apartment)	0.002257	3.96	Y = 0.002257*X + 3.96
B11 (Existing_Standalone house)	0.002054	8.13	Y = 0.002054*X + 8.13
B17 (New-Standalone house)	0.001703	5.96	Y = 0.001703*X + 5.96

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0000879	0.79	Y = 0.0000879*X + 0.79
B09 (New_Mid-rise_apartment)	0.0000879	0.39	Y = 0.0000879*X + 0.39

B10 (New_High-rise_apartment)	0.0000470	0.21	Y = 0.0000470*X + 0.21
B11 (Existing_Standalone house)	0.0002515	5.11	Y = 0.0002515*X + 5.11
B17 (New-Standalone house)	-0.0000182	3.02	Y = -0.0000182*X + 3.02

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0001592	2.22	Y = 0.0001592*X + 2.22
B09 (New_Mid-rise_apartment)	0.0000713	2.03	Y = 7.134e-005*X + 2.03
B10 (New_High-rise_apartment)	0.0000231	1.90	Y = 2.308e-005*X + 1.90
B11 (Existing_Standalone house)	0.0003241	6.06	Y = 0.0003241*X + 6.06
B17 (New-Standalone house)	0.0000544	4.07	Y = 5.440e-005*X + 4.07

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

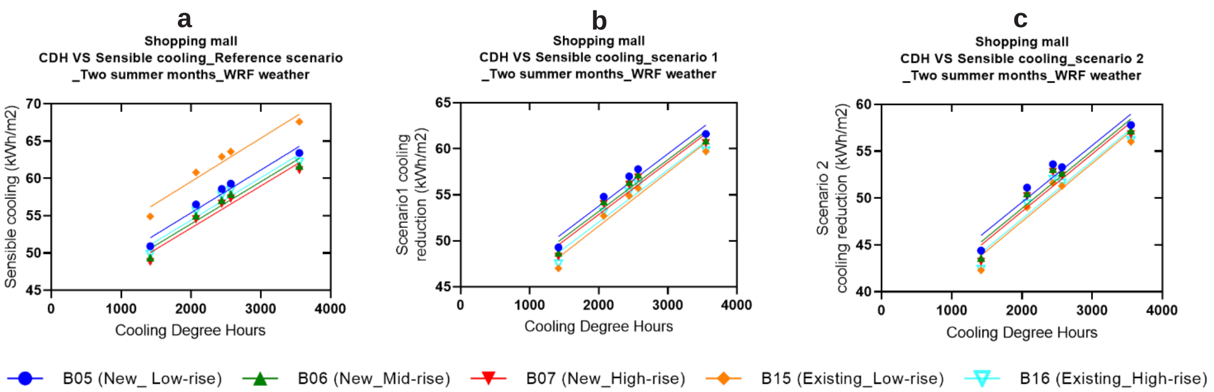


Figure 25 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.5 School

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

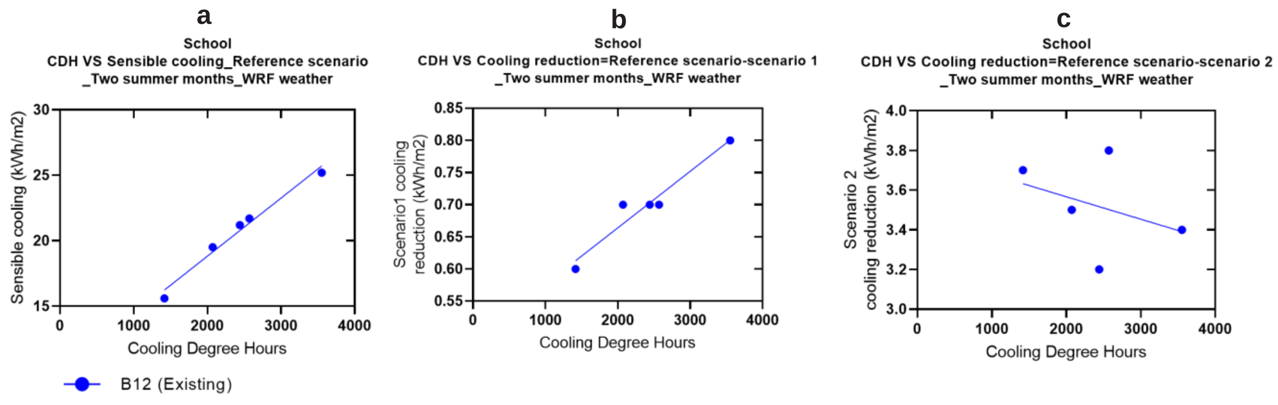


Figure 26 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared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

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

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.004438	9.94	Y = 0.004438*X + 9.94

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.0000879	0.49	Y = 8.788e-005*X + 0.49

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	-0.0001131	3.79	Y = -0.0001131*X + 3.79

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

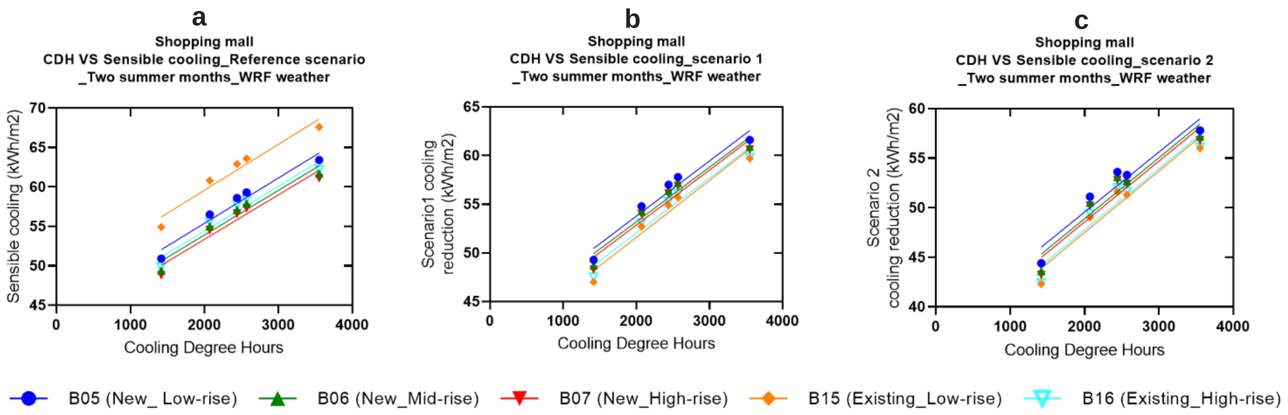


Figure 27 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.6 Conclusion

- Regarding the total cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.
- Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.
- For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present 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 residential buildings, office buildings, school, and shopping mall centres **(Table 16)**.

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

Building No.	Heat loss coefficient
B17 (Standalone house_New)	0.001703
B11 (Standalone house_Existing)	0.002054
B10 (Apartment_New_High-rise)	0.002257
B09 (Apartment_New_Mid-rise)	0.002305
B08 (Apartment_New_Low-rise)	0.002352

B04 (Office_New_High-rise_insulated)	0.002916
B14 (Office_Existing_High-rise_insulated)	0.002957
B02 (Office_Existing_High-rise_no insulation)	0.002998
B03 (Office_New_Low-rise_insulated)	0.003099
B13 (Office_Existing_Low-rise_insulated)	0.003304
B01 (Office_Existing_Low-rise_no insulation)	0.003521
B12 (School_Existing)	0.004438
B07 (Shopping mall_New_High-rise)\	0.005642
B06 (Shopping mall_New_Mid-rise)	0.005654
B16 (Shopping mall_Existing_High-rise)	0.005683
B05 (Shopping mall_New_ Low-rise)	0.005742
B15 (Shopping mall_Existing_Low-rise)	0.005818

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 Adelaide. As estimated, the application of cool roofs can improve the hourly EER of the six selected AC systems by 0.22-0.63 in Kuitpo station in Adelaide. This is equivalent to a noticeable EER-related cooling load saving of around 8-20% in a new high-rise shopping mall centre in Kuitpo 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 11%.

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 show that rooftop AC systems may experience up to 17% lower EER in urban areas compared to the 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 implementation of 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 Adelaide. 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 Adelaide (i.e. Roseworthy and Kuitpo 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 Adelaide. The simulations were performed under three scenarios:

- **Reference scenario**: A reference building with 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-months 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 Kuitpo and Roseworthy 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 Kuitpo 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 Kuitpo and Roseworthy stations, respectively (See **Table 17** and **Figures 28-61**).

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 Kuitpo and Roseworthy 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	Kuitpo	19.7	0.28
	Roseworthy	27.4	0.48
B02- high-rise office building without roof insulation-existing building	Kuitpo	12.4	0.44
	Roseworthy	18.9	0.72
B03- low-rise office building with roof insulation-new building	Kuitpo	11.6	0.55
	Roseworthy	18.3	0.76
B04- high-rise office building with roof insulation-new building	Kuitpo	11.1	0.58
	Roseworthy	17.4	0.8
B05- low-rise shopping mall centre-existing building-new building	Kuitpo	50.9	0.86
	Roseworthy	63.4	0.91
B06- mid-rise shopping mall centre-existing building-new building	Kuitpo	49.4	0.87
	Roseworthy	61.7	0.92
B07- high-rise shopping mall centre-new building	Kuitpo	48.8	0.87
	Roseworthy	61.1	0.92
B08- low-rise apartment building-new building	Kuitpo	7.3	0.32
	Roseworthy	12.4	0.61
B09- mid-rise apartment building-new building	Kuitpo	6.9	0.33
	Roseworthy	11.9	0.64
B10- high-rise apartment building-new building	Kuitpo	6.7	0.33
	Roseworthy	11.6	0.65
B11- typical stand-alone house-existing building	Kuitpo	10.6	0.23
	Roseworthy	15.1	0.42

B12- typical school building-existing building	Kuitpo	15.6	0.57
	Roseworthy	25.2	0.78
B13- low-rise office building with roof insulation-existing building	Kuitpo	14.8	0.56
	Roseworthy	22.0	0.6
B14- high-rise office building with roof insulation-existing building	Kuitpo	11.6	0.49
	Roseworthy	18.0	0.76
B15- low-rise shopping mall centre-existing building	Kuitpo	54.9	0.75
	Roseworthy	67.6	0.81
B16- high-rise shopping mall centre-existing building	Kuitpo	49.8	0.83
	Roseworthy	62.2	0.89
B17- stand-alone house-new building	Kuitpo	7.9	0.27
	Roseworthy	11.6	0.55

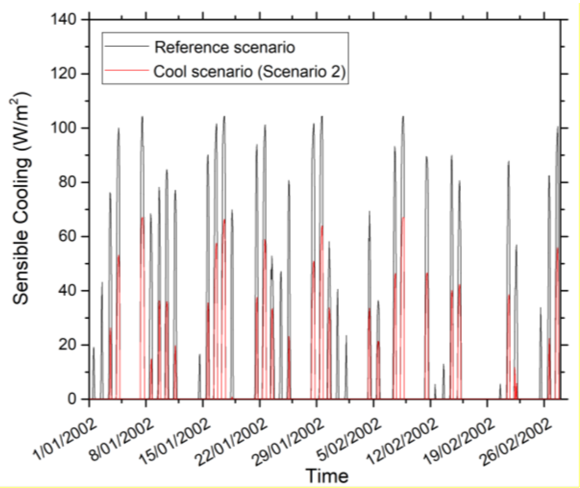


Figure 28 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-existing building in Kuitpo station

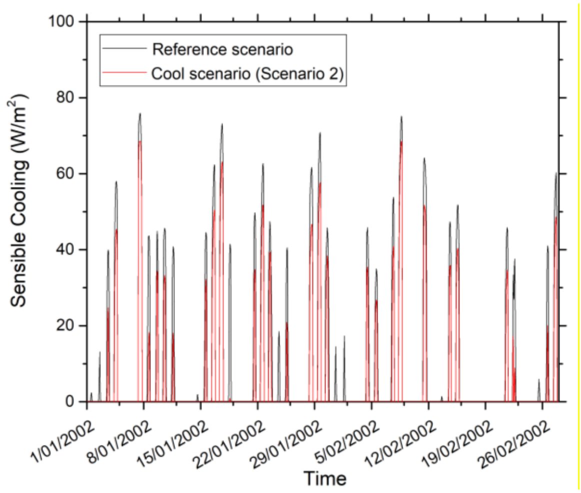


Figure 29 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-existing building in Kuitpo station

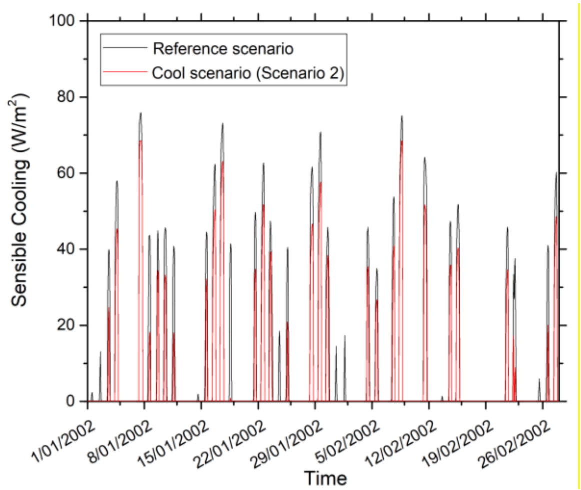


Figure 30 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-existing building in Kuitpo station

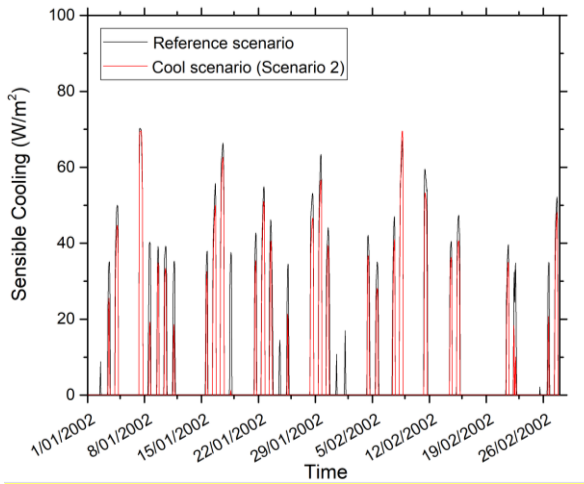


Figure 31 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-new building in Kuitpo station

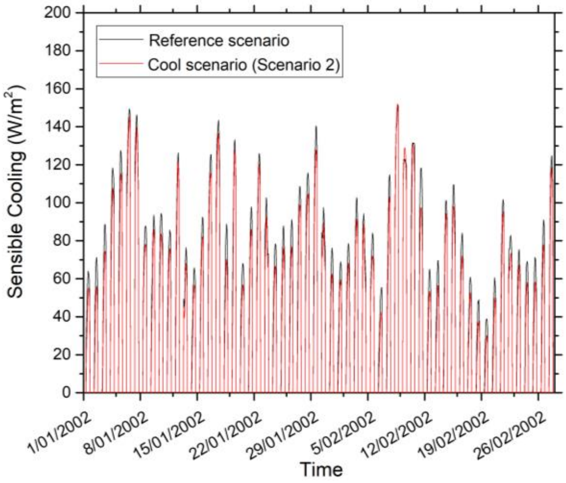


Figure 32 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise shopping mall centre-new building in Kuitpo station.

