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COOL ROOFS COST BENEFIT ANALYSIS

Volume 9 – Adelaide: Analysis and Results of the Climatic and Energy Performance of Cool Roofs. Description and Results of Building Case Studies.

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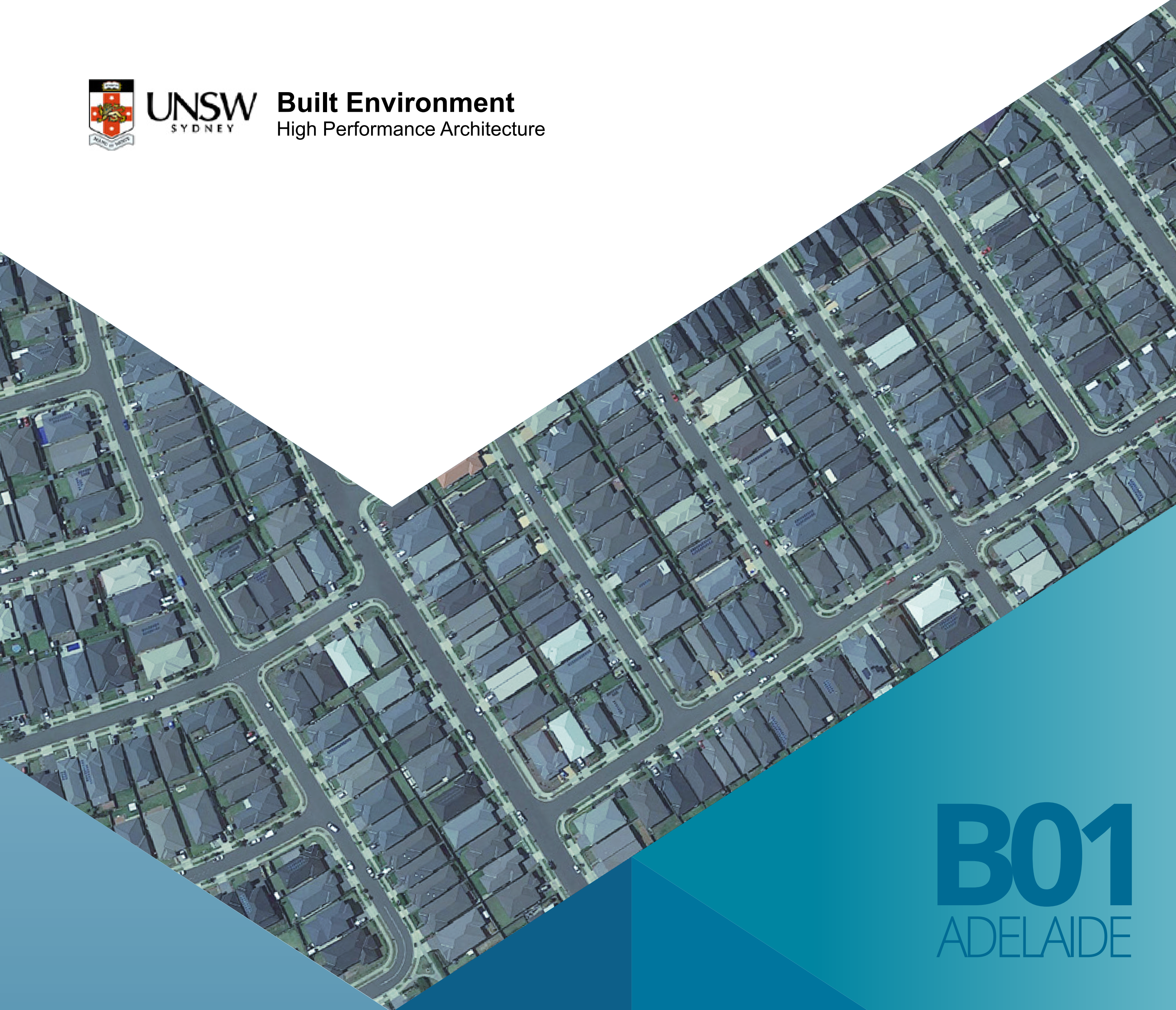

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ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

Low-rise office building without roof insulation
2021

BUILDING 01

LOW-RISE OFFICE BUILDING WITHOUT ROOF INSULATION

Floor area : 1200m^2
Number of stories : 2

Image source: Ecipark Office Building. https://jhmrad.com/21-delightful-two-story-building/ecipark-office-building-two-story/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
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Report contact : Prof Mattheos Santamouris

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SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a typical low-rise office building without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building without roof insulation from 20.9-28.5 kWh/m² to 11.3-17.2 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)
Adelaide Airport	23.5	24.8	12.9	14.0	11.0	11.4
Edinburgh	25.3	26.6	14.4	15.5	12.3	12.7
Kuitpo	19.7	20.9	10.3	11.3	8.1	8.4
Parafield	24.8	26.1	14.0	15.1	12.3	12.8
Roseworthy	27.4	28.5	16.3	17.2	14.5	14.9

Table 2. Sensible and total cooling load saving for a typical low-rise office building without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 9.6-11.3 kWh/m² which is equivalent to 41.5-45.9 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 12.5-13.9 kWh/m² which is equivalent to 47.7-59.8 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Adelaide Airport	10.6	45.1	10.8	43.6	12.5	53.1	13.4	53.9
Edinburgh	10.9	43.0	11.0	41.5	13.0	51.4	13.9	52.2
Kuitpo	9.4	47.7	9.6	45.9	11.6	58.9	12.5	59.8
Parafield	10.8	43.7	11.0	42.2	12.5	50.5	13.3	51.1
Roseworthy	11.1	40.5	11.3	39.6	12.9	47.1	13.6	47.7

In the eleven weather stations in Adelaide, it is estimated that both building-scale and combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of the typical low-rise office building without insulation during the summer season.

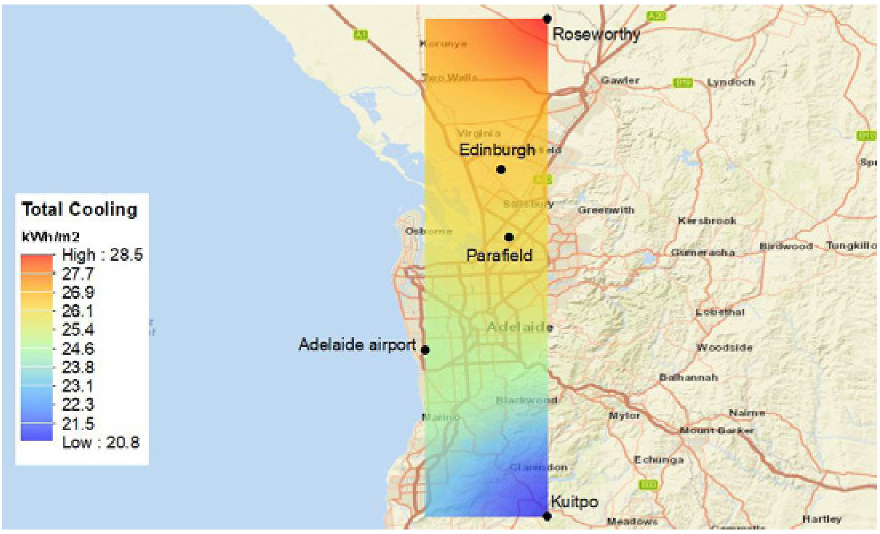

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

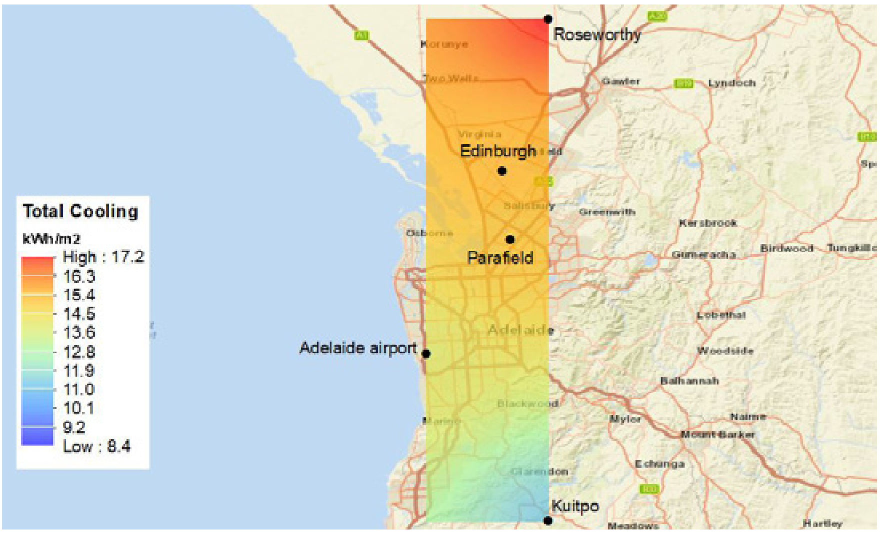

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

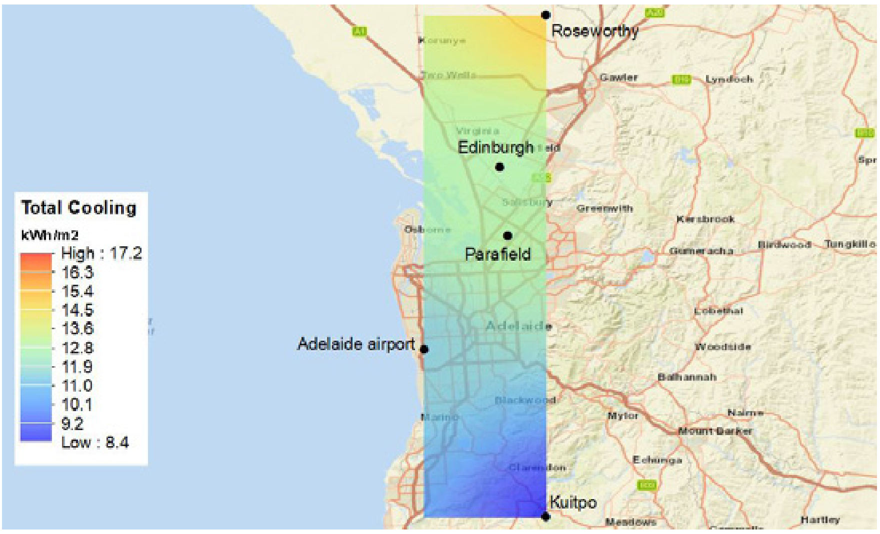

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a low-rise office building without roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (1.4-3.6 kWh/m²) is significantly lower than the annual cooling load reduction (11.0-17.5 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	29.1	31.3	3.4	6.2	16.9	18.7	4.1	7.6
Edinburgh	40.3	42.2	4.3	7.9	23.7	25.2	5.0	9.4
Kuitpo	22.6	23.3	5.9	11.4	11.8	12.4	7.5	14.9
Parafield	44.8	47.4	3.9	7.2	26.1	28.2	4.6	8.6
Roseworthy	42.9	44.5	5.2	9.4	25.7	27.0	5.9	10.9

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 40.2-46.9 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 7.4-17.7 kWh/m² (~21.3-32.5 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	12.3	42.1	12.6	40.3	0.7	1.4	11.6	35.6	11.2	30.0
Edinburgh	16.6	41.2	17.0	40.2	0.7	1.5	15.9	35.7	15.5	30.9
Kuitpo	10.8	47.8	11.0	46.9	1.6	3.6	9.2	32.2	7.4	21.3
Parafield	18.7	41.7	19.2	40.5	0.7	1.4	18.0	36.9	17.7	32.5
Roseworthy	17.2	40.1	17.5	39.3	0.6	1.5	16.6	34.4	16.0	29.7

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

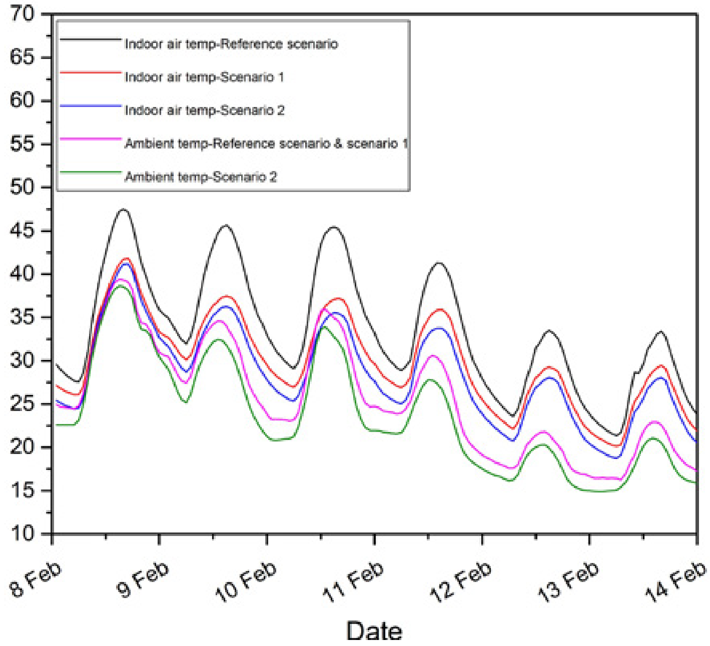

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

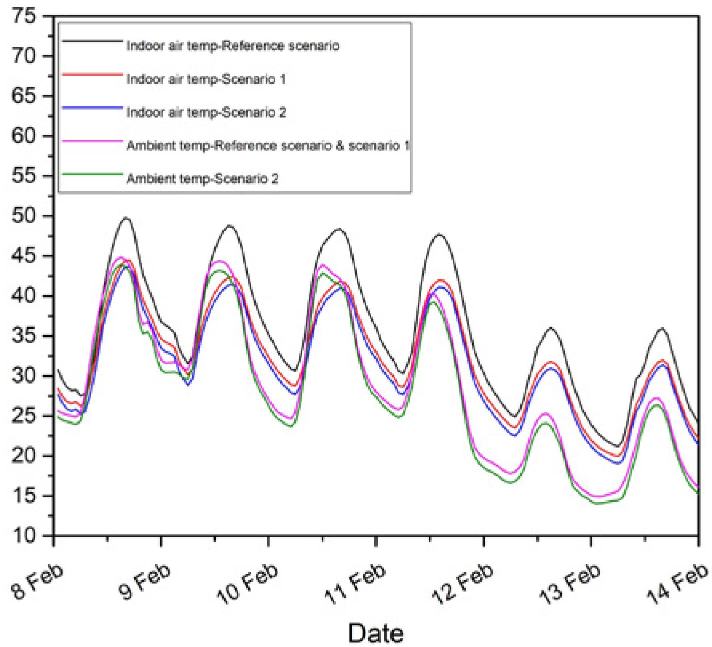

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.1-47.5 °C and 20.3-49.8 °C in Kuitpo and Roseworthy stations, respectively.

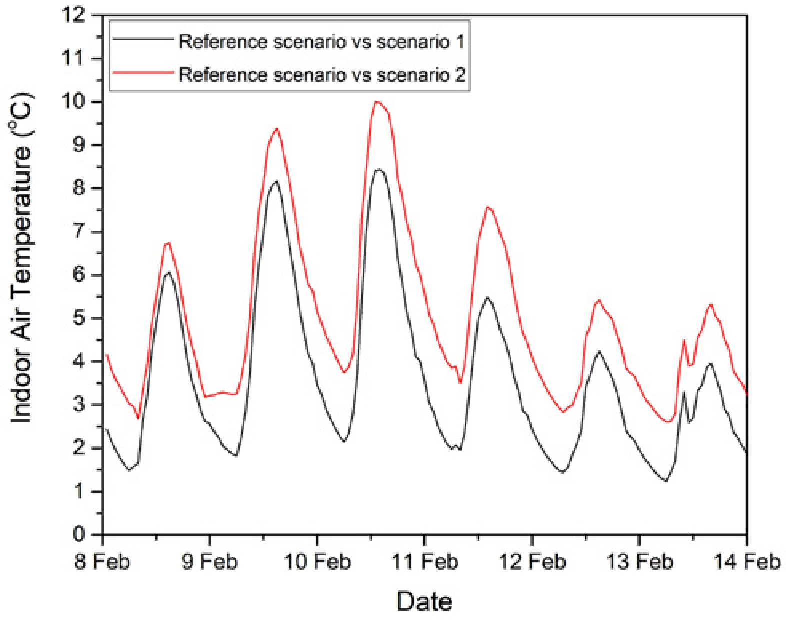

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 8.4 °C and 7.6 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 10.0 °C and 8.4 °C in Kuitpo and Roseworthy stations, respectively.

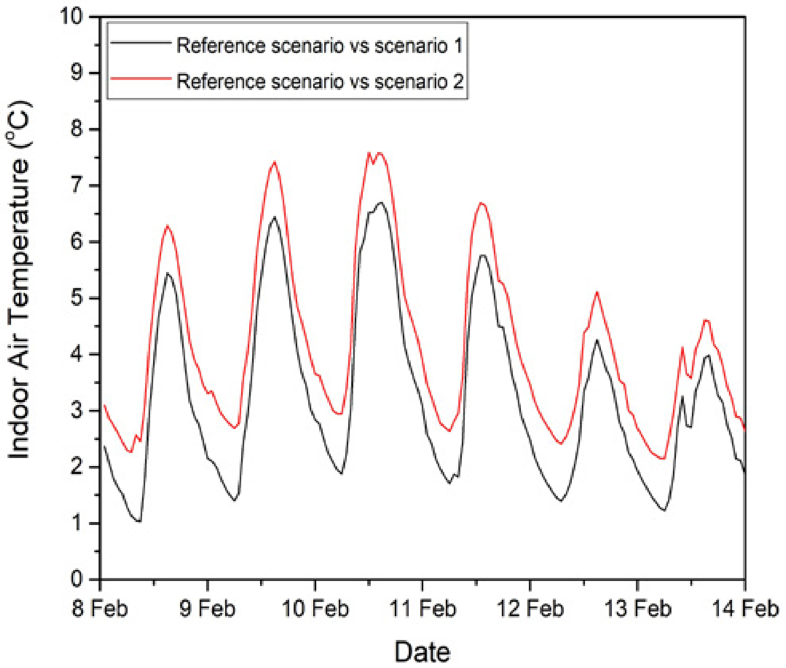

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

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INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 9.6-22.0 °C in reference scenario to a range 9.1-19.5 °C in scenario 1 in Kuitpo station.

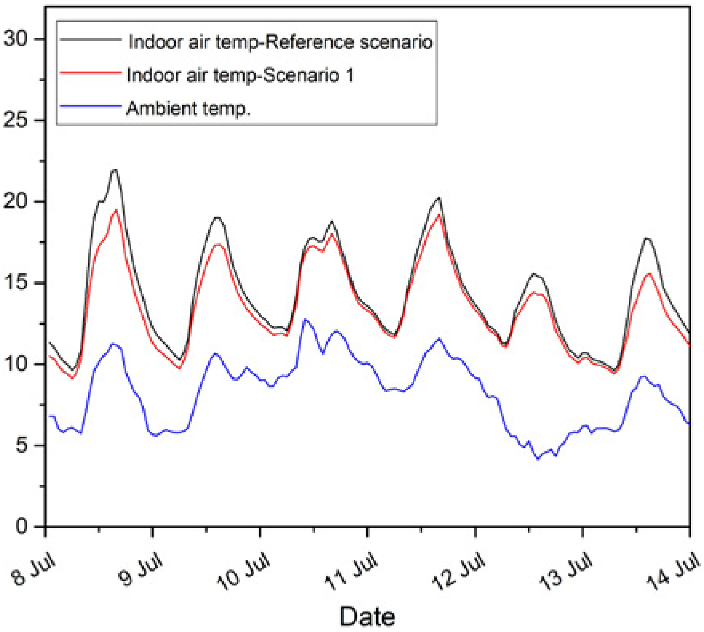

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 9.2-23.5 °C in reference scenario to a range 8.7-21.6 °C in scenario 1 in Roseworthy station.

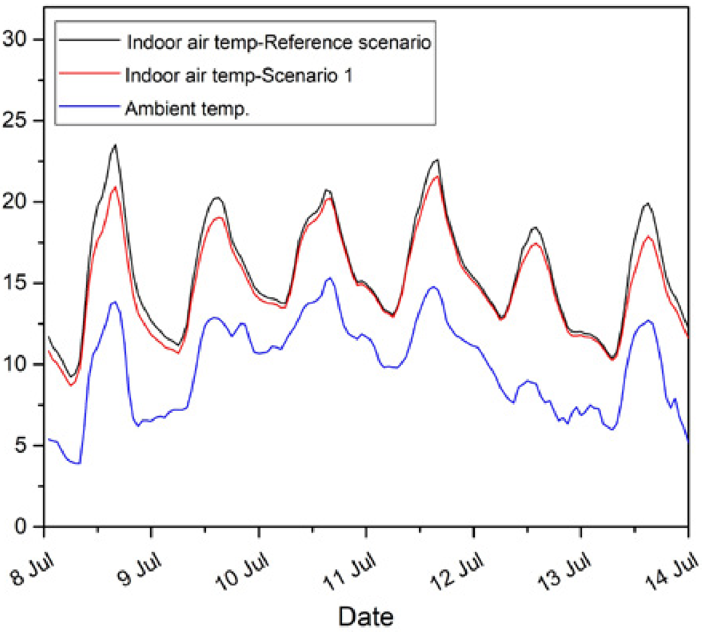

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 3.2 °C and 3.1 °C in Kuitpo and Roseworthy stations, respectively.

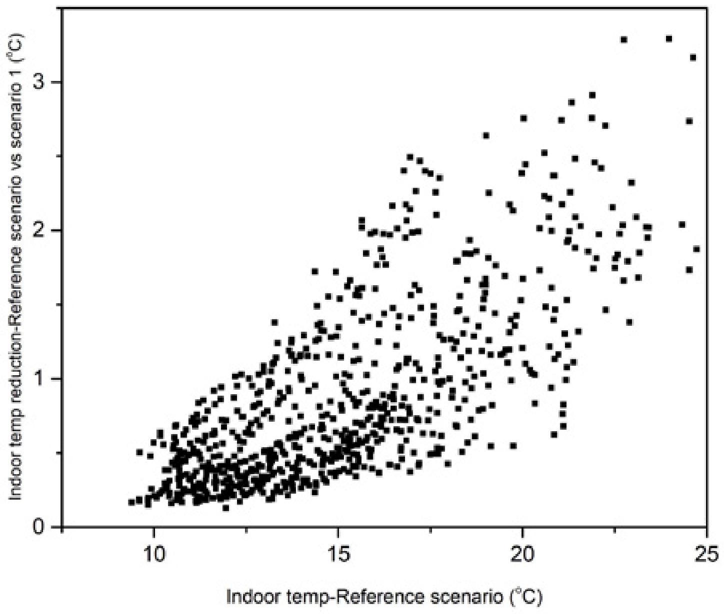

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

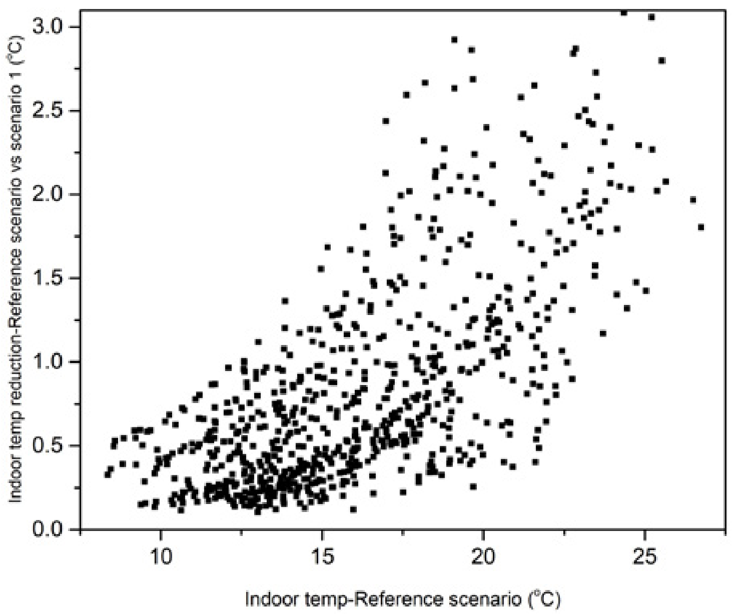

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 635 hours in reference scenario to 681 and hours and from 574 to 622 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to increase from 272 hours in reference scenario to 317 hours; and from 215 to 261 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	272	635	317	681
Roseworthy	215	574	261	622

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decreased from 436 hours in reference scenario to 326 and 251 hours under scenario 1 and 2 in Kuitpo station; and from 457 hours in reference scenario to 367 and 333 hours under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	436	326	251
Roseworthy	457	367	333

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

The 'Do Nothing' approach has clearly the highest cost over the building's life cycle.

The building and its energy performance

Building 01 is a low-rise building, with a total air-conditioned area of 2.400 m^2 distributed on two levels. The 1.200 m^2 roof is uninsulated, resulting in very high energy losses and, consequently, in a very significant energy saving potential. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented inTable 7.

Table 7. Energy performance features of Building 01.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	33.3	51.7
Energy consumption after cool roof (MWh)	26.2	36.4
Energy savings (MWh)	7.1	15.3
Energy savings (%)	21.32%	29.59%
Area (m^2)	1,200	1,200
Roof costs - Metal roof (AU$/m^2)	38.0	38.0
Roof costs - Coating (AU$/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

Building 01 is a very good example of a cool roof's contribution to drastically reducing energy requirements and life cycle costs in low-rise buildings with poor energy performance. The higher initial cost of the metal cool roof leads to less attractive results than the coating cool roof, although they are still very positive.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in energy savings of 21,32% for the Kuitpo and of 29,59% for the Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

> *The coating cool roof option is the most feasible one, resulting in significant reductions of life cycle costs, that vary between 28,1 and 42,4%, depending on the weather and energy price scenarios.*

> *The metal cool roof is also a feasible option; for Roseworthy conditions for all energy prices, for Kuitpo conditions for the higher energy prices and marginally for the lower ones.*

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

Figure 12. Life Cycle Costs for Building 01 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	0.76 %	11.06 %	16.16 %	23.25 %
Coating Cool Roof	28.09 %	33.80 %	38.39 %	42.37 %

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CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the typical low-rise office building without insulation during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 20.9-28.5 kWh/m^2 to 11.3-17.2 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 9.6-11.3 kWh/m^2. This is equivalent to approximately 41.5-45.9 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 & Table 2 and Figure 1 & Figure 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 12.5-13.9 kWh/m^2. This is equivalent to 47.7-59.8 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 & Table 2 and Figure 2 & Figure 3).

• The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (1.4-3.6 kWh/m^2) is significantly lower than the annual cooling load reduction (11.0-17.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 40.2-46.9 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 7.4-17.7 kWh/m^2 (~21.3-32.5 %) (Tables 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 21.1-47.5 °C and 20.3-49.8 °C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 8.4 and 7.6 °C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 10.0 and 8.4 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figure 4, Figure 5, Figure 6 and Figure 7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free-floating condition, the indoor air temperature is expected to decrease slightly from a range between 9.6-22.0 °C in reference scenario to a range between 9.1-19.5 °C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 9.2-23.5 °C in reference scenario to a range between 8.7-21.6°C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figure 8 and Figure 9).

• During a typical winter month and under free-floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 3.2 °C and 3.1 °C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figure 10 and Figure 11).

• During a typical winter month and under free-floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase from 635 hours in reference scenario to 681 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy station also show a increase in total number of hours below 19 °C from 574 hours in reference scenario to 622 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am - 6 pm) is expected to increase from 272 hours in reference scenario to 317 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. Similarly, the calculation in Roseworthy station shows a slightly increase of number of hours below 19 °C from 215 hours to 261 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 436 hours under the reference scenario in Kuitpo station, which significanlty decreases to 326 and 251 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also illustrate a significant reduction in number of hours above 26 °C from 457 hours in reference scenario to 367 in reference with cool roof scenario (scenario 1) and 333 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, the 'Do Nothing' approach has the highest cost over the building's life cycle. The coating cool roof option is the most feasible one, resulting in significant reductions of life cycle costs, that vary between 28,1 and 42,4%, depending on the weather and energy price scenarios, as it can be seen in Table 8. The metal cool roof is also a feasible option; for Roseworthy conditions for all energy prices, for Kuitpo conditions for the higher energy prices and marginally for the lower ones. Building 01 is in that sense a very good example of a cool roof's contribution to drastically reducing energy requirements and life cycle costs in low-rise buildings with poor energy performance. The higher initial cost of the metal cool roof leads to less attractive results than the coating cool roof, although they are still very positive.

B01

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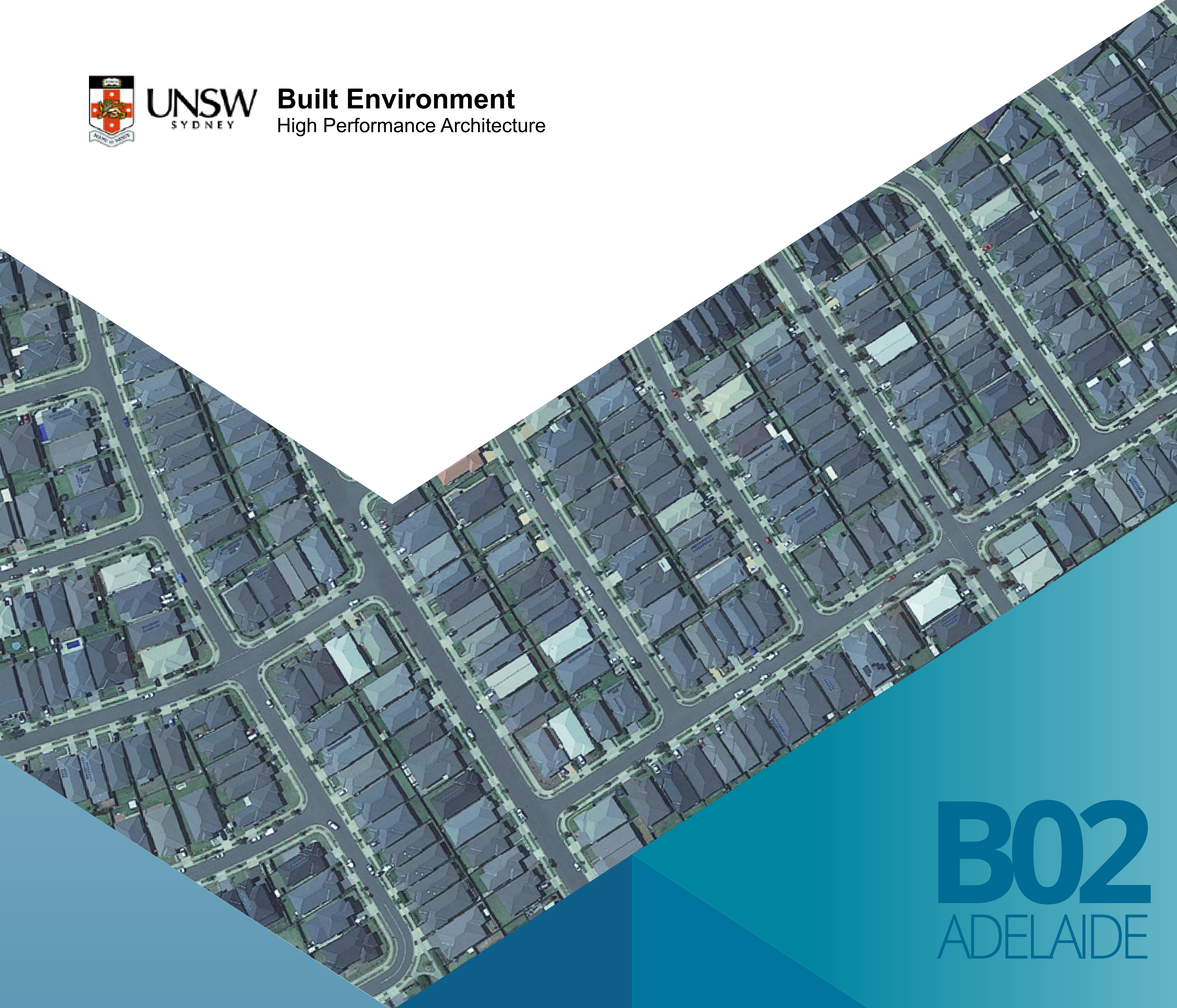

B02
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

High-rise office building without roof insulation
2021

BUILDING 02

HIGH-RISE OFFICE BUILDING WITHOUT ROOF INSULATION

Floor area : 1200m^2
Number of stories : 10

Image source: Ecipark Office Building. https://jerseydigs.com/bayonne-city-council-approves-10-story-building-975-broadway/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a typical high-rise office building without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the high-rise office building withour roof insulation from 13.5-19.9 kWh/m² to 11.8-17.9 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	15.4	16.6	13.5	14.6	11.4	11.9
Edinburgh	17.1	18.2	15.1	16.2	12.7	13.2
Kuitpo	12.4	13.5	10.7	11.8	8.1	8.4
Parafield	16.6	17.8	14.7	15.8	12.8	13.3
Roseworthy	18.9	19.9	16.9	17.9	15.0	15.4

Table 2. Sensible and total cooling load saving for a typical high-rise office building without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 1.7-2.0 kWh/m² which is equivalent to 10.3-12.6 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.5-5.0 kWh/m² which is equivalent to 22.8-37.4 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	1.9	12.3	1.9	11.8	4.0	25.8	4.7	28.4
Edinburgh	1.9	11.4	2.0	10.9	4.3	25.3	5.0	27.7
Kuitpo	1.7	13.5	1.7	12.6	4.3	34.4	5.0	37.4
Parafield	1.9	11.7	2.0	11.2	3.8	23.1	4.5	25.2
Roseworthy	2.0	10.6	2.0	10.3	4.0	21.0	4.5	22.8

In the eleven weather stations in Adelaide, it is estimated that both building-scale and combined building-scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical high-rise office building without roof insulation during the summer season.

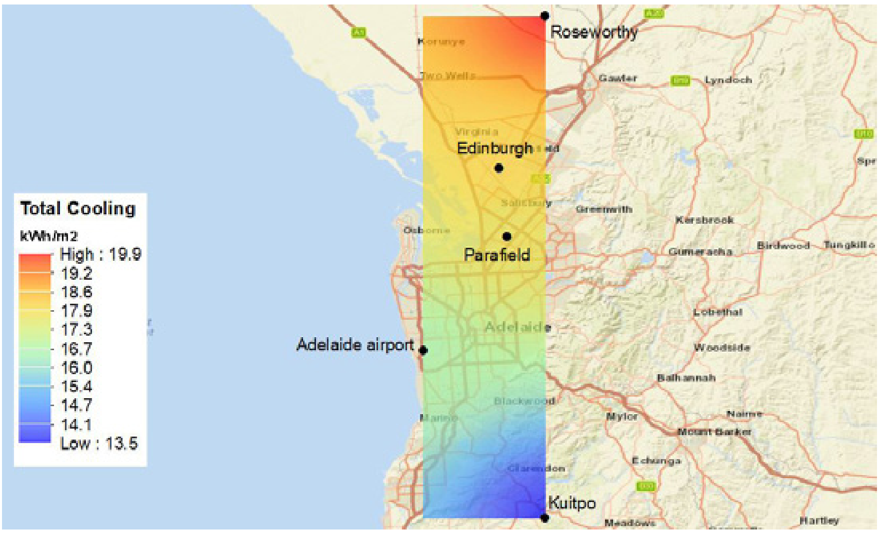

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

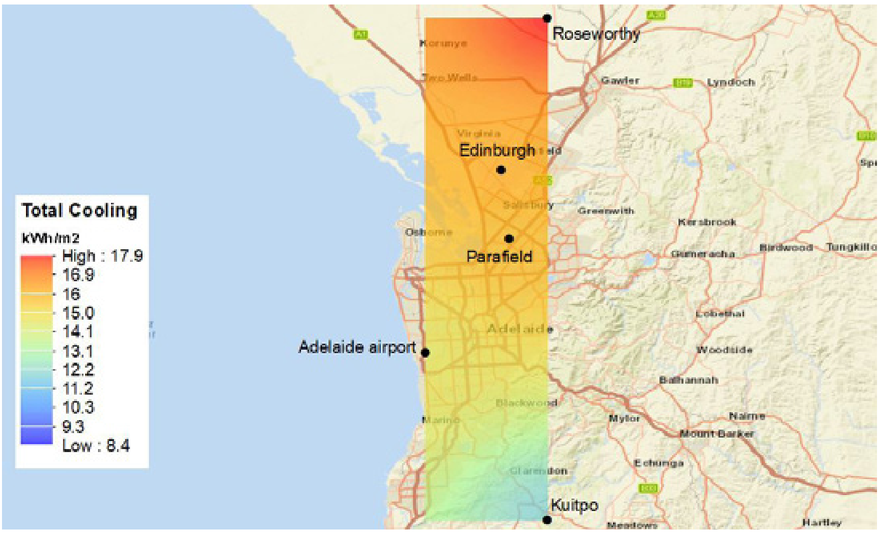

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

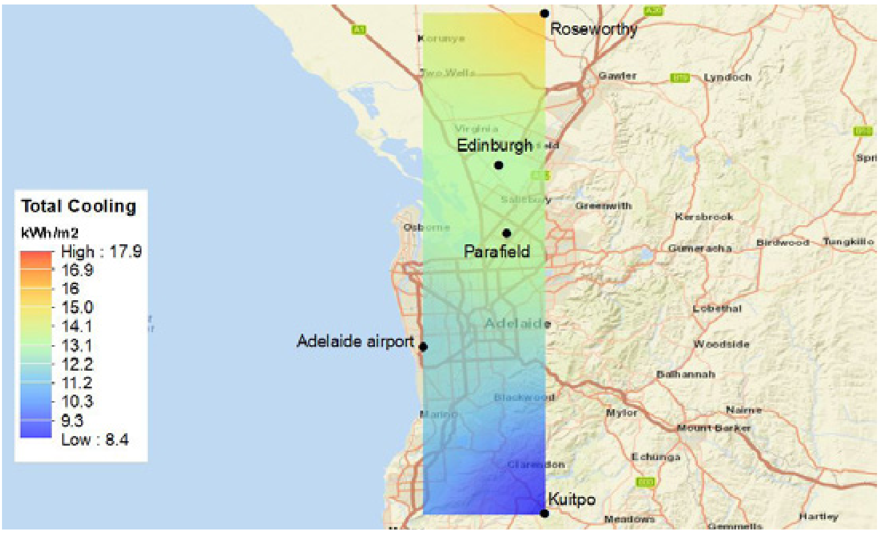

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a high-rise office building without roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.9 kWh/m²) is significantly lower than the annual cooling load reduction (1.8-3.2 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	19.5	21.4	1.1	2.7	17.5	19.3	1.3	3.0
Edinburgh	27.0	28.6	1.7	3.9	24.2	25.8	1.9	4.3
Kuitpo	13.5	14.1	2.5	6.2	11.7	12.3	3.0	7.1
Parafield	29.7	31.9	1.5	3.5	26.6	28.7	1.7	3.9
Roseworthy	28.6	30.0	0.0	0.0	25.8	27.0	0.0	0.0

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 9.6-12.9 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.9-2.9 kWh/m² (~4.6-9.7 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	2.0	10.1	2.0	9.6	0.2	0.3	1.8	8.6	1.7	7.1
Edinburgh	2.8	10.3	2.9	10.0	0.3	0.4	2.5	8.8	2.4	7.4
Kuitpo	1.8	13.3	1.8	12.9	0.5	0.9	1.3	8.1	0.9	4.6
Parafield	3.2	10.6	3.2	10.2	0.3	0.4	2.9	9.3	2.8	8.0
Roseworthy	2.9	10.0	2.9	9.8	0.0	0.0	2.9	10.0	2.9	9.7

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

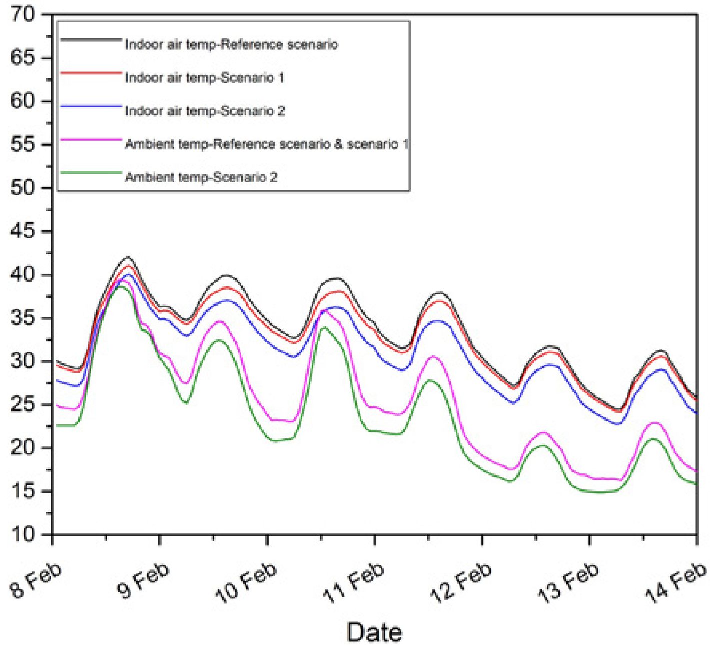

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

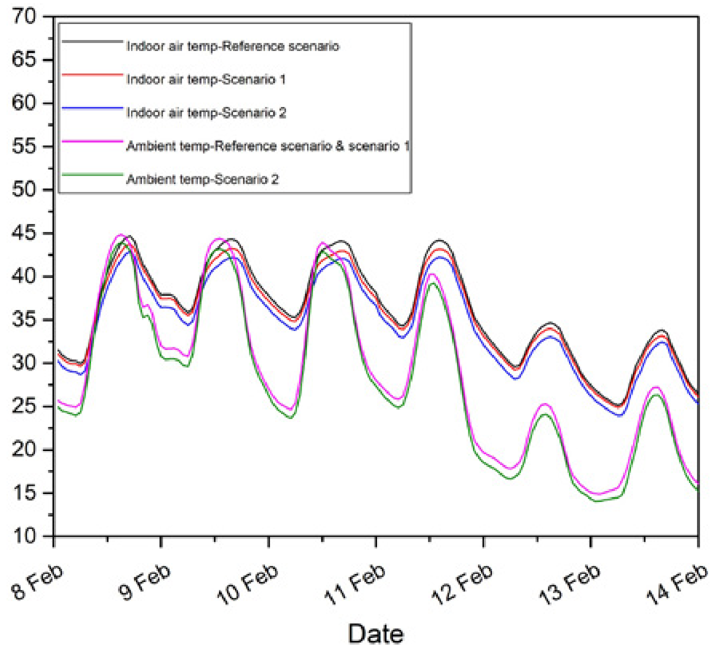

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 24.0-42.1 °C and 23.7-44.7 °C in Kuitpo and Roseworthy stations, respectively.

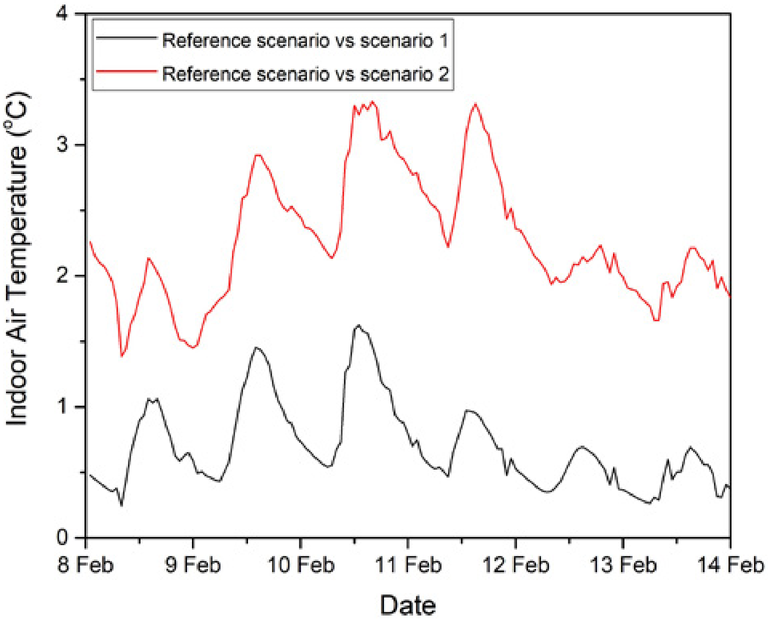

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.6 °C and 1.5 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.3 and 2.4 °C in Kuitpo and Roseworthy stations, respectively.

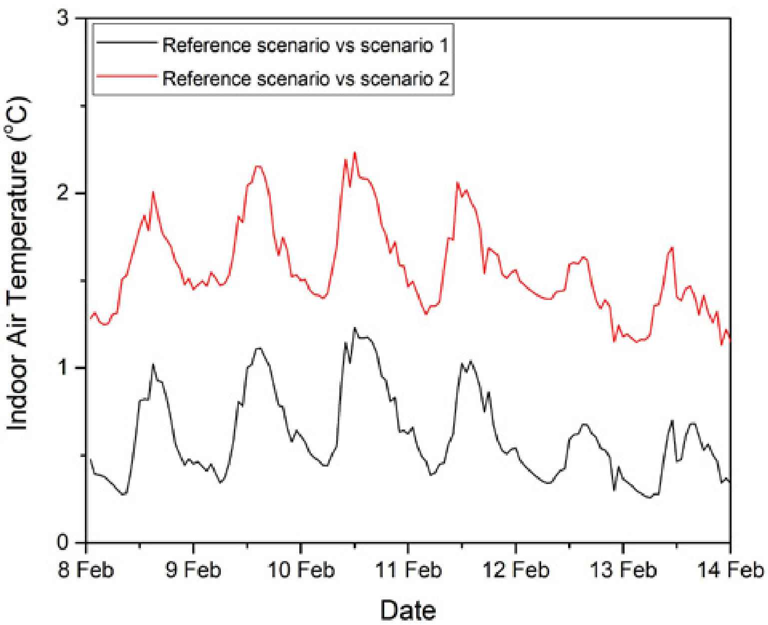

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 12.7 and 21.4 °C in reference scenario to a range between 12.6 and 20.9 °C in scenario 1 in Kuitpo station.

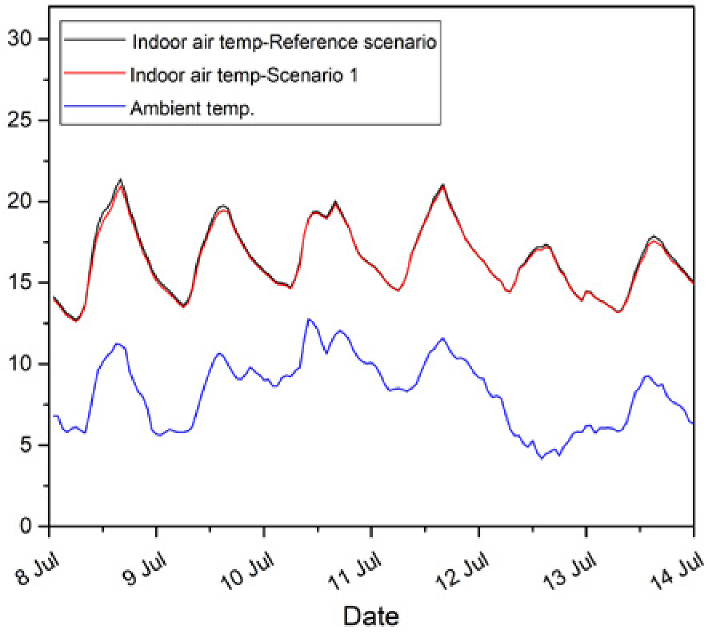

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to slighly reduce from a range between 15.5 and 23.3 °C in reference scenario to a range between 12.4 and 23.1 °C in scenario 1 in Roseworthy station.

