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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 4 – Melbourne: 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 Melbourne, Australia. Specifically, the purposes of this report are:

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

The whole study involved the following phases:

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

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

Phase 3: Climatic parameters analysis. In this phase, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 16 weather stations in Melbourne 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 16 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 Melbourne. 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 Melbourne during a typical summer and winter period.

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

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

Collectively, the following conclusions have been drawn:

1) An increase of albedo fraction in Melbourne city can decrease the peak ambient temperature up to 2.1°C and surface temperature up to 11.1°C.
2) The maximum decrease of sensible heat and latent heat flux was 292.8 Wm^{-2} and 15.1 Wm^{-2}, respectively.
3) The highest decrease of wind speeds up to 3.4 ms-1. Thus, higher urban albedo values decrease the advective flow between the city and its surroundings surface improving the cooling potential of reflective materials. Modification of the urban albedo in Melbourne results in an average 1590.6m reduction up to of the PBL heights over the city. It may increase the concentration of pollutants at ground level and subsequently increase health problems.
4) In average, compared to the reference scenario, temperature with the peak distribution in the cool roof scenario is mostly around 1-7 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Around 51%-75% of the ambient temperatures in all stations concentrate in the range of 10-19 °C.

5) Cooling degree hours, indicating the climatic severity during the summer period, ranging from 185.8 to 1328.5, under the existing conditions, increasing from the southeast of the city to the northwest.
6) When cool roofs are used in the city, CDH ranges from 114.9 to 1059.8. The percentage of CDH reduction due to the implementation of the cool roof ranges from 20.2 % to 42.24 %.
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 6.3-10 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 8.3-11.7 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 2.4-3.3 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 0.6-0.9 kWh/m^2 and 0.1-0.2 kWh/m^2 for new low-rise and high-rise office buildings with insulation, respectively.
11) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.2-0.4 kWh/m^2 in a new high-rise apartment building, which is expected to increase to 1.0-1.4 kWh/m^2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
12) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in all types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 8.8-14.4 kWh/m^2, while the corresponding heating penalty is just 3.3-7.5 kWh/m^2.
13) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum and average indoor air temperature of a low-rise office building without roof insulation by 8.1-10.0 ^{o}C and 3.0-4.5 ^{o}C, respectively.
14) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum and average indoor air temperature of a low-rise office building without roof insulation by 9.0-10.4 ^{o}C and 4.2-5.2 ^{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 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 334-395 hours to 193-253 hours and 152-197 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.

16) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum and average indoor air temperature reduction by application of cool roofs in both individual building and at the whole urban area (scenario 2) in a typical new low-rise office building is predicted to be 2.1-2.2 ^{o}C and 1.5-1.7 ^{o}C, respectively.

17) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the number of hours with an indoor air temperature above 26 ^{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 345-399 hours to 250-305 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).

18) The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by application cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 8.1-10.0 ^{o}C in a typical summer week, while the average maximum indoor air temperature reduction of the same building is expected to be just 1.7-1.9 ^{o}C during a typical winter month. The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ^{o}C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.8 ^{o}C occurs when the indoor air temperature is 22.8 ^{o}C.

19) 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 179-200 hours to 200-229 hours in a typical existing low-rise office building with roof insulation.

20) For all 17 buildings, the solution of the coating for the cool roof presents the least Life Cycle Cost and is, in that sense, the most ‘thrifty’ choice. This is due to the fact that it features a significantly lower initial investment cost compared to cool metal roof, yet achieves comparatively similar savings. This applies both for the low and the high electricity price scenario, albeit as expected for the high electricity price scenario, the results are much more positive.

21) With respect to the 17 buildings considered, it does not come as a surprise that low-rise buildings without thermal insulation of the roof and with high energy requirements are presenting the biggest energy savings potential and consequently the most attractive economic results. For such buildings (like, for example, B01 and B15), the Life Cycle Cost can be reduced by as much as 45%. In such favourable cases, the Payback Period can be as low as 4.2 years.

22) even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B03 and B17) and for lower electricity prices, the Life Cycle Cost of the coating cool roof can be reduced compared to

the “Do nothing” conventional roof, which is more than enough to justify the cool coating’s application, despite comparatively longer Payback Periods.

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

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

Methodology

The whole study involved the following phases:

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

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

Phase 3: Climatic parameters analysis. In this phase, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 16 weather stations in Melbourne 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 16 weather stations, has been calculated. The frequency and spatial distribution of the calculated CDH are analysed as well.

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

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

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

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

1.1 Introduction

Heatwave events exacerbate extreme urban heat, and the frequency and intensity of heatwaves are escalating in southeast Australia. Localized synergies between heatwaves and extreme urban heat are imperative. 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). The extreme urban heat is driving a doubling in consumption of electricity for cooling and a three-fold increase in heat-related deaths. 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 Melbourne, Australia. The magnitude and the characteristics of the extreme urban heat have been assessed in the city of Melbourne through mesoscale simulations. The purpose of this report is:

- To evaluate the existing climatic conditions (base case) in the city of Melbourne.
- To evaluate the cooling potential of cool roof technology when they are implemented in the city of Melbourne.
- 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 Melbourne 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 Melbourne 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)		

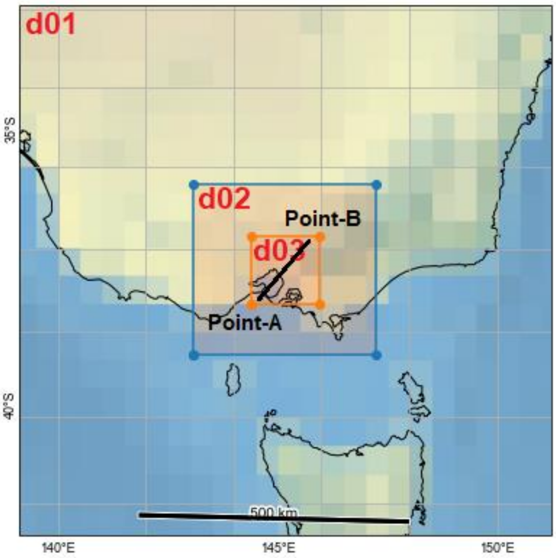


Figure 1 WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500m grid spacing, domain 2 (d02) with 1500m grid spacing and, an innermost domain 3 (d03) with 500m grid spacing; (b) innermost d03 with 500m grid spacing which encompasses the Greater Melbourne.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

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

1.4 Model evaluation

To evaluate the performance of the WRF-SLUCM system, we compared hourly simulated 2-m ambient air temperature against local measurements for the control case simulation over urban grid cells in the innermost domain. A statistical comparison of the mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r), and the index of agreement (IOA) for hourly 2m air temperature for the 24-hour duration are listed in **Table 3** and **Figure 2**. The model evaluation is based on the correlation between the WRF model and observations for 2m-temperature across the diurnal cycle. The coupled WRF-SLUCM model accurately captures the temperature observed at different stations (mean R=0.982; mean bias=0.569) for Avalon, Laverton, Moorabbin Airport, and Cerberus. The base case simulation produced urban meteorological conditions well and statistically, agreed with local observation ($p<0.05$). The simulated average UHI intensity varied from 2.8°C to 5.7C 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 MAS of air temperature was 0.362°C to 0.625°C and 0.465°C to 0.596°C, respectively. The range of IOA was 0.905 to 0.985, with average values of 0.961 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 >22.1°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 strategy.

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

Parameters	**Local weather stations**			
	Avalon	Laverton	Moorabbin Airport	Cerberus
Correlation coefficient	0.985	0.975	0.978	0.976
Mean Bias error	0.362	0.625	0.524	0.576
Mean absolute error	0.596	0.562	0.465	0.534
Root mean square error	1.002	1.024	1.023	1.036
Index of Agreement	0.953	0.966	0.905	0.985
Correlation coefficient	0.901	0.924	0.880	0.905

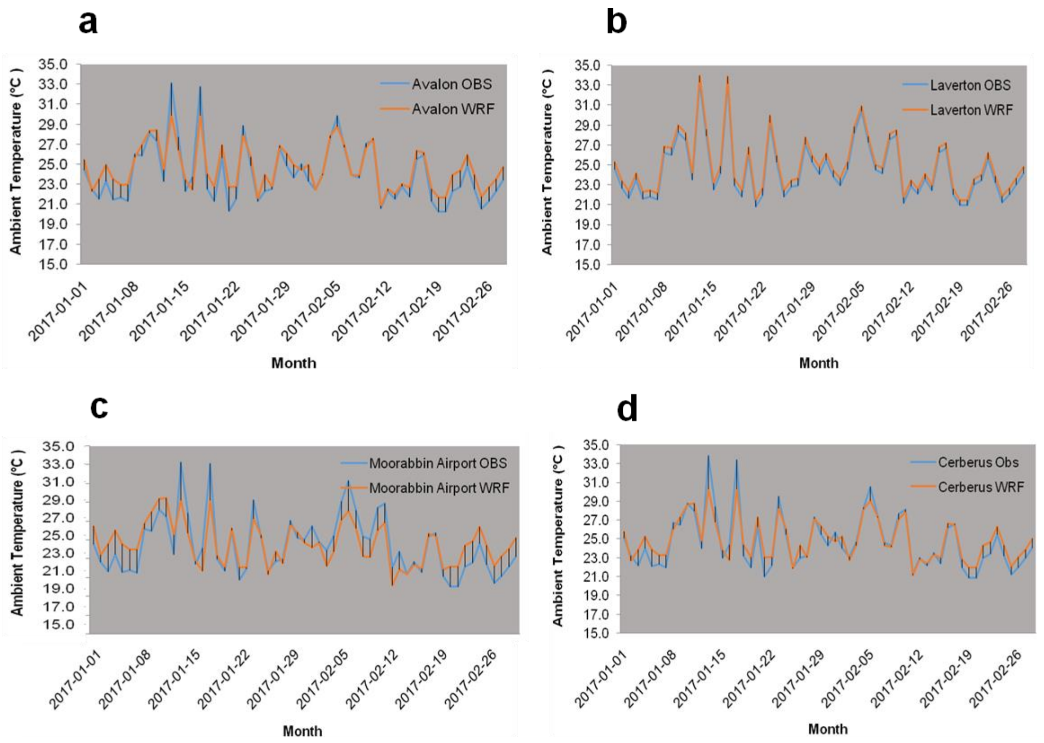


Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Avalon, (b) Laverton, (c) Moorabbin Airport, and (d) Cerberus**.**

1.5 Results of the mesoscale simulations

The results of the control scenario (existing condition) are used as a reference to compare with the cool roof scenario. The predictions of the mesoscale model have been compared against the collected data from the main ground climatic stations in Melbourne to ensure the robustness and accuracy of the model. The results of the base case are presented for two months of summer. The simulated summer period is from January 1st, 2017 to March 2017. The mitigation scenario presented here has been analyzed during the summer period for 59 days of two months (January and February). These two months were warmer than average during 2017 for both daytime and overnight temperatures in Greater Melbourne. For Greater Melbourne, the hottest temperature during January was 38.9°C at Essendon Airport, in a hot northerly airstream that preceded the approaching low-pressure trough on record, behind 2016 (Bureau of Meteorology, Australia, 2017a, b).

1.5.1 Ambient temperatures

Ambient temperatures can be calculated from the surface energy flux partitions in the WRF-SLUCM urban modelling system. Under the cool roof materials scenario, the ambient temperature at 14:00 ranges between 21.3 °C and 39.3 °C. At 06:00 LT, it varies between 20.3°C and 36.5°C. The results show that the use of cool roof materials maximum reduces the peak ambient temperature ($T_{ambient}$) by 2.1ºC over Melbourne and Kingstone compared to the control case. The average ambient temperature reduction at 14:00 over the whole summer is 0.90°C. The maximum decrease of the ambient temperature during 18:00 LT is 1.7°C over the eastern part of Melbourne and the average decrease of summer months is 0.6°C (**Figure 3**).

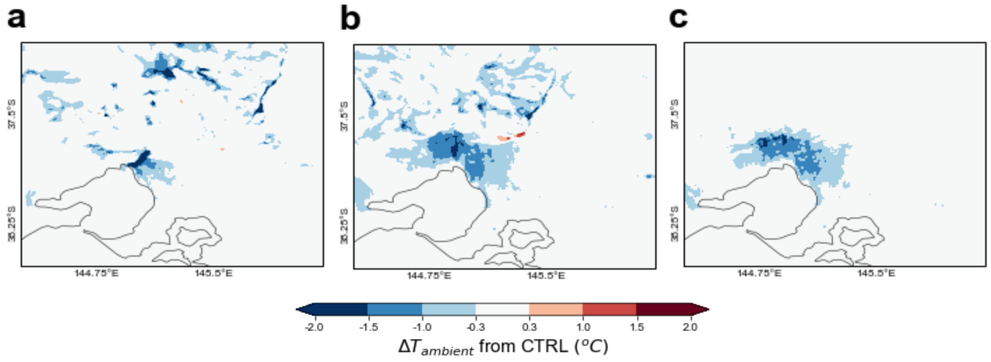


Figure 3 Reduction of ambient temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.2 Surface temperatures

Under the cool roof scenario, the surface temperature ($T_{surface}$) ranges between 22.5 °C to 44.9°C at 14:00, 20.2°C to 39.5°C at 18:00 LT, and 15.1 to 34.9 at 6:00 LT over the city. The maximum decrease of surface temperature during 14:00 LT is 11.1°C over Melbourne and Monash and 3.3°C at 18:00 LT near core Melbourne areas but in the early morning (06:00 LT) it is about 7.1°C over the urban domain. The average decrease of urban surface temperature is 6.1°C at 14:00 LT, 2.8°C at 18:00 LT, and 0.9°C in the city (**Figure 4**).

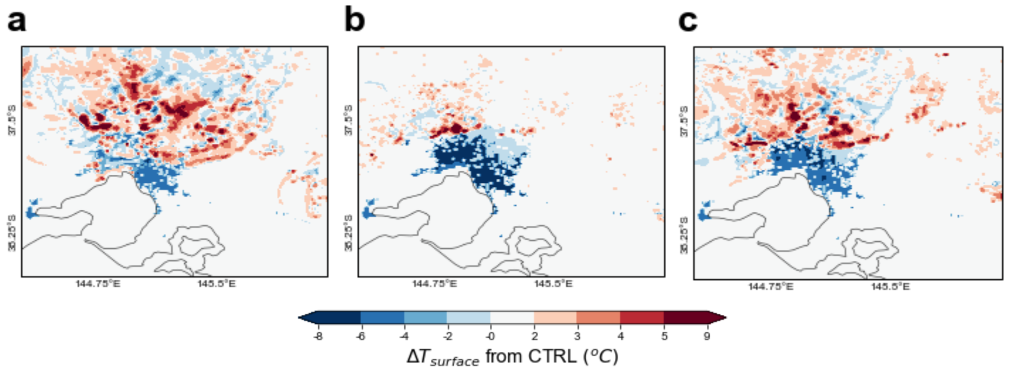


Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

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 398.8 Wm^{-2} and 273.1 Wm^{-2}. At 06:00LT, the average sensible heat flux is 50.2 Wm^{-2}. The maximum decrease in the sensible heat flux is 292.8 Wm^{-2}and the average decrease is 175.1 Wm^{-2} at 14:00 LT over CBD areas of Melbourne city and extends up to Maribyrnong, Moonee Valley, and Moreland. At 18:00LT, the maximum and average reduction of the summer month of sensible heat flux is 118.0 Wm^{-2}and 59.1 Wm^{-2}over the urban domain (**Figure 5**).

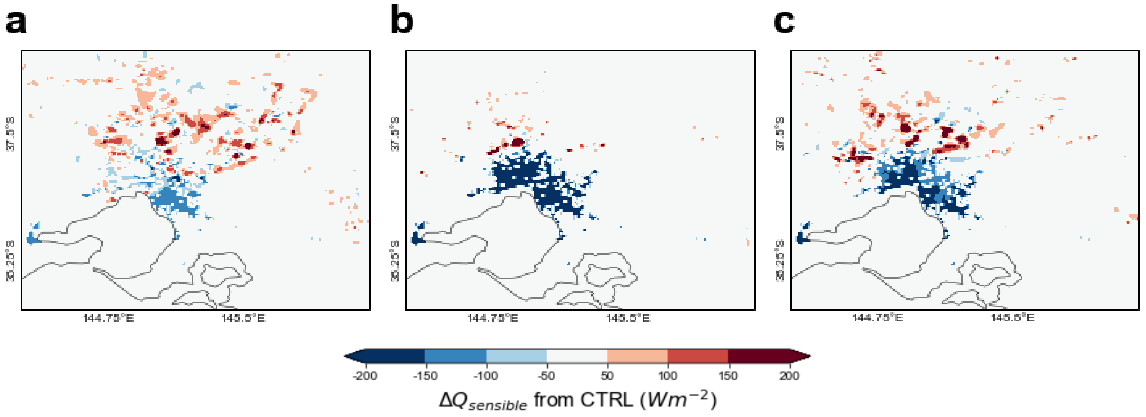


Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.4 Latent heat flux

The maximum and average latent heat flux (Q_{latent}) over the city during 14:00 LT is 33.3 Wm-^{2} and 21.2 Wm-^{2}. At 18:00 LT and 06:00 LT, the average sensible heat flux is 7.8 Wm-^{2}. The maximum decrease in the latent heat flux is 15.1 wm-^{2,} and the average decrease is 12.3 Wm-^{2} at 14:00 LT over CBD and the outer part of Melbourne, including Melton, Hume, Nillumbik, and lower part of Yarra Ranges. At 18:00 LT, the maximum and average reduction of the summer month of latent heat flux is 5.2 Wm-^{2}and 2.4 Wm-^{2} over Melbourne city. At 06:00 LT, the maximum reduction of latent heat flux is 6.4 Wm-2and the average reduction is 4.0 Wm-^{2}over urban domain (**Figure 6**).

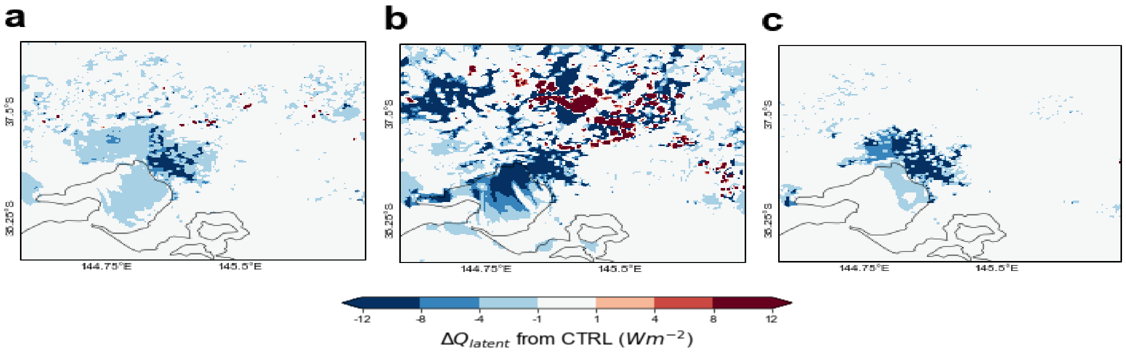


Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.5 Wind

Under the base case simulation, the average wind speed (W_{speed}) is 8.9 ms^{-1}, 10.1 ms$^{-1,}$ and 9.2 ms^{-1} during 06:00 LT, 14:00 LT, and 18:00 LT, respectively, over the city. The maximum decrease of wind speed compared to the control case is 1.8 ms-1, 3.4 ms$^{-1,}$ and 2.2 ms^{-1} at 06:00 LT, 14:00 LT, and 18:00 LT respectively over Monash, Hume, Knox, and Casey. The average decrease of wind speed of whole summer months is 2 ms^{-1} at 14:00 and 1 ms^{-1} and 1.3 ms^{-1} at 06:00 LT and 18:00 LT over the city, respectively (**Figure 7**).

