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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 2 – Sydney: 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 Sydney, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Sydney, 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 Sydney.
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 in Sydney.
5) To investigate the impact of cool roofs on energy efficiency ratio (EER) of air-conditioning (AC) systems and the corresponding cooling load savings.
6) To evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones.

The whole study involved the following phases:

<u>Phase 1: Mesoscale simulation of the current climatic conditions.</u> In the first phase, a full mesoscale climatic model for the entire city of Sydney, 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.

<u>Phase 2: Mesoscale simulation of the climatic conditions when cool roofs are implemented at the city scale</u>. 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.

<u>Phase 3: Climatic parameters analysis.</u> In this phase, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 11 weather stations in Sydney 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 11 weather stations, has been calculated. The frequency and spatial distribution of the calculated CDH are analysed as well.

<u>Phase 4: Assessment of the energy cooling/heating load under various boundary conditions during the summer period</u>. Simulations were performed for seventeen types of buildings and eleven weather stations across Sydney. 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 Sydney during a typical summer and winter period.

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

Phase 8: Analysis of the impact of cool roofs on EER of AC systems and the corresponding cooling load savings. The hourly cooling load savings by lower heat gains by application of cool roofs in seventeen types of buildings was computed for the hottest and coldest weather stations in Sydney (i.e. Richmond and Observatory 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 Observatory Hill and Richmond 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 Sydney.

Collectively, the following conclusions have been drawn:

1) The use of a cool roof at the city scale reduces the maximum peak ambient temperature by 2.4°C over CBD and eastern Sydney compared to the existing conditions, reference case.
2) The maximum decrease in the sensible heat flux that determines the urban overheating caused by the cool roofs is 279.8 W/m^2, and the average decrease is 192 W/m^2 at 14:00 over CBD and the inner west.
3) Modification of the urban albedo in Sydney results in an average reduction up to 1607.8m of the PBL heights over the city, and the maximum decrease of wind speeds is up to 3.9 m/s. Thus, higher urban albedo values decrease the advective flow between the city and the desert area and contribute highly to reducing overheating.
4) In average, compared to the reference scenario, the temperature with the peak distribution in the cool roof scenario is around 1 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Penrith station is an exception with the same peak in cool roof and reference scenario. Around 30%-50% of the ambient temperatures in all stations concentrate in the range of 19-22 °C.
5) Cooling degree hours, indicating the climatic severity during the summer period, ranging from 1095.7 to 3997.7, 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 693.8 to 3245.1. The percentage of CDH reduction due to the implementation of the cool roof ranges from 18% to 39%.
7) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 10.2-13.8 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 14.9-17.4 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 4.8-8.1 kWh/m^2 in a typical new low-rise office building.
10) In new high-rise buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be 1.1-1.7 kWh/m^2 and 0.2-0.3 kWh/m^2 for new low-rise and high-rise office buildings with insulation, respectively.
11) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.5-0.7 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 4-7.1 kWh/m^2 (29.3-48.3%) 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 16.6-28 kWh/m^2, while the corresponding heating penalty is just 1.1-2.5 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 70% and 53% in Observatory and Richmond 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 10.1-11.4 ^{o}C and 3.8-4.9 ^{o}C, 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 11.2-12.0 ^{o}C and 4.7-5.6 ^{o}C, 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 ^{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 553-550 hours to 424-433 hours and 359-390 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 2.1-2.5 ^{o}C and 1.3-1.7 ^{o}C, 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 ^{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 630-658 hours to 595-613 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 10.1-11.4 ^{o}C in a typical summer week, while the average maximum indoor air temperature reduction of the same building is expected to be just 2.6-2.7 ^{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 2.2 ^{o}C occurs when the indoor air temperature is 25.3 ^{o}C.

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 74-95 hours to 89-114 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 0.12-0.32 and 0.12-0.3 and in Observatory and Richmond 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 1.47 and 2.74 kWh/m^2 for a new high-rise office building with roof insulation-new building in Richmond 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 0.4 and 2.4 kWh/m^2, respectively.
23) In low-rise buildings with low level of insulation, the cooling load savings by modified EER is noticeable. For instance, the cooling load savings by modified EER is estimated to range between 1.25 and 2.32 kWh/m^2 for a new high-rise office building with roof insulation-new building in Richmond 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 13.2 and 14.9 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 5.37 and 10.36 kWh/m^2 for a new high-rise shopping mall centre in Richmond 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 0.7 and 3.7 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) As it can be seen from the data depicted, the Cool Coating solution offers in all cases reductions in the Life Cycle Cost that reach for the Observatory Hills weather conditions and for low electricity prices from 6,8% to 38,2%. In the case of high electricity prices, the reductions are more significant, varying from 23,9% to 82,4%. In such favourable cases, the Payback Period can be as low as 2.1 years.
27) Considering the Metal Cool roofs, there are 7 cases for the low energy price scenario and 6 for the high energy prices, where the refurbishment proves to be not feasible.
28) 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.
29) The feasibility of roof refurbishment in low-rise buildings is much more apparent than in high-rise ones, due to the much higher participation of the roof in the overall exposed surface of the building. In exactly the same way, roofs without thermal insulation, and consequently with high energy requirements, present bigger energy savings potential. In the case of uninsulated, low-rise roofs the impact of cool roofs is maximized. The impact

of weather conditions is important since the feasibility is directly linked to energy requirements for each specific building.

30) The impact of electricity prices is paramount, and it gets more important the higher the energy requirements are: 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 of both types examined.
31) 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 Sydney, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Sydney, 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 Sydney.
4) To understand the process of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.
5) To investigate the impact of cool roofs on EER of AC systems and the corresponding cooling load savings.
6) To evaluate the feasibility of energy-saving measures, like the application of cool roofs and the refurbishment of existing ones.

Methodology

The whole study involved the following phases:

Phase 1: Mesoscale simulation of the current climatic conditions. In the first phase, a full mesoscale climatic model for the entire city of Sydney 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 11 weather stations in Sydney 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 11 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 Sydney. 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 Sydney during a typical summer and winter period.

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

Phase 8: Analysis of the impact of cool roofs on EER of AC systems and the corresponding cooling load savings. The hourly cooling load savings by lower heat gains by application of cool roofs in seventeen types of buildings was computed for the hottest and coldest weather stations in Sydney (i.e. Richmond and Observatory 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 Observatory Hill and Richmond weather conditions.

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

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

1.1 Introduction

Heat waves (HWs) are recognized as a significant threat to human health worldwide, with urban areas being more vulnerable due to the urban heat island (UHI) effect. Extreme urban heat with regional climate change can affect the health and wellbeing of humans, the environmental quality, and the socio-economic performance of cities. The higher magnitude of urban temperatures (and for longer periods) is considerably affecting citizens' quality of life and outdoor activities. Extreme urban heat is being augmented by local and regional climate change, which leads to an increase in the magnitude, frequency, and duration of extreme temperature, prolonged thermal distress and heat stress, and increased heat-related mortality and morbidity (Santamouris et al., 2017). To undertake the extreme urban heat and increase the quality and comfort levels of outdoor and indoor environments, it is imperative to investigate and evaluate the performance of cool roof strategies at the city scale during an extreme heat condition.

1.2 Objectives of the study

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

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

1.3 Domain and method of simulation

We use a full mesoscale climatic model for the entire city of Sydney using the weather research forecasting model (WRF v4.3), which is an advanced, commonly used numerical climate model. The model is created to simulate the distribution of the main climatic conditions in the city under all climatic, synoptic, and land use conditions. The resolution of the grid in the simulation is 500 x 500 meters (**Table 1** and

Figure 1). The developed mesoscale model is used to calculate the hourly distribution of the main climatic parameters in Sydney under the existing heatwave conditions and one mitigation scenario. The albedo or emissivity as a single fraction was applied uniformly to all urban grid cells. The cool materials were examined by test case of 100% cool surfaces (on the roof only) with changing albedo and emissivity fractions for roofs at the urban scale (**Table 2**). We performed extensive analysis to analyze the performance of the cool roof scenario and its cooling potential. One mitigation scenario is evaluated in this report. The mitigation strategy is examined in this study at a city scale.

Table 1 WRF/SLUCM Model configuration

Configuration	Domain 01 (d_1)	Domain 02 (d_2)	Domain 03 (d_3)
Version	ARW-WRF v4.3		
Initial and boundary conditions	ERA-Interim reanalysis		
Run time	31 December 00:00h, 2016 to 1 March 00:00h, 2017 IST		
Time period for analysis	1 January 12:00h, 2017 to 28 February 00:00h, 2017 IST		
Grid distance (m)	4500	1500	500
Grid number	200x200	202x202	202x202
Number of vertical layers	40 layers		
Microphysics	WRF Single-Moment 6-class scheme		
Surface layer model	Noah-LSM+Single layer UCM (Chen &Dudhia, 2001; Kusaka et al., 2001)		
Turbulence	Mellor and Yamada's (1974) TKE scheme		
Short-wave radiation	Dudhia scheme (Dudhia, 1989)		
Long-wave radiation	RRTM scheme (Mlawer et al., 1997)		
Planetary boundary layer	Asymmetrical Convective Model version 2 (ACM2) (Pleim, 2007)		
Cumulus parameterization	Kain-Fritsch (KF) scheme (Kain, 2004)		

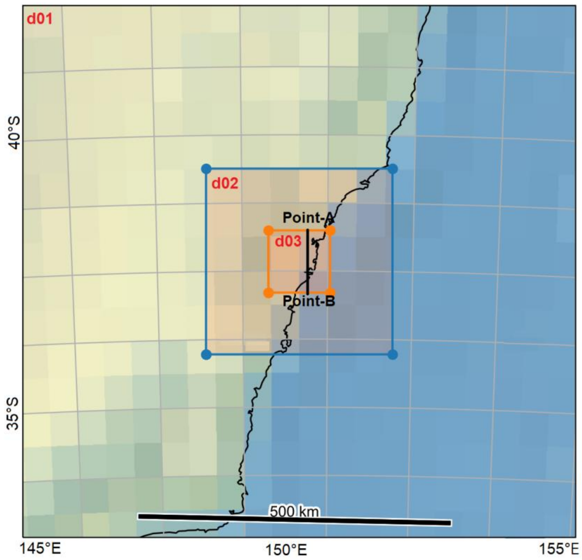

Figure 1 WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500m grid spacing, domain 2 (d02) with 1500m grid spacing and, an innermost domain 3 (d03) with 500m grid spacing; (b) innermost d03 with 500m grid spacing which encompasses the Greater Sydney. Point-A (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 of cool roof for Sydney

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

1.4 Model evaluation

To evaluate the performance of the WRF-SLUCM system, we compared hourly simulated 2-m ambient air temperature against local measurements for the reference 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=0.982; mean bias=0.569) for Penrith, Observatory Park, Sydney Airport, and Olympic Park. The reference case simulation produced urban meteorological conditions well and statistically, agreed with local observation ($p<0.05$). The simulated average UHI intensity varied from 3.2°C to 6.3°C in the high-density urban residential areas relative to rural (i.e., surrounding) landscapes as a function of the prevailing local weather conditions. The range of MBE and RMSE of air temperature was 0.4°C to 0.9°C and 0.5°C to 0.9°C, respectively. The range of IOA was 0.95 to 0.97, with average values of 0.96 when considering all observation stations. The model slightly overestimated the daily average 2m air temperature, potentially resulting from an overestimate of anthropogenic heating over the urban domain. We also assess impacts on local meteorological stations as it is these stations that are most influenced by the utility of the UCM scheme. The well-simulated daytime warming is balanced by equally well-simulated night-time cooling, resulting in a diurnal range that is of a similar magnitude to observations. The comfort level of different dew points is >20°C for the stations, representing the uncomfortable situation in the urban environment. The difference is identical when quantifying impacts on local meteorological stations. Although WRF does not display considerable warm (comfort) bias over urban locales, the representation of the 24-h averaged diurnal range of dew point temperature is well captured. In addition, model biases are most likely caused by: (a) lack of proper urban morphological representation and (b) uncertainties in model physical schemes, input data used, and locally meaningful urban biophysical parameters. Nevertheless, our initial evaluation highlights that the model can replicate the urban environment realistically, including a well-simulated evolution of the diurnal cycle of both near-surface temperature and dewpoint, 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			
	Penrith	Observatory Park	Sydney Airport	Olympic Park
Correlation coefficient	0.975	0.981	0.986	0.985
Mean Bias error	0.352	0.932	0.429	0.563
Mean absolute error	0.523	0.926	0.432	0.501
Root mean square error	1.023	1.031	1.102	1.361
Index of Agreement	0.961	0.954	0.956	0.970
Correlation coefficient	0.972	0.975	0.981	0.982

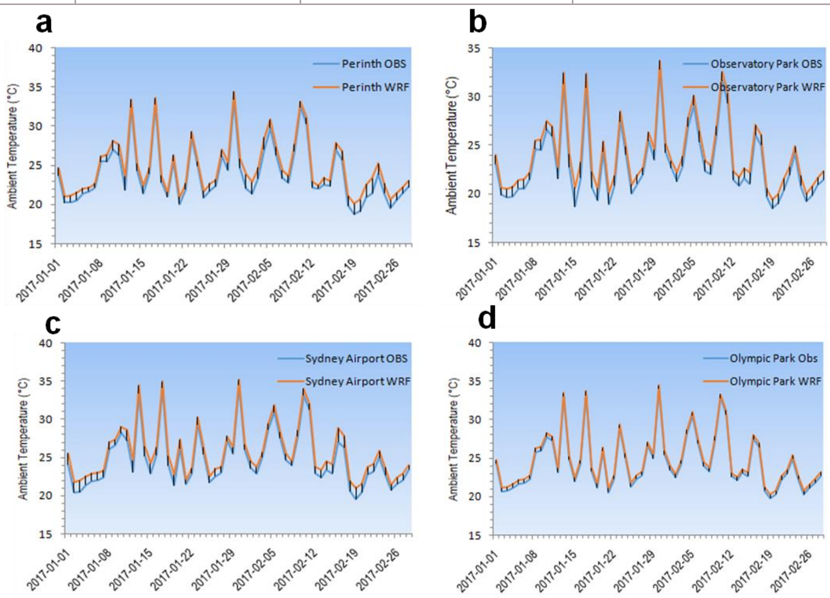

Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Penrith, (b) Observatory Park, (c) Sydney Airport, and (d) Olympic Park.

1.5 Results of the mesoscale simulations

The results of the reference 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 Sydney to ensure the robustness and accuracy of the model. The results of the reference 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 Sydney. The mean temperature at Observatory Hill was the second warmest on record, behind 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 24.4 °C and 42.8 °C. At 06:00 LT, it varies between 22.9°C and 32.5°C. The results show that the use of cool roof materials maximum reduces the peak ambient temperature ($T_{ambient}$) by 2.4°C over CBD and eastern Sydney compared to the reference case. The average ambient temperature reduction at 14:00 over the whole summer is 0.85°C. The maximum decrease of the ambient temperature during 18:00 LT is 1.9°C over eastern Sydney and the average decrease of summer months is 1.1°C (**Figure 3**).

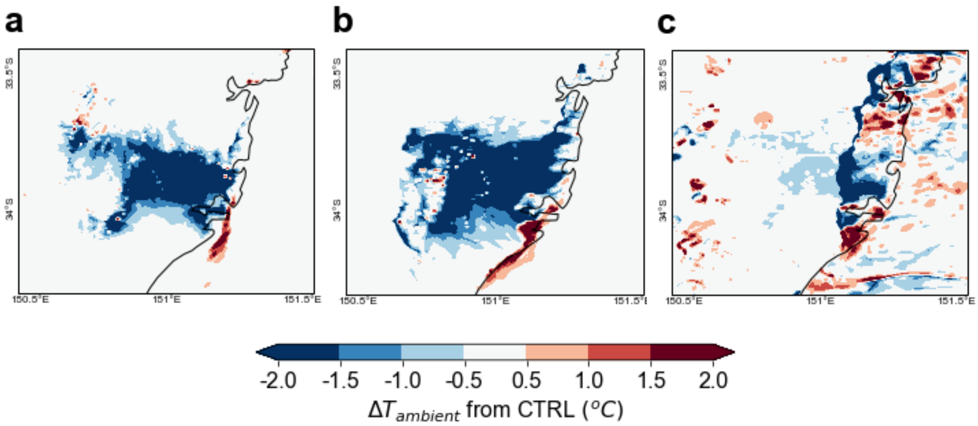

Figure 3 Reduction of ambient temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.2 Surface temperatures

Under the Cool Roof scenario, the surface temperature ($T_{surface}$) ranges between 29.8 °C to 54.5°C at 14:00, 24.6°C to 45.8°C at 18:00 LT, and 20.1 to 32.5 at 6:00 LT over the city. The maximum decrease of surface temperature during 14:00 LT is 11.6°C over eastern Sydney and south Sydney and 3.6°C at 18:00 LT near CBD areas, but in the early morning (06:00 LT), it is about 7.3°Cover urban domain. The average decrease of urban surface temperature is 6.1°C at 14:00 LT, 2.3°C at 18:00 LT, and 1°C in the city (**Figure 4**).

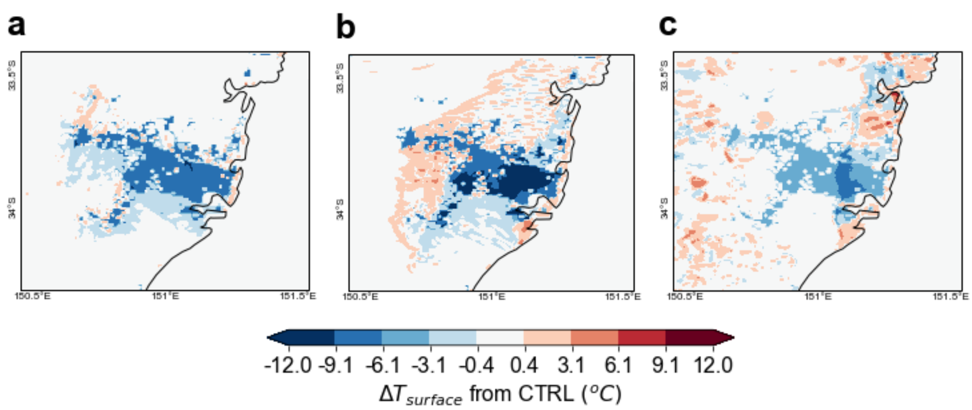

Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.3 Sensible heat flux

The WRF-SLUCM reasonably computed the sensible heat flux from the urban surface. The maximum and average sensible heat flux ($Q_{sensible}$) over the city during 14:00 LT is 411.4 W/m^2 and 391.1 W/m^2. At 18:00LT, the average sensible heat flux is 130 W/m^2. The maximum decrease in the sensible heat flux is 279.8 W/m^2, and the average decrease is 192 W/m^2 at 14:00 LT over CBD and inner west. At 18:00LT, the maximum and average reduction of the summer month of sensible heat flux is 115.0 W/m^2 and 60.1 W/m^2 over the urban domain (**Figure 5**).

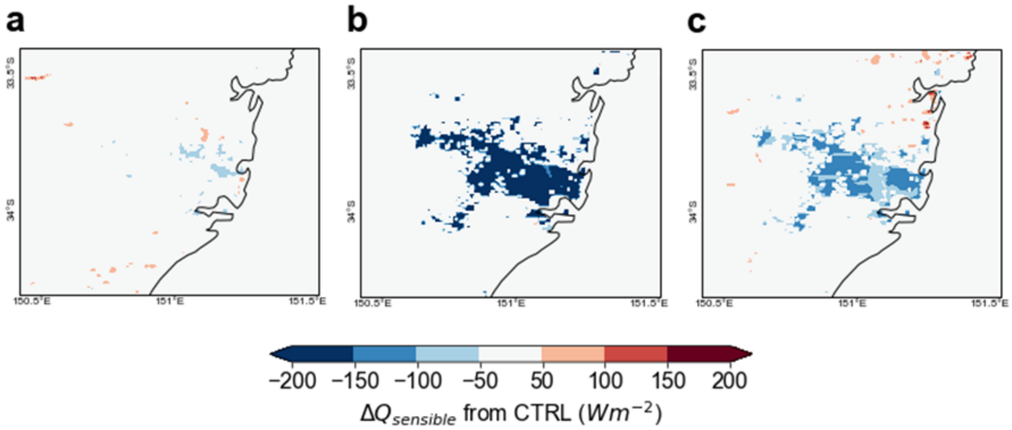

Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.4 Latent heat flux

The maximum and average latent heat flux (Q_{latent}) over the city during 14:00 LT is 31.2 W/m^2 and 20.1 W/m^2. At 18:00 LT and 06:00 LT, the average sensible heat flux is 8.9 W/m^2. The maximum decrease in the latent heat flux is 16.1 W/m^2, and the average decrease is 9.7 W/m^2 at 14:00 LT over CBD and eastern Sydney. At 18:00 LT, the maximum and average reduction of the summer month of latent heat flux is 5.1 W/m^2 and 2.3 W/m^2 over eastern Sydney. At 06:00 LT, the maximum reduction of latent heat flux is 2.5 W/m^2, and the average reduction is 1.9 W/m^2 over the urban domain (**Figure 6**).

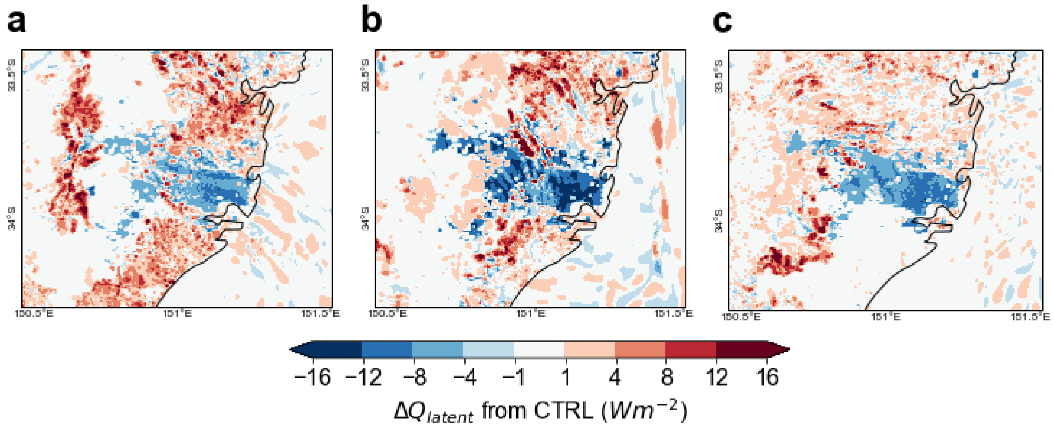

Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.5 Wind

Under the reference case simulation, the average wind speed (W_{speed}) is 8.8 m/s, 9.4 m/s, and 8.9 m/s during 06:00 LT, 14:00 LT, and 18:00 LT, respectively over the city. The maximum decrease of wind speed compared to the reference case is 3.9 m/s, 3.1 m/s, and 2.1 m/s at 06:00 LT, 14:00 LT, and 18:00 LT respectively over inner west, CBD, and lower north shore, the western part of CBD. The average decrease of wind speed of the whole summer months is 3.5 m/s at 14:00 and 2.5 m/s at both 06:00 LT and 18:00 LT over the city (**Figure 7**).

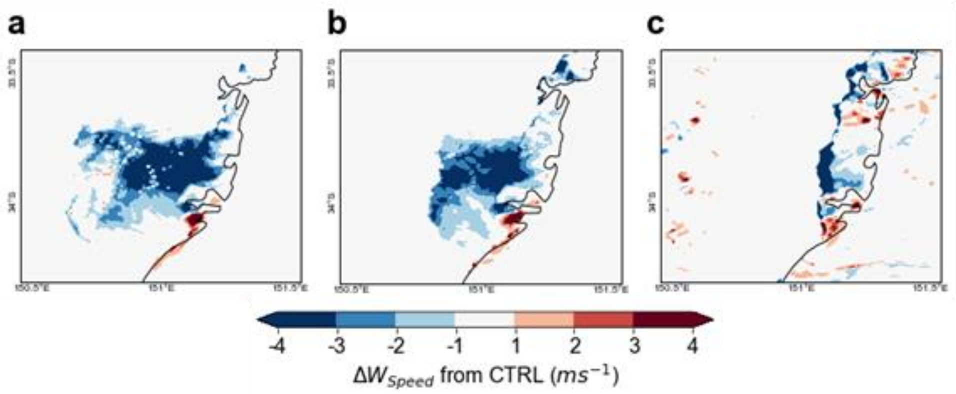

Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

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, 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 133.7m, 1607.8m, and 965.5m, for 6:00LT, 14:00LT, 18:00LT, respectively, with an average value is about 405.6m. The minimum reduction of PBL is 52.4m, 21.7m, and 10.5m, for 6:00LT, 14:00LT, 18:00LT, respectively, with an average value is about 10.4m (**Figure 8**). The maximum reduction is associated with peak hour (14:00 LT) over CBD, Inner West, Parramatta, Southern Sydney. On the other hand, during sunrise and sunset, the maximum reduction is reported for the outer west of the Sydney domain. The prime causes of PBL depth reduction due to cut-off input solar radiation and subsequently decrease in sensible heat and associated turbulence in the lower atmosphere. It is also noted that the increase of the albedo is expected to accelerate the static stability at the diurnal scale of the PBL depth. Modification of the albedo reduces the impacts of urban-induced warming and decreases the intensity of the convective mixing, thereby reducing the PBL depth, with potential penalties for air pollutant dilution and dispersion over the city domain. The reduction of moisture transport from the urban surface to the vertical layer caused by the implementation of reflective materials can also be disadvantageous to cloud formation processes, and as a result, reduce the amount of precipitation in urban areas or their downwind environments.