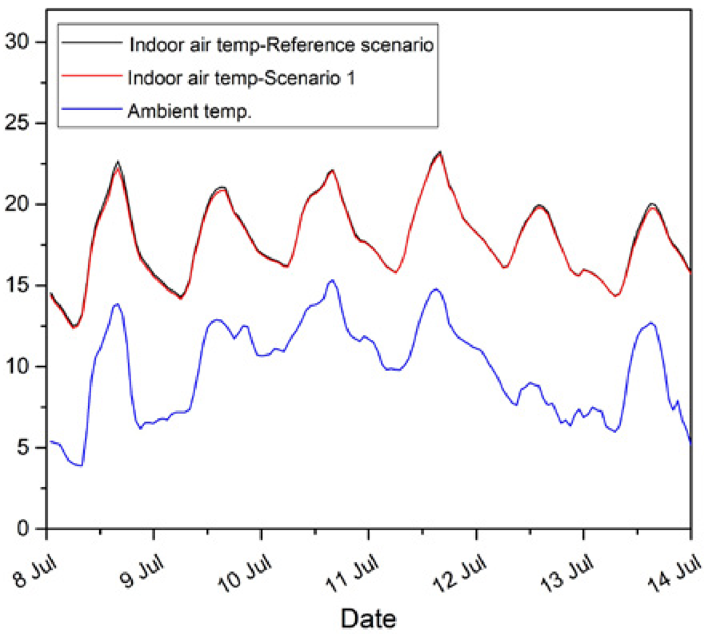

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.7 and 0.6 °C in Kuitpo and Roseworthy stations, respectively.

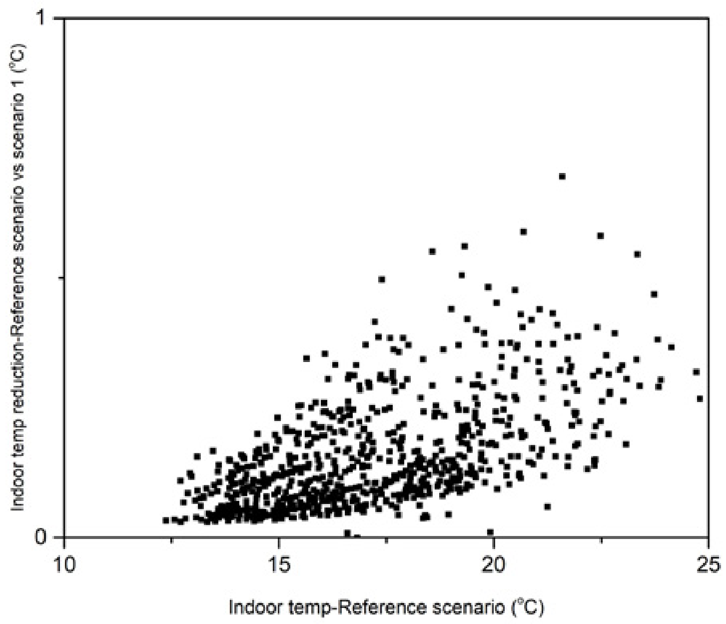

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

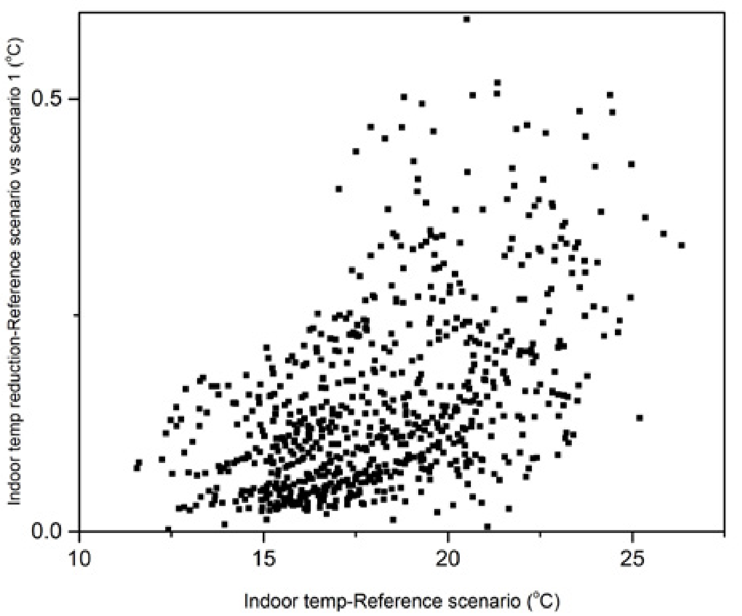

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 551 hours in reference scenario to 569 and hours and from 460 to 473 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 221 hours in reference scenario to 234 hours; and from 156 to 165 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	221	551	234	569
Roseworthy	156	460	165	473

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 510 hours in reference scenario to 485 and 462 hours under scenario 1 and 2, in Kuitpo station, respectively; and from 542 to 521 and 477 in Roseworthy station under scenario 1 and 2, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	510	485	462
Roseworthy	542	521	477

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

The 'Do Nothing' approach has the highest cost over the building's life cycle, for almost all cases examined.

The building and its energy performance

Building 02 is a high-rise office building, with a total air-conditioned area of 12.000 m² distributed on ten levels. The 1.200 m² roof is uninsulated, resulting in high energy losses but with an impact only on the floor directly beneath the roof. Consequently, the energy saving potential is rather limited, but still not insignificant. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 02.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	97.4	144.0
Energy consumption after cool roof (MWh)	93.1	129.6
Energy savings (MWh)	4.3	14.4
Energy savings (%)	4.41%	10.00%
Area (m²)	1,200	1,200
Roof costs - Metal roof (AU$/m²)	38.0	38.0
Roof costs - Coating (AU$/m²)	22.75	22.75
Life expectancy - Metal roof (years)	28.5	28.5
Life expectancy - Coating (years)	22.5	22.5
HVACs COP	2.5	2.5
Existing roof's renovation costs (AU$/m²)	15.0	15.0

Building 02 is a very good example of a cool roof's contribution to drastically reducing energy requirements and life cycle costs in high-rise office buildings with a poor energy performance of the roof.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in energy savings of 4,41% for the Kuitpo weather conditions and of 10,00% for the Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The metal cool roof is due to its higher initial investment cost less attractive than the coating cool roof: it is not feasible for Kuitpo and low energy prices, and it is feasible for Roseworthy and both energy prices scenarios.

The coating cool roof option is the most feasible one, resulting in significant reductions of life cycle costs, that vary between 23,2 and 30,1%, depending on the weather and energy price scenarios.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The impact of the roof is not as big as in low-rise buildings, since it affects only to a limited extent the building's energy requirement, hence the impact of the initial cost of the refurbishment is bigger compared to the low-rise buildings. Still, cool roofs are feasible, the coating option being clearly the more attractive solution.

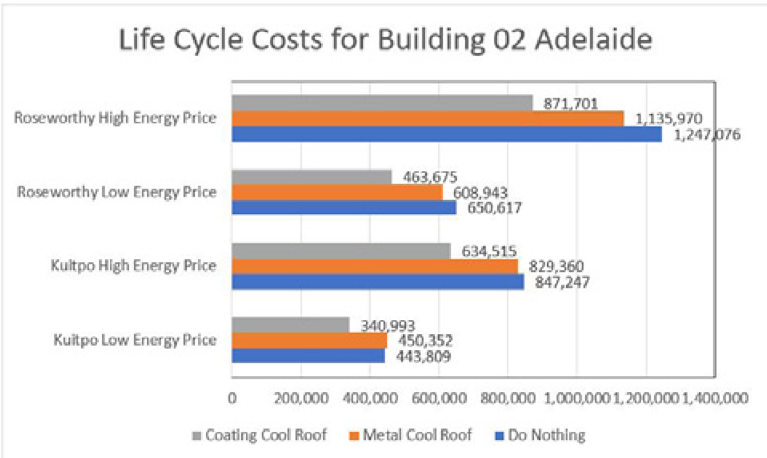

Figure 12. Life Cycle Costs for Building 02 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-1.47 %	2.11 %	6.41 %	8.91 %
Coating Cool Roof	23.17 %	25.11 %	28.73 %	30.10 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the typical low-rise office building without insulation during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 13.5-19.9 kWh/m^2 to 11.8-17.9 kWh/m^2. As computed, the total cooling load saving by building-scale application of cool roofs is around 1.7-2.0 kWh/m^2 for a typical high rise office building without roof insulation. This is equal to 0.3-12.6 % cooling load reduction in reference with cool roof scenario (scenario 1) compared to reference scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale implementation of cool roofs can reduce the total cooling load of the high-rise office building without roof insulation by 4.5-5.0 kWh/m^2. This is equivalent to roughly 22.8-37.4 % lower total cooling load under cool roof and modified urban temperature scenario (scenario 2) with respect to the reference scenario. (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.9 kWh/m^2) is significantly lower than the annual cooling load reduction (1.8-3.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 9.6-12.9 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.9-2.9 kWh/m^2 (~4.6-9.7 %) (See Table 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 24.0-42.1 °C and 23.7-44.7 °C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.6 and 1.5 °C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.3 and 2.4 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figure 4, Figure 5, Figure 6 and Figure 7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 12.7 and 21.4 ^{o}C in reference scenario to a range between 12.6 and 20.9 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 15.5 and 23.3 ^{o}C in reference scenario to a range between 12.4 and 23.1 ^{o}C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.7 and 0.6 ^{o}C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 551 hours in reference scenario to 569 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight increase in total number of hours below 19 ^{o}C from 460 hours in reference scenario to 473 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 ^{o}C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 ^{o}C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to slightly increase from 221 hours in reference scenario to 234 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. Similarly, the calculation in Roseworthy station shows a slight increase of number of hours below 19 ^{o}C from 156 hours to 165 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to slightly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 510 hours under the reference scenario in Kuitpo station, which decreases to 548 under Scenario 1 and 462 under the modified urban temperature scenario (scenario 2). The simulations in Roseworthy station show that the number of hours above 26 ^{o}C (542 hours) decreases to 521 under Scenario 1 and 477 under Scenario 2 (See Table 6).

• As it can be deduced from the feasibility analysis, the 'Do Nothing' approach has the highest cost over the building's life cycle, for almost all cases examined. The coating cool roof option is the most feasible one, resulting in significant reductions of life cycle costs, that vary between 23,2 and 30,1%, depending on the weather and energy price scenarios, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost less attractive than the coating cool roof: it is not feasible for Kuitpo and low energy prices, and it is feasible for Roseworthy and both energy prices scenarios. Building 02 is in that sense a very good example of a cool roof's contribution to drastically reducing energy requirements and life cycle costs in high-rise office buildings with a poor energy performance of the roof. The impact of the roof is not as big as in low-rise buildings, since it affects only to a limited extent the building's energy requirement, hence the impact of the initial cost of the refurbishment is bigger compared to the low-rise buildings. Still, cool roofs are feasible, the coating option being clearly the more attractive solution.

B02

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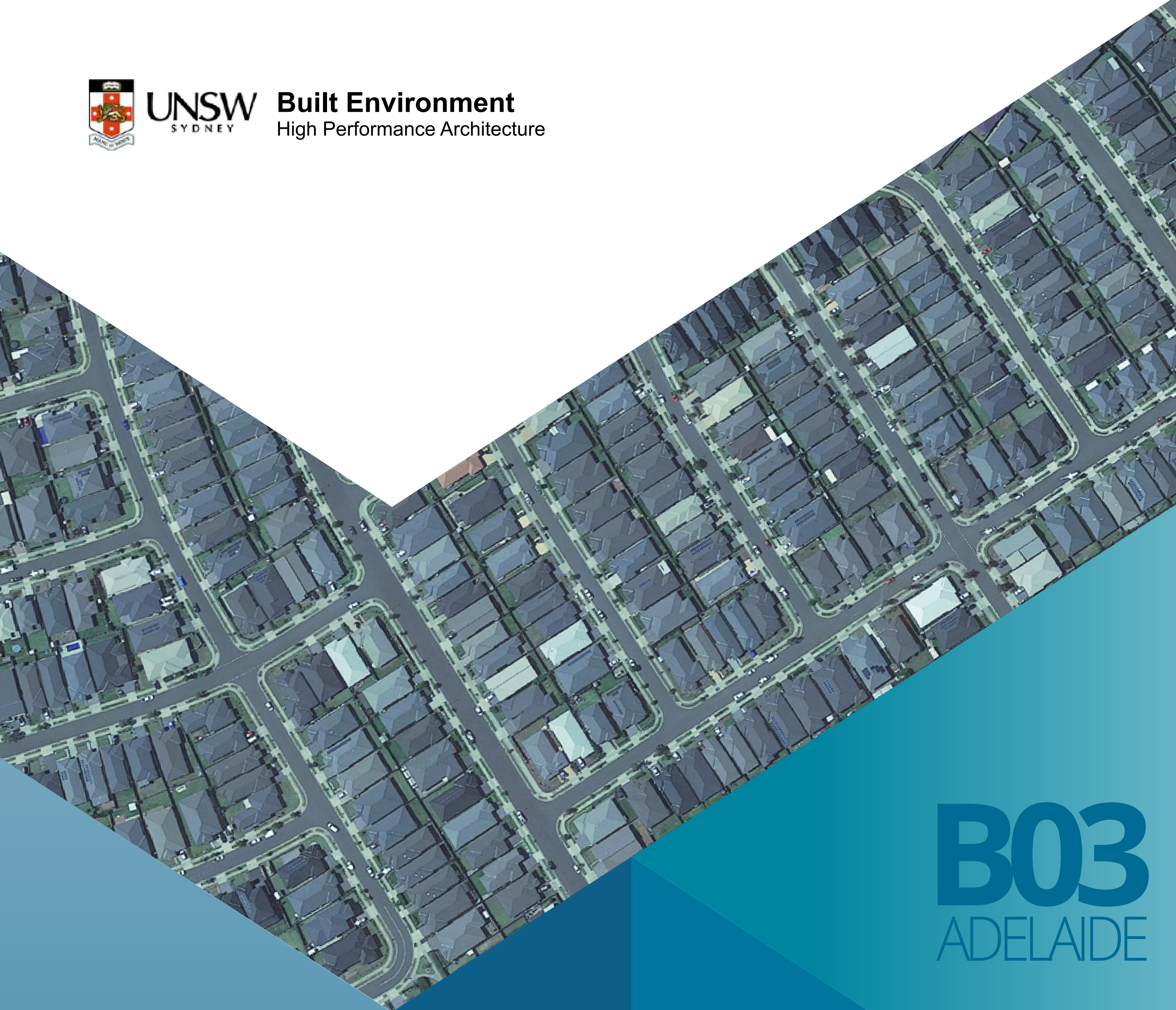

B03
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise office building with roof insulation
2021

BUILDING 03

NEW LOW-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : 1200m²
Number of stories : 2

Image source: Ecipark Office Building. https://jhmrad.com/21-delightful-two-story-building/ecipark-office-building-two-story/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new low-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new low-rise office building with roof insulation from 12.8-19.3 kWh/m² to 11.9-18.1 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	14.5	15.8	13.5	14.7	11.4	11.9
Edinburgh	16.2	17.4	15.2	16.4	12.8	13.3
Kuitpo	11.6	12.8	10.8	11.9	8.2	8.5
Parafield	15.8	17.0	14.7	15.9	12.8	13.3
Roseworthy	18.3	19.3	17.1	18.1	15.1	15.5

Table 2. Sensible and total cooling load saving for a new low-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.9-1.3 kWh/m² which is equivalent to 6.1-6.9 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.6-4.3 kWh/m² which is equivalent to 19.6-33.5 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	1.0	6.8	1.0	6.6	3.1	21.3	3.9	24.7
Edinburgh	1.0	6.4	1.1	6.1	3.4	21.0	4.2	23.9
Kuitpo	0.8	7.3	0.9	6.9	3.5	29.8	4.3	33.5
Parafield	1.0	6.6	1.1	6.3	2.9	18.6	3.6	21.3
Roseworthy	1.2	6.8	1.3	6.5	3.2	17.4	3.8	19.6

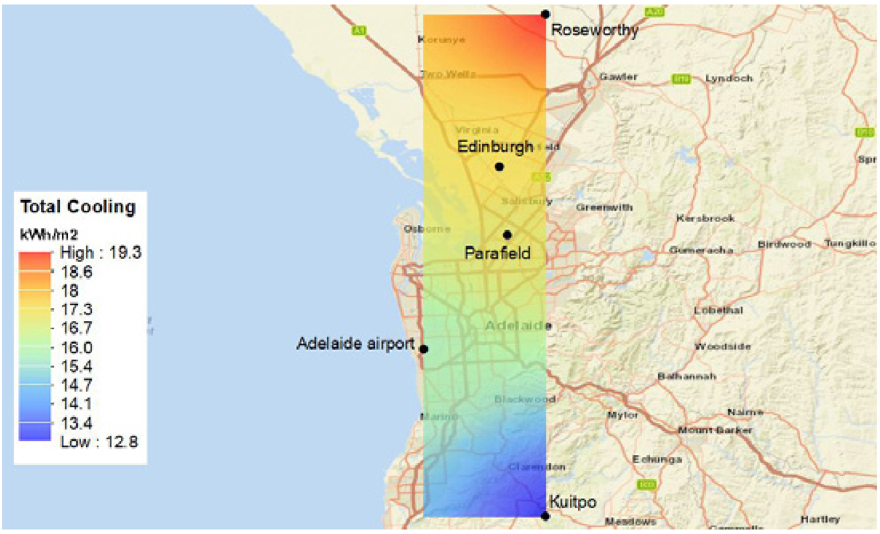

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

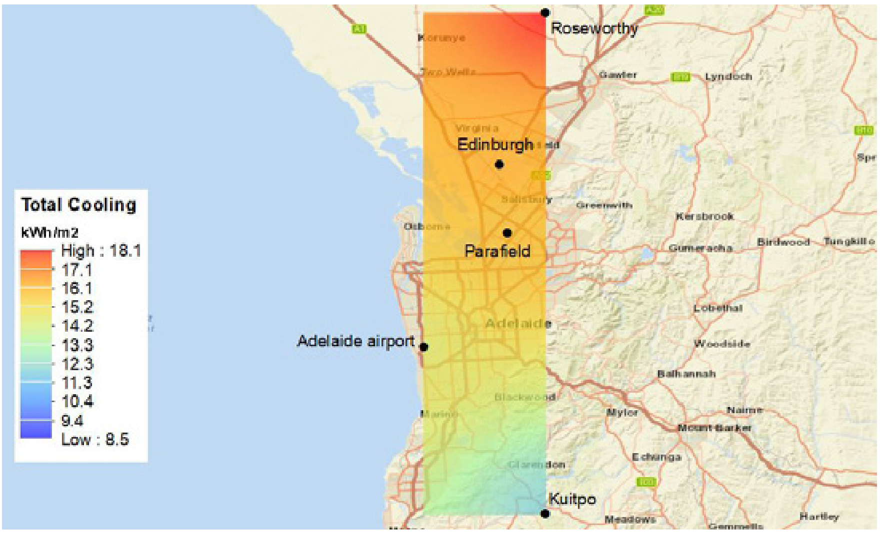

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

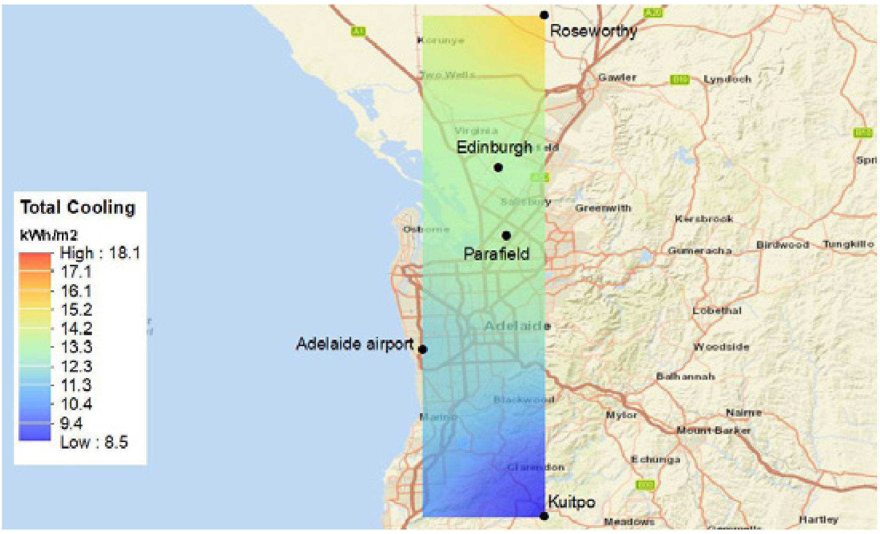

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new low-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data shows an annual heating penalty (0.0-0.3 kWh/m²) that is significantly lower than the annual cooling load reduction (1.0-2.1 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	18.8	20.8	1.2	2.7	17.7	19.6	1.3	2.9
Edinburgh	26.2	27.8	1.8	4.0	24.2	25.8	1.9	4.2
Kuitpo	13.0	13.7	2.4	5.8	12.1	12.8	2.6	6.1
Parafield	28.7	30.9	1.6	3.7	26.9	29.2	1.7	3.8
Roseworthy	28.2	29.6	0.0	0.0	26.4	27.8	0.0	0.0

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 5.5-7.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6-1.9 kWh/m² (~3.2-6.2 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	1.1	5.9	1.1	5.5	0.1	0.1	1.0	5.2	1.0	4.4
Edinburgh	1.9	7.4	2.1	7.5	0.1	0.2	1.8	6.6	1.9	6.0
Kuitpo	0.9	7.2	1.0	7.0	0.1	0.3	0.8	5.1	0.6	3.2
Parafield	1.7	6.0	1.8	5.7	0.1	0.2	1.6	5.4	1.6	4.7
Roseworthy	1.8	6.3	1.8	6.2	0.0	0.0	1.8	6.3	1.8	6.2

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

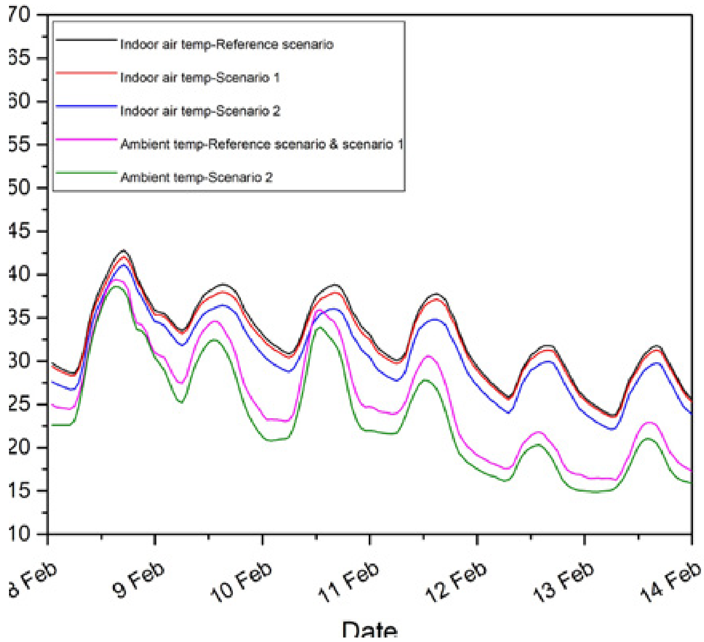

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

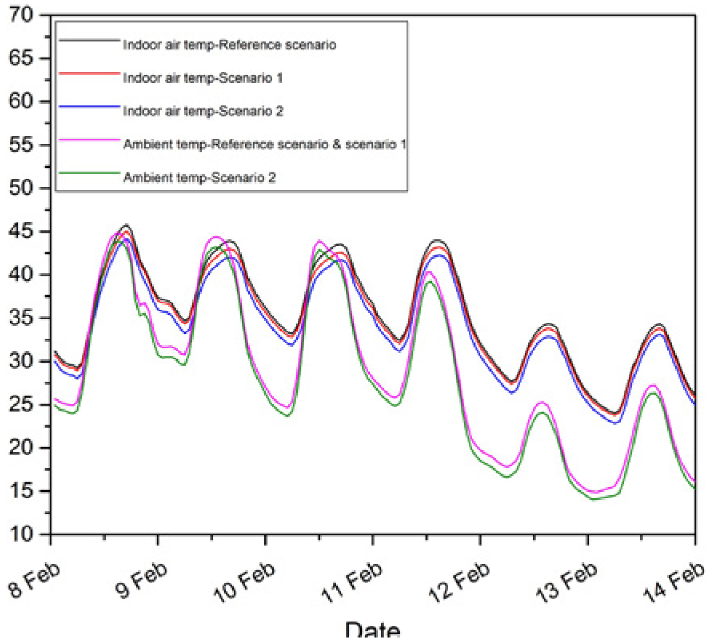

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 23.5-42.8 °C and 23.0-45.8 °C in Kuitpo and Roseworthy stations, respectively.

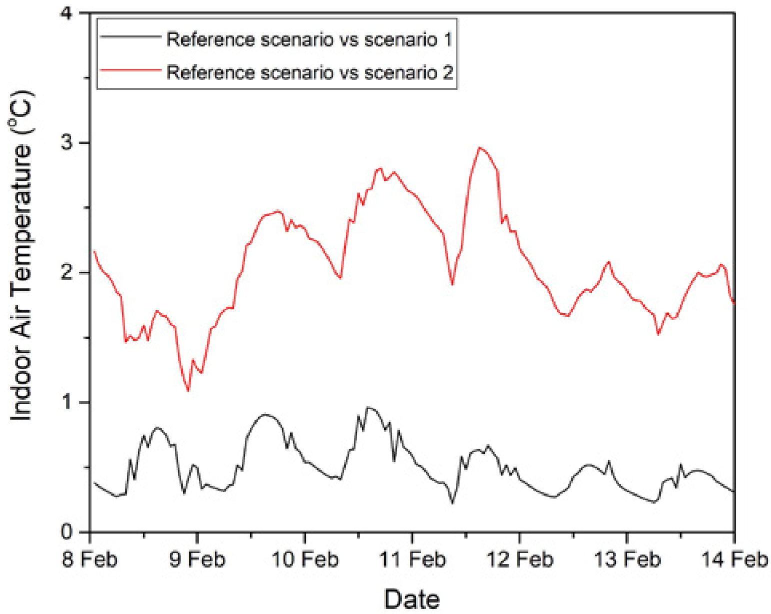

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.0 °C and 1.0 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.0 and 2.1 °C in Kuitpo and Roseworthy stations, respectively.

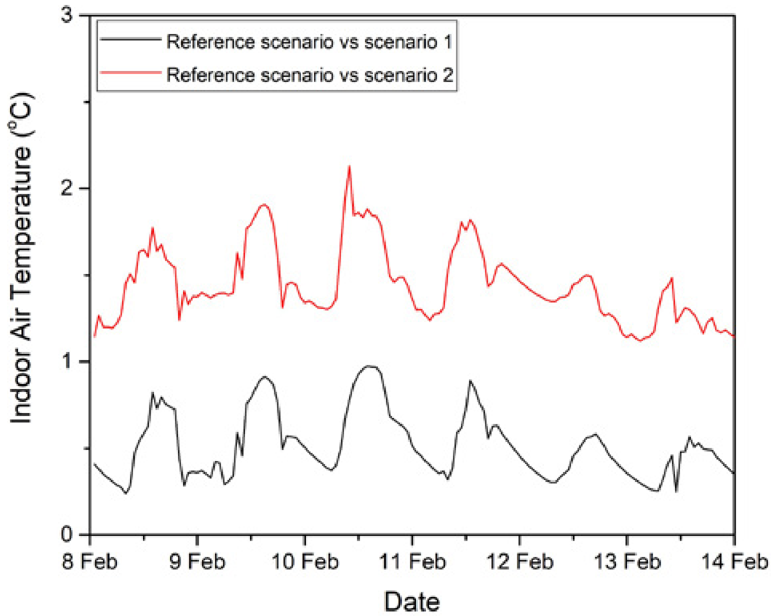

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 12.5 and 22.8 °C in reference scenario to a range between 12.4 and 22.4 °C in scenario 1 in Kuitpo station.

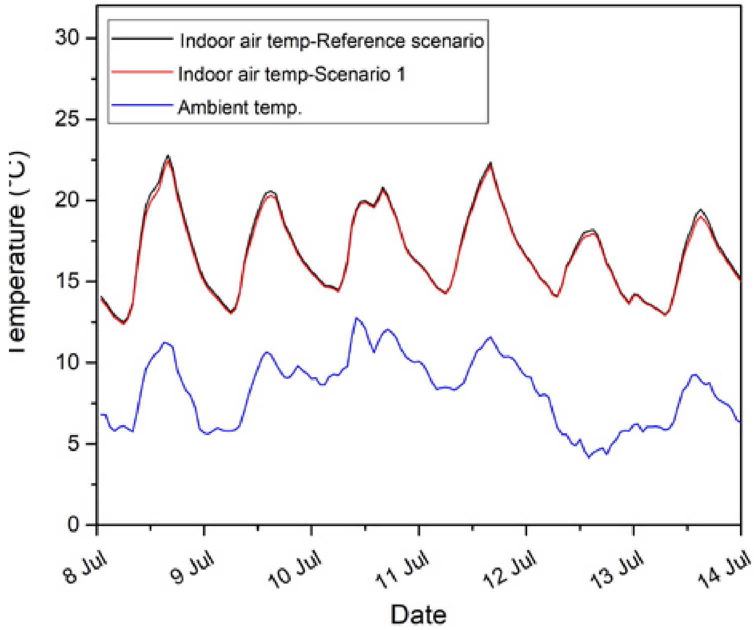

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range between 12.0 and 24.4 °C in reference scenario to a range between 12.4 and 23.1 °C in scenario 1 in Roseworthy station.

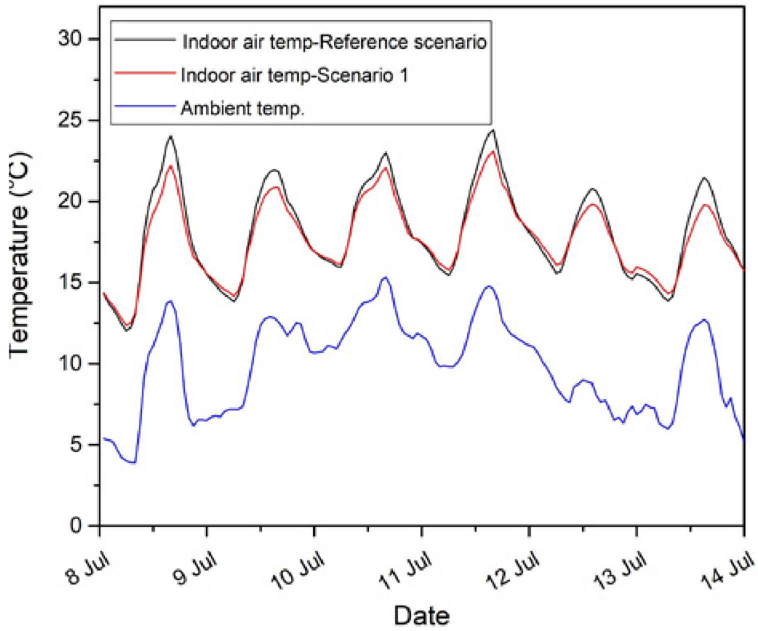

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.6 and 2.2 °C in Kuitpo and Roseworthy stations, respectively.

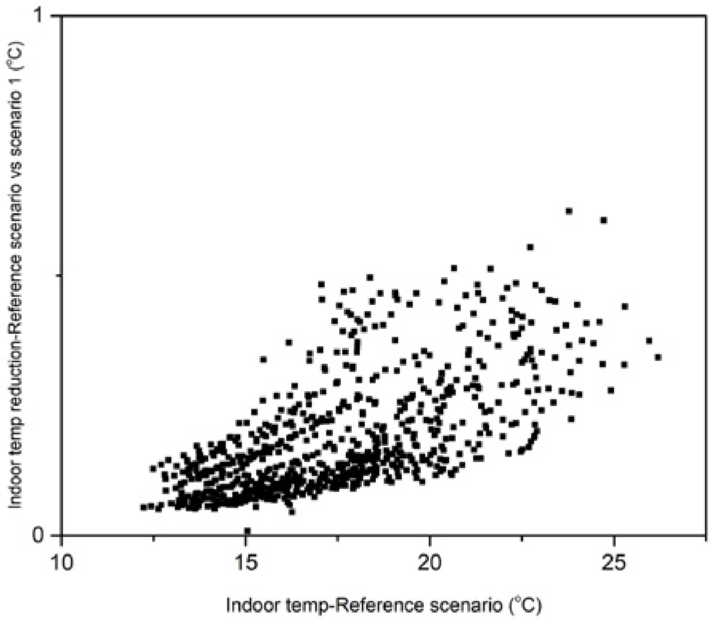

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

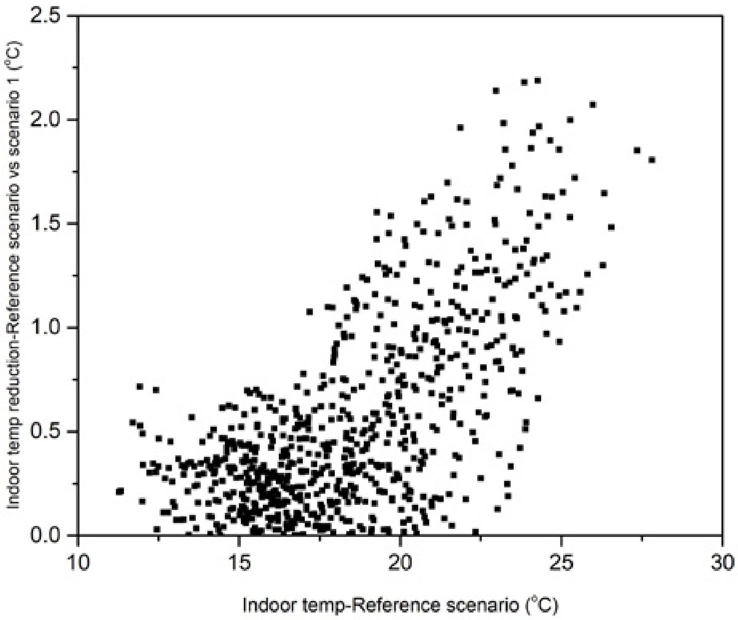

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase slightly from 525 hours in reference scenario to 541 hours, and from 437 to 472 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 195 hours in reference scenario to 205 hours; and from 135 to 165 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	195	525	205	541
Roseworthy	135	437	165	472

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 494 hours in reference scenario to 471 and 338 hours under scenario 1 and 2, in Kuitpo station; and from 510 to 493 and 456 under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	494	471	388
Roseworthy	510	493	456

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 03 is a new, low-rise building, with a total air-conditioned area of 2.400 m^2 distributed on two levels. The 1.200 m2 roof is insulated, resulting in low energy losses and, consequently, in a very limited energy saving potential. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 03.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	18.7	28.4
Energy consumption after cool roof (MWh)	18.1	26.7
Energy savings (MWh)	0.60	1.7
Energy savings (%)	3.21%	5.99%
Area (m^2)	1,200	1,200
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

Building 03 is a very good example of building with limited energy conservation potential. However, even in this case, a coating cool roof is a feasible investment, due its comparatively low initial investment cost and to the reasonable savings it achieves.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in energy savings of 3,21% for the Kuitpo weather conditions and of 5,56% for the Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 7.3% for the low energy price scenario for Kuitpo and 21,3% for the high energy scenario for Roseworthy conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

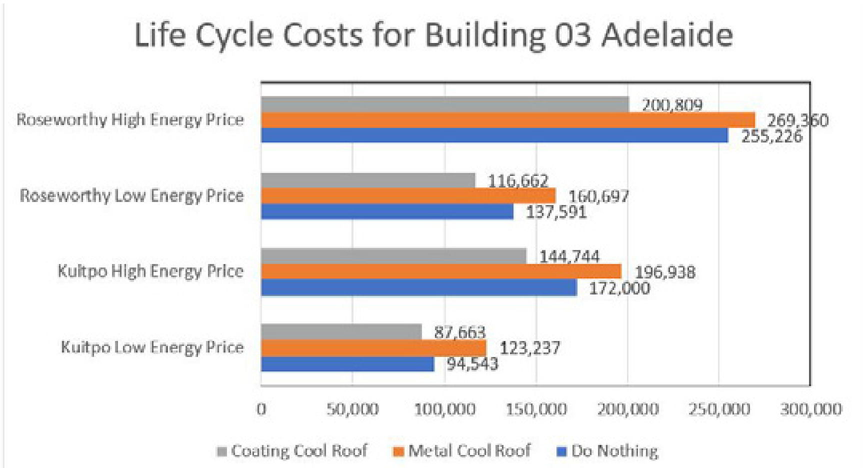

Figure 12. Life Cycle Costs for Building 03 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-30.35 %	-14.50 %	-16.79 %	-5.54 %
Coating Cool Roof	7.28 %	15.85 %	15.21 %	21.32 %

The metal cool roof is due to its higher initial investment cost not feasible.

7

CONCLUSIONS

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to have higher impact on the total cooling load reduction of the new low-rise office building with roof insulation. The building-scale application of cool roofs has a lower but still noticeable impact on the cooling load reduction of the new low-rise office building with roof insulation.

In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 12.8-19.3 kWh/m^2 to 11.9-18.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.9-1.3 kWh/m^2. This is equivalent to approximately 6.1-6.9 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 & Table 2 and Figure 1 & Figure 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.6-4.3 kWh/m^2. This is equivalent to 9.6-33.5 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 & Table 2 and Figure 2 & Figure 3).

• The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty 0.0-0.3 kWh/m^2) is significantly lower than the annual cooling load reduction (1.0-2.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 5.5-7.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6-1.9 kWh/m^2 (~3.2-6.2 %) (Tables 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 29.2-46.4 °C and 29.3-41.8 °C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.0 and 1.0 °C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.0 and 2.1 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figure 4, Figure 5, Figure 6 and Figure 7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free-floating condition, the indoor air temperature is expected to decrease slightly from a range between 12.5 and 22.8 °C in reference scenario to a range between 12.4 and 22.4 °C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 12.0 and 24.4 °C in reference scenario to a range between 12.4 and 23.1 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figure 8 and Figure 9).

• During a typical winter month and under free-floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.6 and 2.2 °C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figure 10 and Figure 11).

• During a typical winter month and under free-floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 525 hours in reference scenario to 541 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy station also show a increase in total number of hours below 19 °C from 437 hours in reference scenario to 472 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am - 6 pm) is expected to slightly increase from 195 hours in reference scenario to 205 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. Similarly, the calculation in Roseworthy station shows a slightly increase of number of hours below 19 °C from 135 hours to 165 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 494 hours under the reference scenario in Kuitpo station, which decreases to 471 and 338 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also shows that the number of hours above 26 °C decreases from 510 to 493 and 456 under Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 7.3% for the low energy price scenario for Kuitpo and 21,3% for the high energy scenario for Roseworthy conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible. Building 03 is in that sense a very good example of building with limited energy conservation potential. However, even in this case, a coating cool roof is a feasible investment, due its comparatively low initial investment cost and to the reasonable savings it achieves.

B03

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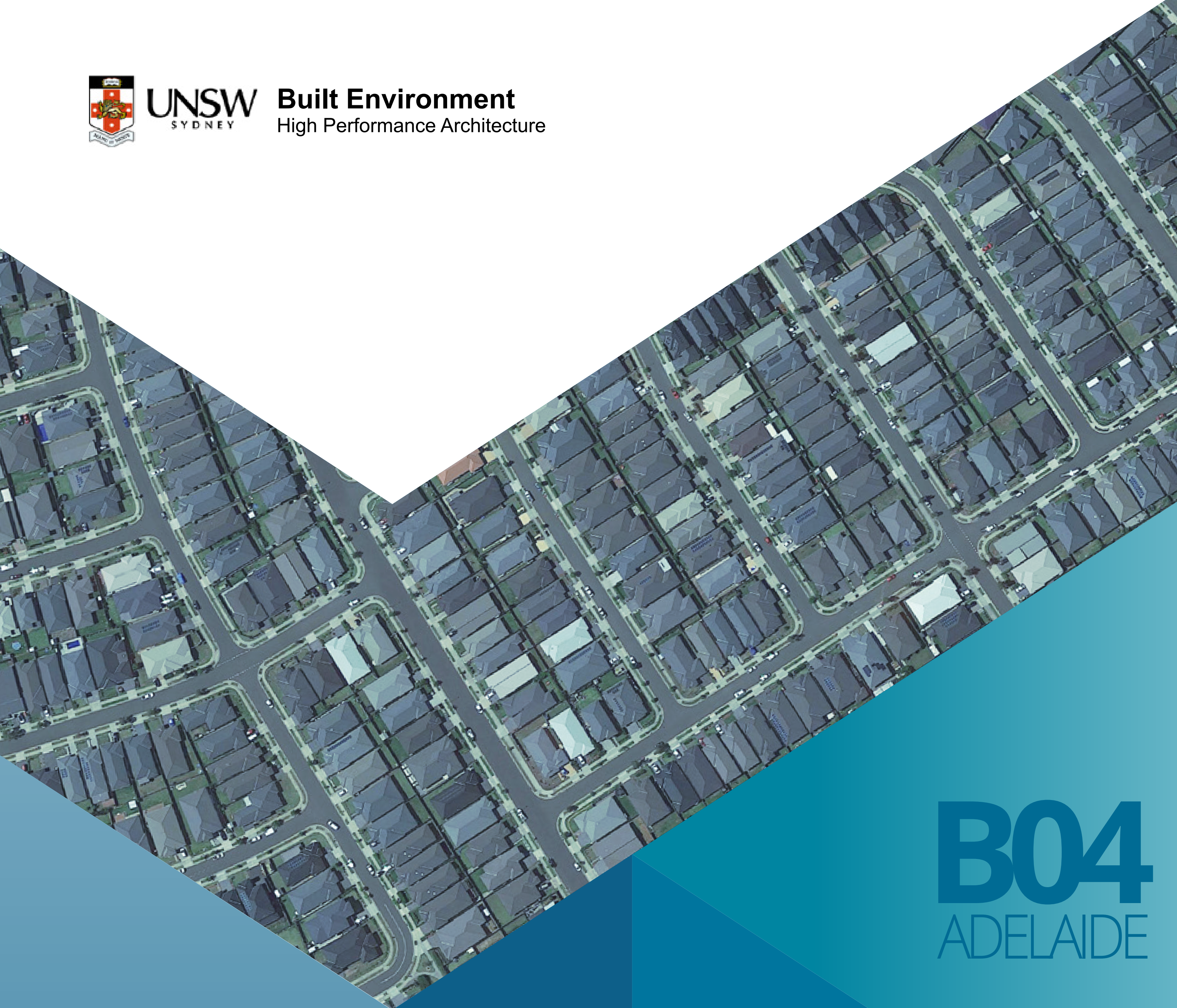

B04
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise office building with roof insulation
2021

BUILDING 04

NEW HIGH-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : $1200m^2$
Number of stories : 10

Image source: Ecipark Office Building. https://jerseydigs.com/bayonne-city-council-approves-10-story-building-975-broadway/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new high-rise office building with roof insulation from 12.2-18.4 kWh/m² to 12.0-18.2 kWh/m².

Table 1. Sensible and total cooling load for a typical new high-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	13.9	15.1	13.7	14.9	11.6	12.1
Edinburgh	15.6	16.7	15.4	16.5	13.0	13.4
Kuitpo	11.1	12.2	10.9	12.0	8.2	8.6
Parafield	15.1	16.3	14.9	16.1	13.0	13.5
Roseworthy	17.4	18.4	17.2	18.2	15.2	15.6

Table 2. Sensible and total cooling load saving for a typical new high-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.2 kWh/m² which is equivalent to 1.2-1.3 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.8-3.6 kWh/m² which is equivalent to 15.1-29.7 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	0.2	1.3	0.2	1.2	2.3	16.5	3.0	20.1
Edinburgh	0.2	1.1	0.2	1.2	2.6	16.8	3.3	19.8
Kuitpo	0.2	1.4	0.2	1.3	2.8	25.6	3.6	29.7
Parafield	0.2	1.3	0.2	1.2	2.1	14.1	2.8	16.9
Roseworthy	0.2	1.3	0.2	1.2	2.2	12.7	2.8	15.1

In the eleven weather stations in Adelaide, the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new high-rise office building with roof insulation during the summer season.

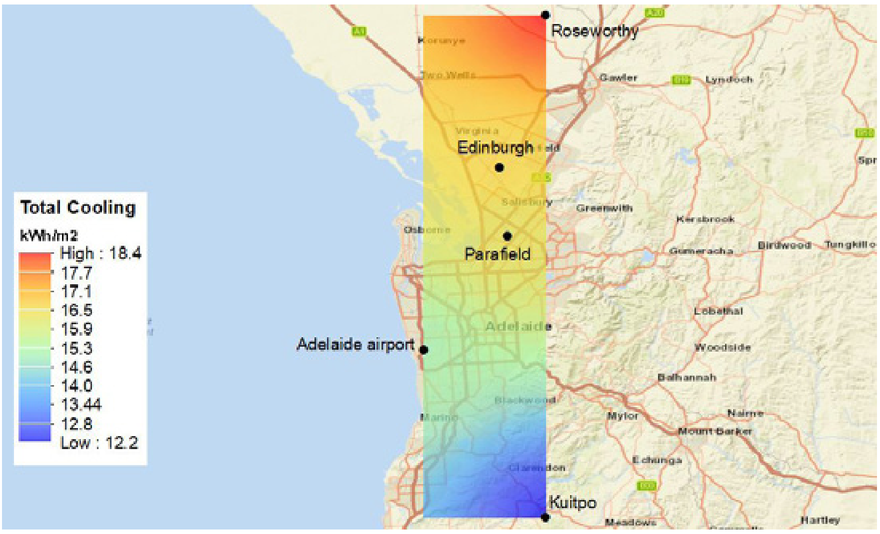

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

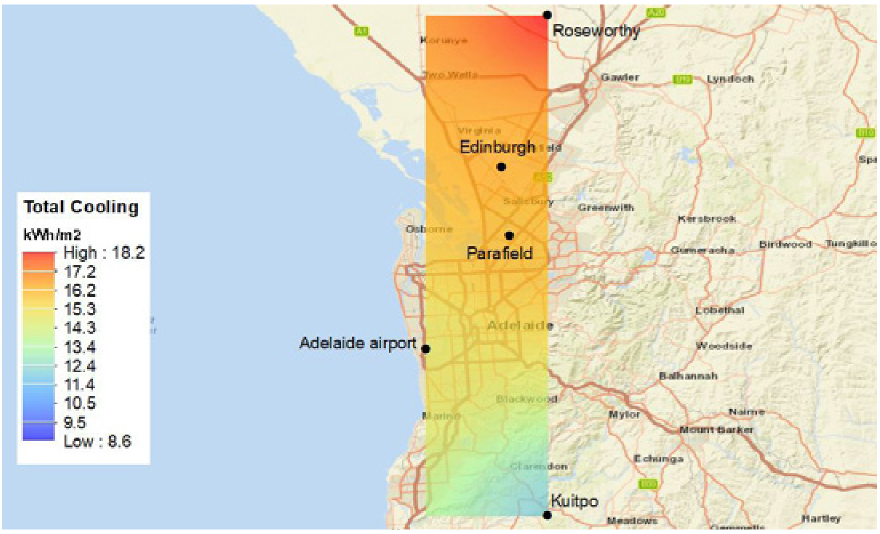

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

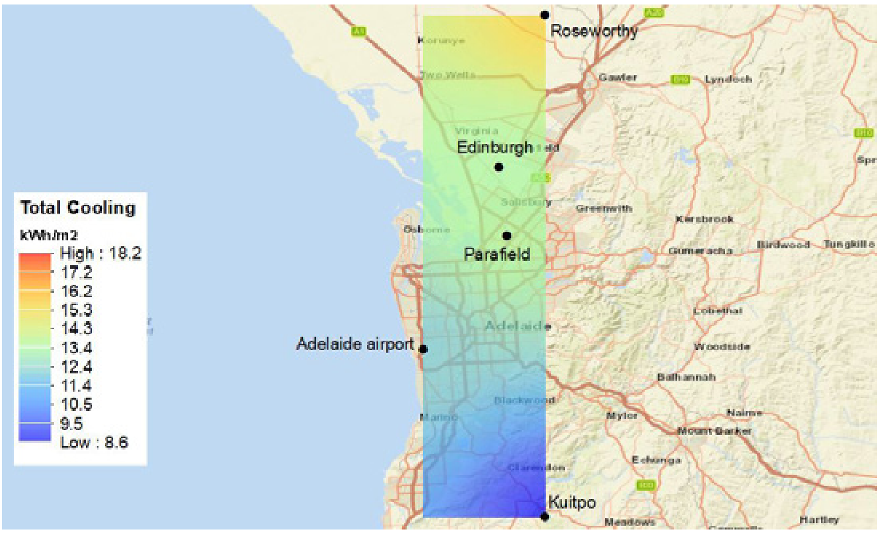

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new high-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is neraly the same that the annual cooling load reduction (0.2-0.3 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)		Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	18.1	19.9	0.7	2.0	17.9	19.7	0.7	2.0
Edinburgh	24.9	26.5	1.2	3.1	24.7	26.2	1.2	3.1
Kuitpo	12.0	12.7	1.8	4.9	11.9	12.6	1.8	5.0
Parafield	27.3	29.4	1.1	2.8	27.0	29.1	1.1	2.8
Roseworthy	26.5	27.8	0.0	0.0	26.2	27.5	0.0	0.0

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 1.0-1.3 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.1 and 0.3 kWh/m² (~0.6-1.1 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2		kWh/m^2	%	kWh/m^2	%
Adelaide Airport	0.2	1.0	0.2	1.0	0.0	0.0	0.2	1.0	0.2	0.8
Edinburgh	0.3	1.0	0.3	1.0	0.0	0.0	0.2	0.9	0.2	0.8
Kuitpo	0.2	1.3	0.2	1.3	0.0	0.1	0.1	0.9	0.1	0.6
Parafield	0.3	1.0	0.3	1.0	0.0	0.0	0.3	0.9	0.3	0.8
Roseworthy	0.3	1.1	0.3	1.1	0.0	0.0	0.3	1.1	0.3	1.1

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

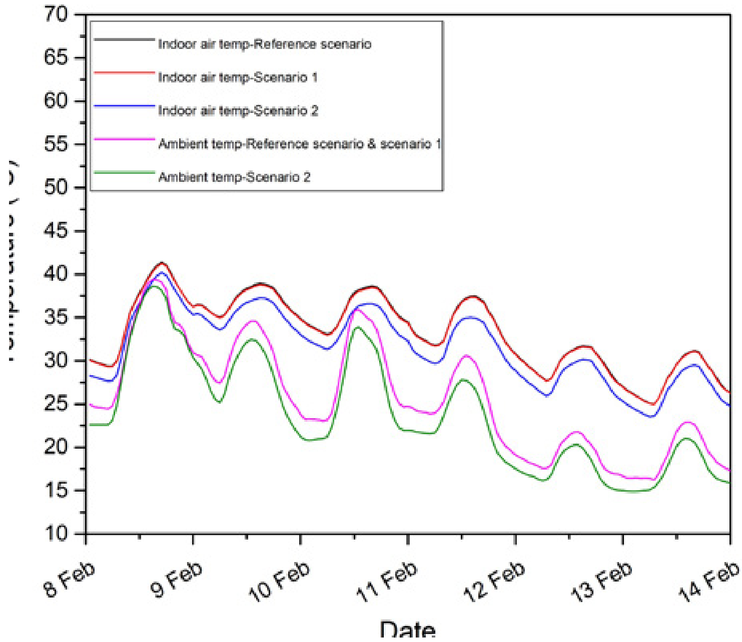

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

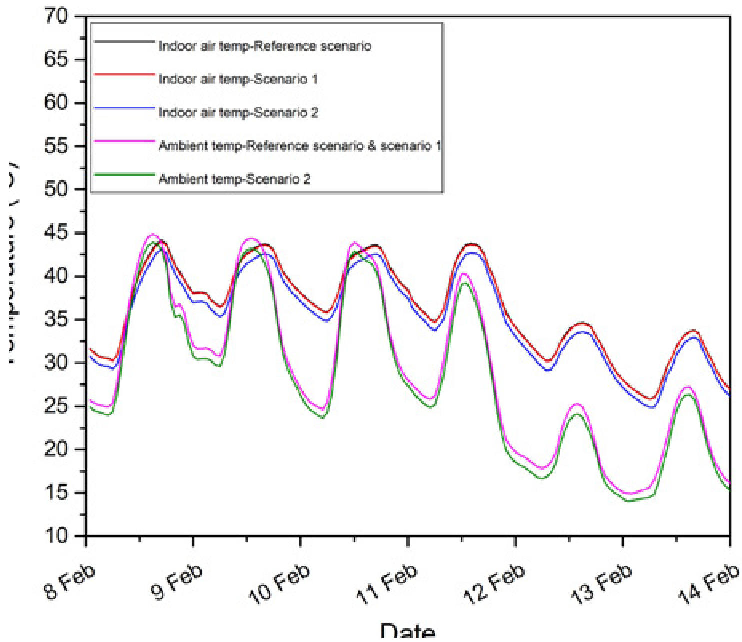

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 24.5-41.4 °C and 24.3-44.2 °C in Kuitpo and Roseworthy stations, respectively.