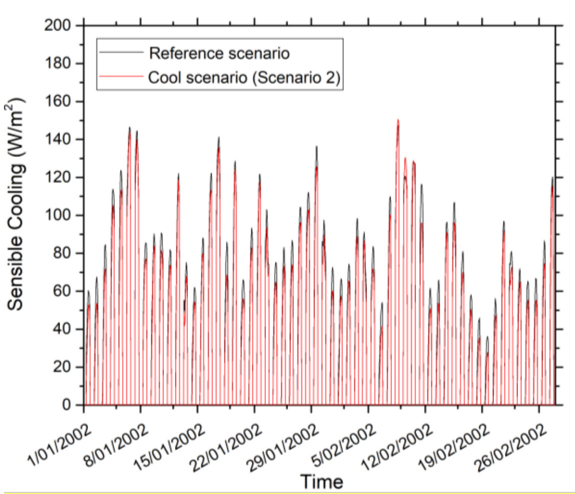


Figure 33 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise shopping mall centre-new building in Kuitpo station

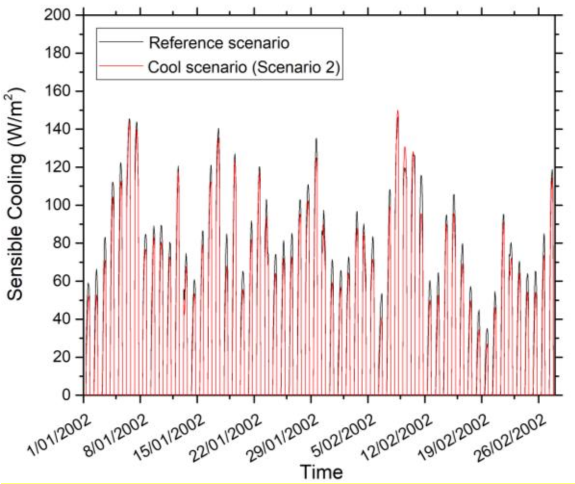


Figure 34 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise shopping mall centre-new building in Kuitpo station

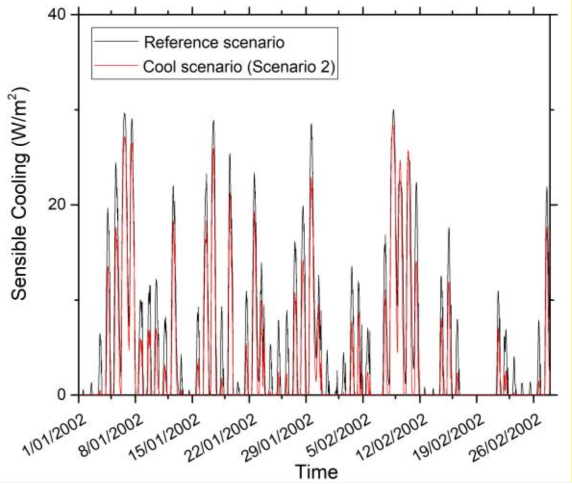


Figure 35 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise apartment-new building in Kuitpo station.

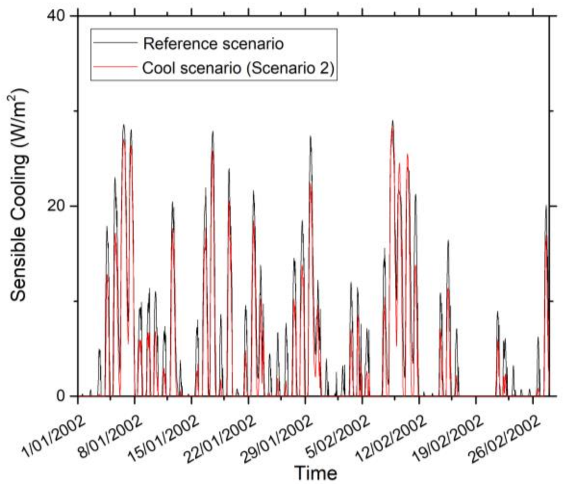


Figure 36 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise apartment-new building in Kuitpo station

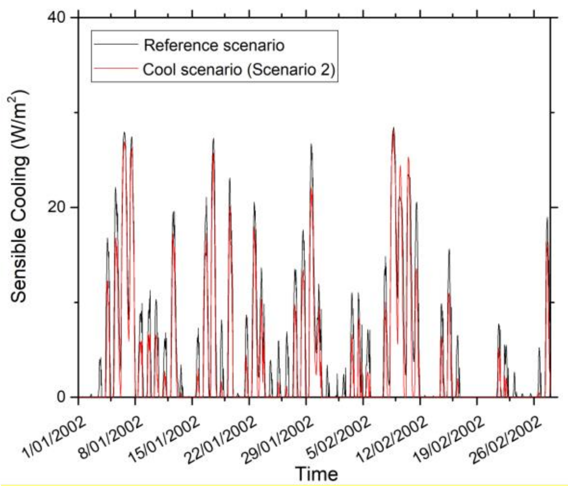


Figure 37 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise apartment-new building in Kuitpo station

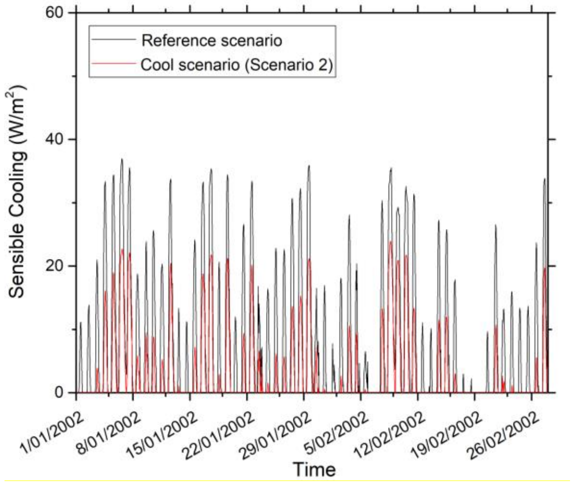


Figure 38 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical stand-alone house-existing building in Kuitpo station

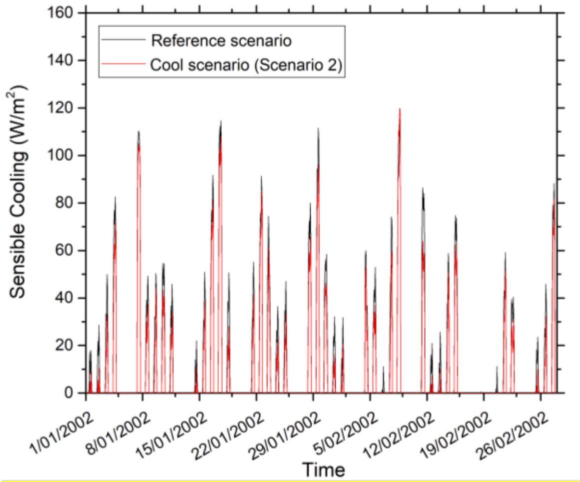


Figure 39 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical school building-existing building in Kuitpo station

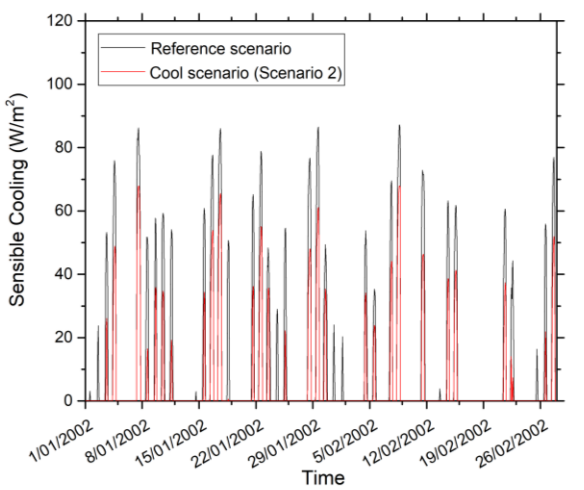


Figure 40 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise office-existing building in Kuitpo station

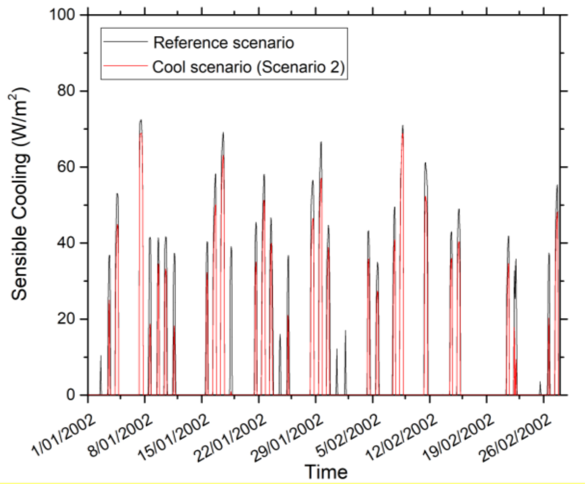


Figure 41 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise office-existing building in Kuitpo station

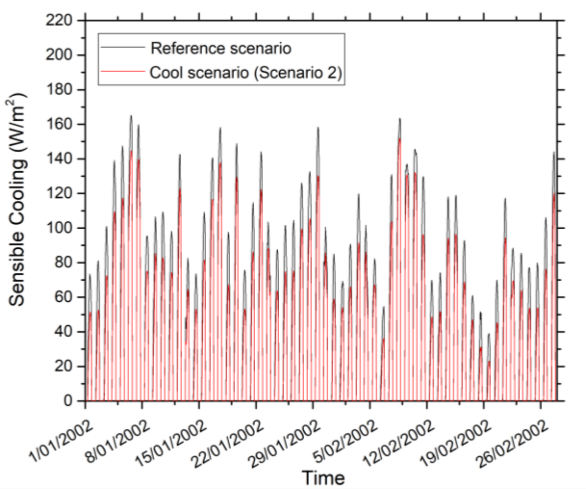


Figure 42 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise shopping mall centre-existing building in Kuitpo station

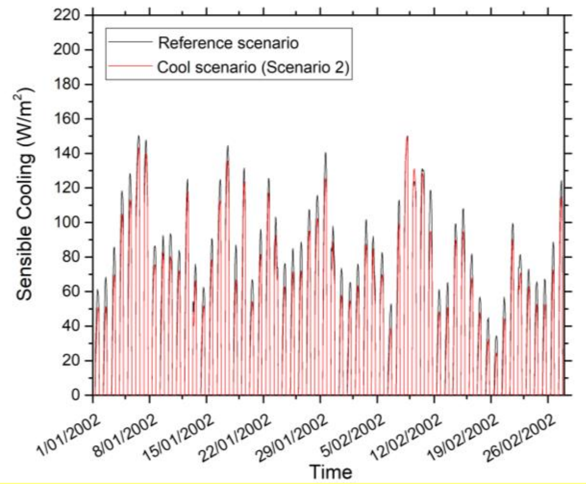


Figure 43 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise shopping mall centre-existing building in Kuitpo station

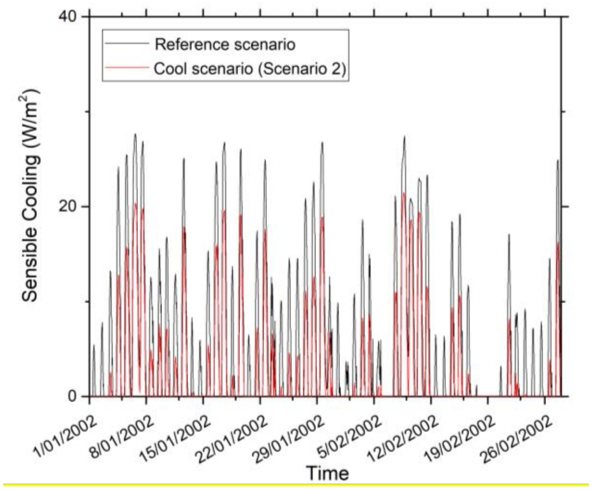


Figure 44 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a stand-alone house-new building in Kuitpo station