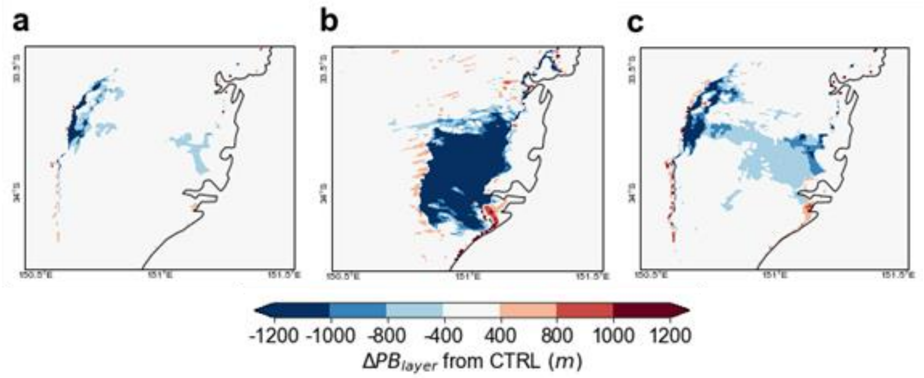

Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.6 Regional impact on sea breeze circulations

The intensification of sea breeze circulation is dependent on the large-scale synoptic background, which plays an important role in modulating the prevailing wind at the near surface. In the vertical dimension, the report revealed the height of the PBL in Sydney is linked closely with the advection of the sea breeze. The circulation can be modified when the cool roof is implemented at the city scale (**Figure 9**). The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Sydney. 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 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 2 to 4 m/s 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, a cool roof for cities has greatly modified the thermal and dynamic profile in the urban boundary layer and sea breeze circulation. This synoptic flow prevails in the opposite direction of sea breeze, and the sea breeze front developed is more prone to the accumulation of secondary pollutants in the back of the front.

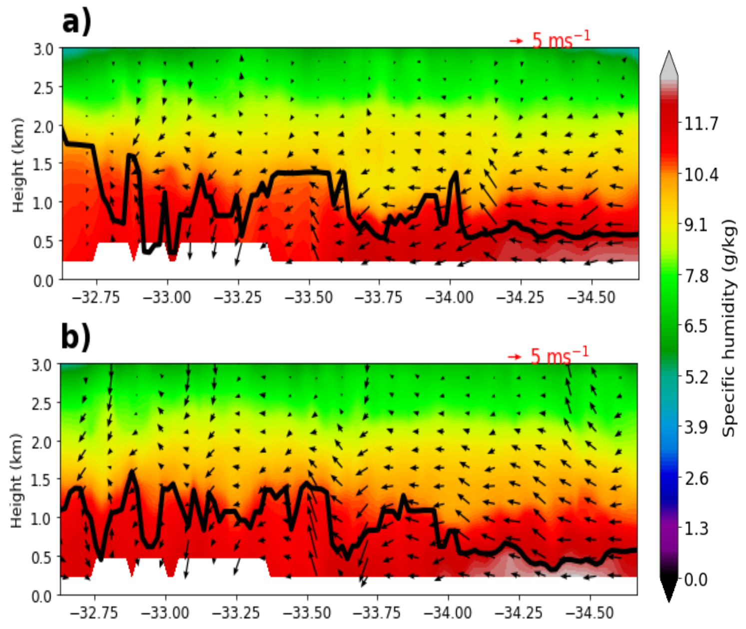

Figure 9 Cross-sectional profile of cool material impacts on sea breeze during peak hour (14:00 LT) over Sydney (north-south): (a) reference case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere. During high solar, the convective boundary layer developed the very fastest way and progressively decreased with the implementation of cool materials.

The report also shows the implementation of the cool roof over the city scale can affect the pressure gradient between the city and surrounding surface due to significant drop ambient temperature up to 2.4°C and wind speed reduced up to 3.9 m/s. Thus, changes in roof reflectivity, sensible heating, and wind result in feedback within the local climate of the city during peak hours (14:00 LT). The higher urban albedo values decrease the advective flow between the city and its surroundings, improving the cooling potential of reflective materials. It creates a 'regional high', which can reduce both horizontal and vertical wind speed over the city. The average decrease of wind speed in NW and SW at 14:00 LT is 2.0 and 1.4 m/s, respectively. Consequently, the increase of albedo may prevent the warm airflow from the adjacent desert towards western Sydney due to the effect of this regional high over the domain **(Figure 10)**. In addition, it is shown that the impact of sea breeze considerably reduced over high-density residential areas.

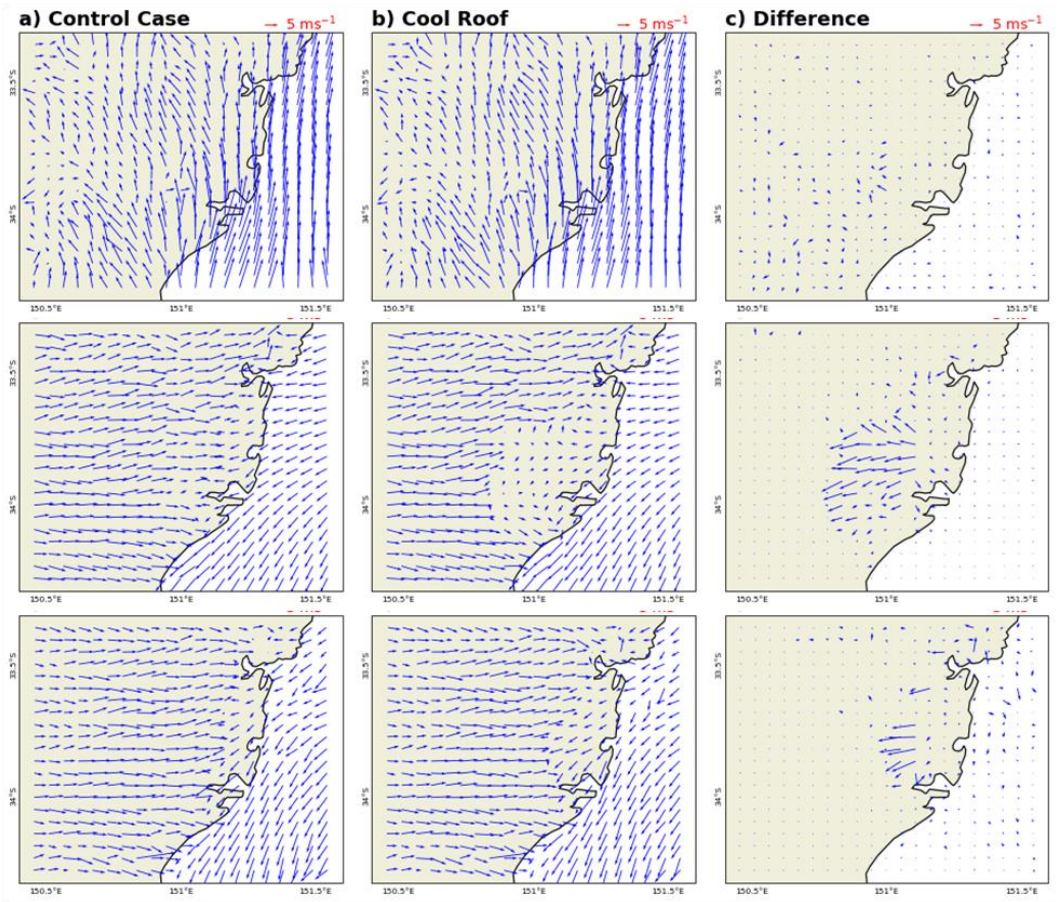

Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) reference case (b) cool roof (c) reference minus scenarios: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain 03.

1.7 Main conclusions

- It is found that both strong urban heat island (UHI) phenomena are developed. The average maximum magnitude of the phenomena may exceed 6°C. The intensity and the characteristics of the phenomena are strongly influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the desert area. The possible existence of an additional heating mechanism, like the advection of warm air from nearby spaces, may intensify the strength of the problem.
- An increase of albedo in Sydney can decrease the peak summer ambient temperature up to 2.4°C and surface temperature up to 11.6°C. It was found that important temperature differences exist between the eastern and western parts 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 strength of the advection flows.
- The maximum decrease of sensible heat and latent heat flux was 279.8 W/m^2 and 16.1 W/m^2, respectively.
- The maximum decrease of wind speeds is up to 3.9 m/s. Thus, higher urban albedo values decrease the advective flow between the city and its surroundings, improving the cooling potential of reflective materials. Modification of the urban albedo in Sydney results in a serious average 1607.8m reduction up to of the PBL heights over the city and may increase the concentration of pollutants at ground level.
- High intensities of the UHI phenomenon were associated with the existence of a sea breeze in the eastern parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that heat the western zones of the city.

2. Climatic Design Parameters _ CDH and air temperature distribution

In this study, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 11 weather stations in Sydney 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 11 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 Sydney

Eleven stations in Sydney, as shown in **Table 4** and **Figure 11**, have been simulated for two months: Jan and Feb, 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 11 stations in Sydney.

No.	Station name	Lat	Long	Climate zone
1	Sydney Airport	-33.947	151.173	5
2	Terrey Hills	-33.691	151.225	5
3	Bankstown Airport AWS	-33.918	150.986	5
4	Canterbury Racecourse AWS	-33.906	151.113	5
5	Olympic Park	-33.834	151.072	6
6	Richmond RAAF	-33.6	150.776	6
7	Horsley Park Equestrian Center AWS	-33.851	150.857	6
8	Camden	-34.039	150.689	6
9	Campbeltown	-34.0615	150.774	6
10	Observatory Hills	-33.8595	151.205	5
11	Penrith	-33.758011	150.705	6

Figure 11 Location of the 11 weather stations in Sydney.

2.2 Histogram of WRF simulated ambient temperature in Sydney

The entire 2-month hourly ambient temperature of 11 stations in Sydney 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.

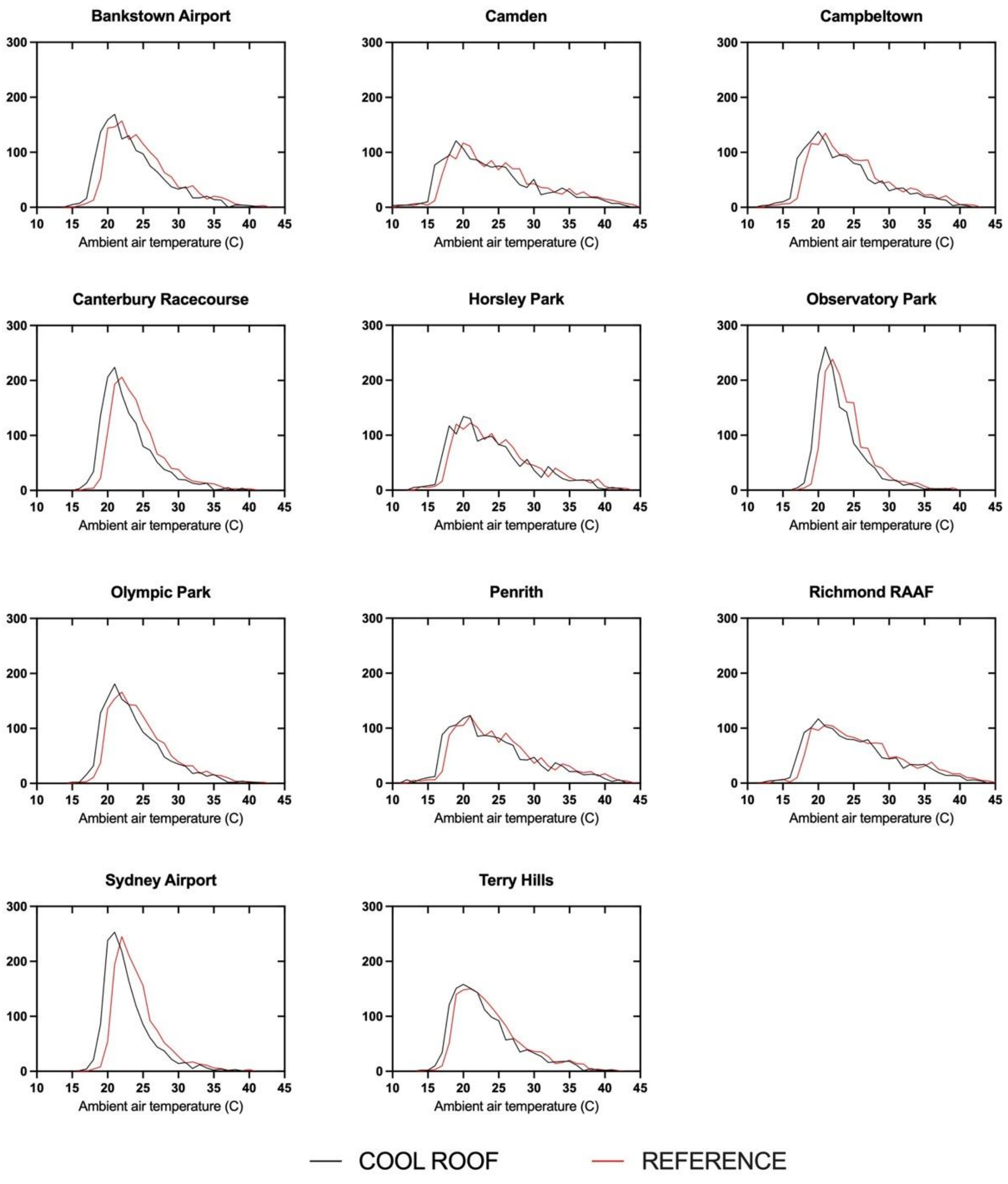

Figure 12 Histogram of WRF simulated ambient temperature in 11 stations in Sydney.

In average, compared to the reference scenario, the peak of the curve of the cool roof scenario is shifted to the left by around 1 °C, indicating the cooling benefits of cool roof, as shown in **Table 5.** Penrith station is an exception with the same peak in cool roof and reference scenario. Around 30%-56% of the ambient temperatures in all stations concentrate in the range of 19-22 °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 (°C)	**19**	**20**	**21**	**22**	**Percentage of data concentrated in 19-22 °C (%)**
Bankstown Airport COOL ROOF			169		42
Bankstown Airport REFERENCE				157	35
Camden COOL ROOF	121				28
Camden REFERENCE		117			28
Campbeltown COOL ROOF		138			33
Campbeltown REFERENCE			135		34
Canterbury Racecourse COOL ROOF			224		52
Canterbury Racecourse REFERENCE				206	37
Horsley park COOL ROOF		134			32
Horsley park REFERENCE			122		33
Observatory Park COOL ROOF			261		38
Observatory Park REFERENCE				238	54
Olympic park COOL ROOF			181		44
Olympic park REFERENCE				166	35
Penrith COOL ROOF			123		31
Penrith REFERENCE			122		31
Richmond RAAF COOL ROOF		117			30
Richmond RAAF REFERENCE			106		29
Sydney Airport COOL ROOF			253		56
Sydney Airport REFERENCE				245	35
Terrey Hills COOL ROOF		158			43
Terrey Hills REFERENCE			150		41

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 11 weather stations are shown in **Table 6** and **Figure 13**. Compared with the reference case, the largest percentage reduction is observed in Richmond RAAF, and the smallest is found in Horsley Park and Penrith, with an average reduction of 24.7%. The mean CDH values of the 11 weather stations for the reference case, cool roof case are 2385.9, 1850.0 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 11 weather stations in Sydney.

Weather Station	CDH_CTRL	CDH_COOL ROOF	CDH_ Difference (CTRL-COOL ROOF)	Percentage of the reduction_% (CDH_Difference/CDH_CTRL)
Bankstown Airport	2197.5	1564.7	632.8	29
Camden	3638	2922.1	715.9	20
Campbelltown	2806.3	2193.7	612.6	22
Canterbury racecourse	1388.6	930.8	457.8	33
Horsley Park	2905.7	2385.5	520.2	18
Observatory Hills	1095.7	765.3	330.4	30
Olympic Park	1984.1	1496.7	487.4	25
Penrith	3306.2	2702.6	603.6	18
Richmond RAAF	3997.7	3245.1	752.6	19
Sydney Airport	1129.3	693.8	435.5	39
Terrey Hills	1796.3	1449.9	346.4	19

Table 7 Mean and SD of the CDH of the 11 weather stations in reference cases and cool roof cases respectively.

	Mean	SD	Sample No.
CDH_CTRL	2385.9	1012.0	11
CDH_COOL ROOF	1850.0	891.7	11
CDH_DIFFERENCE (CTRL-COOL ROOF)	535.9	140.0	11

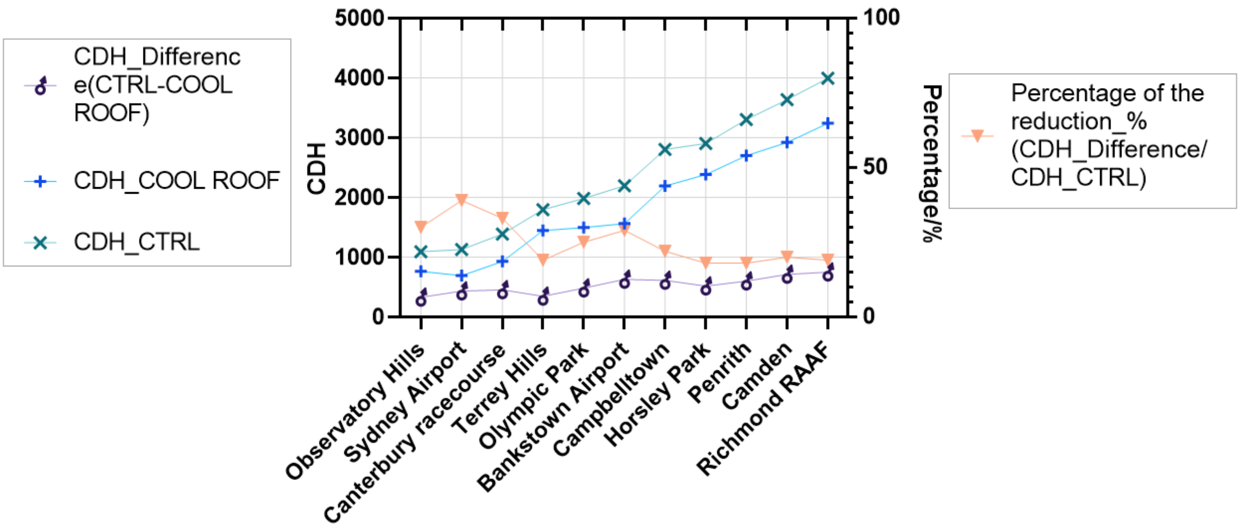

Figure 13 The CDH of reference cases, cool roof applied cases, the difference between these two, and the percentage of the CDH reduction due to the implementation of the cool roof in 11 weather stations in Sydney.

2.3.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 11 weather stations in both the reference cases and the cool roof cases is shown in **Figure 14**. In the reference case, the CDH distribution of the 11 stations is relatively uniform in each interval of 200. In the cool roof case, more than 15% of the data is centred around 1400, with the rest evenly distributed. This means that the CDH variations among most weather stations are relatively uniform.

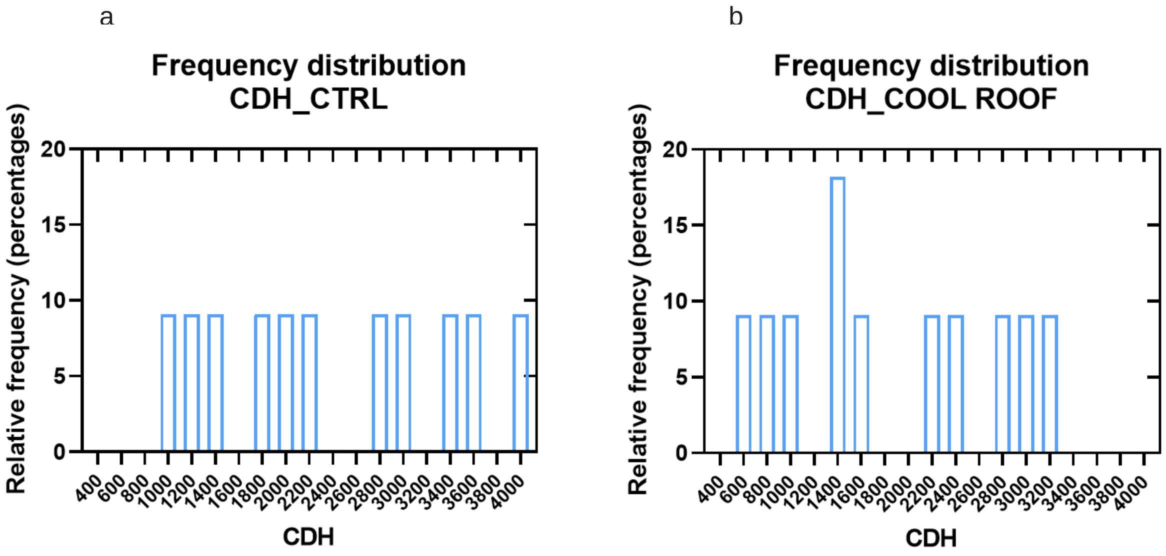

Figure 14 Frequency distribution of the CDH values for the 11 weather stations in reference cases (a) and cool roof cases (b).

2.3.2 Spatial distribution of the results

- **CDH_Reference scenario: (Figure 15)**
  The highest CDH of 3997.7 is observed in Richmond RAAF, and Observatory Hills has the lowest number. CDH gradually increases from southeast to northwest.
- **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 southeast to northwest.
- **CDH_Reference scenario – cool roof scenario: (Figure 17)**
  The maximum decrease occurs in the northwest and southwest regions of the city, while the smallest is observed in the northeast. The average decrease after applying a cool roof is 535.9 (**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 the north and northwest and gradually decreases toward the southeast, as shown in **Figure 18**.

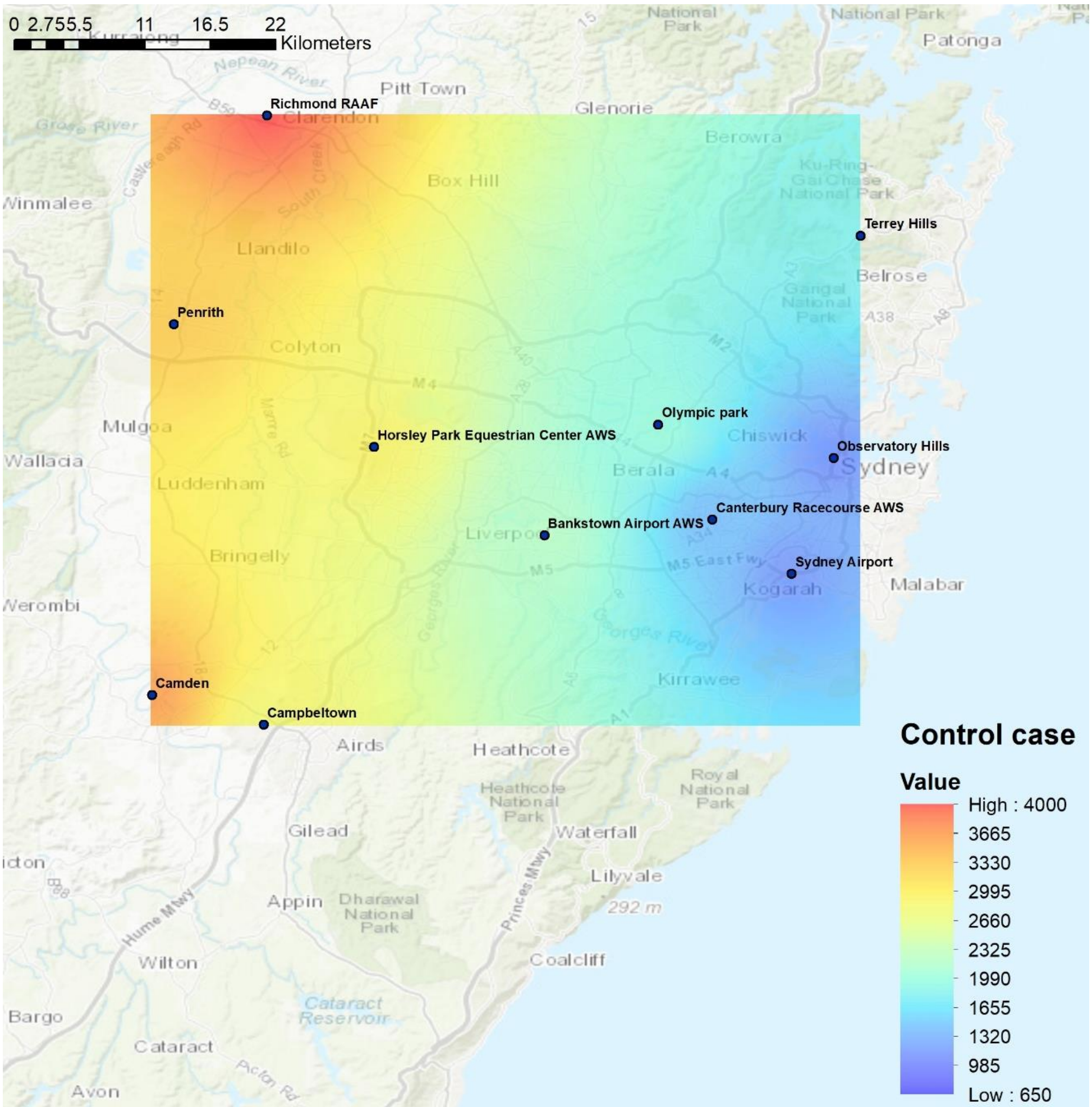

Figure 15 The sum of Cooling degree hours in Jan and Feb of the reference cases in the 11 stations in Sydney.