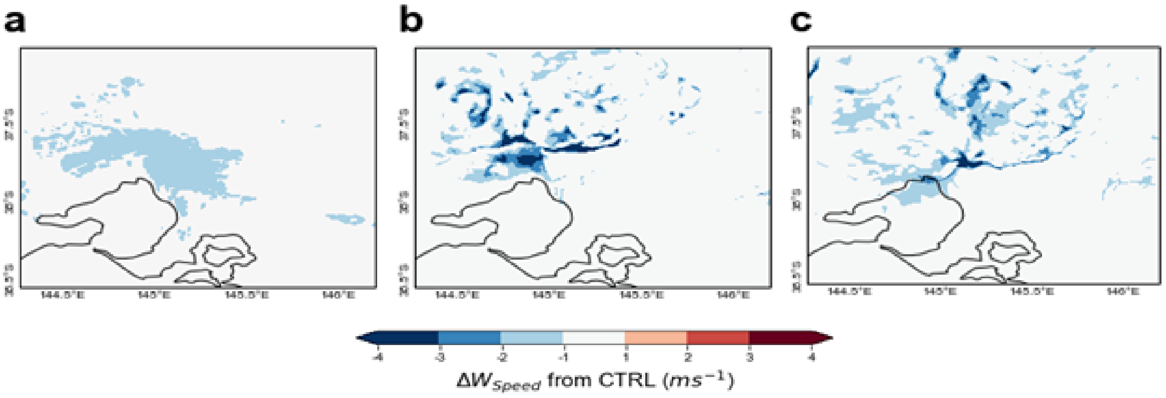


Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

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. Fig. 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 275.7m, 1590.6m, and 986.5m, for 6:00LT, 14:00LT, 18:00LT, respectively, with an average value is about 407.6m. The minimum reduction of PBL is 49.8m, 29.7m, and 29.6m, for 6:00LT, 14:00LT, 18:00LT, respectively, with an average value is about 12.4m (**Figure 8**). The maximum reduction is associated with peak hours (14:00 LT) over Melbourne, Maribyrnong, Monney Valley, Monash, Knox, Whitehorse, Manningham, and Brimbank. On the other hand, during sunrise and sunset, the maximum reduction is reported for the outer west of the Melbourne 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.

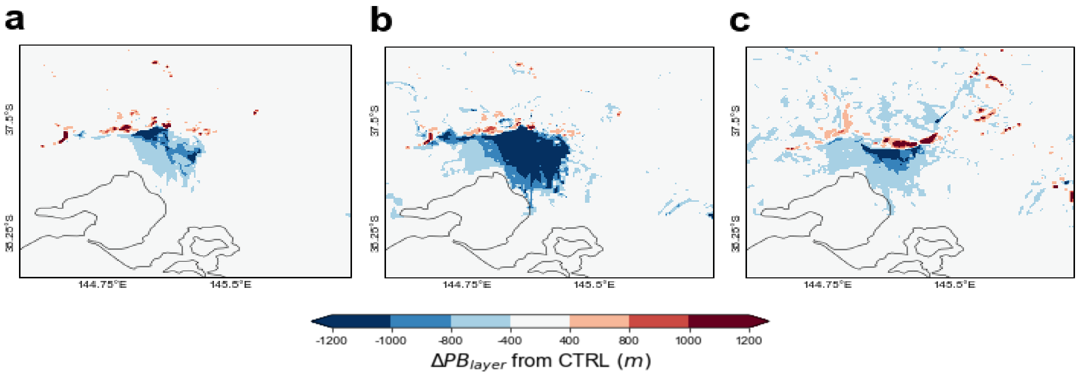


Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.6 Regional impact on sea breeze circulations

The amplification of sea breeze circulation is more variable 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 Melbourne is linked closely with the advection of the sea breeze from Port Philip and the local impact of cool materials. However, based on the numerical analysis of vertical profiles of winds and specific humidity of cool roofs, this report suggests that the advection of moist air from surrounding areas is unlikely to be the driving mechanism due to the extremely hot and dry conditions during the heatwave event. 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 Melbourne. 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 1.5 to 3.5 ms^{-1} induces stronger subsidence over the urban domain where reflective materials are implemented. The surface roughness parameters are painstaking to be useful to pull the cool air of sea breezes down to the surface due to the mixing effects. Besides, the horizontal wind shear and frontal lifting owing to surface roughness parameters could setback the onset of sea breeze front in the urban core. The potency of the sea breeze advection is subjected to the dimension of the city which persuades the urban heating effect. Thus, 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. The location of Port Philip and its geometrical horse-head-shaped enclosed bay on the central coast. This bay may change the wind pattern from the open fetch of the nearby ocean. The winds over the city of Melbourne are indicative of the synoptic pattern over the whole Bay, but there is a modification of the wind component as one moves southward due to the sea breeze effects of Port Phillip Bay itself. There is also an east-west funneling in the vicinity of Port Phillip which increases the frequency of easterlies and westerly components.

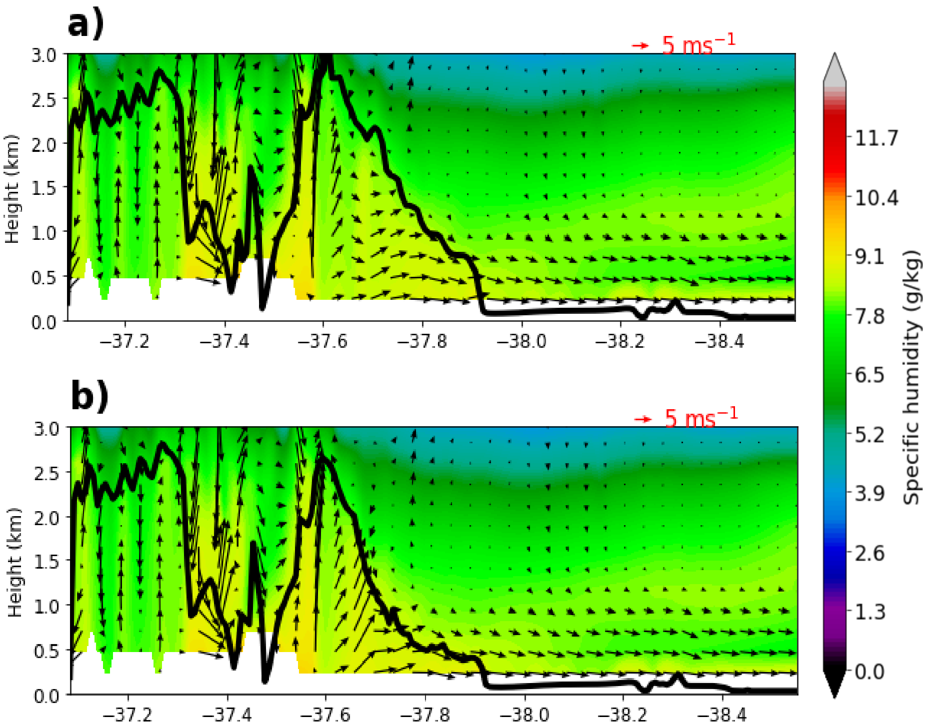


Figure 9 Cross-sectional profile of cool material impacts on sea breeze during peak hour (14:00 LT) over Melbourne (see **Figure 1**): (a) control case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere. During the high solar hour, the convective boundary layer developed the very fastest way and progressively decreases with the implementation of cool materials.

It is also showed that the implementation of a cool roof over the city scale can affect the horizontal and vertical pressure gradient between the city and surrounding urban surface due to significant drop ambient temperature up to 2.1°C and wind speed reduced up to 3.4 ms^{-1}. Thus, changes in roof reflectivity, sensible heating, and wind result in feedbacks within a 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 1.8 and 1.5 ms^{-1}, respectively. As a result, the increase of albedo may put off the flow of warm air from the contiguous desert towards the city of Melbourne due to the effect of this regional high over the urban domain (**Figure 10**). In addition, it is showed that the impact of sea breeze is considerably reduced over high-density residential areas where roof areas are high.

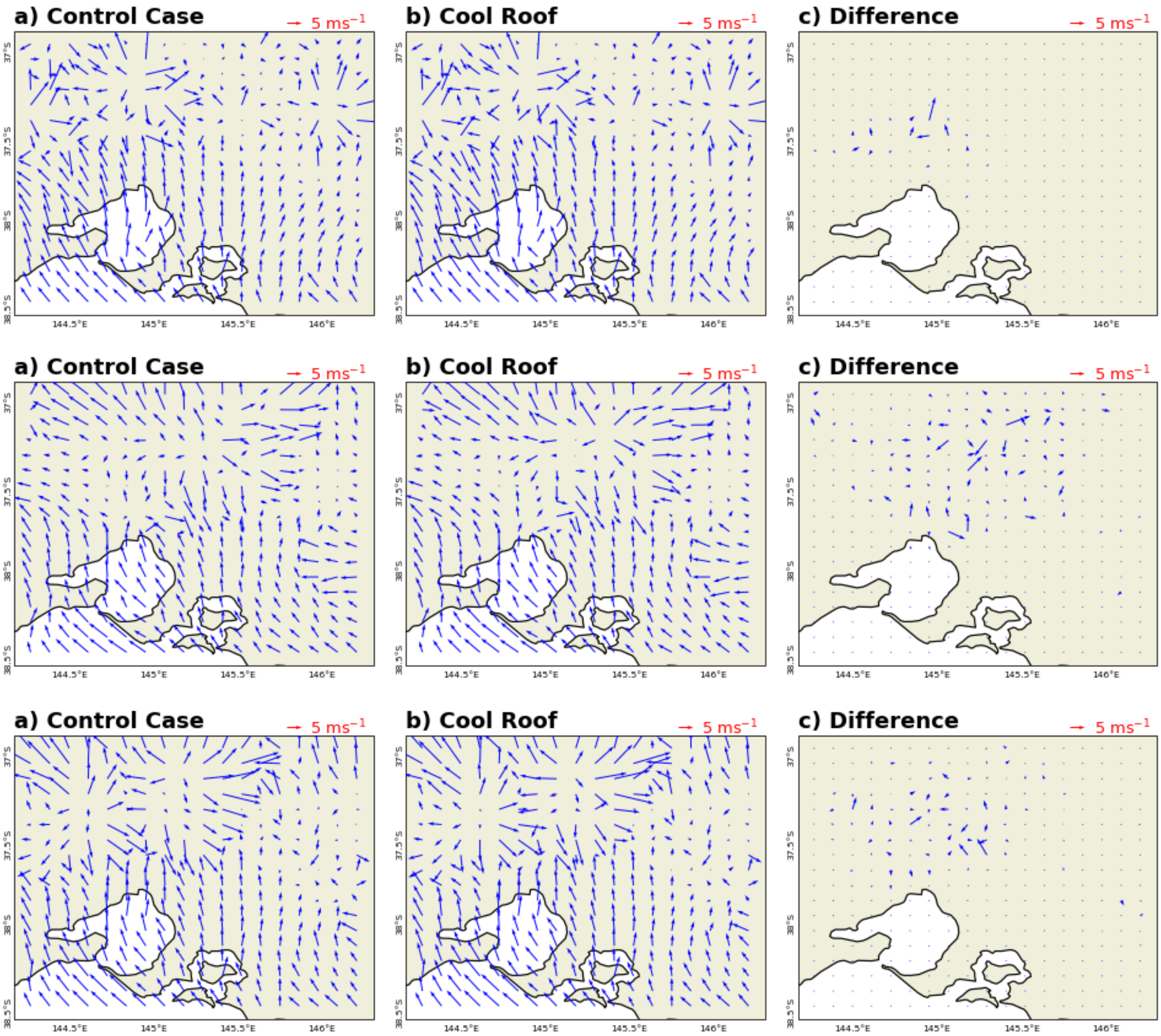


Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) control case (b) cool roof (c) control minus scenarios: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain 03.

1.7 Main conclusions

- It is observed that a sturdy urban heat island (UHI) phenomenon is developed during heatwave over high-density residential areas of Melbourne city. The magnitude of the phenomena may exceed 5°C. The intensity and the spatio-temporal characteristics of the phenomena are strappingly influenced by the synoptic weather conditions and, in particular, the advance of the sea breeze and the westerly winds from the desert area. The potential existence of an additional heating mechanism, like the advection of warm air from nearby spaces, could intensify the strength of the problems of urban heating.

- An increase of albedo fraction in Melbourne city can decrease the peak ambient temperature up to 2.1°C and surface temperature up to 11.1°C. It was noted that significant temperature differences subsist between the eastern and western parts of the city. The spatio-temporal patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the potency of the advection flows.
- The maximum decrease of sensible heat and latent heat flux was 292.8 Wm-^{2} and 15.1 Wm-^{2}, respectively.
- The highest decrease of wind speeds up to -3.4 ms-1. Thus, higher urban albedo values decrease the advective flow between the city and its surroundings surface improving the cooling potential of reflective materials. Modification of the urban albedo in Melbourne results in an average 1590.6m reduction up to of the PBL heights over the city and may increase the concentration of pollutants at ground level and subsequently increase the health problems.
- High intensities of the UHI phenomenon were associated with the existence of a sea breeze in the seaward parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that warm up the western zones of the city.

2. Climatic Design Parameters _ CDH and air temperature distribution

In this study, the characteristics of WRF simulated 2-summer-month ambient air temperatures before and after the intervention of cool roof in 16 weather stations in Melbourne 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 16 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 Melbourne

Two scenarios, one as the control case (Solar reflectance_ roof, streets, and walls=0.15; thermal emissivity _ roof, streets, and walls =0.85), the other applied with the cool roof (Solar reflectance _ roof = 0.80; Solar reflectance _ walls and streets=0.15; thermal emissivity _ roof, streets, and walls =0.85; thermal emittance = 0.85) are simulated and analyzed. 16 stations in Melbourne, 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.

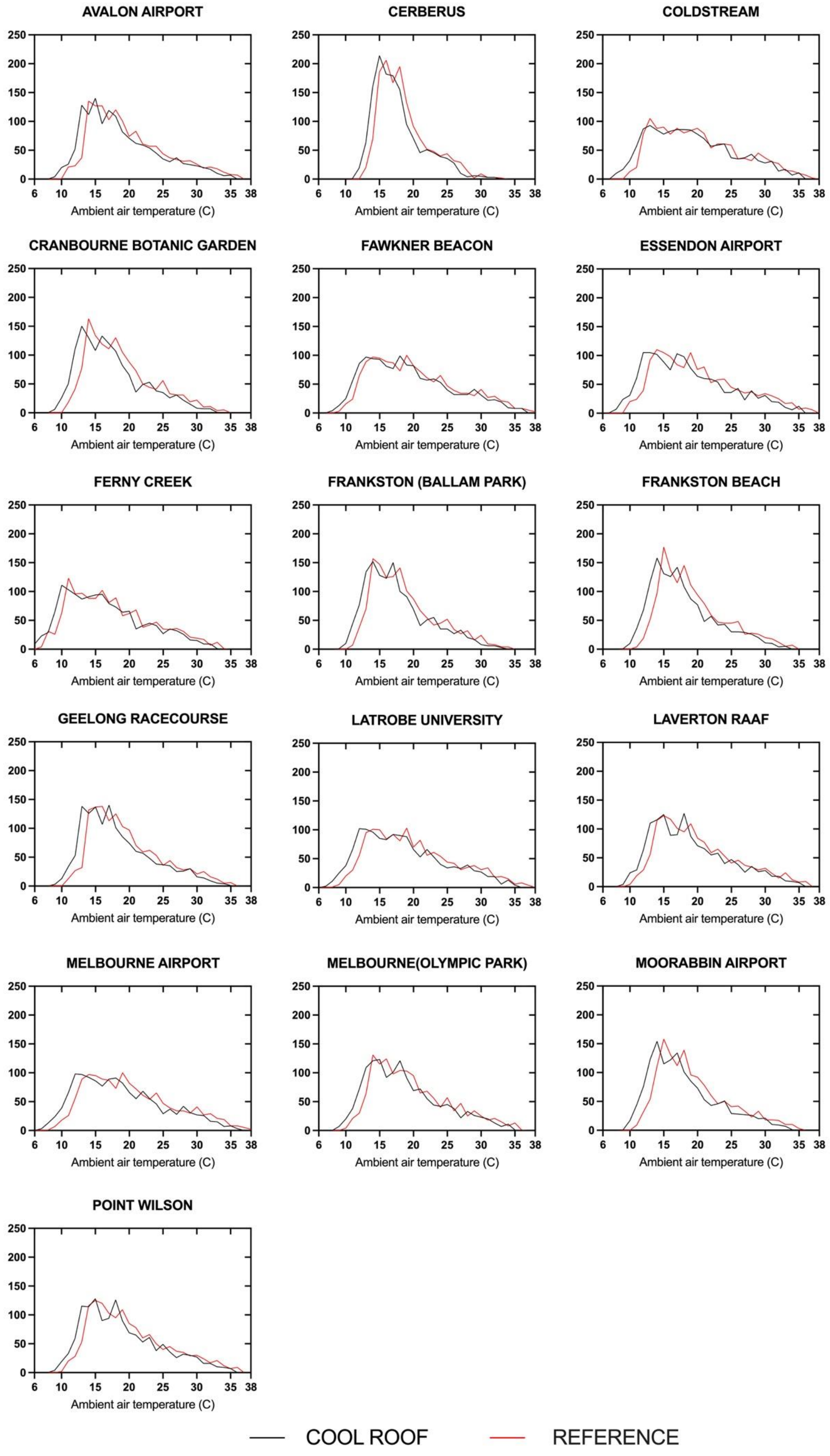
Table 4 Latitude, longitude, and the climate zone of the 16 stations in Melbourne.

No.	Station name	Lat	Long	Climate zone
1	GEELONG RACECOURSE	-38.17	144.38	12.9 m
2	POINT WILSON	-38.1	144.54	18.0 m
3	AVALON AIRPORT	-38.03	144.48	10.6 m
4	LAVERTON RAAF	-37.86	144.76	20.1 m
5	ESSENDON AIRPORT	-37.73	144.91	78.4 m
6	MELBOURNE AIRPORT	-37.67	144.83	113.4 m
7	LATROBE UNIVERSITY	-37.72	145.05	83.0 m
8	COLDSTREAM	-37.72	145.41	83.0 m
9	MELBOURNE (OLYMPIC PARK)	-37.83	144.98	7.53 m
10	FERNY CREEK	-37.87	145.35	512.9 m
11	FAWKNER BEACON	-37.95	144.93	17.0 m
12	MOORABBIN AIRPORT	-37.98	145.1	12.1 m
13	FRANKSTON BEACH	-38.15	145.12	6.0 m
14	FRANKSTON (BALLAM PARK)	-38.15	145.16	58.47 m
15	CRANBOURNE BOTANIC GARDENS	-38.13	145.26	85.0 m
16	CERBERUS	-38.36	145.18	12.69 m

Figure 11 Location of the 16 weather stations in Melbourne.