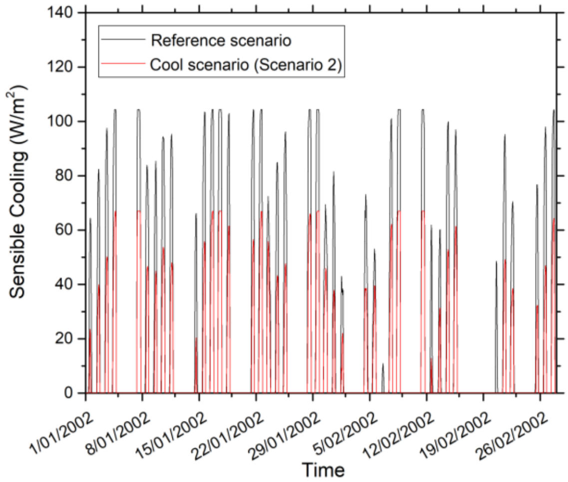


Figure 45 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-existing building in Roseworthy station

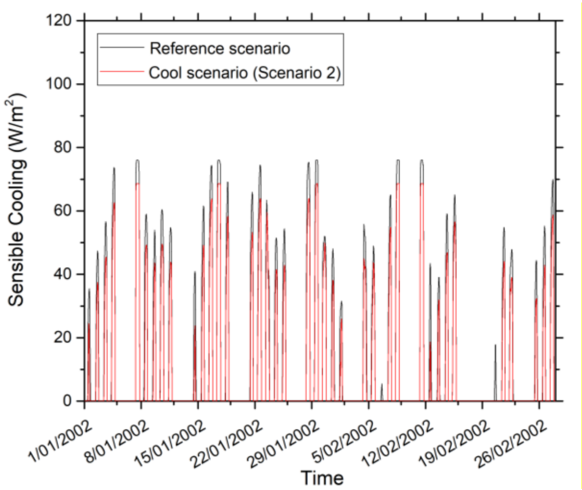


Figure 46 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-existing building in Roseworthy station

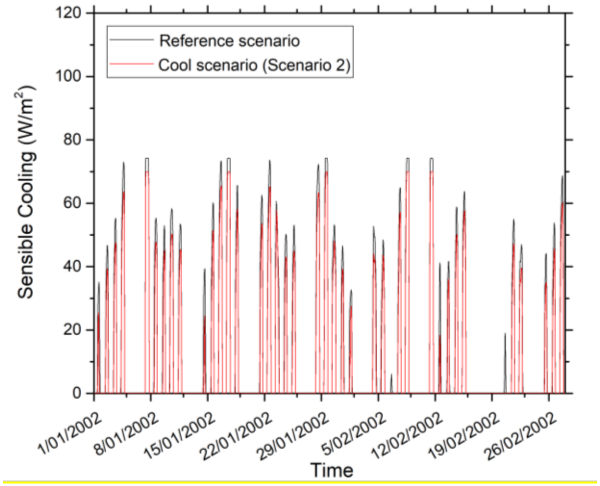


Figure 47 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-new building in Roseworthy station

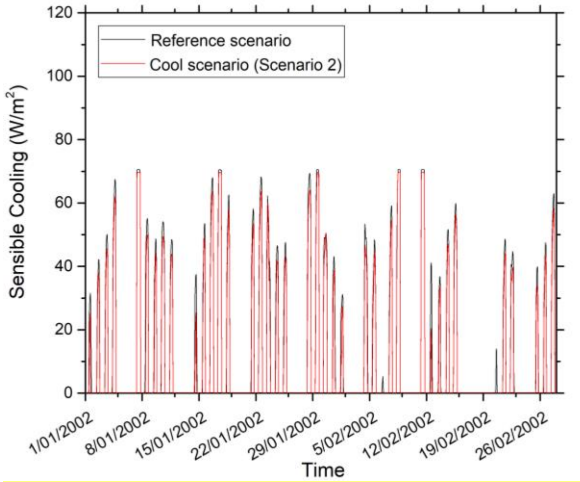


Figure 48 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-new building in Roseworthy station

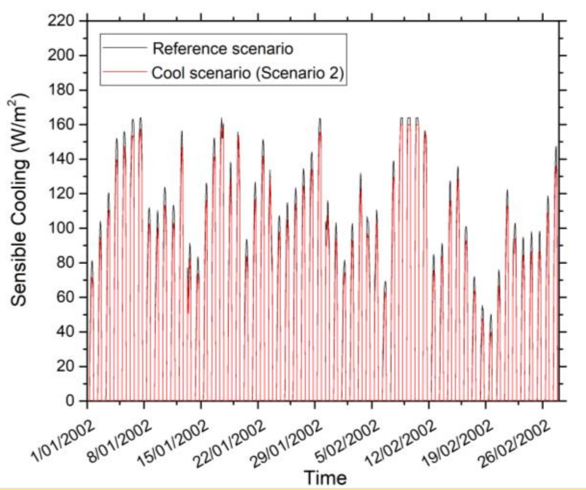


Figure 49 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise shopping mall centre-new building in Roseworthy station

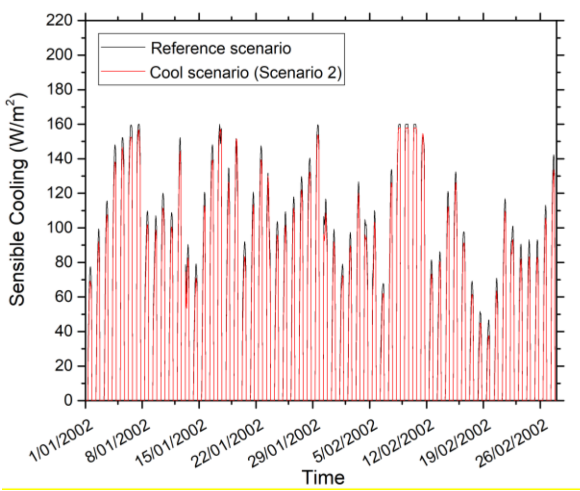


Figure 50 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise shopping mall centre-new building in Roseworthy station

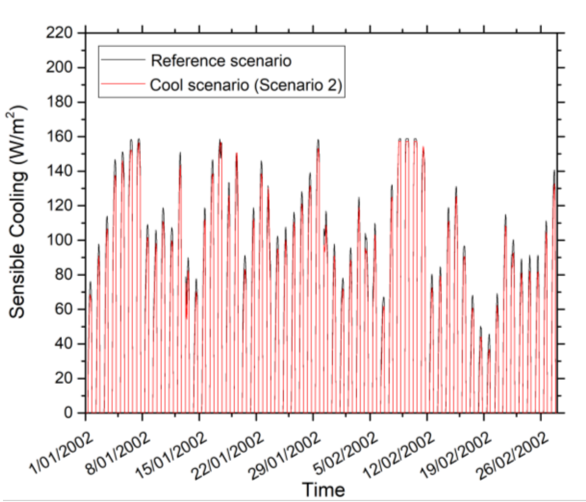


Figure 51 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise shopping mall centre-new building in Roseworthy station

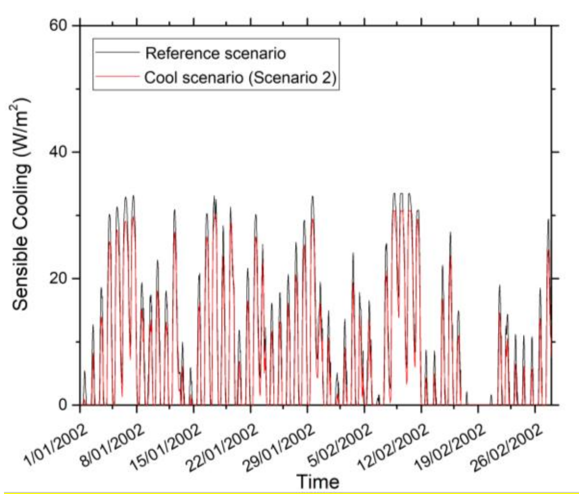


Figure 52 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise apartment-new building in Roseworthy station

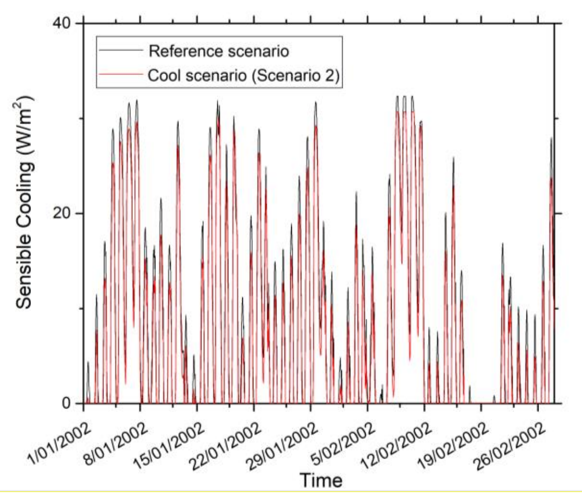


Figure 53 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise apartment-new building in Roseworthy station

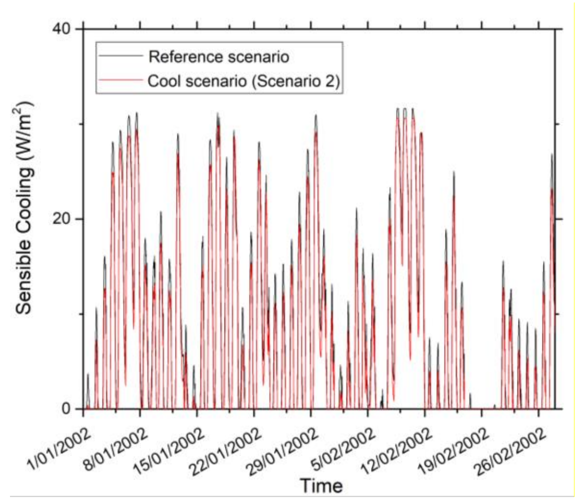


Figure 54 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise apartment-new building in Roseworthy station

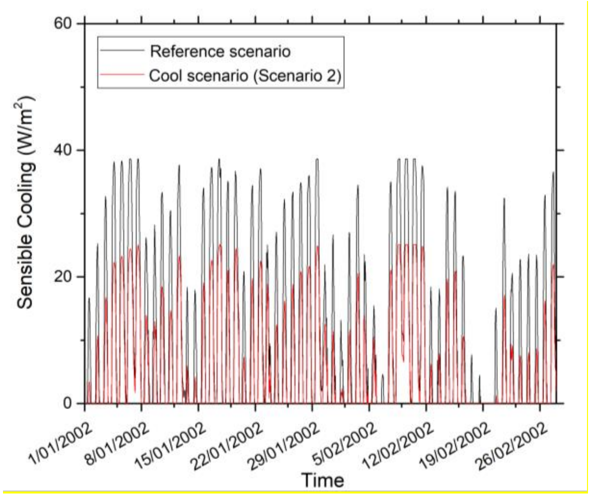


Figure 55 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical stand-alone house-existing building in Roseworthy station

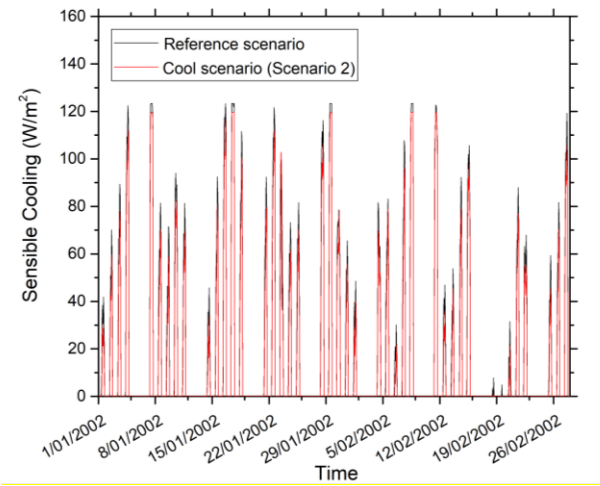


Figure 56 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical school building-existing building in Roseworthy station

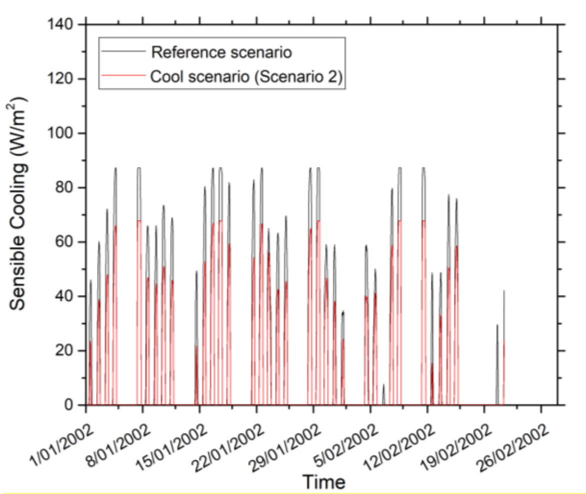


Figure 57 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise office-existing building in Roseworthy station

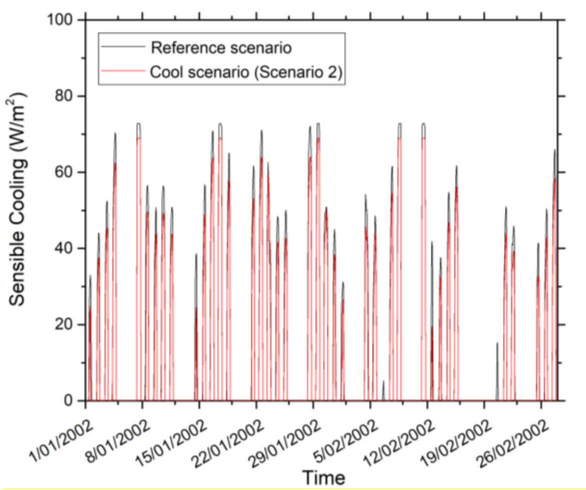


Figure 58 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise office-existing building in Roseworthy station