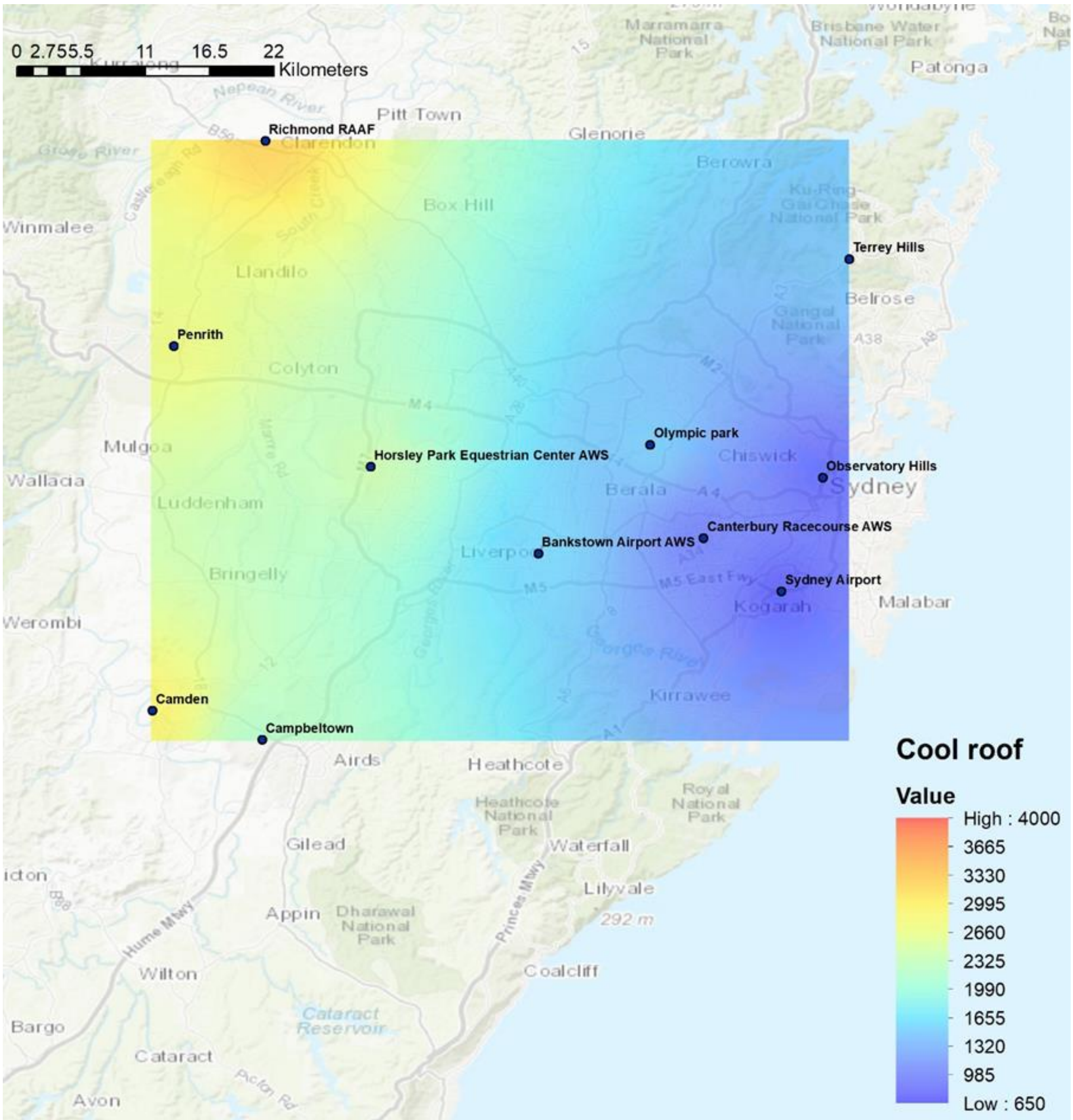

Figure 16 The sum of Cooling degree hours in Jan and Feb of the cool roof cases in the 11 stations in Sydney.

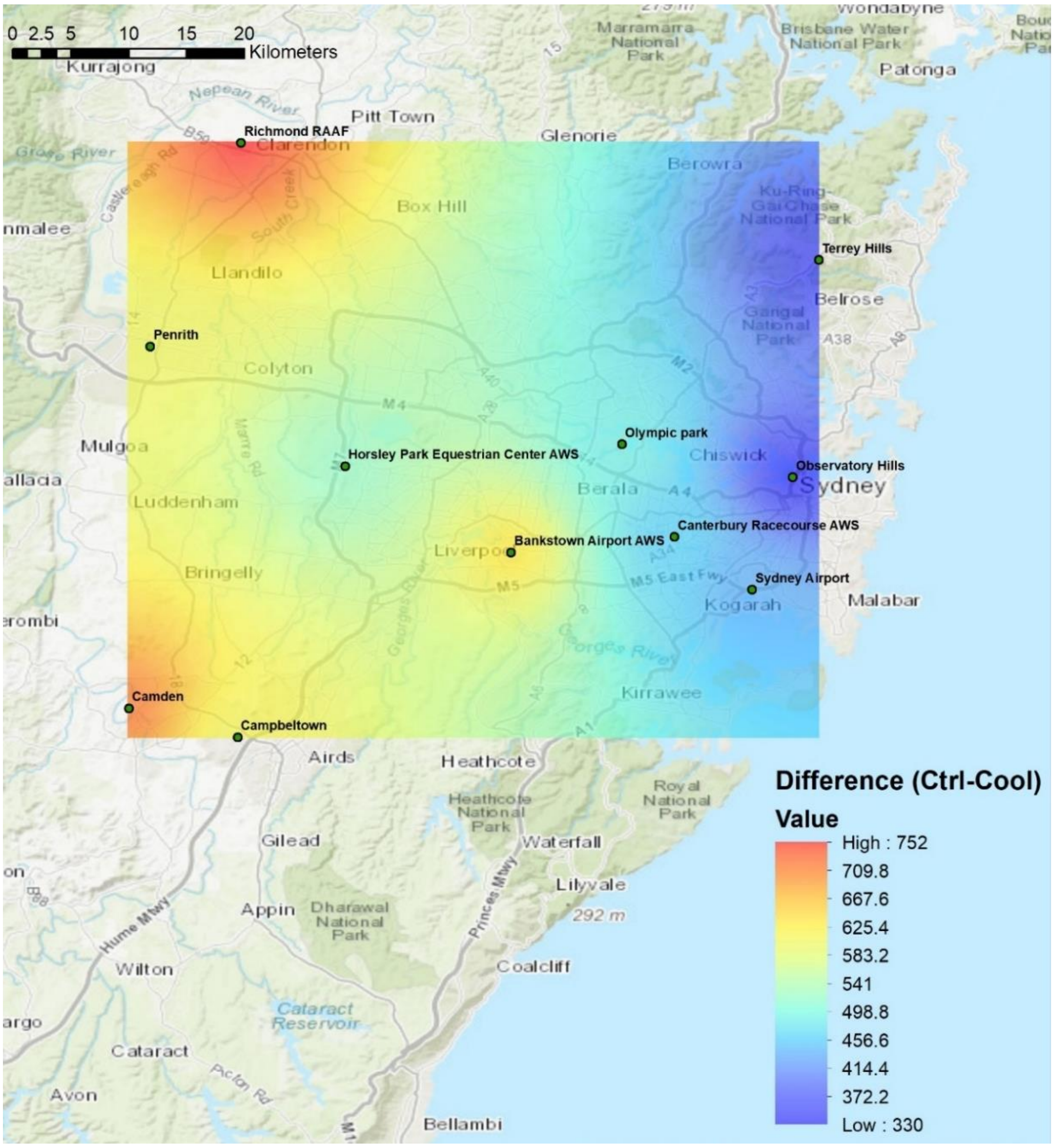

Figure 17 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and reference ones in the 11 stations in Sydney.

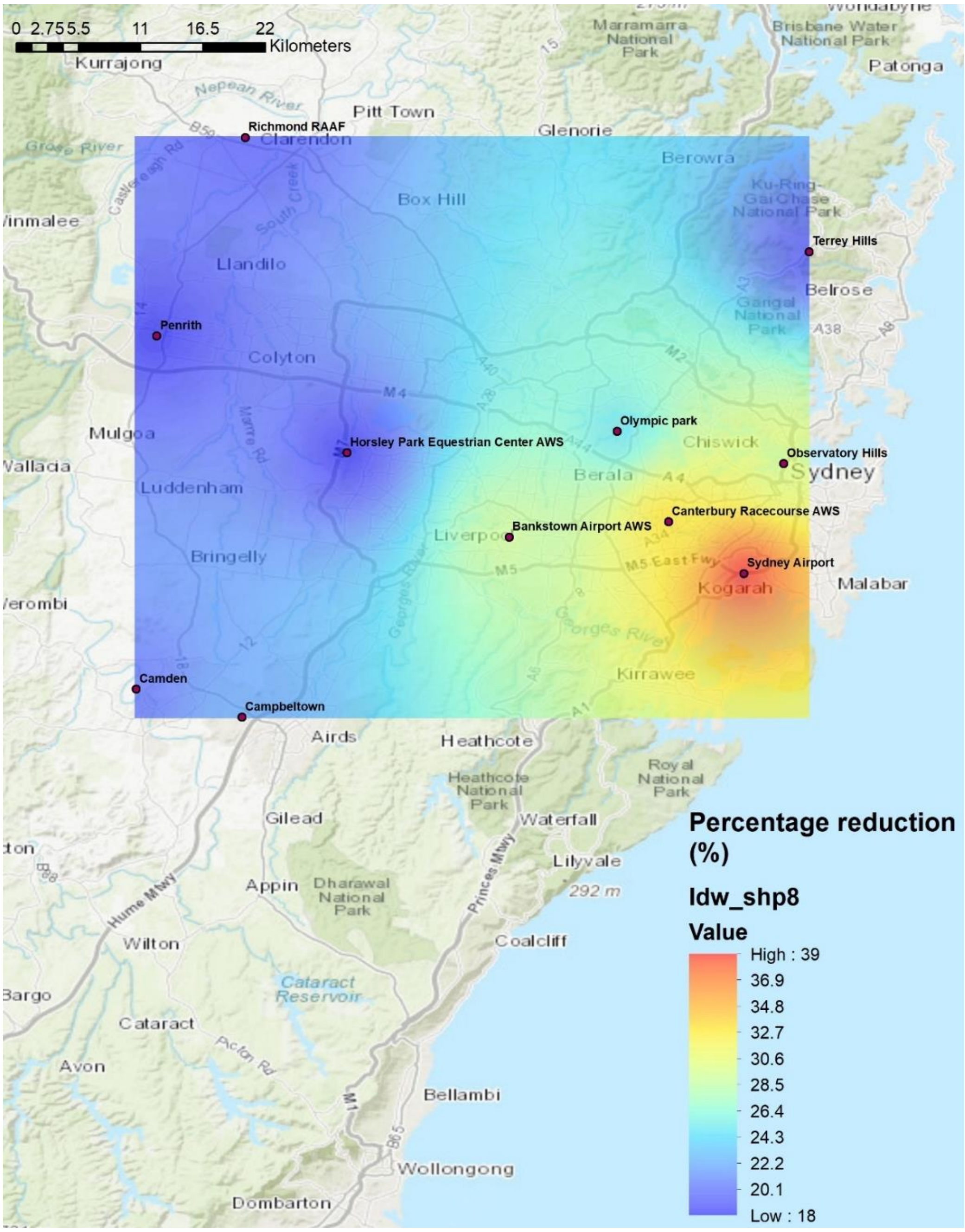

Figure 18 The percentage of CDH reduction due to the implementation of the cool roof in the 11 stations in Sydney.

2.4 Conclusions

- In average, compared to the reference scenario, the temperature with the peak distribution in the cool roof scenario is around 1 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Penrith station is an exception with the same peak in cool roof and reference scenario. Around 30%-50% of the ambient temperatures in all stations concentrate in the range of 19-22 °C.
- In reference cases, CDH ranges from 1095.7 to 3997.7, and the frequency distribution of CDH values is close to uniform. CDH gradually increases from the southeast of the city to the northwest.
- When applied with a cool roof, the decrease of CDH is observed at every station. CDH still increases from southeast to northwest.
- 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 18% to 39%, with an average value of 24.7%. The percentage is small 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 Sydney. 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 Sydney during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and eleven weather stations across Sydney (including five weather stations in climate zone 5 and six weather stations in climate zone 6). The seventeen typical buildings modelled in this study include the following, and their characteristics are listed in **Appendix: Building characteristic**s:

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

16) A high-rise shopping mall centre-existing building,

17) A stand-alone house-new building.

The eleven weather stations modelled in Sydney include (See **Figure 19**):

1) Sydney Airport-Climate zone 5,

2) Canterbury Racecourse-Climate zone 5,

3) Terry Hill-Climate zone 5,

4) Observatory Hill- Climate zone 5,

5) Bankstown Airport-Climate zone 5,

6) Camden-Climate zone 6,

7) Richmond-Climate zone 6,

8) Campbeltown-Climate zone 6,

9) Horsley Park-Climate zone 6,

10) Olympic Park- Climate zone 6,

11) Penrith- Climate zone 6.

Figure 19 Weather stations in Sydney including five weather stations in climate zone 5 (including Sydney Airport, Canterbury, Terry Hill, Observatory Hill, and Bankstown) and six weather stations in climate zone 6 (including Camden, Richmond, Campbeltown, Horsley Park, Olympic Park, and Penrith).

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 Sydney. The simulations were performed under three scenarios:

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

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

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

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

2) Annual cooling and heating load simulations

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

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

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

3) Indoor air temperature simulations under free-floating mode

The impact of cool roofs on indoor air temperature was assessed under free-floating mode in weather stations presenting the lower and higher ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) during a typical summer and winter period. The indoor air temperature simulations for the summer period were performed under three scenarios:

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

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

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

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

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

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

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

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

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

The impact of cool roofs on the cooling/heating load and indoor air temperature of the individual buildings is presented in detail in ***Volume 2***.

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 Sydney. In this section, a summary of the simulation results is presented. A summary table of the impact of the application of cool roofs in individual buildings (scenario 1) or both individual building and in the whole urban area (scenario 2) on the total cooling load of different types of buildings in two summer months are 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/m2	kWh/m2	%	kWh/m2	%
A low-rise office building without roof insulation-existing building	25.8-34.3	10.2-13.8	37.6-42.0	14.9-17.4	50.3-63.7
A high-rise office building without roof insulation-existing building	19.3-25.5	1.9-2.8	9.2-11.1	5.6-8.9	25.6-44.9
A low-rise office building with roof insulation-new building	18.6-24.6	1.1-1.7	5.9-6.9	4.8-8.1	24.9-42.2
A high-rise office building with roof insulation-new building	18.1-23.7	0.2-0.3	0.9-1.7	3.7-7.3	19.9-39.2
A low-rise shopping mall centre-new building	76.6-83	1.5-2.4	1.9-2.9%	11.3-18.2	14.8-22.8%
A mid-rise shopping mall centre-new building	75.4-81.7	0.7-1.1	0.9-1.3%	10.2-17.3	13.5-21.9%
A high-rise shopping mall centre-new building	74.9-81.3	0.5-0.8	0.6-1%	9.9-17.1	13.2-21.8%
A low-rise apartment building-new building,	13.9-19.4	1.3-1.8	7.9-10.8%	4.8-7.8	33.5-52%
A mid-rise apartment building-new building	13.7-19.3	0.7-1.1	4.3-6.6%	4.3-7.3	31.1-49.3%
A high-rise apartment building-new building	13.5-19.1	0.5-0.7	3.1-4.4%	4-7.1	29.3-48.3%
A typical stand-alone house-existing building,	14.9-19.3	6.5-7.6	38.7-45.8%	9.2-10.7	53.9-69.9%
A typical school building-existing building	26.8-33.5	1.2-1.4	3.9-4.9%	6.5-12.2	19.7-43.4%
A low-rise office building with roof insulation-existing building	21.6-28.6	5.1-7.1	22.4-26.2%	9.4-12.1	37.8-54.4%
A high-rise office building with roof insulation-existing building	18.6-24.4	1-1.4	5-5.7	4.6-8.1	21.3-42.2
A low-rise shopping mall centre-existing building	80.3-87.5	7.6-10.1	9.3-11.5	18.5-24.5	23-29.6
A high-rise shopping mall centre-existing building	75.9-82.6	2.3-3.3	2.9-4	12.2-19	16.1-24

A stand-alone house-new building.	13-16.5	3.3-4	23.2-30.8	6.1-8.5	42.2-62%

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

Building Type	**Annual cooling load saving**		**Annual heating load penalty**	**Annual total cooling & heating load saving**	
	kWh/m2	**%**	**kWh/m2**	**kWh/m2**	**%**
A low-rise office building without roof insulation-existing building	16.6-28	35.6-46.0	1.1-2.5	15.5-26.0	30.9-36.1
A high-rise office building without roof insulation-existing building	2.8-5.2	7.6-12.6	0.2-0.5	2.6-4.8	6.9-10.2
A low-rise office building with roof insulation-new building	1.8-8.5	5.1-20.7	0-0.3	1.6-8.3	4.6-18.2
A high-rise office building with roof insulation-new building	0.3-0.7	0.9-1.7	0-0.1	0.3-0.6	0.7-1.3
A low-rise shopping mall centre-new building	4.6-7.6	2-3.4	0-0.1	4.5-7.5	1.9-3.2
A mid-rise shopping mall centre-new building	2.2-3.6	1-1.7	0-0.1	2.2-3.5	1-1.6
A high-rise shopping mall centre-new building	1.4-2.4	0.6-1.1	0-0.1	1.4-2.4	0.6-1.1
A low-rise apartment building-new building,	1.7-3.3	7.8-12.6	0-0.8	1.2-2.4	3-5.5
A mid-rise apartment building-new building	0.9-1.9	4.2-7.7	0.2-0.6	0.7-1.4	1.7-3.1
A high-rise apartment building-new building	0.5-1.4	2.4-7	0.2-0.5	0.3-1.2	0.7-3.3
A typical stand-alone house-existing building,	10.2-16.1	42.4-55.8	2.8-5.2	6.9-12.1	12.1-13
A typical school building-existing building	1.9-3.3	3.6-5.8	0.1-0.5	1.8-2.9	2.7-3.8
A low-rise office building with roof insulation-existing building	8.2-14	20.6-28.5	0.4-1.1	7.8-13.2	18.6-23.2
A high-rise office building with roof insulation-existing building	1.3-2.6	3.7-6	0.1-0.2	1.2-2.5	3.3-5.2
A low-rise shopping mall centre-existing building	20.1-31.5	8.8-13.5	0.1-0.7	20-31.1	8.7-13.1
A high-rise shopping mall centre-existing building	5.6-9.6	2.5-4.3	0-0.2	5.6-9.4	2.5-4.2

A stand-alone house-new building.	5.7-7.8	25.7-38.7	0.7-1.6	4.2-6.5	10.2-18.6

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 the number of hours with the indoor air temperature above 26 ºC in free-floating mode during a typical summer month using weather data simulated by WRF.

Building type	**Maximum Indoor air temp in a typical summer week**	**Maximum indoor air temp reduction in a typical summer week**		**Number of hours above 26 ºC in a typical summer month**		
	Reference scenario (ºC)	**Reference with cool roof scenario (scenario 1) vs reference scenario (ºC)**	**Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario (ºC)**	**Reference scenario (hours)**	**Reference with cool roof scenario (scenario 1) (hours)**	**Cool roof with modified urban temperature scenario (scenario 2) (hours)**
A low-rise office building without roof insulation-existing building	48.5-52.3	10.1-11.4	11.2-12.0	553-550	424-433	359-390
A high-rise office building without roof insulation-existing building	42.8-46.5	2.1-2.3	3.1-3.3	653-670	637-667	614-634
A low-rise office building with roof insulation-new building	43.1-47	1.2-1.6	2.1-2.5	630-658	622-652	595-613
A high-rise office building	41.8-45.7	0.2-0.3	1.4-1.5	661-672	659-672	634-657

with roof insulation-new building						
A low-rise shopping mall centre-new building	48.8-53.2	0.5-0.8	1.8-2.1	641-669	639-668	611-619
A mid-rise shopping mall centre-new building	48.1-52.5	0.4-0.6	1.6-1.8	662-670	661-670	638-668
A high-rise shopping mall centre-new building	47.9-52.4	0.3-0.5	1.6-1.7	665-672	665-672	642-669
A low-rise apartment building-new building,	36.1-39.6	0.8-1	1.7-2	440-529	411-507	341-421
A mid-rise apartment building-new building	35.8-39.4	0.5-0.6	1.5-1.6	450-556	433-540	371-444
A high-rise apartment building-new building	35.8-39.1	0.3-0.4	1.5	480-568	464-556	377-464
A typical stand-alone house-existing building	40.1-43.6	4.7-5.1	5.7-6.1	397-431	273-342	213-287
A typical school building-existing building	39.1-43.2	0.8-1	1.8-2	486-533	471-508	368-446
A low-rise office building with roof insulation-existing building	45.5-49.2	5.5-6.1	6.5-6.8	604-606	544-519	472-473

A high-rise office building with roof insulation-existing building	42.4-46.1	1.1-1.3	2.1-2.3	657-670	653-670	625-650
A low-rise shopping mall centre-existing building	49.9-54.1	2.8-3	4-4.1	624-658	604-650	570-595
A high-rise shopping mall centre-existing building	48.2-52.5	1-1.1	2.1-2.2	660-670	655-670	634-666
A stand-alone house-new building.	38-41.1	2.8-2.9	3.7	422-456	339-415	352-356

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 the 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 ^{o}C in a typical winter month**			
	Reference scenario (^{o}C)	**Reference with cool roof scenario (scenario 1) vs reference scenario (^{o}C)**	**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-	7.9-11.5	2.6-2.7	97-113	377-424	139-159	450-494

existing building						
A high-rise office building without roof insulation-existing building	14.0-16.0	0.5	37-72	118-257	38-80	125-276
A low-rise office building with roof insulation-new building	12.6-15.6	0.5	41-74	147-276	45-116	245-287
A high-rise office building with roof insulation-new building	15.1-16.6	0.1	21-65	67-225	22-82	70-226
A low-rise shopping mall centre-new building	9.4-14.7	0.3-0.4	18-51	131-253	18-51	134-257
A mid-rise shopping mall centre-new building	10.7-15.6	0.2	14-50	89-219	14-50	89-219
A high-rise shopping mall centre-new building	15.9-28.7	0.1-0.2	13-50	79-208	13-50	79-208
A low-rise apartment building-new building,	10.2-14	0.3	N/A	428-549	N/A	438-566
A mid-rise apartment building-new building	10.7-14.4	0.1-0.2	N/A	431-558	N/A	431-572
A high-rise apartment building-new building	11-14.6	0.1	N/A	429-566	N/A	436-576

A typical stand-alone house-existing building,	7.3-11.3	1.9	N/A	504-563	N/A	578-621
A typical school building-existing building	10-12.5	0.2	84-106	383-481	86-111	389-495
A low-rise office building with roof insulation-existing building	10.1-13.8	1.4-1.5	74-95	284-363	89-114	329-407
A high-rise office building with roof insulation-existing building	14.6-16.3	0.3	26-69	88-241	27-75	93-249
A low-rise shopping mall centre-existing building	8.2-13.4	0.9	32-60	208-293	34-62	217-302
A high-rise shopping mall centre-existing building	10.5-15.5	0.3	16-53	97-233	16-54	99-237
A stand-alone house-new building.	8.8-12.7	1-1.1	N/A	429-523	N/A	478-562

3.4 Conclusion

This chapter investigated the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Sydney. The conclusions drawn from this chapter are:

- In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 10.2-13.8 kWh/m^2.
- 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 14.9-17.4 kWh/m^2.
- 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 4.8-8.1 kWh/m^2 in a typical new low-rise office building.
- In new high-rise buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be 1.1-1.7 kWh/m^2 and 0.2-0.3 kWh/m^2 for new low-rise and high-rise office buildings with insulation, respectively.
- 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 0.5-0.7 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 4-7.1 kWh/m^2 (29.3-48.3%) when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
- The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in all types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 16.6-28 kWh/m^2, while the corresponding heating penalty is just 1.1-2.5 kWh/m^2.
- 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 indoor air temperature of a low-rise office building without roof insulation by 10.1-11.4 ^{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 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 11.2-12.0 ^{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 553-550 hours to 424-433 hours and 359-390 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 2.1-2.5 ^{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 630-658 hours to 595-613 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 application cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 10.1-11.4 ^{o}C in a typical summer week, while the average maximum indoor air temperature reduction of the same building is expected to be just 2.6-2.7 ^{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 2.2 ^{o}C occurs when the indoor air temperature is 25.3 ^{o}C.
- The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ^{o}C especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total number of operational hours with ambient temperature below 19 ^{o}C from 74-95 hours to 89-114 hours in a typical existing low-rise office building with roof insulation.

4. Energy loss through building envelopes in various stations in Sydney _ 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 Sydney 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 11 weather stations in Sydney 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/m2);

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 five 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.

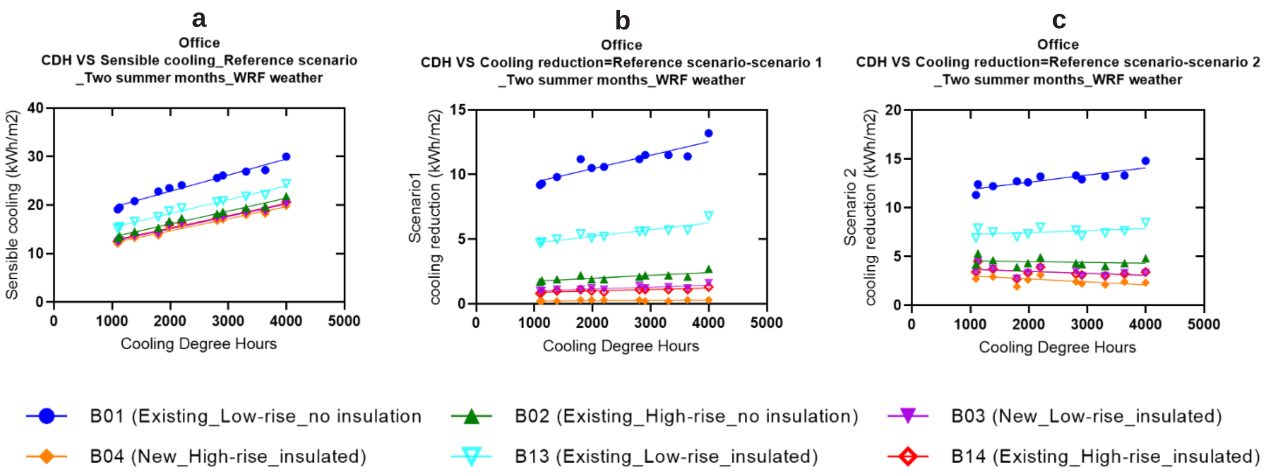

Figure 20 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 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)	0.003336	16.19	Y = 0.003336*X + 16.19
B02 (Existing_High-rise_no insulation)	0.002675	10.74	Y = 0.002675*X + 10.74
B03 (New_Low-rise_insulated)	0.002561	9.97	Y = 0.002561*X + 9.97
B04 (New_High-rise_insulated)	0.002493	9.71	Y = 0.002493*X + 9.71
B13 (Existing_Low-rise_insulated)	0.002865	12.52	Y = 0.002865*X + 12.52
B14 (Existing_High-rise_insulated)	0.00256	10.14	Y = 0.002560*X + 10.14

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.001041	8.37	Y = 0.001041*X + 8.37
B02 (Existing_High-rise_no insulation)	0.0002209	1.54	Y = 0.0002209*X + 1.54
B03 (New_Low-rise_insulated)	0.0001472	0.85	Y = 0.0001472*X + 0.85
B04 (New_High-rise_insulated)	0.0000205	0.21	Y = 0.0000205*X + 0.21
B13 (Existing_Low-rise_insulated)	0.0005185	4.18	Y = 0.0005185*X + 4.18
B14 (Existing_High-rise_insulated)	0.0001111	0.77	Y = 0.0001111*X + 0.77

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.0007401	11.13	Y = 0.0007401*X + 11.13
B02 (Existing_High-rise_no insulation)	-0.0000807	4.63	Y = -0.0000807*X + 4.63
B03 (New_Low-rise_insulated)	-0.0001951	3.87	Y = -0.0001951*X + 3.87
B04 (New_High-rise_insulated)	-0.000303	3.31	Y = -0.0003030*X + 3.31
B13 (Existing_Low-rise_insulated)	0.0002024	7.05	Y = 0.0002024*X + 7.05
B14 (Existing_High-rise_insulated)	-0.000213	3.91	Y = -0.0002130*X + 3.91

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the five 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**.