2.2 Histogram of WRF simulated ambient temperature in Melbourne

The entire 2-month hourly ambient temperature of 16 stations in Melbourne 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.



AVALON AIRPORT

CERBERUS

COLDSTREAM

CRANBOURNE BOTANIC GARDEN

FAWKNER BEACON

ESSENDON AIRPORT

FERNY CREEK

FRANKSTON (BALLAM PARK)

FRANKSTON BEACH

GEELONG RACECOURSE

LATROBE UNIVERSITY

LAVERTON RAAF

MELBOURNE AIRPORT

MELBOURNE(OLYMPIC PARK)

MOORABBIN AIRPORT

POINT WILSON

Figure 12 Histogram of WRF simulated ambient temperature in 16 stations in Melbourne.

In average, compared to the reference scenario, most of the peaks in the curve of the cool roof scenario is shifted to the left by around 1-7 °C, indicating the cooling benefits of cool roof, as shown in **Table 5**. Around 51%-75% of the ambient temperatures in all stations concentrate in the range of 10-19 °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)	10	11	12	13	14	15	16	17	18	19	Percentage of data concentrated in 10-19 °C (%)
AVALON AIRPORT COOL ROOF						140					62
AVALON AIRPORT REFERENCE					135						56
CERBERUS COOL ROOF						214					75
CERBERUS REFERENCE							206				69
COLDSTREAM COOL ROOF				93							55
COLDSTREAM REFERENCE				105							51
CRANBOURNE BOTANIC GARDEN COOL ROOF				150							72
CRANBOURNE BOTANIC GARDEN REFERENCE					163						63
ESSENDON AIRPORT COOL ROOF				105							60
ESSENDON AIRPORT REFERENCE					110						53
FAWKNER BEACON COOL ROOF									99		56
FAWKNER BEACON REFERENCE										100	52
FERNY CREEK COOL ROOF	111										63
FERNY CREEK REFERENCE		123									63
FRANKSTON (BALLAM PARK) COOL ROOF					152						71
FRANKSTON (BALLAM PARK) REFERENCE					157						64
FRANKSTON BEACH COOL ROOF					158						69
FRANKSTON BEACH REFERENCE						177					61
GEELONG RACECOURSE COOL ROOF								140			66
GEELONG RACECOURSE REFERENCE							138				58

LATROBE UNIVERSITY COOL ROOF			102								59
LATROBE UNIVERSITY REFERENCE										103	54
LAVERTON RAAF COOL ROOF									127		61
LAVERTON RAAF REFERENCE						123					54
MELBOURNE AIRPORT COOL ROOF			98								58
MELBOURNE AIRPORT REFERENCE										100	52
MELBOURNE (OLYMPIC PARK) COOL ROOF						123					63
MELBOURNE (OLYMPIC PARK) REFERENCE					131						56
MOORABBIN AIRPORT COOL ROOF					154						69
MOORABBIN AIRPORT REFERENCE						158					59
POINT WILSON COOL ROOF						128					61
POINT WILSON REFERENCE						125					54

2.3 Cooling Degree Hours (CDH) calculation

For all scenarios, Cooling Degree Hours (CDH) Base 26 °C, which measures how much (in degrees), and for how long (in hours), outside air temperature is higher than 26 °C, has been calculated for the entire simulation period. It is a rough indication of the cooling load of a building, and it was calculated by firstly subtracting 26 from the hourly dry-bulb air temperature and then adding all the positive differences in the two months. The calculated CDH for control cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 16 weather stations, are shown in **Table 6** and **Figure 13**. Compared with the control case, the largest percentage reduction is observed in CRANBOURNE BOTANIC GARDENS, and the smallest is found in FAWKNER BEACON, with an average reduction of 31.2%. The mean CDH values of the 16 weather stations for the control case, cool roof case are 876.0, 618.0 respectively, with standard deviations of 354.2 and 281.5 sequentially, see **Table 7.**

Table 6 The CDH of control cases, cool roof applied cases, and the difference between these two, as well as the percentage of CDH reduction due to the implementation of the cool roof in 16 weather stations in Melbourne.

Weather Station	CDH_CTRL	CDH_COOL ROOF	CDH_ Difference (CTRL-COOL ROOF)	Percentage of the reduction_% (CDH_Difference/ CDH_CTRL)
GEELONG RACECOURSE	761.7	513.4	248.3	32.6
POINT WILSON	1037.9	761.4	276.5	26.6
AVALON AIRPORT	995.1	735.6	259.6	26.1
LAVERTON RAAF	1066.5	784.7	281.8	26.4
ESSENDON AIRPORT	1241.9	842.6	399.3	32.2
MELBOURNE AIRPORT	1328.5	910.5	418.0	31.5
LATROBE UNIVERSITY	1166.4	798.1	368.3	31.6
COLDSTREAM	1224.8	957.7	267.1	21.8
MELBOURNE (OLYMPIC PARK)	922.6	667.0	255.6	27.7
FERNY CREEK	532.2	360.1	172.1	32.3
FAWKNER BEACON	1328.5	1059.6	268.8	20.2

MOORABBIN AIRPORT	702.2	450.1	252.1	35.9
FRANKSTON BEACH	576.7	355.9	220.8	38.3
FRANKSTON (BALLAM PARK)	455.0	294.0	161.0	35.4
CRANBOURNE BOTANIC GARDENS	490.4	282.2	208.2	42.4
CERBERUS	185.8	114.9	70.9	38.2

Table 7 Mean and SD of the CDH of the 16 weather stations in control cases and cool roof cases respectively.

	Mean	**SD**	**Sample No.**
CDH_CTRL	876.0	354.2	16
CDH_COOL ROOF	618.0	281.5	16
CDH_DIFFERENCE (CTRL-COOL ROOF)	258.0	87.4	16

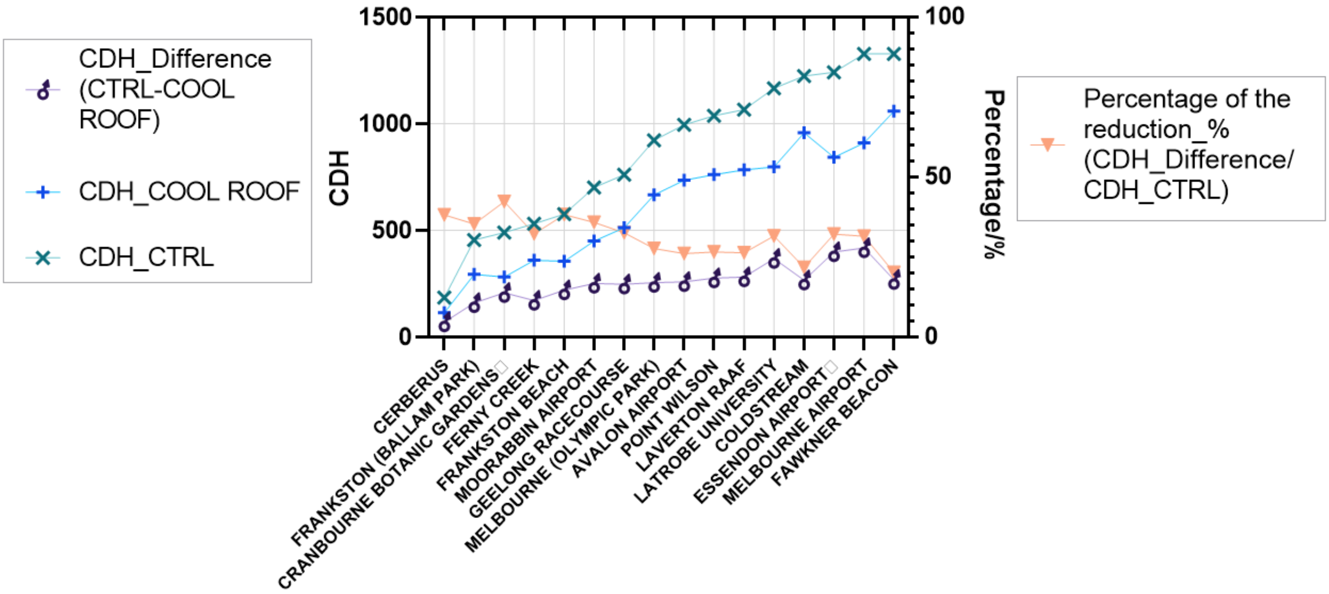


Figure 13 The CDH of control cases, cool roof applied cases, the difference between these two, and the percentage of the CDH reduction due to the implementation of the cool roof in 16 weather stations in Melbourne.

2.3.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 16 weather stations in both the control cases and the cool roof cases is shown in **Figure 14**. In control cases, the CDH centred around 500, and 1200 has the largest proportion: each accounting for 18.8% of the total. Data centred around 1000 and 1300 each account for 12.5% of the total, while all the remaining intervals have the same proportions. In cool roof cases, the CDH centred around 800 has the largest proportion of 25%. The data of all remaining intervals account for less than 15%

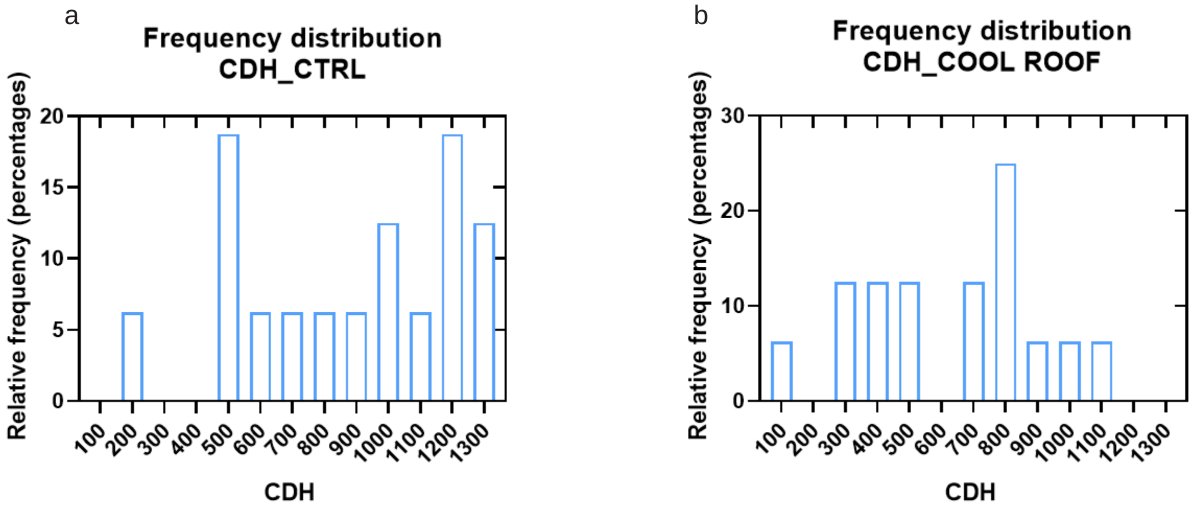


Figure 14 Frequency distribution of the CDH values for the 16 weather stations in control cases (a) and cool roof cases (b).

2.3.2 Spatial distribution of the results

- **CDH_Reference scenario: (Figure 15)**
  The highest CDH of 1328.5 is observed in FAWKNER BEACON and MELBOURNE AIRPORT. CERBERUS 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, as shown in. The highest CDH of 1059.6 is still observed in FAWKNER BEACON and CERBERUS again has the lowest number. The spatial distribution pattern is very similar to that of the control cases: CDH increases from southeast to northwest.

- **CDH_Reference scenario – cool roof scenario: (Figure 17)**
  The maximum decrease occurs in the north (MELBOURNE AIRPORT:418.0) of the city. The smallest decrease is observed in the southeast part of the city (CERBERUS: 70.9). The average decrease due to the implementation of a cool roof is 258.0 (**Table 6**) across the 16 stations.

- **CDH_(Reference scenario – cool roof scenario)/Reference scenario: (Figure 18)**
  The proportion of CDH reduction in the original control volume is relatively large in the southeast corner of the city and gradually decreases toward the northwest and northeast, as shown in **Figure 18**.

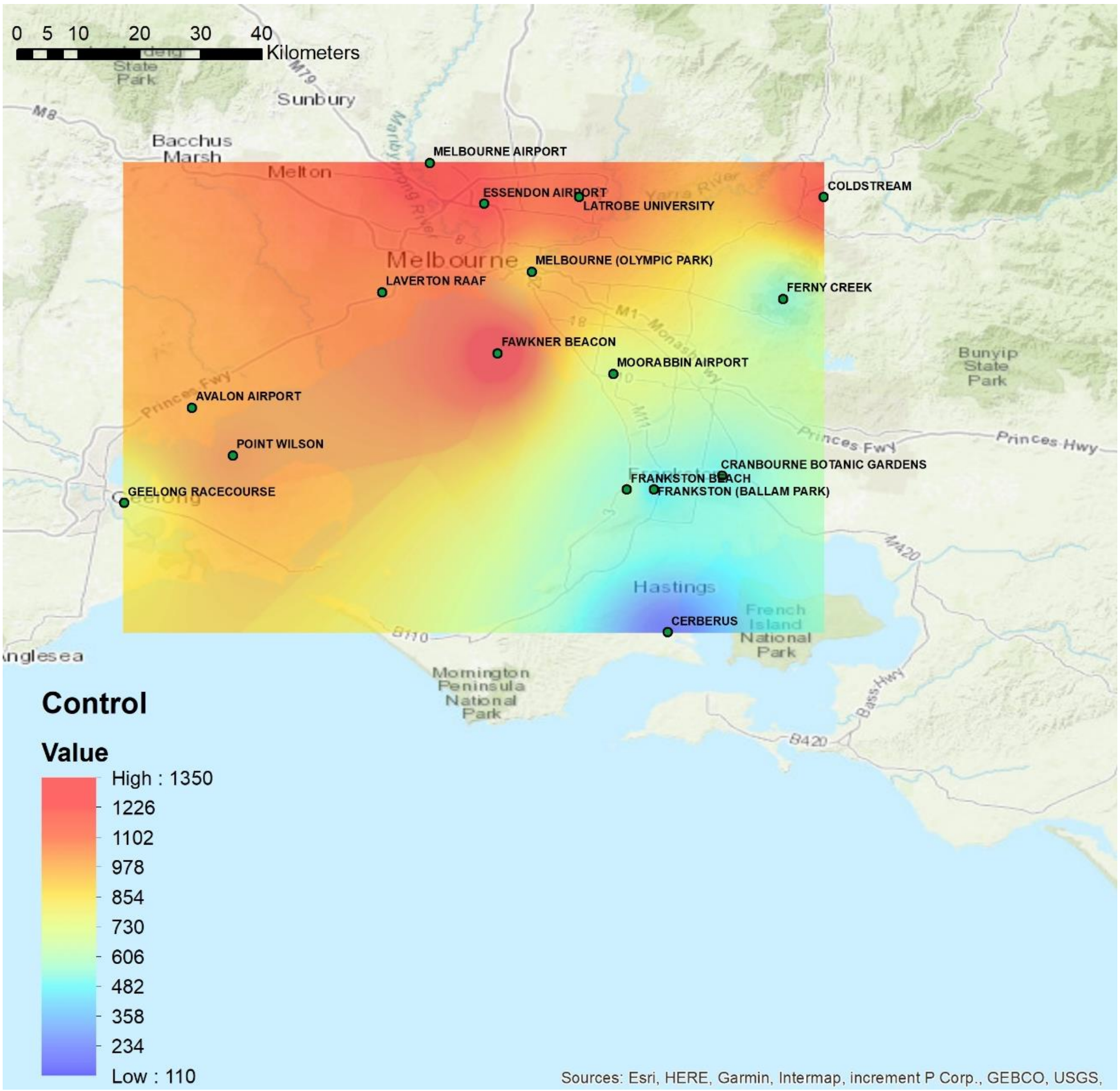
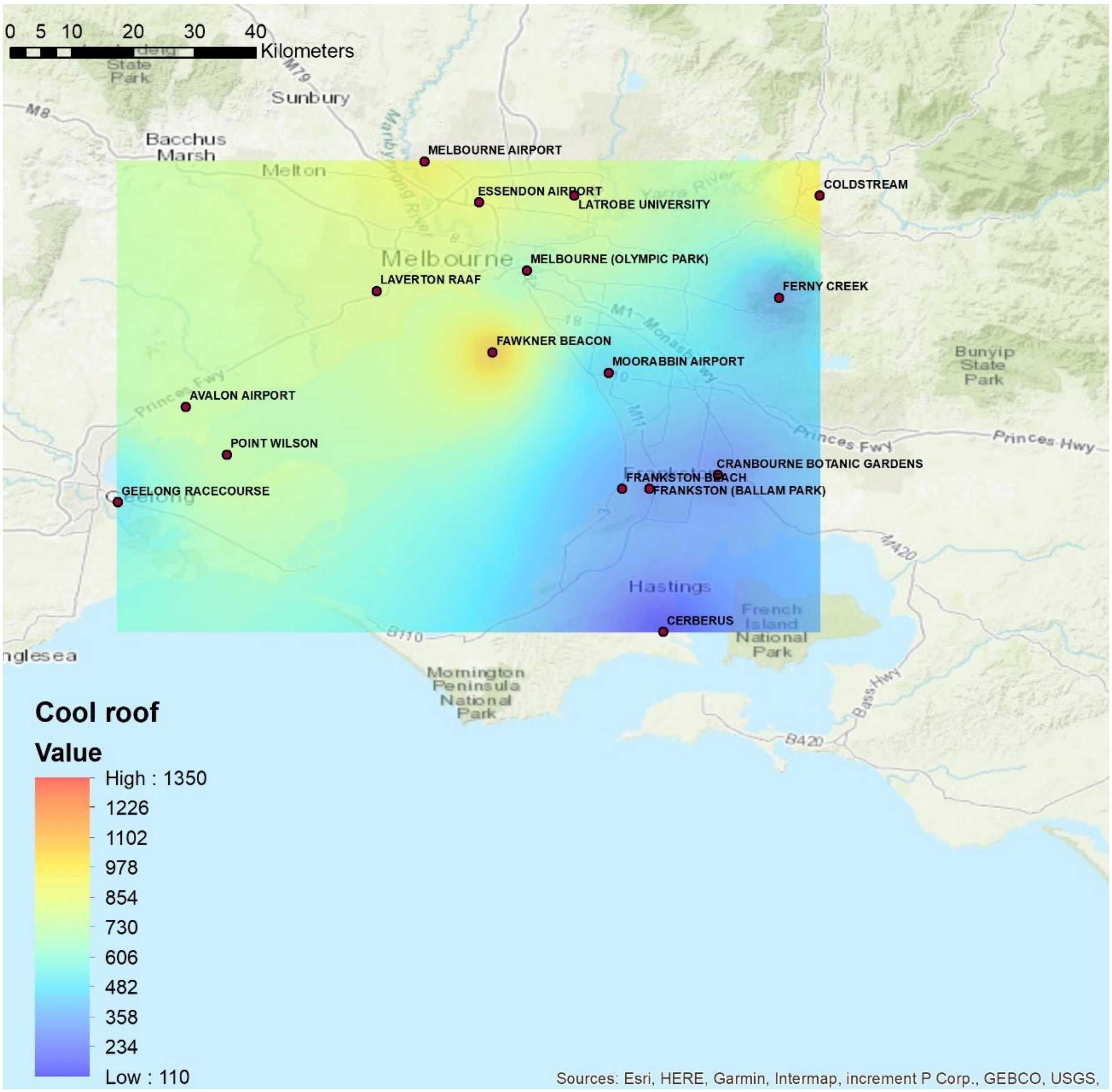