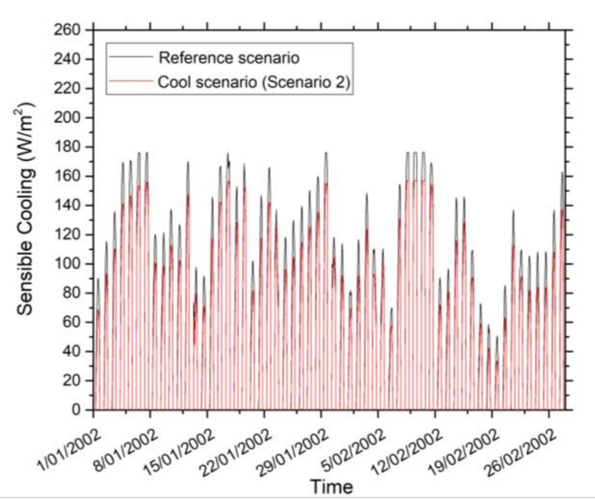


Figure 59 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise shopping mall centre-existing building in Roseworthy station

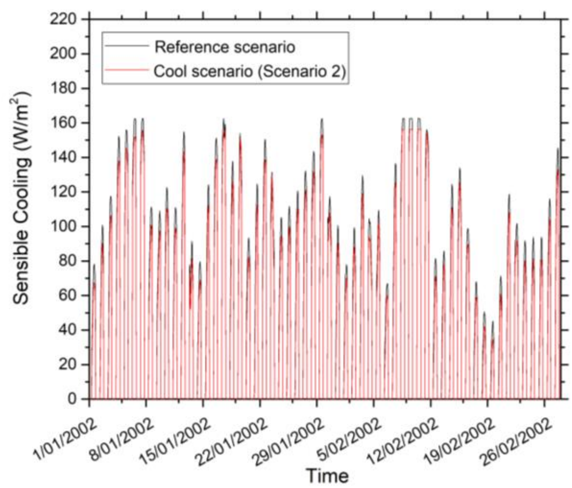


Figure 60 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise shopping mall centre-existing building in Roseworthy station

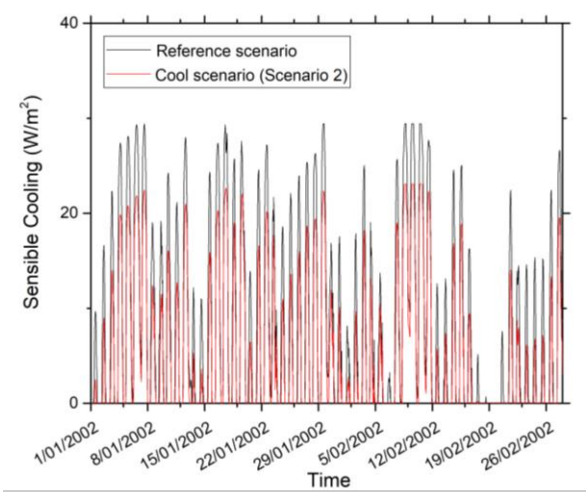


Figure 61 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a stand-alone house-new building in Roseworthy station

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** Average, minimum, and maximum ambient temperature variations in cool roof scenario compared to reference scenario in Kuitpo and Roseworthy stations. shows the minimum, average, and maximum ambient temperature variations in cool roof with modified urban temperature scenario (Scenario 2) compared to reference scenario in Kuitpo and Roseworthy stations. **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 Kuitpo station 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 Kuitpo and Roseworthy stations, respectively. **Error! Reference source not found.** 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 Kuitpo and Roseworthy 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)**
Kuitpo	1.58	0.02	3.18
Roseworthy	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 Kuitpo station

AC systems	**Average hourly EER variation (Cool roof with modified urban temperature scenario**	**Minimum hourly EER variation (Cool roof with modified urban temperature scenario**	**Maximum hourly EER variation (Cool roof with modified urban temperature scenario**

	(Scenario 2) vs reference scenario)	**(Scenario 2) vs reference scenario)**	**(Scenario 2) vs reference scenario)**
Residential-Split system-Eq 1	0.11	0.002	0.22
Residential-Split system-Eq 2	0.12	0.002	0.23
Residential-Split system-Eq 3	0.12	0.002	0.24
Residential-Split system-Eq 4	0.20	0.003	0.39
Residential-Split system-Eq 5	0.32	0.003	0.63
Residential-Split system-Eq 6	0.14	0.001	0.28

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 Roseworthy 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	0.13	0.07	0.22
Residential-Split system-Eq 5	0.19	0.04	0.41
Residential-Split system-Eq 6	0.09	0.03	0.17

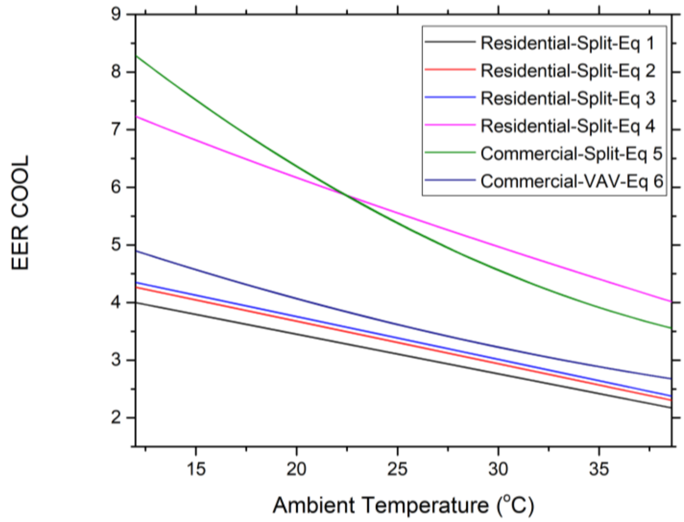


Figure 62 EER for cool roof scenario for six different AC systems

5.4.2. 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 Kuitpo and Roseworthy 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 Kuitpo and Roseworthy 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 Kuitpo 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	19.7	9.4	48	11.6	59	0.6	3	0.7	3	0.7	3	1.0	5	1.3	7	0.7	3
B02	12.4	1.7	14	4.3	34	0.6	5	0.7	5	0.7	5	1.1	9	1.4	11	0.7	6
B03	11.6	0.8	7	3.5	30	0.6	5	0.7	6	0.7	6	1.1	9	1.4	12	0.7	6
B04	11.1	0.2	1	2.8	26	0.6	6	0.7	6	0.7	6	1.1	10	1.4	13	0.7	6
B05	50.9	1.6	3	6.5	13	4.0	8	4.3	8	4.3	8	6.9	13	9.8	19	4.7	9
B06	49.4	0.7	2	5.8	12	3.9	8	4.2	8	4.2	9	6.7	14	9.7	20	4.6	9
B07	48.8	0.5	1	5.6	11	3.9	8	4.2	9	4.2	9	6.7	14	9.6	20	4.6	9
B08	7.3	0.9	12	2.5	34	0.4	5	0.4	6	0.4	6	0.7	9	0.9	12	0.4	6
B09	6.9	0.5	7	2.2	32	0.4	6	0.4	6	0.4	6	0.7	10	0.9	13	0.4	6
B10	6.7	0.3	4	2.0	30	0.4	6	0.4	6	0.4	6	0.7	10	0.9	13	0.4	6
B11	10.6	5.3	50	6.4	60	0.3	3	0.4	3	0.4	3	0.6	5	0.7	7	0.4	3
B12	15.6	0.6	4	3.7	24	0.9	6	1.0	6	1.0	6	1.5	10	2.0	13	1.0	6
B13	14.8	4.4	30	6.8	46	0.6	4	0.7	4	0.7	4	1.0	7	1.3	9	0.7	4
B14	11.6	0.8	7	3.4	30	0.6	5	0.7	6	0.7	6	1.1	9	1.4	12	0.7	6
B15	54.9	7.8	14	12.5	23	3.8	7	4.0	7	4.1	7	6.5	12	9.2	17	4.4	8
B16	49.8	2.3	5	7.4	15	3.8	8	4.1	8	4.1	8	6.5	13	9.3	19	4.4	9
B17	7.9	2.8	36	4.0	51	0.3	4	0.3	4	0.3	4	0.5	7	0.7	9	0.3	4

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 Roseworthy 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	27.4	11.1	41	12.9	4	1.2	5	1.3	5	1.3	5	1.9	7	2.2	8	1.1	4
B02	18.9	2.0	11	4.0	6	1.2	7	1.3	7	1.3	7	2.0	11	2.2	12	1.2	6
B03	18.3	1.2	7	3.2	7	1.2	7	1.3	7	1.3	7	2.0	11	2.2	12	1.2	7
B04	17.4	0.2	1	2.2	7	1.2	8	1.3	8	1.3	8	2.0	12	2.3	13	1.2	7
B05	63.4	1.8	3	5.5	7	4.7	8	5.0	8	5.0	8	7.7	12	9.1	14	4.7	7
B06	61.7	0.8	1	4.6	7	4.6	8	5.0	8	5.0	8	7.6	12	8.9	14	4.6	8
B07	61.1	0.6	1	4.3	7	4.6	8	4.9	8	5.0	8	7.6	12	8.9	15	4.6	8
B08	12.4	1.1	9	2.8	6	0.8	7	0.8	7	0.8	7	1.2	10	1.4	11	0.7	6
B09	11.9	0.7	6	2.3	6	0.8	7	0.8	7	0.8	7	1.2	10	1.4	11	0.7	6
B10	11.6	0.4	3	2.0	6	0.8	7	0.8	7	0.8	7	1.2	11	1.4	12	0.7	6
B11	15.1	5.9	39	7.1	4	0.6	5	0.7	5	0.7	5	1.1	7	1.1	8	0.6	4
B12	25.2	0.8	3	3.4	7	1.8	8	1.9	8	1.9	8	2.9	12	3.2	13	1.7	7
B13	22	5.4	25	7.3	5	1.2	6	1.3	6	1.3	6	2.0	9	2.2	10	1.2	5
B14	18	1.0	5	3.0	7	1.2	7	1.3	7	1.3	7	2.0	11	2.2	12	1.2	7
B15	67.6	7.9	12	11.6	7	4.5	7	4.9	7	4.9	7	7.5	11	8.7	13	4.5	7
B16	62.2	2.4	4	6.1	7	4.5	8	4.9	8	4.9	8	7.5	12	8.7	14	4.5	7
B17	11.6	2.8	24	4.1	5	0.6	6	0.6	6	0.6	6	1.0	8	1.1	9	0.6	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 Adelaide. 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. Kuitpo and Roseworthy) in Adelaide.

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	Kuitpo	0.28	19.7	9.4	48	11.6	59	0.6-1.3	3-7
	Roseworthy	0.48	27.4	11.1	41	12.9	47	1.1-2.2	4-8
B02- high-rise office building without roof insulation-existing building	Kuitpo	0.44	12.4	1.7	14	4.3	34	0.6-1.4	5-11
	Roseworthy	0.72	18.9	2.0	11	4.0	21	1.2-2.2	6-12
B03- low-rise office building with roof insulation-new building	Kuitpo	0.55	11.6	0.8	7	3.5	30	0.6-1.4	5-12
	Roseworthy	0.76	18.3	1.2	7	3.2	17	1.2-2.2	7-12
B04- high-rise office building with roof insulation-new building	Kuitpo	0.58	11.1	0.2	1	2.8	26	0.6-1.4	6-13
	Roseworthy	0.8	17.4	0.2	1	2.2	13	1.2-2.3	7-13
B05- low-rise shopping mall centre-existing	Kuitpo	0.86	50.9	1.6	3	6.5	13	4.0-9.8	8-19
	Roseworthy	0.91	63.4	1.8	3	5.5	9	4.7-9.1	7-14

building-new building									
B06- mid-rise shopping mall centre-existing building-new building	Kuitpo	0.87	49.4	0.7	2	5.8	12	3.9-9.7	8-20
	Roseworthy	0.92	61.7	0.8	1	4.6	7	4.6-8.9	8-14
B07- high-rise shopping mall centre-new building	Kuitpo	0.87	48.8	0.5	1	5.6	11	3.9-9.6	8-20
	Roseworthy	0.92	61.1	0.6	1	4.3	7	4.6-8.9	8-15
B08- low-rise apartment building-new building	Kuitpo	0.32	7.3	0.9	12	2.5	34	0.4-0.9	5-12
	Roseworthy	0.61	12.4	1.1	9	2.8	22	0.7-1.4	6-11
B09- mid-rise apartment building-new building	Kuitpo	0.33	6.9	0.5	7	2.2	32	0.4-0.9	6-13
	Roseworthy	0.64	11.9	0.7	6	2.3	19	0.7-1.4	6-11
B10- high-rise apartment building-new building	Kuitpo	0.33	6.7	0.3	4	2.0	30	0.4-0.9	6-13
	Roseworthy	0.65	11.6	0.4	3	2.0	17	0.7-1.4	6-12
B11- typical stand-alone house-existing building	Kuitpo	0.23	10.6	5.3	50	6.4	60	0.3-0.7	3-7
	Roseworthy	0.42	15.1	5.9	39	7.1	47	0.6-1.1	4-8
B12- typical school building-existing building	Kuitpo	0.57	15.6	0.6	4	3.7	24	0.9-2.0	6-13
	Roseworthy	0.78	25.2	0.8	3	3.4	13	1.7-3.2	7-13
B13- low-rise office building with roof	Kuitpo	0.56	14.8	4.4	30	6.8	46	0.6-1.3	4-9
	Roseworthy	0.6	22.0	5.4	25	7.3	33	1.2-2.2	5-10

insulation-existing building									
B14- high-rise office building with roof insulation-existing building	Kuitpo	0.49	11.6	0.8	7	3.4	30	0.6-1.4	5-12
	Roseworthy	0.76	18.0	1.0	5	3.0	16	1.2-2.2	7-12
B15- low-rise shopping mall centre-existing building	Kuitpo	0.75	54.9	7.8	14	12.5	23	3.8-9.2	7-17
	Roseworthy	0.81	67.6	7.9	12	11.6	17	4.5-8.7	7-13
B16- high-rise shopping mall centre-existing building	Kuitpo	0.83	49.8	2.3	5	7.4	15	3.8-9.3	8-19
	Roseworthy	0.89	62.2	2.4	4	6.1	10	4.5-8.7	7-14
B17- stand-alone house-new building	Kuitpo	0.27	7.9	2.8	36	4.0	51	0.3-0.7	4-9
	Roseworthy	0.55	11.6	2.8	24	4.1	35	0.6-1.1	5-9

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 0.28-0.48 and 0.56-0.6 for a low-rise office building without roof insulation-existing building (b01) and low-rise office building with roof insulation-existing building (b13), 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 0.22-0.63 and 0.12-0.41 in Kuitpo and Roseworthy stations, 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 1.2 and 2.3 kWh/m^2 for a new high-rise office building with roof insulation-new building in Roseworthy 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 0.2 and 2.2 kWh/m^2, 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 1.1 and 2.2 kWh/m^2 for an existing office building without roof insulation in Roseworthy 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 11.1 and 12.9 kWh/m^2, 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 4.6 and 8.9 kWh/m^2 for a new high-rise shopping mall centre in Roseworthy 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 4.3 kWh/m^2, respectively.