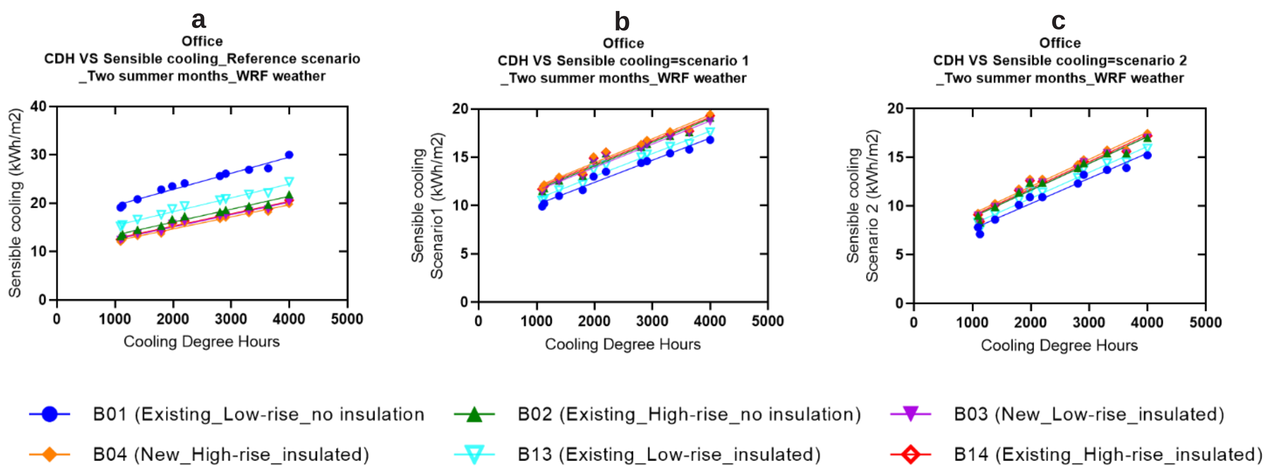

Figure 21 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

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 five 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. A higher increase rate is observed in buildings with fewer floors and older construction years, which often have higher heat loss coefficients in envelopes.

3) For the cooling load reduction in scenario 2 compared with the reference scenario, all buildings present an increasing cooling load reduction with the increase of cooling degree hours. It highlights that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions.

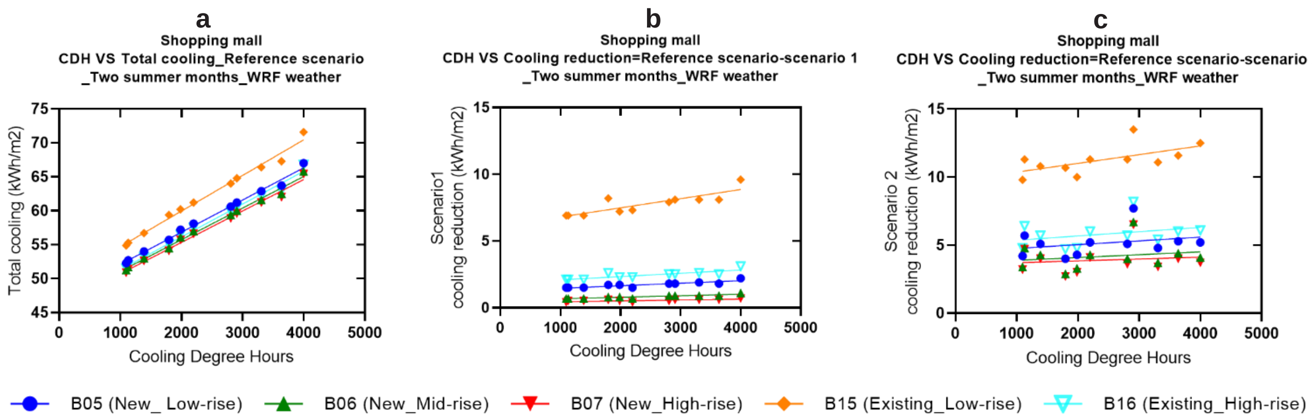

Figure 22 For shopping mall centre a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.004742	47.36	Y = 0.004742*X + 47.36
B06 (New_Mid-rise)	0.004658	46.42	Y = 0.004658*X + 46.42
B07 (New_High-rise)	0.00463	46.08	Y = 0.004630*X + 46.08
B15 (Existing_Low-rise)	0.005246	49.47	Y = 0.005246*X + 49.47
B16 (Existing_High-rise)	0.004836	46.48	Y = 0.004836*X + 46.48

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.0001909	1.26	Y = 0.0001909*X + 1.26
B06 (New_Mid-rise)	0.000114	0.56	Y = 0.0001140*X + 0.56
B07 (New_High-rise)	0.0000664	0.38	Y = 0.0000664*X + 0.38
B15 (Existing_Low-rise)	0.0006874	6.11	Y = 0.0006874*X + 6.11
B16 (Existing_High-rise)	0.0002476	1.84	Y = 0.0002476*X + 1.84

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.0002778	4.48	Y = 0.0002778*X + 4.48
B06 (New_Mid-rise)	0.0002082	3.68	Y = 0.0002082*X + 3.68
B07 (New_High-rise)	0.0001365	3.57	Y = 0.0001365*X + 3.57
B15 (Existing_Low-rise)	0.0006424	9.73	Y = 0.0006424*X + 9.73
B16 (Existing_High-rise)	0.0003144	5.05	Y = 0.0003144*X + 5.05

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the five 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**.

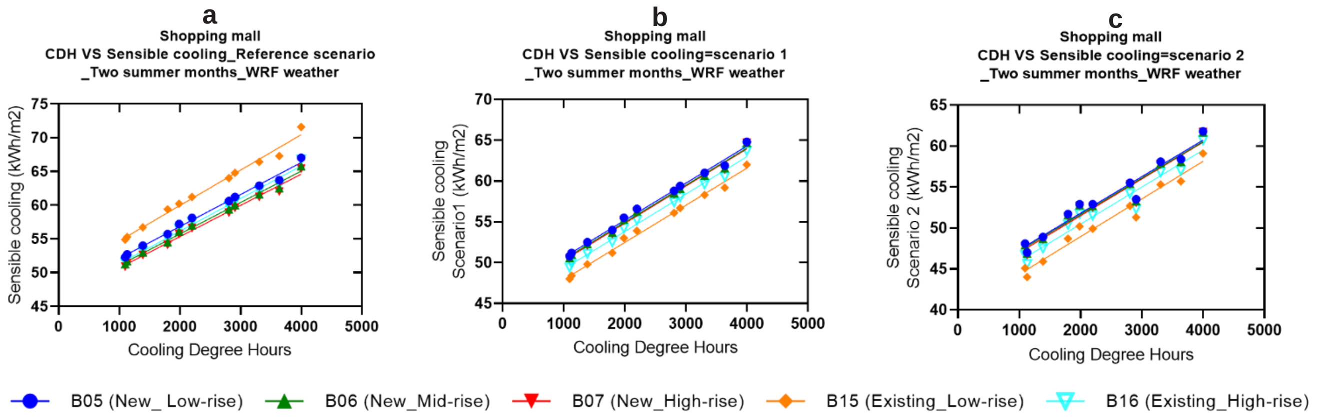

Figure 23 For shopping mall centre a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2**.**

4.4 Residential 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 five 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 five 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 buildings except b17 present an increasing cooling load reduction with the increase of cooling degree hours. It highlights that in most cases, under unmodified climatic conditions, a cool roof is more effective reducing the cooling load in hotter regions.

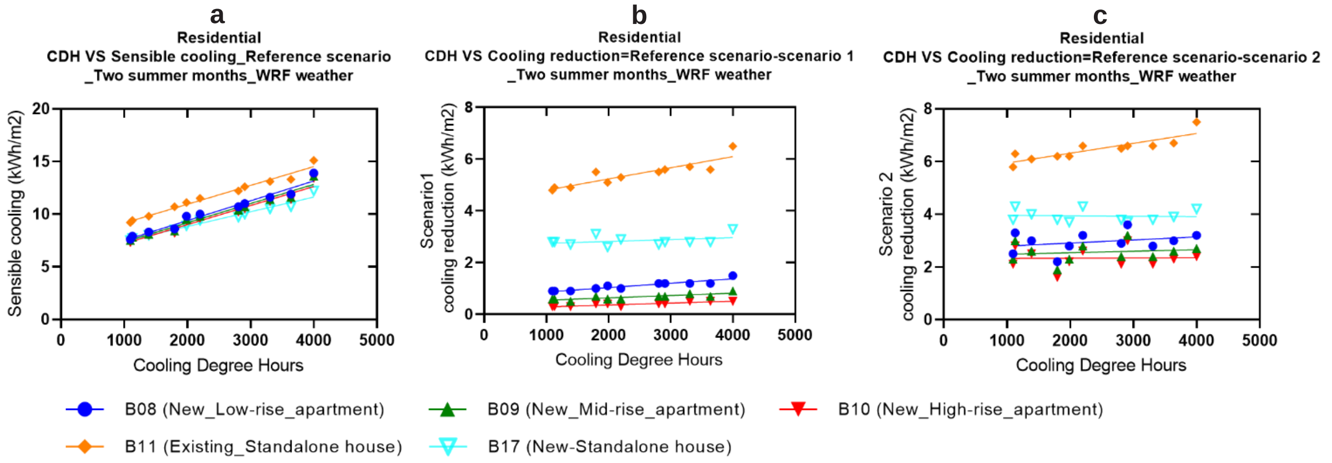

Figure 24 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.001883	5.63	Y = 0.001883*X + 5.625
B09 (New_Mid-rise_apartment)	0.001825	5.54	Y = 0.001825*X + 5.536
B10 (New_High-rise_apartment)	0.001811	5.39	Y = 0.001811*X + 5.387
B11 (Existing_Standalone house)	0.00179	7.37	Y = 0.001790*X + 7.367
B17 (New-Standalone house)	0.001397	6.04	Y = 0.001397*X + 6.040

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0001701	0.69	Y = 0.0001701*X + 0.69
B09 (New_Mid-rise_apartment)	0.0000906	0.46	Y = 0.0000906*X + 0.46
B10 (New_High-rise_apartment)	0.0000734	0.22	Y = 0.0000734*X + 0.22
B11 (Existing_Standalone house)	0.0004322	4.37	Y = 0.0004322*X + 4.37
B17 (New-Standalone house)	0.0000731	2.67	Y = 0.0000731*X + 2.67

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B08 (New_Low-rise_apartment)	0.0001162	2.68	Y = 0.0001162*X + 2.68
B09 (New_Mid-rise_apartment)	0.0000571	2.43	Y = 0.0000571*X + 2.43
B10 (New_High-rise_apartment)	0.00000816	2.32	Y = 0.00000816*X + 2.32
B11 (Existing_Standalone house)	0.0003747	5.57	Y = 0.0003747*X + 5.57
B17 (New-Standalone house)	-0.0000160	3.98	Y = -0.0000160*X + 3.98

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the five 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**.

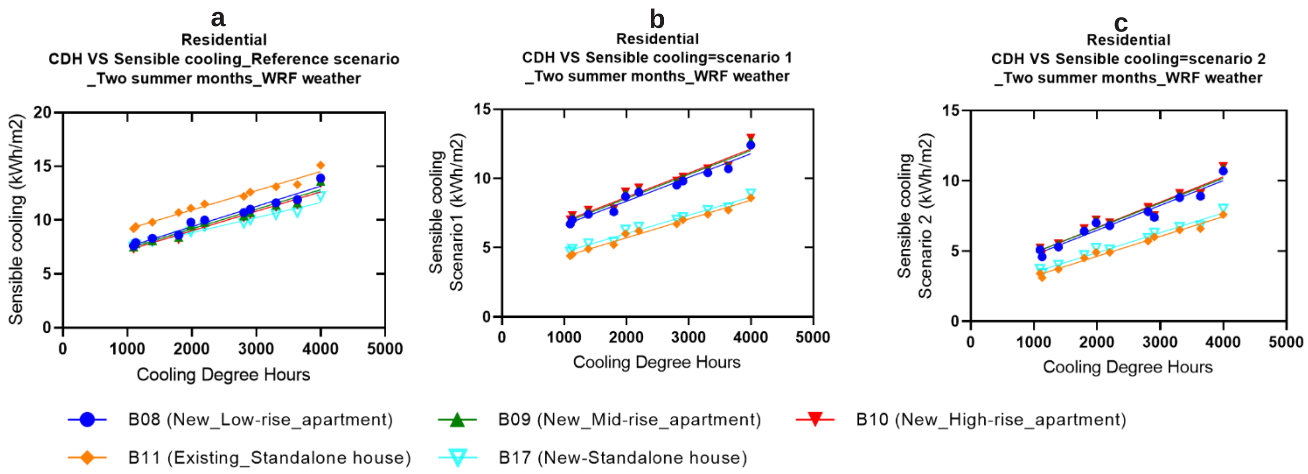

Figure 25 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario.

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 both scenarios 1 and 2 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.

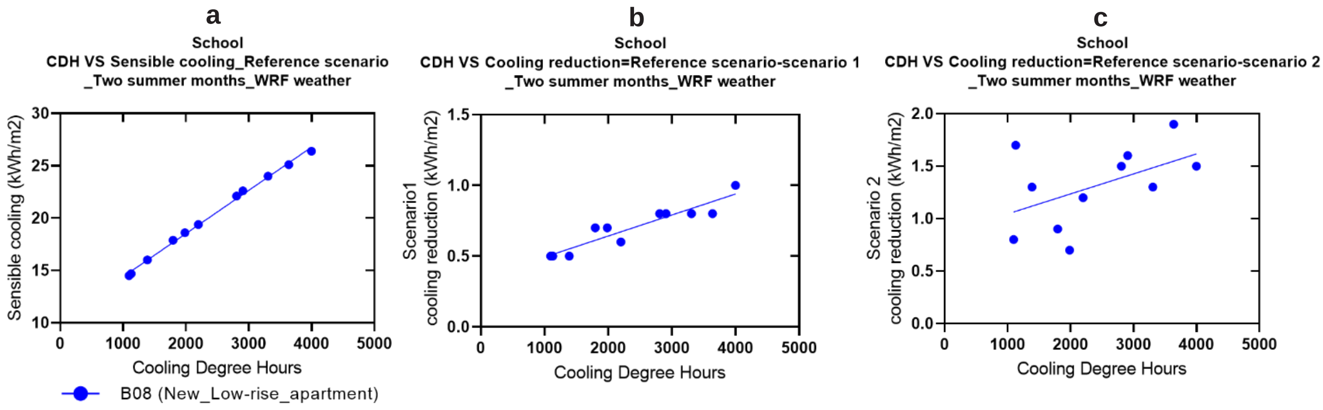

Figure 26 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared 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)	0.004128	10.27	Y = 0.004128*X + 10.27

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B12 (Existing)	0.0001486	0.35	Y = 0.0001486*X + 0.35

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B12 (Existing)	0.0001906	0.85	Y = 0.0001906*X + 0.8544

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**.

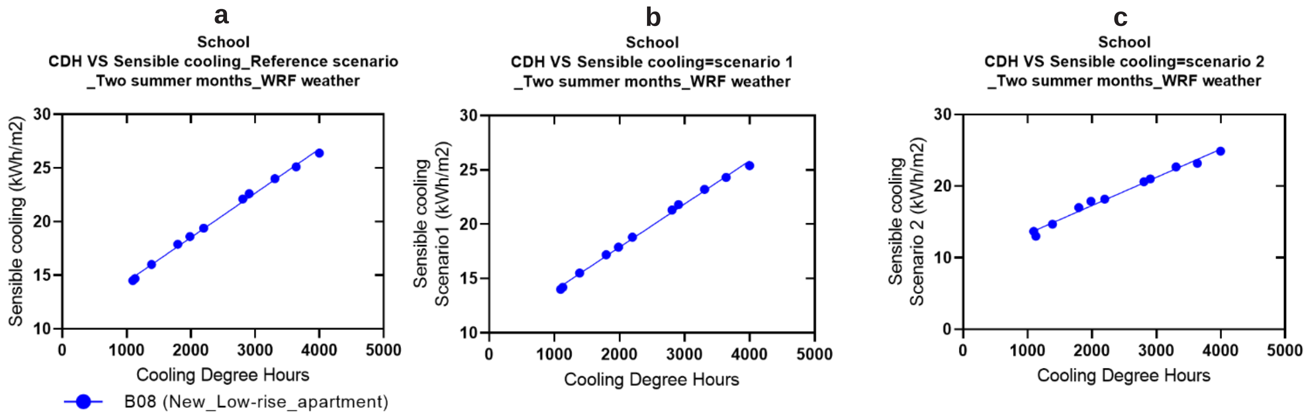

Figure 27 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.6 Conclusion

- Regarding the sensible cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.
- Cooling load reduction in scenario 1 compared with the reference scenario mainly 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 under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions.
- 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)	0.001397
B11 (Standalone house_Existing)	0.00179
B10 (Apartment_New_High-rise)	0.001811
B09 (Apartment_New_Mid-rise)	0.001825
B08 (Apartment_New_Low-rise)	0.001883
B04 (Office_New_High-rise_insulated)	0.002493

B14 (Office_Existing_High-rise_insulated)	0.00256
B03 (Office_New_Low-rise_insulated)	0.002561
B02 (Office_Existing_High-rise_no insulation)	0.002675
B13 (Office_Existing_Low-rise_insulated)	0.002865
B01 (Office_Existing_Low-rise_no insulation)	0.003336
B12 (School_Existing)	0.004128
B07 (Shopping mall_New_High-rise)	0.00463
B06 (Shopping mall_New_Mid-rise)	0.004658
B05 (Shopping mall_New_ Low-rise)	0.004742
B16 (Shopping mall_Existing_High-rise)	0.004836
B15 (Shopping mall_Existing_Low-rise)	0.005246

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 Sydney. As estimated, the application of cool roofs can improve the hourly EER of the six selected AC systems by 0.12-0.3 in Observatory station in Sydney. This is equivalent to a noticeable EER-related cooling load saving of around 8-18% in a new high-rise shopping mall centre in Observatory 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 6%.

5.1 Introduction

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

In this context, this study aims to evaluate the impact of cool roofs on EER of AC systems and the corresponding cooling load savings. The cooling load saving by modified EER is in addition to the primary cooling load savings by lower heat gains and improved urban climate by the 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 Sydney. 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 Sydney (i.e. Richmond and Observatory 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 Sydney. 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 Observatory and Richmond 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 Observatory 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 0.23-0.93 and 0.4-0.94 in Observatory and Richmond 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 Observatory

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	Observatory	19.1	0.3
	Richmond	30.0	0.47
B02- high-rise office building without roof insulation-existing building	Observatory	13.2	0.49
	Richmond	21.8	0.72
B03- low-rise office building with roof insulation-new building	Observatory	12.4	0.57
	Richmond	20.3	0.79
B04- high-rise office building with roof insulation-new building	Observatory	12.0	0.61
	Richmond	19.8	0.83
B05- low-rise shopping mall centre-existing building-new building	Observatory	52.3	0.91
	Richmond	67.0	0.92
B06- mid-rise shopping mall centre-existing building-new building	Observatory	51.3	0.93
	Richmond	65.8	0.93
B07- high-rise shopping mall centre-new building	Observatory	50.9	0.93
	Richmond	65.4	0.94
B08- low-rise apartment building-new building	Observatory	7.6	0.4
	Richmond	13.9	0.61
B09- mid-rise apartment building-new building	Observatory	7.5	0.45
	Richmond	13.6	0.64
B10- high-rise apartment building-new building	Observatory	7.3	0.45
	Richmond	13.4	0.66
	Observatory	9.2	0.23

B11- typical stand-alone house-existing building	Richmond	15.1	0.4
B12- typical school building-existing building	Observatory	14.5	0.92
	Richmond	26.4	0.91
B13- low-rise office building with roof insulation-existing building	Observatory	15.2	0.4
	Richmond	24.4	0.61
B14- high-rise office building with roof insulation-existing building	Observatory	12.5	0.56
	Richmond	20.6	0.77
B15- low-rise shopping mall centre-existing building	Observatory	54.9	0.82
	Richmond	71.6	0.82
B16- high-rise shopping mall centre-existing building	Observatory	51.5	0.9
	Richmond	66.8	0.91
B17- stand-alone house-new building	Observatory	7.5	0.31
	Richmond	12.2	0.53

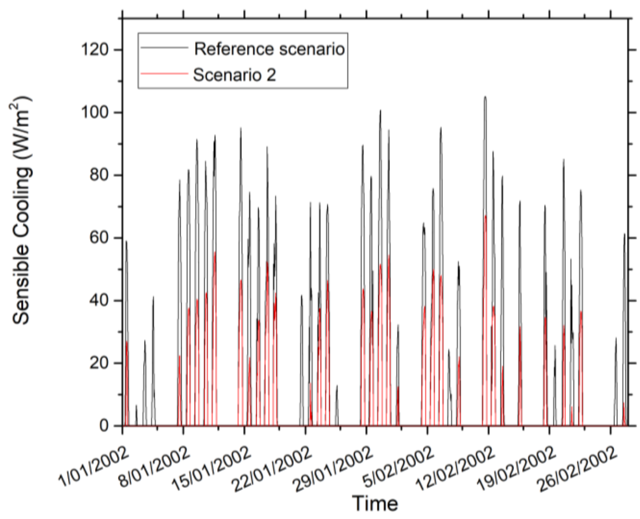

Figure 28 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-existing building in Observatory station

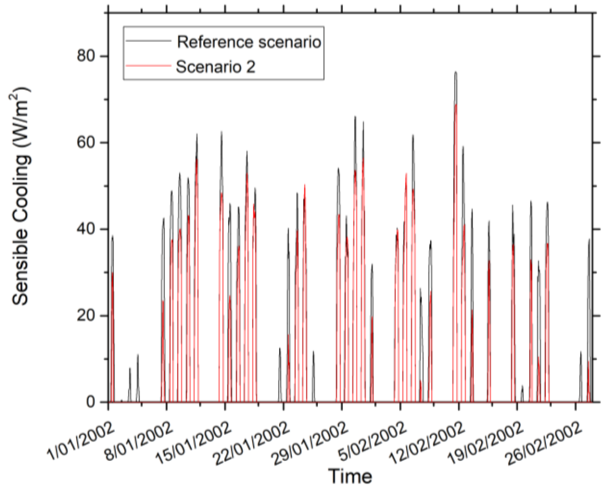

Figure 29 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-existing building in Observatory station

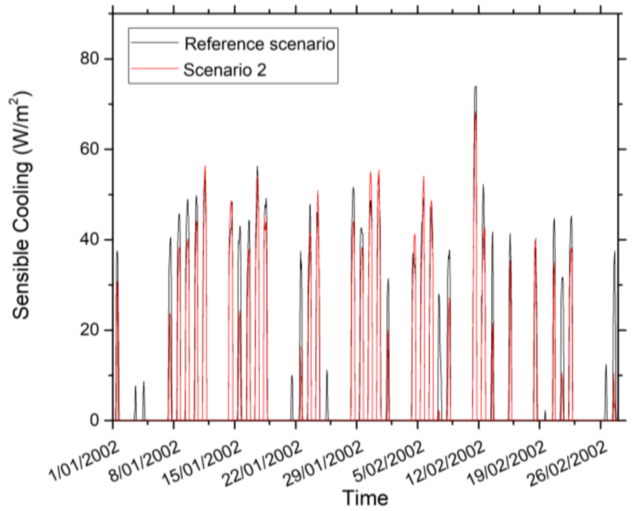

Figure 30 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-new building in Observatory station.

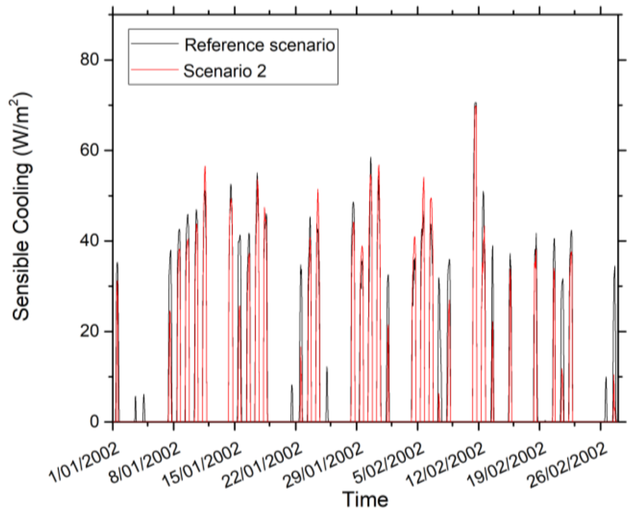

Figure 31 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-new building in Observatory station

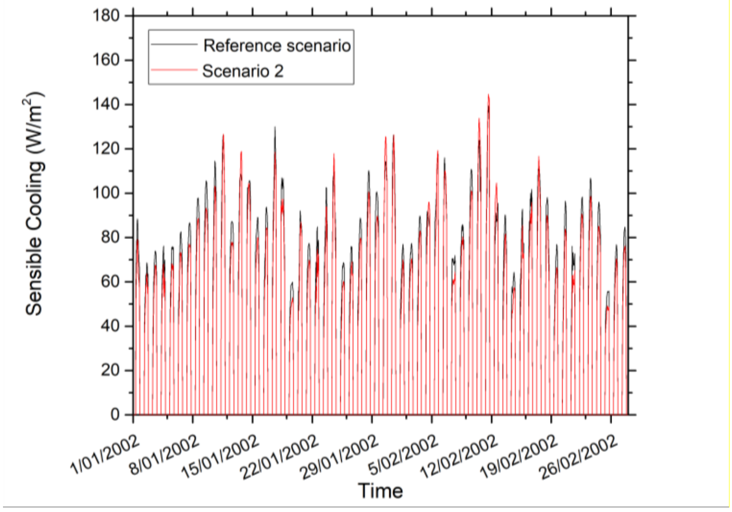

Figure 32 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise shopping mall centre-new building in Observatory station.