Figure 15 The sum of Cooling degree hours in Jan and Feb of the control cases in the 16 stations in Melbourne.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS,

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

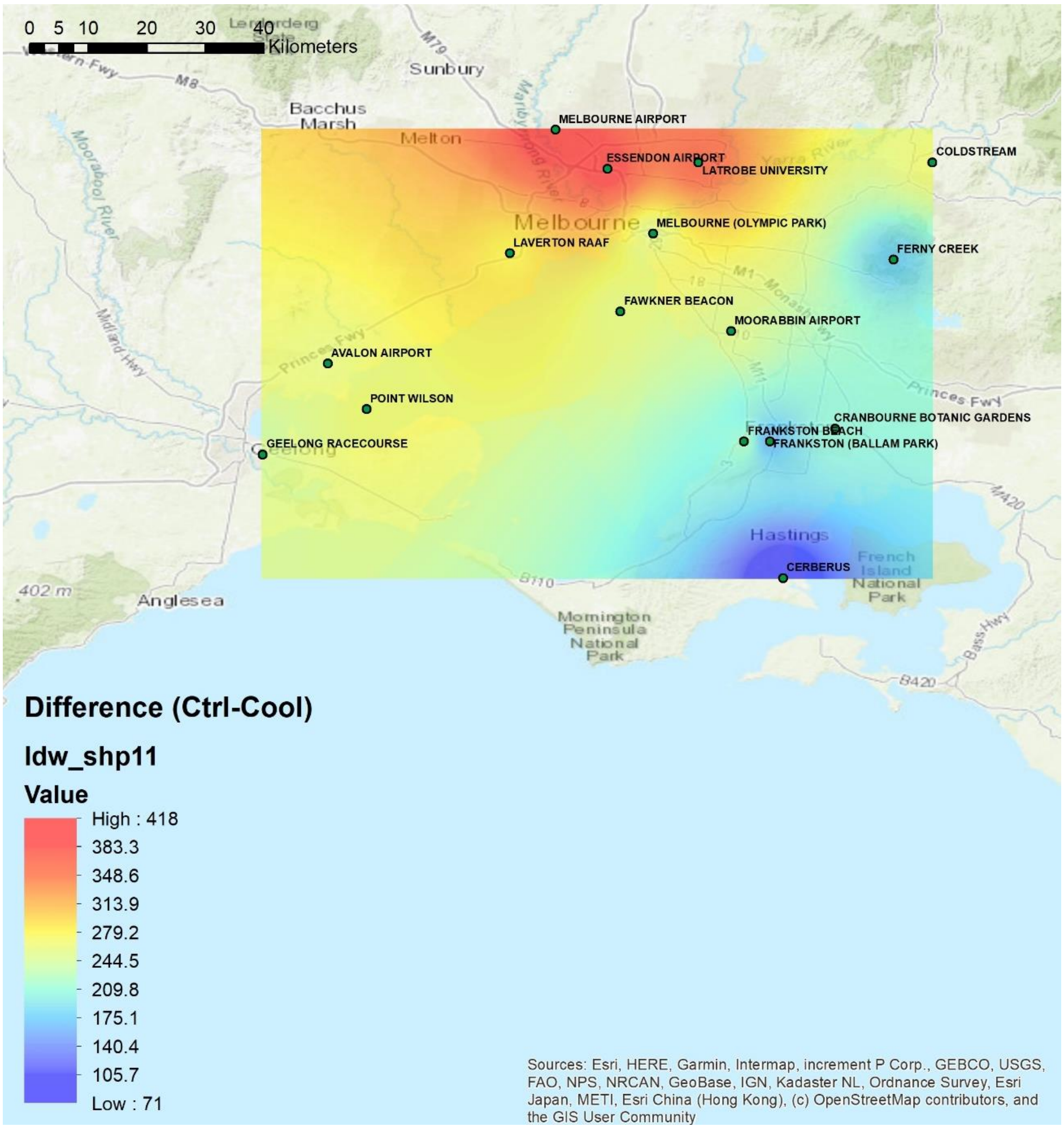


Figure 17 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and control ones in the 16 stations in Melbourne.

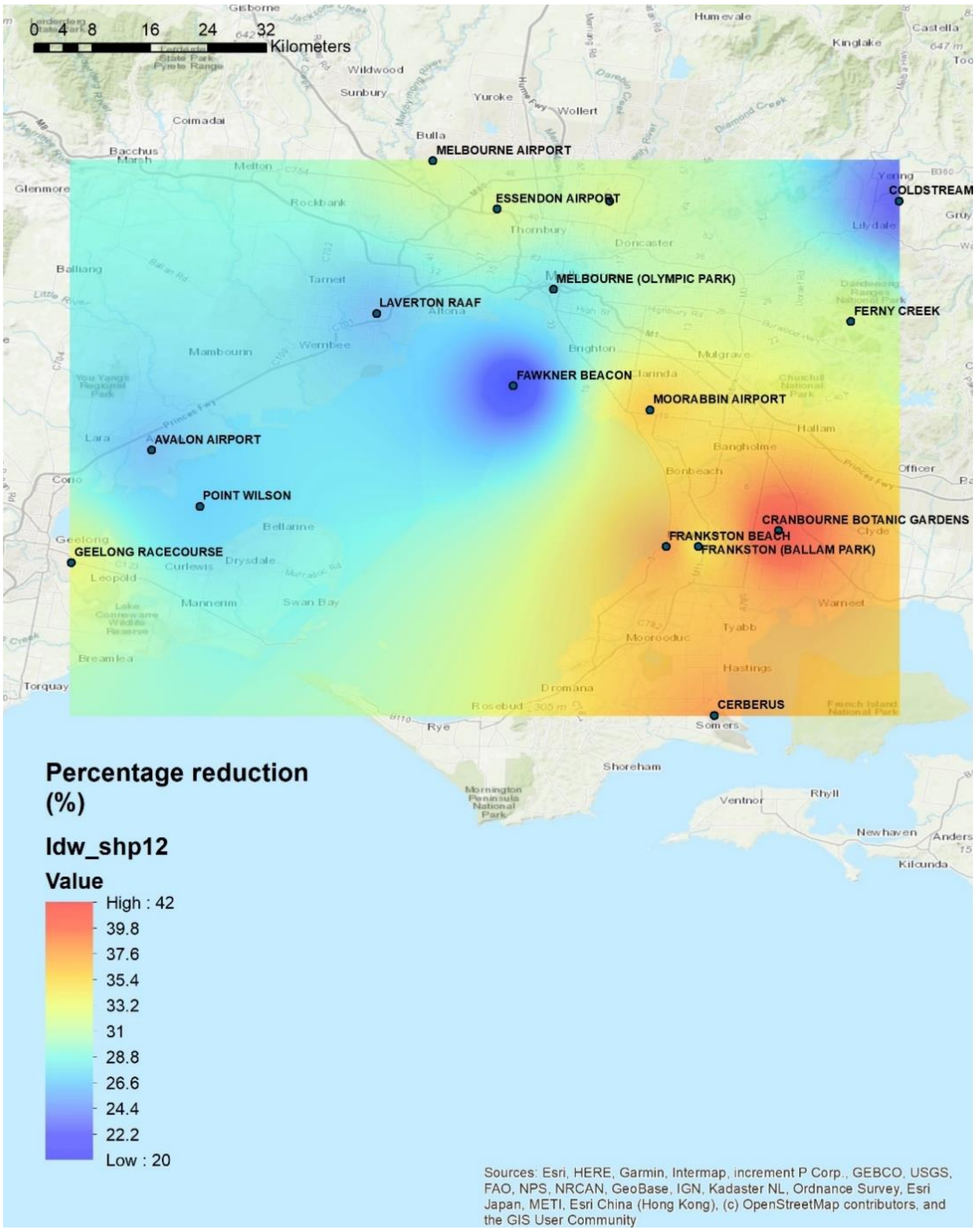


Figure 18 The percentage of CDH reduction due to the implementation of the cool roof in the 16 stations in Melbourne.

2.4 Conclusions

- In average, compared to the reference scenario, temperature with the peak distribution in the cool roof scenario is mostly around 1-7 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Around 51%-75% of the ambient temperatures in all stations concentrate in the range of 10-19 °C.
- In control cases, CDH ranges from 185.8 to 1328.5, and about half of the data is concentrated in 1000-1300. CDH gradually increases from the southeast of the city to the northwest.
- In cool roof cases, CDH ranges from 114.9 to 1059.8, and about 75% of the data is concentrated in 300-800. Its spatial distribution is also similar to that of the control case.
- In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in control 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 20.2% to 42.4%, with an average value of 31.2%. The percentage of CDH reduction in the original control volume is relatively large in the southeast corner of the city and gradually decreases toward the northwest and northeast.

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 Melbourne. 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 Melbourne during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and Seven weather stations across Melbourne (in climate zone 6). The seventeen typical buildings modeled in this study include the following and their characteristics are listed in **Appendix: Building characteristic**s:

1) A low-rise office building without roof insulation-existing building,

2) A high-rise office building without roof insulation-existing building,

3) A low-rise office building with roof insulation-new building,

4) A high-rise office building with roof insulation-new building,

5) A low-rise shopping mall center- new building,

6) A mid-rise shopping mall center- new building,

7) A high-rise shopping mall center-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 center-existing building,

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

17) A stand-alone house-new building.

The seven weather stations modelled in Melbourne include (See **Figure 19**):

1) Avalon Airport-Climate zone 6,
2) Essendon Airport-Climate zone 6,
3) Melbourne Airport-Climate zone 6,
4) Coldstream-Climate zone 6,
5) Melbourne (Olympic Park)-Climate zone 6,
6) Moorabbin Airport-Climate zone 6,
7) Frankston Beach-Climate zone 6.

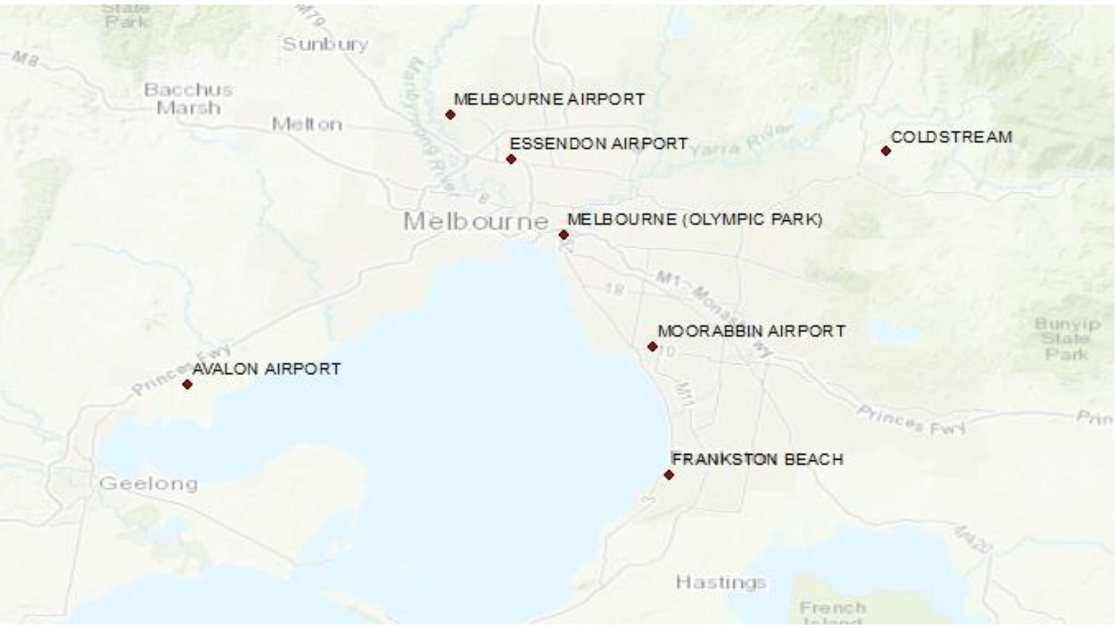


Figure 19 Weather stations in Melbourne in climate zone 6, including Avalon Airport, Essendon Airport, Melbourne Airport, Coldstream, Melbourne (Olympic Park), Moorabbin Airport and Frankston Beach.

The corresponding building specifications for the buildings in climate zones 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 Melbourne. The simulations were performed under three scenarios:

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

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

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

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

2) Annual cooling and heating load simulations

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

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

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

3) Indoor air temperature simulations under free-floating mode

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

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

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

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

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

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

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

The indoor air temperature difference between the cool roof scenario and the reference scenario was then computed. The indoor air temperature reduction in scenario 1 vs reference scenario was plotted against the indoor air temperature in the reference scenario to determine the periods when the undesired temperature reduction occurs. In addition, the number of hours below 19 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 4***.

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 Melbourne. In this chapter, a summary of the simulation results and detailed discussions are 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 is given in **Table 8**.

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

Building Type	Cooling load-reference	Reference with cool roof scenario (scenario 1) vs reference scenario		Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario	
	kWh/m^2	kWh/m^2	%	kWh/m^2	%
A low-rise office building without roof insulation-existing building	12.6-18.3	6.3-10	47.6-54.9	8.3-11.7	59.3-65.7
A high-rise office building without roof insulation-existing building	7.9-10.9	1.1-2.0	13-18.1	3.0-4.0	32-40.9

A low-rise office building with roof insulation-new building	7.5-10.3	0.6-0.9	7.1-9.4	2.4-3.3	26.8-35.7
A high-rise office building with roof insulation-new building	7.1-9.7	0.1-0.2	1.3-1.9	1.8-2.7	21.5-31.8
A low-rise shopping mall centre-new building	41.8-47.7	1.4-2.0	3.2-4.2	6.9-9.1	15.5-21.4
A mid-rise shopping mall centre-new building	40.2-45.9	0.7-1.0	1.6-2.1	6.2-8.4	14.4-20.4
A high-rise shopping mall centre-new building	39.6-45.3	0.4-0.6	1-1.4	5.9-8.1	14.0-20.0
A low-rise apartment building-new building,	3.4-6.1	0.6-1.0	13.3-18.3	1.8-2.5	40.3-54.0
A mid-rise apartment building-new building	3.1-5.7	0.4-0.6	8.3-11.7	1.5-2.2	36.9-49.5
A high-rise apartment building-new building	2.9-5.4	0.2-0.4	5.2-7.4	1.0-1.4	34.8-47.3
A typical stand-alone house-existing building,	6.6-10.0	3.4-7.5	51.9-75.3	5.1-6.8	67.4-77.4
A typical school building-new building	9.3-13.7	0.5-0.7	4.1-5.6	2.9-3.9	22.6-32.4
A low-rise office building with roof insulation-existing building	9.4-13.3	2.9-4.8	29.4-36.0	4.9-6.4	45.2-52.4
A high-rise office building with roof insulation-existing building	7.4-10.1	0.5-0.9	6.5-9.4	2.3-3.2	26.5-35.9
A low-rise shopping mall centre-existing building	44.7-52.9	6.9-9.8	14.7-18.6	12.2-15.6	25.8-32.4
A high-rise shopping mall centre-existing building	40.2-46.8	2.1-3.2	4.8-6.8	7.5-9.7	17.4-23.7
A stand-alone house-new building.	4.6-7.1	2.1-3.0	37.5-46.9	3.2-4.1	57.1-69.9

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

Building Type	**Annual cooling load saving**		**Annual heating load penalty**	**Annual total cooling & heating load saving**	
	kWh/m^2	**%**	**kWh/m^2**	**kWh/m^2**	**%**
A low-rise office building without roof insulation-existing building	8.8-14.4	40.1-58.5	3.3-7.5	4.0-9.7	12.3-27.6
A high-rise office building without roof insulation-existing building	1.5-2.5	9.4-20.2	0.6-1.5	0.7-1.6	3.1-7.5
A low-rise office building with roof insulation-new building	0.8-1.3	5.6-10.5	0.2-0.8	0.2-1.0	1.2-4.6
A high-rise office building with roof insulation-new building	0.1-0.2	1.0-2.2	0-0.2	0-0.2	0.2-0.9
A low-rise shopping mall centre-new building	3.7-5.0	3.3-4.5	0.1-0.3	3.5-4.9	2.9-4.2
A mid-rise shopping mall centre-new building	1.6-2.3	1.6-2.2	0-0.1	1.6-2.3	1.4-2.1
A high-rise shopping mall centre-new building	1.0-1.5	1.0-1.4	0-0.1	1.0-1.4	0.9-1.3
A low-rise apartment building-new building,	0.8-1.3	10.8-16.7	1.1-1.5	-0.3-0.1	-0.9-0.2
A mid-rise apartment building-new building	0.6-1.2	8.3-14.5	0.6-0.9	-0.1-0.5	-0.3-1.1
A high-rise apartment building-new building	0.2-0.6	4.1-8.6	0.4-0.5	-0.1-0.3	-0.3-0.5
A typical stand-alone house-existing building,	5.6-8.3	48.8-63.5	6.8-8.5	-1.6-1.2	-3.1-2.5
A typical school building-new building	0.8-1.1	3.4-7.0	0.5-0.8	0.2-0.6	0.4-1.3
A low-rise office building with roof insulation-existing building	4.1-6.6	23.4-32.2	1.0-1.7	2.9-4.9	12.4-18.2

A high-rise office building with roof insulation-existing building	0.7-1.2	4.7-7.5	0.2-0.3	0.5-0.8	2.5-4.1
A low-rise shopping mall centre-existing building	25.5-22.1	14.1-19.2	0.4-0.9	12.6-15.0	12.5-18.0
A high-rise shopping mall centre-existing building	4.3-6.4	4.3-6.2	0.1-0.3	4.2-6.2	3.8-5.9
A stand-alone house-new building.	2.9-4.2	33.4-46.7	1.9-2.9	0.8-2.1	2.2-6.5

Table 10 Maximum indoor air temperature in reference scenario, maximum indoor air temperature reduction between reference scenario vs reference with cool roof scenario (scenario 1) and reference scenario vs cool roof with modified urban temperature scenario (scenario 2) for all building types under free floating conditions during a typical summer week using weather data simulated by WRF, and number of hours with indoor air temperature above 26 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	41.1-44.4	8.1-10.0	9-10.4	334-395	193-253	152-197
A high-rise office building without roof insulation-existing building	36.4-38.0	1.4-2.1	2.6-2.8	297-424	249-372	186-310

A low-rise office building with roof insulation-new building	37.3-38.6	0.9-1.3	2.1-2.2	345-399	317-359	250-305
A high-rise office building with roof insulation-new building	36.0-37.0	0.2	1.5-1.7	382-427	375-419	286-353
A low-rise shopping mall centre-new building	42.2-45.9	0.5-0.6	2.0	430-455	418-444	382-408
A mid-rise shopping mall centre-new building	41.8-45.4	0.4-0.5	1.8	455-479	451-473	398-425
A high-rise shopping mall centre-new building	41.6-45.2	0.4	1.7-1.8	460-482	459-482	404-431
A low-rise apartment building-new building,	31.4-33.8	0.6-0.8	1.7-1.9	135-212	114-191	64-138
A mid-rise apartment building-new building	31.1-33.4	0.3-0.5	1.5-1.6	125-210	108-197	64-133
A high-rise apartment building-new building	30.9-33.1	0.2-0.3	1.4-1.5	114-205	106-198	63-132
A typical stand-alone house-existing building	34.3-37.4	4.1-4.7	5.0-5.6	192-250	96-151	62-121
A typical school building-new building	33.2-34.4	0.5-0.7	1.7-1.8	159-226	154-211	120-173

A low-rise office building with roof insulation-existing building	39.0-41.1	4.3-5.4	5.4-6.0	340-393	236-276	185-240
A high-rise office building with roof insulation-existing building	36.2-37.5	0.8-1.2	2.0-2.1	375-424	341-395	262-332
A low-rise shopping mall centre-existing building	42.7-46.7	2.1-2.7	3.1-3.7	401-436	378-401	333-364
A high-rise shopping mall centre-existing building	41.7-45.4	0.6-0.9	2.0-2.1	448-474	440-465	383-416
A stand-alone house-new building.	32.6-35.4	2.3-2.7	3.3-3.7	171-230	107-161	64-129

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 ºC in free-floating mode during a typical winter month using annual measured weather data.