6. Feasibility of cool roofs: Evaluation of refurbishment of Buildings 01 to 17 for Kuitpo and Roseworthy 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, the project with shorter economic life is preferred if other things are equal. This method does not attach importance to the shorter economic life of the project.

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

2) Internal Rate of Return Method

Internal rate of return (IRR) is a percentage discount rate used in capital investment appraisals which brings the cost of a project and its future cash inflows into equality. It is the rate of return 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 it 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 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 requirement.

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 Kuitpo	B01 Roseworthy
Energy consumption prior cool roof (MWh)	33.30	51.7
Energy consumption after cool roof (MWh)	26.20	36.40
Energy savings (MWh)	7.10	15.30
Energy savings (%)	21.32%	29.59%
Area (m^2)	1,200	1,200
Roof costs - Metal roof (AU$/$m^2$)	38.00	38.00
Roof costs - Coating (AU$/$m^2$)	22.75	22.75
Life expectancy - Metal roof (years)	28.5	28.5
Life expectancy - Coating (years)	22.5	22.5
HVACs COP	2.5	2.5
Existing roof's renovation costs (AU$/$m^2$)	15.0	15.0

Table 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	0,035
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 I refers to Kuitpo weather conditions, whilst Part 2 to Roseworthy 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. Net Present Value for Kuitpo weather data

Table 26 Net Present Value for Kuitpo weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	-12,762	-1,980	16,646	20,909
2	-25,189	-11,652	-7,378	2,211
3	-41,609	-24,432	-39,124	-22,498
4	-44,272	-26,505	-44,272	-26,505
5	-25,494	-12,552	-11,410	-1,591
6	-26,825	-13,588	-13,984	-3,594
7	-27,712	-14,279	-15,700	-4,930
8	-25,240	-15,510	-27,311	-17,122
9	-25,240	-15,510	-27,311	-17,122

10	-25,654	-15,837	-28,112	-17,754
11	-9,806	-6,030	-10,625	-6,669
12	-41,460	-24,981	-42,279	-25,620
13	-30,070	-15,452	-16,816	-5,135
14	-33,621	-18,215	-23,680	-10,478
15	27,762	28,898	91,550	78,545
16	17,998	21,298	72,674	63,853
17	-8,484	-5,000	-8,070	-4,677

Table 27 Internal Rate of Return for Kuitpo weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	0.74%	2.31%	5.41%	9.01%
2	-2.19%	-1.70%	1.75%	3.73%
3	-11.22%	-13.41%	-8.49%	-9.95%
4	-	-	-	-
5	-2.99%	-2.76%	0.80%	2.40%
6	-3.47%	-3.40%	0.23%	1.60%
7	-3.81%	-3.86%	-0.18%	1.05%
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	-	-	-	-
13	-3.75%	-3.78%	-0.11%	1.14%
14	-5.18%	-5.67%	-1.77%	-1.13%
15	7.14%	11.59%	14.47%	23.33%
16	5.81%	9.59%	12.44%	19.96%
17	-11.97%	-14.35%	-9.30%	-10.99%

Table 28 Life Cycle Cost for Kuitpo weather data

LCC	Low Electricity Price			High Electricity Price		
Building	**As built**	**Metal Roof**	**Coating**	**As built**	**Metal Roof**	**Coating**
1	159,337	158,121	114,578	297,268	264,380	196,781
2	443,809	450,352	340,993	847,247	829,360	634,515
3	94,543	123,237	87,663	172,000	196,938	144,744
4	386,559	413,125	312,226	736,565	757,388	578,900
5	443,734	451,530	342,569	848,000	835,080	639,624
6	822,734	825,643	632,370	1,580,734	1,558,366	1,199,906
7	1,200,846	1,198,439	921,149	2,311,751	2,279,105	1,758,212
8	177,756	194,171	146,367	338,055	353,910	270,112
9	285,598	300,243	228,533	546,549	558,984	428,966

10	444,841	457,206	350,930	854,419	862,445	665,602
11	24,710	31,815	23,120	45,599	53,176	39,709
12	337,083	362,535	274,290	641,809	663,023	507,619
13	118,508	135,270	96,941	218,332	220,201	110,574
14	410,081	425,609	321,858	782,039	781,524	597,520
15	467,699	421,846	319,378	894,333	777,692	594,789
16	1,215,048	1,166,697	896,392	2,320,763	2,217,736	1,710,348
17	18,750	24,635	17,511	34,076	39,295	28,865

Table 29 Payback Period for Kuitpo weather data

PB	**Low Electricity Price**		**High Electricity Price**	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	-	-	16.0	10.4
2	-	-	23.2	15.8
3	-	-	-	-
4	-	-	-	-
5	-	-	25.7	17.8
6	-	-	27.3	19.1
7	-	-	-	20
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	-	-	-	-
13	-	-	-	19.9
14	-	-	-	-
15	13.6	8.7	7.6	4.6
16	15.4	10.0	8.8	5.4
17	-	-	-	-

In order to comparatively illustrate the results for the 17 buildings, in the following figures are depicted their Net Present Value, Internal Rate of Return, Life Cycle Cost and Depreciated Payback Period values.

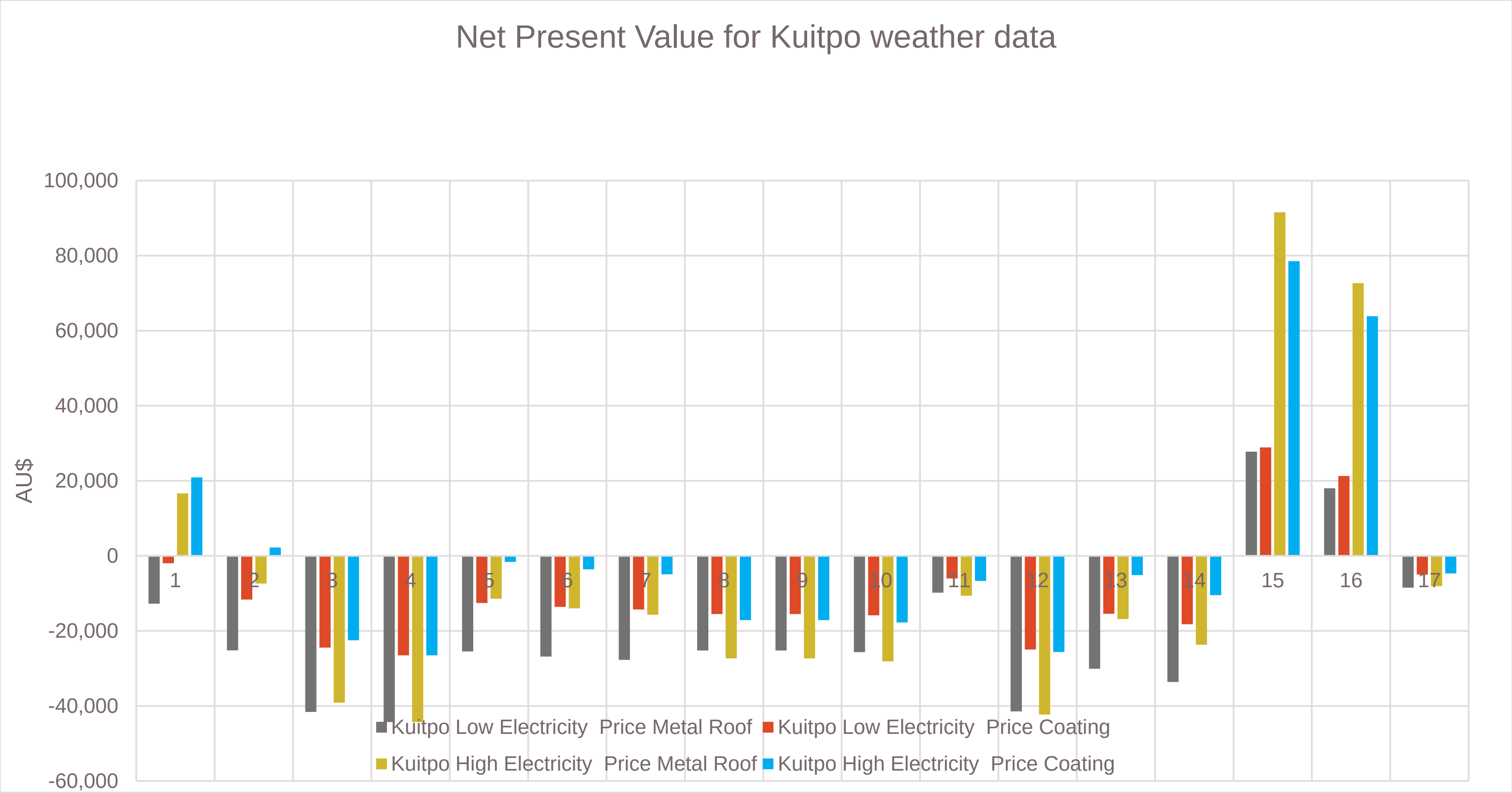


Figure 63 Net Present Value for the buildings for Kuitpo weather conditions

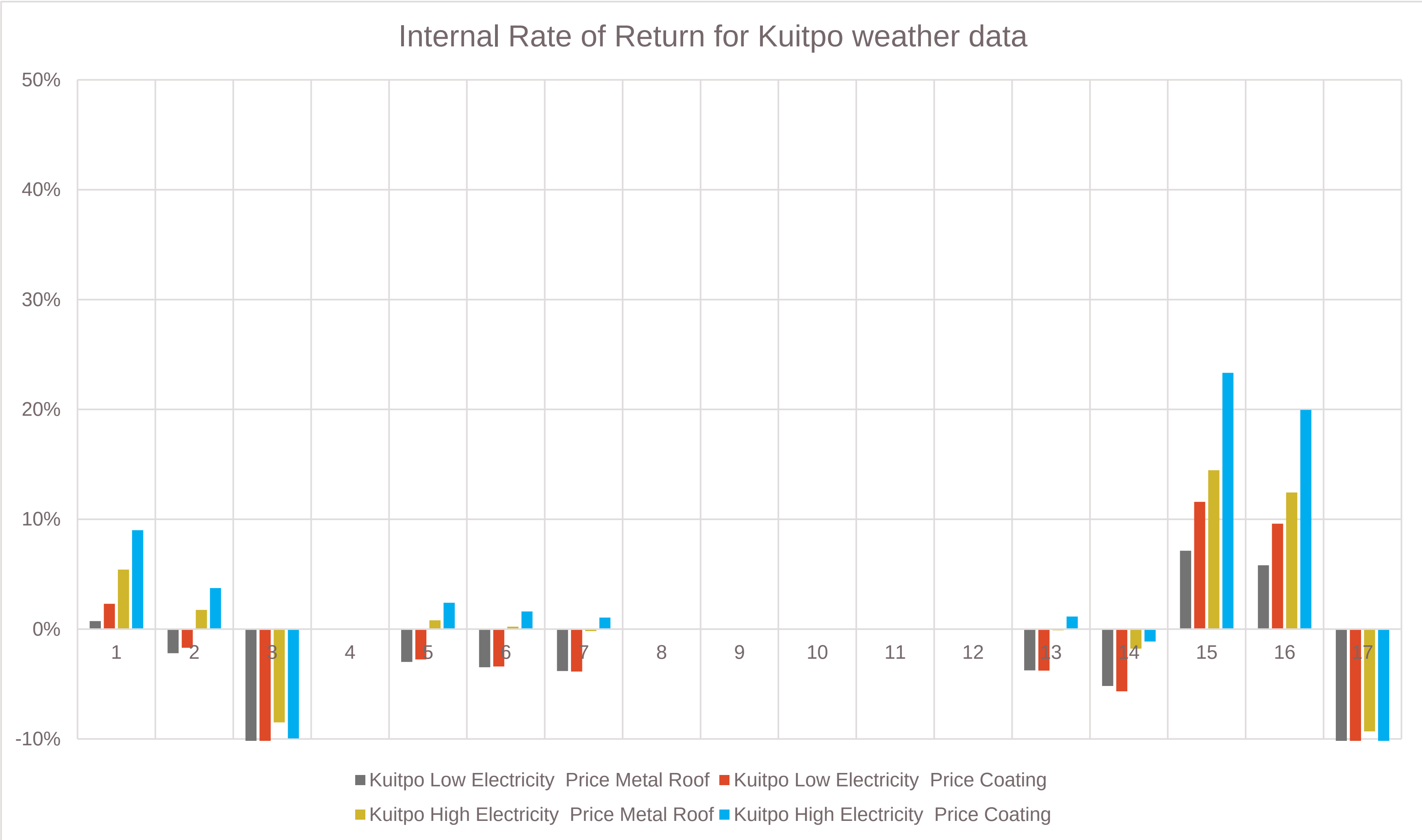


Figure 64 Internal Rate of Return for the buildings for Kuitpo weather conditions