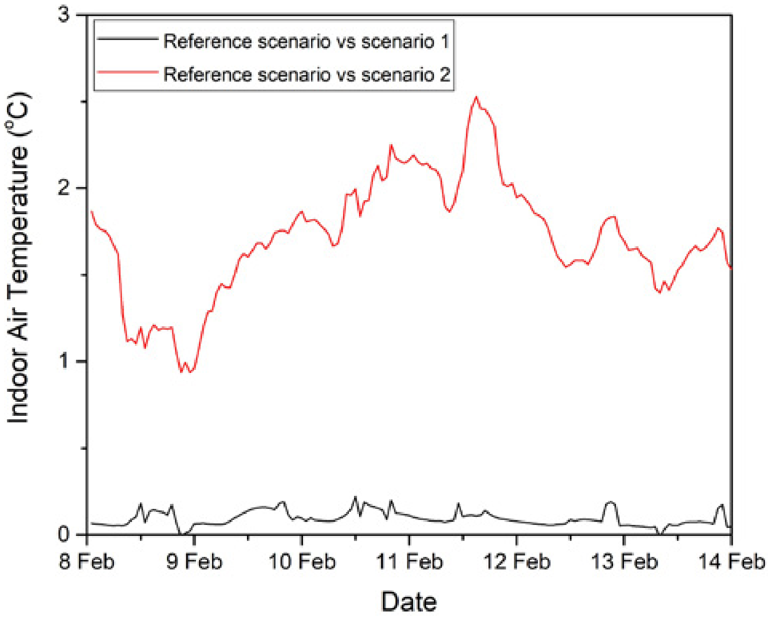

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.2 °C and 0.2 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.5 and 1.5 °C in Kuitpo and Roseworthy stations, respectively.

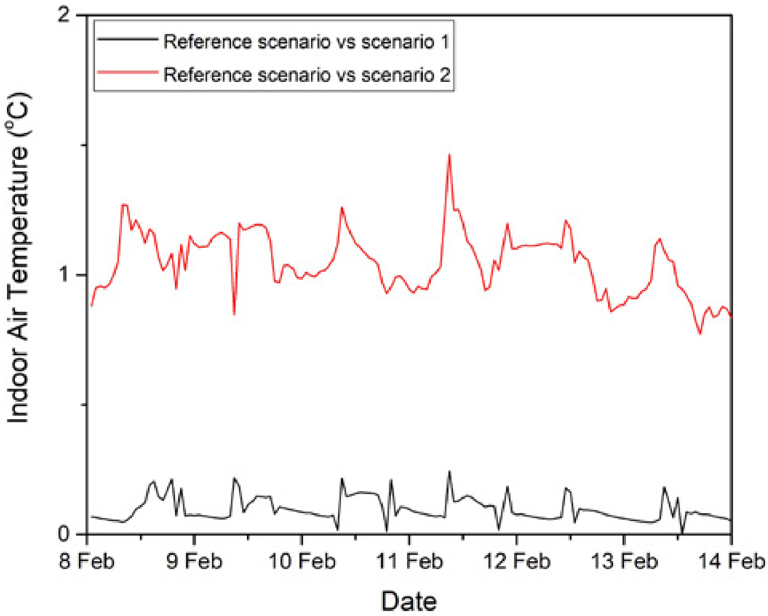

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to remain almost the same in reference scenario and reference with cool roof scenario (scenario 1) in Kuitpo and Roseworthy stations, respectively.

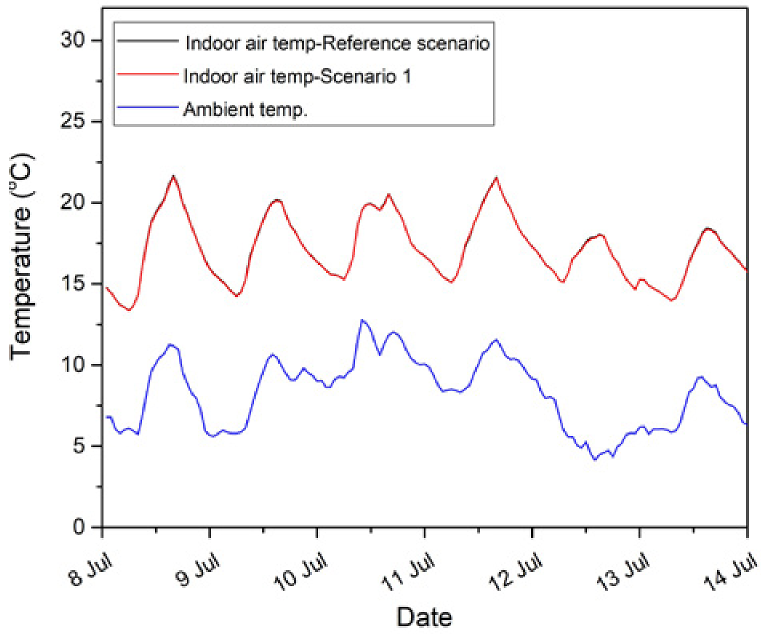

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

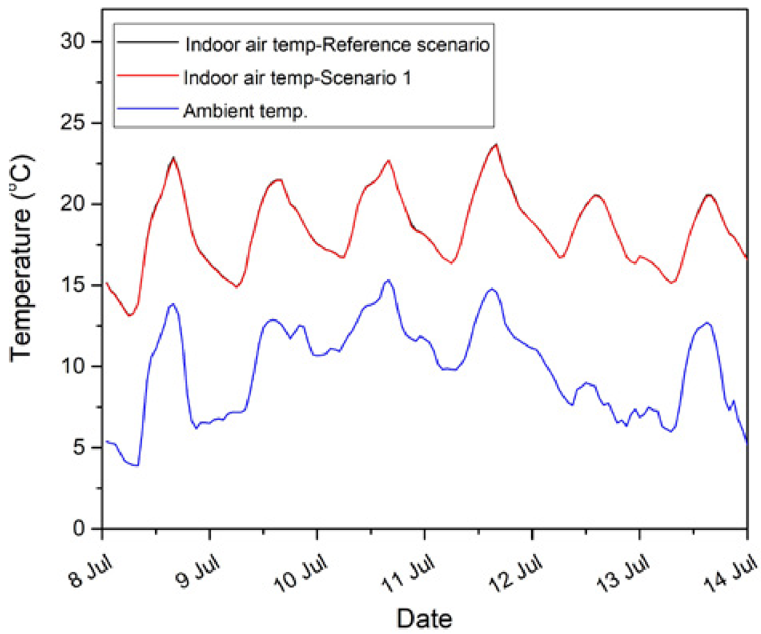

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C in Kuitpo and Roseworthy stations.

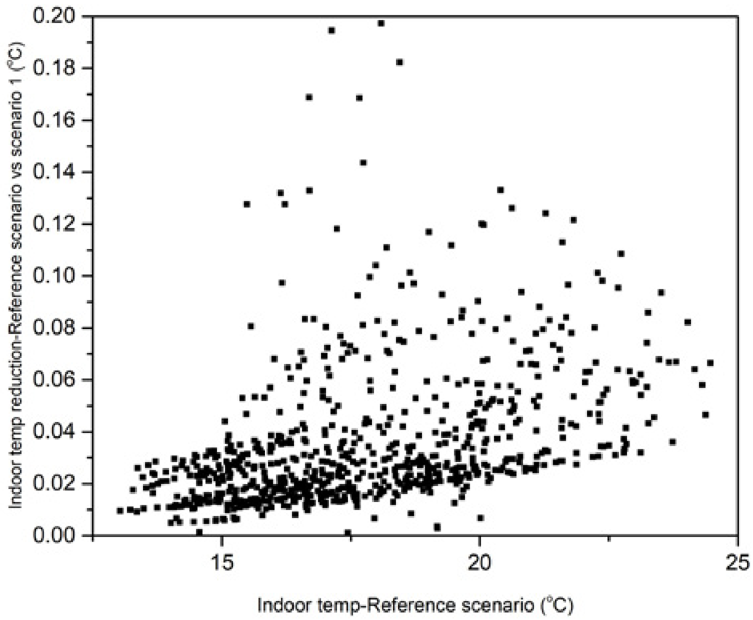

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

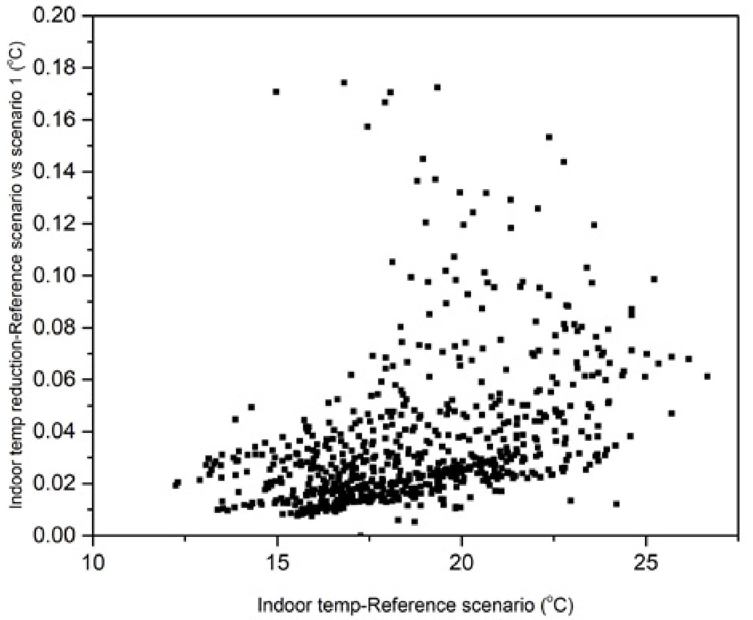

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 505 hours to 510 hours in reference scenario in Kuitpo station while remains almost the same (416-417) for Roseworthy station.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 199 to 202 hours in Kuitpo stations and remain almost the same (136-137) for reference scenario and scenario 1 in Roseworthy station.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	199	505	202	510
Roseworthy	136	416	137	417

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 529 hours to 523 and 436 for scanerio 1 and 2 in Kuitpo station, and from 560 hours to 556 and 511 hours for Scenario 1 and 2 in Roseworthy station.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	529	523	436
Roseworthy	560	556	511

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a significantly higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 04 is a new, high-rise building, with a total air-conditioned area of 12.000 m^2 distributed on ten levels. The 1.200 m^2 roof is insulated, resulting in low energy losses. In addition, the roof has an impact only on the floor directly underneath. Hence, there is only a very limited energy saving potential. The main features of the building's energy performance both for Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 04.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	84.5	133.4
Energy consumption after cool roof (MWh)	84.5	132.0
Energy savings (MWh)	0.00	1.4
Energy savings (%)	0.00%	1.05%
Area (m^2)	1,200	1,200
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

The cool roof refurbishment options

Building 04 is a very good example of building with very limited energy conservation potential. Still, even in this case, a coating cool roof is a feasible investment over the building's life cycle.

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in no energy savings for the Kuitpo and in very modest 1,05% for the Roseworthy weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 19,2% for Kuitpo and 23,1% for Roseworthy conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

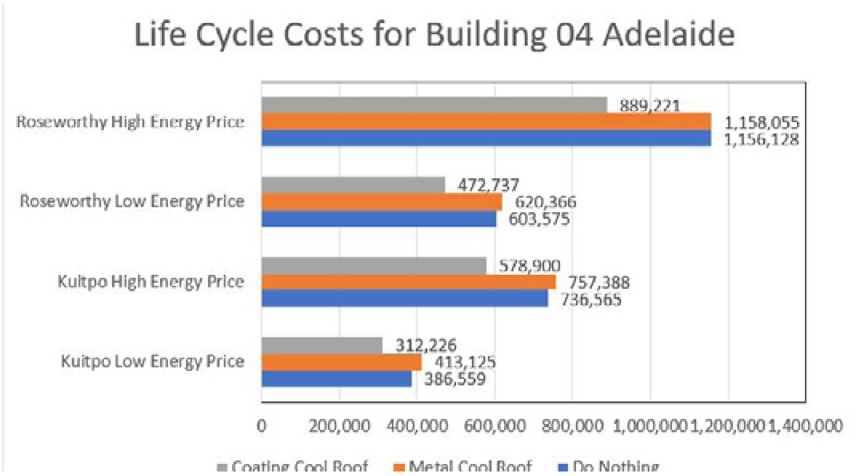

Figure 12. Life Cycle Costs for Building 04 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

The metal cool roof is due to its higher initial investment cost not feasible.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-6.87 %	-2.83 %	-2.78 %	-0.17 %
Coating Cool Roof	19.23 %	21.41 %	21.68 %	23.09 %

7

CONCLUSIONS

• In the eleven weather stations in Adelaide, the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new high-rise office building with roof insulation during the summer season. Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• The building-scale application of cool roofs can decrease the two summer months total cooling load of the new high-rise office building with roof insulation from 12.2-18.4 kWh/m^2 to 12.0-18.2 kWh/m^2. As computed, the building-scale application of cool roofs is predicted to reduce the cooling load of new high-rise office building with roof insulation by 0.2 kWh/m^2 (~1.2-1.3 %) (See Table 1 and 2 and Figures 1 and 2). The combined building-scale and urban-scale application of cool roofs is foreseen to have a significant contribution to cooling load reduction. It is estimated that the cooling load of cool roof with modified urban temperature scenario (scenario 2) is around 2.8-3.6 kWh/m^2 (~15.1-29.7 %) lower than the reference scenario (See Table 1 and 2 and Figures 2 and 3) . Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0-0.1 kWh/m^2) is neraly the same that the annual cooling load reduction (0.2-0.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.0-1.3%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.1 and 0.3 kWh/m^2 (~0.6-1.1 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 24.5-41.4 ^{o}C and 24.3-44.2 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.2 ^{o}C and 0.2 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.5 and 1.5 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to remain almost the same in reference scenario and reference with cool roof scenario (scenario 1) in Kuitpo and Roseworthy stations (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 ^{o}C in Kuitpo and Roseworthy stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 505 hours in reference scenario to 510 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations show that the total number of hours below 19 ^{o}C remain almost the same (416-417) for the reference scenario and scenario 1. Also, the number of hours below 19 ^{o}C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to slightly increase from 199 to 202 hours in Kuitpo stations and remain almost the same (136-137) for reference scenario and scenario 1 in Roseworthy station. (See Table 5).

• During a typical summer month, the total number of hours with an indoor air temperature (>26 ^{o}C) is predicted to slightly decreased from 529 hours to 523 and 436 for scanerio 1 and 2 in Kuitpo station, and from 560 hours to 556 and 511 hours for Scenario 1 and 2 in Roseworthy station. (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a significantly higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 19,2% for Kuitpo and 23,1% for Roseworthy conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible. Building 04 is in that sense a very good example of building with very limited energy conservation potential. Still, even in this case, a coating cool roof is a feasible investment over the building's life cycle.

B04

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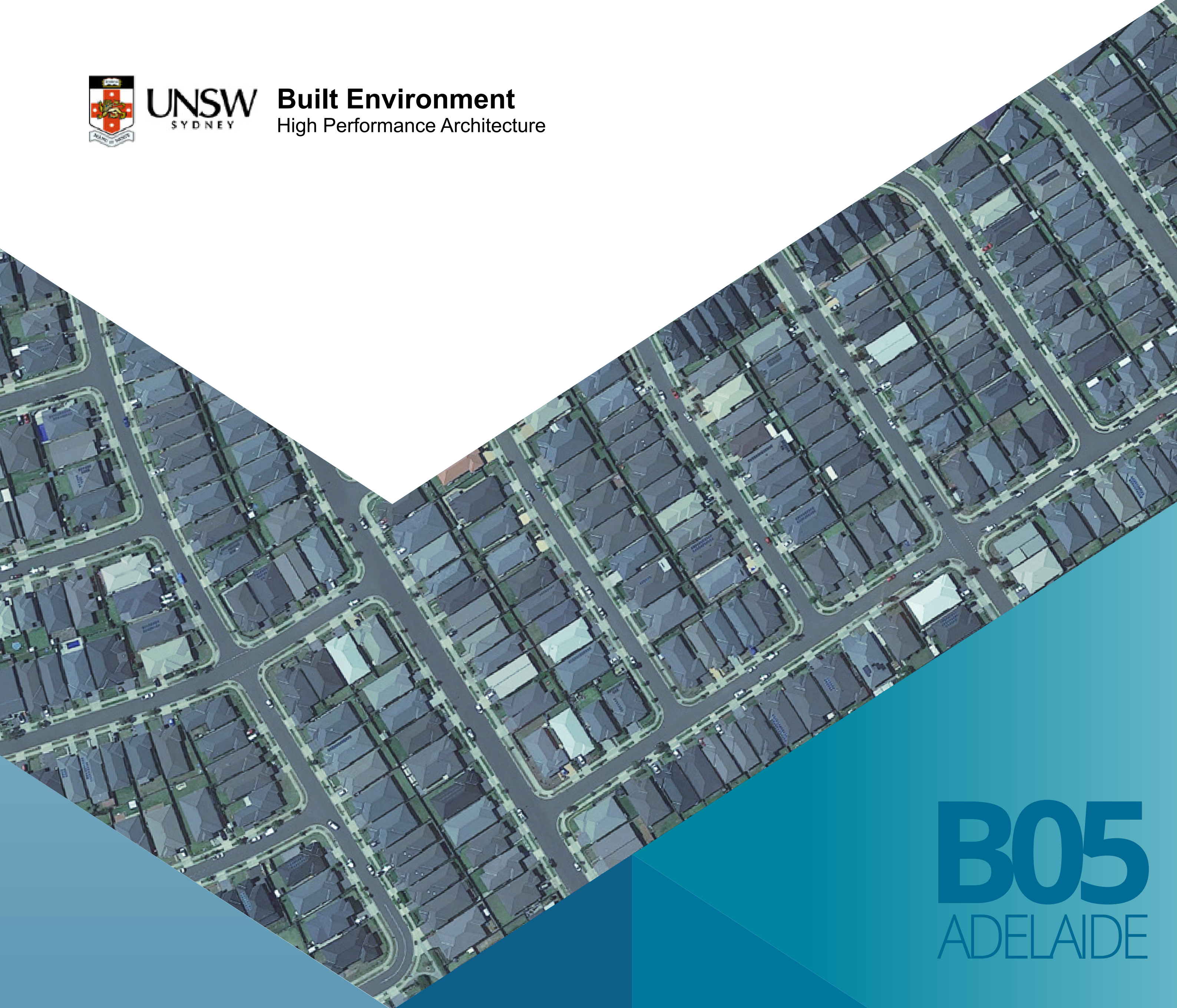

B05
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise shopping mall centre
2021

BUILDING 05

NEW LOW-RISE SHOPPING MALL CENTRE

Floor area : 1100m^2
Number of stories : 2

Image source: Westfield Tea Tree Plaza, Tea Tree Plaza 976 North East Rd, Modbury, Tea Tree Gully, South Australia 5092, Australia

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new low-rise office building from 56.3-66.3 kWh/m² to 54.7-64.5 kWh/m².

Table 1. Sensible and total cooling load for a new low-rise shopping mall centre without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	56.5	60.9	54.8	59.3	51.1	52.7
Edinburgh	59.3	63.4	57.8	61.8	53.3	54.7
Kuitpo	50.9	56.3	49.3	54.7	44.4	46.1
Parafield	58.6	62.6	57.0	61.0	53.6	55.3
Roseworthy	63.4	66.3	61.6	64.5	57.8	59.0

For Scenario 1, the total cooling load saving is around 1.6-1.8 kWh/m² which is equivalent to 2.5-2.9 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.3-10.2 kWh/m² which is equivalent to 11.0-18.1 % total cooling load reduction.

Table 2. Sensible and total cooling load saving for a new low-rise shopping mall centre without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	1.6	2.9	1.6	2.7	5.4	9.5	8.2	13.5
Edinburgh	1.6	2.7	1.6	2.5	6.0	10.1	8.7	13.7
Kuitpo	1.6	3.1	1.6	2.9	6.5	12.8	10.2	18.1
Parafield	1.6	2.7	1.6	2.6	4.9	8.4	7.3	11.7
Roseworthy	1.8	2.8	1.8	2.7	5.5	8.7	7.3	11.0

In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs can reduce the cooling load of the new low-rise shopping mall centre with insulation during the summer season.

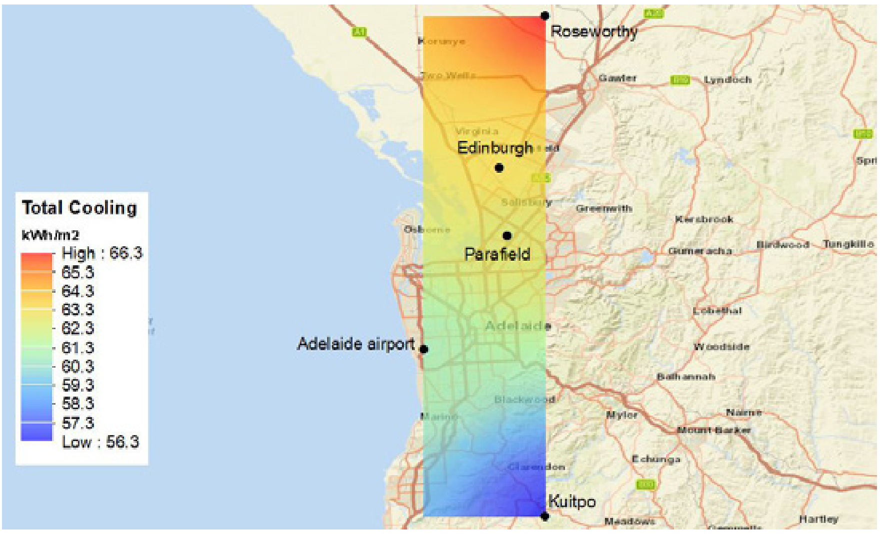

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

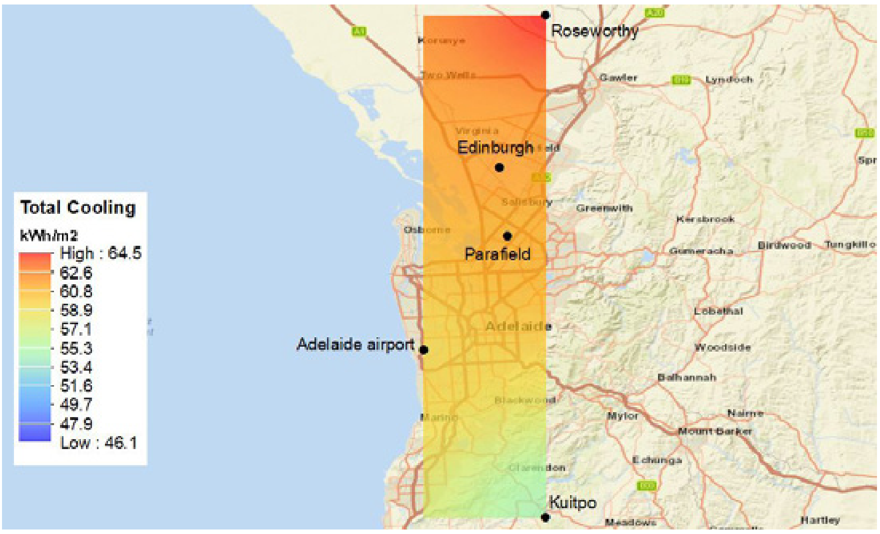

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

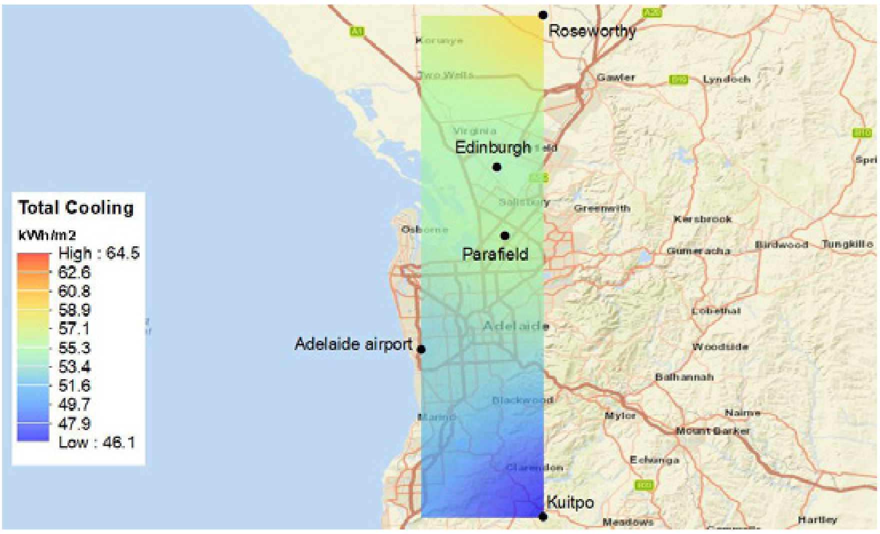

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1-0.2 kWh/m²) is significantly lower than the annual cooling load reduction (4.1-5.0 kWh/m²).

Table 3. Annual cooling and heating loads for a new low-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	137.1	151.0	1.3	3.2	132.6	146.5	1.3	3.3
Edinburgh	147.7	158.3	1.9	5.1	143.2	153.8	1.9	5.3
Kuitpo	94.3	104.0	2.3	6.9	90.3	99.9	2.3	7.1
Parafield	155.7	169.0	1.8	4.8	150.9	164.1	1.8	4.9
Roseworthy	146.9	156.2	2.7	7.3	142.0	151.2	2.8	7.4

The annual cooling load saving by building-scale application of cool roofs is around 2.9-3.9 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.9-4.8 kWh/m² (~2.7-3.5 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for new low-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	4.4	3.2	4.5	3.0	0.0	0.1	4.4	3.2	4.5	2.9
Edinburgh	4.5	3.0	4.6	2.9	0.0	0.1	4.5	3.0	4.4	2.7
Kuitpo	4.0	4.2	4.1	3.9	0.1	0.2	3.9	4.1	3.9	3.5
Parafield	4.8	3.1	4.8	2.9	0.0	0.1	4.7	3.0	4.7	2.7
Roseworthy	4.9	3.3	5.0	3.2	0.1	0.2	4.8	3.2	4.8	2.9

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

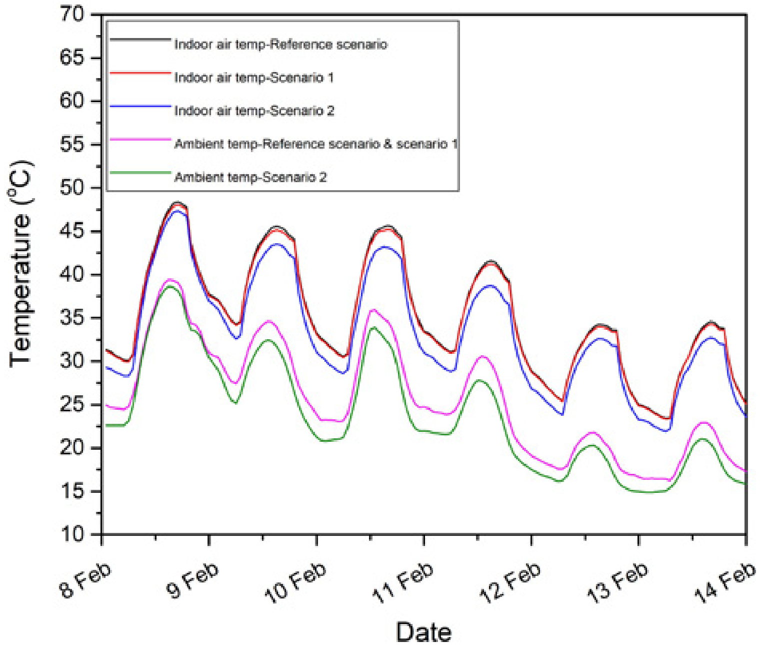

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new low-rise shopping mall centre under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

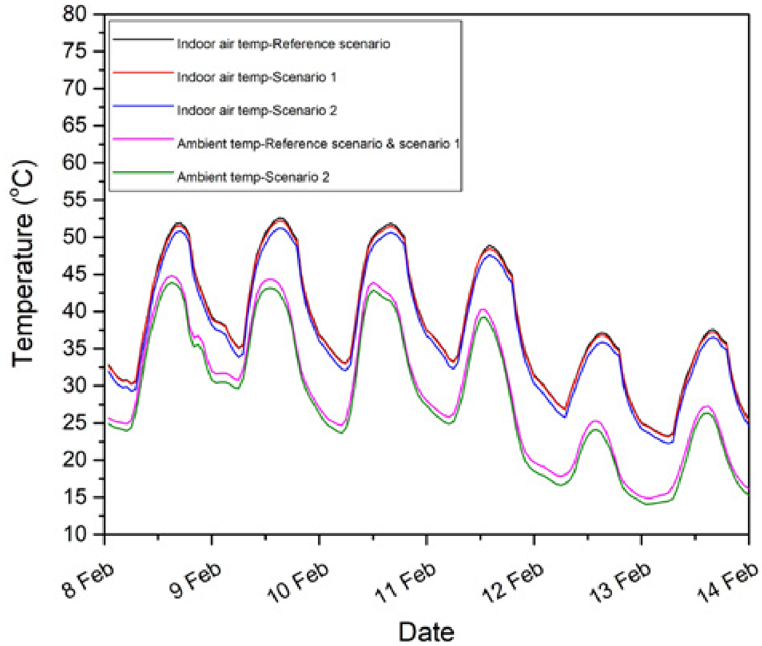

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 23.4-48.4 °C and 24.3-44.2 °C in Kuitpo and Roseworthy stations, respectively.

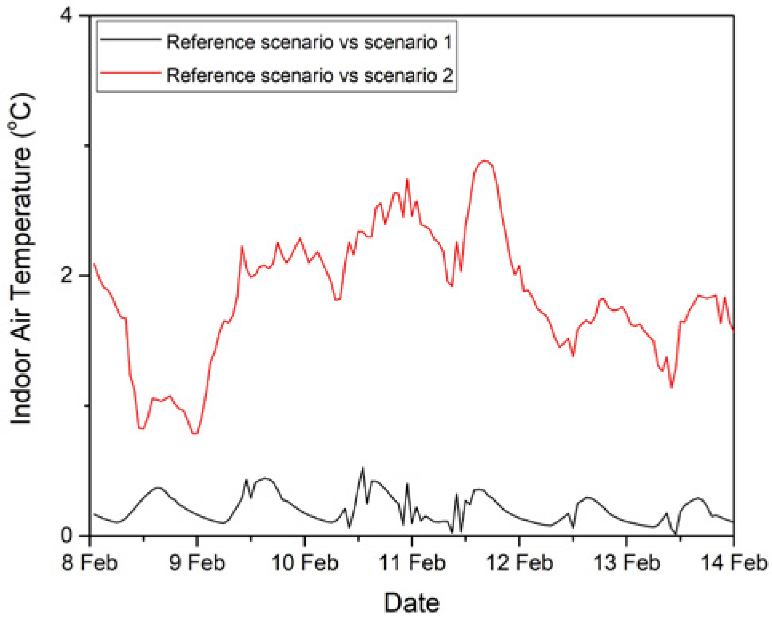

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.6 °C and 0.2 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.9 °C and 1.5 °C in Kuitpo and Roseworthy stations, respectively.

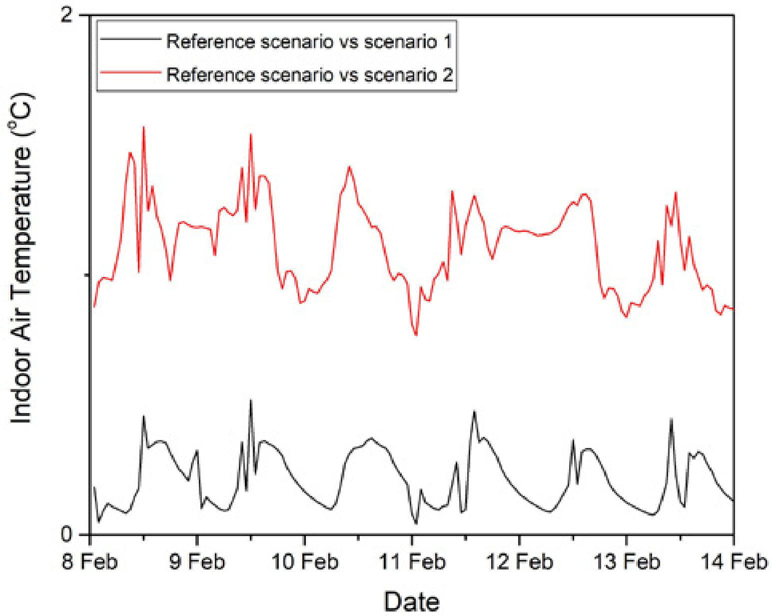

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.1-25.8 °C in reference scenario to a range 12.1-25.5 °C in scenario 1 in Kuitpo station.

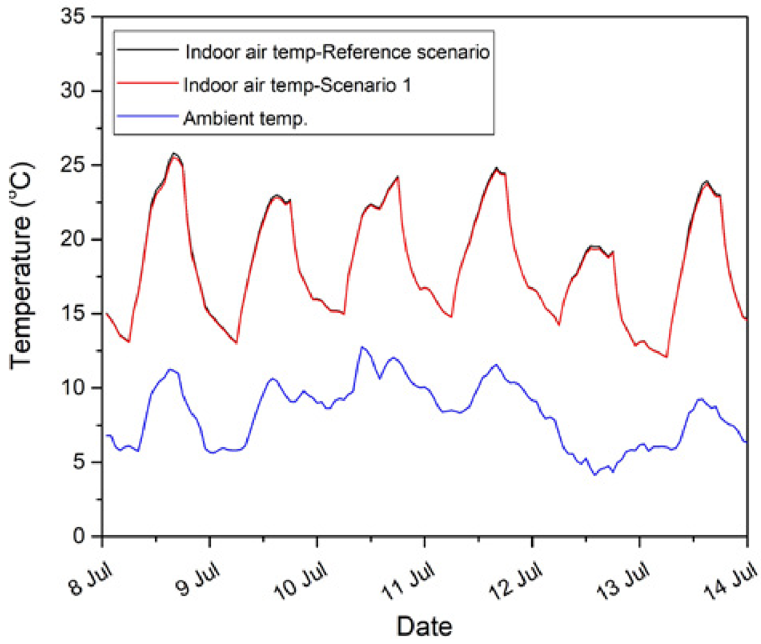

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 13.1-23.7 °C in reference scenario to a range 13.1-23.6 °C in scenario 1 in Roseworthy station.

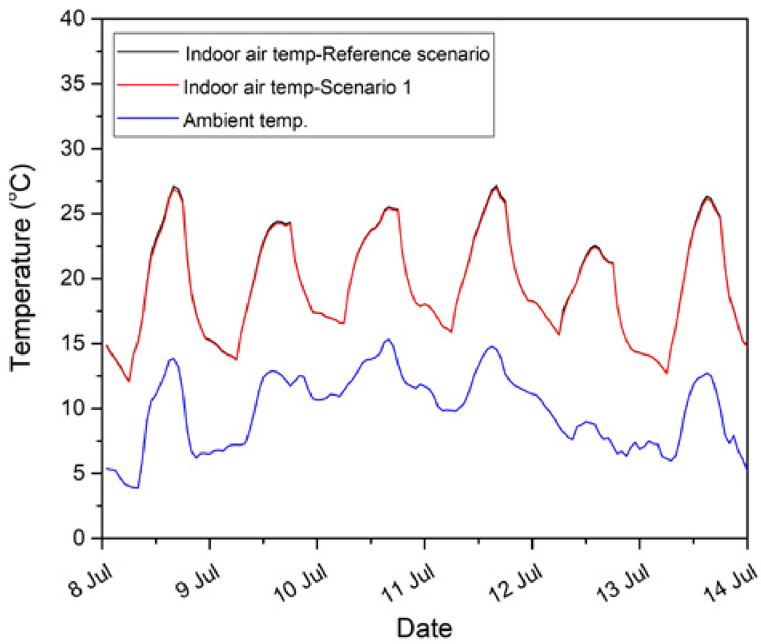

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.5 °C in Kuitpo and Roseworthy stations.

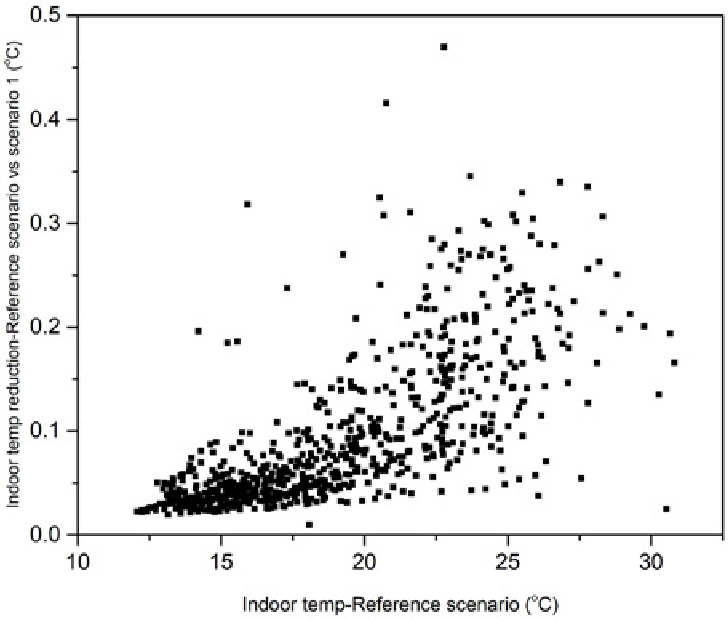

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

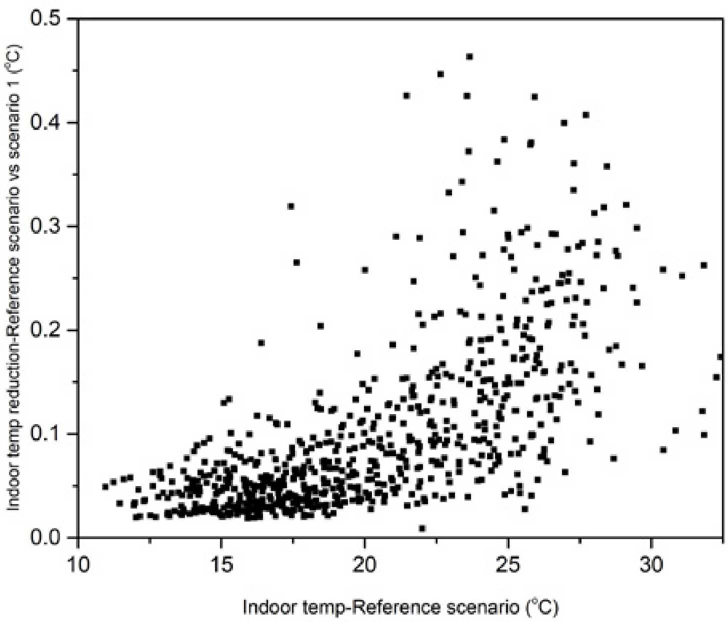

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 388 hours in reference scenario to 392 hours, and from 345 to 348 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 79 to 81 hours and from 64 to 65 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	79	388	81	392
Roseworthy	64	345	65	348

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 520 hours in reference scenario to 518 and from 533 hours to 530 and 506 hours under scenario 1 and 2 in Kuitpo station and Roseworthy stations, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	520	518	467
Roseworthy	533	530	506

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a significantly higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 05 is a new, low-rise commercial building, with a total air-conditioned area of 2.200 m^2 distributed on two levels. The 1.100 m^2 roof is insulated, resulting in low energy losses and, consequently, in a limited energy saving potential, despite the roof's significant impact on the building's energy requirements. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 05.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	97.6	143.9
Energy consumption after cool roof (MWh)	94.2	139.6
Energy savings (MWh)	3.4	4.3
Energy savings (%)	3.48%	2.99%
Area (m^2)	1,100	1,100
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

Building 05 is a good example of a new, insulated, low-rise building where, despite its rather limited energy conservation potential, the coating cool roof is a feasible investment, over the building's life cycle, due to the impact of the roof on the building's cooling loads.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in energy savings of 3,48% for the Kuitpo and of 2,99% for the Roseworthy weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option achieves a significant reduction of life cycle costs over the building's life cycle, that varies between 22,8% for the low energy price scenario for Kuitpo and 24,8% for the high energy scenario for Roseworthy.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is due to its higher initial investment marginally feasible for both locations for high energy prices' scenarios, and marginally not feasible for the low energy prices scenarios.

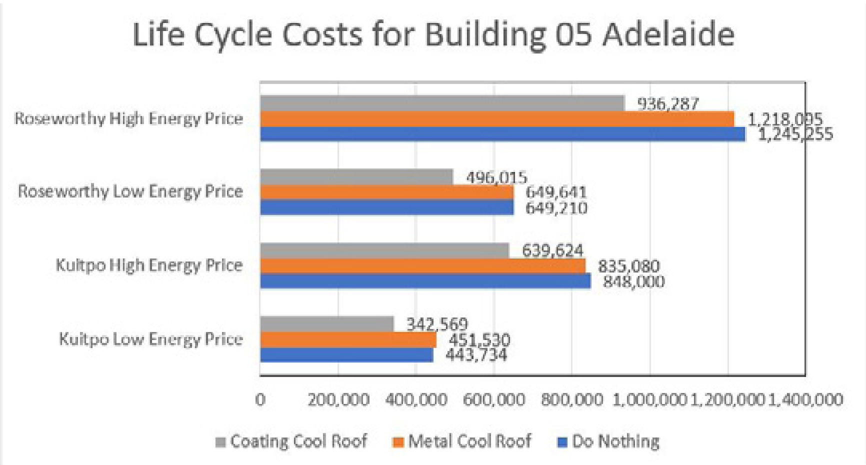

Figure 12. Life Cycle Costs for Building 05 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-1.76 %	1.52 %	-0.07 %	2.18 %
Coating Cool Roof	22.80 %	24.57 %	23.60 %	24.81 %

7

CONCLUSIONS

• In the eleven weather stations in Adelaide, the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new low-rise shopping mall centre during the summer season. Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• In the eleven weather stations in Adelaide, the total cooling load of a typical low-rise shopping mall centre under the reference scenario is approximately 56.3-66.3 kWh/m^2, which reduces to a range between 54.7-64.5 kWh/m^2 under Reference with cool roof scenario (scenario 1). As computed, the total cooling load saving by building-scale application of cool roofs is around 1.6-1.8 kWh/m^2 (~2.5-2.9 %) (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the total cooling load of low-rise shopping mall centre is estimated to be around 7.3-10.2 kWh/m^2 lower under cool roof with modified urban temperature scenario (scenario 2) compared to the reference scenario. This is equivalent to 11.0-18.1 % total cooling load saving by combined building-scale and urban-scale application of cool roof.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1-0.2 kWh/m^2) is significantly lower than the annual cooling load reduction (4.1-5.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 2.9-3.9 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.9-4.8 kWh/m^2 (~2.7-3.5%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 23.4-48.4 ^{o}C and 24.3-44.2 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.6 and 0.2 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.9 ^{o}C and 1.5 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 12.1-25.8 ^{o}C in reference scenario to a range between 12.1-25.5 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 13.1-23.7 °C in reference scenario to a range between 13.1-23.6°C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.5 °C in Kuitpo and Roseworthy stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 388 hours in reference scenario to 392 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight increase in total number of hours below 19 °C from 345 hours in reference scenario to 348 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number operational hours with air temperature <19 °C during is expected to slightly increase from 79 hours in reference scenario to 81 hours and from 64 to 65 hours in Kuitpo and in Roseworthy stations, respectively.

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 520 hours under the reference scenario in Kuitpo station, which slightly decreases to 518 and 467 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station shows that the total number of hours above 26 °C decreases from 533 hours to 530 and 506 hours for Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has clearly the higher cost over the building's life cycle compared to the coating cool roof, which achieves a significant reduction of life cycle costs over the building's life cycle, that varies between 22,8% for the low energy price scenario for Kuitpo and 24,8% for the high energy scenario for Roseworthy, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment marginally feasible for both locations for high energy prices' scenarios, and marginally not feasible for the low energy prices scenarios. Building 05 is in that sense a good example of a new, insulated, low-rise building where, despite its rather limited energy conservation potential, the coating cool roof is a feasible investment, over the building's life cycle, due to the impact of the roof on the building's cooling loads.