Building type	**Minimum Indoor air temp in a typical winter week**	**Average maximum indoor air temp reduction in a typical winter month**	**Number of hours below 19 ºC in a typical winter month**			
	Reference scenario (ºC)	**Reference with cool roof scenario (scenario 1) vs reference scenario (ºC)**	**Reference scenario (hours)**		**Reference with cool roof scenario (scenario 1) (hours)**	
			Operational hours	**Total**	**Operational hours**	**Total**
A low-rise office building without	9.1-11.1	1.7-1.9	217-230	580-597	276-285	645-656

roof insulation-existing building						
A high-rise office building without roof insulation-existing building	13.2-14.4	0.3-0.4	69-185	430-517	71-194	439-531
A low-rise office building with roof insulation-new building	12.2-14.6	0.3-0.4	132-163	415-492	138-173	432-509
A high-rise office building with roof insulation-new building	13.6-14.8	0.1	124-164	353-461	124-164	367-461
A low-rise shopping mall centre-new building	11.7-13.3	0.2-0.3	32-65	283-355	34-68	287-361
A mid-rise shopping mall centre-new building	12.7-14.1	0.1-0.2	26-63	244-331	27-64	247-334
A high-rise shopping mall centre-new building	13.0-14.3	0.1	26-63	236-325	26-64	236-326
A low-rise apartment building-new building,	11.2-12.3	0.2	N/A	729-731	N/A	735-737
A mid-rise apartment building-new building	11.5-12.6	0.1	N/A	736-738	N/A	737-741
A high-rise apartment building-new building	11.6-12.7	0.1	N/A	737-743	N/A	738-743
A typical stand-alone house-existing building,	8.7-10.5	1.2-1.4	N/A	708-717	N/A	735-743

A typical school building-new building	8.8-11.3	0.1	186-206	664-684	190-210	672-680
A low-rise office building with roof insulation-existing building	10.5-13.0	0.9-1.1	179-200	520-558	200-229	556-595
A high-rise office building with roof insulation-existing building	13.4-14.6	0.2	137-175	398-488	140-179	405-501
A low-rise shopping mall centre-existing building	10.6-12.2	0.5-0.0.7	48-84	350-407	54-86	364-412
A high-rise shopping mall centre-existing building	12.6-13.9	0.2	36-71	269-349	38-72	275-354
A stand-alone house-new building.	9.8-11.6	0.7-0.8	N/A	702-704	N/A	720-728

3.4 Conclusion

The conclusions drawn from this study are:

- In existing low-rise buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in individual buildings (scenario 1) is significant. For instance, the application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 6.3-10 kWh/m^2.
- In existing low-rise buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in both individual building and in the whole urban area (scenario 2) is significant. For instance, the application of cool roofs in both individual building and in the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 8.3-11.7 kWh/m^2.
- In new low-rise buildings with high insulation level, the application of cool roofs in both individual building and in the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and in the whole urban area (scenario 2) is predicted to be 2.4-3.3 kWh/m^2 in a typical new low-rise office building.
- In high-rise buildings, the application of cool roofs in individual buildings (scenario 1) is predicted to have a relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by

application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.1-0.2 kWh/m^2 for a new high-rise office building with insulation.

- In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and in the whole urban area (scenario 2) is significantly higher than the cooling load savings by the implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 2.1-3.2 kWh/m^2 in an existing high-rise shopping mall centre, which is expected to increase to 7.5-9.7 kWh/m^2 when cool roofs are applied both in individual buildings and in the whole urban area (scenario 2).
- The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in a majority of building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 8.8-14.4 kWh/m^2, while the corresponding heating penalty is just 3.3-7.5 kWh/m^2.
- The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Melbourne. For instance, the heating penalty can be up to 6.8-8.5 kWh/m^2 compared to the equivalent 5.6-8.3 kWh/m^2 in an existing stand-alone house.
- In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, the application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 8.1-10.0 ^oC.
- In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, the application of cool roofs in both individual building and in the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and in the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 9-10.4 ^oC.
- In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and in the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^oC. For instance, the number of hours with an indoor air temperature above 26 ^oC in a typical low-rise office building without insulation is predicted to reduce from 334-395 hours to 193-253 hours and 152-197 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
- In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, the application of cool roofs in both individual building and in the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum indoor air temperature reduction by application of cool roofs in both individual building and in the whole urban area (scenario 2) is predicted to be 2.1-2.2 ^oC in a typical new low-rise office building.
- In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, application of cool roofs in both individual building and in 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 345-399 hours to 250-305 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).

- The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by applying cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 8.1-10 ^{o}C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 1.7-1.9 ^{o}C during a typical winter month.
- The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ^{o}C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.8 ^{o}C occurs when the indoor air temperature is 22.8 ^{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 179-200 hours to 200-229 hours in a typical existing low-rise office building with roof insulation.

4. Energy loss through building envelopes in various stations in Melbourne _ 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 Melbourne has been investigated. Specifically, for the 17 building types, the correlation between cooling degree hours (Base 26) and the sensible cooling load in **reference scenarios** (A reference building with conventional roof using the climatic data simulated by WRF for the current condition), and the cooling load reduction in **scenario 1** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition) and **scenario 2** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city) has been plotted using the simulated data in 7 weather stations in Melbourne for two summer months. For each plot, the linear regression line has been generated in the format of

$$Y=a X + b$$

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

X is the cooling degree hours (K);

For reference scenarios:

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).

For the cooling load reduction in scenarios 1 and 2:

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

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

4.2 Office buildings

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

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B03 VS B13; or B04 VS B14) have a lower heat loss coefficient of the overall envelope; the envelope of an insulated building loses less heat (B01 VS B13 or B02 VS B14).
2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all office building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, no insulation, and older construction years, which often have higher heat loss coefficients in envelopes.
3) For the cooling load reduction in scenario 2 compared with the reference scenario, all office building types present an increased cooling load reduction with the increase of cooling degree hours. Similar to the scenario 1, a higher increase rate is observed in buildings with fewer floors, no insulation, and older construction years, which often have higher heat loss coefficients in envelopes.

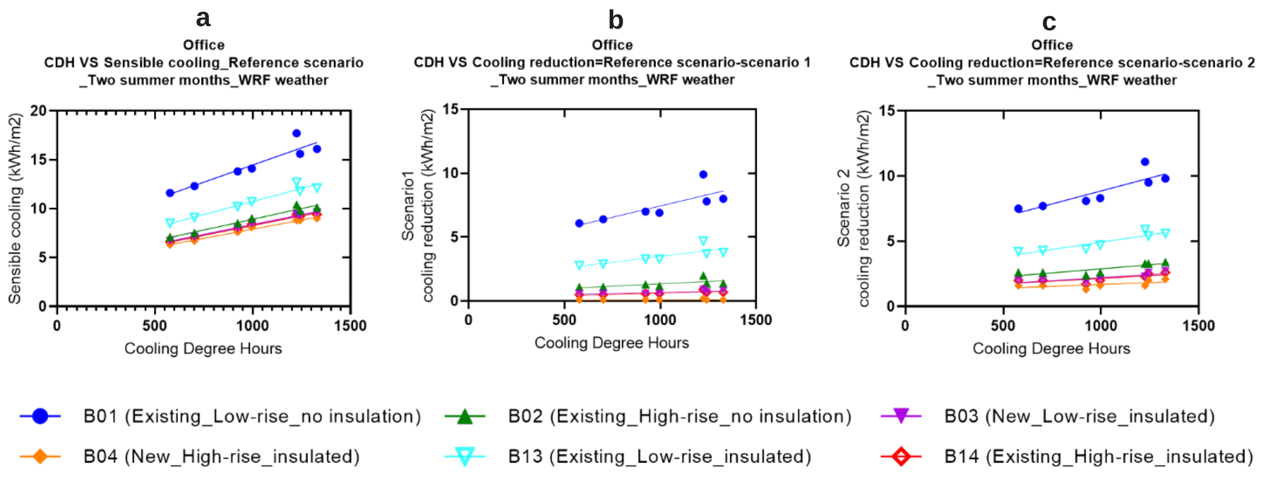


Figure 20 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 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)	0.007028	7.437	Y = 0.007028*X + 7.437
B02 (Existing_High-rise_no insulation)	0.004398	4.522	Y = 0.004398*X + 4.522
B03 (New_Low-rise_insulated)	0.004021	4.355	Y = 0.004021*X + 4.355
B04 (New_High-rise_insulated)	0.003745	4.159	Y = 0.003745*X + 4.159
B13 (Existing_Low-rise_insulated)	0.005342	5.392	Y = 0.005342*X + 5.392
B14 (Existing_High-rise_insulated)	0.004	4.276	Y = 0.004000*X + 4.276

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.00354	3.907	Y = 0.003540*X + 3.907
B02 (Existing_High-rise_no insulation)	0.0007326	0.625	Y = 0.0007326*X + 0.625
B03 (New_Low-rise_insulated)	0.000322	0.364	Y = 0.0003220*X + 0.364
B04 (New_High-rise_insulated)	0.00004604	0.068	Y = 0.00004604*X + 0.068
B13 (Existing_Low-rise_insulated)	0.00185	1.652	Y = 0.001850*X + 1.652
B14 (Existing_High-rise_insulated)	0.0004012	0.242	Y = 0.0004012*X + 0.242

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B01 (Existing_Low-rise_no insulation)	0.003972	4.889	Y = 0.003972*X + 4.889
B02 (Existing_High-rise_no insulation)	0.001237	1.650	Y = 0.001237*X + 1.650
B03 (New_Low-rise_insulated)	0.0009357	1.280	Y = 0.0009357*X + 1.280
B04 (New_High-rise_insulated)	0.0005805	1.106	Y = 0.0005805*X + 1.106
B13 (Existing_Low-rise_insulated)	0.002222	2.709	Y = 0.002222*X + 2.709
B14 (Existing_High-rise_insulated)	0.0008353	1.323	Y = 0.0008353*X + 1.323

4.3 Shopping mall centres

The correlation between cooling degree hours and the sensible cooling load in reference scenarios and the cooling load reduction in scenario 1 and scenario 2 for the 5 shopping mall centre building types (B05_New_Low-rise; B06_New_Mid-rise; B07_New_High-rise; B15_Existing_Low-rise; B16_Existing_High-rise) is shown in **Figure 21** and **Table 13**.

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

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all shopping mall 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.

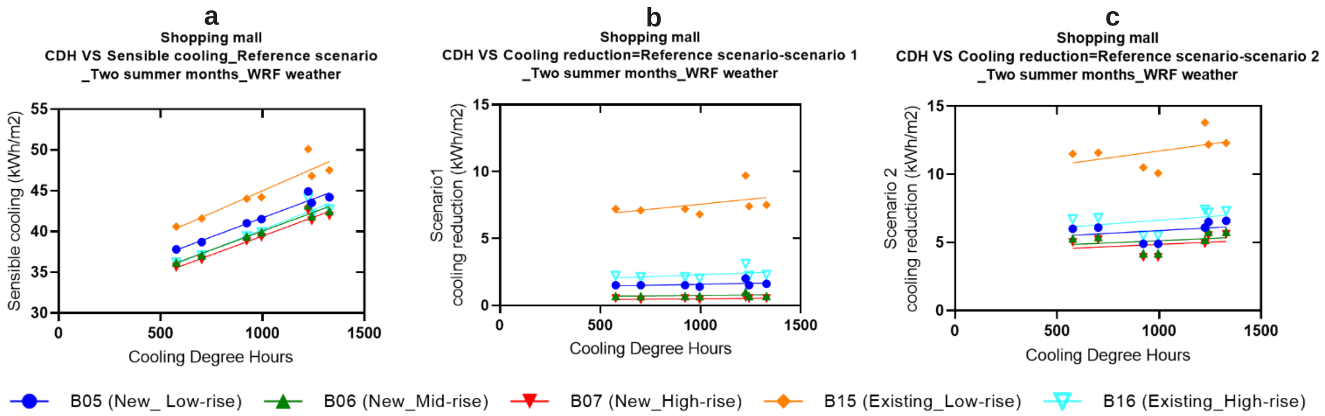


Figure 21 For shopping mall centre a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.009321	32.35	Y = 0.009321*X + 32.35
B06 (New_Mid-rise)	0.009208	30.83	Y = 0.009208*X + 30.83
B07 (New_High-rise)	0.009208	30.23	Y = 0.009208*X + 30.23
B15 (Existing_Low-rise)	0.01092	34.07	Y = 0.01092*X + 34.07
B16 (Existing_High-rise)	0.009806	30.41	Y = 0.009806*X + 30.41

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.0002981	1.274	Y = 0.0002981*X + 1.274
B06 (New_Mid-rise)	0.0001381	0.6049	Y = 0.0001381*X + 0.6049
B07 (New_High-rise)	0.0001072	0.3786	Y = 0.0001072*X + 0.3786
B15 (Existing_Low-rise)	0.001515	6.044	Y = 0.001515*X + 6.044
B16 (Existing_High-rise)	0.000559	1.727	Y = 0.0005590*X + 1.727

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B05 (New_ Low-rise)	0.0008154	5.057	Y = 0.0008154*X + 5.057
B06 (New_Mid-rise)	0.0006562	4.473	Y = 0.0006562*X + 4.473
B07 (New_High-rise)	0.0006629	4.195	Y = 0.0006629*X + 4.195
B15 (Existing_Low-rise)	0.002048	9.668	Y = 0.002048*X + 9.668
B16 (Existing_High-rise)	0.001108	5.522	Y = 0.001108*X + 5.522

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 5 residential building types (B08_Existing_Low-rise_apartment; B09_New_Mid-rise_apartment; B10_New_High-rise_apartment; B11_Existing_Standalone house; B17_New_Standalone house) is shown in **Figure 22** and **Table 14**.

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

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

3) For the cooling load reduction in scenario 2 compared with the reference scenario, all residential building types present an increased cooling load reduction with the increase of cooling degree hours. A higher increase rate is observed in buildings with fewer floors, no insulation, and older construction years, which often have higher heat loss coefficients in envelopes.

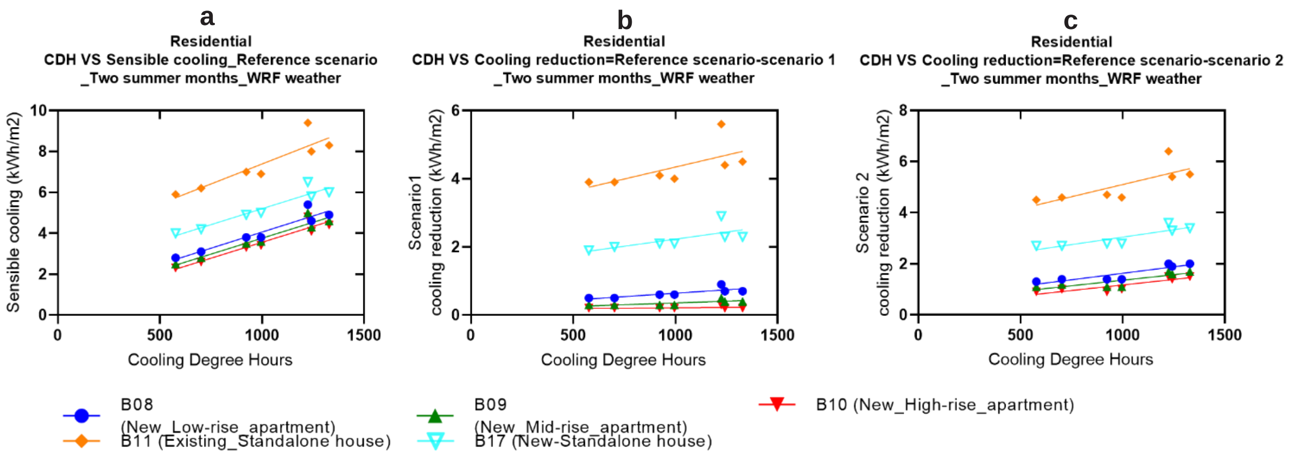


Figure 22 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.003155	0.9062	Y = 0.003155*X + 0.9062
B09 (New_Mid-rise_apartment)	0.003108	0.6529	Y = 0.003108*X + 0.6529
B10 (New_High-rise_apartment)	0.003108	0.4529	Y = 0.003108*X + 0.4529
B11 (Existing_Standalone house)	0.003904	3.487	Y = 0.003904*X + 3.487
B17 (New-Standalone house)	0.003117	2.086	Y = 0.003117*X + 2.086

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0004012	0.2421	Y = 0.0004012*X + 0.2421
B09 (New_Mid-rise_apartment)	0.0002088	0.1486	Y = 0.0002088*X + 0.1486
B10 (New_High-rise_apartment)	0.00004604	0.1683	Y = 0.00004604*X + 0.1683
B11 (Existing_Standalone house)	0.001401	2.943	Y = 0.001401*X + 2.943
B17 (New-Standalone house)	0.0008341	1.395	Y = 0.0008341*X + 1.395

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.001013	0.6169	Y = 0.001013*X + 0.6169
B09 (New_Mid-rise_apartment)	0.0008664	0.4918	Y = 0.0008664*X + 0.4918
B10 (New_High-rise_apartment)	0.0008656	0.3068	Y = 0.0008656*X + 0.3068
B11 (Existing_Standalone house)	0.0019	3.202	Y = 0.001900*X + 3.202
B17 (New-Standalone house)	0.001165	1.879	Y = 0.001165*X + 1.879

4.5 School

School load reduction in scenario 1 and scenario 2 for the one building type (B12_Existing) is shown in **Figure 23** 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 total cooling load increases with the increase of cooling degree hours. Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree, indicating that in most cases, under unmodified climatic conditions, a cool roof is more effective reducing the cooling load in hotter regions. For the cooling load reduction in scenario 2 compared with the reference scenario, B12 presents an increased cooling load reduction with the increase of cooling degree hours.