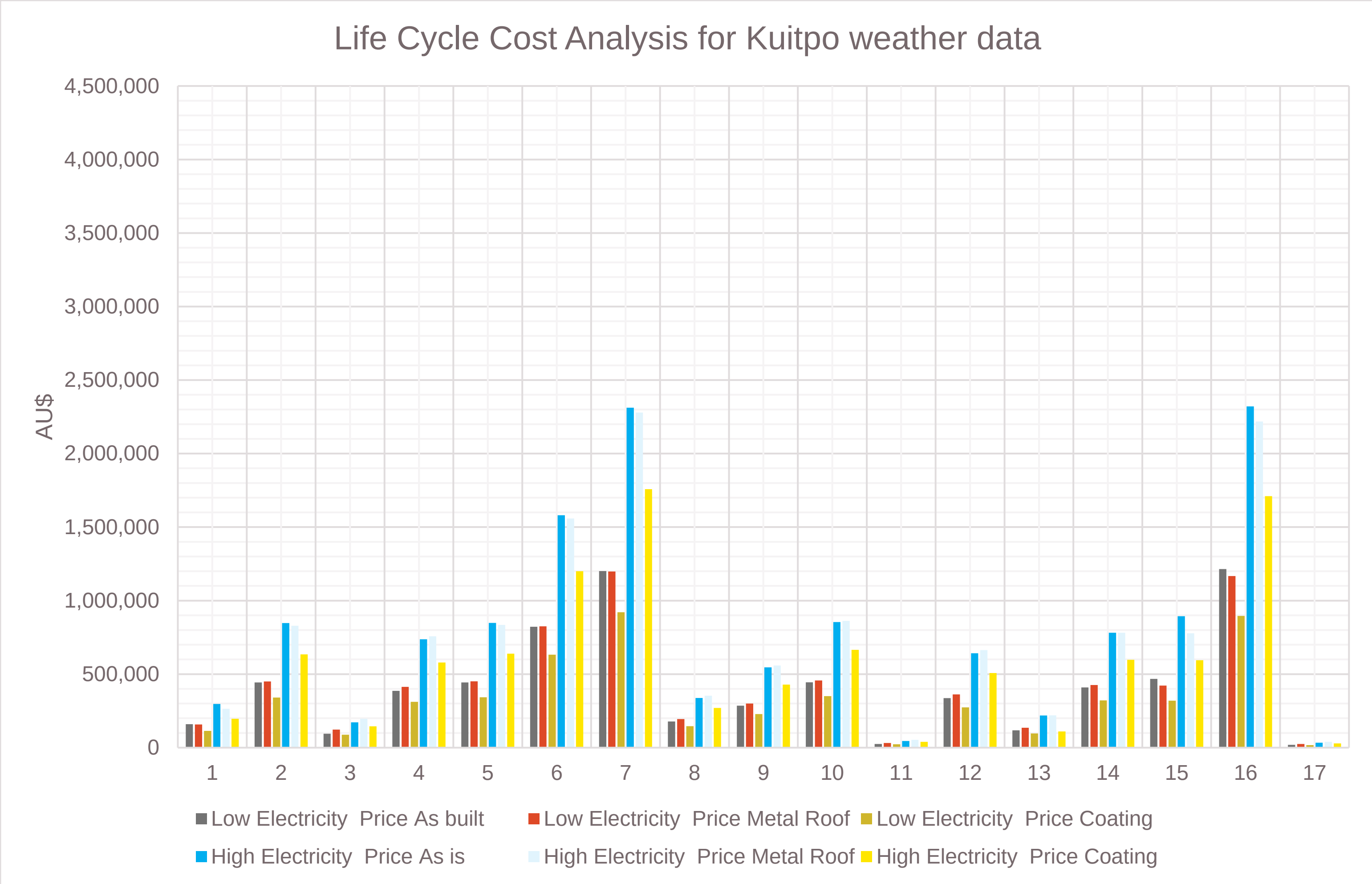


Figure 65 Life Cycle Cost for the buildings for Kuitpo weather conditions

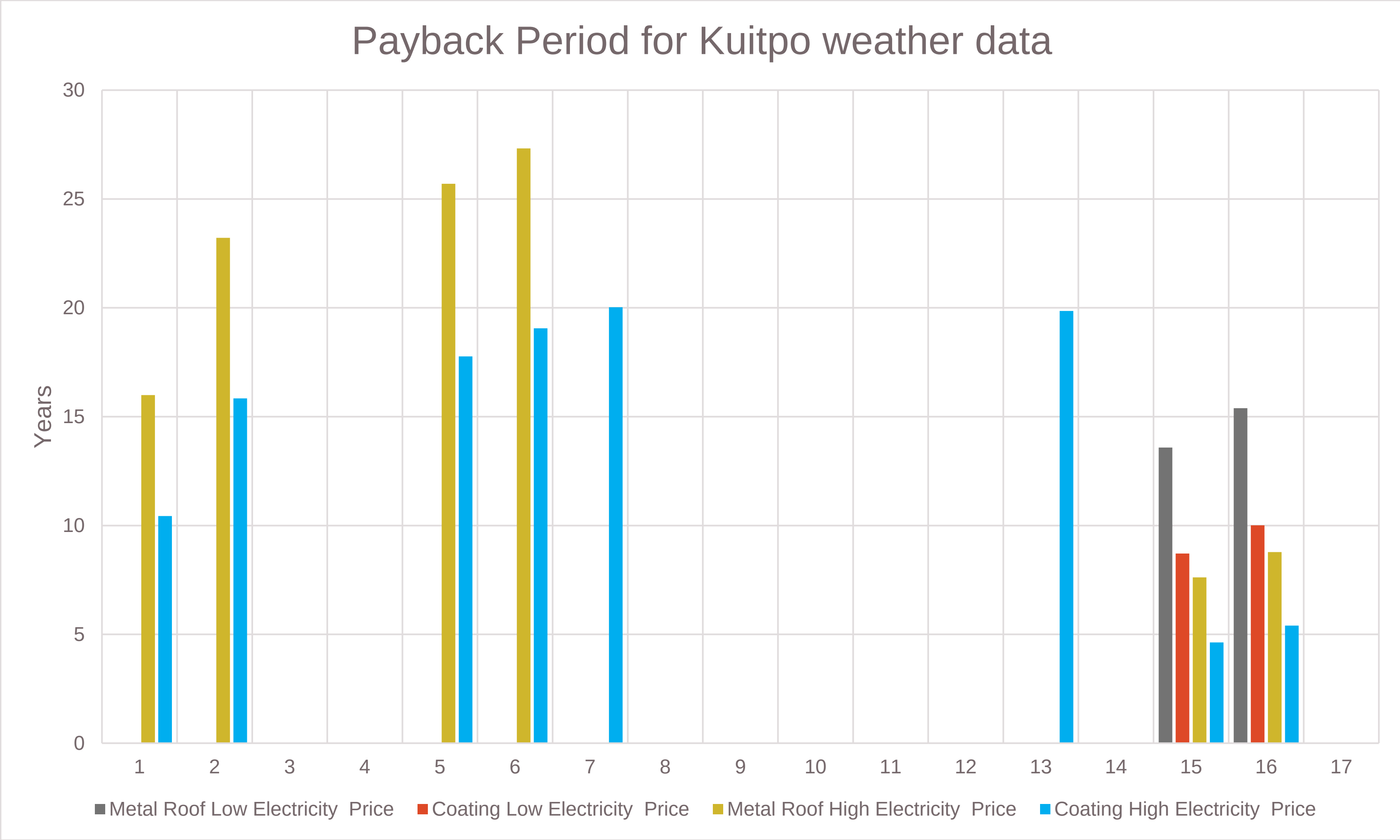


Figure 66 Payback Period for the buildings for Kuitpo weather conditions

6.5.2 Part 2. Results for Roseworthy weather

Table 30 Net Present Value for Roseworthy weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	23,629	26,343	87,002	75,668
2	19,634	23,235	79,280	69,658
3	-36,727	-20,633	-29,686	-15,152
4	-38,059	-21,669	-32,260	-17,156
5	-21,499	-9,443	-3,688	4,419
6	-23,718	-11,170	-7,978	1,080
7	-23,275	-10,825	-7,120	1,748
8	-21,246	-12,401	-19,589	-11,111
9	-20,802	-12,055	-18,731	-10,444
10	-22,144	-13,098	-21,325	-12,459
11	-7,173	-3,976	-5,535	-2,697
12	-34,878	-19,845	-29,553	-15,691
13	-13,650	-2,671	14,930	19,573
14	-16,313	-4,744	9,782	15,567
15	34,419	34,079	104,420	88,562
16	22,436	24,753	81,254	70,531
17	-7,597	-4,309	-6,354	-3,342

Table 31 Internal Rate of Return for Roseworthy weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	6.32%	10.36%	13.21%	21.22%
2	5.81%	9.59%	12.44%	19.96%
3	-6.80%	-7.77%	-3.62%	-3.60%
4	-7.67%	-8.90%	-4.59%	-4.89%
5	-1.71%	-1.05%	2.34%	4.56%
6	-2.39%	-1.96%	1.51%	3.40%
7	-2.25%	-1.77%	1.68%	3.63%
8	-10.21%	-12.15%	-7.40%	-8.55%
9	-9.29%	-10.97%	-6.39%	-7.24%
10	-13.01%	-15.64%	-10.42%	-12.39%
11	-6.16%	-6.92%	-2.88%	-2.60%
12	-7.68%	-8.89%	-4.60%	-4.88%
13	0.56%	2.06%	5.18%	8.67%
14	0.00%	1.29%	4.47%	7.63%
15	7.99%	12.90%	15.82%	25.63%
16	6.42%	10.51%	13.37%	21.49%
17	-7.40%	-8.55%	-4.29%	-4.50%

Table 32 Life Cycle Cost for Roseworthy weather data

LCC	Low Electricity Price			High Electricity Price		
Building	As built	Metal Roof	Coating	As built	Metal Roof	Coating
1	240,995	202,048	148,471	455,140	349,306	262,306
2	650,617	608,943	463,675	1,247,076	1,135,970	871,701
3	137,591	160,697	116,662	255,226	269,360	200,809
4	603,575	620,366	472,737	1,156,128	1,158,055	889,221
5	649,210	649,641	496,015	1,245,255	1,218,095	936,287
6	1,220,373	1,213,651	932,918	2,349,503	2,308,515	1,780,966
7	1,790,205	1,773,689	1,366,735	3,451,178	3,391,256	2,619,677
8	187,963	200,216	151,035	357,789	365,598	279,137
9	300,243	310,210	236,237	574,863	578,253	443,861
10	463,272	471,821	362,265	890,052	890,700	687,516
11	27,782	32,203	23,411	51,538	53,926	40,273
12	402,030	419,822	318,749	767,374	692,980	593,571
13	189,071	188,255	137,924	354,754	322,639	241,915
14	716,742	709,931	542,036	1,374,918	1,331,213	1,023,198
15	667,406	611,620	466,357	1,280,433	1,144,588	878,947
16	1,795,974	1,733,653	1,335,553	1,795,974	1,732,688	1,334,588
17	21,413	26,367	18,849	39,224	42,643	31,452

Table 33 Payback Period for Roseworthy weather data

PB	Low Electricity Price		High Electricity Price	
Building	Metal Roof	Coating	Metal Roof	Coating
1	24.4	16.6	8.3	5.1
2	15.4	10.0	8.8	5.4
3	-	-	-	-
4	-	-	-	-
5	-	-	21.8	14.8
6	-	-	23.8	16.3
7	-	-	23	16
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	-	-	-	-
13	26.4	18.3	16.3	10.7
14	28.0	19.6	17.5	11.6
15	12.6	8.0	7.0	4.2
16	14.5	9.4	8.2	5.0
17	-	-	-	-

In order to comparatively illustrate the results for the 17 buildings, in the following Figures are depicted their Net Present Value, Internal Rate of Return, Life Cycle Cost and Depreciated Payback Period values.