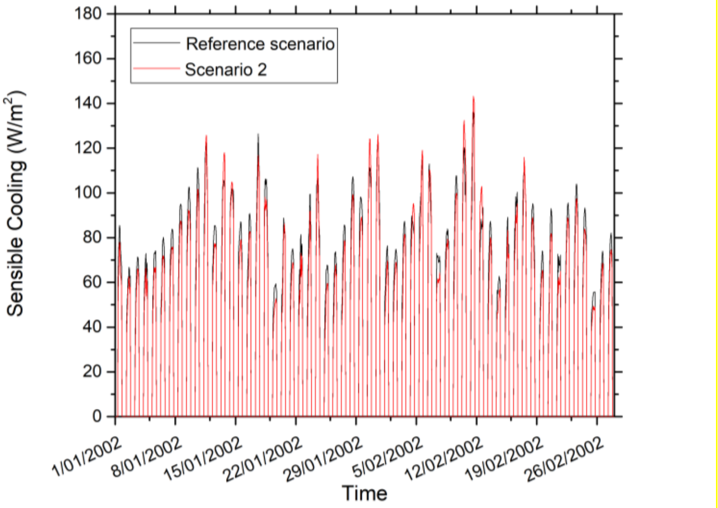

Figure 33 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise shopping mall centre-new building in Observatory station

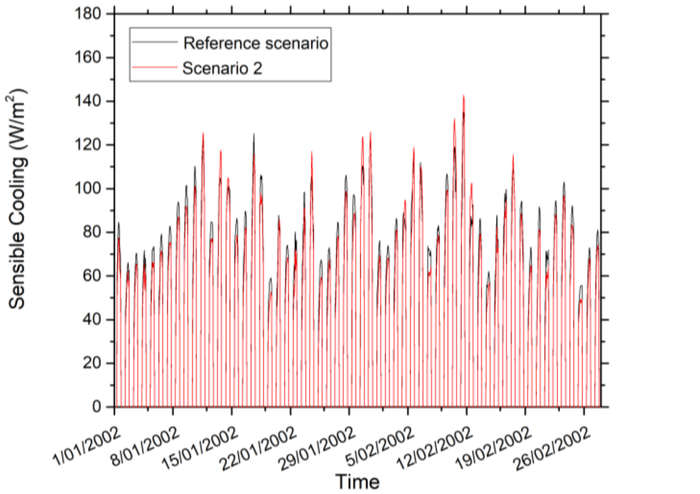

Figure 34 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise shopping mall centre-new building in Observatory station

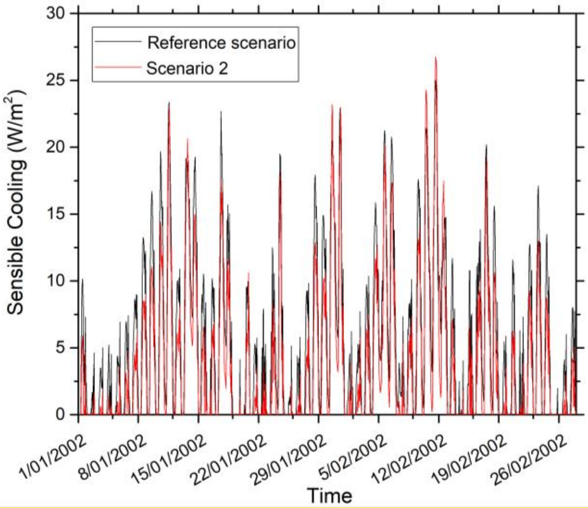

Figure 35 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise apartment-new building in Observatory station

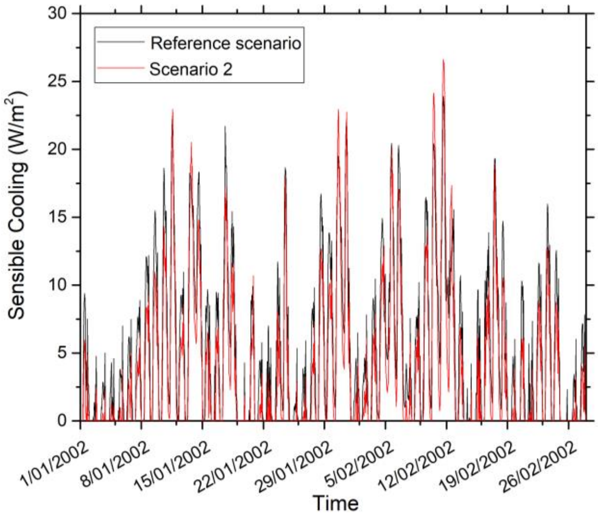

Figure 36 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise apartment-new building in Observatory station

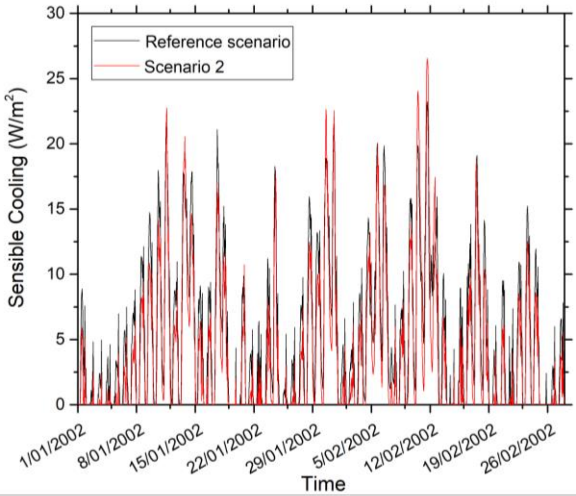

Figure 37 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise apartment-new building in Observatory station.

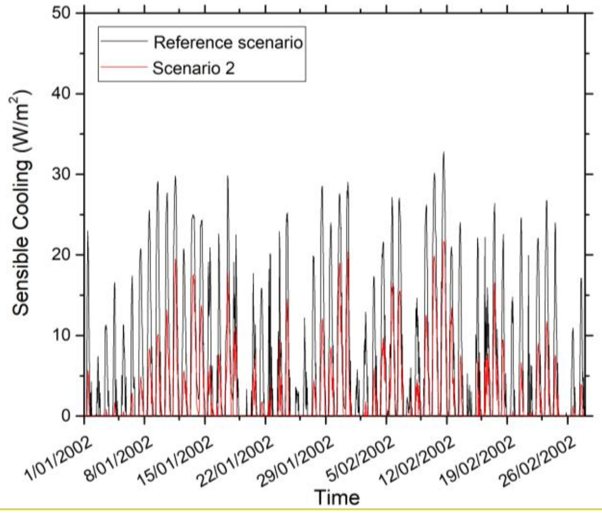

Figure 38 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical stand-alone house-existing building in Observatory station

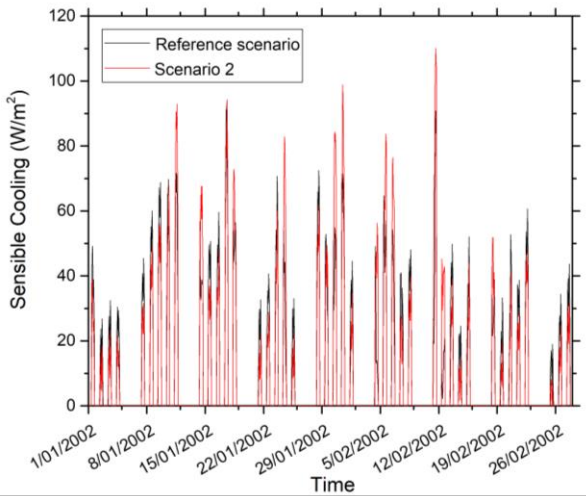

Figure 39 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical school building-existing building in Observatory station.

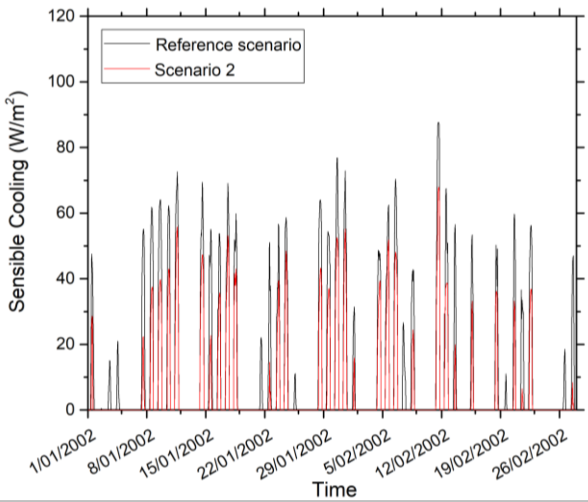

Figure 40 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise office-existing building in Observatory station

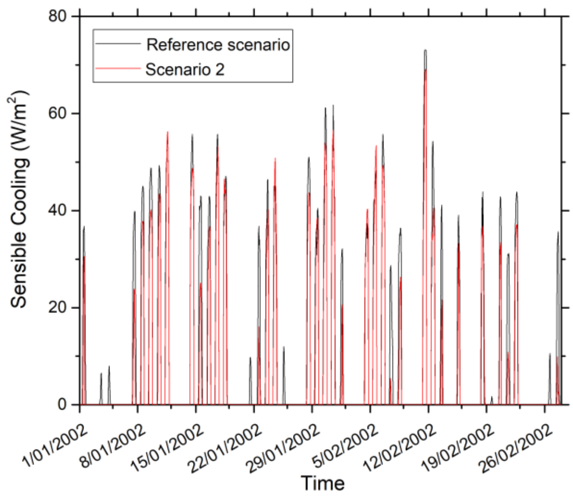

Figure 41 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise office-existing building in Observatory station

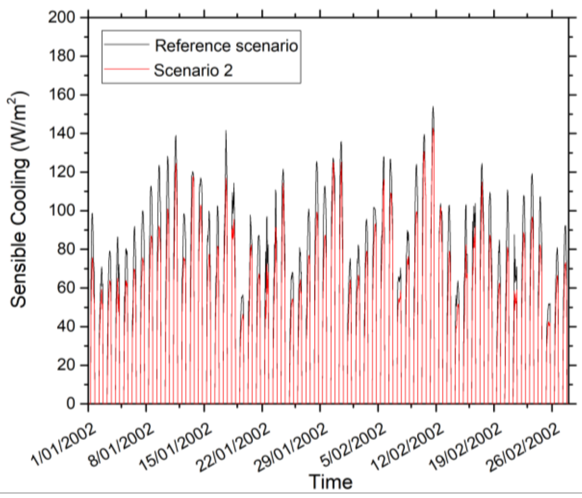

Figure 42 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise shopping mall centre-existing building in Observatory station

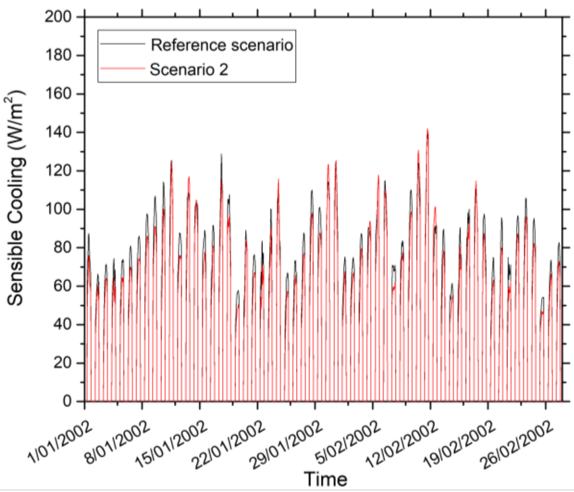

Figure 43 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise shopping mall centre-existing building in Observatory station

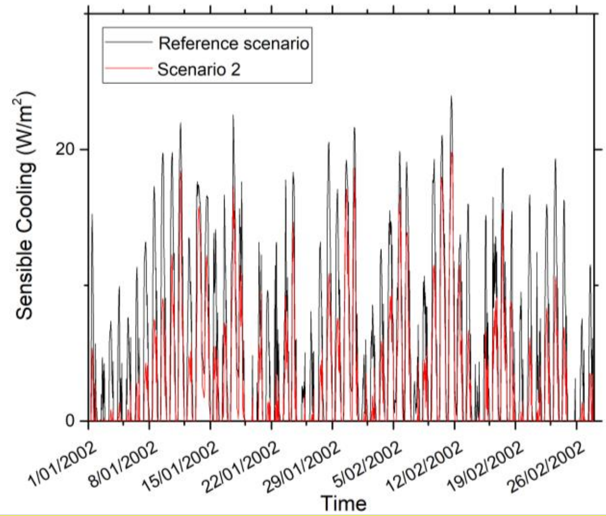

Figure 44 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a stand-alone house-new building in Observatory station

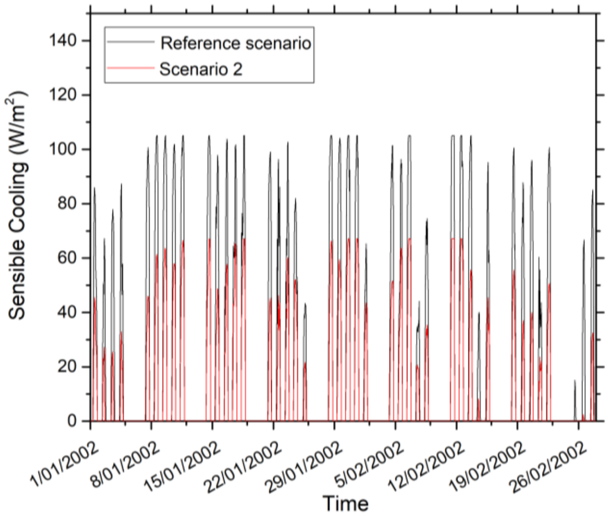

Figure 45 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-existing building in Richmond station

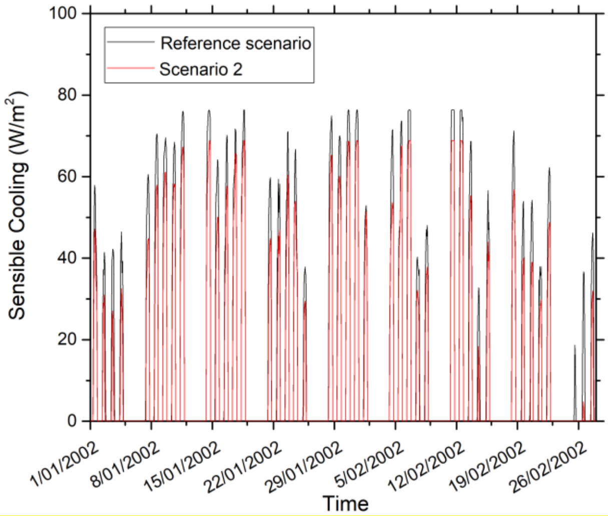

Figure 46 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-existing building in Richmond station.

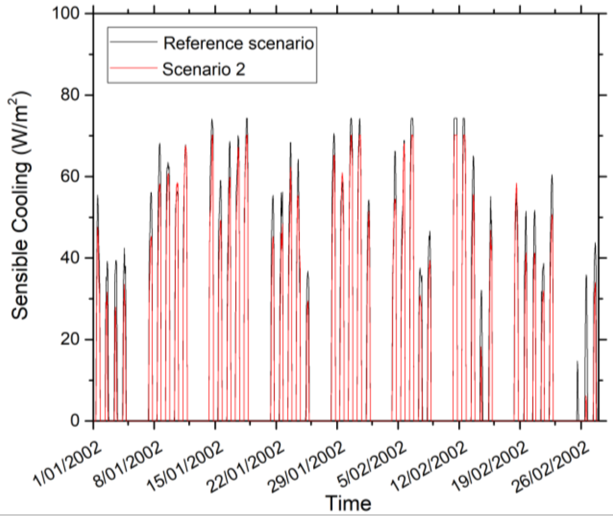

Figure 47 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise office building without roof insulation-new building in Richmond station

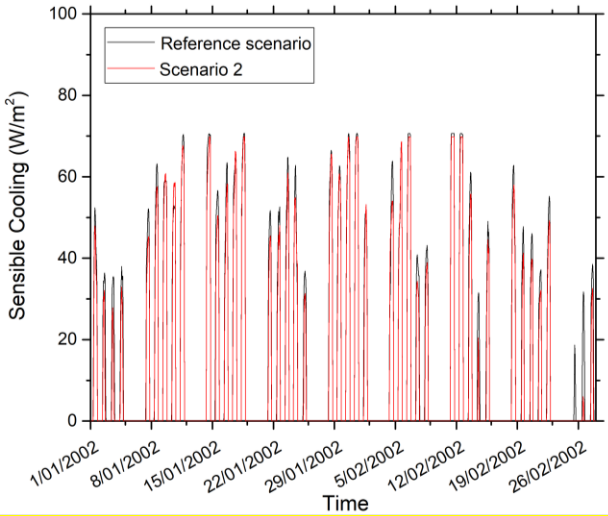

Figure 48 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise office building without roof insulation-new building in Richmond station.

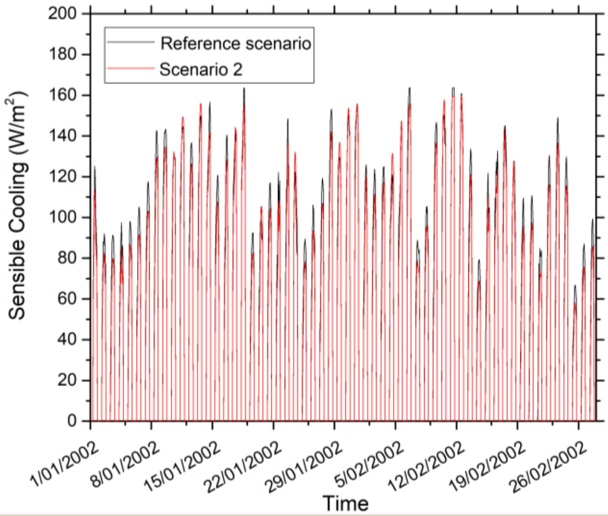

Figure 49 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise shopping mall centre-new building in Richmond station

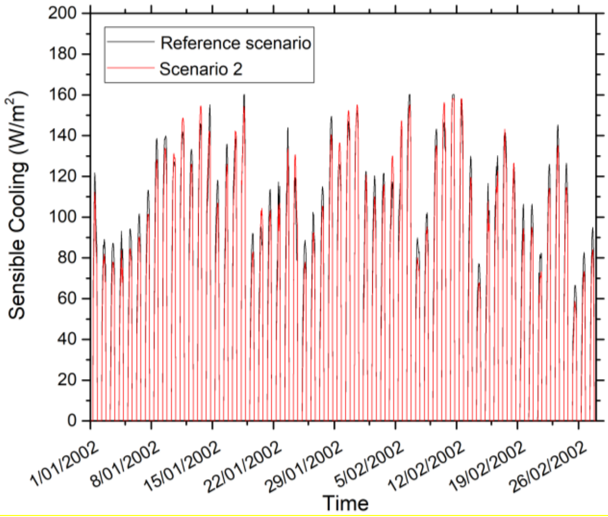

Figure 50 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise shopping mall centre-new building in Richmond station

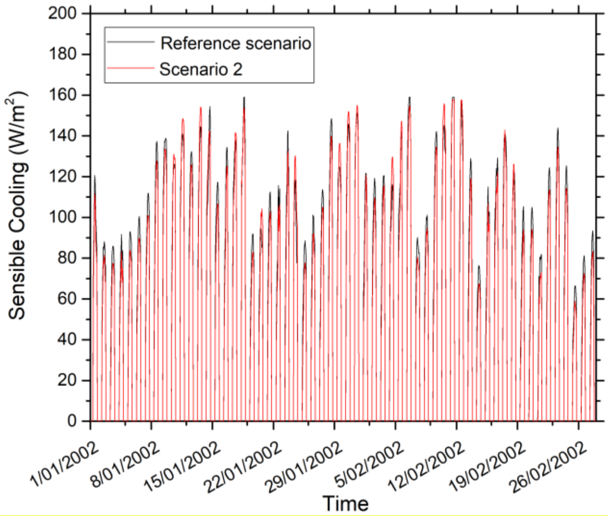

Figure 51 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise shopping mall centre-new building in Richmond station

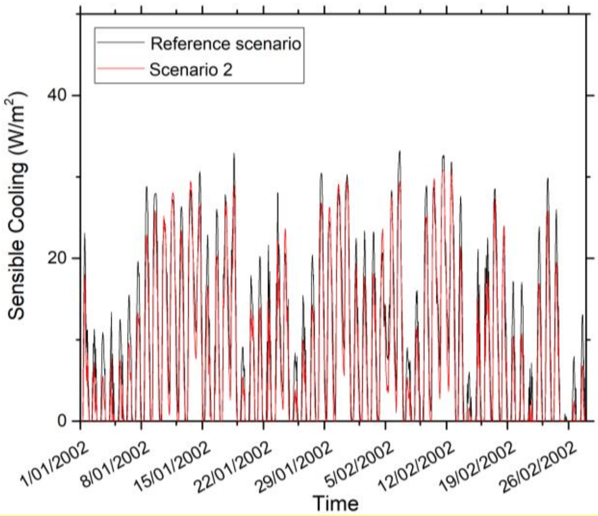

Figure 52 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a low-rise apartment-new building in Richmond station

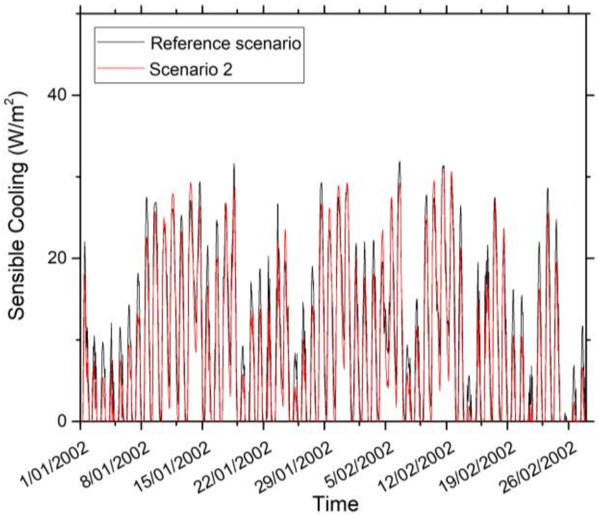

Figure 53 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a mid-rise apartment-new building in Richmond station

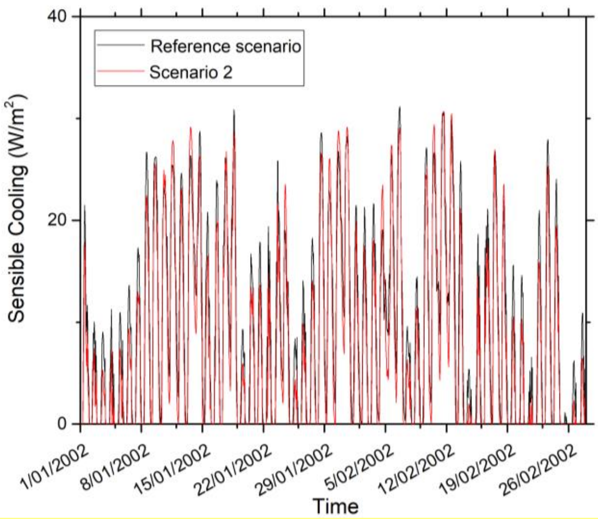

Figure 54 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a high-rise apartment-new building in Richmond station

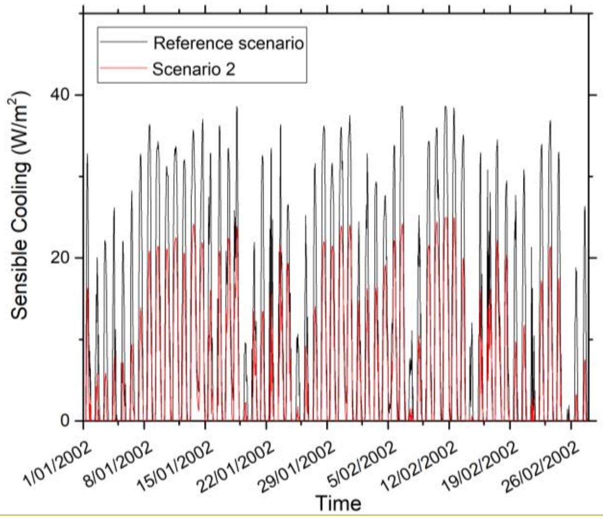

Figure 55 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical stand-alone house-existing building in Richmond station

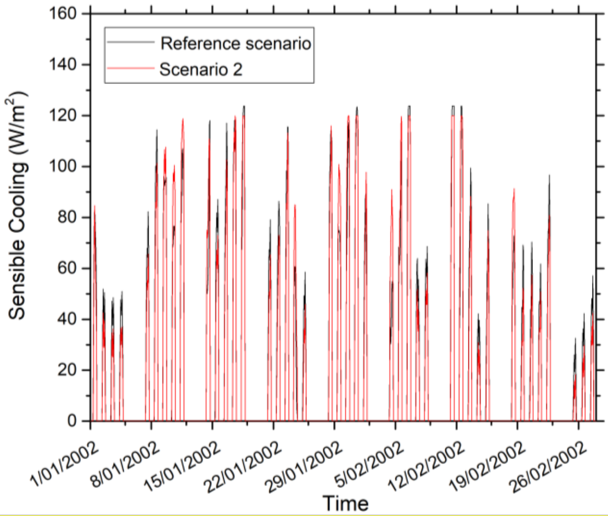

Figure 56 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical school building-existing building in Richmond station