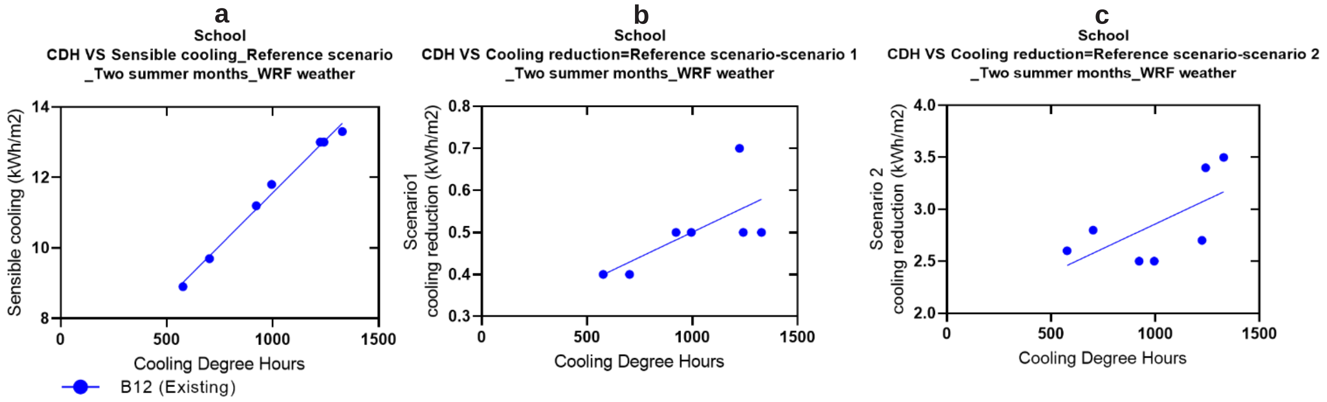


Figure 23 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared 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)	0.006011	5.554	Y = 0.006011*X + 5.554

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.0002385	0.2618	Y = 0.0002385*X + 0.2618

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.0009421	1.916	Y = 0.0009421*X + 1.916

4.6 Conclusion

- Regarding the sensible cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.
- Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.
- For the cooling load reduction in scenario 2 compared with the reference scenario, 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.
- 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
B09 (Apartment_New_Mid-rise)	0.003108
B10 (Apartment_New_High-rise)	0.003108
B17 (Standalone house_New)	0.003117
B08 (Apartment_New_Low-rise)	0.003155
B04 (Office_New_High-rise_insulated)	0.003745
B11 (Standalone house_Existing)	0.003904
B14 (Office_Existing_High-rise_insulated)	0.004
B03 (Office_New_Low-rise_insulated)	0.004021
B02 (Office_Existing_High-rise_no insulation)	0.004398
B13 (Office_Existing_Low-rise_insulated)	0.005342
B12 (School_Existing)	0.006011
B01 (Office_Existing_Low-rise_no insulation)	0.007028
B06 (Shopping mall_New_Mid-rise)	0.009208
B07 (New_High-rise)	0.009208
B05 (Shopping mall_New_ Low-rise)	0.009321
B16 (Shopping mall_Existing_High-rise)	0.009806
B15 (Shopping mall_Existing_Low-rise)	0.01092

5. Feasibility of cool roofs: Evaluation of refurbishment of 17 buildings for Frankston beach and Coldstream weather conditions

5.1 Methodological approach

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

1) Net Present Value

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

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

Merits:

(a) It recognizes the time value of money.

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

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

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

Demerits:

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

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

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

2) Internal Rate of Return Method

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

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

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

3) Depreciated Payback Period Method:

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

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

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

Merits:

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

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

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

Demerits:

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

4) Life Cycle Cost Analysis

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

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

Merits:

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

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

Demerits:

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

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

5) Synopsis:

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

5.2 Input data and information

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

- About the building:
    - Roof area
    - Building's energy consumption before and after the refurbishment
    - Installation cost of the cool roof (Metal roof – MR, and Coating – Coat)
    - Lifetime expectancy of the cool roofs
- On the cost of energy and economic parameters
    - Electricity retail price (Business as usual and high price scenario)
    - Increase rate of electricity price (incl. inflation)
    - Capital cost rate (incl. inflation)

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

Table 17 Building Features

Building features	B01 Frankston beach	BO1 Coldstream
Energy consumption prior cool roof (MWh)	23,50	38,8
Energy consumption after cool roof (MWh)	18,70	29,50
Energy savings (MWh)	4,80	9,30
Energy savings (%)	20,43%	23,97%
Area (m^2)	1.200	1.200
Roof costs - Metal roof (AU$/$m^2$)	38,00	38,00
Roof costs - Coating (AU$/$m^2$)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/$m^2$)	15,0	15,0

Table 18 Energy cost and economics

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

5.3 Assumptions

In order to be able to comparatively evaluate the feasibility of the ‘do nothing’, the metallic cool roof and the cool roof paint, 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.

5.4 Selection of most suitable methods

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

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

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

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

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

5.5 Presentation of results

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

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

5.1.1 Part 1. Results for Frankston Beach weather conditions

Table 19 Net Present Value for Frankston Beach weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	-23.208	-10.071	-47.820	-21.237
2	-25.402	-11.783	-7.790	1.958
3	-41.639	-24.451	-39.181	-22.533
4	-42.078	-24.793	-40.030	-23.195
5	-23.468	-10.943	-7.494	1.519
6	-25.223	-12.313	-10.888	-1.129
7	-25.662	-12.655	-11.737	-1.791
8	-23.899	-14.467	-24.718	-15.106
9	-23.460	-14.125	-23.870	-14.444
10	-24.777	-15.152	-26.415	-16.430
11	-9.367	-5.688	-9.777	-6.007
12	-39.705	-23.611	-38.886	-22.972
13	-31.985	-16.918	-20.516	-7.971
14	-33.740	-18.288	-23.910	-10.619
15	34.458	34.250	104.496	88.893
16	24.365	26.375	84.982	73.669
17	-8.489	-5.003	-8.080	-4.683

Table 20 Internal Rate of Return for Frankston Beach weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	-1,66%	-0,95%	-1,85%	-1,21%
2	-2,27%	-1,77%	-2,27%	3,65%
3	-11,28%	-13,48%	-8,56%	-10,02%
4	-12,00%	-14,38%	-9,34%	-11,01%
5	-2,33%	-1,85%	1,60%	3,55%
6	-2,91%	-2,63%	0,90%	2,57%
7	-3,06%	-2,84%	0,72%	2,32%
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	-15,11%	-18,25%	-12,66%	-15,20%
13	-4,50%	-4,75%	-0,97%	-0,02%

14	-5,25%	-5,74%	-1,85%	-1,21%
15	8,02%	12,98%	15,91%	25,84%
16	6,70%	10,97%	13,83%	22,32%
17	-12,03%	-14,42%	-9,37%	-11,06%

Table 21 Life Cycle Cost for Frankston Beach weather data

LCC	**Low Electricity Price**			**High Electricity Price**		
Building	**As built**	**Metal Roof**	**Coating**	**As is**	**Metal Roof**	**Coating**
1	114.679	124.623	88.818	222.484	243.888	173.481
2	308.644	317.563	238.641	585.928	572.634	436.635
3	67.724	96.877	67.343	120.150	145.976	105.458
4	264.322	290.652	217.807	500.238	520.606	396.355
5	413.879	420.064	318.894	790.281	774.247	593.853
6	769.772	771.808	592.025	1.478.342	1.454.285	1.121.905
7	1.122.595	1.119.215	861.783	2.160.465	2.125.938	1.643.437
8	135.903	151.638	113.655	257.138	271.681	206.869
9	215.331	229.310	173.965	410.700	421.847	323.468
10	336.449	349.735	267.478	644.861	654.668	504.259
11	21.639	28.355	20.432	39.660	46.487	34.512
12	231.763	257.207	192.499	438.190	459.390	349.487
13	86.594	105.780	74.219	156.632	163.187	66.532
14	280.997	298.713	224.035	532.478	536.191	408.397
15	426.166	374.222	283.084	814.036	685.618	524.619
16	1.125.228	1.071.777	824.762	2.148.293	2.034.225	1.571.864
17	14.617	20.573	14.385	26.085	31.441	22.823

Table 22 Payback Period for Frankston Beach weather data

PB	**Low Electricity Price**		**High Electricity Price**	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	-	-	-	-
2	-	-	23,4	15,9
3	-	-	-	-
4	-	-	-	-
5	-	-	23,6	16,1
6	-	-	-	17,5
7	-	-	25,9	17,9
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-

11	-	-	-	-
12	-	-	-	-
13	-	-	-	-
14	-	-	-	-
15	12,5	7,9	6,9	4,2
16	14,1	9,1	7,9	4,8
17	-	-	-	-

In order to comparatively illustrate the results for the 17 buildings, in the following **Figure 25** and **Figure 26** are depicted their Internal Rate of Return and their Life Cycle Cost values.

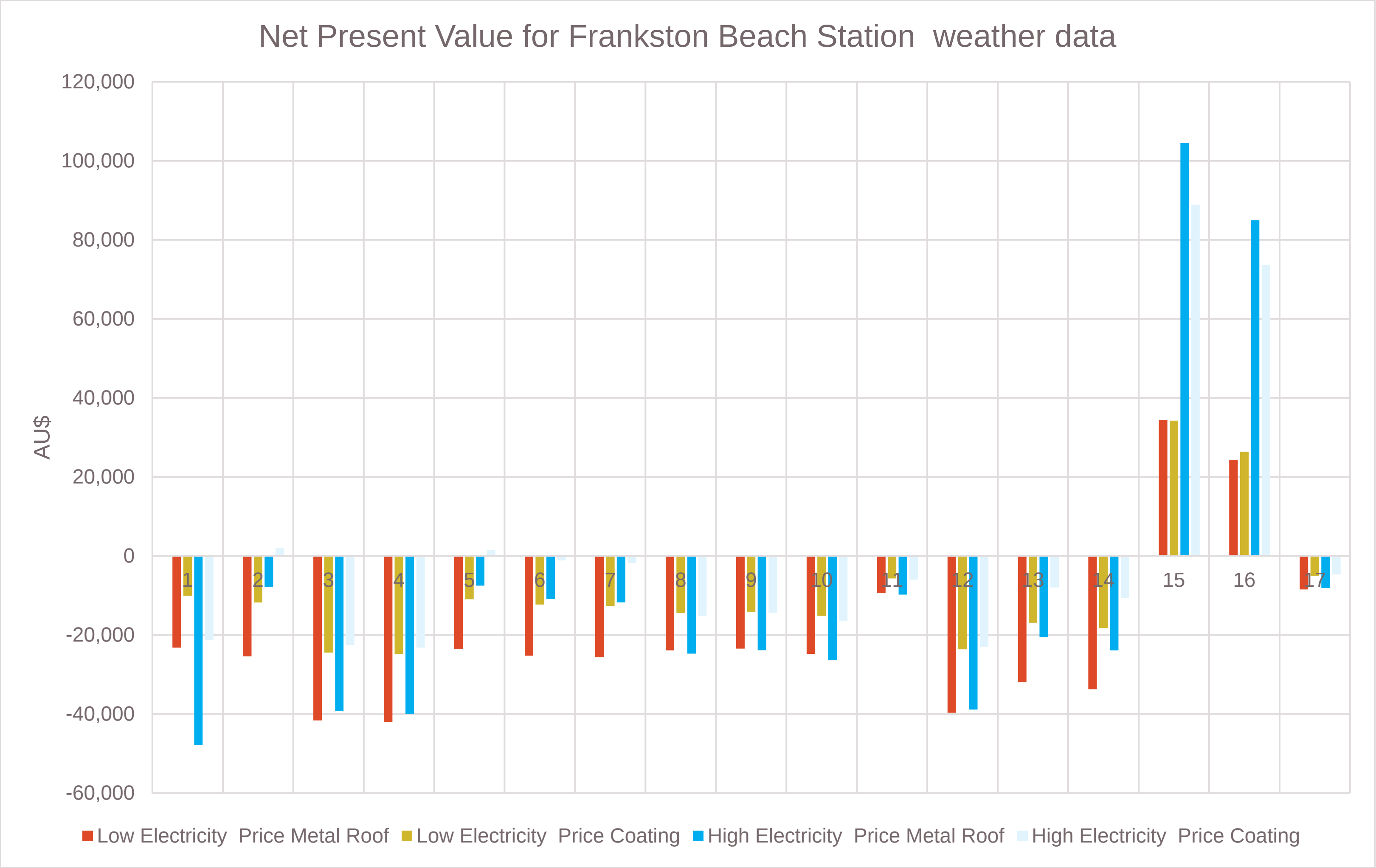


Figure 24 Net Present Value for the buildings for Frankston Beach weather conditions

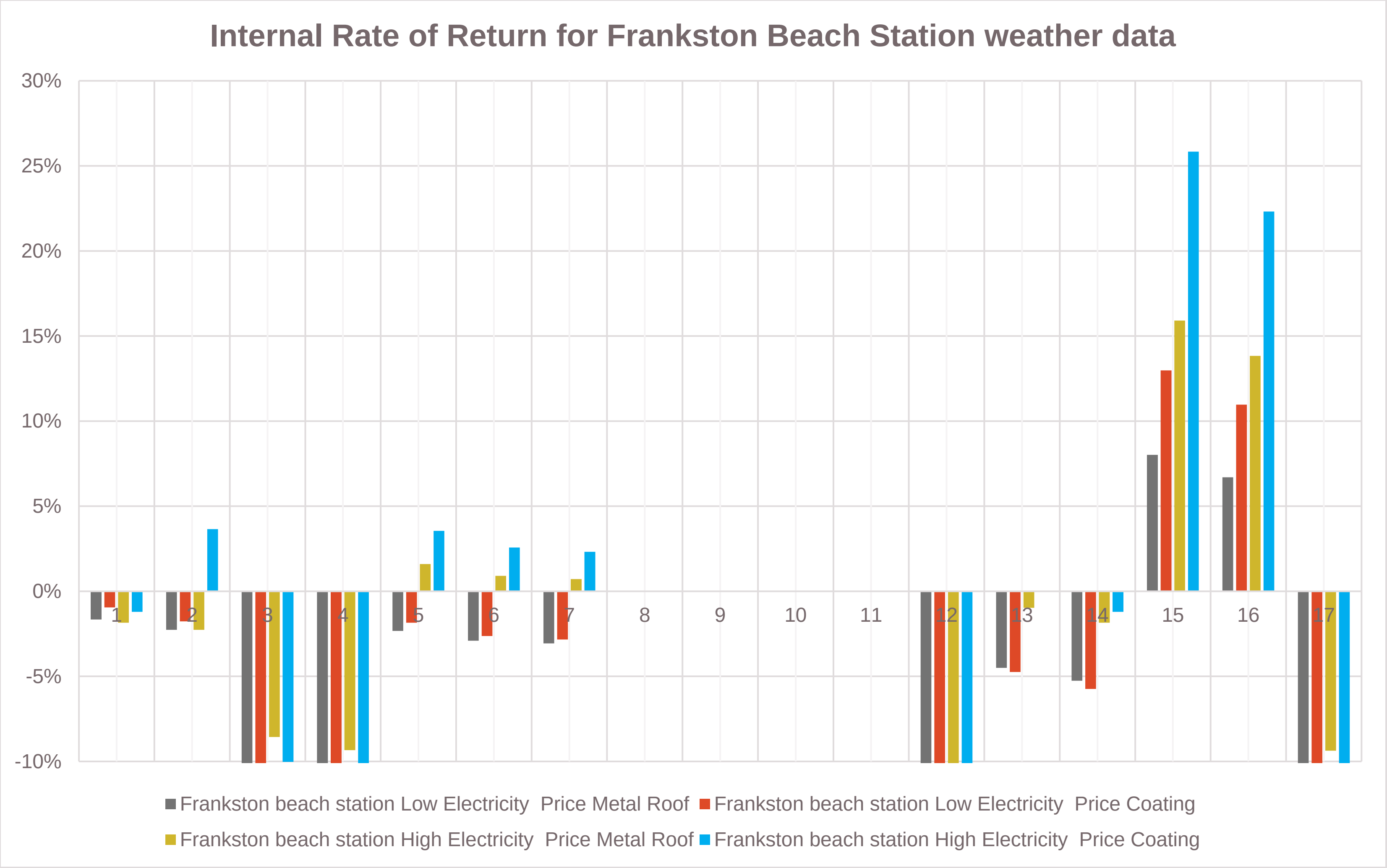


Figure 25 Internal Rate of Return for the buildings for Frankston Beach weather conditions