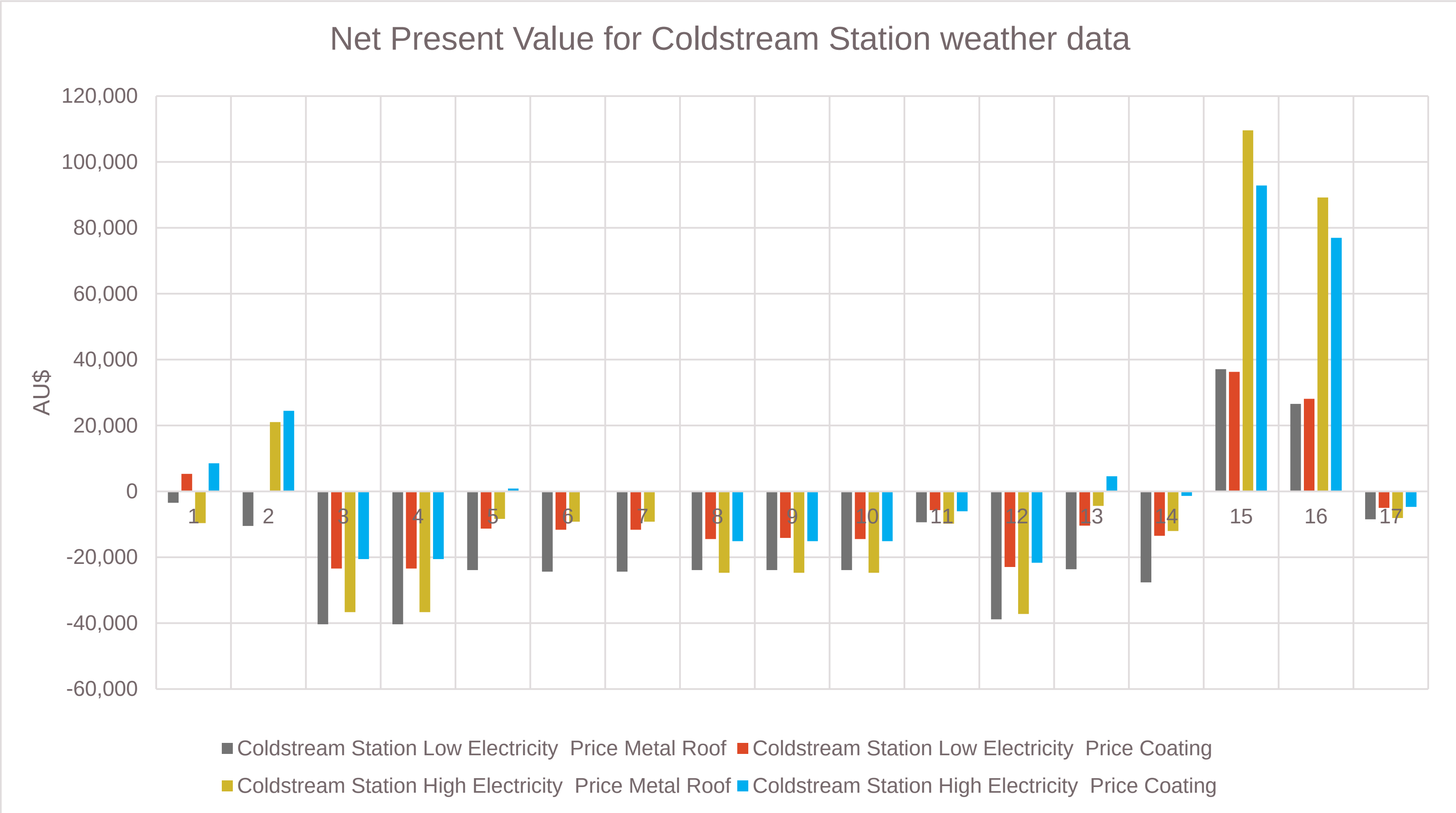


Figure 67 Net Present Value for the buildings for Roseworthy weather conditions

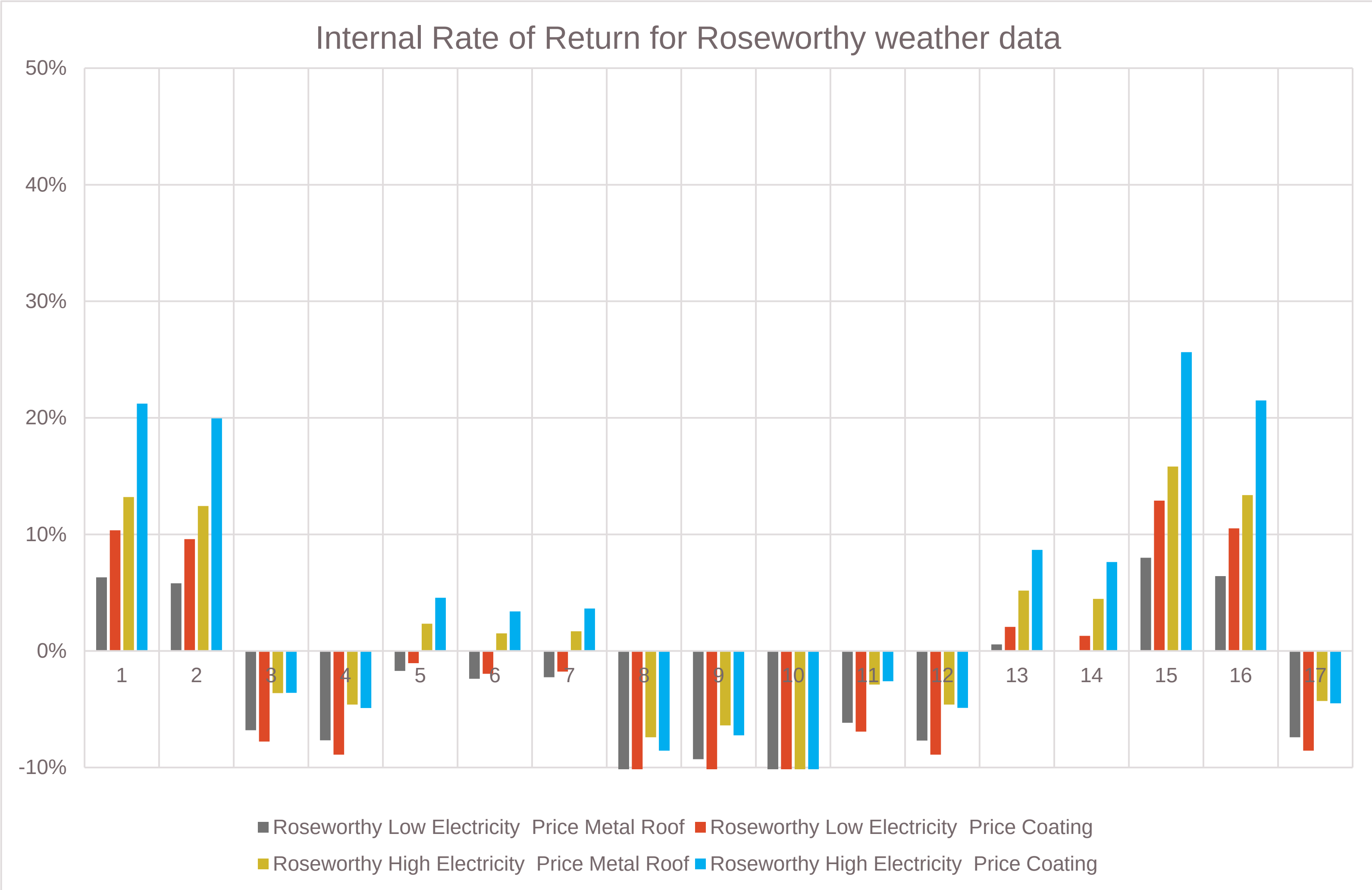


Figure 68 Internal Rate of Return for the buildings for Roseworthy weather conditions

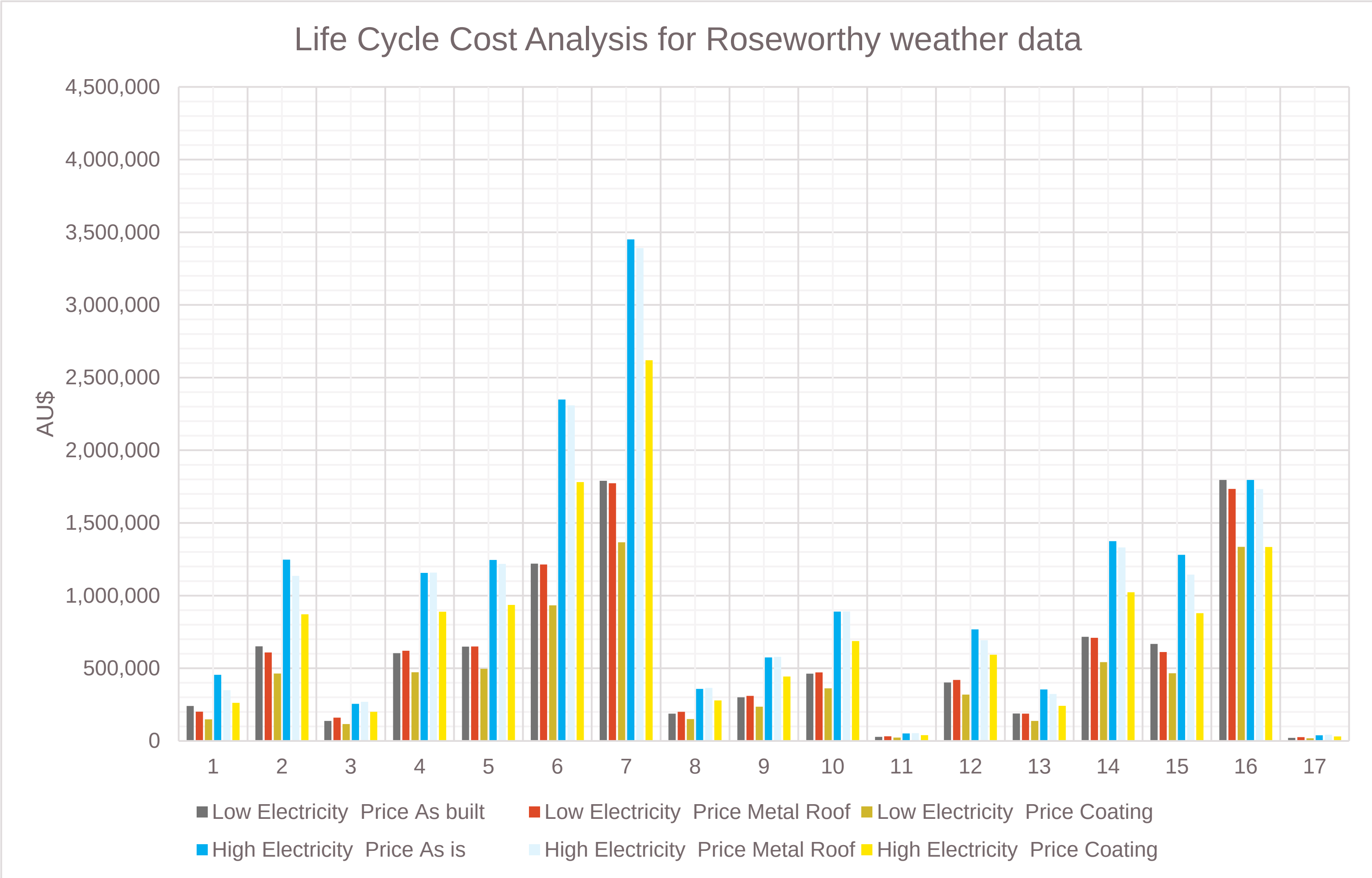


Figure 69 Life Cycle Cost for the buildings for Roseworthy weather conditions

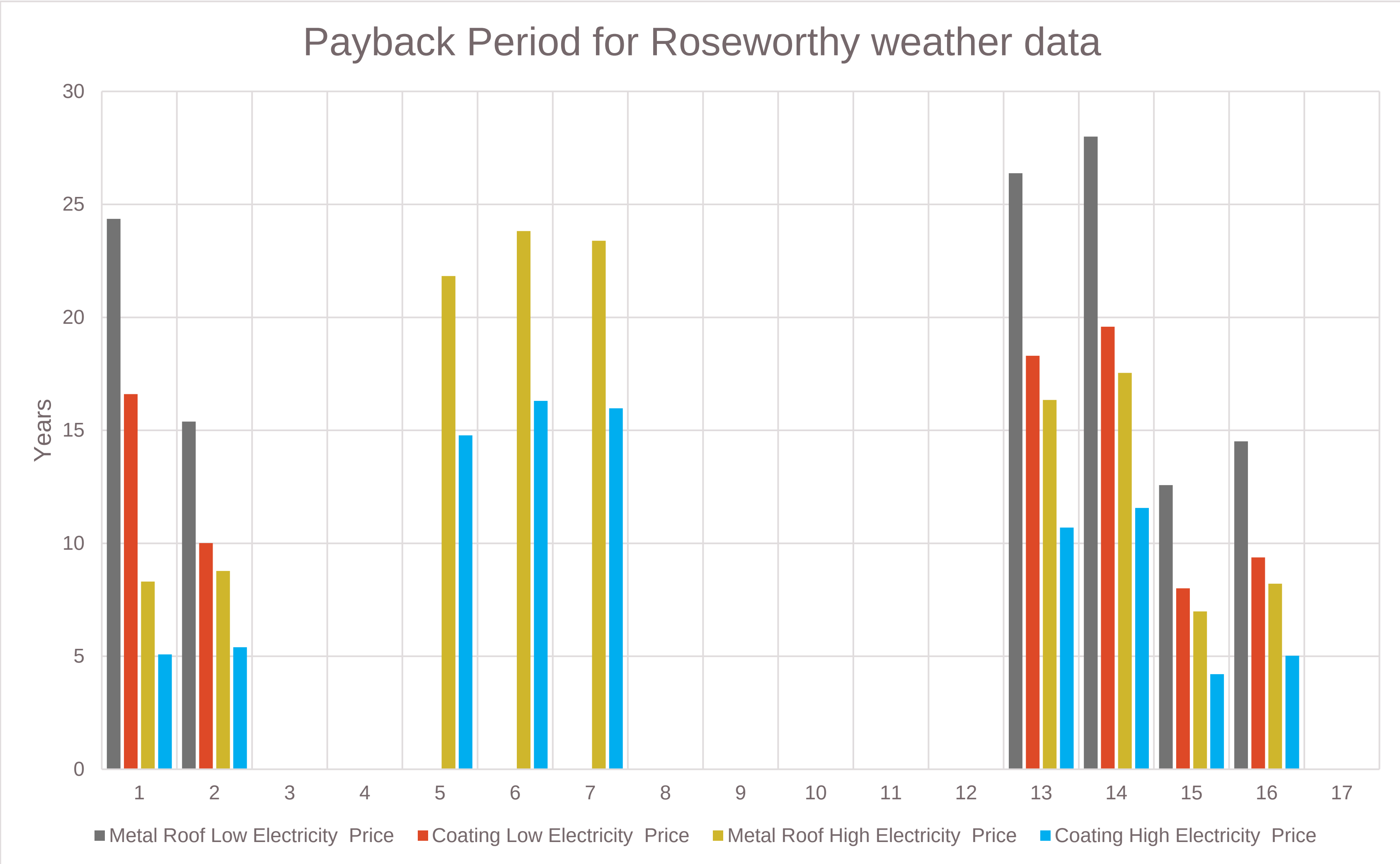


Figure 70 Payback Period for the buildings for Roseworthy weather conditions

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 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, 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 and B13), the Life Cycle Cost can be reduced by as much as 42%. In such favourable cases, the Payback Period can be as low as 4.2 years.