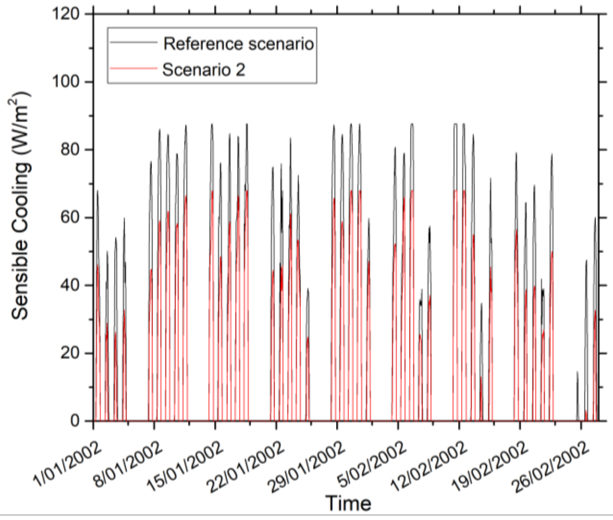

Figure 57 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise office-existing building in Richmond station

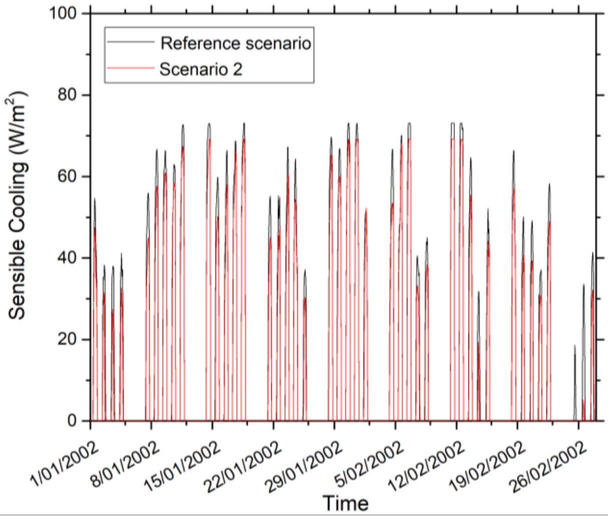

Figure 58 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise office-existing building in Richmond station

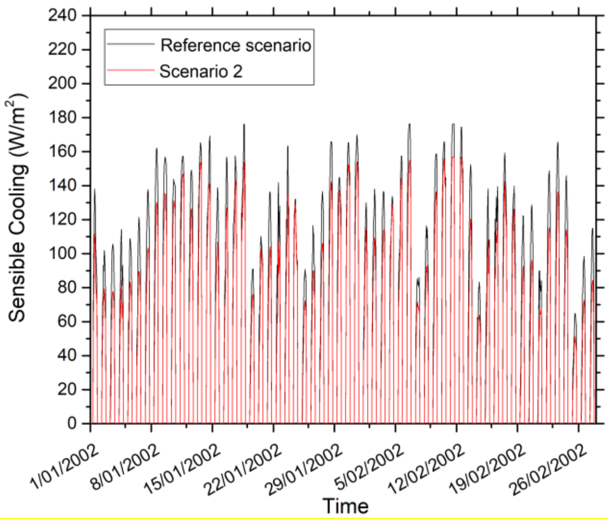

Figure 59 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical low-rise shopping mall centre-existing building in Richmond station

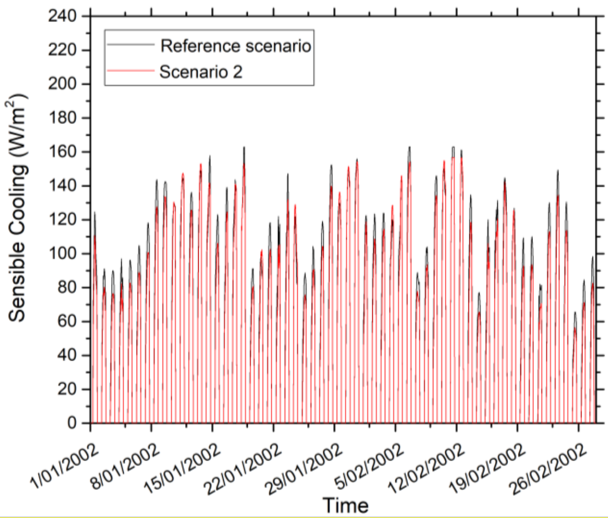

Figure 60 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a typical high-rise shopping mall centre-existing building in Richmond station

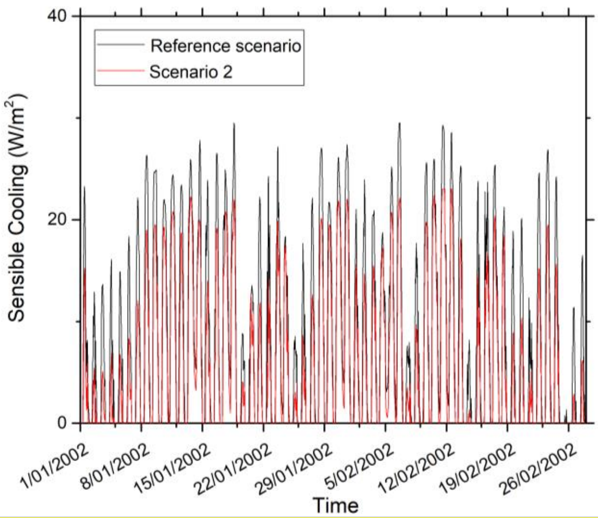

Figure 61 Sensible cooling load in cool roof with modified urban temperature scenario (scenario 2) and reference scenario for a stand-alone house-new building in Richmond station

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, EER of the six different AC systems under the reference scenario and cool roof with modified urban temperature scenario (Scenario 2) is computed. The estimations illustrate a noticeable improvement in the EER of all cooling systems due to lower temperatures in cool roof with modified urban temperature scenario (Scenario 2) compared to the reference scenario. **Table 18** shows the minimum, average, and maximum ambient temperature variations in cool roof with modified urban temperature scenario (Scenario 2) compared to reference scenario in Observatory and Richmond stations. **Table 19** and 4 illustrate the average, minimum, and maximum variations of the EER in cool roof with modified urban temperature scenario (Scenario 2) compared to reference scenario for the different AC systems in Observatory and Richmond stations, respectively. **Figure 62** 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 Observatory and Richmond 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)
Observatory	1.05	0.6	1.68
Richmond	1.15	0.7	1.78

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 Observatory 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	0.2
Residential-Split system-Eq 5	0.19	0.12	0.32
Residential-Split system-Eq 6	0.09	0.05	0.15

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 Richmond 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	0.08	0.05	0.12
Residential-Split system-Eq 2	0.08	0.05	0.13
Residential-Split system-Eq 3	0.09	0.05	0.13
Residential-Split system-Eq 4	0.14	0.09	0.21
Residential-Split system-Eq 5	0.2	0.14	0.3
Residential-Split system-Eq 6	0.09	0.06	0.14

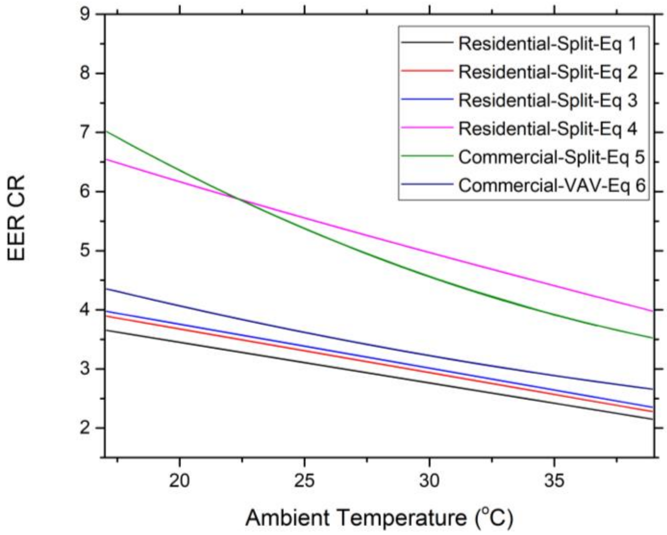

Figure 62 EER for cool roof scenario for six different AC systems

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 Observatory and Richmond 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 Observatory and Richmond 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 Observatory 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	19.1	9.2	48	11.3	59	0.63	3	0.68	4	0.68	4	1.07	6	1.40	7	0.69	4
B02	13.2	1.7	13	4.2	32	0.73	6	0.78	6	0.79	6	1.22	9	1.62	12	0.80	6
B03	12.4	1.0	8	3.3	27	0.73	6	0.79	6	0.79	6	1.23	10	1.63	13	0.80	6
B04	12.0	0.3	3	2.7	23	0.76	6	0.81	7	0.82	7	1.27	11	1.69	14	0.83	7
B05	52.3	1.4	3	4.2	8	3.85	7	4.13	8	4.15	8	6.61	13	9.45	18	4.51	9
B06	51.3	0.7	1	3.4	7	3.83	7	4.12	8	4.14	8	6.59	13	9.42	18	4.50	9
B07	50.9	0.4	1	3.2	6	3.82	8	4.10	8	4.13	8	6.57	13	9.39	18	4.48	9
B08	7.6	0.9	12	2.6	34	0.38	5	0.41	5	0.41	5	0.65	9	0.87	11	0.43	6
B09	7.5	0.5	7	2.3	31	0.39	5	0.42	6	0.42	6	0.66	9	0.90	12	0.44	6
B10	7.3	0.3	4	2.1	29	0.39	5	0.42	6	0.43	6	0.67	9	0.91	12	0.44	6
B11	9.2	4.8	52	5.8	63	0.26	3	0.28	3	0.29	3	0.44	5	0.58	6	0.29	3
B12	14.5	0.5	3	0.8	6	1.12	8	1.20	8	1.21	8	1.90	13	2.57	18	1.25	9
B13	15.2	4.7	31	6.9	45	0.67	4	0.72	5	0.73	5	1.13	7	1.49	10	0.74	5
B14	12.5	0.9	7	3.4	27	0.74	6	0.80	6	0.80	6	1.25	10	1.65	13	0.81	6
B15	54.9	6.9	13	9.8	18	3.61	7	3.88	7	3.90	7	6.20	11	8.83	16	4.22	8
B16	51.5	2.1	4	4.9	10	3.74	7	4.01	8	4.03	8	6.42	12	9.16	18	4.38	9
B17	7.5	2.7	36	3.8	51	0.28	4	0.31	4	0.31	4	0.48	6	0.64	9	0.32	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 Richmond station.

Building	Cooling load-Reference	EG-Scenario 1		EG-Scenario 2		EG-EER-Equation 1		EG-EER-Equation 2		EG-EER-Equation 3		EG-EER-Equation 4		EG-EER-Equation 5		EG-EER-Equation 6	
		kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
B01	30.0	13.2	44	14.9	50	1.33	4	1.43	5	1.44	5	2.16	7	2.32	8	1.25	4
B02	21.8	2.7	12	4.8	22	1.49	7	1.60	7	1.61	7	2.43	11	2.66	12	1.42	7
B03	20.3	1.6	8	3.4	17	1.49	7	1.60	8	1.61	8	2.43	12	2.65	13	1.42	7
B04	19.8	0.4	2	2.4	12	1.53	8	1.65	8	1.66	8	2.50	13	2.74	14	1.47	7
B05	67.0	2.2	3	5.2	8	5.38	8	5.78	9	5.81	9	8.88	13	10.37	15	5.39	8
B06	65.8	1.1	2	4.1	6	5.38	8	5.77	9	5.81	9	8.87	13	10.36	16	5.38	8
B07	65.4	0.7	1	3.7	6	5.37	8	5.77	9	5.80	9	8.86	14	10.36	16	5.38	8
B08	13.9	1.5	11	3.2	23	0.88	6	0.95	7	0.96	7	1.45	10	1.62	12	0.86	6
B09	13.6	0.9	7	2.7	20	0.90	7	0.97	7	0.97	7	1.48	11	1.66	12	0.88	6
B10	13.4	0.6	4	2.4	18	0.91	7	0.98	7	0.98	7	1.49	11	1.69	13	0.89	7
B11	15.1	6.5	43	7.5	50	0.65	4	0.69	5	0.70	5	1.05	7	1.13	7	0.61	4
B12	26.4	1.0	4	1.5	6	2.21	8	2.37	9	2.38	9	3.59	14	3.86	15	2.08	8
B13	24.4	6.8	28	8.5	35	1.39	6	1.50	6	1.51	6	2.27	9	2.45	10	1.32	5
B14	20.6	1.4	7	3.5	17	1.51	7	1.62	8	1.63	8	2.46	12	2.70	13	1.44	7
B15	71.6	9.5	13	12.5	17	5.15	7	5.53	8	5.56	8	8.48	12	9.83	14	5.13	7
B16	66.8	3.1	5	6.1	9	5.28	8	5.68	9	5.71	9	8.71	13	10.16	15	5.28	8
B17	12.2	3.3	27	4.2	34	0.67	5	0.72	6	0.72	6	1.09	9	1.20	10	0.64	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 Sydney. 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. Observatory and Richmond) in Sydney.

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	Observatory	0.3	19.1	9.2	48	11.3	59	0.63-1.4	3-7
	Richmond	0.47	30.0	13.2	44	14.9	50	1.25-2.32	4-8
B02- high-rise office building without roof insulation-existing building	Observatory	0.49	13.2	1.7	13	4.2	32	0.73-1.62	6-12
	Richmond	0.72	21.8	2.7	12	4.8	22	1.42-2.66	7-12
B03- low-rise office building with roof insulation-new building	Observatory	0.57	12.4	1.0	8	3.3	27	0.73-1.63	6-13
	Richmond	0.79	20.3	1.6	8	3.4	17	1.42-2.65	7-13
B04- high-rise office building with	Observatory	0.61	12.0	0.3	3	2.7	23	0.76-1.69	6-14
	Richmond	0.83	19.8	0.4	2	2.4	12	1.47-2.74	7-14

roof insulation-new building									
B05- low-rise shopping mall centre-existing building-new building	Observatory	0.91	52.3	1.4	3	4.2	8	3.85-9.45	7-18
	Richmond	0.92	67.0	2.2	3	5.2	8	5.38-10.37	8-15
B06- mid-rise shopping mall centre-existing building-new building	Observatory	0.93	51.3	0.7	1	3.4	7	3.83-9.42	7-18
	Richmond	0.93	65.8	1.1	2	4.1	6	5.38-10.36	8-16
B07- high-rise shopping mall centre-new building	Observatory	0.93	50.9	0.4	1	3.2	6	3.82-9.39	8-18
	Richmond	0.94	65.4	0.7	1	3.7	6	5.37-10.36	8-16
B08- low-rise apartment building-new building	Observatory	0.4	7.6	0.9	12	2.6	34	0.38-0.65	5-9
	Richmond	0.61	13.9	1.5	11	3.2	23	0.86-1.62	6-12
B09- mid-rise apartment building-new building	Observatory	0.45	7.5	0.5	7	2.3	31	0.39-0.9	5-12
	Richmond	0.64	13.6	0.9	7	2.7	20	0.88-1.66	6-12
B10- high-rise apartment building-new building	Observatory	0.45	7.3	0.3	4	2.1	29	0.39-0.91	5-12
	Richmond	0.66	13.4	0.6	4	2.4	18	0.89-1.69	7-13
B11- typical stand-alone house-existing building	Observatory	0.23	9.2	4.8	52	5.8	63	0.26-0.58	3-6
	Richmond	0.4	15.1	6.5	43	7.5	50	0.61-1.13	4-7

B12- typical school building- existing building	Observatory	0.92	14.5	0.5	3	0.8	6	1.12-2.57	8-18
	Richmond	0.91	26.4	1.0	4	1.5	6	2.08-3.86	8-15
B13- low-rise office building with roof insulation-existing building	Observatory	0.4	15.2	4.7	31	6.9	45	0.67-1.49	4-10
	Richmond	0.61	24.4	6.8	28	8.5	35	1.32-2.45	5-10
B14- high-rise office building with roof insulation-existing building	Observatory	0.56	12.5	0.9	7	3.4	27	0.74-1.65	6-13
	Richmond	0.77	20.6	1.4	7	3.5	17	1.44-2.70	7-13
B15- low-rise shopping mall centre-existing building	Observatory	0.82	54.9	6.9	13	9.8	18	3.61-8.83	7-16
	Richmond	0.82	71.6	9.5	13	12.5	17	5.13-9.83	7-14
B16- high-rise shopping mall centre-existing building	Observatory	0.9	51.5	2.1	4	4.9	10	3.74-9.16	7-18
	Richmond	0.91	66.8	3.1	5	6.1	9	5.28-10.16	8-15
B17- stand-alone house-new building	Observatory	0.31	7.5	2.7	36	3.8	51	0.28-0.64	4-9
	Richmond	0.53	12.2	3.3	27	4.2	34	0.64-1.20	5-10

The conclusions drawn from this study are:

- In low-rise buildings without roof insulation/with low level of insulation, the application of cool roofs in both individual buildings and at the whole urban area can significantly reduce the hourly cooling loads. For instance, the average median ratio of cooling load in cool roof with modified urban temperature scenario (scenario 2) to reference scenario is estimated to be 0.47 and 0.61 for a low-rise office building without roof insulation-existing building (b01) and low-rise office building with roof insulation-existing building (b13), respectively.
- In high-rise buildings with high level of insulation, the cooling load savings by modified EER is significant. For instance, the two-months cooling load savings by modified EER is estimated to range between 1.47 and 2.74 kWh/m^2 for a new high-rise office building with roof insulation-new building in Richmond 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 0.4 and 2.4 kWh/m^2, 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 0.12-0.32 and 0.12-0.3 and in Observatory and Richmond stations, respectively.
- In low-rise buildings with low level of insulation, the cooling load savings by modified EER is noticeable. For instance, the cooling load savings by modified EER is estimated to range between 1.25 and 2.32 kWh/m^2 for a new high-rise office building with roof insulation-new building in Richmond 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 13.2 and 14.9 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 5.37 and 10.36 kWh/m^2 for a new high-rise shopping mall centre in Richmond 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 0.7 and 3.7 kWh/m^2, respectively.

6. Feasibility of cool roofs: Evaluation of refurbishment of 17 buildings for Observatory Hill and Richmond 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 the yield is positive, the project is acceptable. If it is negative, the project is unable to pay for itself and is thus unacceptable.

Merits:

(a) It recognizes the time value of money.

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

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

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

Demerits:

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

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

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

2) Internal Rate of Return Method

Internal rate of return (IRR) is a percentage discount rate used in capital investment appraisals which brings the cost of a project and its future cash inflows into equality. It is the rate of return which equates the present value of anticipated net cash flows with the initial outlay. The IRR is also defined as the rate at which the net present value is zero.

The rate for computing IRR depends on bank lending rate or opportunity cost of funds to invest. The test of profitability of a project is the relationship between the IRR (96) of the project and the minimum acceptable rate of return. The IRR is to be obtained by trial-and-error to ascertain the discount rate at which the present values of total cash inflows will be equal to the present values of total cash outflows.

In appraising the investment proposals, IRR is compared with the desired rate of return or the 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, an assessment of cash flows cannot be correctly made.

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

3) Life Cycle Cost Analysis

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

In that sense, it is ideally suited to energy-saving measures, and project-related costs are classified into initial costs, fuel costs, replacement costs, operation and maintenance costs, finance charges, and residual values. Replacement costs are incurred every cycle based on the predefined age of replacement for different assets and the manufacturer’s preference. Another important element of LCCA is disposal cost. When the disposal cost is incorporated, it is possible to offset any additional cost incurred during a particular year.

All the costs involved are treated as base year values equivalent to present-day monetary amounts; LCCA transforms all dollar values into future year occurrence equivalents and then discounts all the values to their base dates. In such a way, it’s easy to find their present value.

Merits:

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

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

Demerits:

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

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

4) Depreciated Payback Period Method

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

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

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

Merits:

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

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

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

Demerits:

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

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)
  - Lifetime expectancy of the cool roofs
- On the cost of energy and economic parameters
  - Electricity retail price (Business as usual and high price scenario)
  - Increase rate of electricity price (incl. inflation)
  - Capital cost rate (incl. inflation)

An example of how these data are included in the analysis is presented in the form of **Table 24** and **Table 25**.

Table 24 Building Features

Building features	**B01 OH**	**BO1 R**
Energy consumption prior cool roof (MWh)	66,40	86
Energy consumption after cool roof (MWh)	40,10	54,00
Energy savings (MWh)	26,30	31,90
Energy savings (%)	39,61%	37,14%
Area (m2)	2.400	2.400
Roof costs - Metal roof (AU$/m2)	38,00	38,00
Roof costs - Coating (AU$/m2)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m2)	15,0	15,0

Table 25 Energy cost and economics

Energy cost and economics	
Electricity cost - Low (AU$/MWh)	150
Electricity cost - High (AU$/MWh)	290
Increase rate of electricity	0,024
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 6th month of year 0.

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

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

6.4 Selection of most suitable methods

Given the differences in the economic approach that form 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 Observatory Hills weather conditions, whilst Part 2 to Richmond. In each table, there is a set of results for the lower and one for the higher initial electricity price. Coloured cells depict the solution that achieves the best economic performance.

6.5.1 Part 1. Results for Observatory Hills weather conditions

Table 26 Net Present Value for Observatory Hills weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	12.013	27.746	105.866	103.119
2	34.491	36.749	108.004	95.786
3	-37.772	-21.285	-31.705	-16.413
4	91.843	82.808	218.884	184.832
5	-22.230	-9.557	-5.101	4.199
6	-22.612	-9.864	-5.840	3.605
7	-24.524	-11.400	-9.536	637
8	-18.816	-10.405	-14.890	-7.252
9	-18.816	-10.405	-14.890	-7.252
10	-19.198	-10.712	-15.629	-7.846
11	-5.869	-2.889	-3.015	-596
12	-29.877	-15.699	-19.885	-7.674
13	-9.861	1.130	22.256	26.923
14	-14.831	-2.861	12.647	19.206
15	41.239	41.414	117.607	102.744
16	30.916	33.124	97.648	86.715
17	-7.016	-3.810	-5.232	-2.377

Table 27 Internal Rate of Return for Observatory Hills weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	3,97%	7,37%	10,19%	16,95%
2	7,94%	13,38%	16,35%	27,35%
3	-7,77%	-8,74%	-4,62%	-4,61%
4	14,59%	24,29%	28,50%	50,14%
5	-2,12%	-1,24%	2,03%	4,55%
6	-2,24%	-1,41%	1,88%	4,34%
7	-2,87%	-2,25%	1,11%	3,24%
8	-6,77%	-7,43%	-3,48%	-3,08%
9	-6,77%	-7,43%	-3,48%	-3,08%
10	-7,21%	-8,01%	-3,99%	-3,76%
11	-3,65%	-3,30%	0,17%	1,92%
12	-4,99%	-5,10%	-1,43%	-0,29%
13	1,22%	3,39%	6,33%	10,90%
14	0,20%	1,96%	4,98%	8,86%

15	9,24%	15,43%	18,55%	31,27%
16	7,84%	13,23%	16,19%	27,07%
17	-6,02%	-6,45%	-2,62%	-1,92%

Table 28 Life Cycle Cost for Observatory Hills weather data

LCC	**Low Electricity Price**			**High Electricity Price**		
Building	**As built**	**Metal Roof**	**Coating**	**As is**	**Metal Roof**	**Coating**
1	276.984	237.029	171.305	513.937	375.616	281.713
2	798.803	737.765	580.489	1.533.569	1.385.026	1.097.541
3	146.521	170.170	127.106	272.491	287.674	221.000
4	786.185	668.036	524.538	1.509.175	1.250.216	989.369
5	771.458	768.607	606.111	1.584.350	1.542.236	1.224.355
6	1.489.503	1.473.359	1.169.397	2.869.820	2.810.617	2.238.157
7	2.202.959	2.175.140	1.730.314	4.249.170	4.167.394	3.322.596
8	96.241	107.331	81.152	180.459	186.019	144.030
9	150.534	160.590	123.720	285.426	288.987	226.329
10	231.974	240.861	187.879	442.876	444.177	350.370
11	17.624	20.872	14.880	31.898	32.019	23.779
12	308.820	322.427	249.524	587.168	585.481	459.736
13	169.845	165.137	122.977	317.583	277.945	162.542
14	674.158	664.817	522.373	1.292.589	1.243.992	985.183
15	766.105	699.887	550.943	1.471.252	1.315.237	1.042.479
16	2.184.607	2.101.697	1.671.401	4.175.045	4.025.404	3.208.699
17	13.418	17.893	12.503	23.767	26.261	19.184

Table 29 Payback Period for Observatory Hills weather data

PB	**Low Electricity Price**		**High Electricity Price**	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	17,9	11,5	6,1	8,4
2	12,2	7,5	6,5	3,8
3	-	-	-	-
4	7,3	4,3	3,7	2,1
5	-	-	22,2	14,5
6	-	-	22,5	14,7
7	-	-	24,6	16,2
8	-	-	-	-

9	-	-	-	-
10	-	-	-	-
11	-	-	27,4	18,3
12	-	-		
13	24,3	16,0	14,1	8,8
14	27,4	18,3	16,2	10,2
15	10,8	6,7	5,7	3,4
16	12,3	7,6	6,6	3,9
17	-	-	-	-

In order to comparatively illustrate the results for the 17 buildings, in the following figures are depicted the respective values for all four methods, for the two cool roof options and for both electricity price scenarios, for the Observatory Hills weather data.