B05

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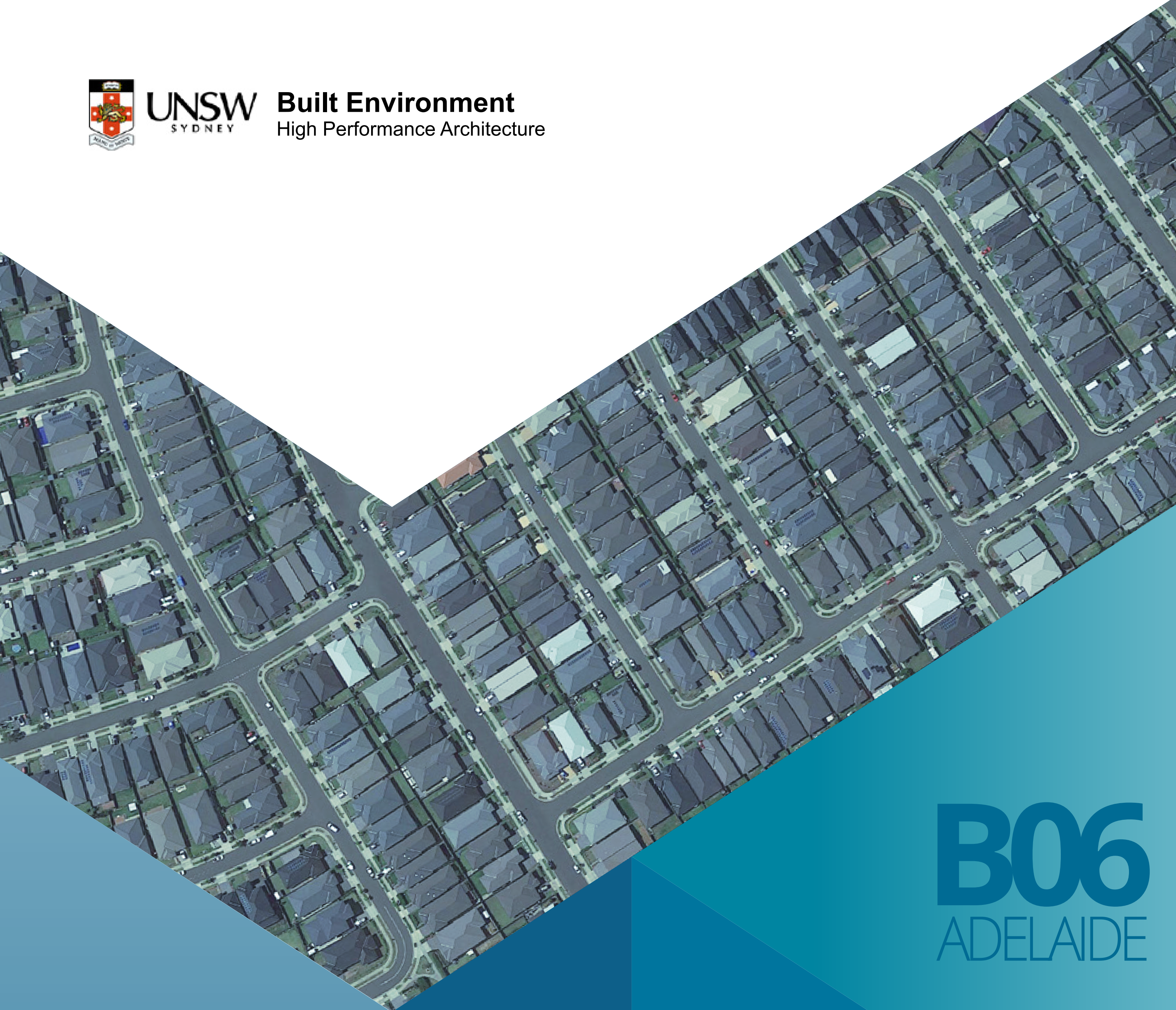

B06
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New mid-rise shopping mall centre
2021

BUILDING 06

NEW MID-RISE SHOPPING MALL CENTRE

Floor area : 1100m²
Number of stories : 4

Image source: Yamanto Central, Brisbane

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise shopping mall centre from 54.8-64.6 kWh/m² to 54.1-63.8 kWh/m².

Table 1. Sensible and total cooling load for a new mid-rise shopping mall centre without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	55.0	59.4	54.3	58.7	50.5	52.1
Edinburgh	57.9	61.9	57.2	61.2	52.7	54.1
Kuitpo	49.4	54.8	48.7	54.1	43.6	45.4
Parafield	57.1	61.1	56.4	60.4	53.1	54.7
Roseworthy	61.7	64.6	60.9	63.8	57.2	58.3

For Scenario 1, the total cooling load saving is around 0.7-0.9 kWh/m² which is equivalent to 1.2-1.4 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.3-9.4 kWh/m² which is equivalent to 19.8-17.2 % total cooling load reduction.

Table 2. Sensible and total cooling load saving for a new mid-rise shopping mall centre without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	0.8	1.4	0.8	1.3	4.5	8.2	7.3	12.3
Edinburgh	0.7	1.3	0.7	1.2	5.2	9.0	7.8	12.6
Kuitpo	0.7	1.5	0.8	1.4	5.8	11.8	9.4	17.2
Parafield	0.8	1.3	0.8	1.3	4.1	7.1	6.4	10.5
Roseworthy	0.8	1.4	0.9	1.3	4.6	7.4	6.3	9.8

In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of a new mid-rise shopping mall centre during the summer season.

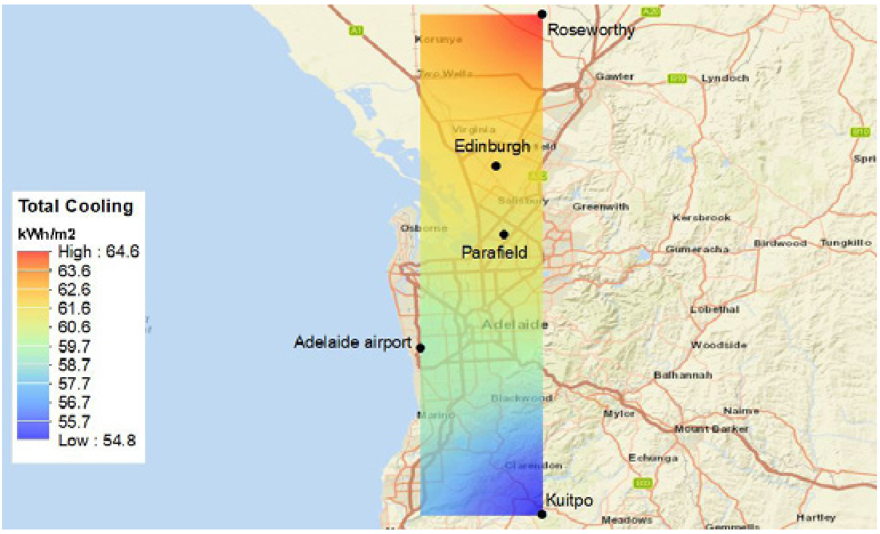

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

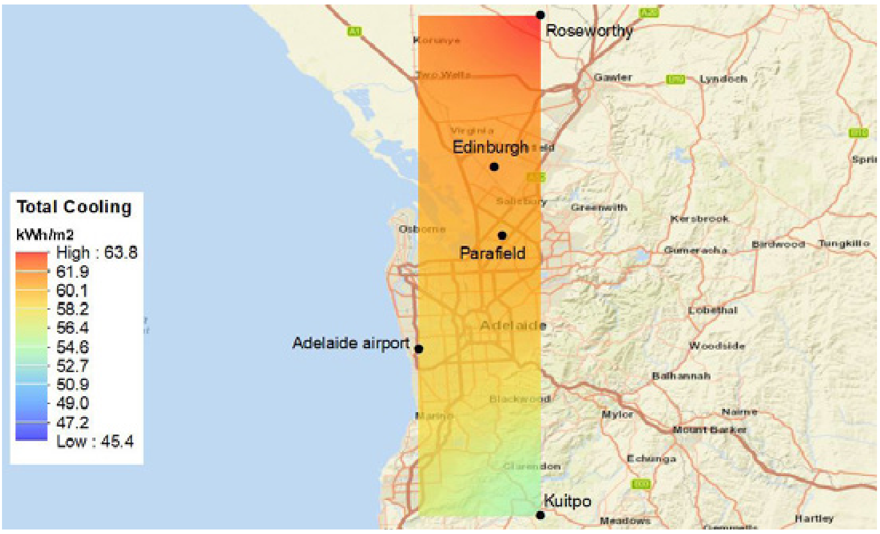

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

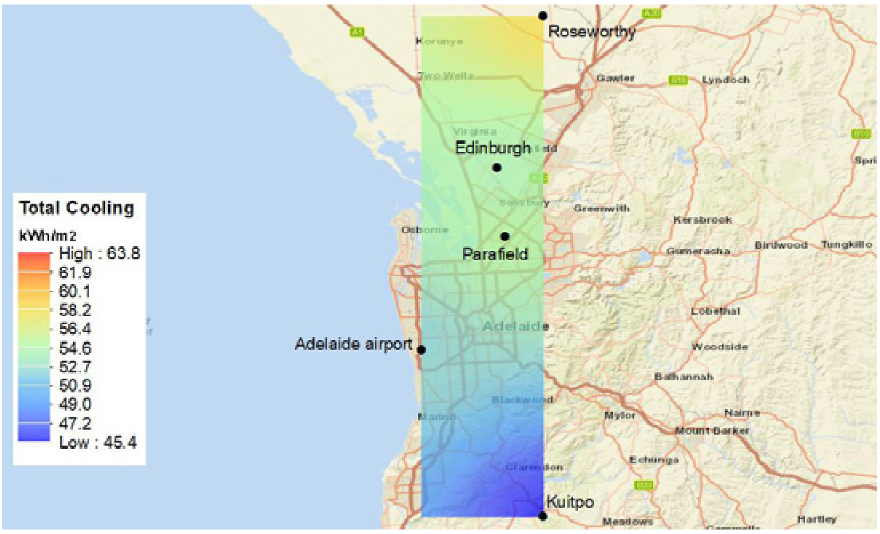

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new mid-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (1.9-2.3 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	130.3	144.2	1.0	2.7	128.3	142.1	1.0	2.8
Edinburgh	140.6	151.2	1.5	4.6	138.5	149.1	1.5	4.6
Kuitpo	87.9	97.5	1.9	6.5	86.1	95.6	1.9	6.6
Parafield	148.3	161.5	1.4	4.2	146.1	159.2	1.5	4.3
Roseworthy	139.0	148.3	2.2	6.6	136.8	146.0	2.2	6.7

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for new mid-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 1.4-1.9 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.8-2.2 kWh/m² (~1.3-1.7 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	2.0	1.6	2.1	1.4	0.0	0.0	2.0	1.5	2.0	1.4
Edinburgh	2.1	1.5	2.1	1.4	0.0	0.1	2.1	1.4	2.0	1.3
Kuitpo	1.8	2.1	1.9	1.9	0.0	0.1	1.8	2.0	1.8	1.7
Parafield	2.2	1.5	2.2	1.4	0.0	0.1	2.2	1.5	2.2	1.3
Roseworthy	2.2	1.6	2.3	1.5	0.0	0.1	2.2	1.6	2.2	1.4

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

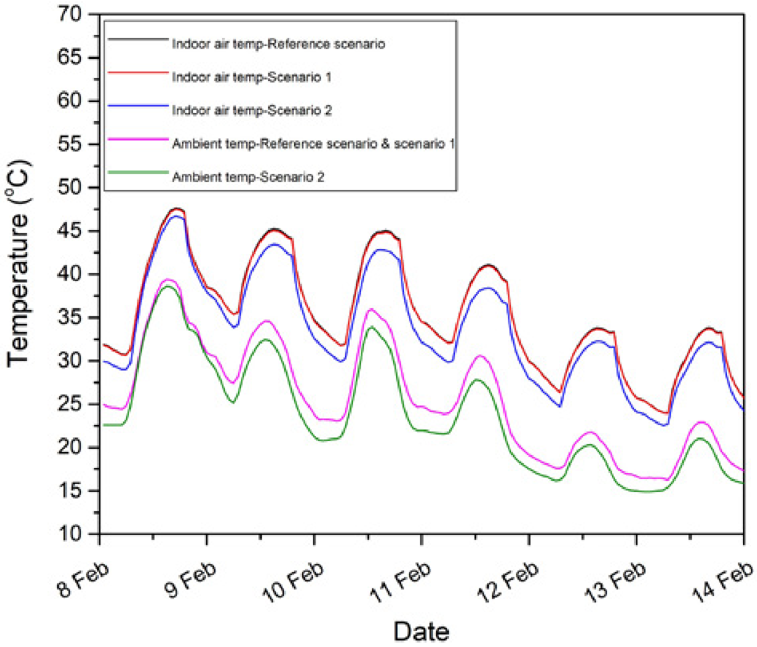

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new mid-rise shopping mall centre under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

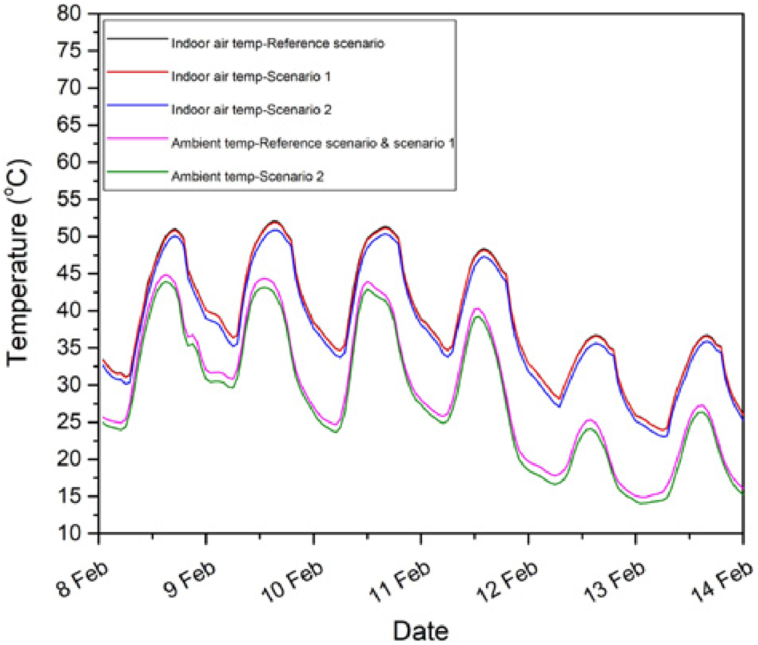

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 24.0-47.7 °C and 23.1-52.1 °C in Kuitpo and Roseworthy stations, respectively.

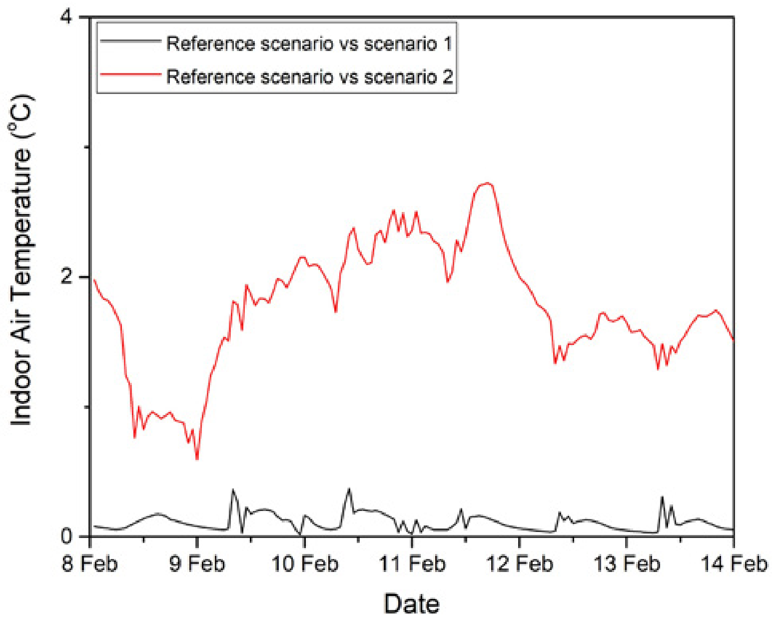

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.4 °C and 0.6 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.7 °C and 1.7 °C in Kuitpo and Roseworthy stations, respectively.

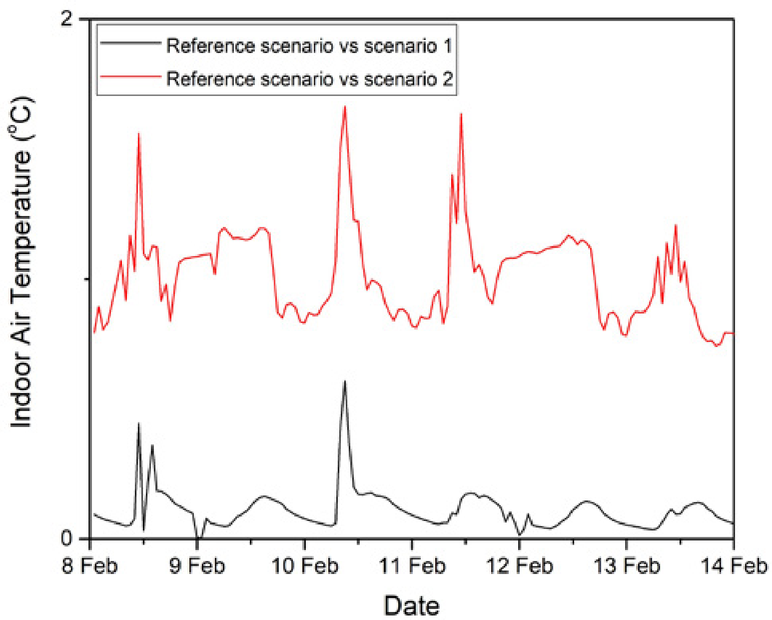

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly reduce from a range 12.5-25.1 °C in reference scenario to a range 12.5-24.9 °C in scenario 1 in Kuitpo station.

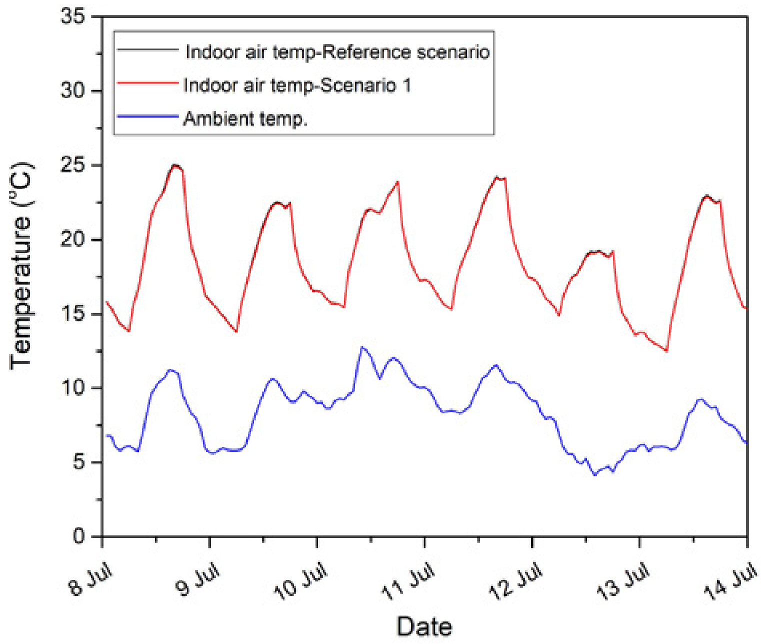

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to slightly reduce from a range 12.8-26.6 °C in reference scenario to a range 12.7-26.5 °C in scenario 1 in Roseworthy station.

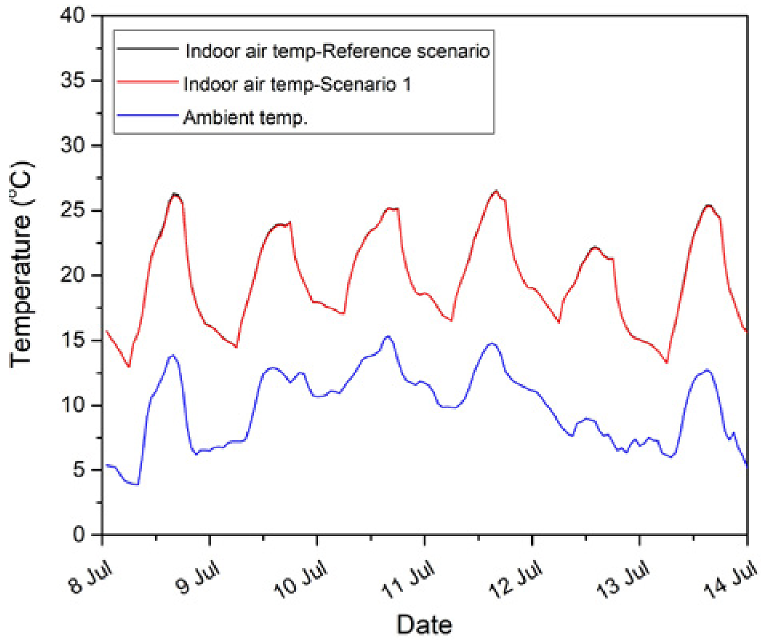

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.4 °C in Kuitpo and Roseworthy stations, respectively.

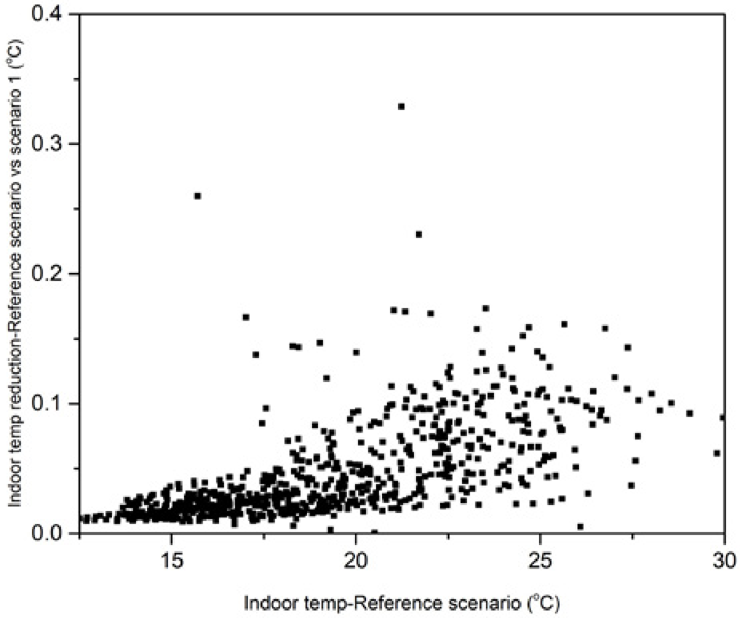

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

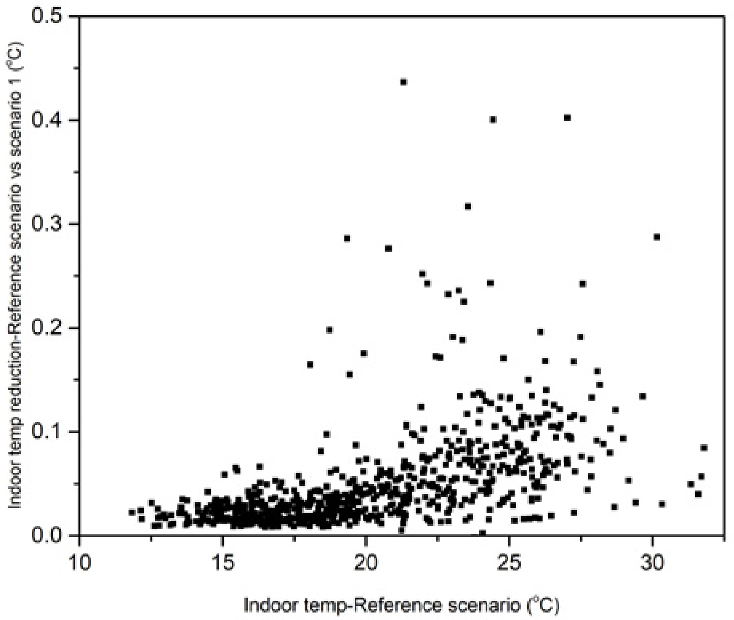

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 369 hours in reference scenario to 372 hours, and from 325 to 327 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 81 hours in reference scenario to 82 hours; and from 62 to 63 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	81	369	82	372
Roseworthy	62	325	63	327

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 543 hours in reference scenario to 542 and 493 hours under scenario 1 and 2, in Kuitpo station; and from 552 to 549 and 532 under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	543	542	493
Roseworthy	552	549	532

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has clearly the higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 06 is a new, mid-rise commercial building, with a total air-conditioned area of 4.400 m^2 distributed on four levels. The 1.100 m^2 roof is insulated, resulting in low energy losses and, consequently, in a very limited energy saving potential. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 06.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	183.0	272.6
Energy consumption after cool roof (MWh)	179.9	268.8
Energy savings (MWh)	3.1	3.8
Energy savings (%)	1.69%	1.39%
Area (m^2)	1,100	1,100
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

Building 06 is an interesting example of a new, insulated, mid-rise commercial building where, despite its rather limited energy conservation potential.

The cool roof refurbishment options

The coating cool roof is a feasible investment, over the building's life cycle, due to the large impact of the roof on the building's cooling loads and the low initial investment cost of the coating cool roof.

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in energy savings of 1,69% for the Kuitpo and of 1,39% for the Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,1% for the low energy price scenario for Kuitpo and 24,2% for the high energy scenario for Roseworthy.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is due to its higher initial investment marginally feasible for both locations for high energy prices' scenarios, and marginally not feasible for the low energy price scenario for Kuitpo conditions.

Figure 12. Life Cycle Costs for Building 06 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-0.35 %	1.42 %	0.55 %	1.74 %
Coating Cool Roof	23.14 %	24.09 %	23.55 %	24.20 %

7

CONCLUSIONS

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of a new mid-rise shopping mall centre during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the mid-rise shopping mall centre from 54.8-64.6 kWh/m^2 to 54.1-63.8 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.7-0.9 kWh/m^2. This is equivalent to approximately 1.2-1.4 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 6.3-9.4 kWh/m^2. This is equivalent to 19.8-17.2 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (1.9-2.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.4-1.9 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.8-2.2 kWh/m^2 (~1.3-1.7 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 30.9-50.9 ^{o}C and 31.2-45.3 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.4 and 0.6 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.7 ^{o}C and 1.7 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to reduce slightly from a range between 12.5-25.1 ^{o}C in reference scenario to a range between 12.5-24.9 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce between 12.8-26.6 °C in reference scenario to a range between 12.7-26.5 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.4 °C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 369 hours in reference scenario to 372 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight increase in total number of hours below 19 °C from 325 hours in reference scenario to 327hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number operational hours with air temperature <19 °C during is expected to slightly increase from 81 hours in reference scenario to 82 hours; and from 62 to 63 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 543 hours under the reference scenario in Kuitpo station, which decreases to 542 and 493 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also shows that the number of hours above 26 °C decreases from 552 to 549 and 532 under Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has clearly the higher cost over the building's life cycle compared to the coating cool roof option, which leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,1% for the low energy price scenario for Kuitpo and 24,2% for the high energy scenario for Roseworthy, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment marginally feasible for both locations for high energy prices' scenarios, and marginally not feasible for the low energy price scenario fir Kuitpo conditions. Building 06 is in that sense an interesting example of a new, insulated, mid-rise commercial building where, despite its rather limited energy conservation potential, the coating cool roof is a feasible investment, over the building's life cycle, due to the large impact of the roof on the building's cooling loads and the low initial investment cost of the coating cool roof.

B06

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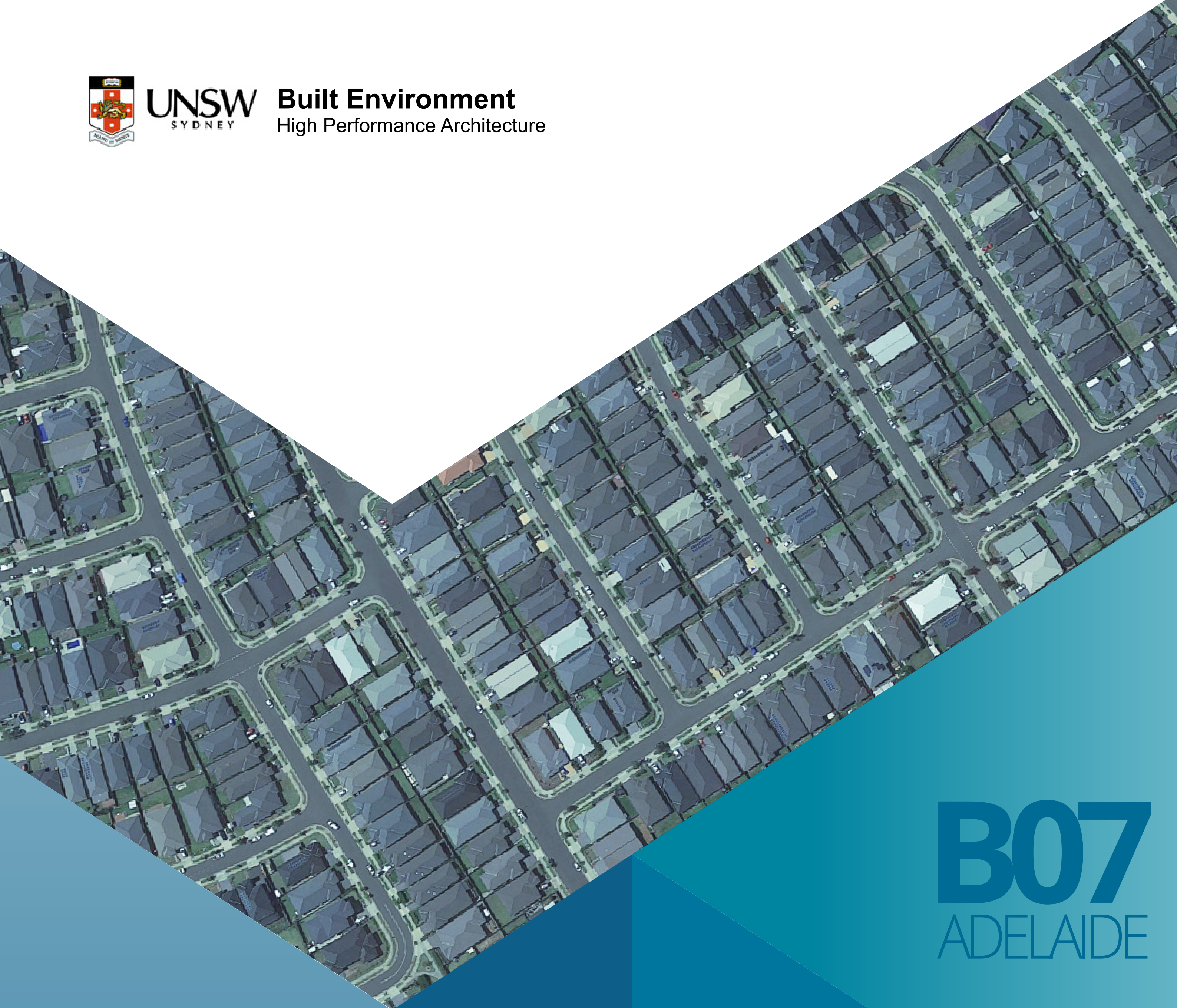

B07
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise shopping mall centre
2021

BUILDING 07

NEW HIGH-RISE SHOPPING MALL CENTRE

Floor area : 1100m²
Number of stories : 6

Image source: Mall of America, Minneapolis

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new high-rise shopping mall centre for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise shopping mall centre from 54.2-64.0 kWh/m² to 53.7-63.4 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)
Adelaide Airport	54.5	58.9	54.0	58.4	50.2	51.9
Edinburgh	57.3	61.4	56.9	60.9	52.4	53.8
Kuitpo	48.8	54.2	48.3	53.7	43.2	45.0
Parafield	56.6	60.6	56.1	60.1	52.8	54.4
Roseworthy	61.1	64.0	60.6	63.4	56.8	58.0

Table 2. Sensible and total cooling load saving for a new high-rise shopping mall centre for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.5-0.6 kWh/m² which is equivalent to 0.8-0.9 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.0-9.2 kWh/m² which is equivalent to 9.4-16.9 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Adelaide Airport	0.5	0.9	0.5	0.9	4.2	7.8	7.0	11.9
Edinburgh	0.5	0.8	0.5	0.8	4.9	8.6	7.6	12.3
Kuitpo	0.5	1.0	0.5	0.9	5.6	11.5	9.2	16.9
Parafield	0.5	0.9	0.5	0.8	3.8	6.7	6.1	10.1
Roseworthy	0.6	0.9	0.6	0.9	4.3	7.0	6.0	9.4

In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of a new high-rise shopping mall centre during the summer season.

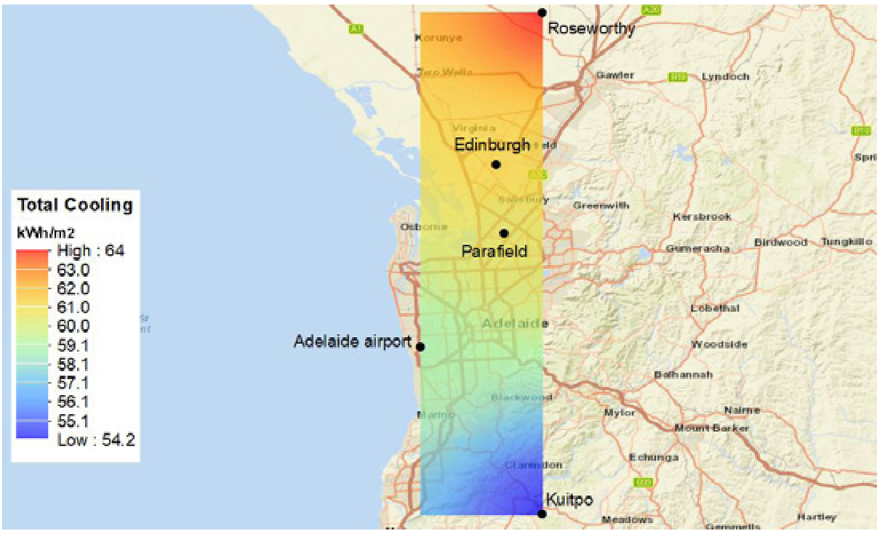

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

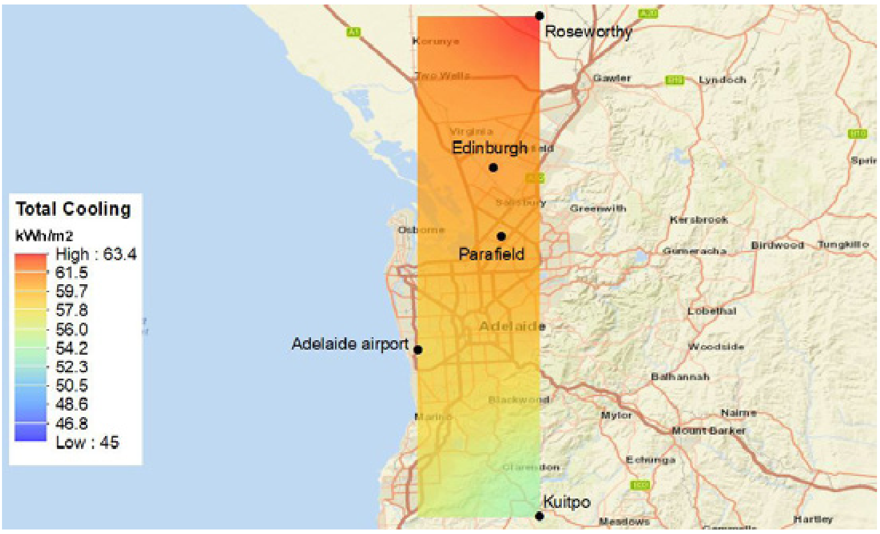

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

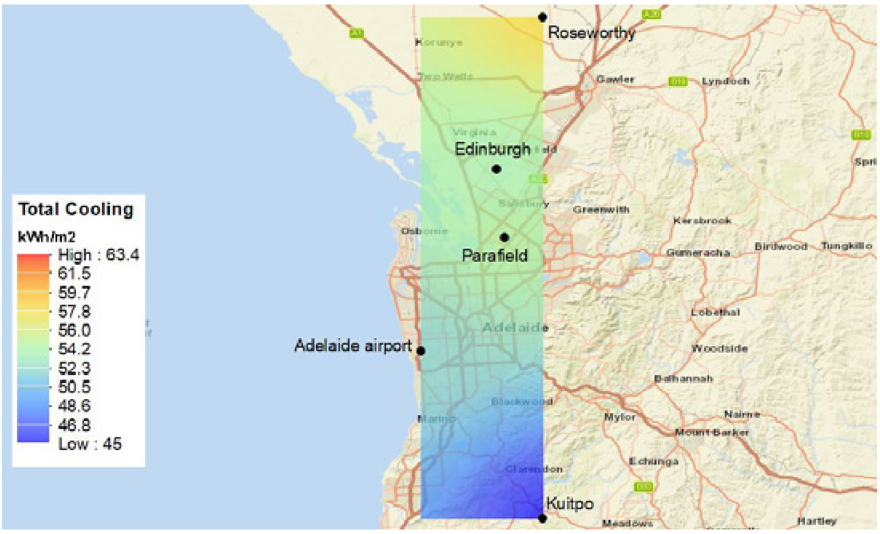

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new high-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (1.2-1.4 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)		Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	127.7	141.5	0.9	2.6	126.4	140.2	0.9	2.7
Edinburgh	137.9	148.5	1.4	4.5	136.6	147.1	1.4	4.5
Kuitpo	85.5	95.1	1.8	6.5	84.4	93.9	1.8	6.6
Parafield	145.5	158.6	1.4	4.1	144.1	157.2	1.4	4.1
Roseworthy	136.2	145.4	2.1	6.5	134.8	143.9	2.1	6.5

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 0.9-1.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.1-1.4 kWh/m² (~0.8-1.1 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2		kWh/m^2	%	kWh/m^2	%
Adelaide Airport	1.3	1.0	1.3	0.9	0.0	0.0	1.3	1.0	1.3	0.9
Edinburgh	1.3	1.0	1.3	0.9	0.0	0.0	1.3	0.9	1.3	0.8
Kuitpo	1.1	1.3	1.2	1.2	0.0	0.1	1.1	1.3	1.1	1.1
Parafield	1.4	1.0	1.4	0.9	0.0	0.0	1.4	0.9	1.4	0.9
Roseworthy	1.4	1.0	1.4	1.0	0.0	0.0	1.4	1.0	1.4	0.9

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

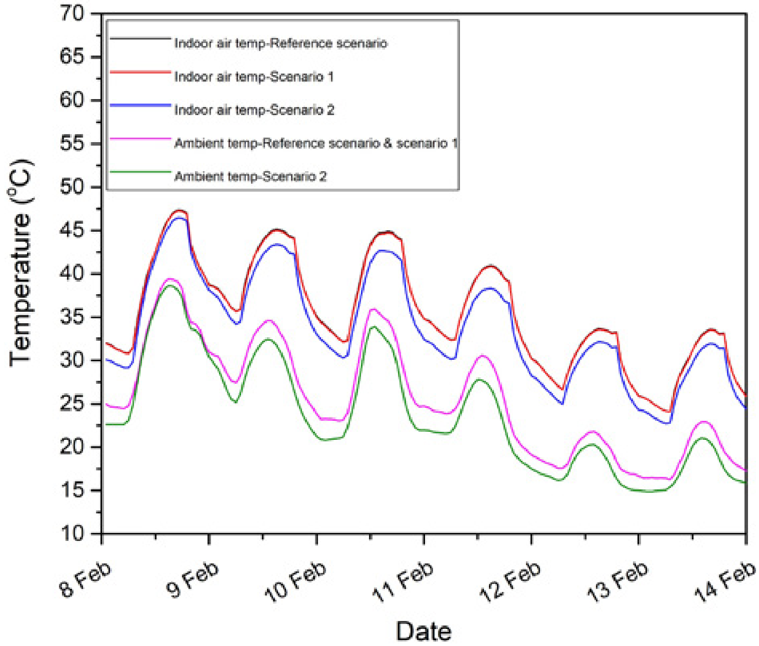

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

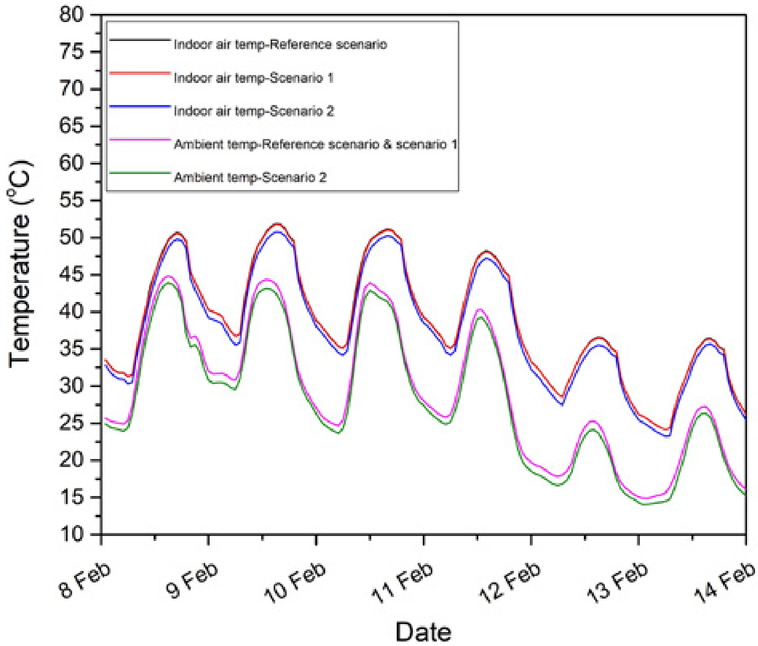

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 24.1-47.4 °C and 23.3-51.9 °C in Kuitpo and Roseworthy stations, respectively.

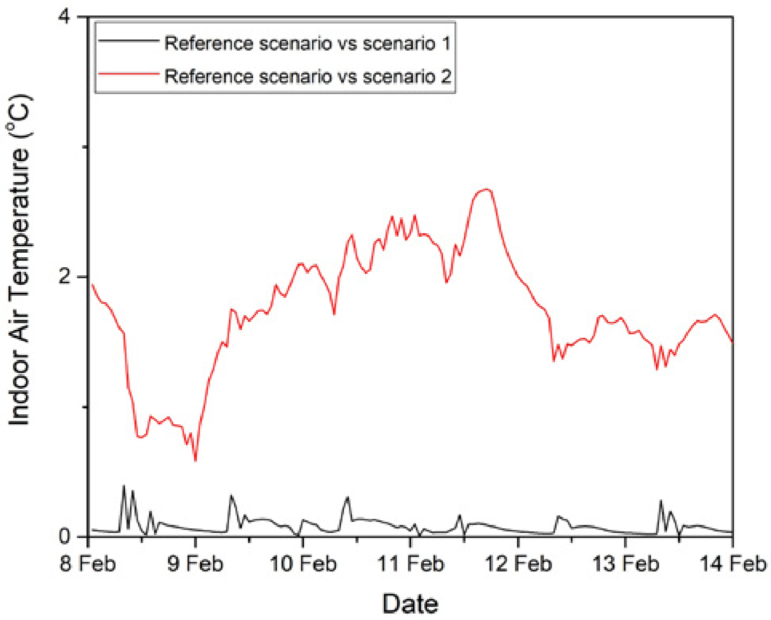

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.4 °C and 0.5 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.7 °C and 1.6 °C in Kuitpo and Roseworthy stations, respectively.

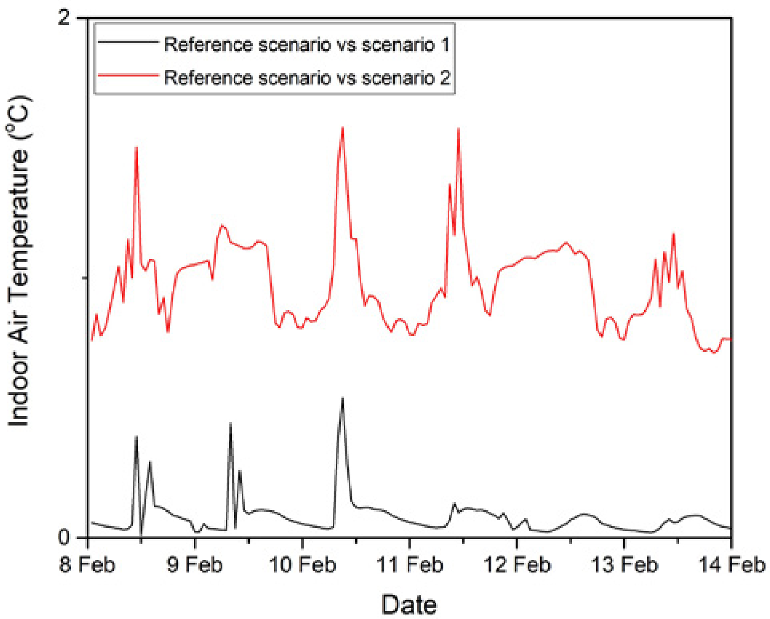

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new highrise shopping mall centre under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 12.6-24.8 °C in reference scenario to a range12.6-24.7 °C in scenario 1 in Kuitpo station.

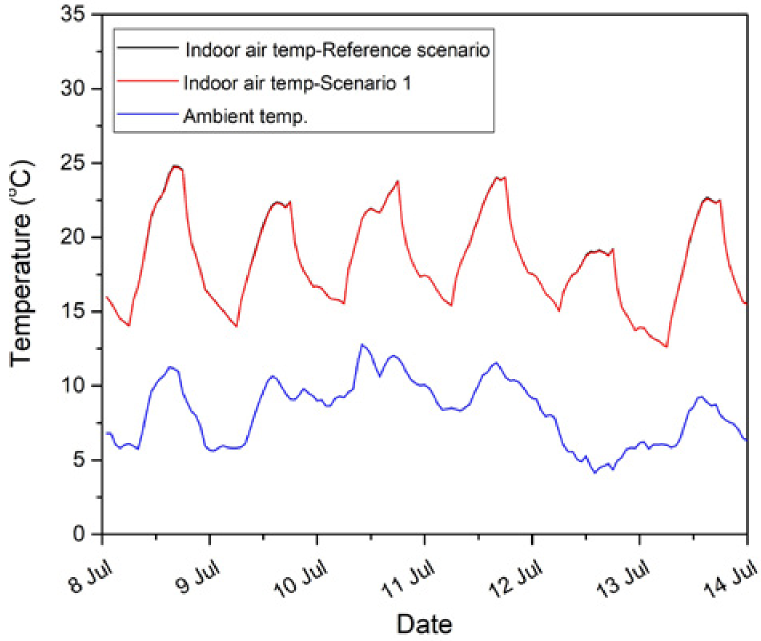

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 13.0-26.4 °C in reference scenario to a range 13.0-26.3 °C in scenario 1 in Roseworthy station.