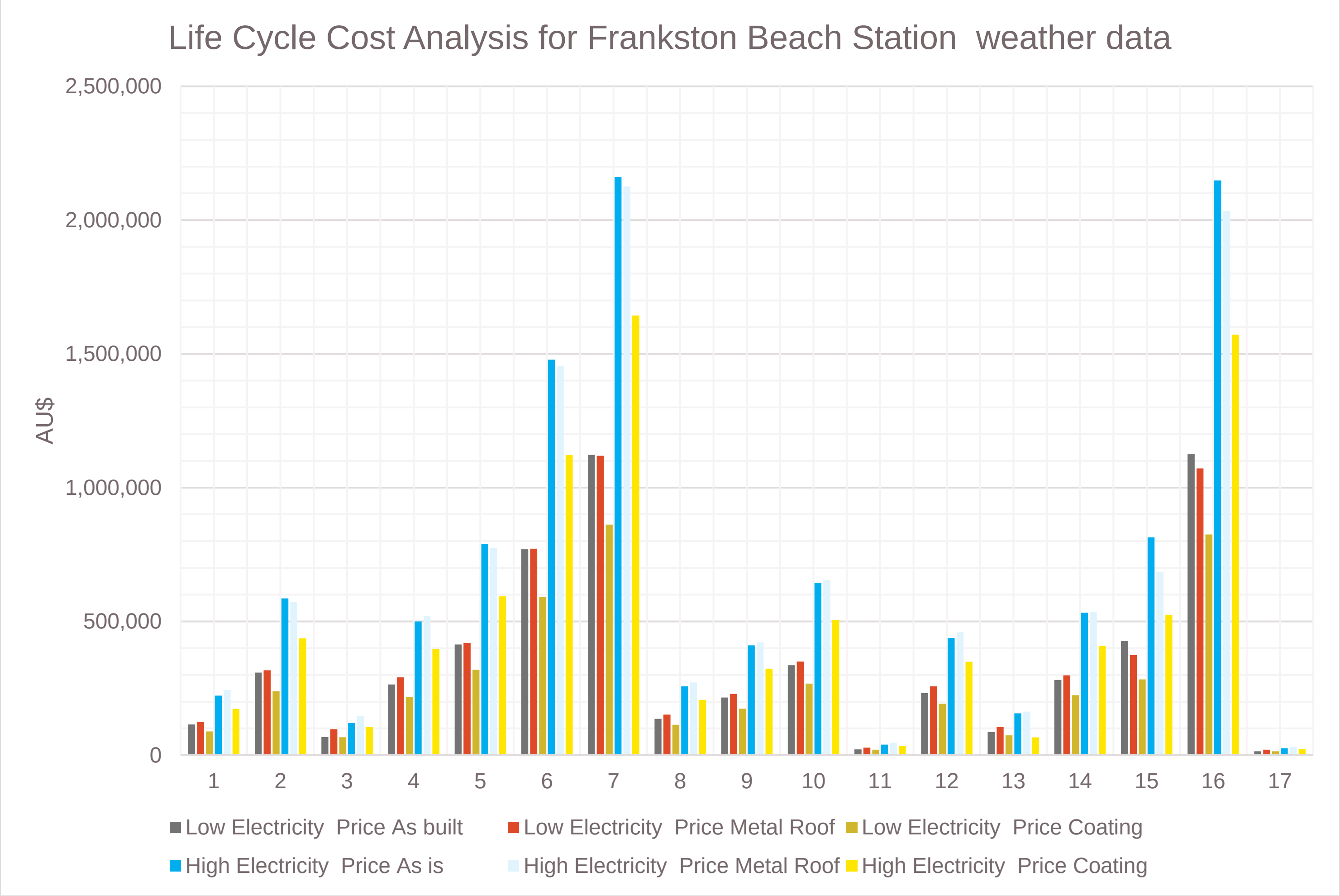


Figure 26 Life Cycle Cost for the buildings for Frankston Beach weather conditions

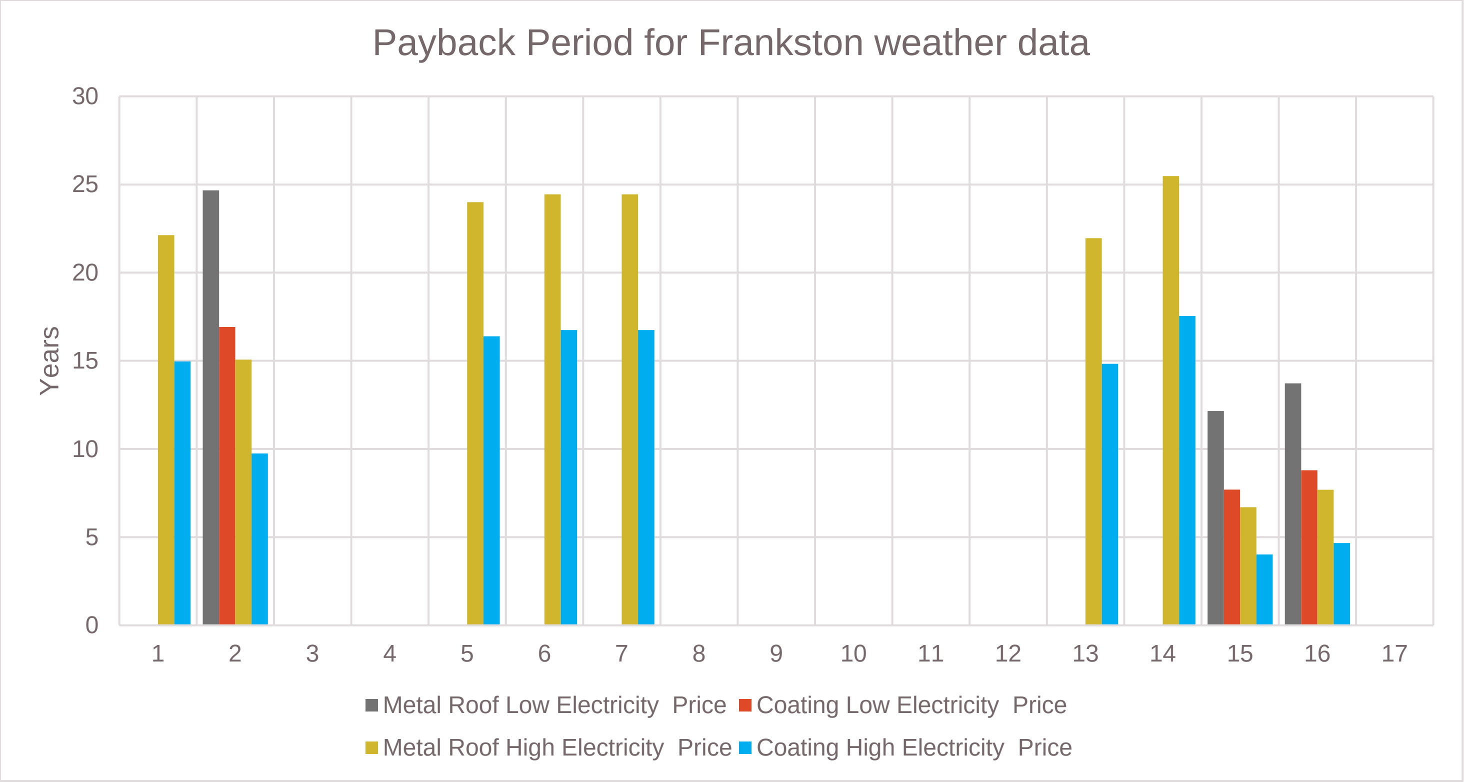


Figure 27 Payback Period for the buildings for Frankston Beach weather conditions

5.1.2 Part 2. Results for Coldstream weather conditions

Table 23 Net Present Value for Coldstream weather data

NPV	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	-3.460	5.336	-9.641	8.549
2	-10.482	-142	21.056	24.463
3	-40.322	-23.423	-36.636	-20.548
4	-40.322	-23.423	-36.636	-20.548
5	-23.907	-11.286	-8.343	857
6	-24.346	-11.628	-9.191	195
7	-24.346	-11.628	-9.191	195
8	-23.899	-14.467	-24.718	-15.106
9	-23.899	-14.125	-24.718	-15.106
10	-23.899	-14.467	-24.718	-15.106
11	-9.367	-5.688	-9.777	-6.007
12	-38.827	-22.927	-37.189	-21.648
13	-23.647	-10.413	-4.397	4.606
14	-27.596	-13.495	-12.032	-1.352
15	37.091	36.304	109.586	92.865
16	26.559	28.087	89.224	76.978
17	-8.489	-5.003	-8.080	-4.683

Table 24 Internal Rate of Return for Coldstream weather data

IRR	Low Electricity Price		High Electricity Price	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	2,43%	4,72%	2,20%	4,39%
2	1,17%	2,95%	1,17%	9,92%
3	-9,64%	-11,39%	-6,76%	-7,71%
4	-9,64%	-11,39%	-6,76%	-7,71%
5	-2,47%	-2,04%	1,43%	3,32%
6	-2,61%	-2,23%	1,26%	3,07%
7	-2,61%	-2,23%	1,26%	3,07%
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	-12,53%	-15,04%	-9,90%	-11,73%
13	-1,78%	-1,11%	2,27%	4,50%
14	-2,93%	-2,66%	0,87%	2,53%
15	8,35%	13,49%	16,44%	26,77%

16	7,00%	11,42%	14,29%	23,08%
17	-12,03%	-14,42%	-9,37%	-11,06%

Table 25 Life Cycle Cost for Coldstream weather data

LCC	**Low Electricity Price**			**High Electricity Price**		
Building	**As built**	**Metal Roof**	**Coating**	**As is**	**Metal Roof**	**Coating**
1	181.821	170.902	124.680	352.291	333.363	242.816
2	569.750	559.416	426.381	1.090.733	1.040.216	799.599
3	120.384	147.347	106.527	221.959	243.551	181.214
4	512.701	533.155	406.100	980.439	989.445	760.390
5	508.228	513.287	391.282	972.689	954.477	733.802
6	947.500	945.709	727.053	1.821.949	1.790.493	1.382.960
7	1.384.578	1.375.534	1.060.806	2.666.966	2.621.490	2.028.216
8	181.980	196.951	148.840	346.221	359.286	274.893
9	289.494	302.682	230.938	554.081	563.698	433.616
10	453.618	464.082	356.263	871.387	875.738	675.911
11	26.466	33.102	24.118	48.993	55.665	41.639
12	361.219	383.637	290.666	688.471	622.769	539.279
13	144.959	154.838	112.282	269.471	258.034	192.340
14	533.765	541.143	412.256	1.021.163	1.004.889	772.290
15	530.608	474.298	360.782	1.015.958	879.099	674.835
16	1.395.988	1.335.850	1.029.803	1.395.988	1.334.810	1.028.763
17	21.639	27.478	19.747	39.660	31.441	33.189

Table 26 Payback Period for Coldstream weather data

PB	**Low Electricity Price**		**High Electricity Price**	
Building	**Metal Roof**	**Coating**	**Metal Roof**	**Coating**
1	-	-	22,1	15,0
2	24,7	16,9	15,1	9,8
3	-	-	-	-
4	-	-	-	-
5	-	-	24,0	16,4
6	-	-	24,4	16,7
7	-	-	24,4	16,7
8	-	-	-	-
9	-	-	-	-
10	-	-	-	-
11	-	-	-	-
12	-	-	-	-
13	-	-	22,0	14,8

14	-	-	25,5	17,5
15	12,1	7,7	6,7	4,0
16	13,7	8,8	7,7	4,7
17	-	-	-	-

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

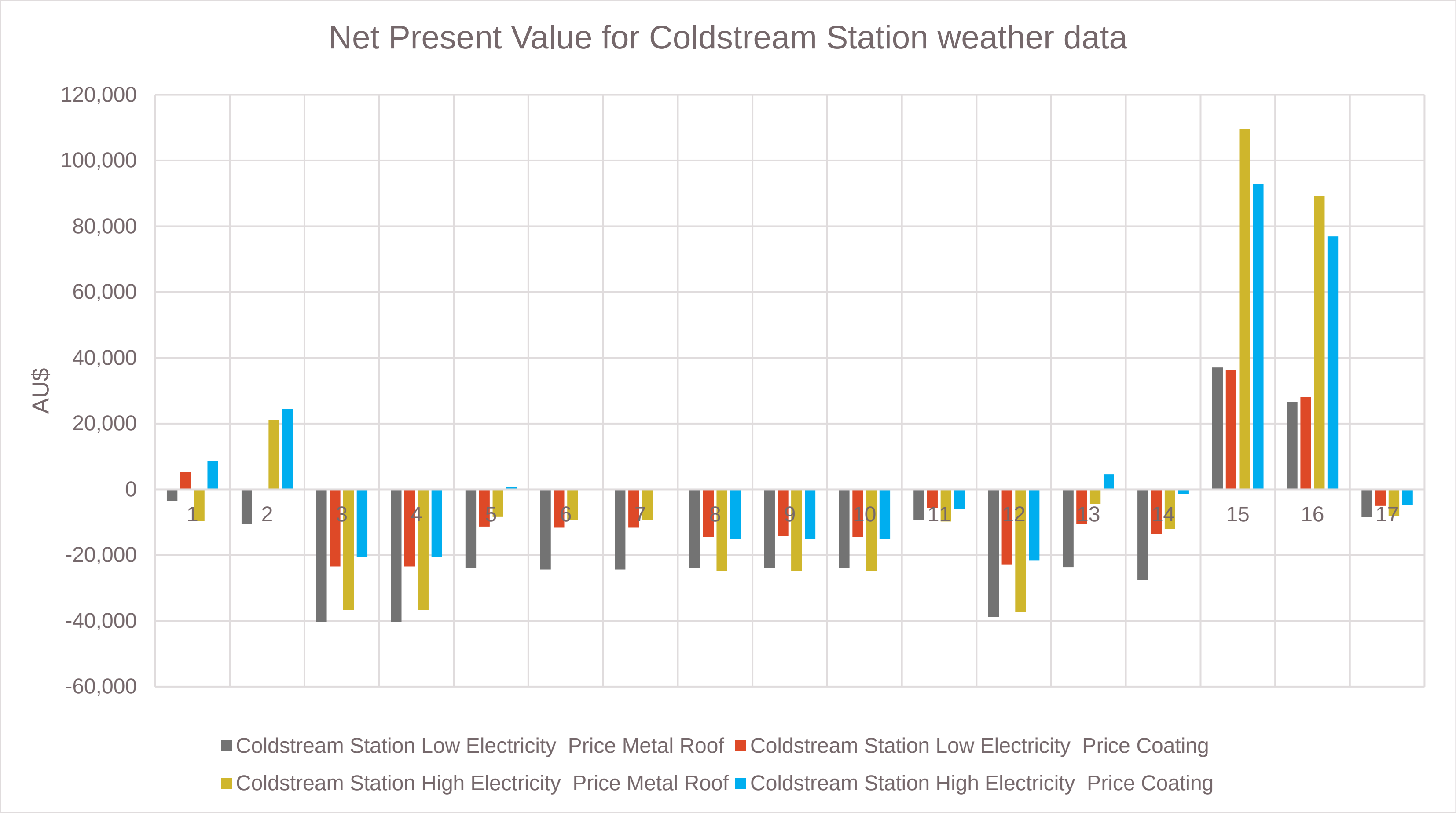


Figure 28 Net Present Value for the buildings for Coldstream weather conditions

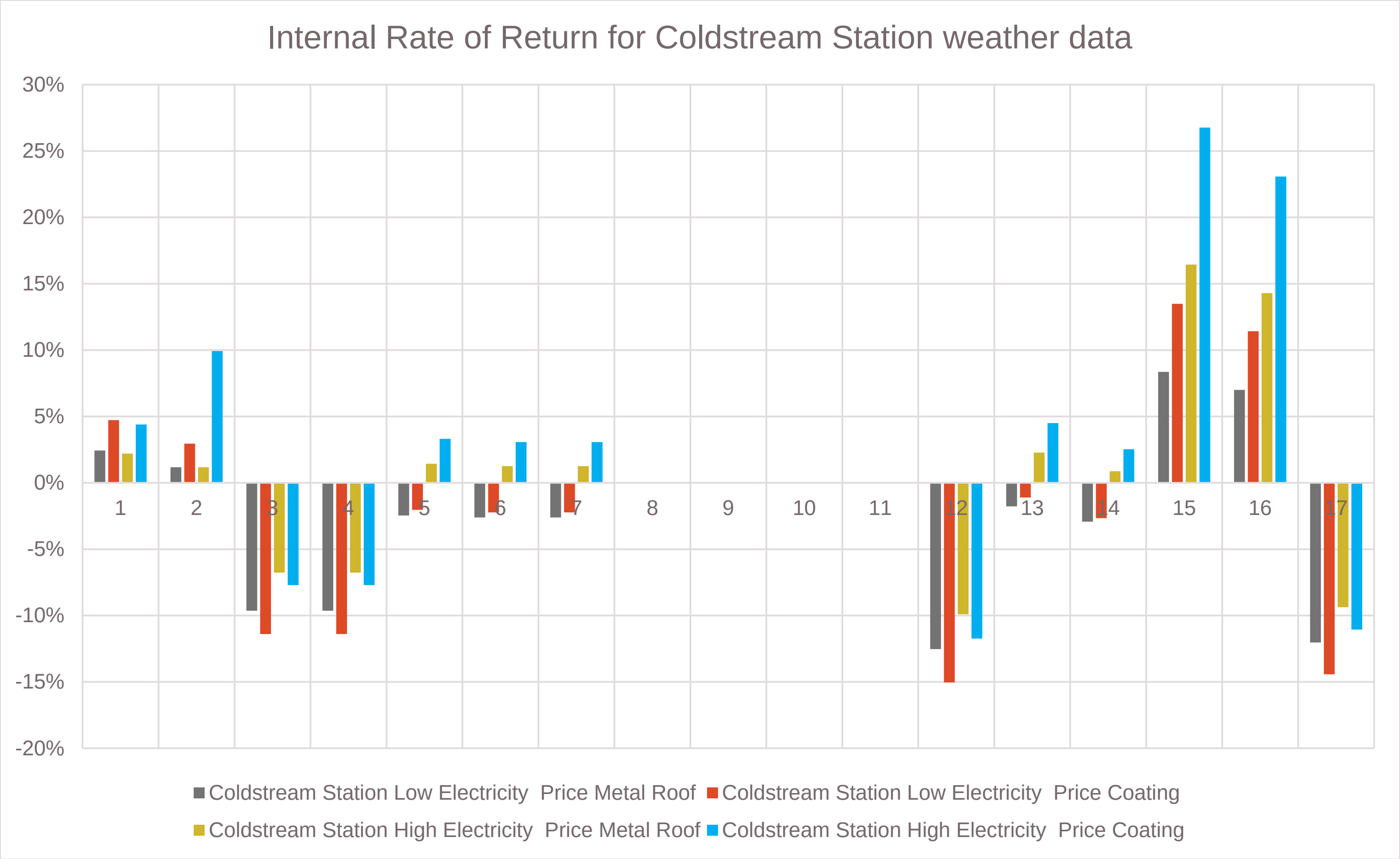


Figure 29 Internal Rate of Return for the buildings for Coldstream weather conditions