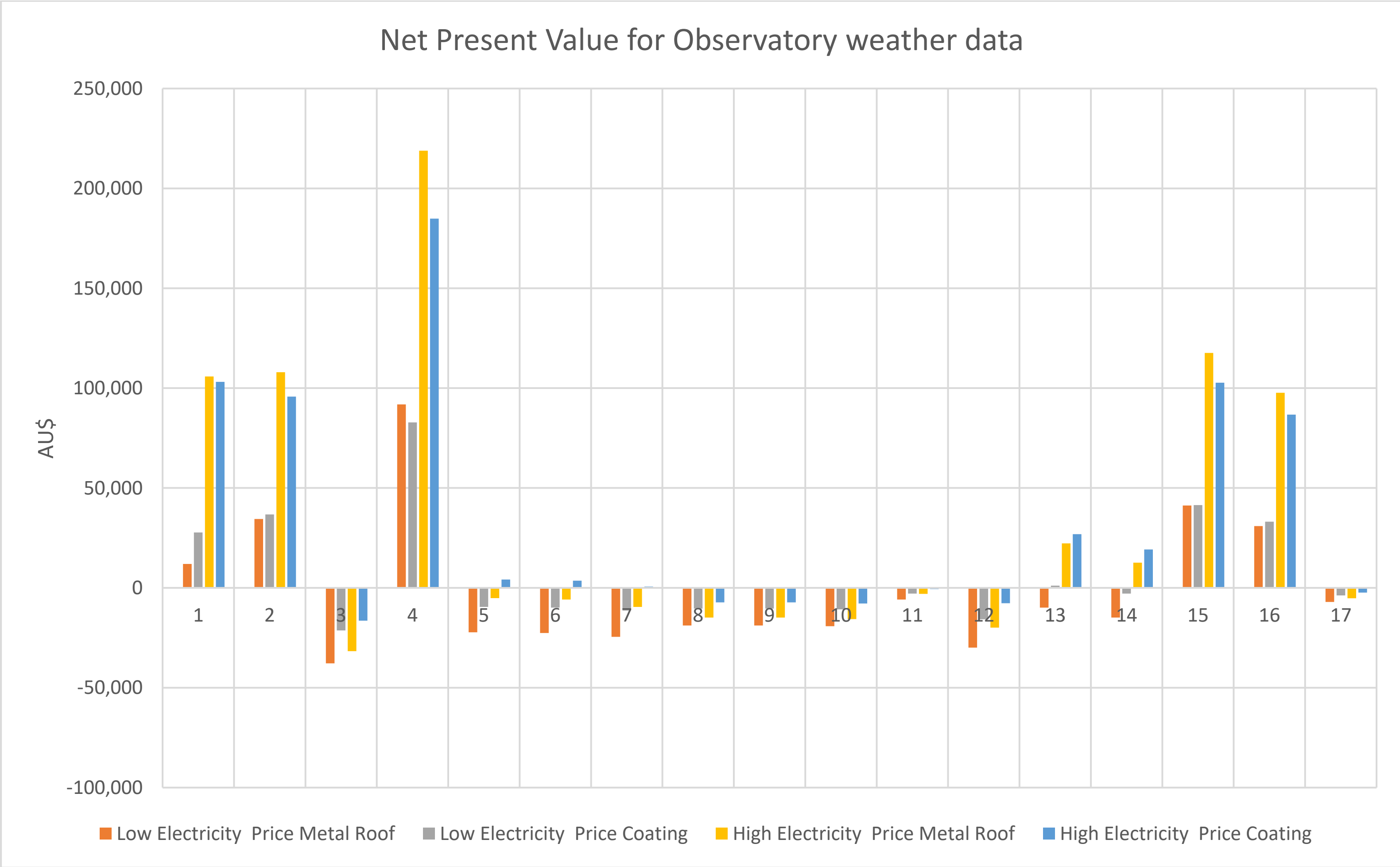

Figure 63 Net Present Value for the buildings for Observatory weather conditions

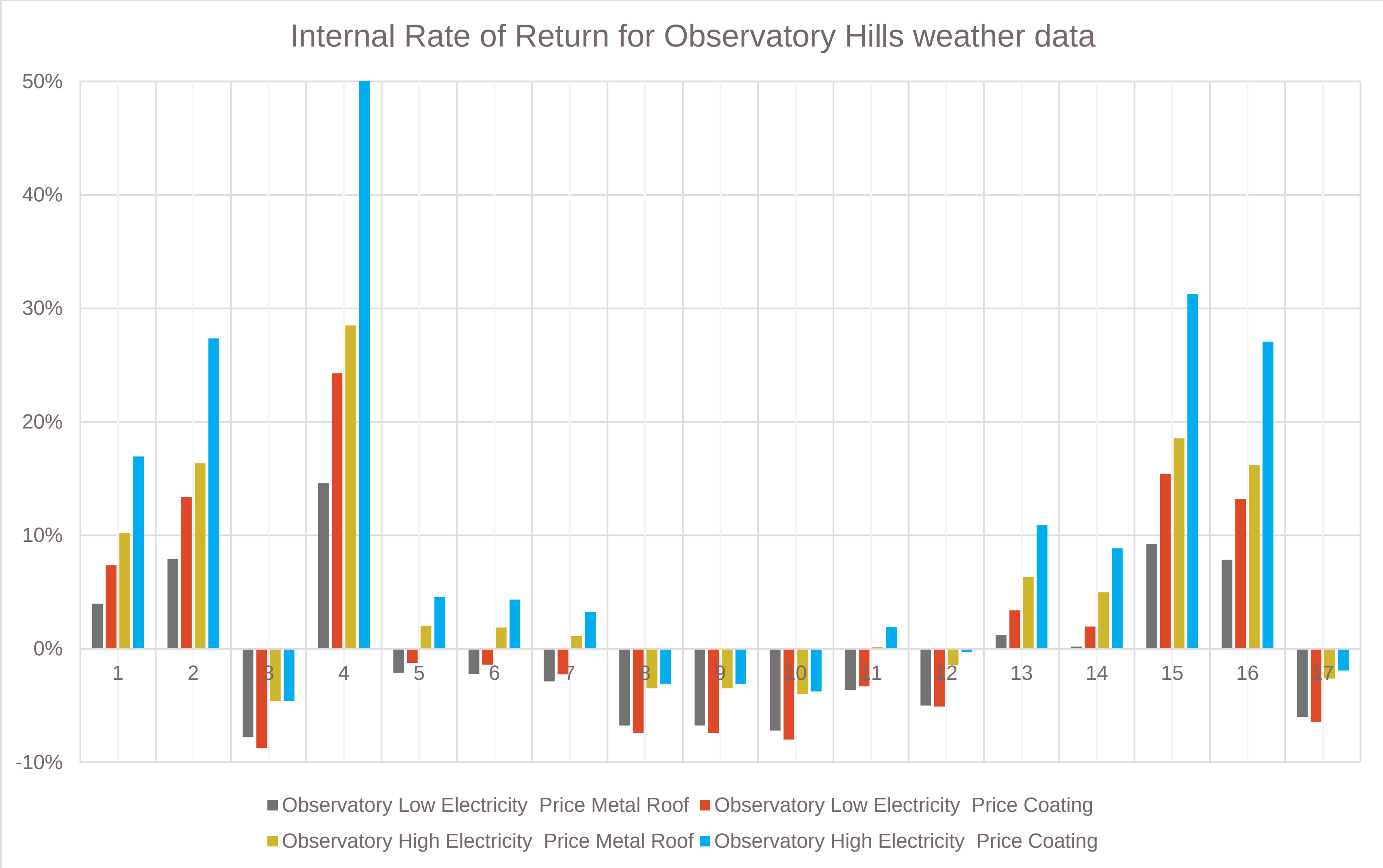

Figure 64 Internal Rate of Return for the buildings for Observatory weather conditions

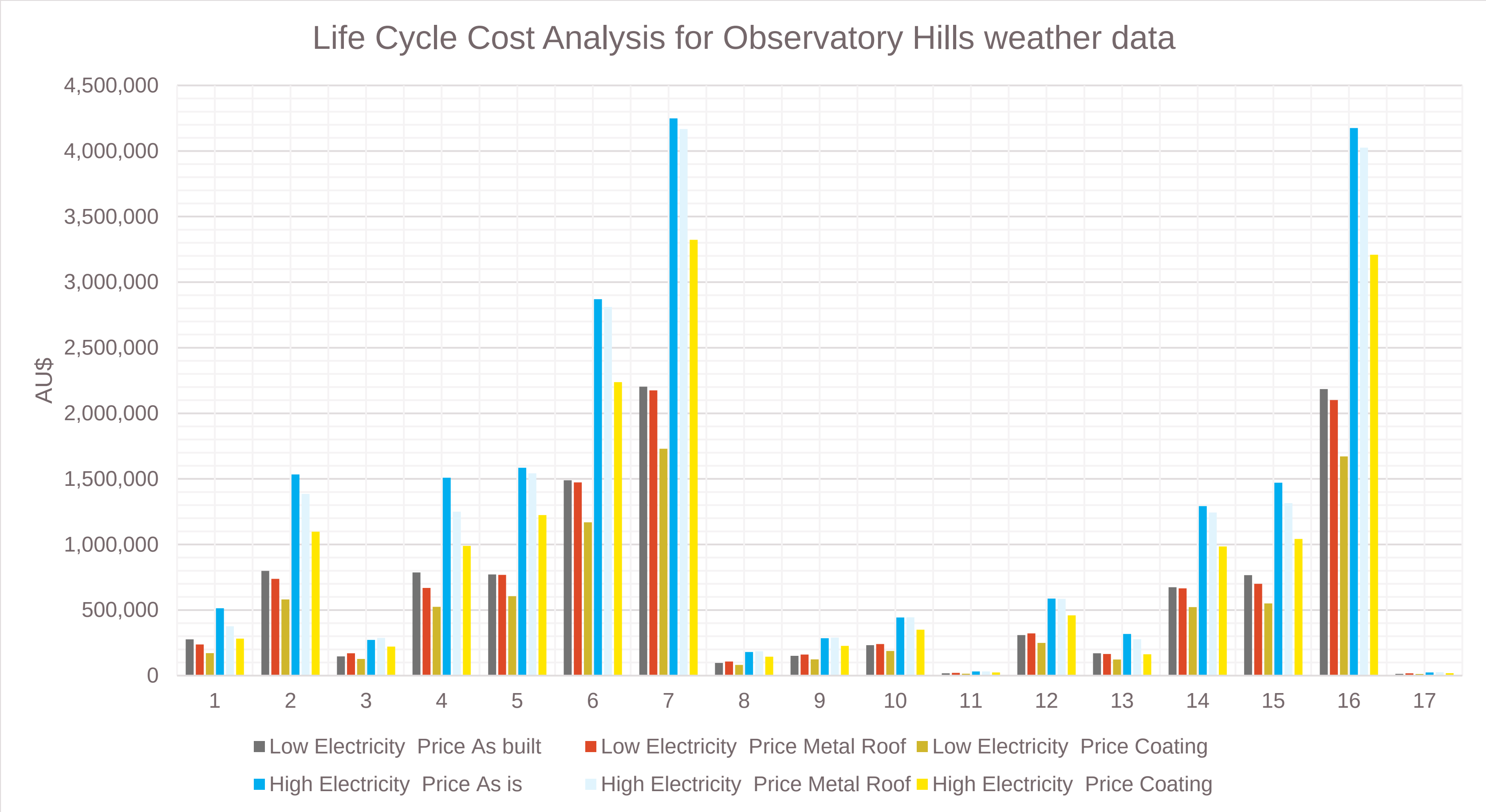

Figure 65 Life Cycle Cost for the buildings for Observatory Hills weather conditions

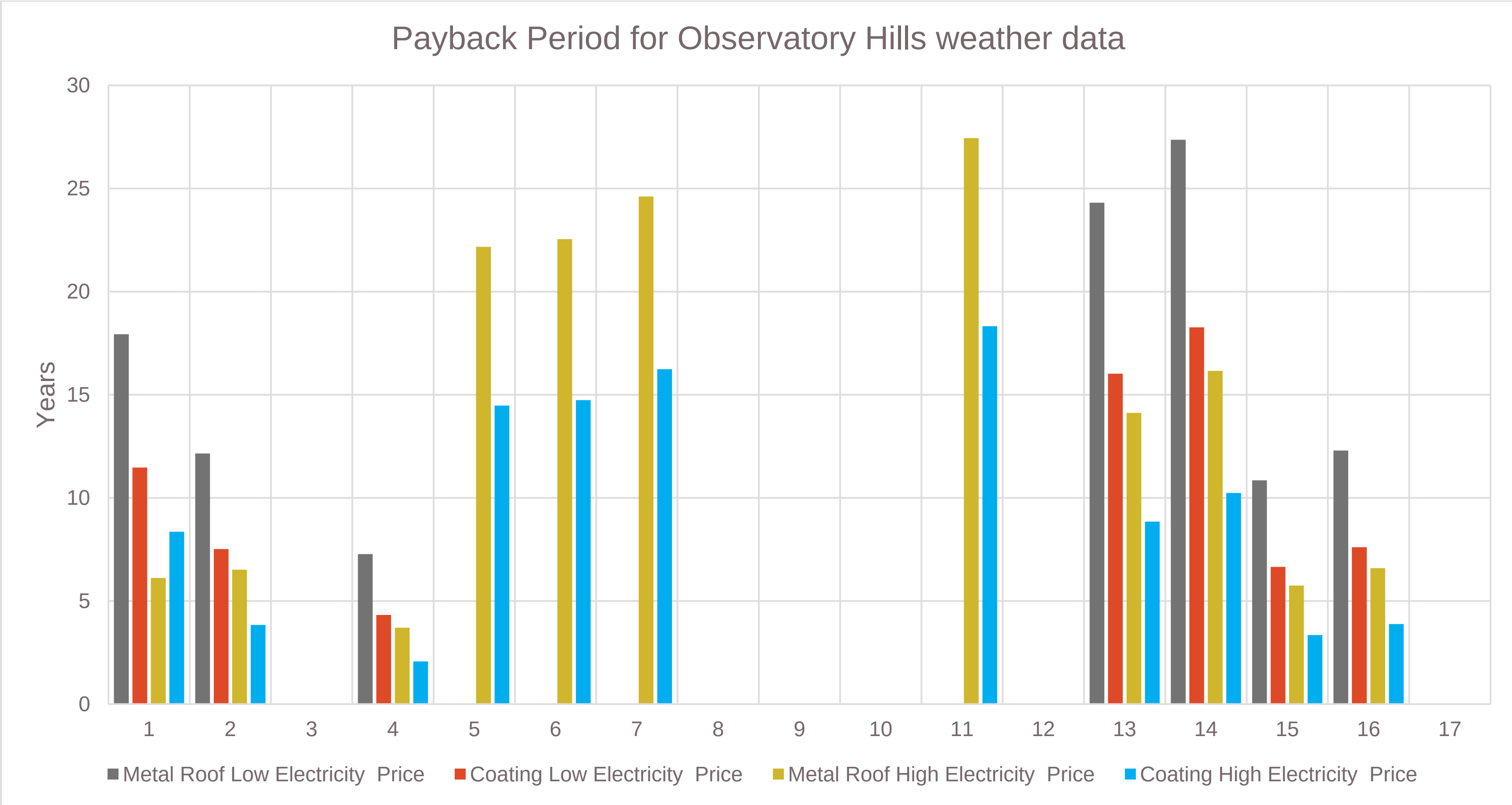

Figure 66 Payback Period for the buildings for Observatory weather conditions

6.5.2 Part 2. Results for Richmond weather conditions

Table 30 Net Present Value for Richmond weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	33.424	44.942	147.261	136.363
2	58.579	56.094	154.573	133.185
3	-34.713	-18.828	-25.792	-11.664
4	-35.096	-19.135	-26.531	-12.257
5	-18.789	-6.794	1.552	9.542
6	-19.554	-7.408	74	8.354
7	-20.318	-8.022	-1.405	7.167
8	-17.669	-9.484	-12.673	-5.472
9	-17.669	-9.484	-12.673	-5.472
10	-18.433	-10.098	-14.151	-6.659
11	-5.487	-2.582	-2.275	-2
12	-27.965	-14.163	-16.189	-4.706
13	-2.979	6.657	35.562	37.609
14	-9.478	1.437	22.995	27.517
15	46.592	45.713	127.955	111.055
16	38.181	38.958	111.693	97.995
17	-7.016	-3.810	-5.232	-2.377

Table 31 Internal Rate of Return for Richmond weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	5,56%	9,74%	12,57%	20,86%
2	10,85%	18,02%	21,39%	36,48%
3	-5,98%	-6,39%	-2,57%	-1,86%
4	-6,17%	-6,65%	-2,80%	-2,16%
5	-1,12%	0,13%	3,28%	6,36%
6	-1,33%	-0,16%	3,01%	5,97%
7	-1,55%	-0,46%	2,74%	5,57%
8	-5,62%	-5,92%	-2,16%	-1,29%
9	-5,62%	-5,92%	-2,16%	-1,29%
10	-6,36%	-6,90%	-3,01%	-2,45%
11	-3,01%	-2,45%	0,94%	3,00%
12	-4,15%	-3,98%	-0,44%	1,07%
13	2,49%	5,21%	8,07%	13,59%
14	1,29%	3,50%	6,43%	11,06%

15	9,94%	16,55%	19,77%	33,48%
16	8,83%	14,78%	17,85%	30,01%
17	-6,02%	-6,45%	-2,62%	-1,92%

Table 32 Life Cycle Cost for Richmond weather data

LCC	Low Electricity Price			High Electricity Price		
Building	As built	Metal Roof	Coating	As is	Metal Roof	Coating
1	276.984	237.029	171.305	658.081	475.620	361.485
2	798.803	737.765	580.489	2.076.881	1.871.422	1.486.123
3	194.697	214.369	162.421	365.631	373.126	289.276
4	868.772	875.989	691.233	1.668.842	1.652.258	1.311.645
5	824.604	817.300	645.016	1.584.350	1.542.236	1.224.355
6	1.581.266	1.560.316	1.238.887	3.047.229	2.978.733	2.372.504
7	2.335.251	2.300.706	1.830.658	4.504.933	4.410.155	3.516.596
8	149.005	157.942	121.600	282.469	283.869	222.229
9	235.033	242.332	189.049	448.789	447.021	352.632
10	364.648	370.243	291.287	699.378	694.317	550.292
11	23.359	26.116	19.069	42.986	42.157	31.878
12	439.582	448.787	350.512	839.974	749.541	654.979
13	221.843	209.264	158.219	418.114	363.256	281.153
14	890.566	871.750	687.747	1.710.977	1.644.063	1.304.906
15	834.545	761.670	600.304	1.603.569	1.434.686	1.137.911
16	2.334.104	2.241.082	1.782.779	2.334.104	2.239.682	1.781.379
17	18.771	23.144	16.700	34.116	36.412	27.298

Table 33 Payback Period for Richmond weather data

PB	Low Electricity Price		High Electricity Price	
Building	Metal Roof	Coating	Metal Roof	Coating
1	17,9	11,5	8,4	5,0
2	9,5	5,8	5,0	2,9
3	-	-	-	-
4	7,3	4,3	-	-
5	-	21,7	19,3	12,4
6	-	-	19,9	12,8
7	-	-	20,5	13,3
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-

11	-	-	25,1	16,6
12	-	-	-	19,8
13	21,1	13,7	12,0	7,4
14	24,1	15,9	14,0	8,8
15	10,2	6,2	5,4	3,1
16	11,2	6,9	6,0	3,5
17	-	-	-	-

In order to comparatively illustrate the results for the 17 buildings, in the following figures are depicted the respective values for all four methods, for the two cool roof options and for both electricity price scenarios, for the Richmond weather data.

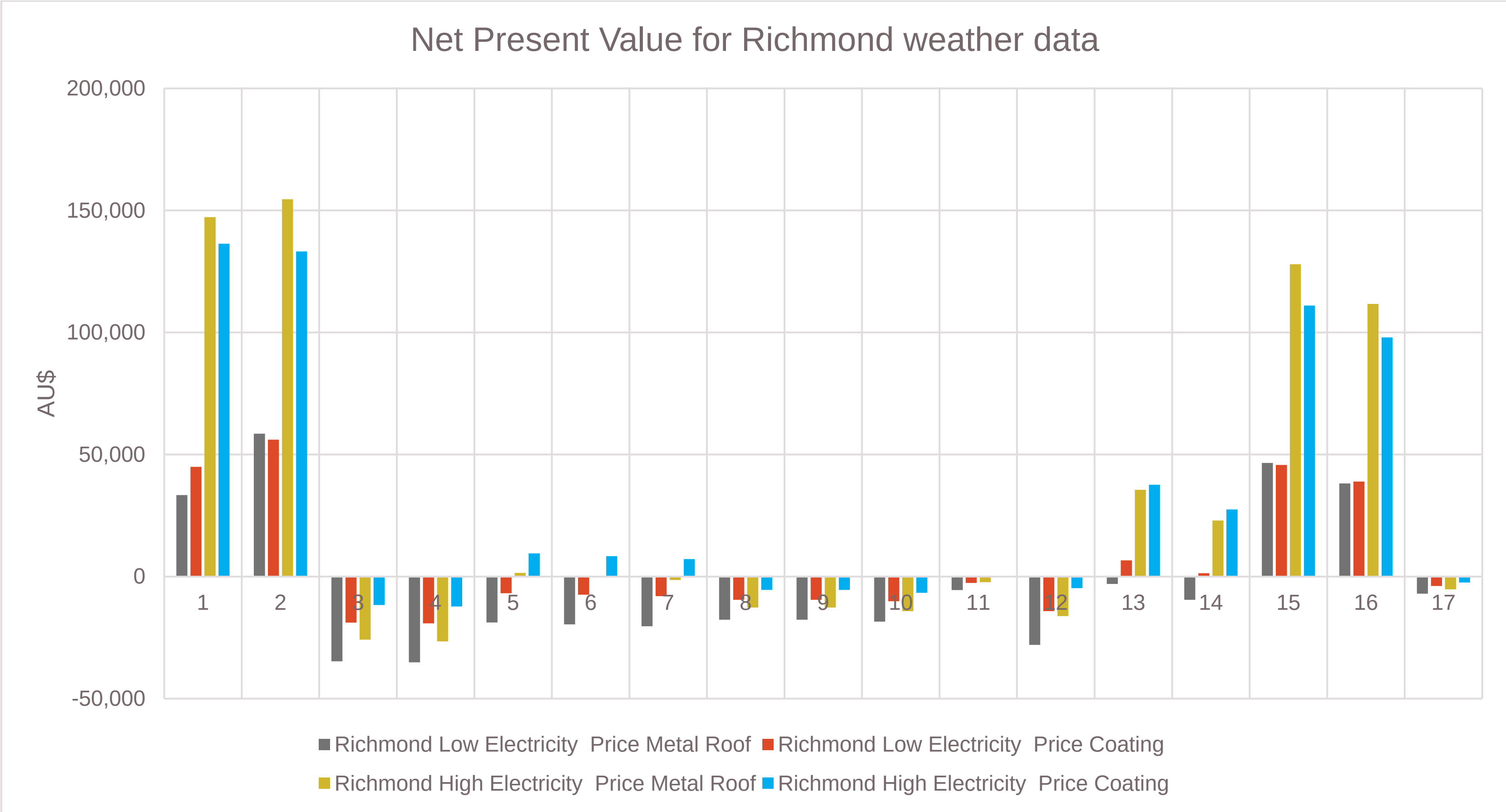

Figure 67 Net Present Value for the buildings for Richmond weather conditions

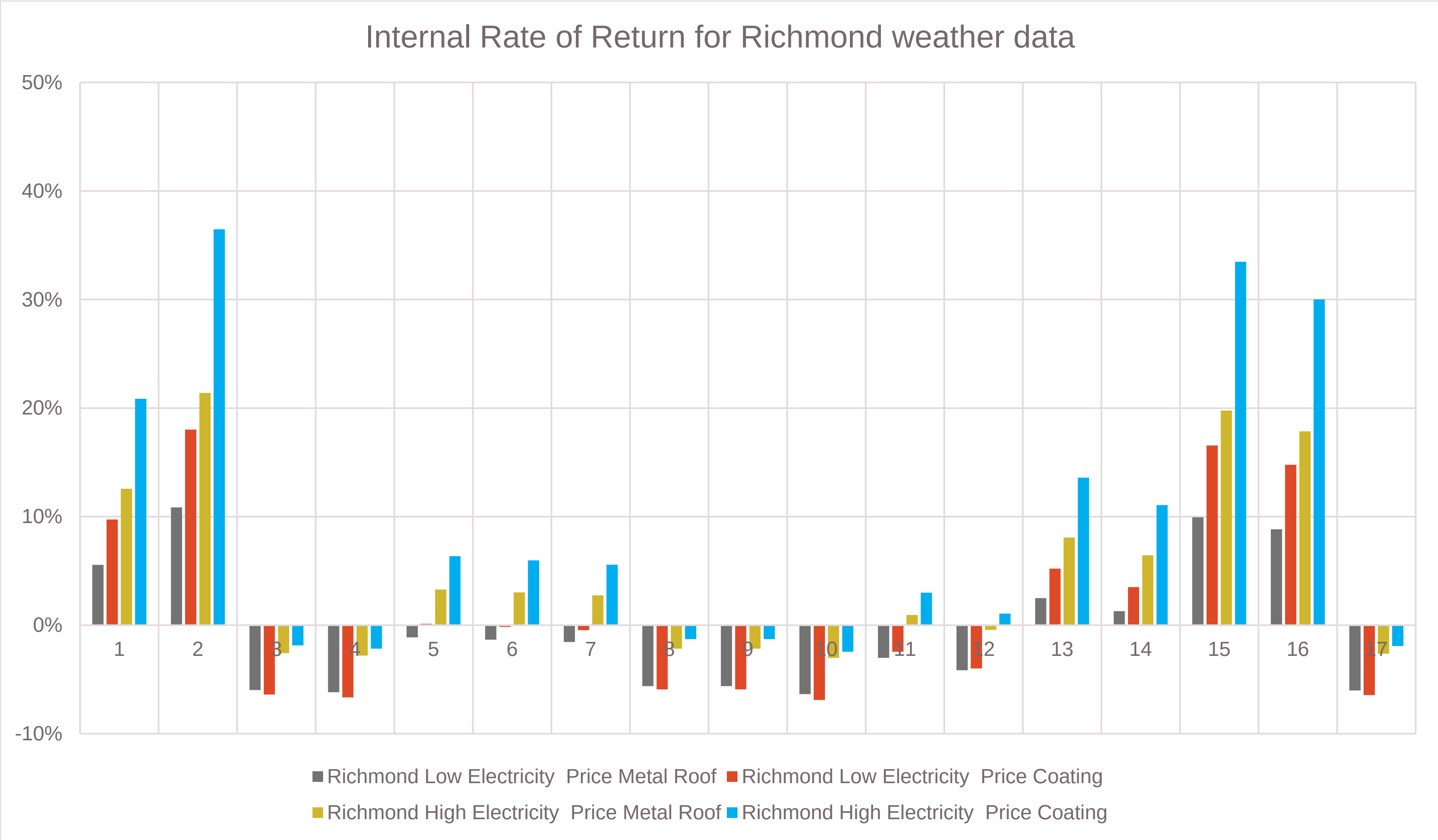

Figure 68 Internal Rate of Return for the buildings for Richmond weather conditions