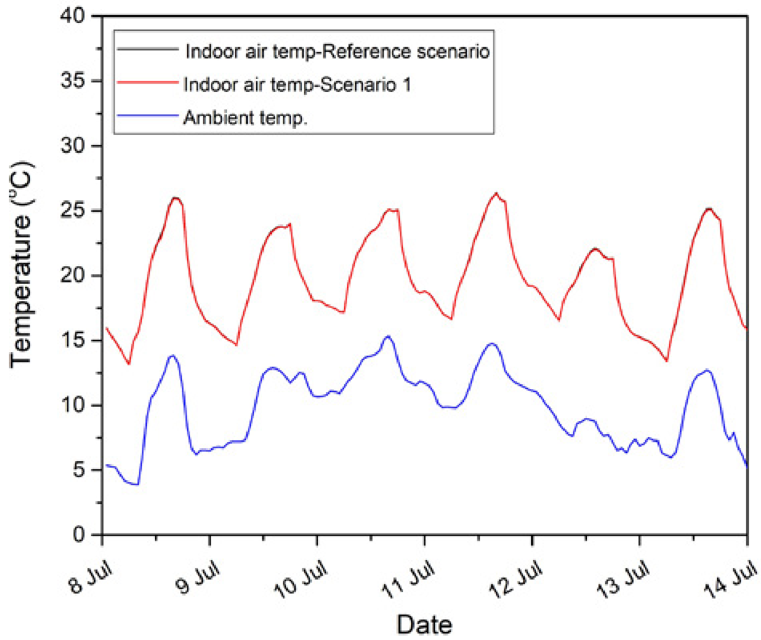

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

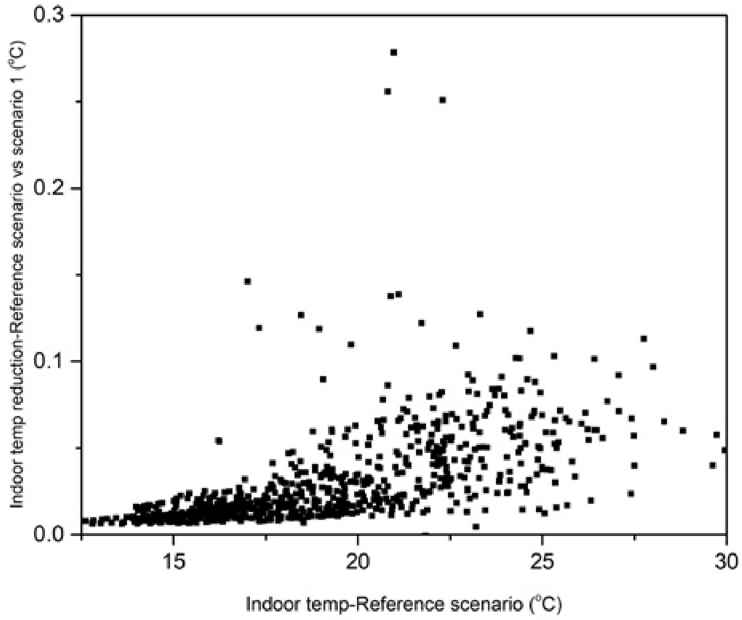

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

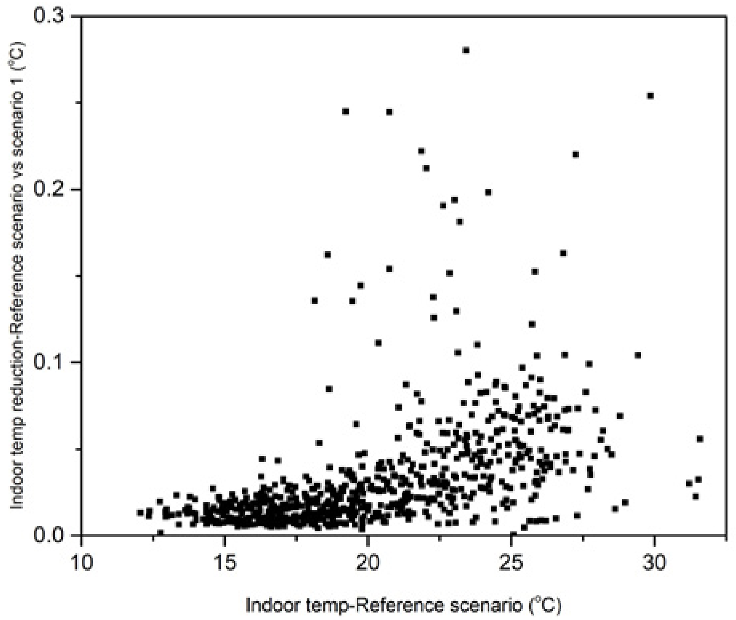

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase slightly from 365 hours in reference scenario to 370 hours, and from 316 to 318 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 81 hours in reference scenario to 85 hours; while remains the same in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	81	365	85	370
Roseworthy	62	316	62	318

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 548 hours in reference scenario to 547 and 498 hours under scenario 1 and 2, in Kuitpo station; and from 556 to 555 and 536 under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	548	547	498
Roseworthy	556	555	536

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has clearly the higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 07 is a new, high-rise commercial building, with a total air-conditioned area of 6.600 m² distributed on six levels. The 1.100 m² roof is insulated, resulting in low energy losses and, consequently, in a very limited energy saving potential, also given the small impact of the roof on the overall building's energy demand. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 07.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	268.2	401.0
Energy consumption after cool roof (MWh)	265.3	397.1
Energy savings (MWh)	2.9	3.9
Energy savings (%)	1.08%	0.97%
Area (m²)	1,100	1,100
Roof costs - Metal roof (AU$/m²)	38.0	38.0
Roof costs - Coating (AU$/m²)	22.75	22.75
Life expectancy - Metal roof (years)	28.5	28.5
Life expectancy - Coating (years)	22.5	22.5
HVACs COP	2.5	2.5
Existing roof's renovation costs (AU$/m²)	15.0	15.0

Building 07 is ia very interesting example of a new, insulated, high-rise commercial building where, despite its rather limited energy conservation potential,

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

The coating cool roof is a clearly feasible investment, over the building's life cycle, due to the large impact of the roof on the building's cooling loads.

Both options have the same energy efficiency, resulting in roughly the same energy savings of 1,08% and 0,97% for the two locations. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

> *The coating cool roof option leads to a reduction of life cycle costs over the building's life cycle, that varies between 23,3% and 24,1% for both locations and energy prices scenarios.*

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

> *The metal cool roof is due to its higher initial investment cost only marginally feasible. The feasibility results are practically identical for both locations.*

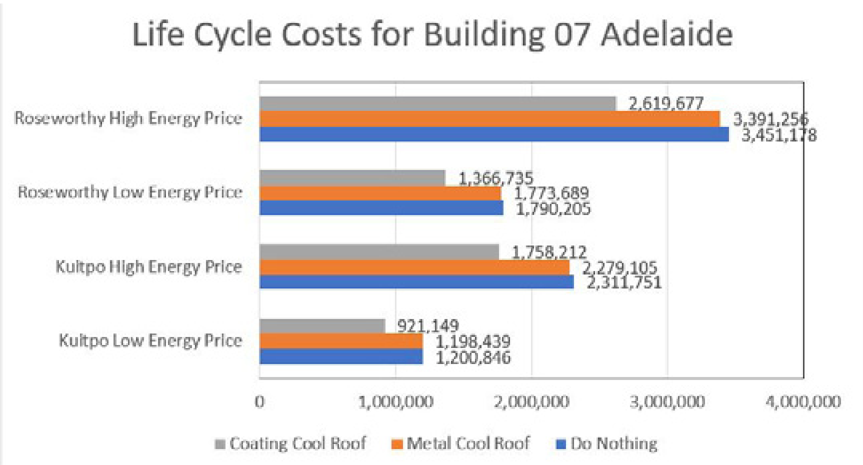

Figure 12. Life Cycle Costs for Building 07 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	0.20 %	1.41 %	0.92 %	1.74 %
Coating Cool Roof	23.29 %	23.94 %	23.65 %	24.09 %

7

CONCLUSIONS

• It is estimated that the combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the new high-rise shopping mall centre during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the new high-rise shopping mall centre from 54.2-64.0 kWh/m^2 to 53.7-63.4 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5-0.6 kWh/m^2. This is equivalent to approximately 0.8-0.9 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 6.0-9.2 kWh/m^2. This is equivalent to 9.4-16.9 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (1.2-1.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.9-1.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.1-1.4 kWh/m^2 (~0.8-1.1 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 24.1-47.4°C and 23.3-51.9 °C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.4 °C and 0.5 °C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.7 and 1.6 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 12.6-24.8 °C in reference scenario to a range between 12.6-24.7 °C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 13.0-26.4 °C in reference scenario to a range between 13.0-26.3 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.3 °C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

•• During a typical winter month and under free-floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 365 hours in reference scenario to 370 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy station also show a increase in total number of hours below 19 °C from 316 hours in reference scenario to 318 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am - 6 pm) is expected to slightly increase from 81 hours in reference scenario to 85 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. However, the calculation in Roseworthy station shows the number of hours below 19 °C during the operational hours remain the same (62 hours) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 548 hours under the reference scenario in Kuitpo station, which decreases to 547 and 498 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also shows that the number of hours above 26 °C decreases from 556 to 555 and 536 under Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's existing roof insulation, the 'Do Nothing' approach has clearly the higher cost over the building's life cycle compared to the coating cool roof option, with a reduction of life cycle costs over the building's life cycle, that varies between 23,3% and 24,1% for both locations and energy prices scenarios. The metal cool roof achieves marginally feasible reductions, as it can be seen in Table 8. Building 07 is in that sense a very interesting example of a new, insulated, high-rise commercial building where, despite its rather limited energy conservation potential, the coating cool roof is a clearly feasible investment, over the building's life cycle, due to the large impact of the roof on the building's cooling loads. The metal cool roof is due to its higher initial investment cost only marginally feasible. The feasibility results are practically identical for both locations.

B07

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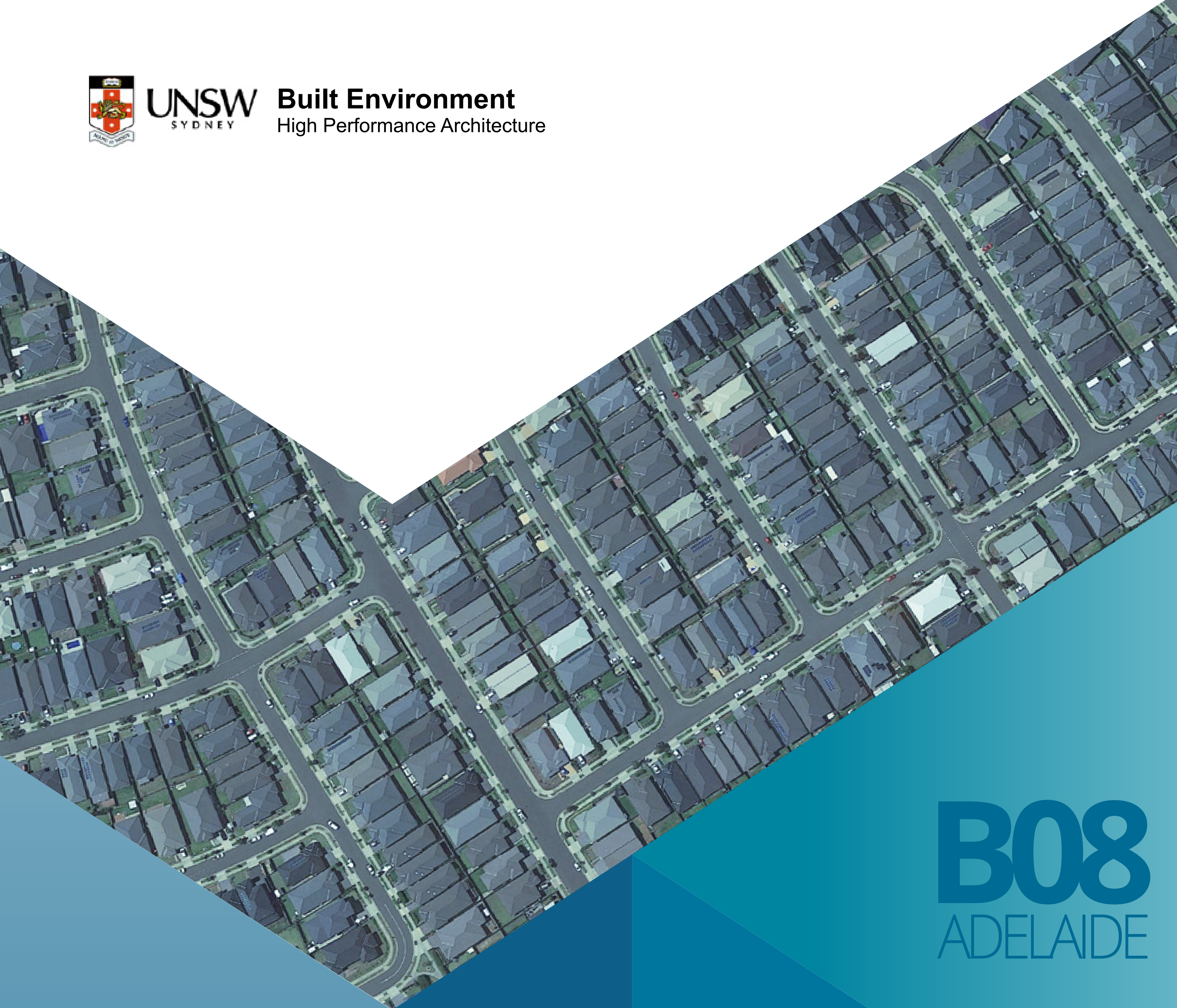

B08
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise apartment
2021

BUILDING 08

NEW LOW-RISE APARTMENT

Floor area : 624m^2
Number of stories : 3

Image source: KTGY Architecture and Planning - Multi Family 3-Story Walk Up - Boulder View Apartments.

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise aparment building from 8.7-13.4 kWh/m² to 7.7-12.2 kWh/m².

Table 1. Sensible and total cooling load for a new low-rise apartment building for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	9.5	10.8	8.5	9.8	7.0	7.4
Edinburgh	10.7	12.0	9.7	11.0	7.9	8.2
Kuitpo	7.3	8.7	6.4	7.7	4.8	5.1
Parafield	10.4	11.6	9.4	10.6	8.0	8.4
Roseworthy	12.4	13.4	11.2	12.2	9.6	9.9

Table 2. Sensible and total cooling load saving for a new low-rise apartment building for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 1.0-1.2 kWh/m² which is equivalent to 8.6-11.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.2-3.8 kWh/m² which is equivalent to 25.7-41.5 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	1.0	10.3	1.0	9.6	2.5	26.1	3.4	31.5
Edinburgh	1.0	9.2	1.0	8.6	2.8	26.5	3.8	31.5
Kuitpo	0.9	11.7	1.0	11.0	2.5	34.5	3.6	41.5
Parafield	1.0	9.6	1.0	9.0	2.4	23.0	3.2	27.6
Roseworthy	1.1	9.3	1.2	8.9	2.8	22.3	3.4	25.7

In the eleven weather stations in Adelaide, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of a new low-rise apartment buiding with insulation during the summer season.

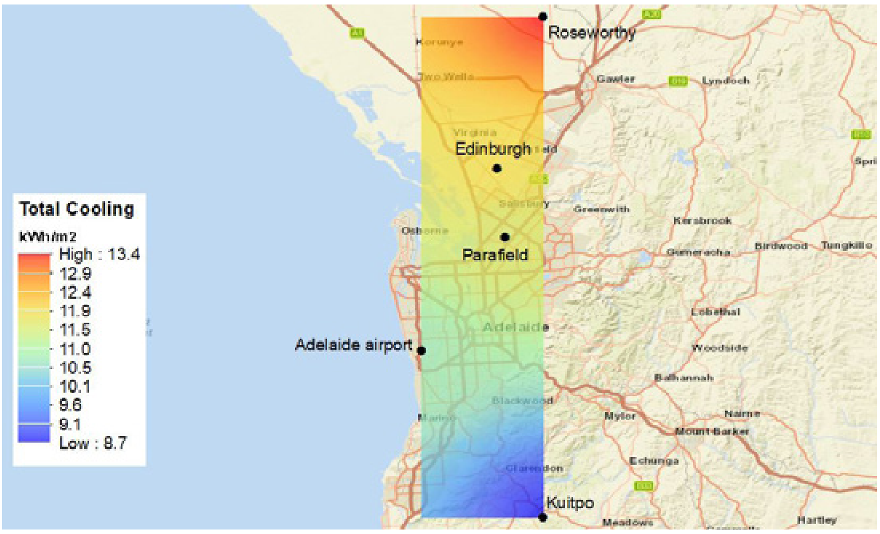

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

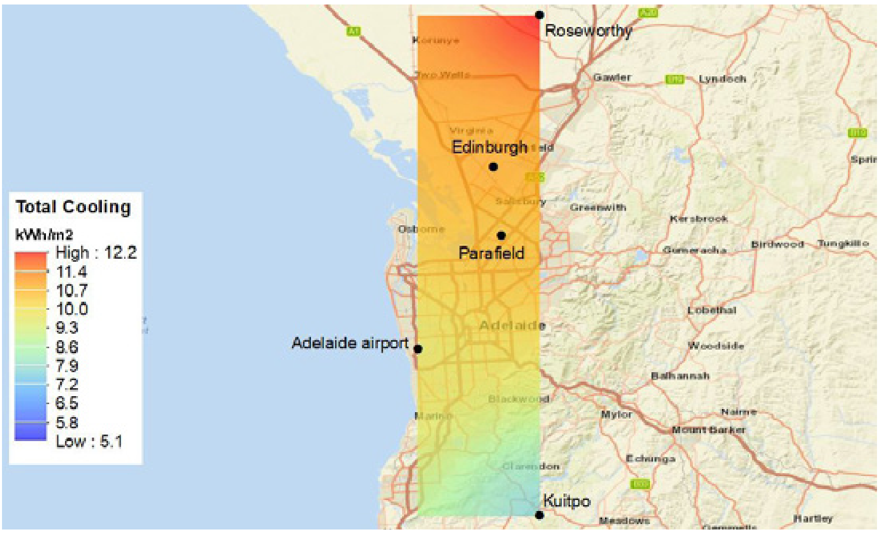

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

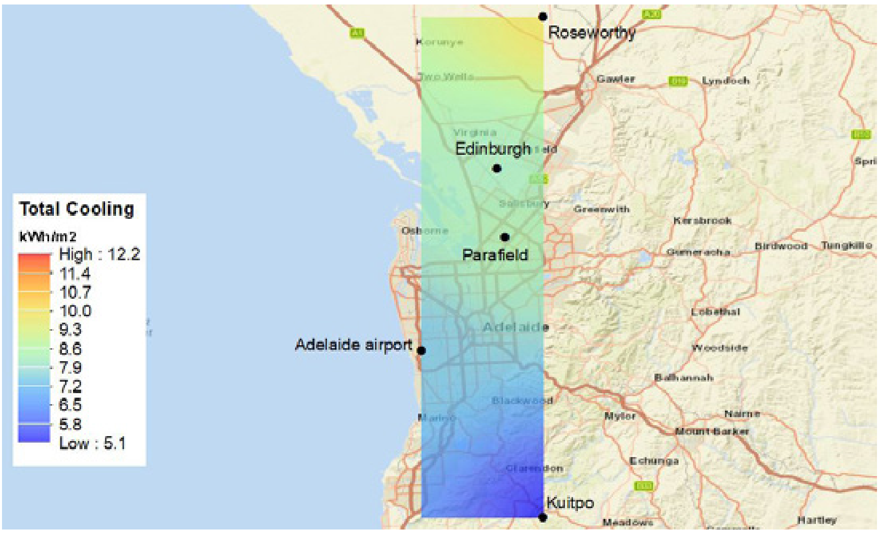

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new low-rise apartment building for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.6-1.2 kWh/m²) is slightly lower than the annual cooling load reduction (0.9-1.8 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	12.4	15.0	15.2	23.7	11.2	13.6	15.8	24.6
Edinburgh	16.3	18.6	19.0	29.1	14.8	17.0	19.7	30.0
Kuitpo	6.1	6.9	29.4	44.8	5.3	6.0	30.5	46.3
Parafield	17.8	20.8	17.5	27.2	16.1	19.0	18.2	28.1
Roseworthy	16.0	17.9	24.4	36.9	14.4	16.2	25.3	38.0

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 8.5-13.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.6 and 0.9 kWh/m² (~ -1.2-1.8 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	1.2	9.6	1.4	9.1	0.6	0.8	0.6	2.1	0.5	1.4
Edinburgh	1.5	9.1	1.6	8.6	0.7	0.9	0.8	2.2	0.7	1.5
Kuitpo	0.8	13.1	0.9	13.0	1.2	1.5	-0.4	-1.0	-0.6	-1.2
Parafield	1.6	9.2	1.8	8.5	0.7	0.9	0.9	2.7	0.9	1.8
Roseworthy	1.6	10.2	1.7	9.7	0.9	1.1	0.8	1.9	0.6	1.2

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

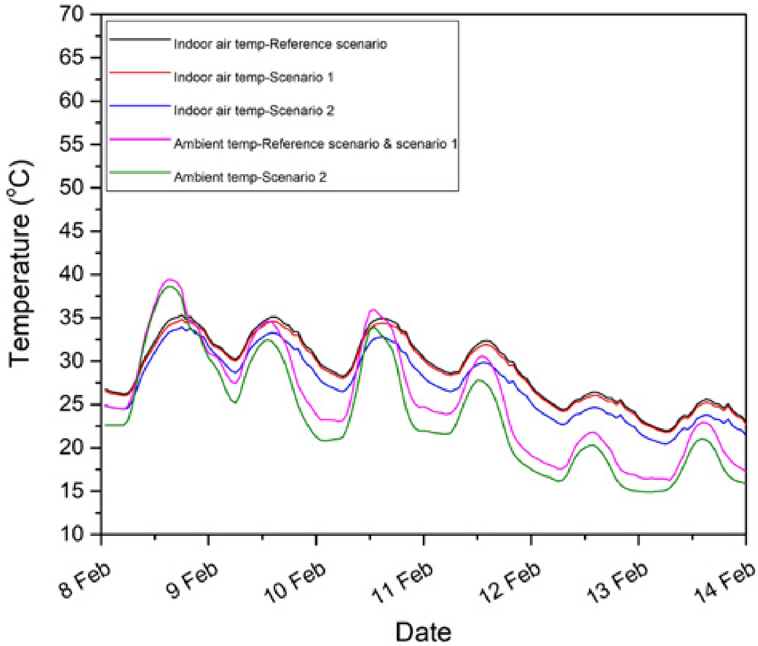

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

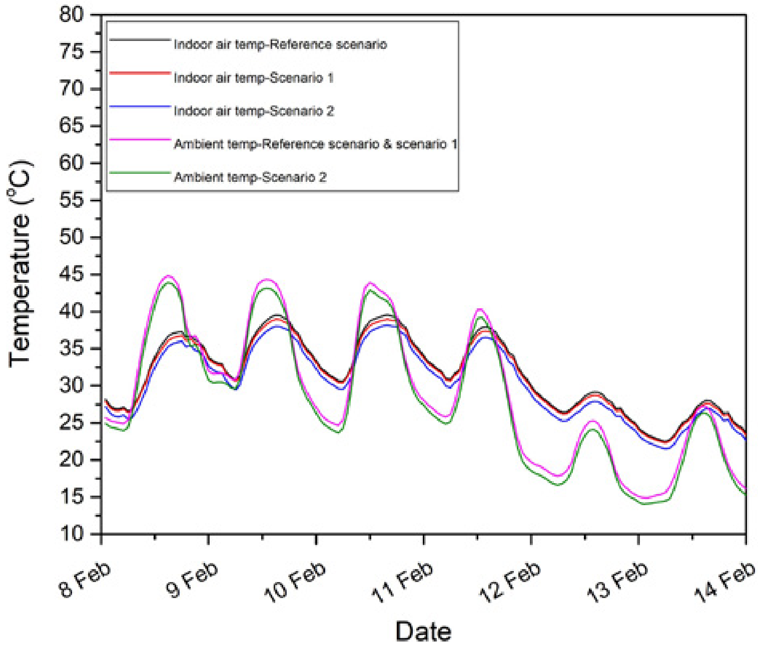

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.5-35.3 °C and 21.3-39.6 °C in Kuitpo and Roseworthy stations, respectively.

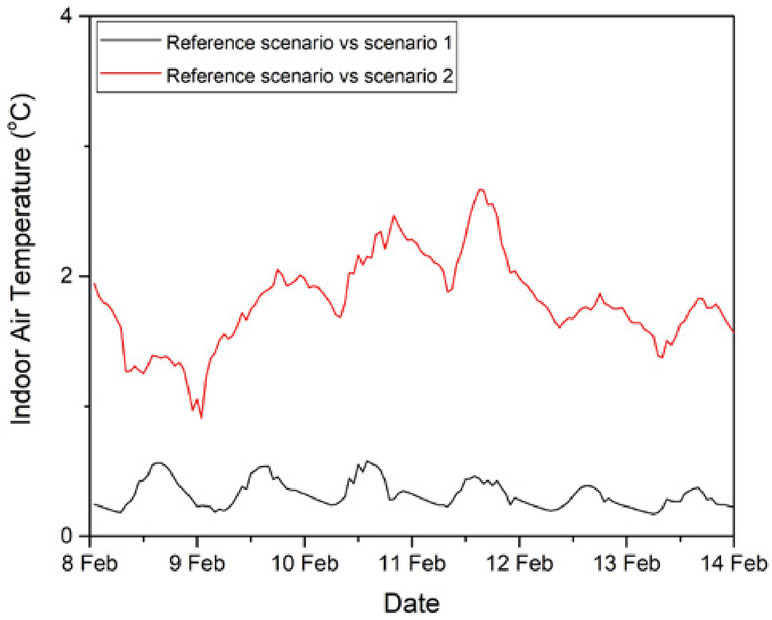

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.7 °C and 0.7 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.7 °C and 1.6 °C in Kuitpo and Roseworthy stations, respectively.

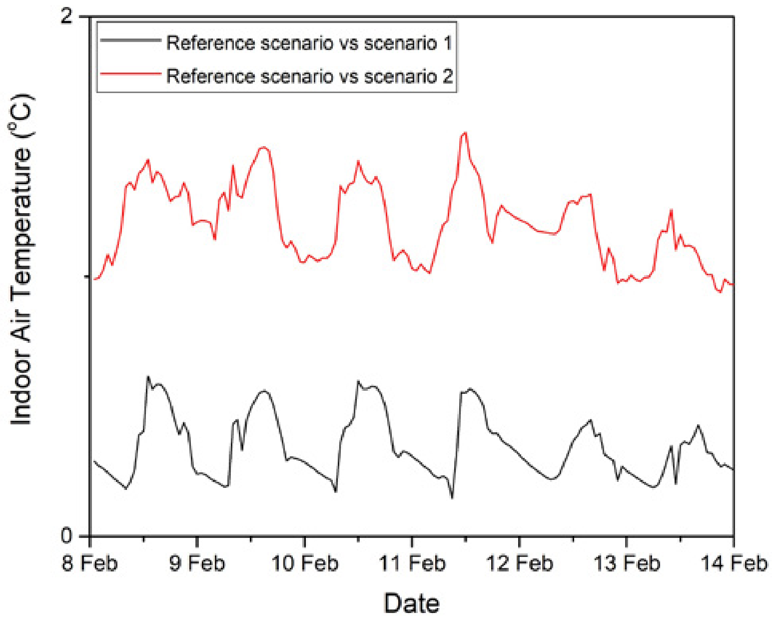

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 10.2-16.3 °C in reference scenario to a range 10.2-16.1 °C in scenario 1 in Kuitpo station.

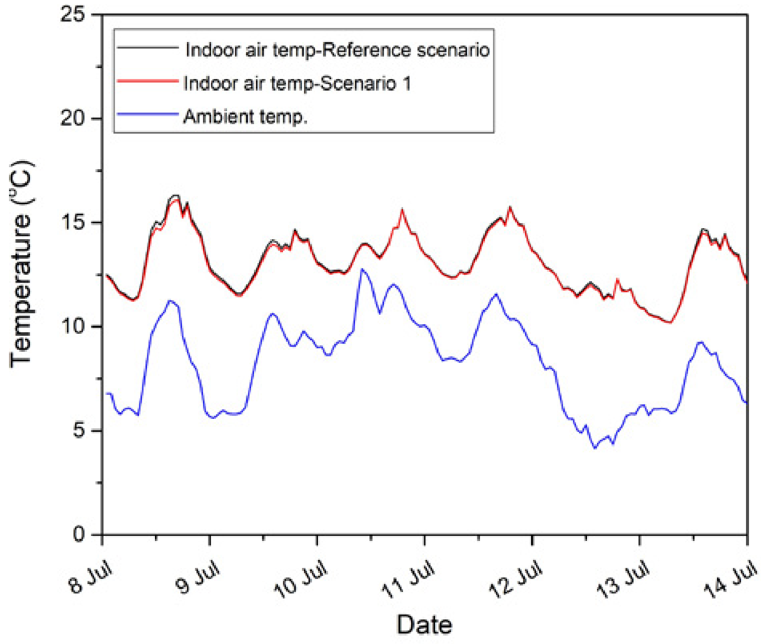

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 11.1-17.6 °C in reference scenario to a range 11.0-17.3 °C in scenario 1 in Roseworthy station.

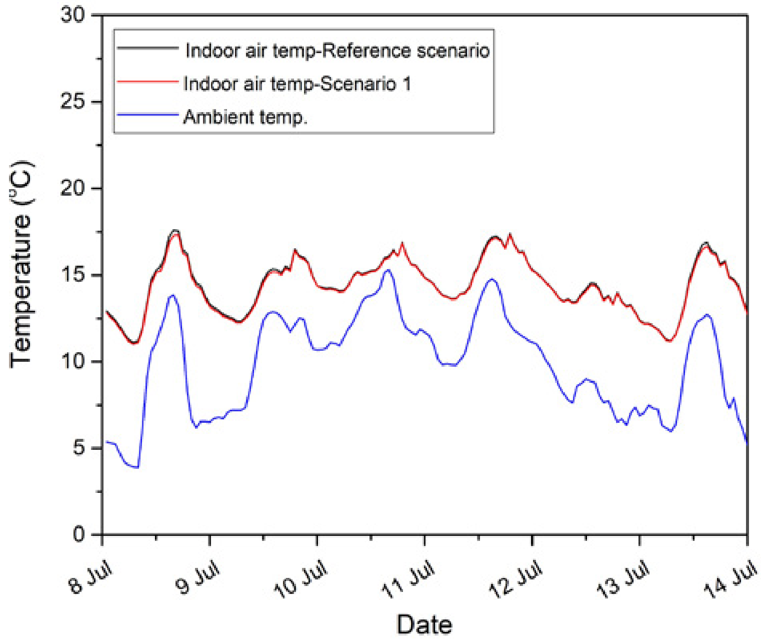

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.4 °C for both Kuitpo and Roseworthy stations.

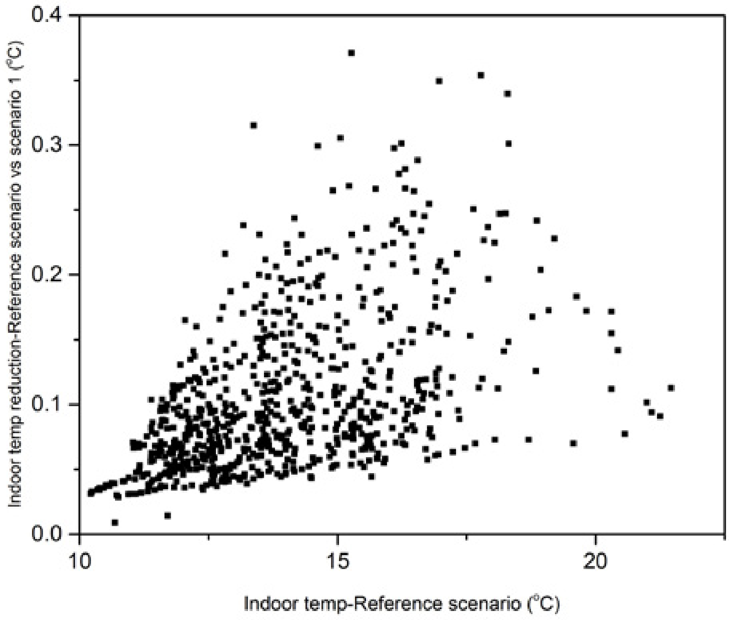

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

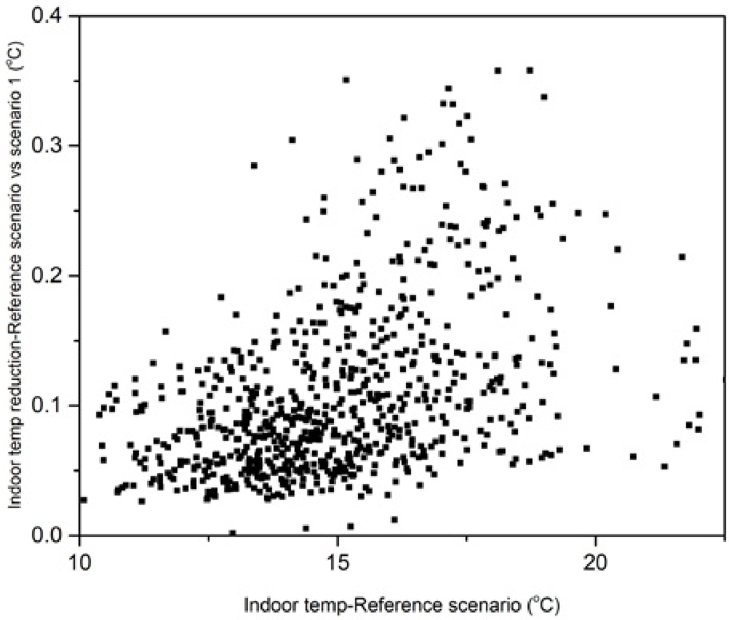

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 365 hours in reference scenario to 370 hours and from 316 to 318 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Kuitpo	365	370
Roseworthy	316	318

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 593 hours in reference scenario to 593 and 532 hours under scenario 1 and 2 in Kuitpo station; and from 556 hours in reference scenario to 555 and 536 hours under scenario 1 and 2 in Roseworthy station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	593	593	532
Roseworthy	556	555	536

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 08 is a new, low-rise apartment building, with a total air-conditioned area of 1.872 m^2 distributed on three levels. The 624 m^2 roof is insulated, resulting in modest energy savings. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 08.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	38.7	41.0
Energy consumption after cool roof (MWh)	39.2	40.6
Energy savings (MWh)	-0.5	0.4
Energy savings (%)	-1.29%	0.98%
Area (m^2)	624	624
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

Building 08 is an interesting example of a new, low-rise residential building, where the energy conservation potential is rather limited. However, even so, the coating cool technology emerges as a meaningful investment.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in an energy requirements' increase of 1,29% for Kuitpo and a decrease of 0,98% for the Roseworthy weather. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 17,7% for the low energy price scenario for Kuitpo and 22,0% for the high energy scenario and for Roseworthy conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations.

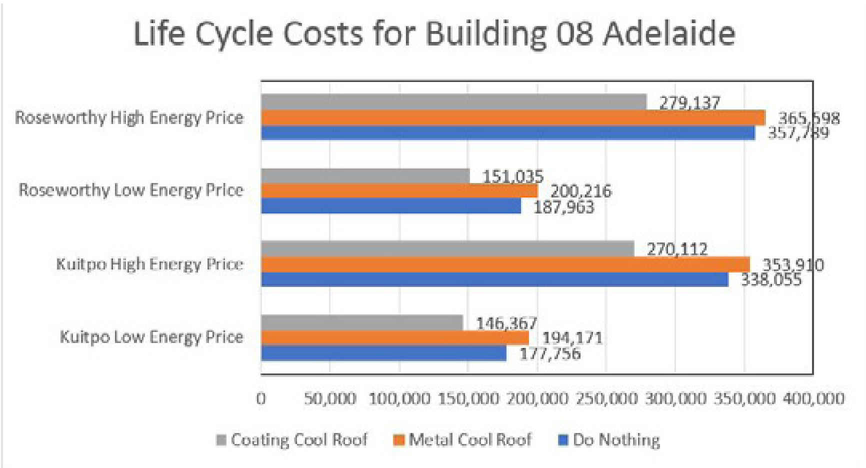

Figure 12. Life Cycle Costs for Building 08 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-9.23 %	-4.69 %	-6.52 %	-2.18 %
Coating Cool Roof	17.66 %	20.10 %	19.65 %	21.98 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of a new low-rise apartment building during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment from 8.7-13.4 kWh/m^2 to 7.7-12.2 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.0-1.2 kWh/m^2. This is equivalent to approximately 8.6-11.0 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.2-3.8 kWh/m^2. This is equivalent to 25.7-41.5 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.6-1.2 kWh/m^2) is slightly lower than the annual cooling load reduction (0.9-1.8 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 8.5-13.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.6 and 0.9 kWh/m^2 (~ -1.2-1.8 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 21.5-35.3 ^{o}C and 21.3-39.6 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.7 and 0.7 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.7 and 1.6 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 10.2-16.3 ^{o}C in reference scenario to a range between 10.2-16.1 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.1-17.6 °C in reference scenario to a range between 11.0-17.3 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.4 °C for both Kuitpo and Roseworthy stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 365 hours in reference scenario to 370 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slightly increase in total number of hours below 19 °C from 316 hours in reference scenario to 318 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 593 hours under the reference scenario in Kuitpo station, which decreases to 593 and 532 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also illustrate a significant reduction in number of hours above 26 °C from 556 hours in reference scenario to 555 in reference with cool roof scenario (scenario 1) and 536 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

•As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 17,7% for the low energy price scenario for Kuitpo and 22,0% for the high energy scenario and for Roseworthy conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations. Building 08 is in that sense an interesting example of a new, low-rise residential building, where the energy conservation potential is rather limited. However, even so, the coating cool technology emerges as a meaningful investment.

B08

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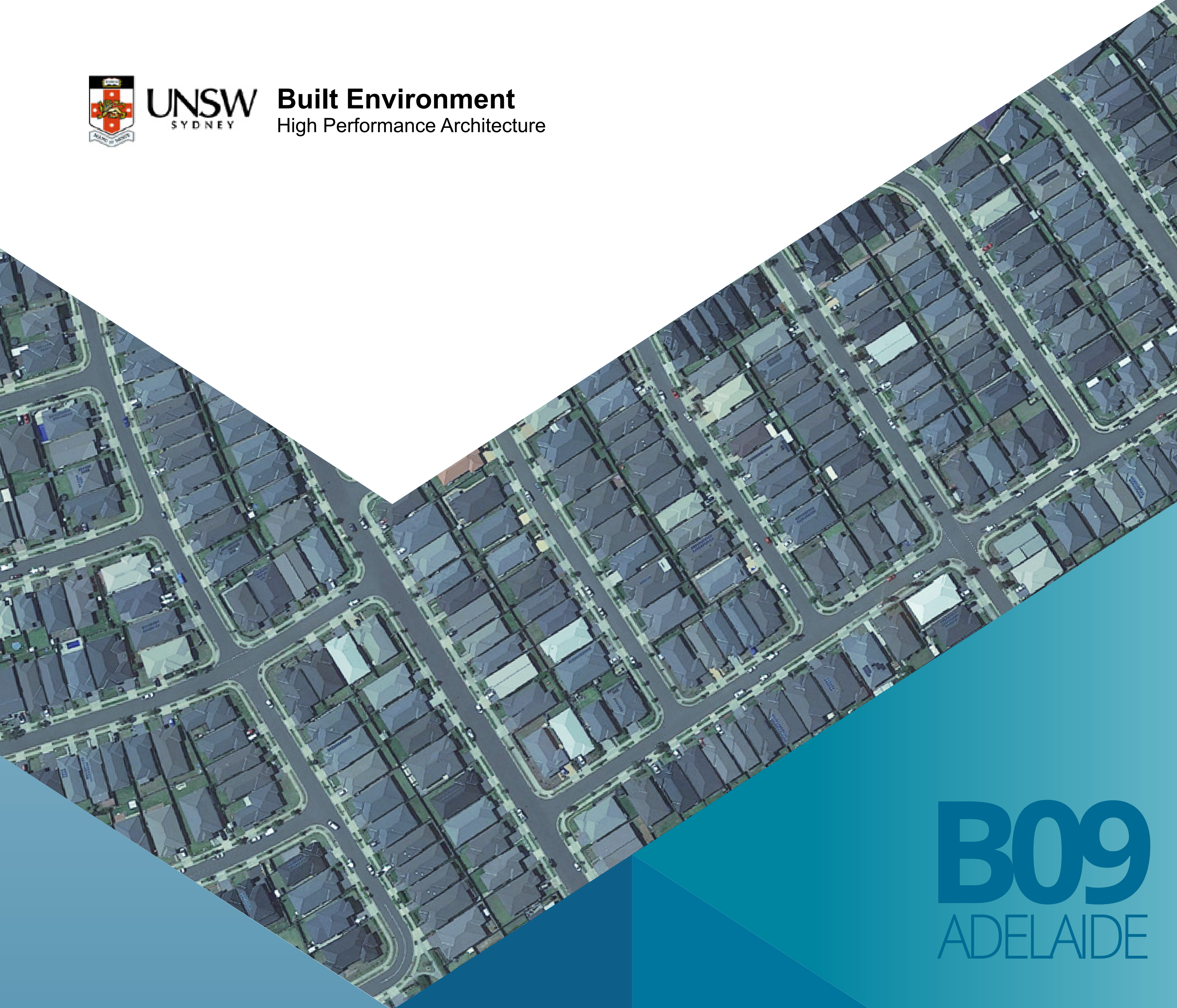
High Performance Architecture



B09
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New mid-rise apartment
2021

BUILDING 09

NEW MID-RISE APARTMENT

Floor area : 624m²
Number of stories : 5

Image source: 282 Eldert Street, Bushwick.

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new mid-rise apartment building for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise aparment building from 8.3-12.9 kWh/m² to 7.8-12.2 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	9.1	10.5	8.6	9.9	7.0	7.5
Edinburgh	10.3	11.6	9.8	11.0	7.9	8.3
Kuitpo	6.9	8.3	6.5	7.8	4.7	5.0
Parafield	10.0	11.3	9.4	10.7	8.0	8.5
Roseworthy	11.9	12.9	11.3	12.2	9.6	10.0

Table 2. Sensible and total cooling load saving for a new mid-rise apartment building for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.5-0.7 kWh/m² which is equivalent to 35.1-6.6 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.8-3.4 kWh/m² which is equivalent to 22.9-39.4 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	0.6	6.2	0.6	5.7	2.1	22.8	3.0	28.7
Edinburgh	0.6	5.5	0.6	5.1	2.4	23.7	3.4	29.1
Kuitpo	0.5	7.1	0.5	6.6	2.2	31.7	3.3	39.4
Parafield	0.6	5.8	0.6	5.4	2.0	19.8	2.8	24.8
Roseworthy	0.7	5.6	0.7	5.3	2.3	19.2	3.0	22.9

In the eleven weather stations in Adelaide, both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new mid-rise apartment during the summer season.

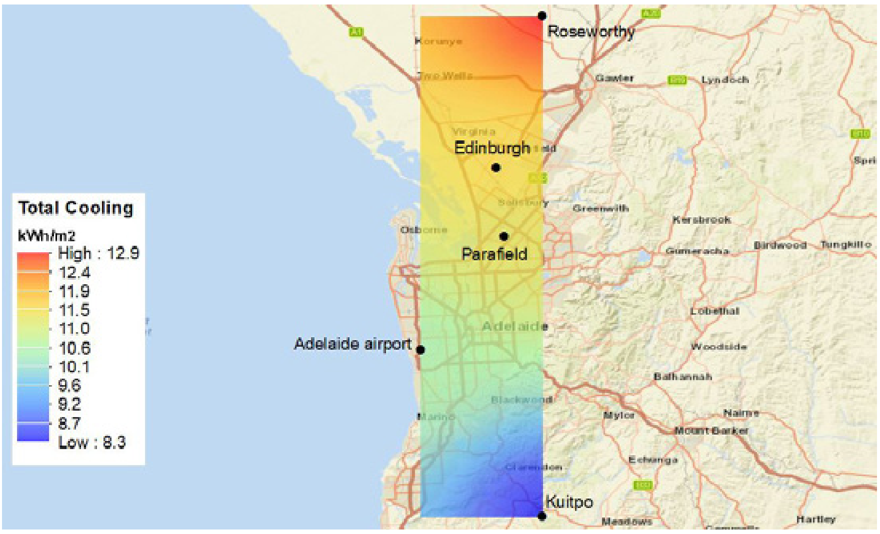


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

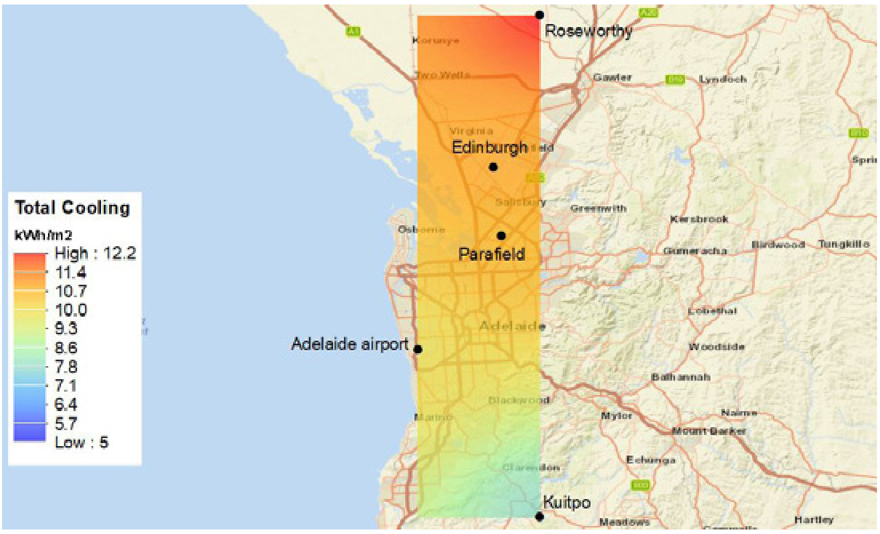


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

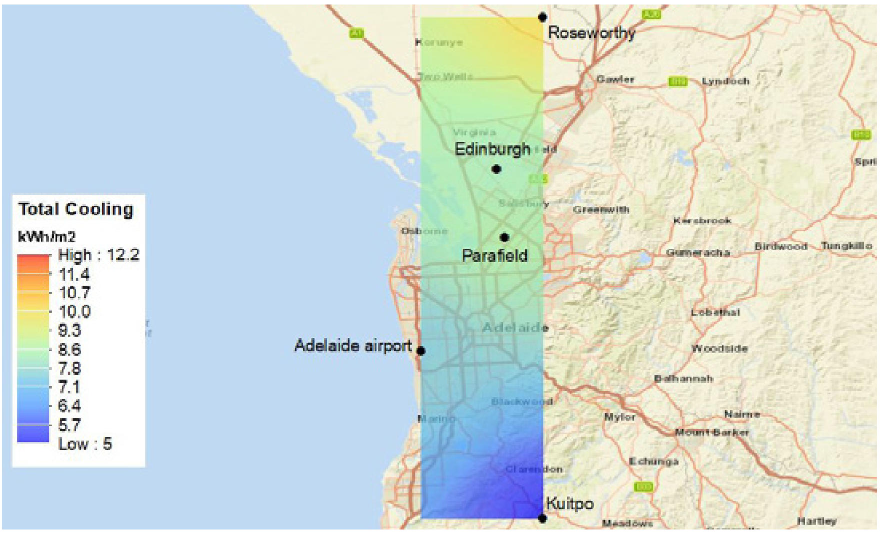


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new mid-rise apartment building for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.5-0.9 kWh/m²) is nearly the same that the annual cooling load reduction (0.5-1.0 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	11.8	14.3	14.5	22.9	11.1	13.6	14.9	23.4
Edinburgh	15.5	17.8	18.3	28.4	14.7	16.9	18.7	28.9
Kuitpo	5.6	6.3	28.8	44.2	5.1	5.8	29.5	45.1
Parafield	16.9	19.9	16.8	26.4	16.0	18.9	17.2	26.9
Roseworthy	15.1	17.0	23.6	36.1	14.2	16.0	24.1	36.7

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 5.0-7.8 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.4 and 0.5 kWh/m² (~ -0.7-1.0 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	0.7	5.6	0.8	5.4	0.4	0.5	0.3	1.2	0.3	0.8
Edinburgh	0.8	5.3	0.9	5.0	0.4	0.5	0.4	1.3	0.4	0.8
Kuitpo	0.4	7.9	0.5	7.8	0.7	0.9	-0.2	-0.7	-0.4	-0.7
Parafield	0.9	5.4	1.0	5.0	0.4	0.5	0.5	1.6	0.5	1.0
Roseworthy	0.9	6.0	1.0	5.6	0.5	0.6	0.4	1.0	0.3	0.6

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

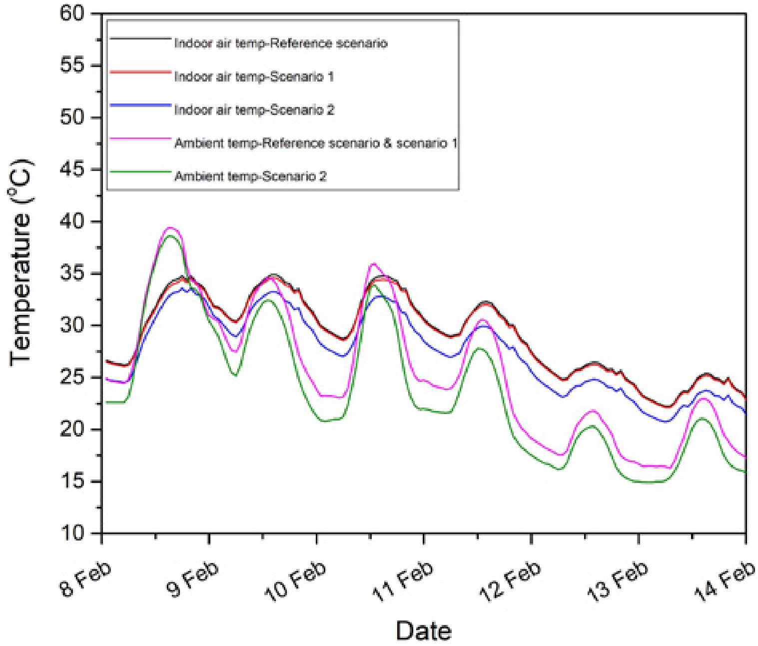


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

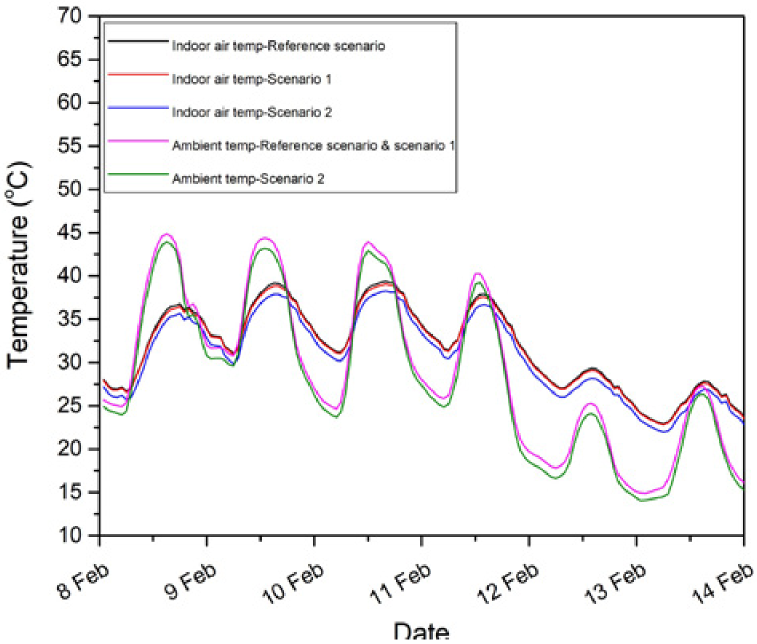


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.6-34.9 °C and 21.5-39.4 °C in Kuitpo and Roseworthy stations, respectively.