It must be noted that Adelaide’s weather conditions, and in particular the ones of Kuitpo, are the least feasible ones for cool roof applications, compared to other locations. But even under these conditions and 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 by 10% to 15% compared to the “Do nothing” conventional roof, which is more than enough to justify the cool coating’s application.

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 Adelaide, Australia. Specifically, it has

1) Evaluated the existing climatic conditions (reference case) in the city of Adelaide.
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 Adelaide.
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 Adelaide.
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 Frankston beach and Coldstream weather conditions.

Specifically, the following conclusions have been drawn:

1) The most intense temperature differences occurred between city cores to surroundings. 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 strappingly influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the long fetch desert area. The possible existence of an extra heating mechanism, like the advection of warm air from nearby desert spaces, may intensify the strength of the problem.
2) High-density parts of the city exhibit a higher temperature reduction than the urban average. The locations and magnitudes of urban heating in the high-density urban areas vary spatially and diurnally.
3) An increase of albedo in Adelaide can decrease the peak summer ambient temperature up to 1.9°C and surface temperature up to 6.6°C. Such cooling improves human comfort levels and could be feasible for reducing cooling energy demand.
4) It was found that important temperature differences exist near the coast and core 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 horizontal thermal gradient.
5) The city of Adelaide experiences an aggravate UHI at night during extreme urban heatwaves. In the daytime, a pocket of urban heat happens in the northwest part of the high-density urban areas, while at night, a hotspot occurs in the northern part of the city.
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 58%-95% of the ambient temperatures in all stations concentrate in the range of 12-25 °C.
7) The maximum decrease of sensible heat and latent heat flux were up to 179.5 Wm^{-2} and 15.8 Wm^{-2}, respectively.
8) The maximum decrease of wind speeds is up to 2.3 ms^{-1}. Cool roofs increase the pressure over core urban at a local scale and decrease the wind advection from the adjacent bare surface of desert fetch.

9) The results show that the increase in albedo fraction leads to a decrease in wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during the heatwave scenario.
10) Modification of the urban albedo in Adelaide city results in an average reduction up to 682.1 m of the PBL heights over high density parts of the city and may increase the concentration of bad pollutants at ground level during peak hour (14:00 LT) due to low level urban mixing.
11) The sea breeze is significantly affected by cool roof due to higher local pressure over city, which greatly reduces the sea breeze penetration.
12) The amplitude of the UHI was linked with the subsistence of the sea breeze in the central parts of the city with a thermal gradient from Adelaide Hills to Western Beach. And it was decreasing the temperature of the coastal zone, combined with wind effects from the inland and nearby surfaces.
13) In reference cases, CDH ranges from 261.5 to 3551.5, and the CDH values are mainly concentrated in 1400-2600. CDH gradually increases from southwest to northeast.
14) When applied with a cool roof, the decrease of CDH is observed at every station. The average decrease is 399.2 in all stations. CDH still increases from southwest to northeast.
15) In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions.
16) The percentage of CDH reduction due to the implementation of the cool roof ranges from 16.2% to 44.3% with an average value of 23.1%. The percentage is smaller in the hotter regions.
17) 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 9.6-11.3 kWh/m^2.
18) In existing buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 12.5-13.9 kWh/m^2.
19) In new low-rise buildings with high insulation level, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.6-4.3 kWh/m^2 in a typical new low-rise office building.
20) In high-rise buildings, the application of cool roofs in individual buildings (scenario 1) is predicted to have a relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2 kWh/m^2 for a new high-rise office building with insulation.
21) In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by the implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.5-0.6 kWh/m^2 in an existing high-rise shopping mall centre, which is expected to increase to 6.0-9.2 kWh/m^2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
22) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in a majority of building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 11.0-19.2 kWh/m^2, while the corresponding heating penalty is just 1.4-3.6 kWh/m^2.

23) The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Adelaide. For instance, the heating penalty can be up to 6.9-11.4 kWh/m^2 compared to the equivalent 5.1-8.7 kWh/m^2 in an existing stand-alone house.
24) In existing low-rise buildings without insulation/with low level of insulation and under free-floating condition 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 7.6-8.4 °C.
25) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, the application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 8.4-10.0 °C.
26) 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 °C. For instance, the number of hours with an indoor air temperature above 26 °C in a typical low-rise office building without insulation is predicted to reduce from 436-457 hours to 326-367 hours and 251-333 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
27) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, the 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 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 2.1-3.0 °C in a typical new low-rise office building.
28) 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 °C during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 °C in new low-rise office building with insulation is predicted to reduce from 494-510 hours to 388-456 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
29) 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 7.6-8.4 °C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 0.4-1.8 °C during a typical winter month.
30) 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 °C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.3 °C occurs when the indoor air temperature is 24.0 °C.
31) The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 °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 °C from 176-239 hours to 210-274 hours in a typical existing low-rise office building with roof insulation.

32) Regarding the total cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.

33) 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.

34) For the cooling load reduction in scenario 2 compared with the reference scenario, except four shopping mall centre building types (B05, B06, B07, B16), 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 most buildings.

8. Reference

Bureau of Meteorology (2017a). Humidity, heavy rain and heat in central and southern Australia, Australia. http://www.bom.gov.au/climate/current/statements/scs59.pdf. Accessed 28 July, 2021.

Bureau of Meteorology (2017b). Exceptional heat in southeast Australia in early 2017, Australia. http://www.bom.gov.au/climate/current/statements/scs61.pdf. Accessed 28 July, 2021.

Chen, F., & Dudhia, J. (2001). Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity. Monthly Weather Review, 129(4), 569-585.

Dudhia, J. (1989). Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. Journal of Atmospheric Sciences, 46(20), 3077-3107.

Gracik, S. et al. (2015) “Effect of urban neighborhoods on the performance of building cooling systems,” Building and Environment, 90, pp. 15–29. doi:10.1016/j.buildenv.2015.02.037.

Kain, J. S. (2004). The Kain–Fritsch convective parameterization: an update. Journal of Applied Meteorology, 43(1), 170-181.

Kusaka, H., Kondo, H., Kikegawa, Y., & Kimura, F. (2001). A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Boundary-layer Meteorology, 101(3), 329-358.

Mellor, G. L., & Yamada, T. (1974). A hierarchy of turbulence closure models for planetary boundary layers. Journal of Atmospheric Sciences, 31(7), 1791-1806.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., & Clough, S. A. (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. Journal of Geophysical Research: Atmospheres, 102(D14), 16663-16682.

Perez, K.X. et al. (2014) “Nonintrusive disaggregation of residential air-conditioning loads from sub-hourly smart meter data,” Energy and Buildings, 81, pp. 316–325. doi:10.1016/j.enbuild.2014.06.031.

Pleim, J. E. (2007). A combined local and nonlocal closure model for the atmospheric boundary layer. Part II: Application and evaluation in a mesoscale meteorological model. Journal of Applied Meteorology and Climatology, 46(9), 1396-1409.

Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., ...& Synnefa, A. J. S. E. (2017). Passive and active cooling for the outdoor built environment–Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. Solar Energy, 154, 14-33.

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	-1.1	-1.6	-1.3	-1.1
Minimum	-0.2	-0.6	-0.3	-0.4
Average of January	-0.6	-1.1	-0.8	-0.8
Average of February	-0.6	-1.2	-0.9	-0.9

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

Parameters	**Surface Temperature (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-2.1	-6.1	-4.9	-4.7
Minimum	-1.1	-4.5	-3.3	-3.1
Average of January	-1.5	-5.4	-4.2	-4.0
Average of February	-1.6	-5.7	-4.4	-4.2

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

Parameters	**Sensible Heat Flux (Wm^{-2})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-61.2	-171.3	-79.4	-104.3

Minimum	-12.4	-110.0	-48.7	-58.1
Average of January	-30.9	-136.4	-60.9	-74.7
Average of February	-43.2	-155.0	-69.0	-76.1

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

Parameters	**Latent Heat Flux (Wm^{-2})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-4.7	-15.0	-6.0	-7.1
Minimum	-1.7	-9.0	-2.4	-3.6
Average of January	-2.6	-11.1	-3.8	-5.1
Average of February	-3.7	-12.8	-4.9	-6.3

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

Parameters	**Wind Speed (ms^{-1})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-1.4	-2.1	-2.0	-1.7
Minimum	-0.4	-1.1	-0.9	-0.7
Average of January	-0.8	-1.4	-1.2	-1.0
Average of February	-1.1	-1.7	-1.4	-1.2

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

Parameters	PBL Height (m)			
	06:00 LT	14:00 LT	18:00 LT	24-h avg.
Maximum	-176.5	-694.0	-373.5	-355.4
Minimum	-61.2	-417.5	-110.2	-141.3
Average of January	-109.7	-540.2	-244.6	-263.2
Average of February	-133.3	-643.0	-308.7	-242.8

10. Appendix: Building characteristics_ Cool roofs project simulations inputs _ Climate zone 5 & 6

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, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type		Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Floor area (m^2)		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		2 (L)			2 (L)	2 (L)	3	1		3 (L)
Low rise (L), mid-rise (M), high-rise		-			4 (M)	-				5 (M)
(H)		10 (H)			6 (H)	4 (H)				8 (H)
Building height (m)		7.2 (L)			13.8 (L)	13.8 (L)	12.6	2.8		8.4 (L)
Low rise (L), mid-rise (M), high-rise					27.6 (M)					14 (M)
(H)		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/m^2)		0.1			0.2		0.5	0.02	0.025	0.04

Continues

Table 41 Operation schedules

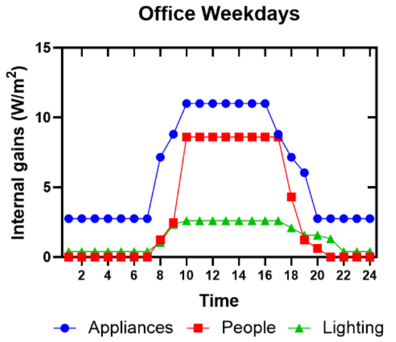
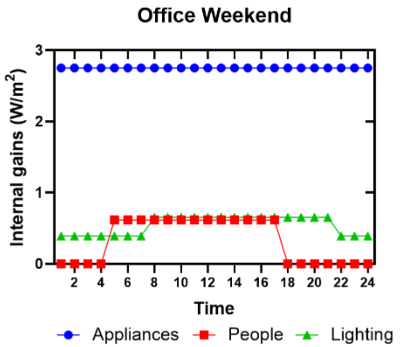
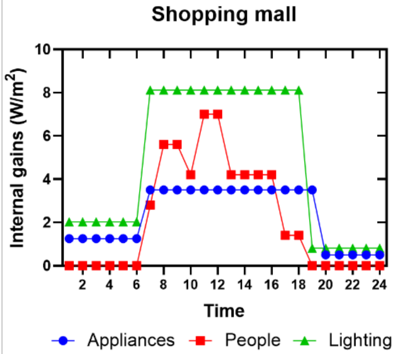
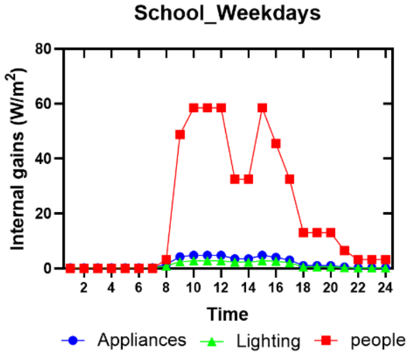
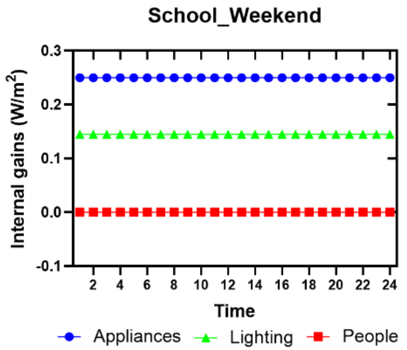
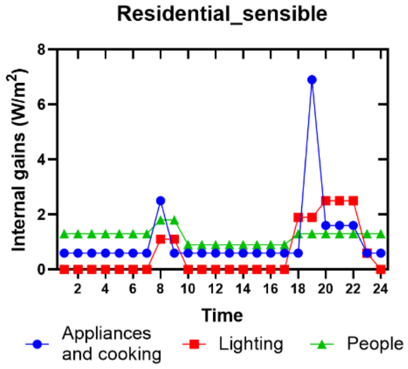
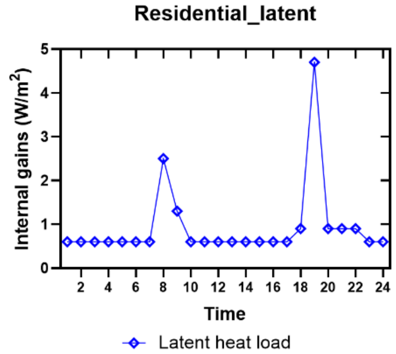
	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Intensity of internal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

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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 ($m^2 \cdot K/W$)	0	3.7 in climate zone 5 and 3.2 in climate zone 6	0.5	3.7 in climate zone 5 and 3.2 in climate zone 6	0.5	3.7 in climate zone 5 and 3.2 in climate zone 6	2	4.1 in climate zone 5 and 4.6 in climate zone 6	3.7 in climate zone 5 and 3.2 in climate zone 6
Roof solar reflectance	0.15_CTRL								
	0.80_COOL								
Roof thermal emittance	0.85								
Wall R-value ($m^2 \cdot K/W$)	0	1	1	1		1	2.8		1
Wall solar reflectance	0.15								
Wall thermal emittance	0.85								
Window U-value (W/m^2K)	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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