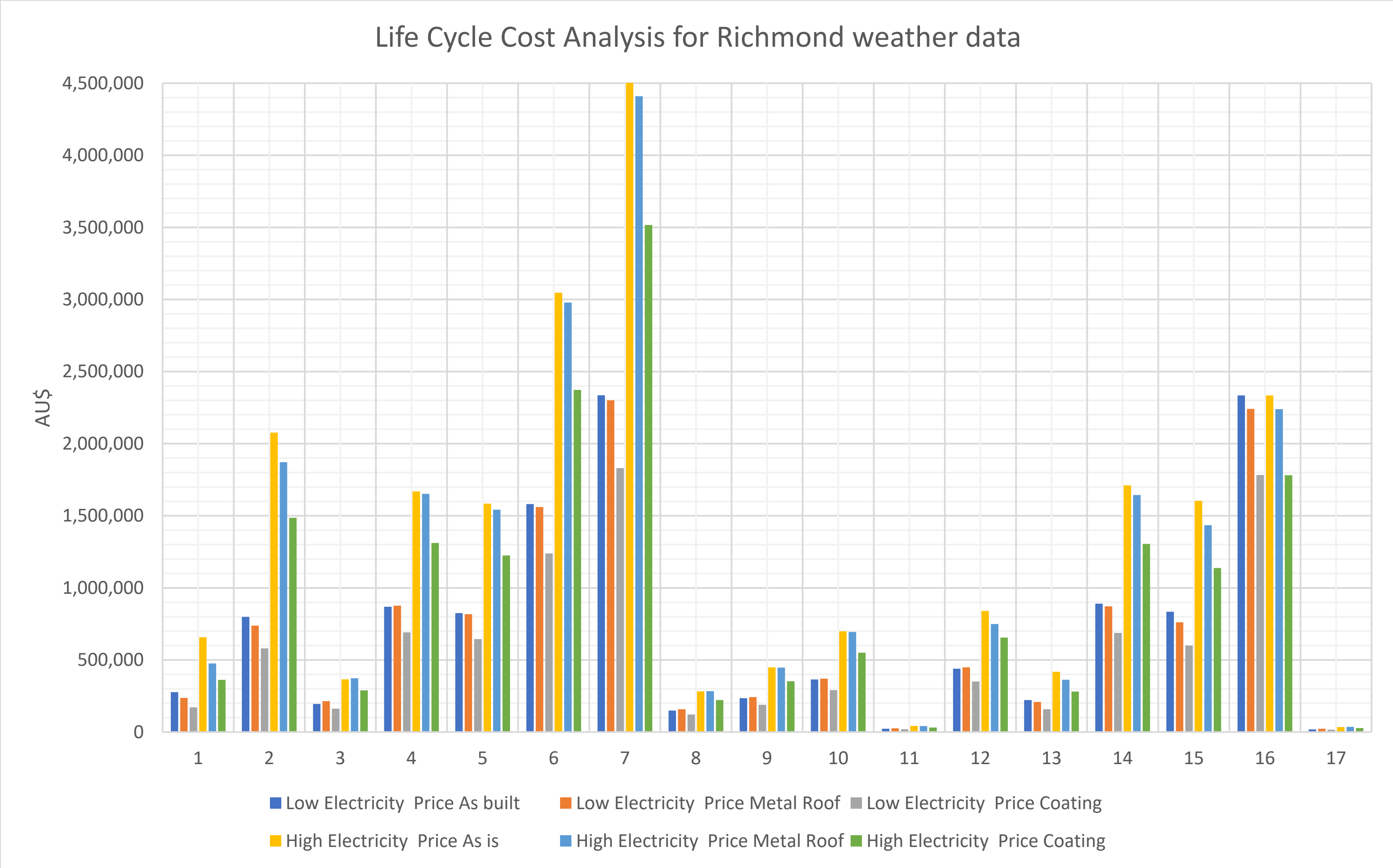

Figure 69 Life Cycle Cost for the buildings for Richmond weather conditions

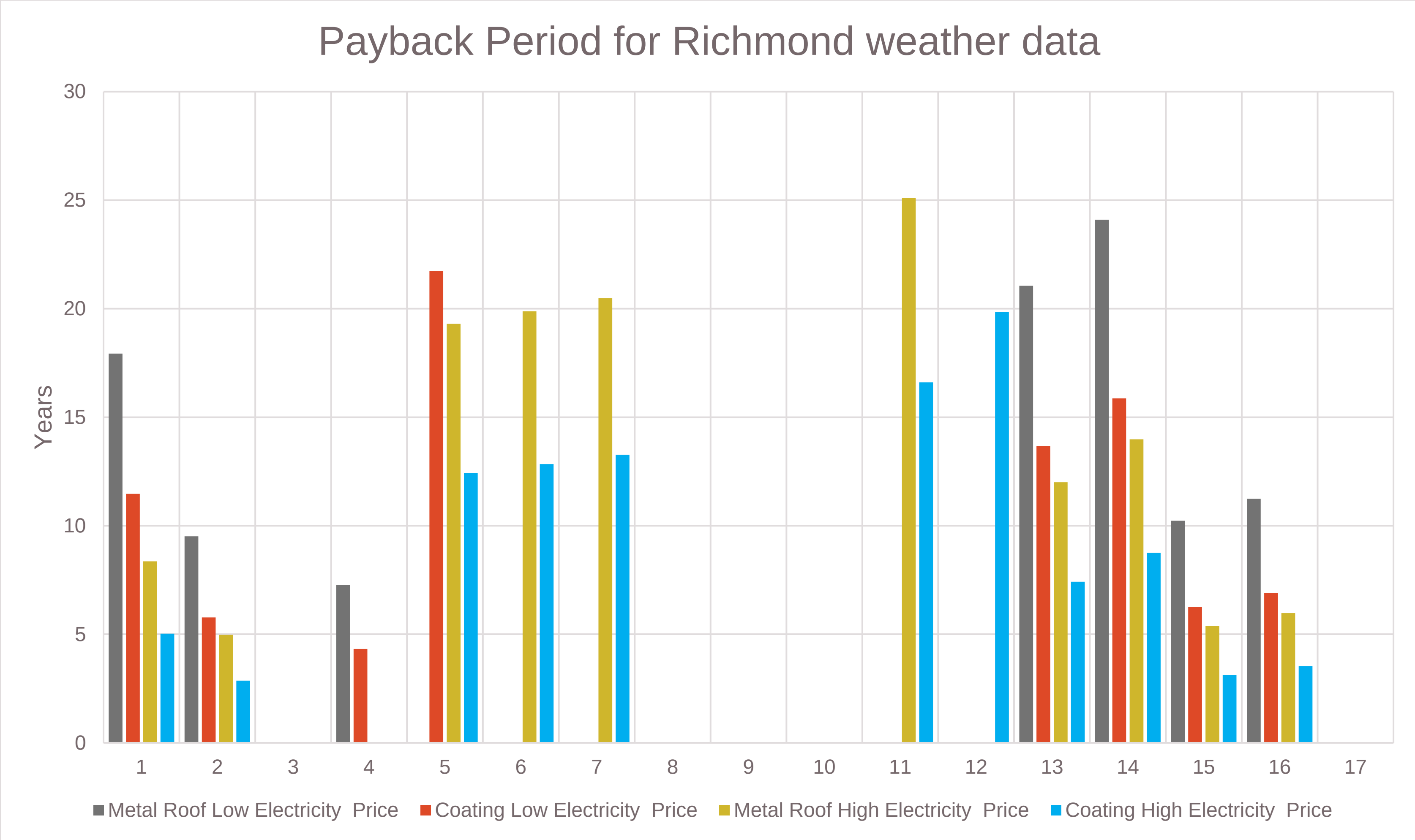

Figure 70 Payback Period for the buildings for Richmond weather conditions

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 'thriftiest' and most cost-effective choice. This is due to the fact that it features a significantly lower initial investment cost compared to the cool metal roof, yet achieves similar energy 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.

Figure 71 and **Figure 72** are presented the reductions in the Life Cycle Cost for both electricity price scenarios, for Observatory Hill and for Richmond weather conditions, respectively.

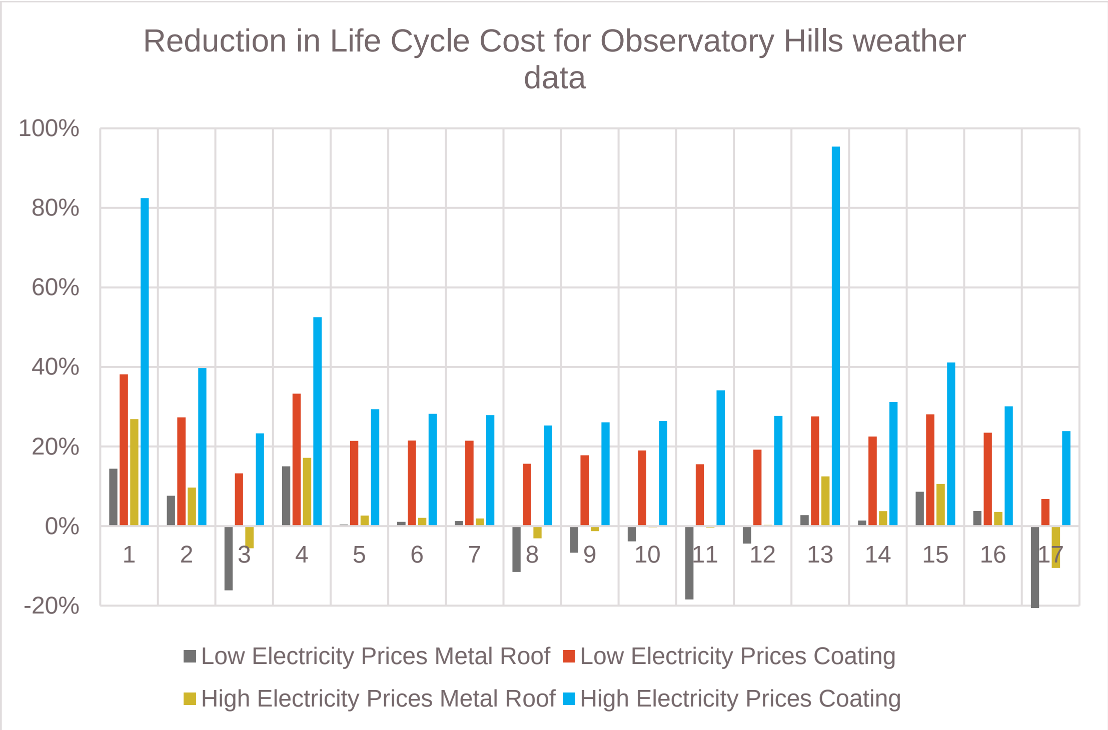

Figure 71 Reduction in LCC for Observatory Hills weather conditions

As it can be seen from the data depicted, the Cool Coating solution offers in all cases reductions in the Life Cycle Cost that reach for the Observatory Hills weather conditions and for low electricity prices from 6,8% to 38,2%. In the case of high electricity prices, the reductions are more significant, varying from 23,9% to 82,4%. In such favourable cases, the Payback Period can be as low as 2.1 years.

Considering the Metal Cool roofs, there are 7 cases for the low energy price scenario and 6 for the high energy prices, where the refurbishment proves to be not feasible.

The results are similar for Richmond weather conditions, although due to the reduced energy requirements, the reductions in LCC are in most of cases smaller. There are exceptions due to the architectural and typological differences of the buildings.

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.

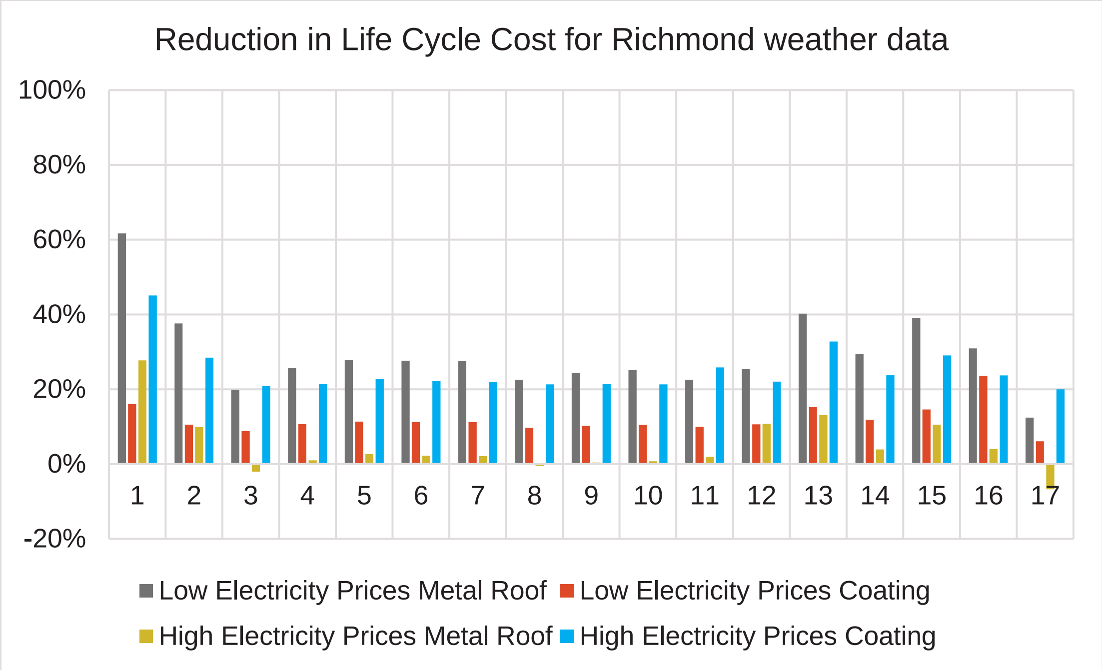

Figure 72 Reduction in LCC for Richmond weather conditions

With respect to a comparative assessment of the 17 buildings considered, one can deduce some conclusions with a generic validity:

The feasibility of roof refurbishment in low-rise buildings is much more apparent than in high-rise ones due to the much higher participation of the roof in the overall exposed surface of the building.

In exactly the same way, roofs without thermal insulation, and consequently with high energy requirements, present bigger energy savings potential.

In the case of uninsulated, low-rise roofs the impact of cool roofs is maximized.

The impact of weather conditions is important, since the feasibility is directly linked to energy requirements for each specific building

Finally, the impact of electricity prices is paramount, and it gets more important the higher the energy requirements are: 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 of both types examined.

This last point should act as a reminder, of how expensive being long-sighted can be. The dramatic increase in electricity prices in 2021, and the prevailing volatility in the energy markets, can only underline that cost-effective 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 Sydney, Australia. Specifically, it has

1) Evaluated the existing climatic conditions (reference case) in the city of Sydney.
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 Sydney.
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 Sydney.
5) Compared the energy loss through building envelopes in various building types and the advantages of applying cool roofs in various stations.
6) Investigated the impact of cool roofs on EER of AC systems and the corresponding cooling load savings.
7) Evaluated the feasibility of cool roofs by assessing the refurbishment of 17 buildings for Observatory Hill and Richmond weather conditions.

Specifically, the following conclusions have been drawn:

1) It is found that both strong urban heat island (UHI) phenomena are developed. The average maximum magnitude of the phenomena may exceed 6°C. The intensity and the characteristics of the phenomena are strongly influenced by the synoptic weather conditions and, in particular, the development of the sea breeze and the westerly winds from the desert area. The possible existence of an additional heating mechanism, like the advection of warm air from nearby spaces, may intensify the strength of the problem.
2) An increase of albedo in Sydney can decrease the peak summer ambient temperature up to 2.4°C and surface temperature up to 11.6°C. It was found that important temperature differences exist between the eastern and western parts 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 strength of the advection flows.
3) The maximum decrease of sensible heat and latent heat flux was 279.8 W/m^2 and 16.1 W/m^2, respectively.
4) The maximum decrease of wind speeds is up to 3.9 m/s. Thus, higher urban albedo values decrease the advective flow between the city and its surroundings, improving the cooling potential of reflective materials. Modification of the urban albedo in Sydney results in a serious average 1607.8m reduction up to of the PBL heights over the city and may increase the concentration of pollutants at ground level.
5) High intensities of the UHI phenomenon were associated with the existence of a sea breeze in the eastern parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that heat the western zones of the city.
6) In average, compared to the reference scenario, temperature with the peak distribution in the cool roof scenario is around 1 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Penrith station is an exception with the same peak in cool roof and reference scenario. Around 30%-50% of the ambient temperatures in all stations concentrate in the range of 19-22 °C.
7) In reference cases, CDH ranges from 1095.7 to 3997.7, and the frequency distribution of CDH values is close to uniform. CDH gradually increases from the southeast of the city to the northwest.

8) When applied with a cool roof, the decrease of CDH is observed at every station. CDH still increases from southeast to northwest.
9) 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.
10) The percentage of CDH reduction due to the implementation of the cool roof ranges from 18% to 39%, with an average value of 24.7%. The percentage is small in the hotter regions.
11) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 10.2-13.8 kWh/m^2.
12) 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 14.9-17.4 kWh/m^2.
13) 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 4.8-8.1 kWh/m^2 in a typical new low-rise office building.
14) In new high-rise buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be 1.1-1.7 kWh/m^2 and 0.2-0.3 kWh/m^2 for new low-rise and high-rise office buildings with insulation, respectively.
15) 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 0.5-0.7 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 4-7.1 kWh/m^2 (29.3-48.3%) when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
16) 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 16.6-28 kWh/m^2, while the corresponding heating penalty is just 1.1-2.5 kWh/m^2.
17) 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 indoor air temperature of a low-rise office building without roof insulation by 10.1-11.4 ^oC.
18) 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 indoor air temperature of a low-rise office building without roof insulation by 11.2-12.0 ^oC.
19) 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 553-550 hours to 424-433 hours and 359-390 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.

20) 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 2.1-2.5 ºC in a typical new low-rise office building.
21) 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 630-658 hours to 595-613 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
22) 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 10.1-11.4 ºC in a typical summer week, while the average maximum indoor air temperature reduction of the same building is expected to be just 2.6-2.7 ºC during a typical winter month.
23) The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ºC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 2.2 ºC occurs when the indoor air temperature is 25.3 ºC.
24) 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 74-95 hours to 89-114 hours in a typical existing low-rise office building with roof insulation.
25) Regarding the sensible cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.
26) Cooling load reduction in scenario 1 compared with the reference scenario mostly 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.
27) For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present a decreasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for all buildings.
28) A general ranking of the heat loss coefficients of these buildings from low to high is shopping mall centre, standalone house, apartment, and office.
29) 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 0.47 and 0.61 for a low-rise office building without roof insulation-existing building (b01) and low-rise office building with roof insulation-existing building (b13), respectively.

30) 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 1.47 and 2.74 kWh/m^2 for a new high-rise office building with roof insulation-new building in Richmond 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 0.4 and 2.4 kWh/m^2, respectively.
31) 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 0.12-0.32 and 0.12-0.3 and in Observatory and Richmond stations, respectively.
32) 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 1.25 and 2.32 kWh/m^2 for a new high-rise office building with roof insulation-new building in Richmond 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 13.2 and 14.9 kWh/m^2, respectively.
33) In commercial buildings, the cooling load savings by modified EER is quite significant. For instance, the cooling load savings by modified EER is estimated to range between 5.37 and 10.36 kWh/m^2 for a new high-rise shopping mall centre in Richmond 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 0.7 and 3.7 kWh/m^2, respectively.
34) 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.
35) The feasibility of roof refurbishment in low-rise buildings is much more apparent than in high-rise ones, due to the much higher participation of the roof in the overall exposed surface of the building.
36) In exactly the same way, roofs without thermal insulation, and consequently with high energy requirements, present bigger energy savings potential.
37) In the case of uninsulated, low-rise roofs the impact of cool roofs is maximized.
38) The impact of weather conditions is important since the feasibility is directly linked to energy requirements for each specific building.
39) Finally, the impact of electricity prices is paramount, and it gets more important the higher the energy requirements are: 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 of both types examined.

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9. Appendix: Meso-scale simulation results

Table 34 Reduction of ambient temperature: cool roof minus reference scenario

Parameters	**Ambient Temperature at 2m (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-2.2	-2.4	-1.9	-1.9
Minimum	-0.2	-0.1	-0.2	-0.1
Average of January	-0.4	-0.8	-0.7	-0.5
Average of February	-0.3	-0.9	-0.5	-0.8

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

Parameters	**Surface Temperature (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-7.3	-11.6	-3.6	-3.7
Minimum	-0.3	-0.5	-0.1	-0.4
Average of January	-1.4	-6.2	-2.5	-2.8
Average of February	-0.5	-5.9	-2.1	-2.6

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

Parameters	**Sensible Heat Flux (W/m^2)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-29.4	-279.8	-115.0	-106.7
Minimum	3.8	-64.7	-23.2	-29.4
Average of January	-12.1	-198.6	-65.2	-75.6
Average of February	-3.9	-185.3	-54.9	-67.0

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

Parameters	**Latent Heat Flux (W/m^2)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-4.5	-16.1	-5.1	-7.3
Minimum	1.3	-1.6	-1.4	-1.1
Average of January	-2.54	-10.52	-2.25	-5.10
Average of February	-1.22	-8.79	-2.34	-4.12

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

Parameters	**Wind Speed (m/s)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-3.9	-3.1	-2.1	-2.5
Minimum	0.9	1.0	1.7	0.1
Average of January	-0.3	-0.3	-0.2	-0.2
Average of February	-0.2	-0.4	-0.3	-0.4

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

Parameters	**PBL Height (m)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-133.7	-1607.8	-965.5	-405.6
Minimum	52.4	21.7	-10.5	-10.4
Average of January	-34.6	-223.7	-122.7	-99.9
Average of February	-16.8	-287.1	-108.4	-96.8

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

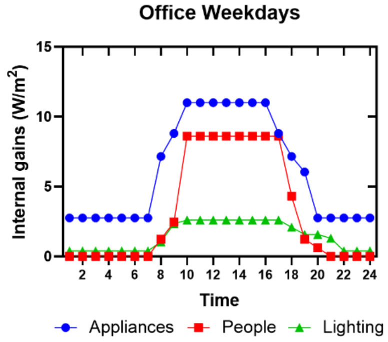
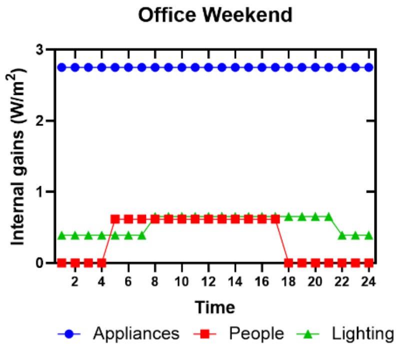
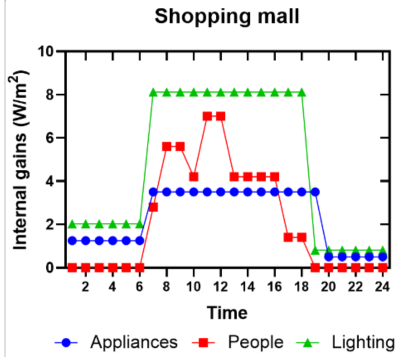
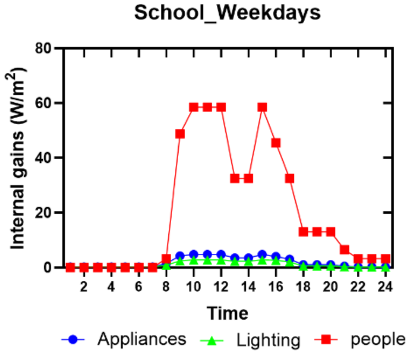
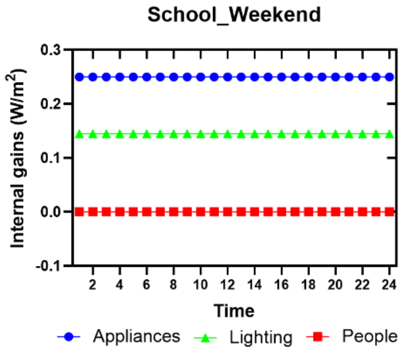
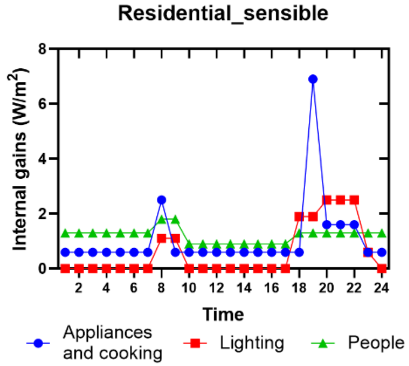
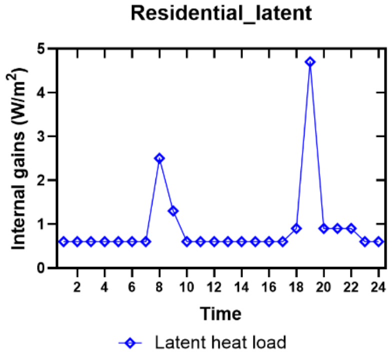
The following **Table 40** to **Table 43** have presented the general building parameters, internal gains, and ventilation; operation schedules; ventilation, HVAC, and setpoints parameters and building envelope parameters employed in the simulations in **Chapter 3**.

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 (m2)		1200			1100		1100	242		624
Aspect ratio		1:1			2:1		2:1	1:2		1:4.3
Window to Wall Ratio (WWR)		0.6			0.3		0.32	0.14	0.15	0.24
Year Built		1990		2018	1990	2018	1990	1990	2018	1990
Number of stories *Low rise (L), mid-rise (M), high-rise (H)*		2 (L)			2 (L)	2 (L)	3	1		3 (L)
		-			4 (M)	-				5 (M)
		10 (H)			6 (H)	4 (H)				8 (H)
Building height (m) *Low rise (L), mid-rise (M), high-rise (H)*		7.2 (L)			13.8 (L)	13.8 (L)	12.6	2.8		8.4 (L)
					27.6 (M)					14 (M)
		36 (H)			41.4 (H)	41.4 (H)				22.4 (H)
Lighting power density (W/m^2) **(before operation profile and radiant fraction)**		4.5			14		4.5	4.5		
Lighting internal gains (W/m^2) ***(radiant fraction 0.42)***	Hourly Max	2.61			8.12		2.76	2.5		
	Hourly Mean	1.45			4.77		1.13	0.6		
	Hourly Min	0.39			0.81		0.15	0		
Equipment gains ***(before operation profile)***		11			5		5	6.88		
Equipment internal gains (W/m^2)	Hourly Max	11			3.5		4.75	6.88		
	Hourly Mean	6.16			2.31		1.86	1.1		
	Hourly Min	2.75			0.5		0.25	0.6		
Occupancy density (person/m2)		0.1			0.2		0.5	0.02	0.025	0.04

Continues

Table 41 Operation schedules

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

continues

Table 42 Ventilation, HVAC, and setpoints parameters

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

Continues

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

Table 43 Building envelope parameters

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

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