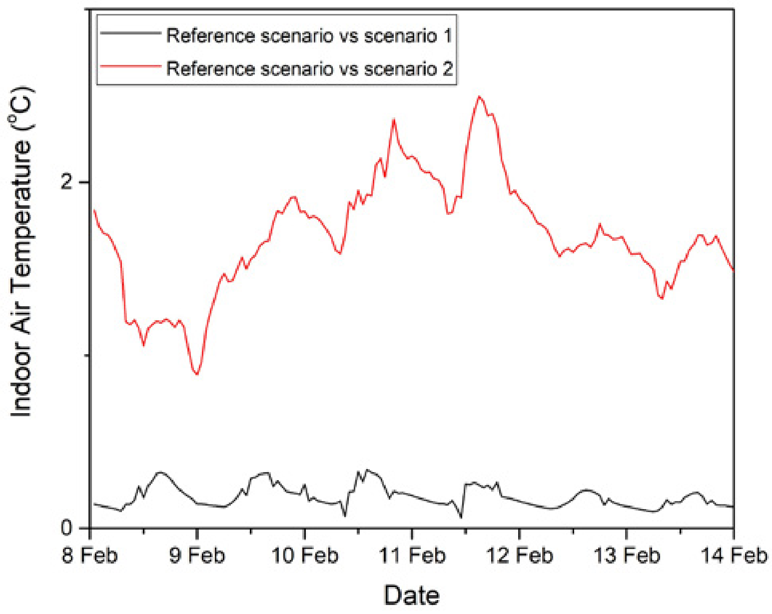


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.4 °C and 0.5 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.5 °C and 1.4 °C in Kuitpo and Roseworthy stations, respectively.

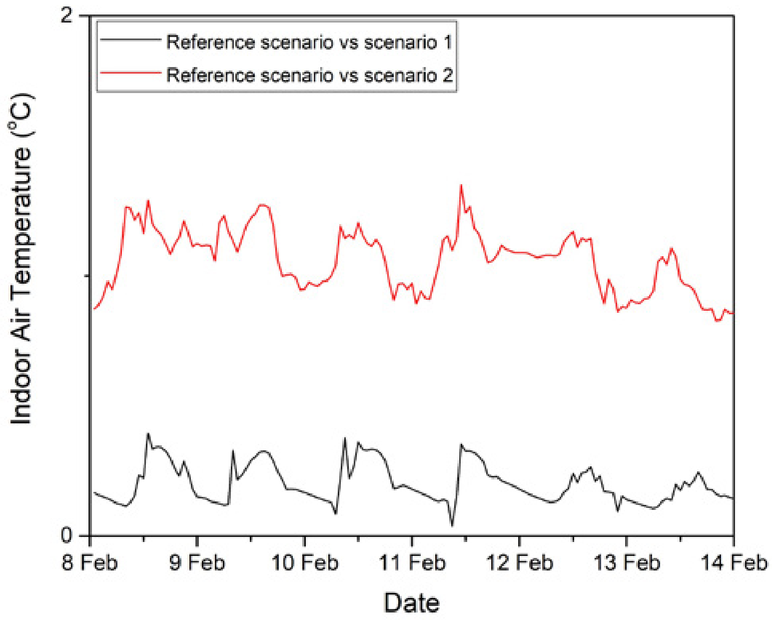


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 10.3-16.1 °C in reference scenario to a range 10.3-15.9 °C in scenario 1 in Kuitpo station.

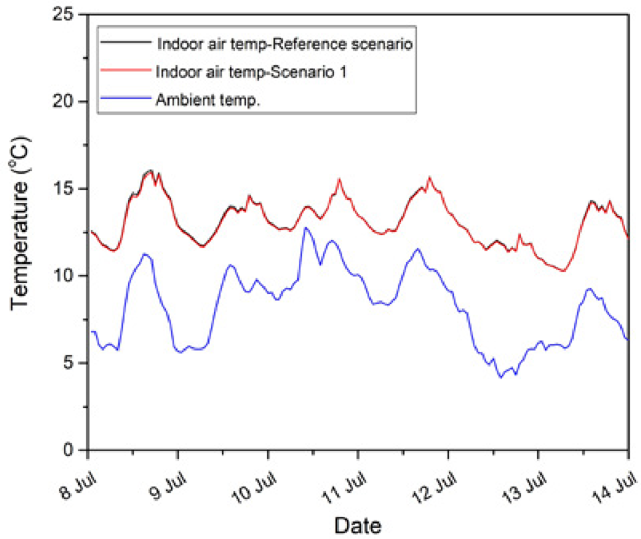


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 11.3-17.3 °C in reference scenario to a range 11.2-17.3 °C in scenario 1 in Roseworthy station.

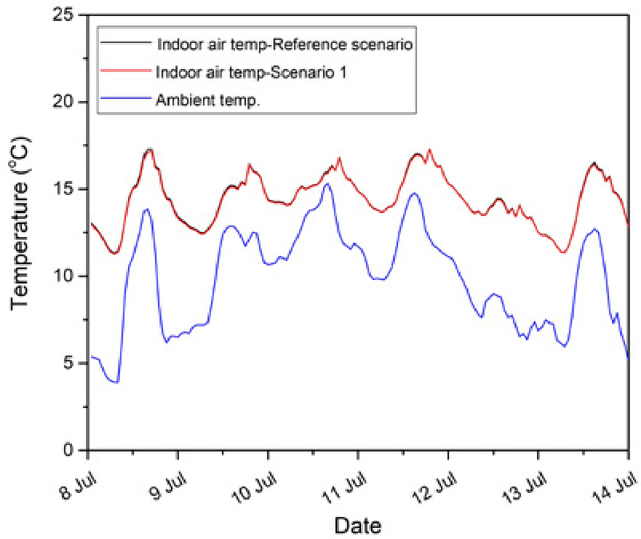


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

> *For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C in Kuitpo and Roseworthy stations.*

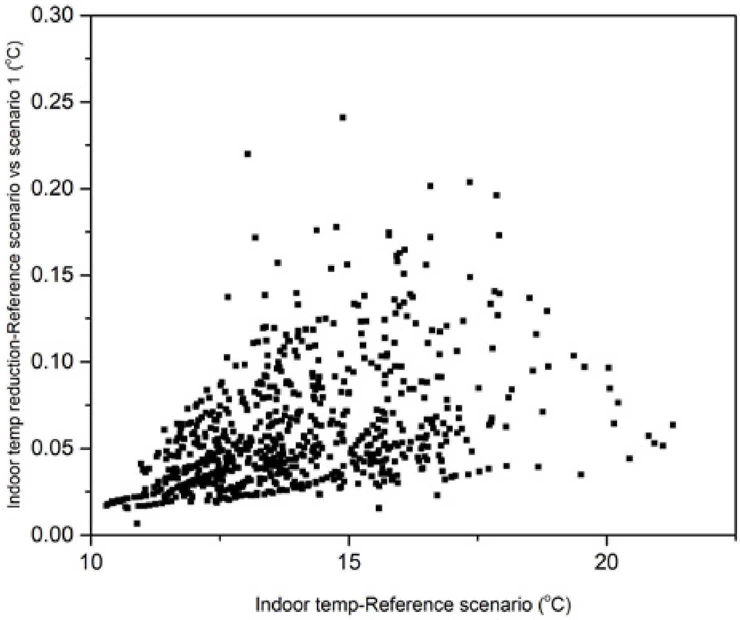


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

> *Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.*

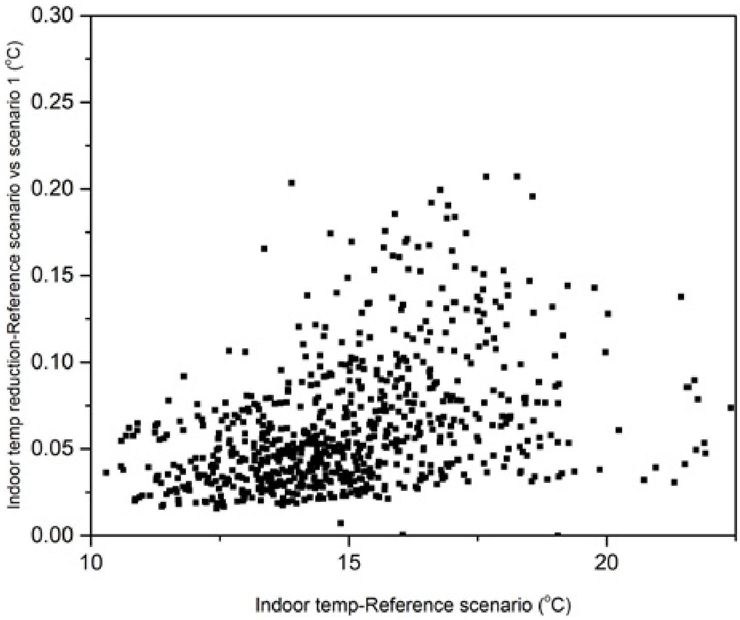


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to remain the same (732 hours) in Kuitpo station and slightly increase from 714 hours to 718 in Roseworthy station.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Kuitpo	732	732
Roseworthy	714	718

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 328 hours in reference scenario to 311 and 219 hours under scenario 1 and 2 in Kuitpo station; and from 421 hours in reference scenario to 409 and 355 hours under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	328	311	219
Roseworthy	421	409	355

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a clearly higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 09 is a new, mid-rise apartment building, with a total air-conditioned area of 3.120 m^2 distributed on five levels. The 624 m^2 roof is insulated, resulting in modest, but not insignificant, energy savings. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 09.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	63.0	66.3
Energy consumption after cool roof (MWh)	63.5	65.8
Energy savings (MWh)	-0.5	0.5
Energy savings (%)	-0.79%	0.75%
Area (m^2)	624	624
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

Building 09 is an interesting example of a mid-rise residential building, where the energy conservation potential is not big. However, even so the application of a coating cool roof technology emerges as a meaningful investment.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in an energy requirements' increase of 0,79% for Kuitpo and a reduction of 0,75% for Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 20,0% for the low energy price scenario for Kuitpo and 22,8% for the high energy scenario and for Roseworthy conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations.

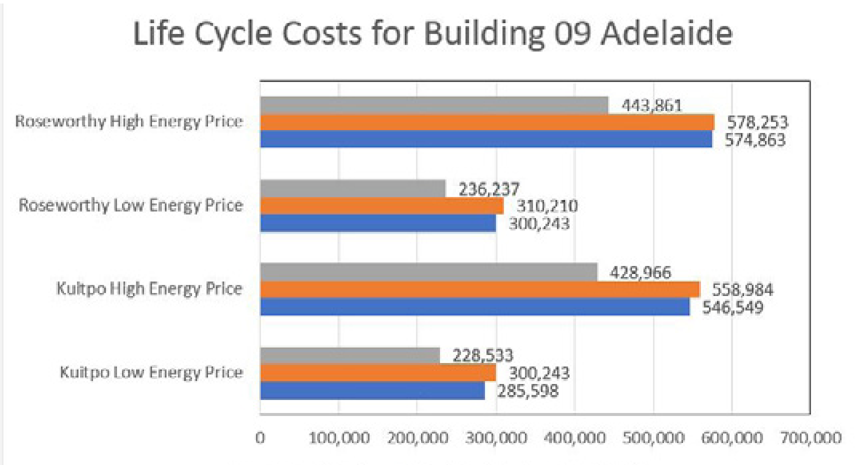


Figure 12. Life Cycle Costs for Building 09 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-5.13 %	-2.28 %	-3.32 %	-0.59 %
Coating Cool Roof	19.98 %	21.51%	21.32 %	22.79 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new mid-rise apartment building during the summer season .

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise apartment from 8.3-12.9 kWh/m^2 to 7.8-12.2 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5-0.7 kWh/m^2. This is equivalent to approximately 35.1-6.6 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 2.8-3.4 kWh/m^2 . This is equivalent to 22.9-39.4 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.5-0.9 kWh/m^2) is nearly the same that the annual cooling load reduction (0.5-1.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 5.0-7.8 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.4 and 0.5 kWh/m^2 (~ -0.7-1.0 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 21.6-34.9 ^{o}C and 21.5-39.4 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.4 and 0.5 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.5 and 1.4 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to slightly decrease from a range between 10.3-16.1 ^{o}C in reference scenario to a range between 10.3-15.9 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.3-17.3 °C in reference scenario to a range between 11.2-17.3°C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C in Kuitpo and Roseworthy stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to remain the same (732 hours) in Kuitpo station, and slightly increase from 714 hours to 718 hours in Roseworthy station (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 328 hours under the reference scenario in Kuitpo station, which decreases to 311 and 219 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also illustrate a significant reduction in number of hours above 26 °C from 421 hours in reference scenario to 409 in reference with cool roof scenario (scenario 1) and 355 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a clearly higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 20,0% for the low energy price scenario for Kuitpo and 22,8% for the high energy scenario and for Roseworthy conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations. Building 09 is in that sense an interesting example of a mid-rise residential building, where the energy conservation potential is not big. However, even so the application of a coating cool roof technology emerges as a meaningful investment.

B09

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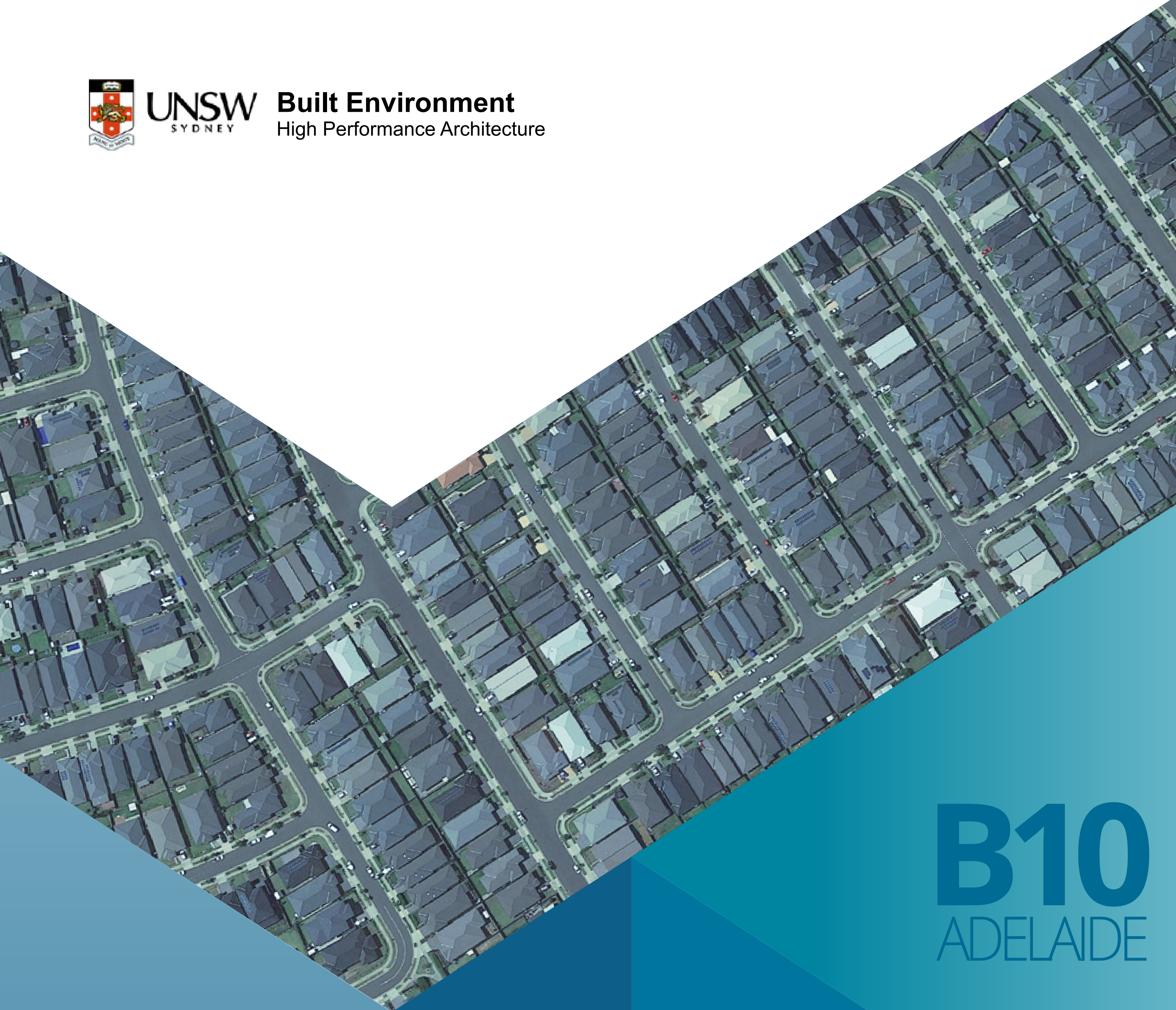
Built Environment
High Performance Architecture



B10
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise apartment
2021

BUILDING 10

NEW HIGH-RISE APARTMENT

Floor area : 624m^2
Number of stories : 8

Image source: Sunshine Gardens, City of Fredericton.

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new high-rise apartment building for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment building from 8.1-12.6 kWh/m² to 7.7-12.2 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)
Adelaide Airport	8.9	10.2	8.5	9.8	7.0	7.4
Edinburgh	10.1	11.4	9.7	11.0	7.8	8.2
Kuitpo	6.7	8.1	6.4	7.7	4.7	5.0
Parafield	9.7	11.0	9.4	10.7	8.0	8.5
Roseworthy	11.6	12.6	11.2	12.2	9.6	9.9

Table 2. Sensible and total cooling load saving for a new high-rise apartment building for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.3-0.4 kWh/m² which is equivalent to 3.1-4.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.6-3.1 kWh/m² which is equivalent to 21.3-38.2 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Adelaide Airport	0.3	3.8	0.4	3.5	1.9	20.9	2.8	27.1
Edinburgh	0.3	3.4	0.4	3.1	2.2	22.1	3.2	27.7
Kuitpo	0.3	4.4	0.3	4.0	2.0	30.1	3.1	38.2
Parafield	0.3	3.5	0.4	3.3	1.7	17.9	2.6	23.2
Roseworthy	0.4	3.4	0.4	3.3	2.0	17.4	2.7	21.3

In the eleven weather stations in Adelaide, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new high-rise apartment building during the summer season.

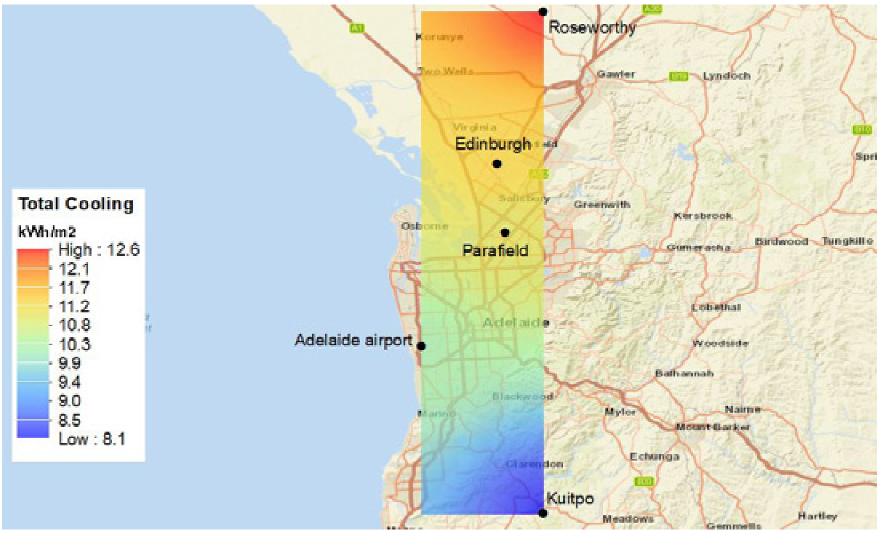


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

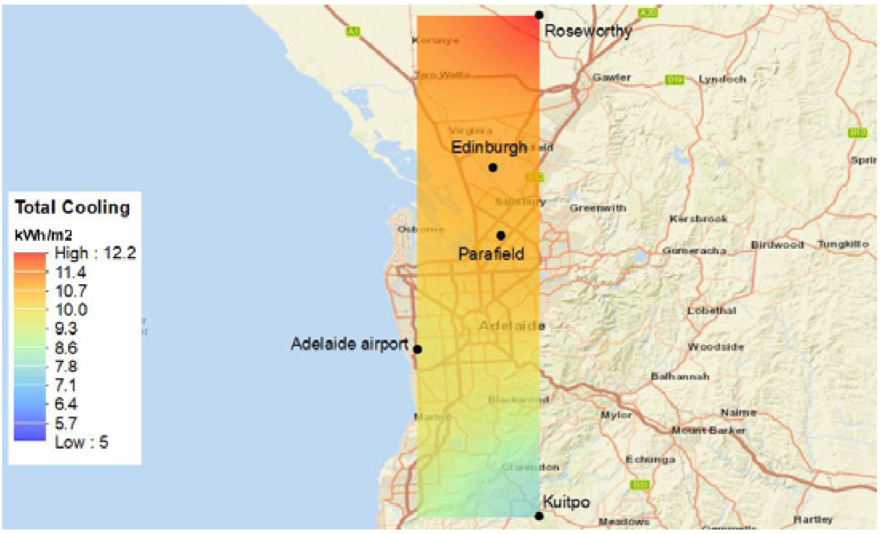


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

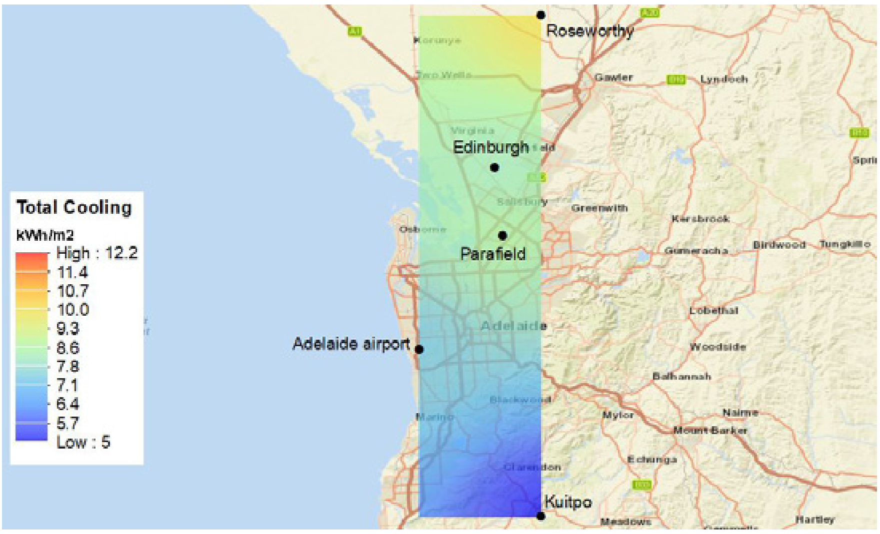


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

Table 3. Annual cooling and heating loads for a new high-rise apartment building for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.3-0.5 kWh/m²) is slightly lower than the annual cooling load reduction (0.3-0.6 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	11.4	13.8	14.3	22.7	11.0	13.4	14.5	23.0
Edinburgh	15.0	17.2	18.1	28.2	14.5	16.7	18.3	28.5
Kuitpo	5.2	5.9	28.8	44.2	5.0	5.7	29.2	44.7
Parafield	16.3	19.3	16.6	26.1	15.8	18.7	16.8	26.4
Roseworthy	14.4	16.3	23.4	35.9	13.9	15.8	23.7	36.3

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 3.0-4.8 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.2 and 0.3 kWh/m² (~ -0.5-0.6 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	0.4	3.4	0.4	3.2	0.2	0.3	0.2	0.7	0.2	0.4
Edinburgh	0.5	3.2	0.5	3.0	0.2	0.3	0.2	0.7	0.2	0.5
Kuitpo	0.3	4.8	0.3	4.8	0.4	0.5	-0.2	-0.4	-0.2	-0.5
Parafield	0.5	3.3	0.6	3.0	0.2	0.3	0.3	0.9	0.3	0.6
Roseworthy	0.5	3.6	0.6	3.4	0.3	0.4	0.2	0.6	0.2	0.3

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

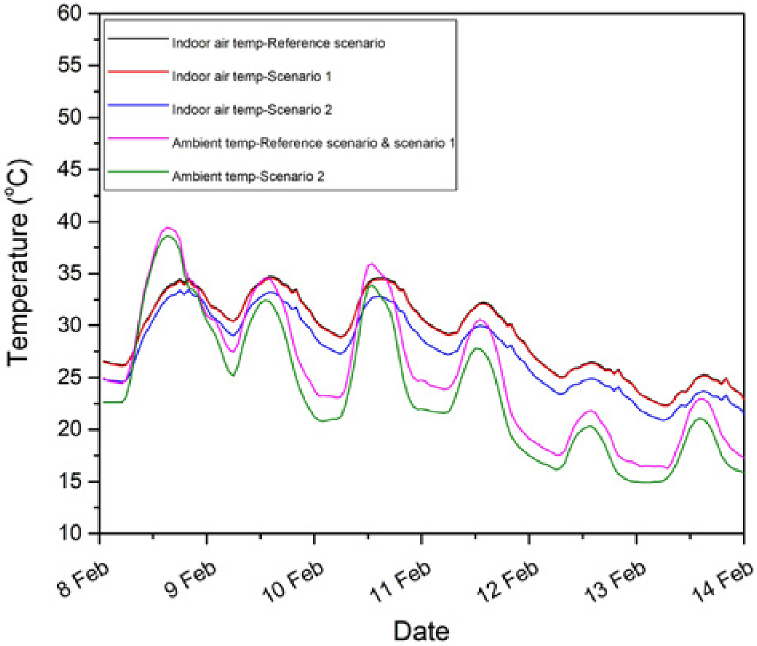


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

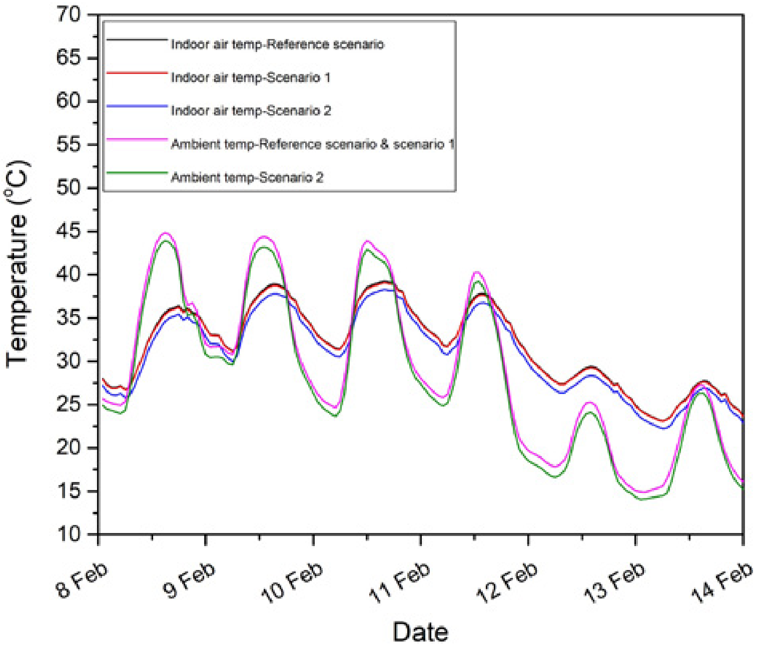


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.6-37.7 °C and 21.6-39.3 °C in Kuitpo and Roseworthy stations, respectively.

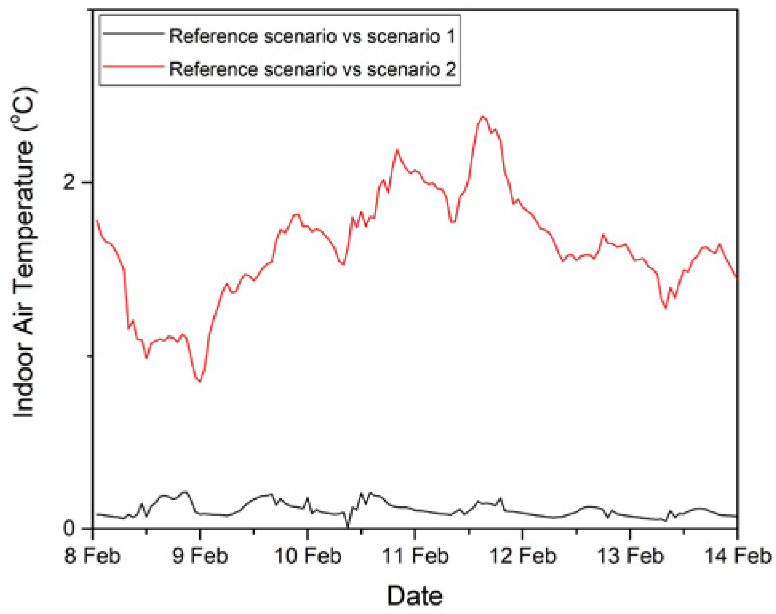


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.3 °C and 0.4 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.4 °C and 1.2 °C in Kuitpo and Roseworthy stations, respectively.

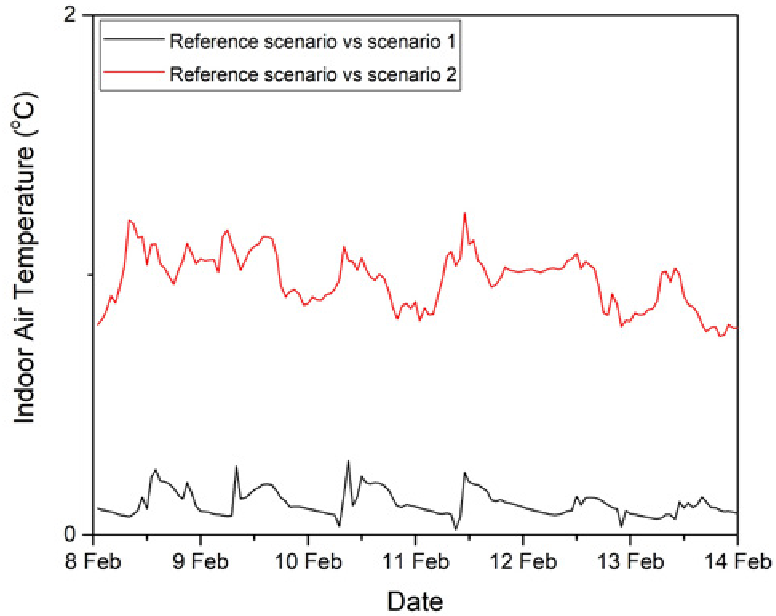


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 10.3-15.9 °C in reference scenario to a range 10.3-15.8 °C in scenario 1 in Kuitpo station.

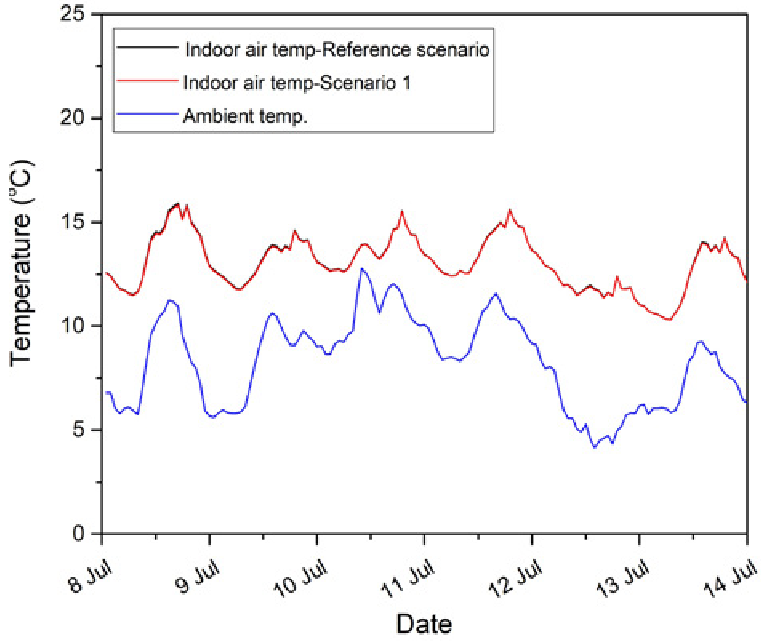


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 11.3-17.3 °C in reference scenario to a range 11.3-17.2 °C in scenario 1 in Roseworthy station.

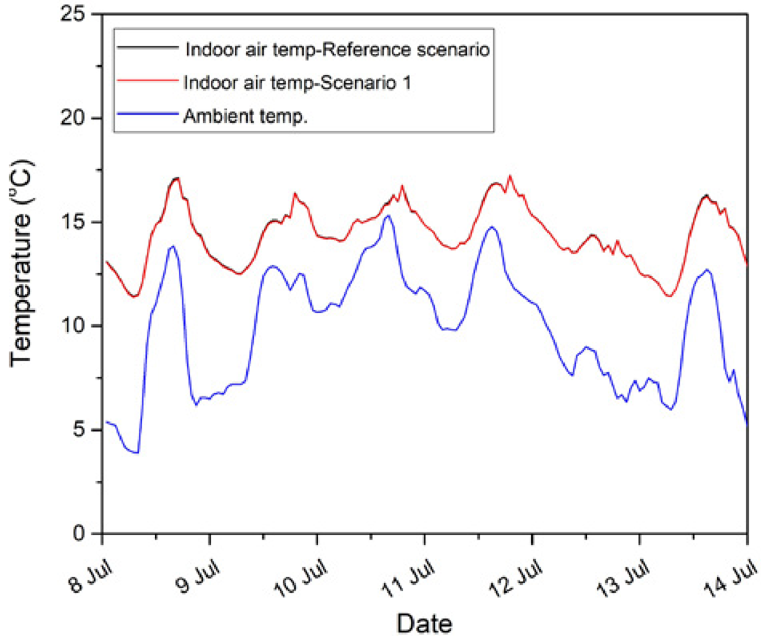


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 and 0.2 °C in Kuitpo and Roseworthy stations, respectively.

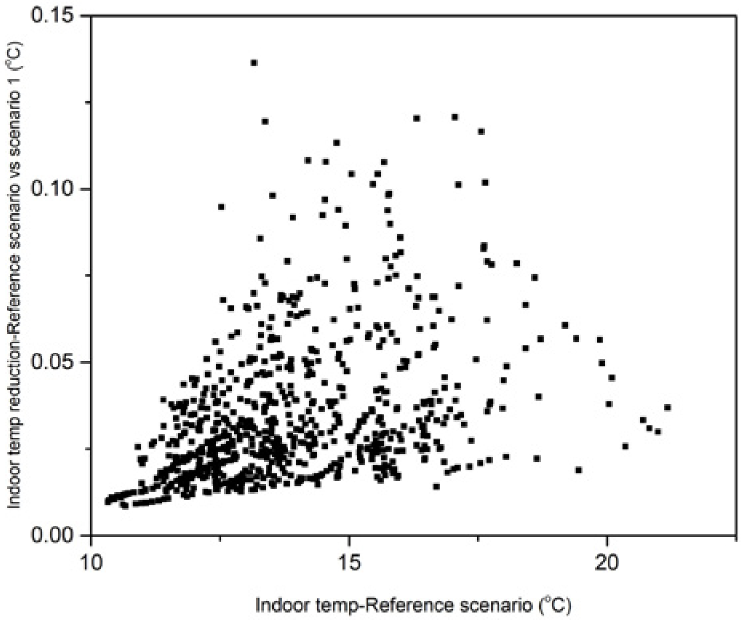


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

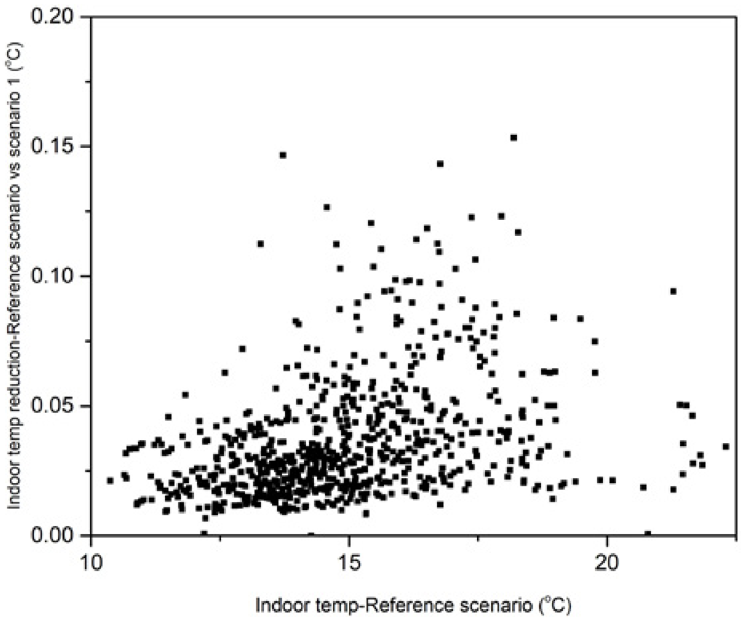


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to remain the same in reference scenario and scenario 1 in Kuitpo (732 hours) and Roseworthy (721 hours) stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Kuitpo	732	732
Roseworthy	721	721

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 245 hours in reference scenario to 241 and 150 hours under scenario 1 and 2 in Kuitpo station; and from 349 hours in reference scenario to 343 and 295 hours under scenario 1 and 2 in Roseworthy station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	245	241	150
Roseworthy	349	343	295

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 10 is a new, high-rise apartment building, with a total air-conditioned area of 4.992 m^2 distributed on six levels. The 624 m^2 roof is insulated, resulting in modest energy savings. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 10.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	100.0	104.2
Energy consumption after cool roof (MWh)	100.6	104.0
Energy savings (MWh)	-0.6	0.2
Energy savings (%)	-0.60%	0.19%
Area (m^2)	624	624
Roof costs - Metal roof (AU$/m^2)	38.0	38.0
Roof costs - Coating (AU$/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

The cool roof refurbishment options

Building 10 is an interesting example of a new, high-rise residential building, where the energy conservation potential is truly modest. However, even so, the application of a coating cool technology emerges as a very meaningful investment.

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in an energy requirements' increase of 0,60% for the Kuitpo weather conditions and a reduction of 0,19% for the Roseworthy conditions. These savings are within the limits of simulative errors, but even so it is of interest to examine the feasibility The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

Despite the marginal energy savings, the coating cool roof option leads to a significant reduction of life cycle costs, that varies between 21,1% for the low energy price scenario for Kuitpo and 22,8% for the high energy scenario and for Roseworthy conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is, due to its higher initial investment cost and the modest energy savings, not feasible.

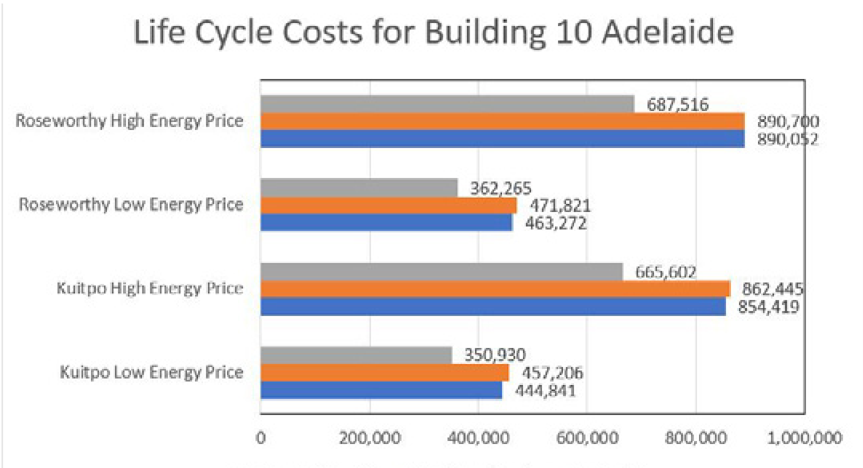


Figure 12. Life Cycle Costs for Building 10 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-2.78 %	-0.94 %	-1.85 %	-0.07 %
Coating Cool Roof	21.11 %	22.10 %	21.80 %	22.76 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new high-rise apartment building during the summer season . Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 8.1-12.6 kWh/m^2 to 7.7-12.2 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.3-0.4 kWh/m^2. This is equivalent to approximately 3.1-4.0 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 2.6-3.1 kWh/m^2. This is equivalent to 21.3-38.2 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.3-0.5 kWh/m^2) is slightly lower than the annual cooling load reduction (0.3-0.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.0-4.8 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.2 and 0.3 kWh/m^2 (~ -0.5-0.6 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 28.0-38.1 ^{o}C and 28.0-34.4 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.3 and 0.4 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.4 and 1.2 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to slightly decrease from a range between 110.3-15.9 ^{o}C in reference scenario to a range between 10.3-15.8 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8). Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.3-17.3 ^{o}C in reference scenario to a range between 11.3-17.2 ^{o}C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 and 0.2 ^{o}C for Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to remain the same in reference scenario and in reference with cool roof scenario (scenario 1) in Kuitpo (732 hours) and Roseworthy (721 hours) stations, respectively (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 245 hours under the reference scenario in Kuitpo station, which decreases to 241 and 150 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also illustrate a significant reduction in number of hours above 26 ^{o}C from 349 hours in reference scenario to 343 in reference with cool roof scenario (scenario 1) and 295 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option, which leads, despite the marginal energy savings, to a significant reduction of life cycle costs, that varies between 21,1% for the low energy price scenario for Kuitpo and 22,8% for the high energy scenario and for Roseworthy conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the modest energy savings, not feasible. Building 10 is in that sense an interesting example of a new, high-rise residential building, where the energy conservation potential is truly modest. However, even so, the application of a coating cool technology emerges as a very meaningful investment.

B10

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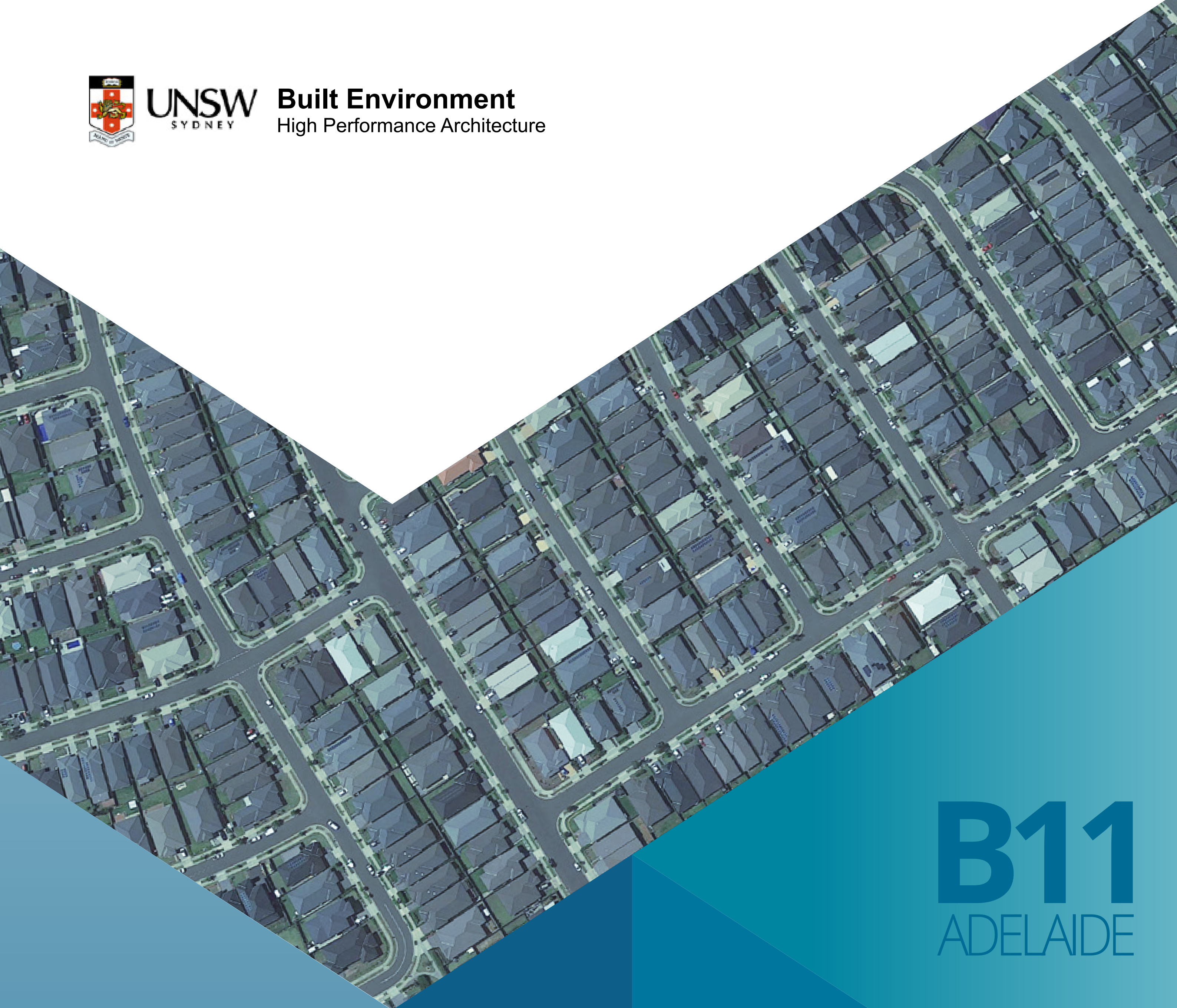

B11 ADELAIDE

COOL ROOFS COST BENEFIT **ANALYSIS STUDY**

Existing standalone house
2021

BUILDING 11

EXISTING STANDALONE HOUSE

Floor area : $242m^2$
Number of stories : 1

Image source: https://www.newhomesguide.com.au/builders/long-island-homes/homes/new-homes/moonbi-240

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for an existing stand-alone house for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing standalone house from 11.8-15.8 kWh/m² to 6.1-9.8 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	12.7	13.7	6.9	7.7	5.8	6.0
Edinburgh	13.6	14.6	7.8	8.6	6.5	6.7
Kuitpo	10.6	11.8	5.3	6.1	4.3	4.4
Parafield	13.4	14.4	7.6	8.3	6.6	6.8
Roseworthy	15.1	15.8	9.2	9.8	8.0	8.2

Table 2. Sensible and total cooling load saving for an existing stand-alone house for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 5.7-6.0 kWh/m² which is equivalent to 38.1-48.1 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.3-7.9 kWh/m² which is equivalent to 48.1-62.2 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	5.8	45.7	6.0	44.0	6.8	54.0	7.6	55.7
Edinburgh	5.8	42.5	6.0	41.1	7.1	52.1	7.9	54.0
Kuitpo	5.3	50.2	5.7	48.1	6.4	59.9	7.3	62.2
Parafield	5.8	43.6	6.0	42.1	6.8	50.9	7.5	52.4
Roseworthy	5.9	39.0	6.0	38.1	7.1	46.8	7.6	48.1

In the eleven weather stations in Adelaide, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the existing standalone house during the summer season.