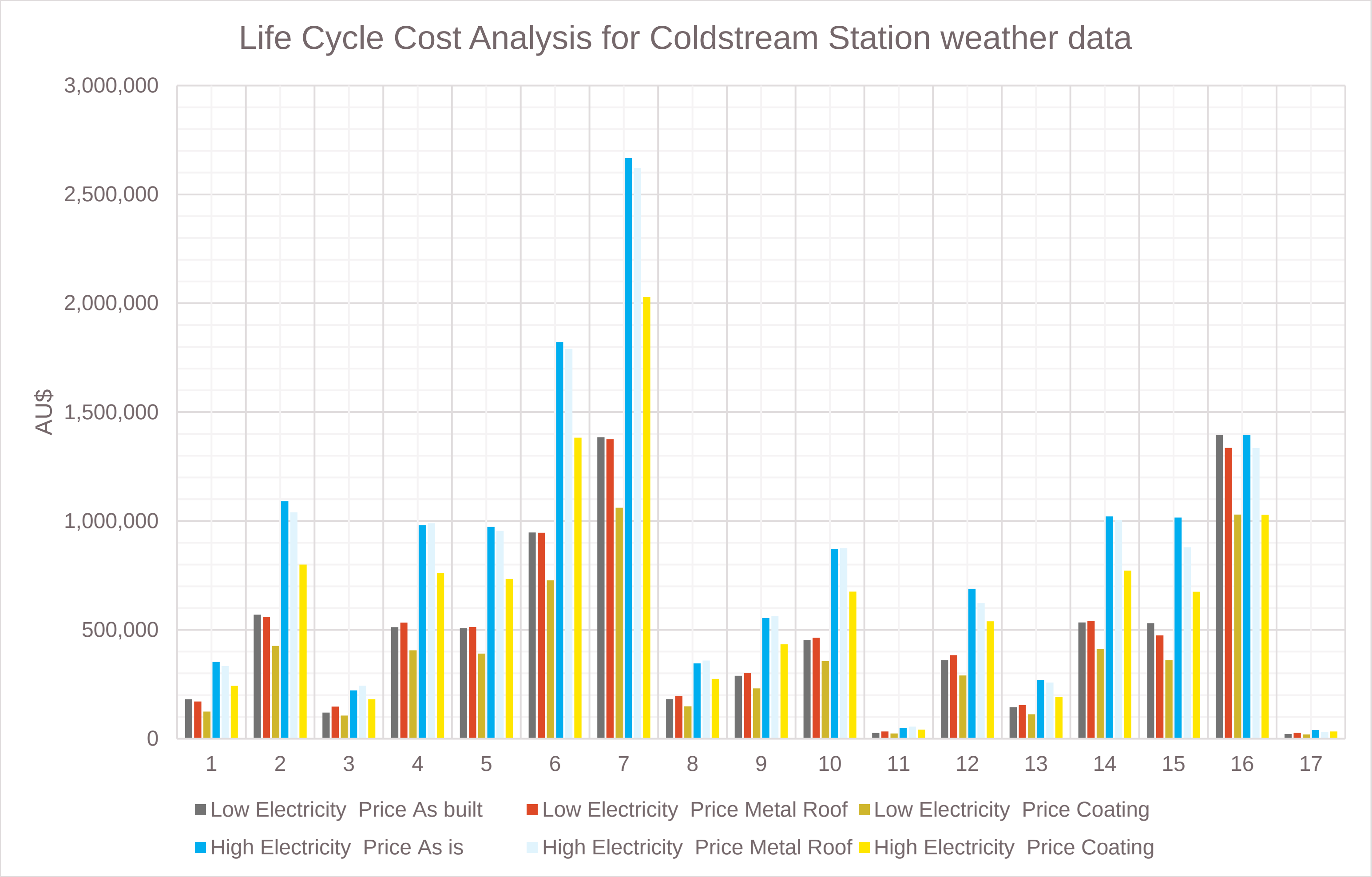


Figure 30 Life Cycle Cost for the buildings for Coldstream weather conditions

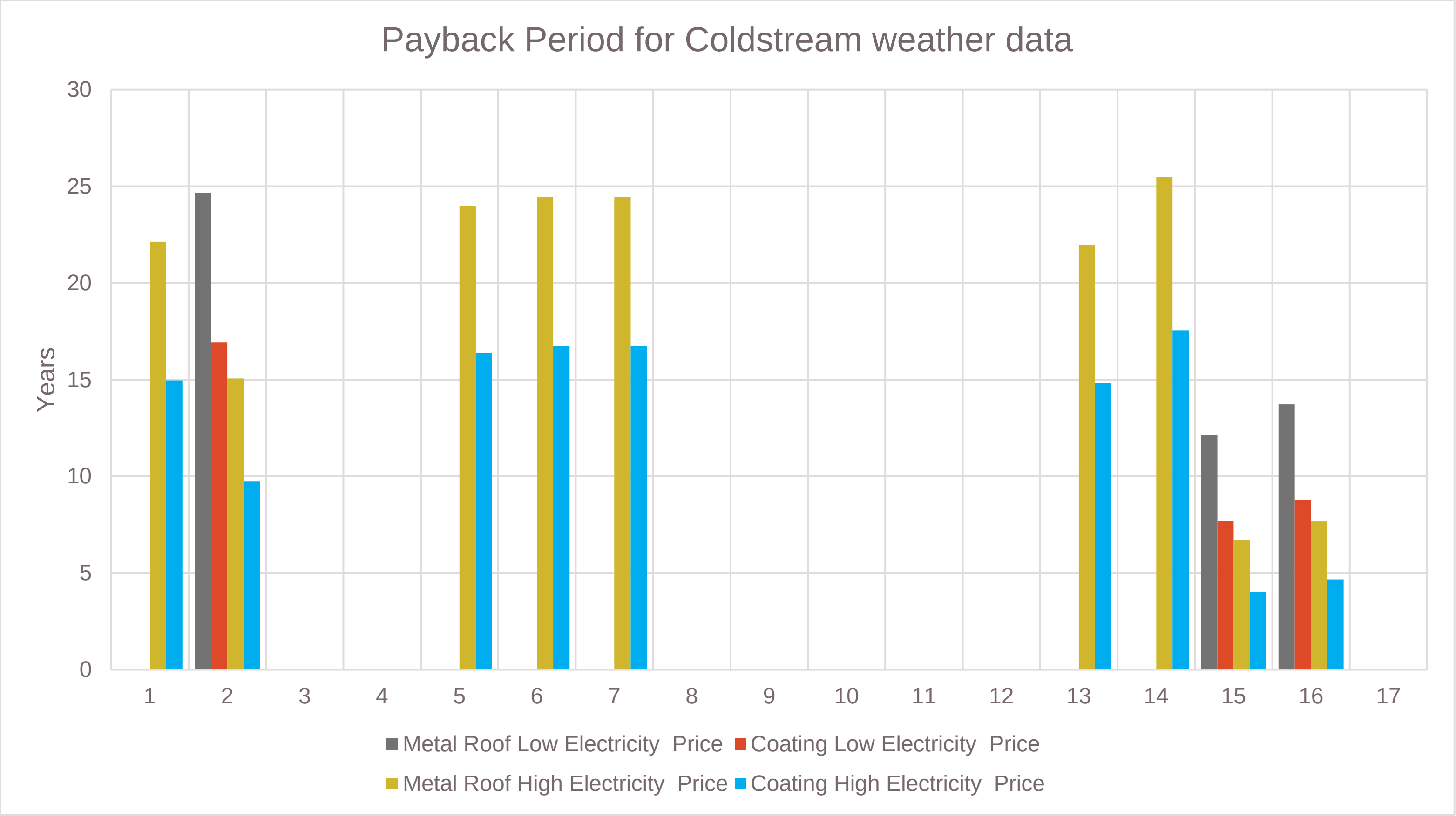


Figure 31 Payback Period for the buildings for Coldstream weather conditions

5.6 Discussion of the results

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

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

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

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

Considering the NPV and IRR results, when the differences between the savings are flow, there 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, which affects the NPV and IRR results stronger than the LCC. In any case, the differences are minor and, given the fact that we are considering energy and cost savings, the LCC is the method that produces the most valid results.

With respect to the 17 buildings considered, it does not come as a surprise that low-rise buildings without thermal insulation of the roof and with high energy requirements are presenting the biggest energy savings potential and consequently the most attractive economic results. For such buildings (like, for example, B01 and B15), the Life Cycle Cost can be reduced by as much as 45%. In such favourable cases, the Payback Period can be as low as 4.2 years.

But even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B03 and B17) and for lower electricity prices, the Life Cycle Cost of the coating cool roof can be reduced compared to the “Do nothing” conventional roof, which is more than enough to justify the cool coating’s application, despite comparatively longer Payback Periods.

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

6. Conclusions

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

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

Specifically, the following conclusions have been drawn:

1) It is observed that a sturdy urban heat island (UHI) phenomenon is developed during heatwave over high-density residential areas of Melbourne city. The magnitude of the phenomena may exceed 5°C. The intensity and the spatio-temporal characteristics of the phenomena are strappingly influenced by the synoptic weather conditions and, in particular, the advance of the sea breeze and the westerly winds from the desert area. The potential existence of an additional heating mechanism, like the advection of warm air from nearby spaces, could intensify the strength of the problems of urban heating.
2) An increase of albedo fraction in Melbourne city can decrease the peak ambient temperature up to 2.1°C and surface temperature up to 11.1°C. It was noted that significant temperature differences subsist between the eastern and western parts of the city. The spatio-temporal patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the potency of the advection flows.
3) The maximum decrease of sensible heat and latent heat flux was 292.8 Wm-^{2} and 15.1 Wm-^{2}, respectively.
4) The highest decrease of wind speeds up to -3.4 ms-1. Thus, higher urban albedo values decrease the advective flow between the city and its surroundings surface improving the cooling potential of reflective materials. Modification of the urban albedo in Melbourne results in an average 1590.6m reduction up to of the PBL heights over the city and may increase the concentration of pollutants at ground level and subsequently increase the health problems.
5) High intensities of the UHI phenomenon were associated with the existence of a sea breeze in the seaward parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that warm up 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 mostly around 1-7 °C lower than that in the reference scenario, indicating the cooling benefits of cool roof. Around 51%-75% of the ambient temperatures in all stations concentrate in the range of 10-19 °C.
7) In control cases, CDH ranges from 185.8 to 1328.5, and about half of the data is concentrated in 1000-1300. CDH gradually increases from the southeast of the city to the northwest.
8) In cool roof cases, CDH ranges from 114.9 to 1059.8, and about 75% of the data is concentrated in 300-800. Its spatial distribution is also similar to that of the control case.

9) In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in control 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 20.2% to 42.4%, with an average value of 31.2%. The percentage of CDH reduction in the original control volume is relatively large in the southeast corner of the city and gradually decreases toward the northwest and northeast.
11) In existing low-rise buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in individual buildings (scenario 1) is significant. For instance, the application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 6.3-10 kWh/m^2.
12) In existing low-rise buildings without insulation/with low level of insulation, the cooling load saving by the implementation of cool roofs in both individual building and in the whole urban area (scenario 2) is significant. For instance, the application of cool roofs in both individual building and in the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 8.3-11.7 kWh/m^2.
13) In new low-rise buildings with high insulation level, the application of cool roofs in both individual building and in the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and in the whole urban area (scenario 2) is predicted to be 2.4-3.3 kWh/m^2 in a typical new low-rise office building.
14) In high-rise buildings, the application of cool roofs in individual buildings (scenario 1) is predicted to have a relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.1-0.2 kWh/m^2 for a new high-rise office building with insulation.
15) In high-rise buildings, the cooling load reduction through the application of cool roofs in both individual building and in the whole urban area (scenario 2) is significantly higher than the cooling load savings by the implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 2.1-3.2 kWh/m^2 in an existing high-rise shopping mall centre, which is expected to increase to 7.5-9.7 kWh/m^2 when cool roofs are applied both in individual buildings and in the whole urban area (scenario 2).
16) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in a majority of building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 8.8-14.4 kWh/m^2, while the corresponding heating penalty is just 3.3-7.5 kWh/m^2.
17) The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Melbourne. For instance, the heating penalty can be up to 6.8-8.5 kWh/m^2 compared to the equivalent 5.6-8.3 kWh/m^2 in an existing stand-alone house.
18) In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, the application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 8.1-10.0 ^{o}C.
19) In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, the application of cool roofs in both individual building and in the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and in the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 9-10.4 ^{o}C.

20) In existing buildings without insulation/with low level of insulation and under free-floating conditions in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and in the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ºC. For instance, the number of hours with an indoor air temperature above 26 ºC in a typical low-rise office building without insulation is predicted to reduce from 334-395 hours to 193-253 hours and 152-197 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
21) In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, the application of cool roofs in both individual building and in the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum indoor air temperature reduction by application of cool roofs in both individual building and in the whole urban area (scenario 2) is predicted to be 2.1-2.2 ºC in a typical new low-rise office building.
22) In new low-rise buildings with high insulation level and under free-floating conditions in a typical summer period, application of cool roofs in both individual building and in 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 a new low-rise office building with insulation is predicted to reduce from 345-399 hours to 250-305 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
23) The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by applying cool roofs in individual buildings in a low-rise office building without roof insulation is predicted to be 8.1-10 ºC in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 1.7-1.9 ºC during a typical winter month.
24) The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ºC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.8 ºC occurs when the indoor air temperature is 22.8 ºC.
25) 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 179-200 hours to 200-229 hours in a typical existing low-rise office building with roof insulation.
26) 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.
27) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors and older construction years, which often have higher heat loss coefficients in envelopes.
28) For the cooling load reduction in scenario 2 compared with the reference scenario, except for four shopping mall centre building types (B05, B06, B07, B16), most buildings present an increasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in hotter areas for most buildings.

29) A general ranking of the heat loss coefficients of these buildings from low to high is shopping mall centre, standalone house, apartment, and office.
30) With respect to the 17 buildings considered, it does not come as a surprise that low-rise buildings without thermal insulation of the roof and with high energy requirements are presenting the biggest energy savings potential and consequently the most attractive economic results. . For such buildings (like, for example, B01 and B15), the Life Cycle Cost can be reduced by as much as 45%. In such favourable cases, the Payback Period can be as low as 4.2 years.
31) But even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B03 and B17) and for lower electricity prices, the Life Cycle Cost of the coating cool roof can be reduced compared to the “Do nothing” conventional roof, which is more than enough to justify the cool coating’s application, despite comparatively longer Payback Periods.
32) Finally, the impact of electricity prices is, as expected, a big one: it leads to drastically higher Life Cycle Costs for the ‘Do Nothing’ solution, and consequently to shortened Payback Periods for the application of cool roofs. The currently prevailing volatility in the energy markets is a good reminder that energy conservation measures pay off, especially when implemented on time and not after having been hit by an energy crisis.

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8. Appendix: Meso-scale simulation results

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

Parameters	**Ambient Temperature at 2m (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-1.9	-2.1	-1.7	-1.8
Minimum	-0.2	-0.1	-0.3	-0.2
Average of January	-0.4	-0.9	-0.5	-0.7
Average of February	-0.4	-0.8	-0.7	-0.9

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

Parameters	**Surface Temperature (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-7.1	-11.1	-3.3	-3.2
Minimum	-0.4	-0.7	-0.2	-0.5
Average of January	-1.0	-6.3	-3.0	-2.9
Average of February	-0.9	-5.8	-2.6	-2.7

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

Parameters	**Sensible Heat Flux (Wm^{-2})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-58.8	-292.8	-118.0	-105.8

Minimum	-8.6	-67.1	-22.2	-31.2
Average of January	-50.4	-178.6	-62.2	-74.6
Average of February	-49.7	-171.6	-56.9	-69.2

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

Parameters	**Latent Heat Flux (Wm^{-2})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-6.4	-15.1	-5.2	-7.1
Minimum	-2.1	-1.1	-1.6	-1.2
Average of January	-3.8	-12.8	-2.3	-5.2
Average of February	-4.2	-11.9	-2.5	-4.3

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

Parameters	**Wind Speed (ms^{-1})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-1.8	-3.4	-2.2	-2.6
Minimum	-0.7	-1.1	-1.6	-0.3
Average of January	-0.8	-1.4	-0.9	-1.6
Average of February	-1.2	-2.6	-1.6	-1.9

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

Parameters	**PBL Height (m)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-235.7	-1590.6	-986.5	-407.6
Minimum	-49.8	-29.7	-29.6	-12.4
Average of January	-34.9	-228.7	-124.7	-102.6
Average of February	-16.1	-284.1	-112.4	-95.6

9. Appendix: Building characteristics_ Cool roofs project simulations inputs _ Climate zone 6

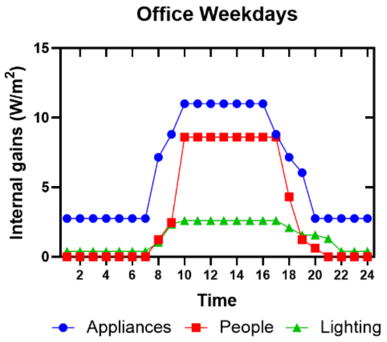
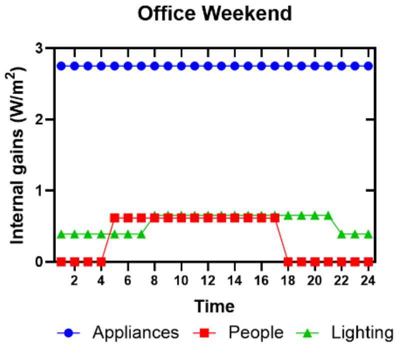
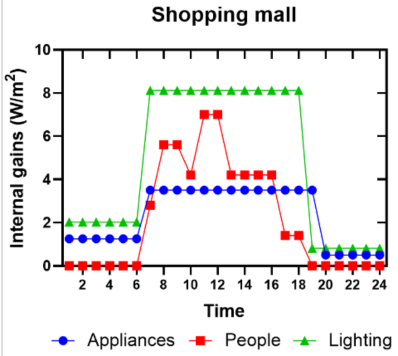
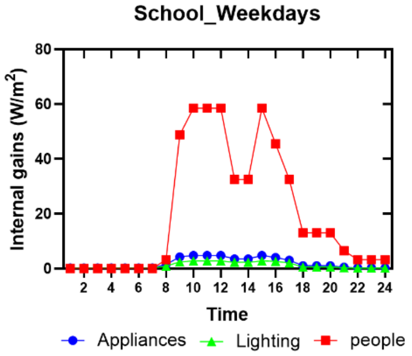
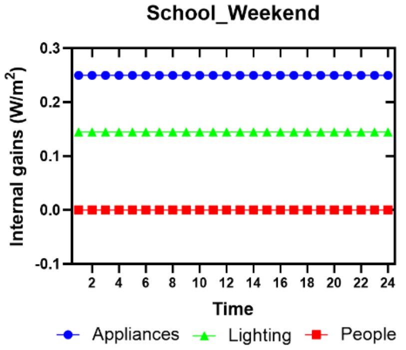
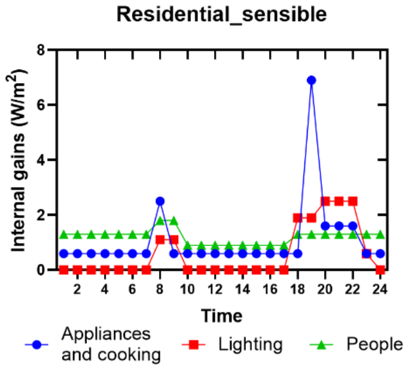
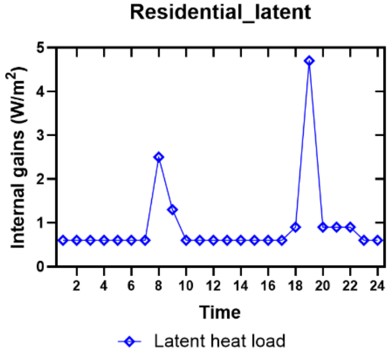
The following **Table 33** to **Table 36** have presented the general building parameters, internal gains, and ventilation; operation schedules; ventilation, HVAC, and setpoints parameters and building envelope parameters employed in the simulations in **Chapter 3**.

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

		Office			Shopping mall		School	Standalone House		Apartment
Building ID		**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type		Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Floor area (m^2)		1200			1100		1100	242		624
Aspect ratio		1:1			2:1		2:1	1:2		1:4.3
Window to Wall Ratio (WWR)		0.6			0.3		0.32	0.14	0.15	0.24
Year Built		1990		2018	1990	2018	1990	1990	2018	1990
Number of stories ***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/m^2)		0.1			0.2		0.5	0.02	0.025	0.04

Continues

Table 34 Operation schedules

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

continues

Table 35 Ventilation, HVAC, and setpoints parameters

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

Continues

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

Table 36 Building envelope parameters

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

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