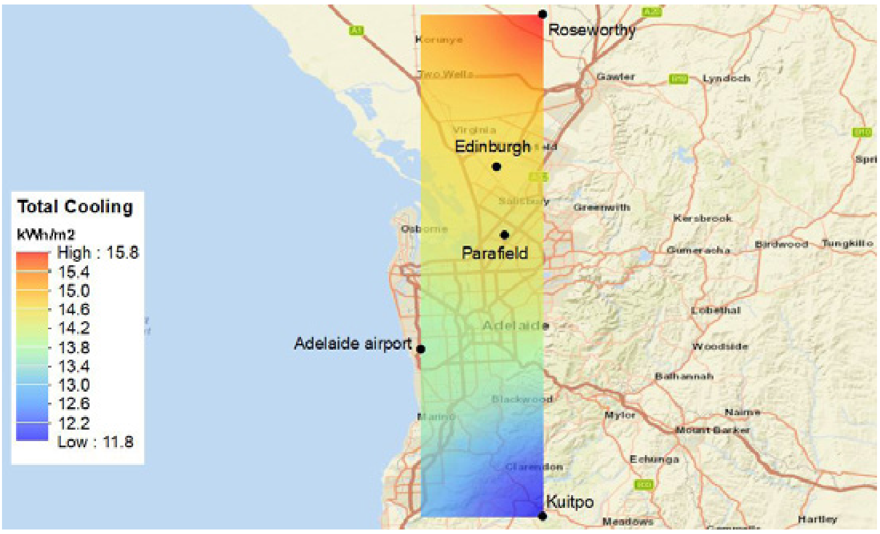

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

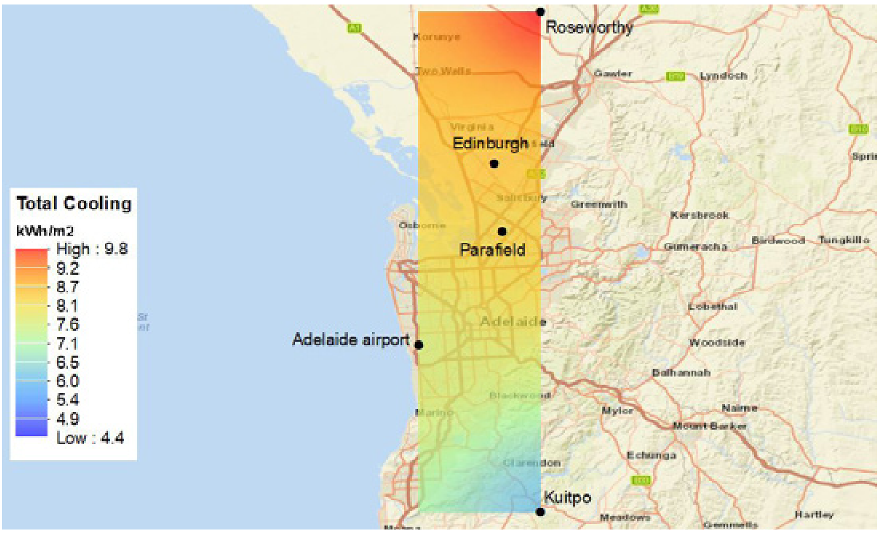

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

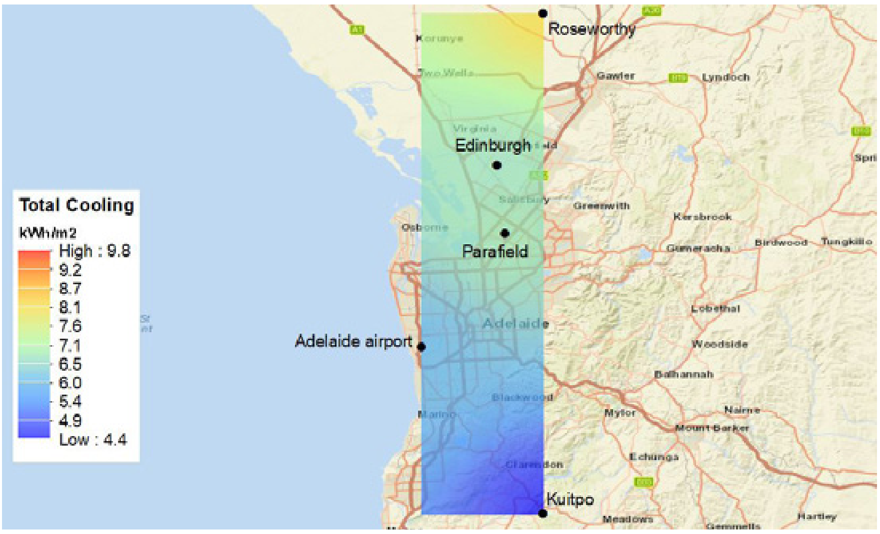

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (5.1-8.7 kWh/m²) is lower than the annual cooling load reduction (6.9-11.4 kWh/m²).

Table 3. Annual cooling and heating loads for an existing stand-alone house for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	17.6	20.0	22.1	26.7	9.3	11.0	26.8	31.7
Edinburgh	22.5	24.5	25.0	30.1	12.7	14.2	30.1	35.6
Kuitpo	11.4	12.5	33.4	40.7	5.0	5.6	41.3	49.4
Parafield	24.6	27.2	24.0	28.9	13.8	15.8	28.9	34.3
Roseworthy	22.7	24.3	29.3	35.3	13.0	14.3	35.1	41.6

The annual cooling load saving by building-scale application of cool roofs is around 41.3-55.4 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -1.8 and 5.9 kWh/m² (~ -3.3-10.6 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing stand-alone house using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	8.3	47.0	9.0	45.0	4.6	5.1	3.6	9.2	3.9	8.4
Edinburgh	9.8	43.5	10.3	41.9	5.1	5.6	4.7	9.9	4.7	8.6
Kuitpo	6.4	56.3	6.9	55.4	7.9	8.7	-1.5	-3.3	-1.8	-3.3
Parafield	10.8	43.8	11.4	41.8	5.0	5.4	5.8	12.0	5.9	10.6
Roseworthy	9.7	42.7	10.1	41.3	5.8	6.2	3.9	7.6	3.8	6.4

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

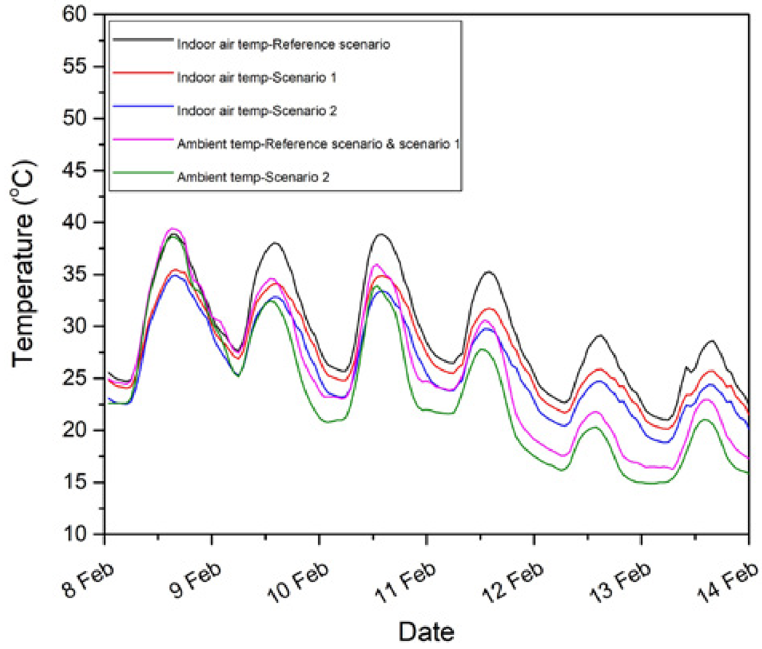

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

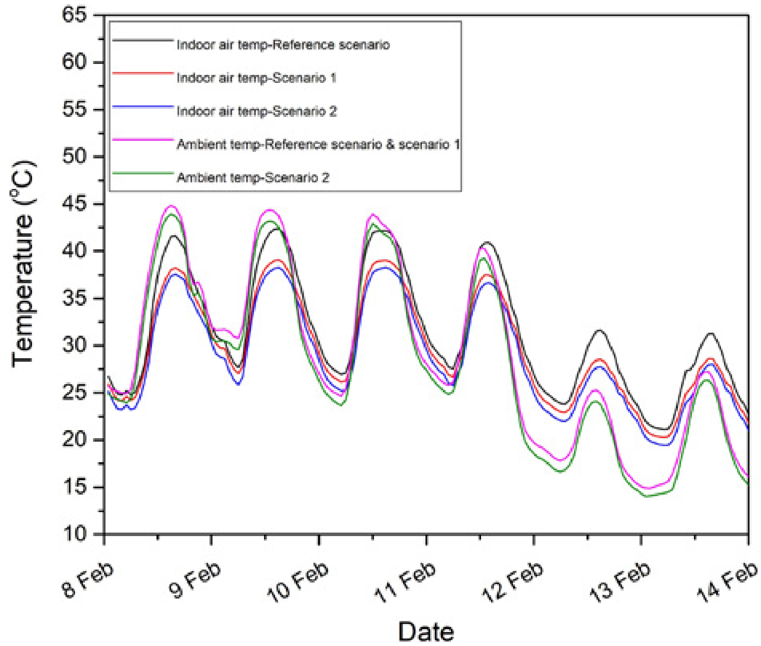

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 20.5-38.9 °C and 19.8-42.4 °C in Kuitpo and Roseworthy stations, respectively.

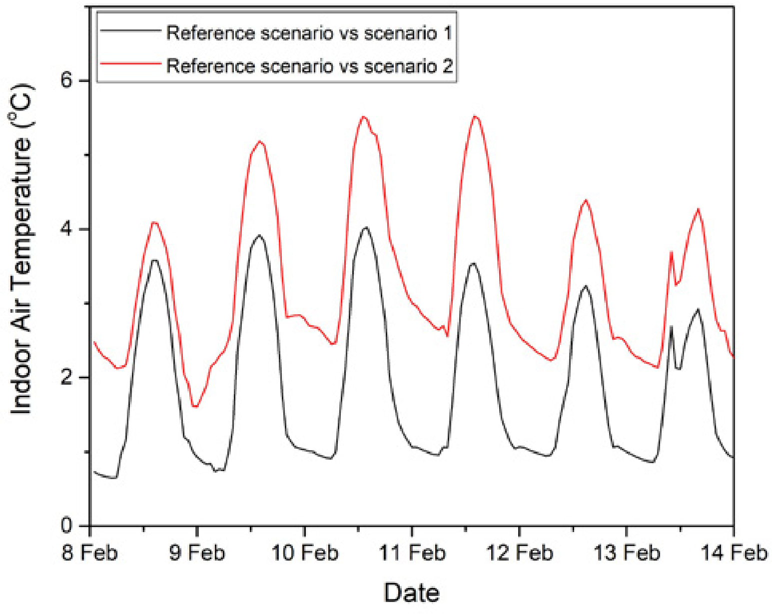

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 4.5 °C and 4.4 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 5.5 °C and 5.1 °C in Kuitpo and Roseworthy stations, respectively.

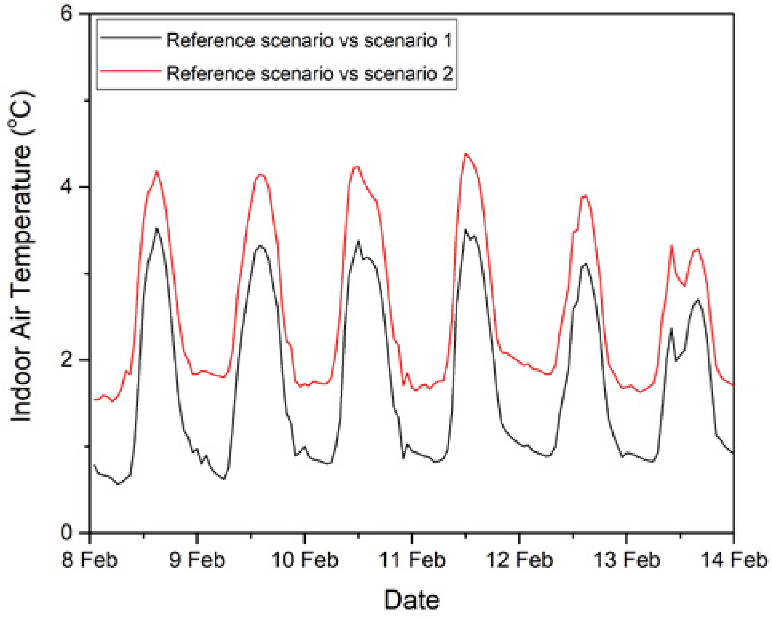

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 9.5-17.8 °C in reference scenario to a range 9.2-16.1 °C in scenario 1 in Kuitpo station.

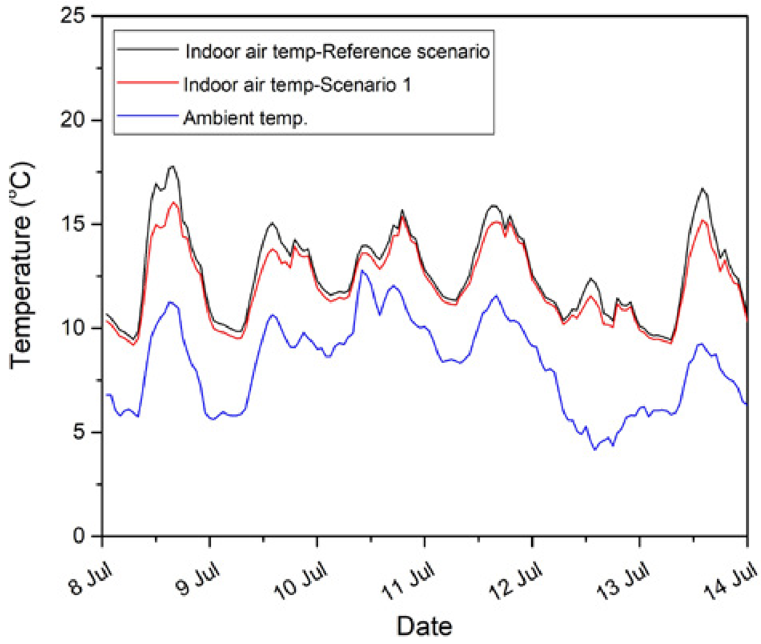

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 9.1-19.3 °C in reference scenario to a range 8.8-17.7 °C in scenario 1 in Roseworthy station.

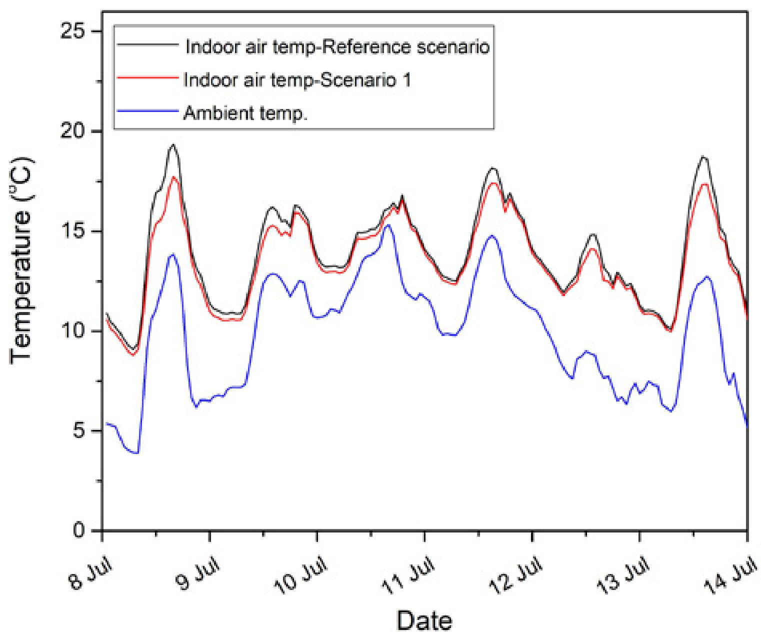

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 2.4 °C and 2.2 °C in Kuitpo and Roseworthy stations, respectively.

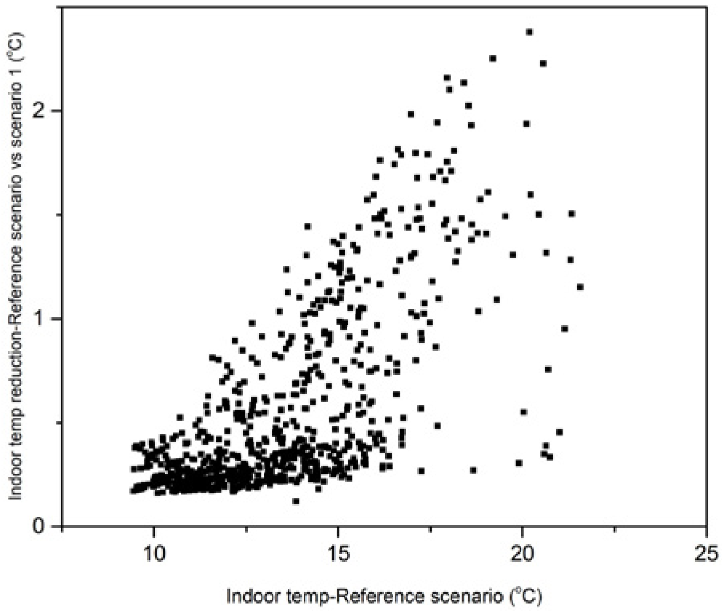

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

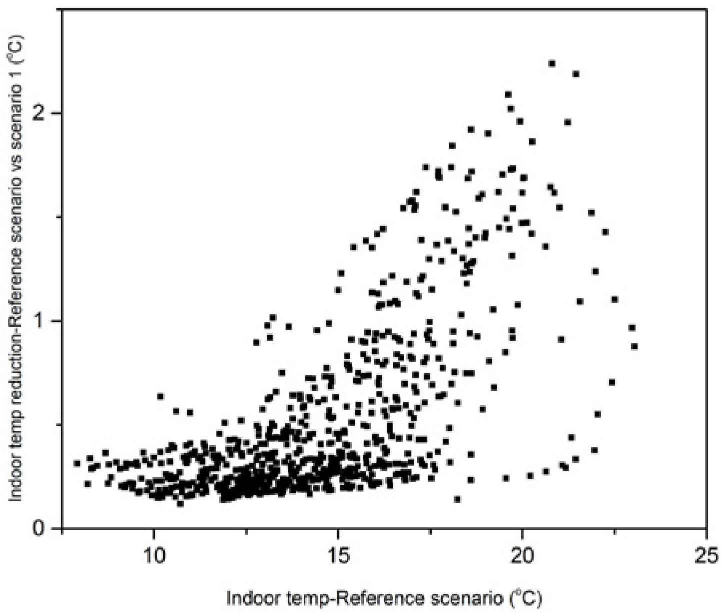

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 721 hours in reference scenario to 732 hours; and from 691 to 720 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Kuitpo	721	732
Roseworthy	691	720

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 297 hours in reference scenario to 185 and 136 hours under scenario 1 and 2 in Kuitpo station; and from 354 hours in reference scenario to 282 and 248 hours under scenario 1 and 2 in Roseworthy station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	297	185	136
Roseworthy	354	282	248

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 11 is an existing, stand-alone residential building, with a total air-conditioned area of 242 m² distributed on one level. Despite the fact that the 242 m² roof is insulated, its big impact on the building's energy balance leads to overall significant energy savings. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 11.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	5.1	5.8
Energy consumption after cool roof (MWh)	5.3	5.4
Energy savings (MWh)	-0.2	0.4
Energy savings (%)	-3.92%	6.90%
Area (m²)	242	242
Roof costs - Metal roof (AU$/m²)	38.0	38.0
Roof costs - Coating (AU$/m²)	22.75	22.75
Life expectancy - Metal roof (years)	28.5	28.5
Life expectancy - Coating (years)	22.5	22.5
HVACs COP	2.5	2.5
Existing roof's renovation costs (AU$/m²)	15.0	15.0

Building 11 is an interesting example of a new, stand-alone residential building, with a single floor and an insulated roof, where the energy conservation potential is significant.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Given the low in absolute terms energy expenditure and the high initial cost of the metal cool roof, this is not feasible. On the contrary, the coating cool technology emerges as an appealing investment under all conditions.

Both options have the same energy efficiency, resulting in an energy requirements' increase of 3,92% for Kuitpo and a decrease of 6,90% for the Roseworthy weather conditions. The value for Kuitpo however is in absolute terms within the margin of simulation error and it therefore interesting to still examine the feasibility. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 6,4% for the low energy price scenario and 21,9% for the high energy scenario for Roseworthy conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations.

Figure 12. Life Cycle Costs for Building 11 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-28.75 %	-16.62 %	-15.91 %	-4.63 %
Coating Cool Roof	6.44 %	12.92 %	15.73 %	21.86 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of an existing standalone house during the summer season.

• In the eleven weather stations in Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 11.8-15.8 kWh/m^2 to 6.1-9.8 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 5.7-6.0 kWh/m^2. This is equivalent to approximately 38.1-48.1 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.3-7.9 kWh/m^2. This is equivalent to 48.1-62.2 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (5.1-8.7 kWh/m^2) is lower than the annual cooling load reduction (6.9-11.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 41.3-55.4 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -1.8 and 5.9 kWh/m^2 (~ -3.3-10.6 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 20.5-38.9 ^{o}C and 19.8-42.4 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 4.5 and 4.4 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 5.5 and 5.1 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease from a range between 9.5-17.8 ^{o}C in reference scenario to a range between 9.2-16.1 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 9.1-19.3 ^{o}C in reference scenario to a range between 8.8-17.7^{o}C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 2.4 and 2.2 ^{o}C for Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase from 721 hours in reference scenario to 732 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slightly increase in total number of hours below 19 ^{o}C from 691 hours in reference scenario to 720 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 297 hours under the reference scenario in Kuitpo station, which significantly decreases to 185 and 136 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Roseworthy station also illustrate a significant reduction in number of hours above 26 ^{o}C from 354 hours in reference scenario to 282 in reference with cool roof scenario (scenario 1) and 248 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 6,4% for the low energy price scenario and 21,9% for the high energy scenario for Roseworthy conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations. Building 11 is in that sense an interesting example of a new, stand-alone residential building, with a single floor and an insulated roof, where the energy conservation potential is significant. However, given the low in absolute terms energy expenditure and the high initial cost of the metal cool roof, this is not feasible. On the contrary, the coating cool technology emerges as an appealing investment under all conditions.

B11

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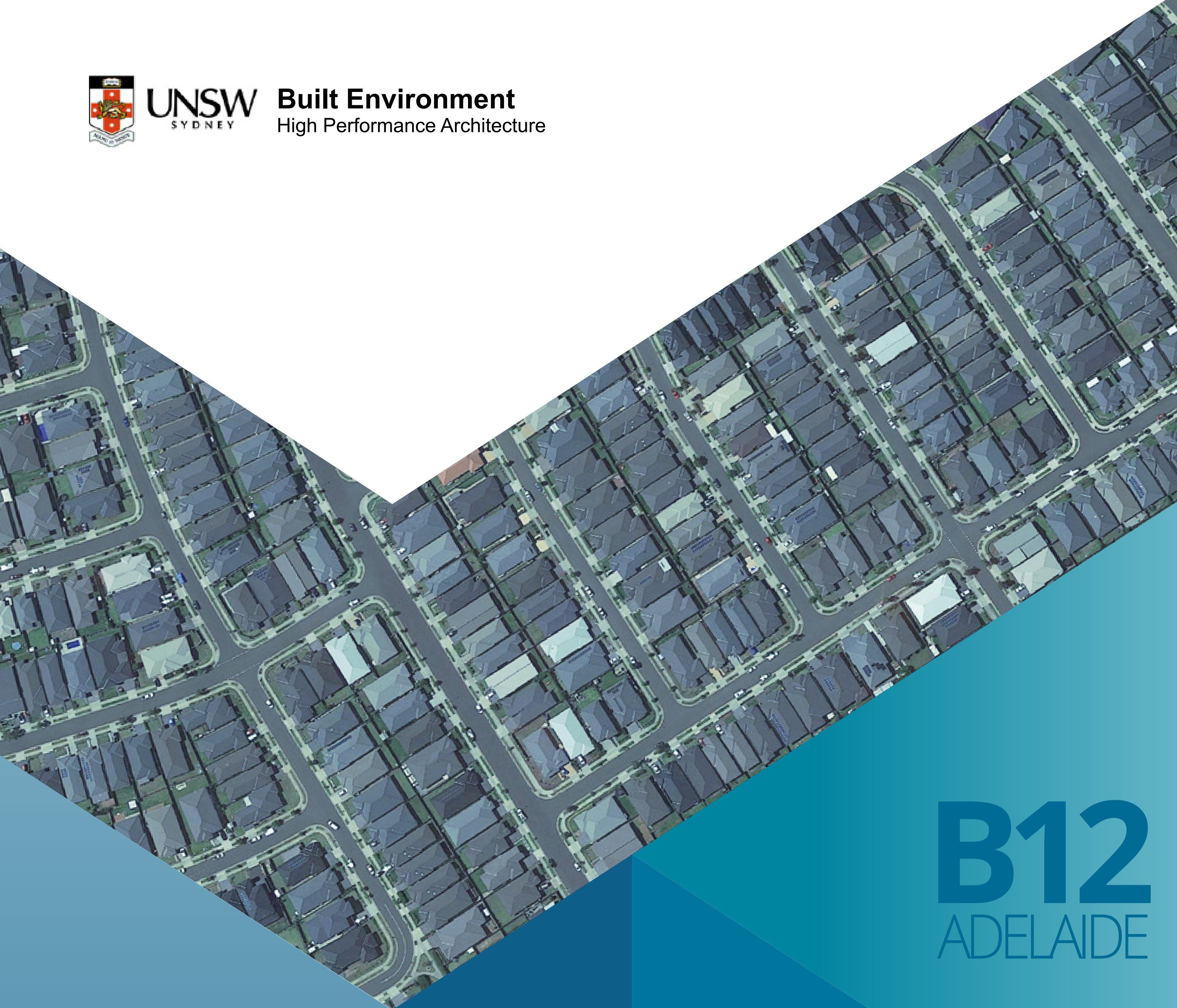

B12
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

Existing school
2021

BUILDING 12

EXISTING SCHOOL

Floor area : 1100m^2
Number of stories : 3

Image source: Pavia National High School, Evangelista St., Pavia, Iloilo

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for an existing school for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing school from 17.0-26.5 kWh/m² to 16.2-25.6 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	19.5	20.9	18.8	20.2	16.0	16.2
Edinburgh	21.7	23.4	21.1	22.6	17.9	18.2
Kuitpo	15.6	17.0	15.0	16.2	11.9	12.0
Parafield	21.2	22.7	20.5	21.9	18.0	18.3
Roseworthy	25.2	26.5	24.4	25.6	21.8	22.0

Table 2. Sensible and total cooling load saving for an existing school for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.7-0.9 kWh/m² which is equivalent to 3.4-4.2 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.4-5.2 kWh/m² which is equivalent to 17.1-29.1 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	0.7	3.4	0.8	3.8	3.5	17.9	4.7	22.5
Edinburgh	0.7	3.1	0.8	3.4	3.8	17.5	5.2	22.4
Kuitpo	0.6	3.9	0.7	4.2	3.7	23.8	4.9	29.1
Parafield	0.7	3.2	0.8	3.5	3.2	15.1	4.4	19.5
Roseworthy	0.8	3.1	0.9	3.4	3.4	13.5	4.5	17.1

In the eleven weather stations in Adelaide, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of an existing school during the summer season.

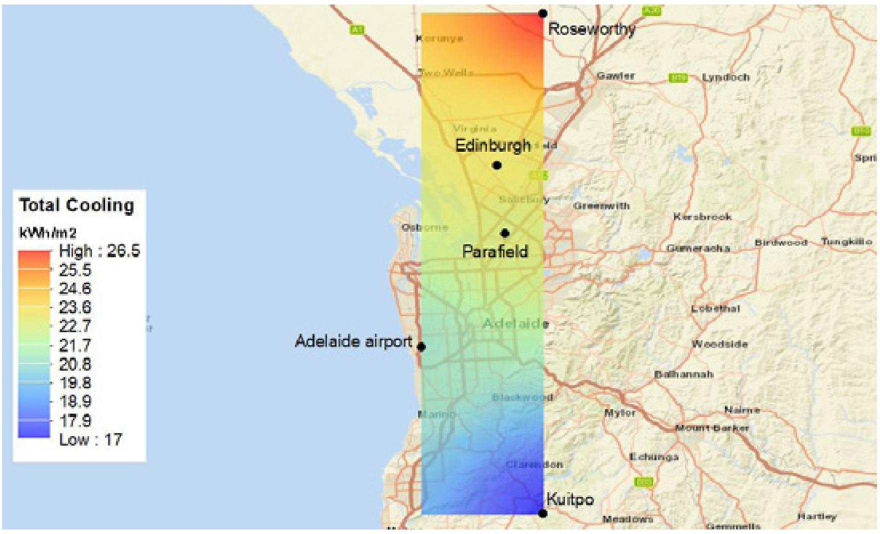

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for aan existing school with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

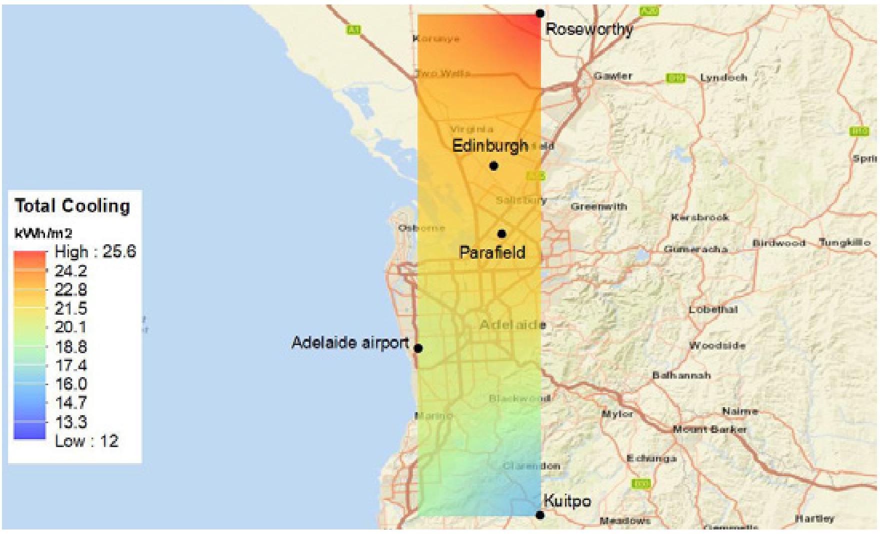

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

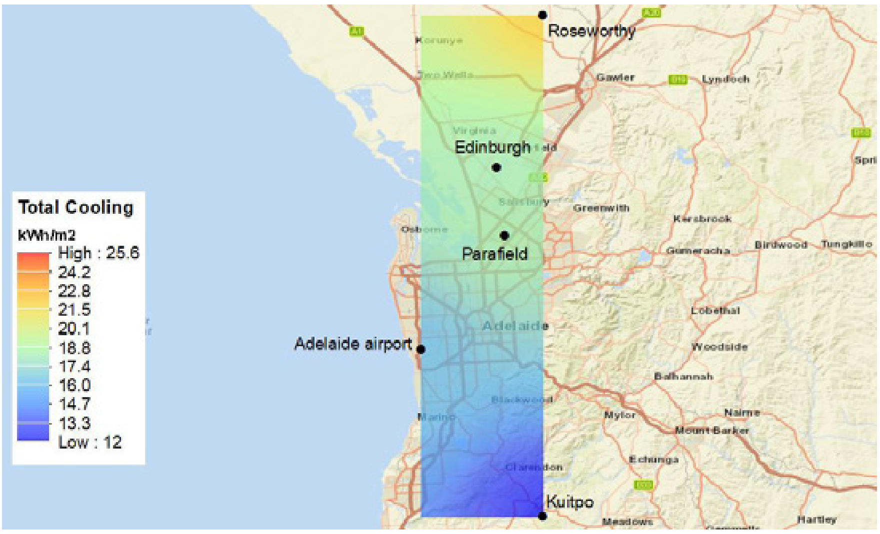

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing school for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.3-0.8 kWh/m²) is significantly slower than the annual cooling load reduction (0.8-1.5 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	27.0	29.6	3.0	17.3	26.0	28.4	3.1	17.6
Edinburgh	36.3	38.5	3.9	22.2	35.2	37.3	3.9	22.6
Kuitpo	18.2	19.0	5.1	37.4	17.4	18.2	5.2	38.3
Parafield	39.1	42.6	3.7	20.4	37.9	41.2	3.7	20.7
Roseworthy	39.3	41.4	4.9	26.2	38.1	39.9	4.9	26.7

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing school using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 3.3-4.3 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8-1.1 kWh/m² (~0.0-1.8 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	0.9	3.5	1.2	4.0	0.1	0.3	0.9	2.9	0.8	1.8
Edinburgh	1.1	3.1	1.3	3.3	0.1	0.4	1.0	2.6	0.9	1.5
Kuitpo	0.7	4.0	0.8	4.3	0.1	0.8	0.6	2.7	0.0	0.0
Parafield	1.2	3.1	1.5	3.5	0.1	0.4	1.1	2.6	1.1	1.8
Roseworthy	1.3	3.2	1.4	3.4	0.1	0.5	1.2	2.6	0.9	1.4

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

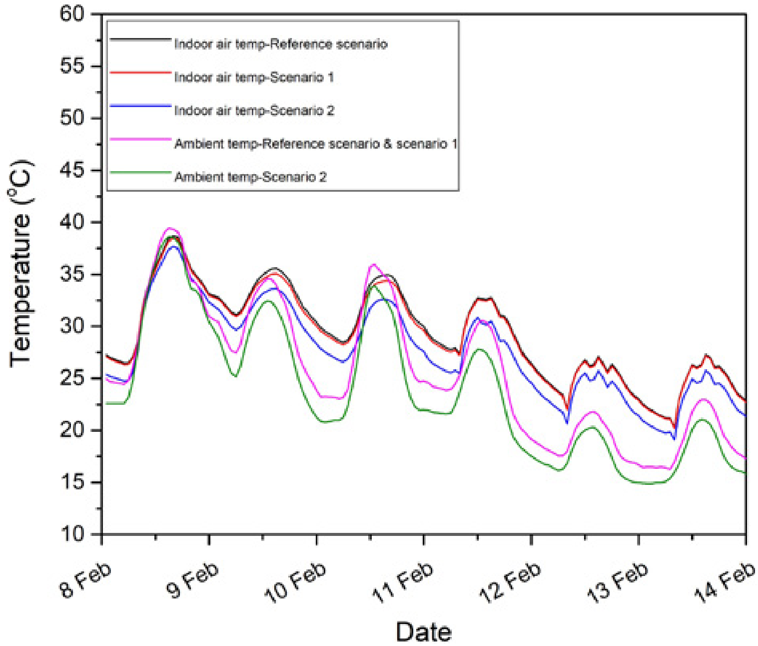

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

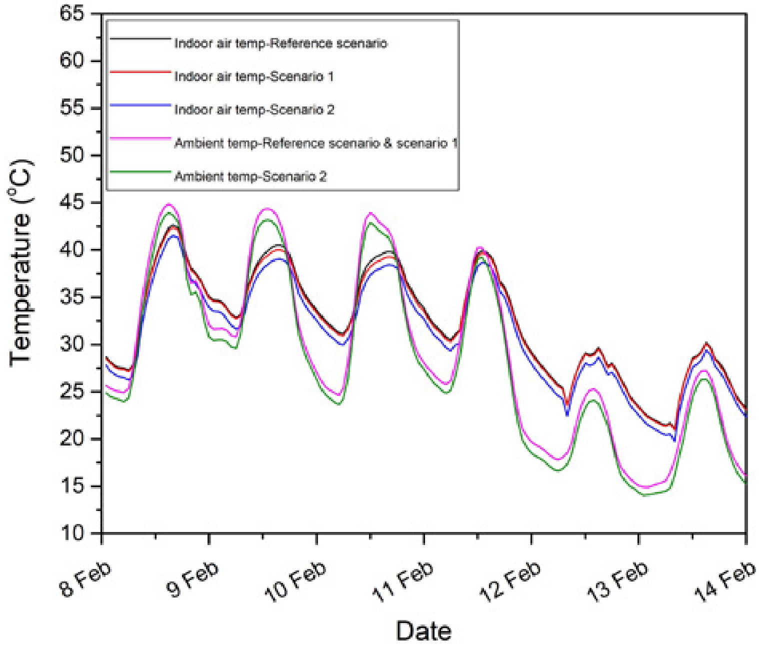

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 20.3-38.7 °C and 20.5-42.6 °C in Kuitpo and Roseworthy stations, respectively.

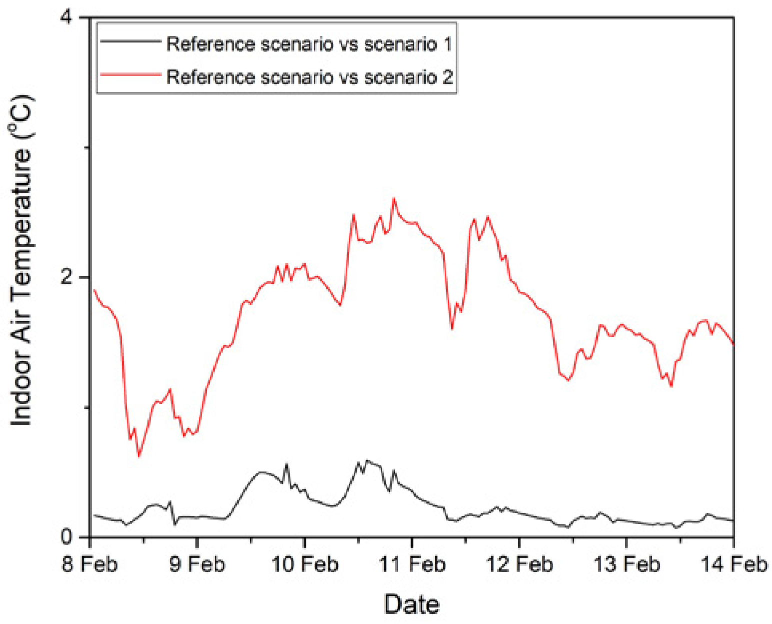

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.6 °C and 0.6 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.6 °C and 1.6 °C in Kuitpo and Roseworthy stations, respectively.

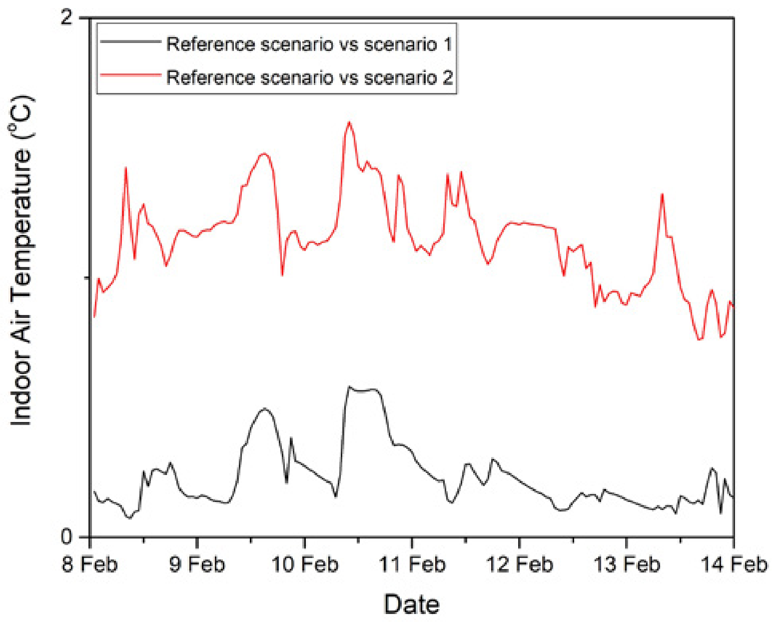

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 8.9-18.3 °C in reference scenario to a range 8.8-18.3 °C in scenario 1 in Kuitpo station.

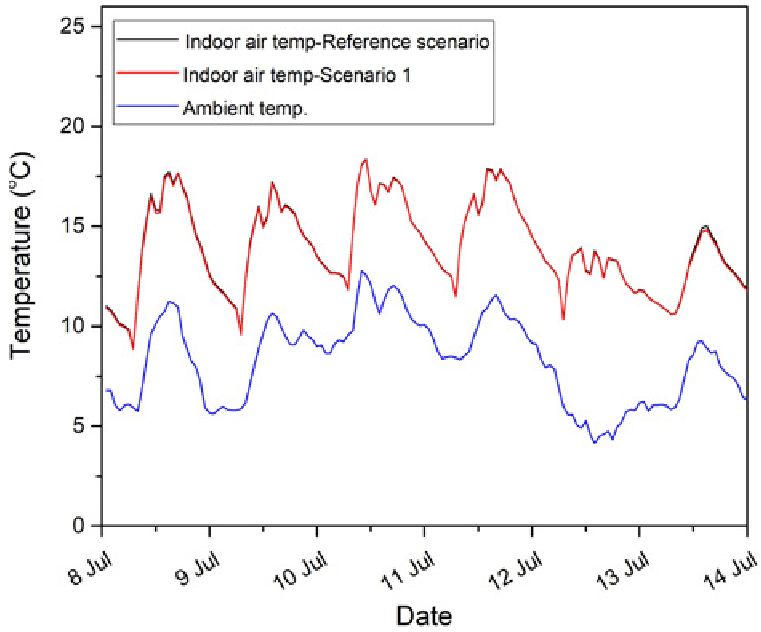

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 8.1-20.4 °C in reference scenario to a range 8.0-20.4 °C in scenario 1 in Roseworthy station.

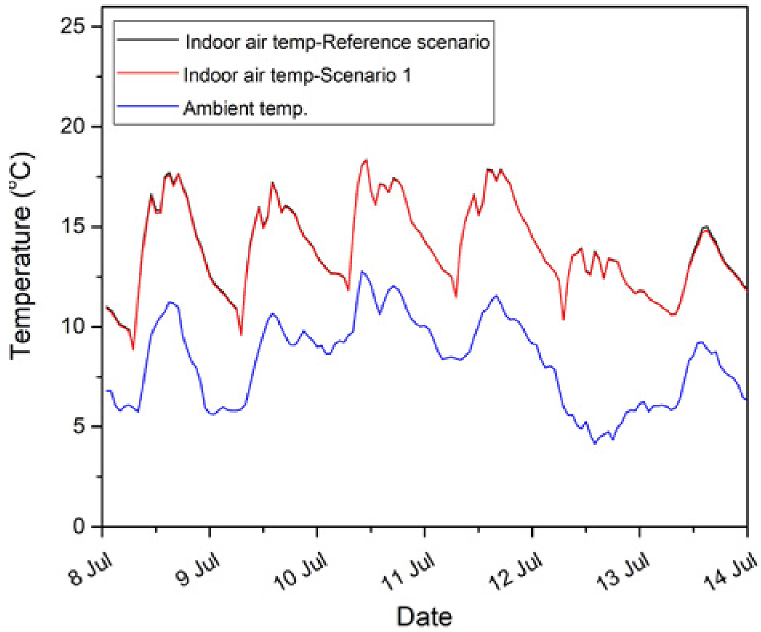

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C in Kuitpo and Roseworthy stations.

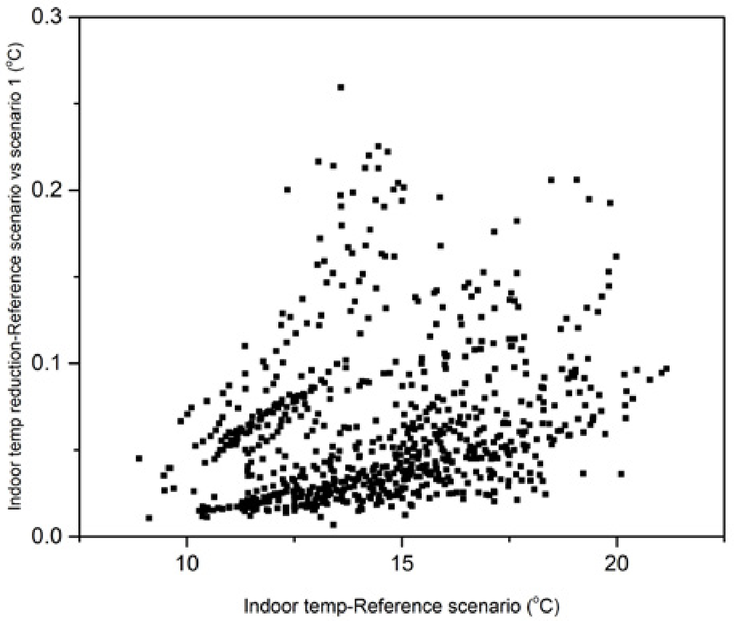

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

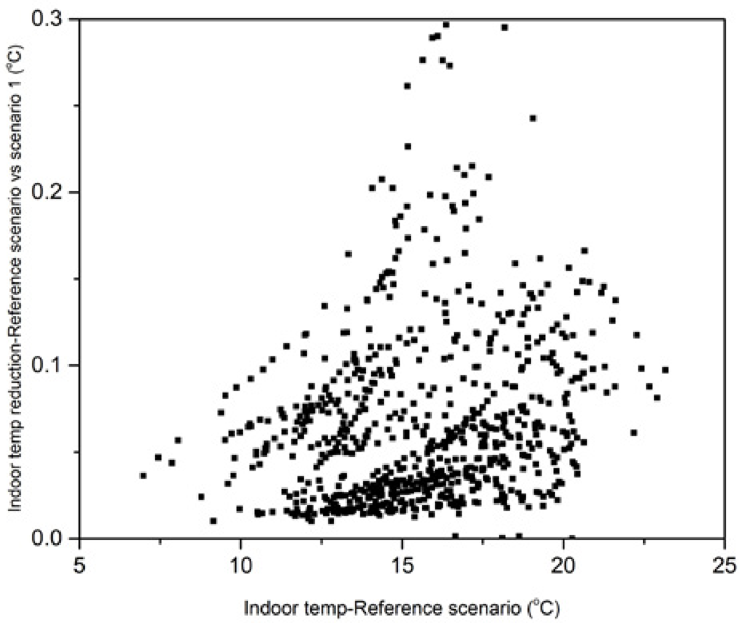

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 707 hours in reference scenario to 712 hours; and from 642 to 647 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 313 hours in reference scenario to 316 hours; and from 257 to 262 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	313	707	316	712
Roseworthy	257	642	262	647

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 285 hours in reference scenario to 275 and 200 hours under scenario 1 and 2, in Kuitpo station; and from 371 hours in reference scenario to 358 and 316hours under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	285	275	200
Roseworthy	371	358	316

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a clearly higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 12 is a new, mid-rise apartment building, with a total air-conditioned area of 3,300 m² distributed on three levels. The 1,100 m² roof is insulated, resulting in only modest energy savings. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 12.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	74.4	89.2
Energy consumption after cool roof (MWh)	74.6	87.9
Energy savings (MWh)	-0.20	1.3
Energy savings (%)	-0.27%	1.46%
Area (m²)	1,100	1,100
Roof costs - Metal roof (AU$/m²)	38.0	38.0
Roof costs - Coating (AU$/m²)	22.75	22.75
Life expectancy - Metal roof (years)	28.5	28.5
Life expectancy - Coating (years)	22.5	22.5
HVACs COP	2.5	2.5
Existing roof's renovation costs (AU$/m²)	15.0	15.0

The cool roof refurbishment options

Building 12 is a good example of a new, mid-rise educational building, where the energy conservation potential is modest. The coating cool roof is a clearly feasible option leading to significant reductions of life cycle costs.

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in a marginal energy requirements' increase of 0,27% for the Kuitpo and a decrease of 1,46% for the Roseworthy weather conditions. The value for Kuitpo however is in absolute terms within the margin of simulation error and it therefore interesting to still examine the feasibility.The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 18,6% for the low energy price scenario for Kuitpo and 22,7% for the high energy scenario and for Roseworthy conditions.

The metal cool roof is, due to its higher initial investment cost and the modest energy savings, feasible only for the high energy prices scenario for Roseworthy weather conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

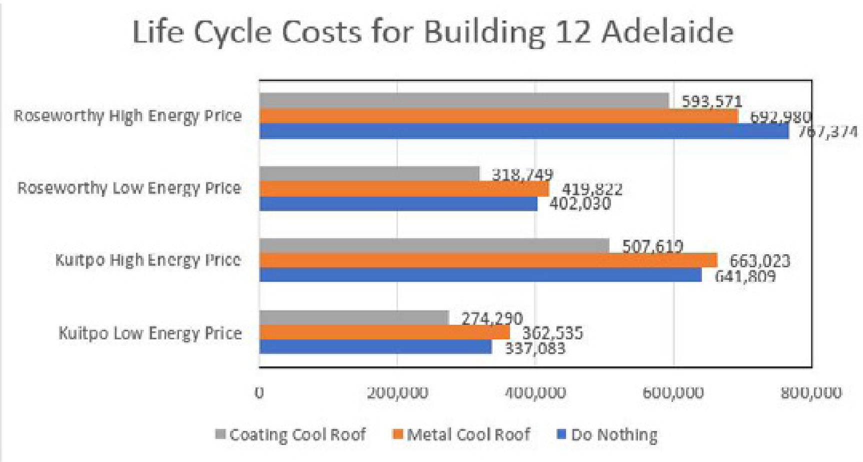

Figure 12. Life Cycle Costs for Building 12 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	**Observatory**		**Richmond**	
	Low Energy Price	**High Energy Price**	**Low Energy Price**	**High Energy Price**
Metal Cool Roof	-7.55 %	-3.31 %	-4.43 %	9.69 %
Coating Cool Roof	18.63 %	20.91 %	20.72 %	22.65 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the typical existing school during the summer season. Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing school from 17.0-26.5 kWh/m2 to 16.2-25.6 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.7-0.9 kWh/m^2. This is equivalent to approximately 3.4-4.2 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 4.4-5.2 kWh/m^2. This is equivalent to 17.1-29.1 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.3-0.8 kWh/m^2) is significantly lower than the annual cooling load reduction (0.8-1.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.3-4.3 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8-1.1 kWh/m^2 (~0.0-1.8 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 20.3-38.7 °C and 20.5-42.6 °C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.6 and 0.6 °C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.6 and 1.6 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 18.9-18.3 °C in reference scenario to a range between 8.8-18.3 °C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 8.1-20.4 °C in reference scenario to a range between 8.0-20.4 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 707 hours in reference scenario to 712 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight increase in total number of hours below 19 °C from 642 hours in reference scenario to 647 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday-Friday, 7am-6 pm) is expected to slightly increase from 313 hours in reference scenario to 316 hours in scenario 1 in Kuitpo station. Similarly, the calculation in Roseworthy station shows a slight increase of number of hours below 19 °C from 257 hours to 262 hours during the operational hours (Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 285 hours under the reference scenario in Kuitpo station, which slightly decreases to 275 and 200 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also illustrate a significant reduction in number of hours above 26 °C from 371 hours in reference scenario to 358 in reference with cool roof scenario (scenario 1) and 316 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a clearly higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 18,6% for the low energy price scenario for Kuitpo and 22,7% for the high energy scenario and for Roseworthy conditions, as it can be seen in Table 2. The metal cool roof is, due to its higher initial investment cost and the modest energy savings, feasible only for the high energy prices scenario for Roseworthy weather conditions. Building 12 is in that sense a good example of a new, mid-rise educational building, where the energy conservation potential is modest. The coating cool roof is a clearly feasible option leading to significant reductions of life cycle costs.

B12

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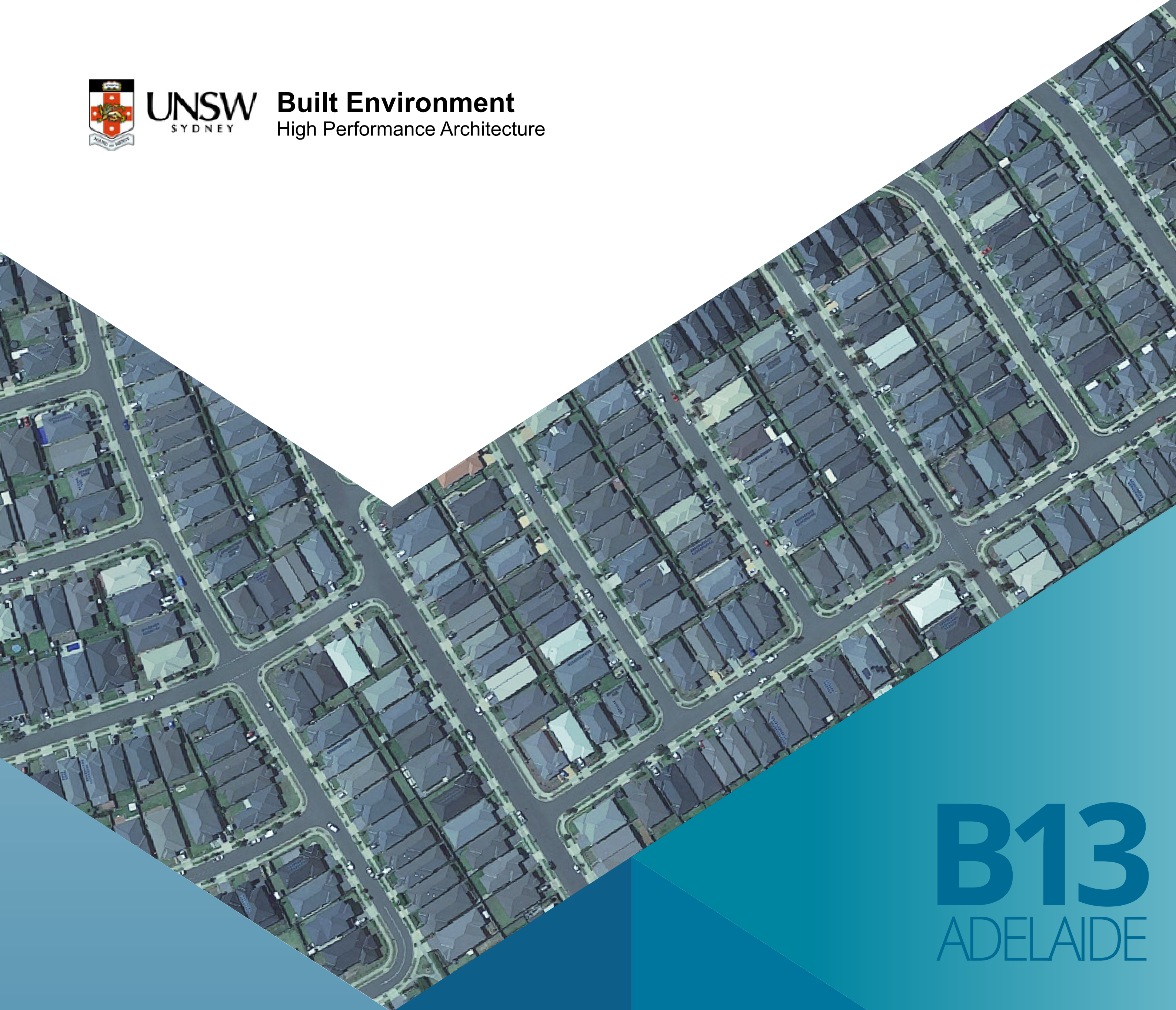

B13
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

Existing low-rise office building with roof insulation
2021

BUILDING 13

EXISTING LOW-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : $1200m^2$
Number of stories : 2

Image source: Ecipark Office Building. https://jhmrad.com/21-delightful-two-story-building/ecipark-office-building-two-story/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for an existing low-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise office building with roof insulation from 16.0-23.0 kWh/m² to 11.5-17.5 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)
Adelaide Airport	18.2	19.4	13.1	14.2	11.1	11.5
Edinburgh	19.9	21.2	14.7	15.8	12.4	12.8
Kuitpo	14.8	16.0	10.4	11.5	8.0	8.3
Parafield	19.5	20.7	14.2	15.3	12.4	12.9
Roseworthy	22.0	23.0	16.5	17.5	14.7	15.0

Table 2. Sensible and total cooling load saving for an existing low-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 4.5-5.5 kWh/m² which is equivalent to 24.1-28.3 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.7-8.3 kWh/m² which is equivalent to 34.6-48.0 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Adelaide Airport	5.1	28.0	5.2	26.9	7.1	39.0	7.9	40.8
Edinburgh	5.2	26.3	5.4	25.3	7.5	37.7	8.3	39.4
Kuitpo	4.4	29.7	4.5	28.3	6.8	45.9	7.7	48.0
Parafield	5.2	26.9	5.4	25.9	7.0	36.2	7.8	37.6
Roseworthy	5.4	24.8	5.5	24.1	7.3	33.3	8.0	34.6

In the eleven weather stations in Adelaide, both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the existing low-rise office building with roof insulation during the summer season.

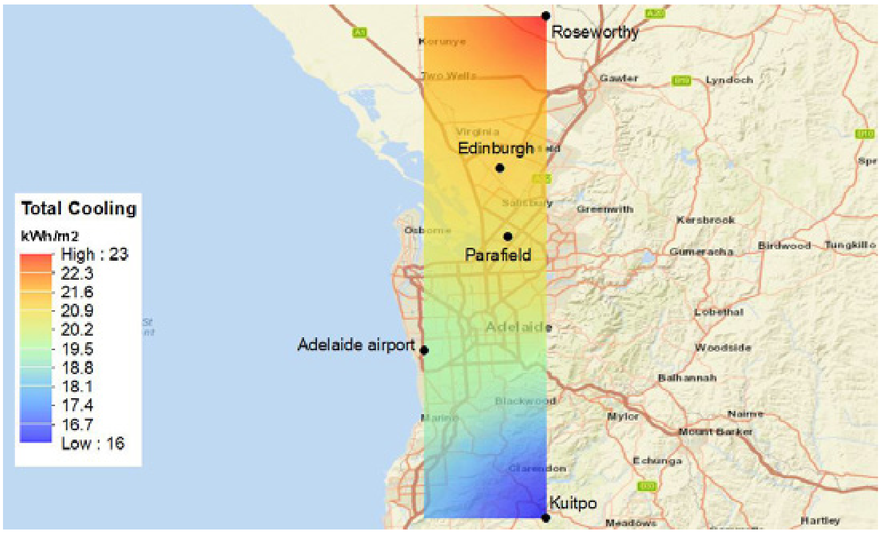

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

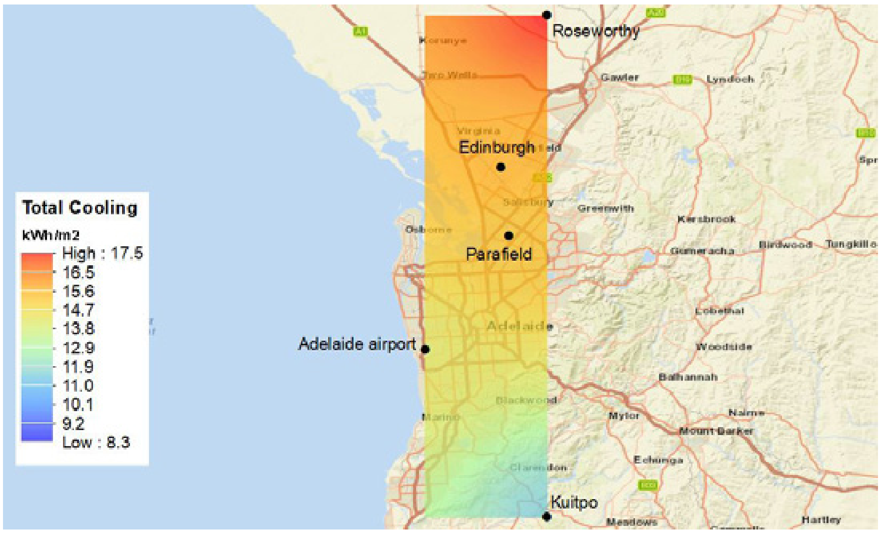

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

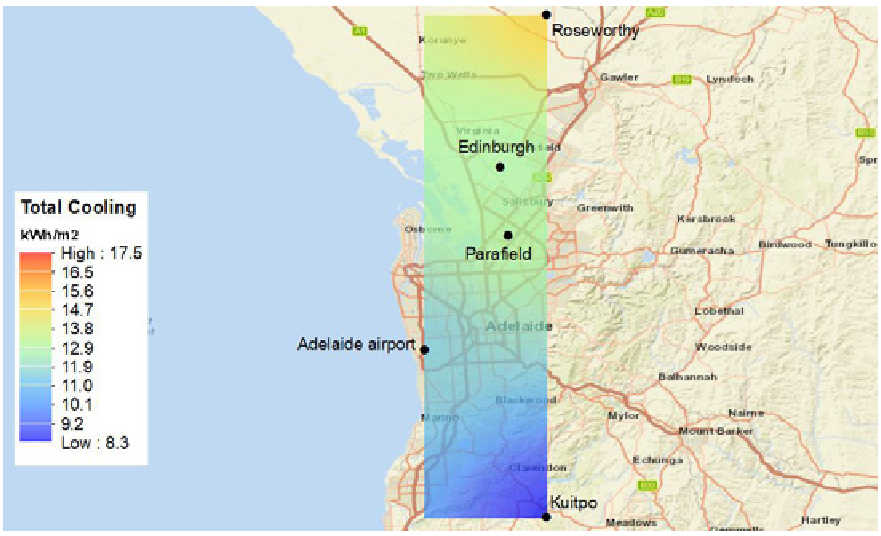

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing low-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.6-1.6 kWh/m²) is significantly lower than the annual cooling load reduction (4.9-9.0 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	22.7	24.8	1.8	4.0	17.1	19.0	2.1	4.6
Edinburgh	31.6	33.4	2.5	5.4	23.9	25.5	2.9	6.2
Kuitpo	16.6	17.3	3.4	7.8	11.8	12.4	4.1	9.4
Parafield	34.9	37.3	2.3	4.9	26.2	28.3	2.7	5.7
Roseworthy	33.7	35.2	3.1	6.5	25.8	27.1	3.5	7.4

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 23.1-28.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.3-8.3 kWh/m² (~13.2-19.5 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	5.6	24.7	5.8	23.4	0.3	0.6	5.3	21.6	5.2	18.1
Edinburgh	7.7	24.4	7.9	23.8	0.4	0.8	7.3	21.5	7.1	18.4
Kuitpo	4.8	29.1	4.9	28.5	0.7	1.6	4.1	20.6	3.3	13.2
Parafield	8.7	24.8	9.0	24.1	0.4	0.7	8.3	22.3	8.3	19.5
Roseworthy	7.9	23.5	8.1	23.1	0.5	0.9	7.5	20.3	7.3	17.4

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

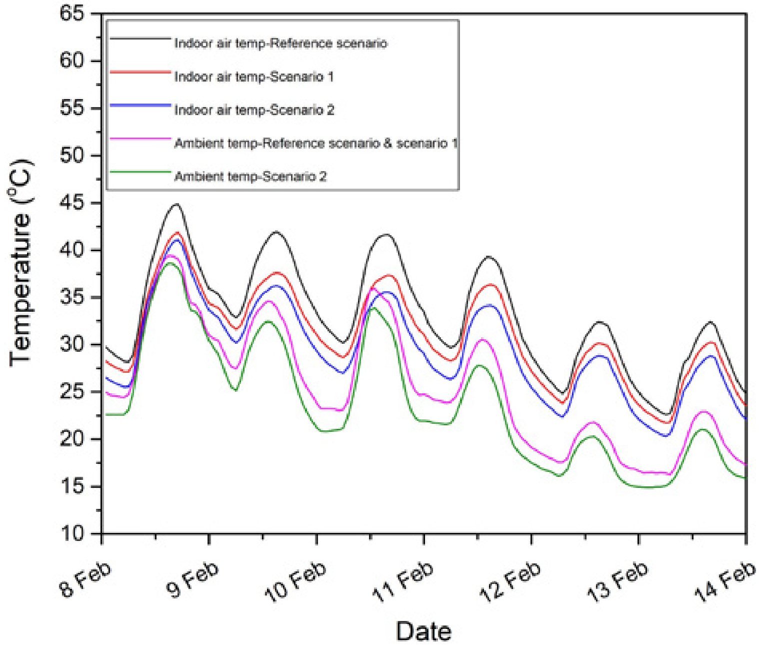

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

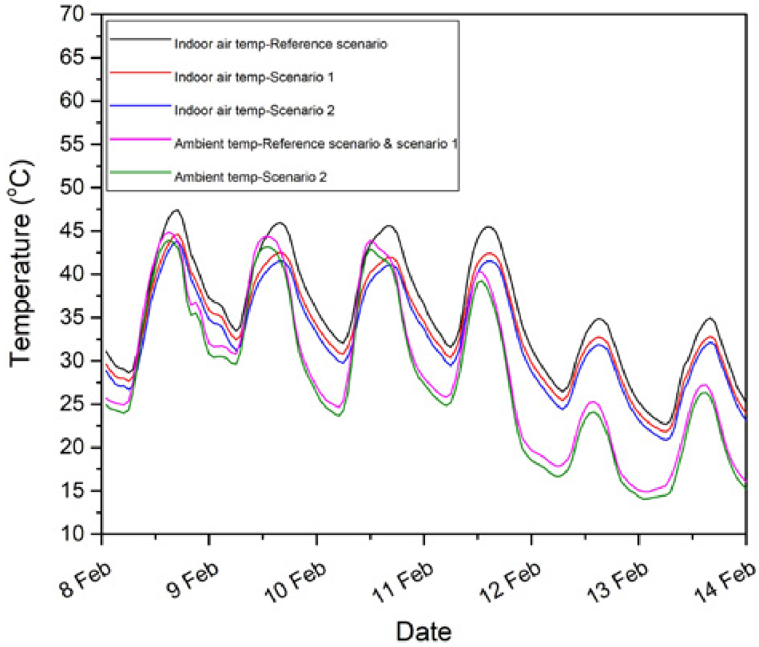

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.4-44.9 °C and 21.7-47.4 °C in Kuitpo and Roseworthy stations, respectively.

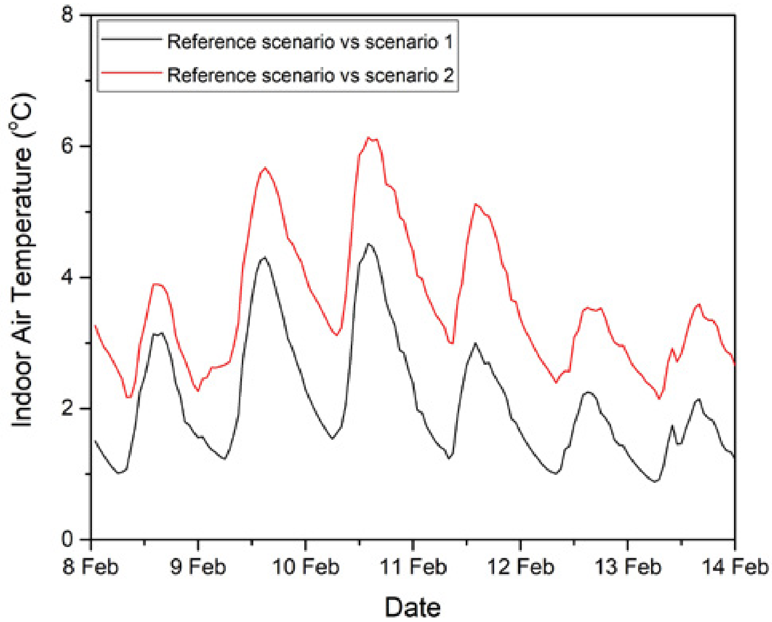

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 4.5 °C and 3.9 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 6.1 and 4.8 °C in Kuitpo and Roseworthy stations, respectively.

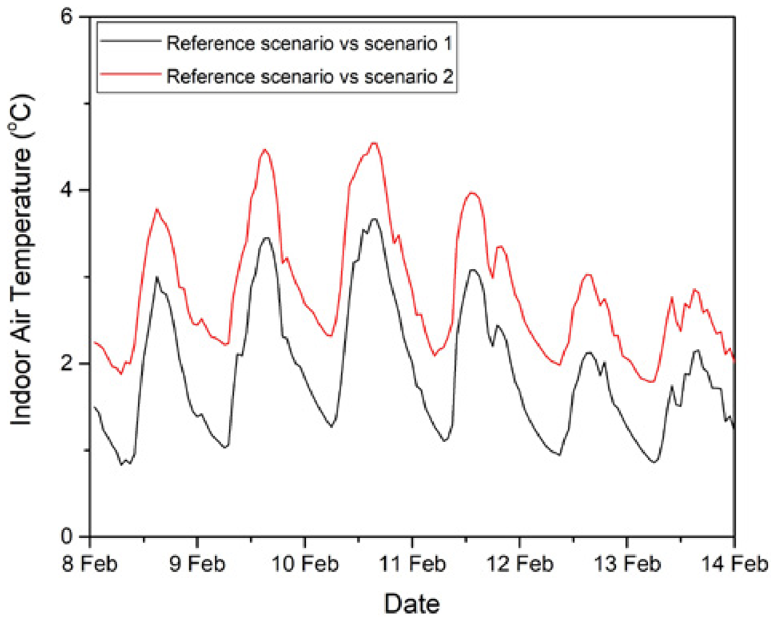

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 10.9-22.2 °C in reference scenario to a range between 10.5-20.9 °C in scenario 1 in Kuitpo station.

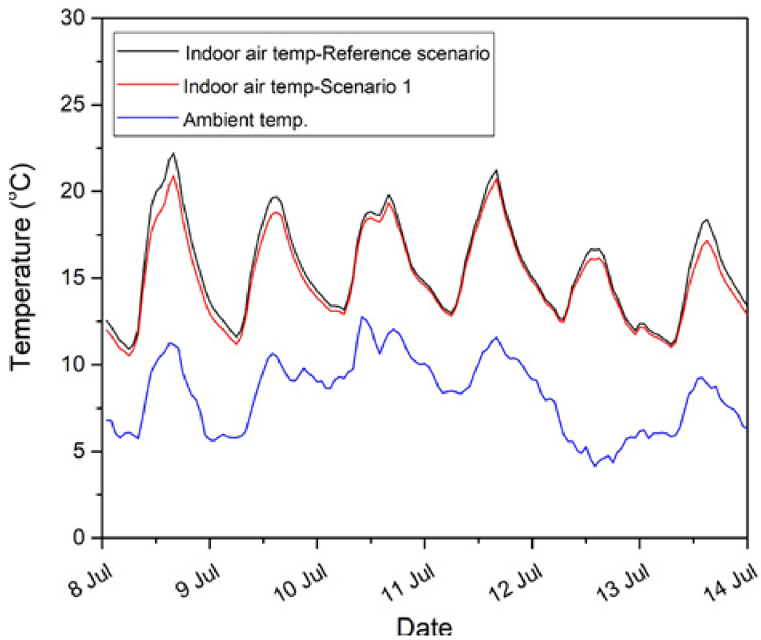

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range between 10.6-23.7 °C in reference scenario to a range between 10.1-23.0 °C in scenario 1 in Roseworthy station.

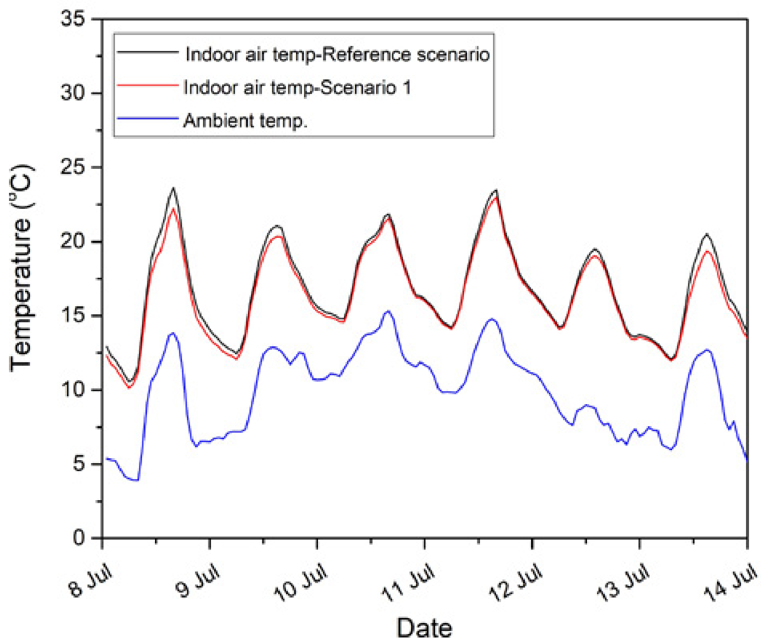

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.9 °C and 1.7 °C in Kuitpo and Roseworthy stations, respectively.

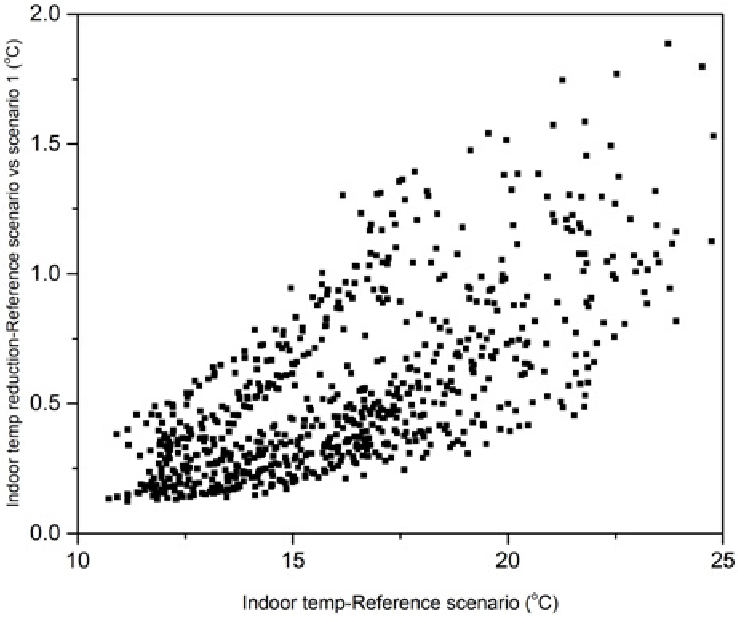

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

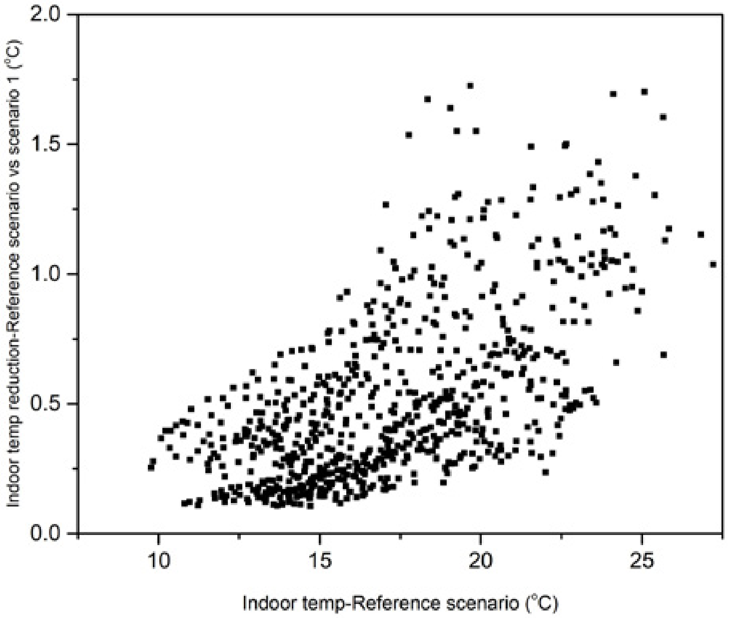

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 595 hours in reference scenario to 636 hours and from 516 to 560 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 239 hours in reference scenario to 274 hours; and from 176 to 210 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	239	595	274	636
Roseworthy	176	516	210	560

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 459 hours in reference scenario to 373 and 308 hours under scenario 1 and 2, in Kuitpo station; and from 493 hours in reference scenario to 428 and 385 hours under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	459	373	308
Roseworthy	493	428	385

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

The building and its energy performance

Building 13 is an existing, low-rise building, with a total air-conditioned area of 2.400 m^2 distributed on two levels. The 1.200 m^2 roof is insulated, but since it has a direct impact on half the air-conditioned area, it eventually results in significant energy losses and, consequently, in a respectively significant energy saving potential. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Building 13 is in that sense a good example of an existing, low-rise office building, with a significant energy conservation potential, where the coating cool roof techniques lead to significant reductions of life cycle cost, whilst the metal cool roof is only feasible for the more favourable Roseworthy conditions.

Table 7. Energy performance features of Building 13.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	24.1	40.0
Energy consumption after cool roof (MWh)	20.90	33.1
Energy savings (MWh)	3.2	6.9
Energy savings (%)	13.28%	17.25%
Area (m^2)	1,200	1,200
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in energy savings of 13,28% for the Kuitpo weather conditions and of 17,25% for the Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The 'Do Nothing' approach has clearly the higher costs over the building's life cycle, compared to the coating cool roof for both locations and both energy prices scenario, achieving reductions of to 49,4%.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is only feasible for Roseworthy conditions; marginally for the low energy price scenario and clearly for the high one.

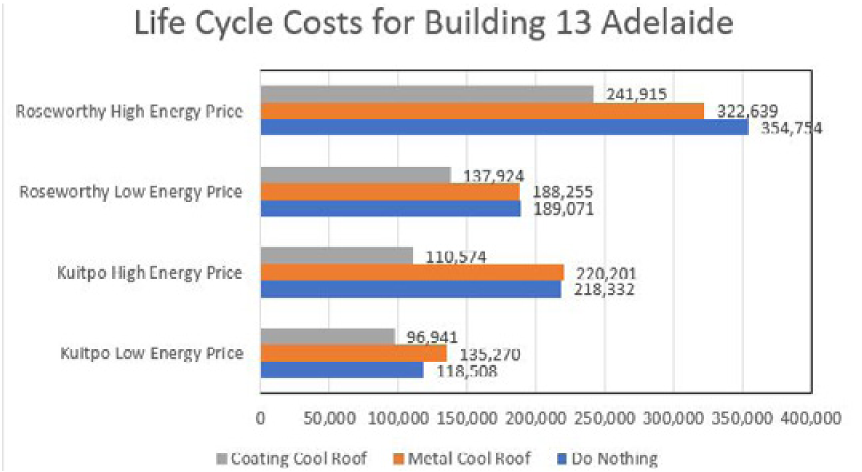

Figure 12. Life Cycle Costs for Building 13 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-14.14 %	-0.86 %	0.43 %	9.05 %
Coating Cool Roof	18.20 %	49.36 %	27.05 %	31.81 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale ap-plication of cool roof can significantly reduce the cooling load of the existing low-rise office building with roof insulation during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise office building with roof insulation from 16.0-23.0 kWh/m^2 to 11.5-17.5 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 4.5-5.5 kWh/m^2. This is equivalent to approximately 24.1-28.3 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.7-8.3 kWh/m^2. This is equivalent to 34.6-48.0 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the ref-erence scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illus-trate that the annual heating penalty (0.6-1.6 kWh/m^2) is significantly lower than the annual cooling load reduction (4.9-9.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 23.1-28.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.3-8.3 kWh/m^2 (~13.2-19.5 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 22.4-44.9 ^{o}C and 21.7-47.4 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 4.5 and 3.9 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 6.1 and 4.8 ^{o}C by com-bined building-scale and urban-scale application of cool roofs (scenario 2) in Observato-ry and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 10.9-22.2 ^{o}C in reference scenario to a range between 10.5-20.9 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 10.6-23.7 °C in reference scenario to a range between 10.1-23.0 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.9 °C and 1.7 °C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when in-door temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase from 595 hours in reference scenario to 636 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight in-crease in total number of hours below 19 °C from 516 hours in reference scenario to 560 hours in reference with cool roof scenario (scenario 1). The results show less in-crease in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 239 hours in reference scenario to 274 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. Similarly, the calculation in Roseworthy station shows a slight increase of number of hours below 19 °C from 176 hours to 210 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 459 hours under the reference scenario in Observa-tory station, which significantly decreases to 373 and 308 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also illustrate a significant reduc-tion in number of hours above 26 °C from 493 hours in reference scenario to 428 in ref-erence with cool roof scenario (scenario 1) and 385 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the fact that it is a low-rise building with roof insulation, the ‘Do Nothing’ approach has clearly the higher costs over the building’s life cycle, compared to the coating cool roof for both locations and both energy prices scenario, achieving reductions of to 49,4%. The metal cool roof is only feasible for Roseworthy conditions; marginally for the low energy price scenario and clearly for the high one, as it can be seen in Table 8. Building 13 is in that sense a good example of an existing, low-rise office building, with a significant energy conservation potential, where the coating cool roof techniques lead to significant reductions of life cycle cost, whilst the metal cool roof is only feasible for the more favourable Roseworthy conditions.

B13

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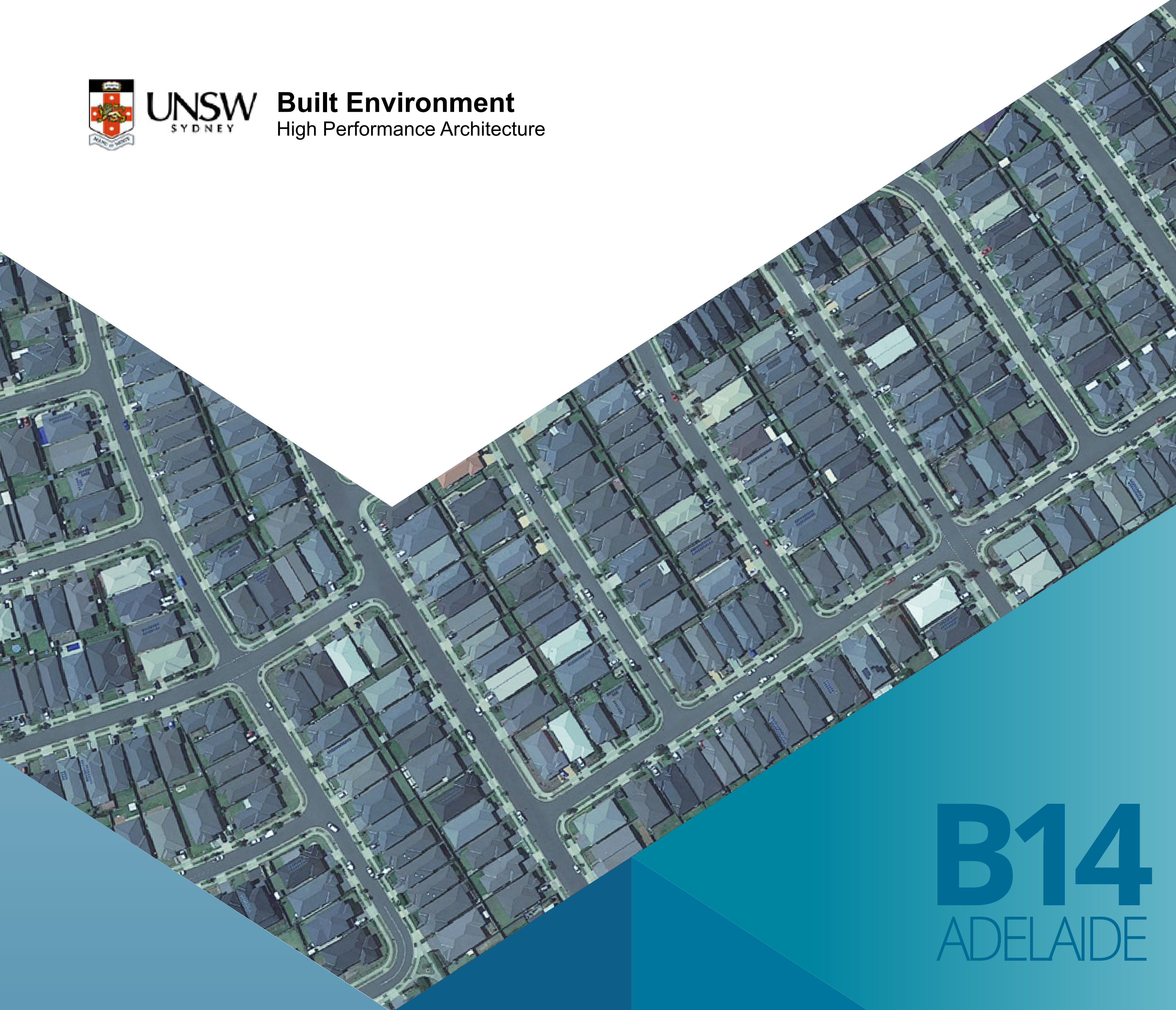

B14
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

Existing high-rise office building with roof insulation
2021

BUILDING 14

EXISTING HIGH-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : 1200m^2
Number of stories : 10

Image source: Ecipark Office Building. https://jerseydigs.com/bayonne-city-council-approves-10-story-building-975-broadway/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building with roof insulation from 12.7-19.0 kWh/m² to 11.9-18.0 kWh/m².

Table 1. Sensible and total cooling load for an existing high-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	14.5	15.7	13.6	14.8	11.5	11.9
Edinburgh	16.2	17.3	15.2	16.4	12.8	13.3
Kuitpo	11.6	12.7	10.8	11.9	8.2	8.5
Parafield	15.7	16.9	14.8	15.9	12.9	13.4
Roseworthy	18.0	19.0	17.0	18.0	15.1	15.5

For Scenario 1, the total cooling load saving is around 0.8-1.0 kWh/m² which is equivalent to 5.3-6.3 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.5-4.2 kWh/m² which is equivalent to 18.5-33.2 % of total cooling load reduction.

Table 2. Sensible and total cooling load saving for an existing high-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	0.9	6.2	0.9	6.0	3.0	20.7	3.7	23.9
Edinburgh	0.9	5.8	1.0	5.5	3.3	20.7	4.1	23.4
Kuitpo	0.8	6.8	0.8	6.3	3.4	29.5	4.2	33.2
Parafield	0.9	5.9	1.0	5.7	2.9	18.2	3.5	20.7
Roseworthy	1.0	5.4	1.0	5.3	3.0	16.4	3.5	18.5

In the eleven weather stations in Sydney, the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the existing high-rise office building with roof insulation during the summer season.

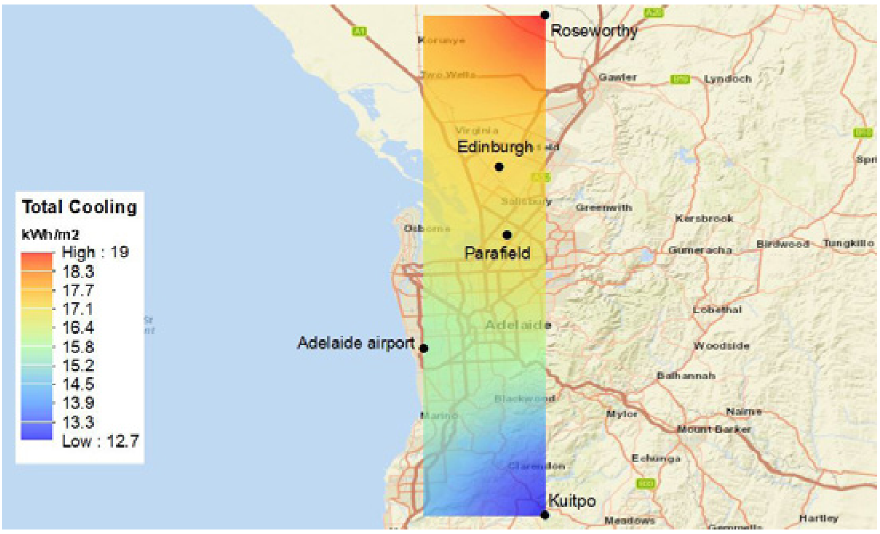

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

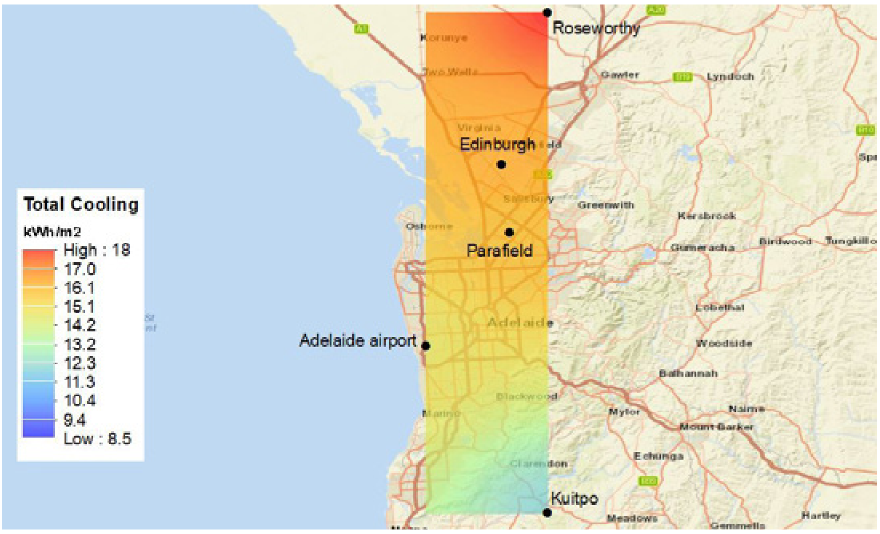

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

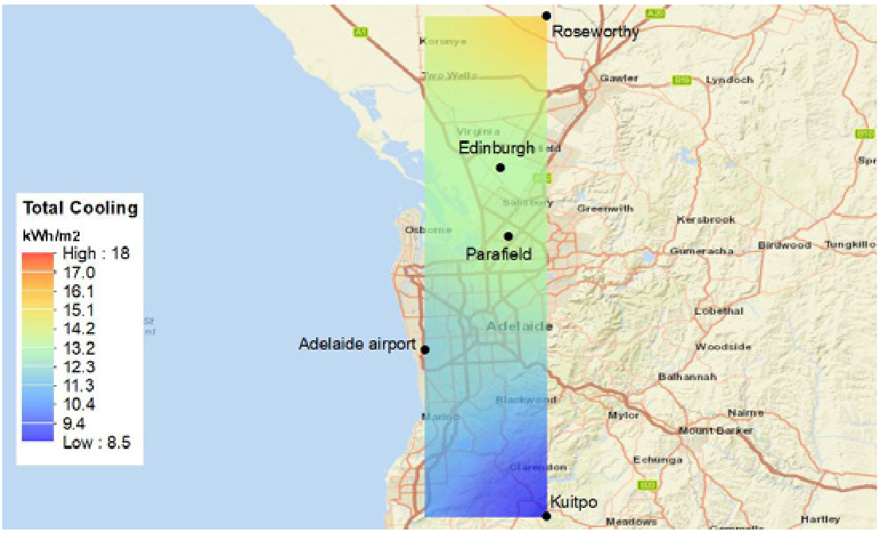

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing high-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1-0.3 kWh/m²) is lower than the annual cooling load reduction (0.8-1.5 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	18.6	20.5	0.9	2.2	17.7	19.5	0.9	2.3
Edinburgh	25.7	27.3	1.3	3.4	24.4	25.9	1.4	3.6
Kuitpo	12.6	13.2	2.0	5.5	11.8	12.4	2.2	5.8
Parafield	28.2	30.4	1.2	3.1	26.7	28.8	1.3	3.2
Roseworthy	27.3	28.6	1.8	4.5	25.9	27.2	1.9	4.6

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 4.8-6.3 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.5-1.4 kWh/m² (~2.9-4.2 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	0.9	5.0	1.0	4.8	0.0	0.1	0.9	4.6	0.9	3.9
Edinburgh	1.3	5.1	1.3	4.9	0.1	0.1	1.2	4.6	1.2	3.9
Kuitpo	0.8	6.4	0.8	6.3	0.1	0.3	0.7	4.6	0.5	2.9
Parafield	1.5	5.2	1.5	5.0	0.1	0.1	1.4	4.7	1.4	4.2
Roseworthy	1.3	4.9	1.4	4.8	0.1	0.2	1.3	4.3	1.2	3.7

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

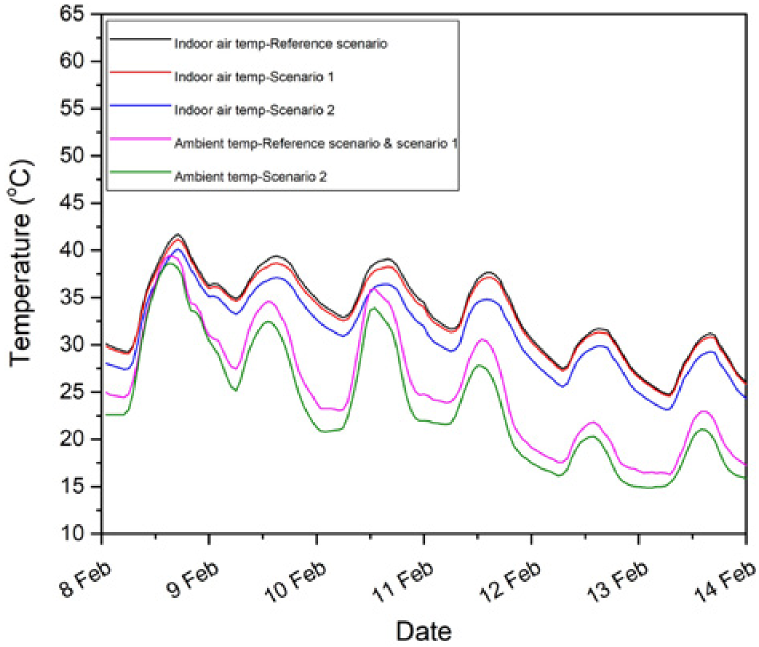

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

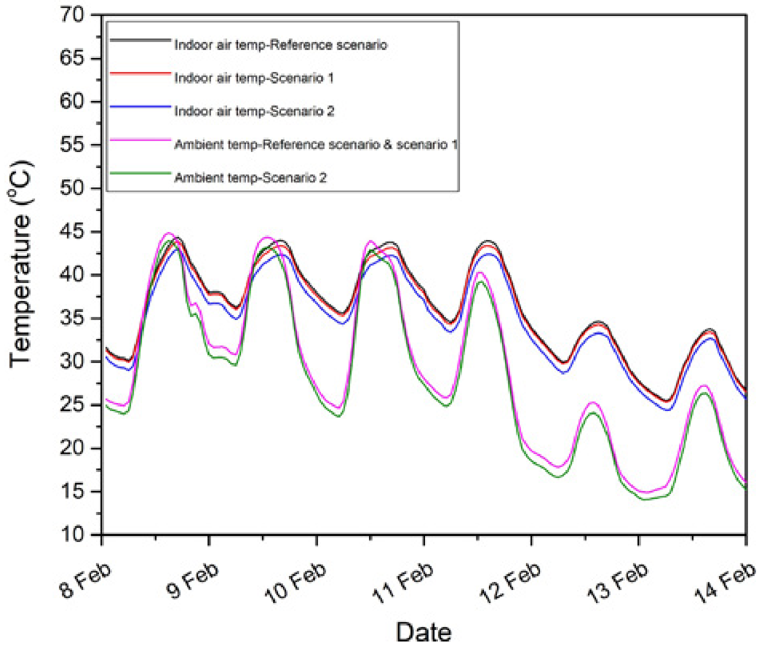

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 24.3-41.7 °C and 24.0-44.4 °C in Kuitpo and Roseworthy stations, respectively.

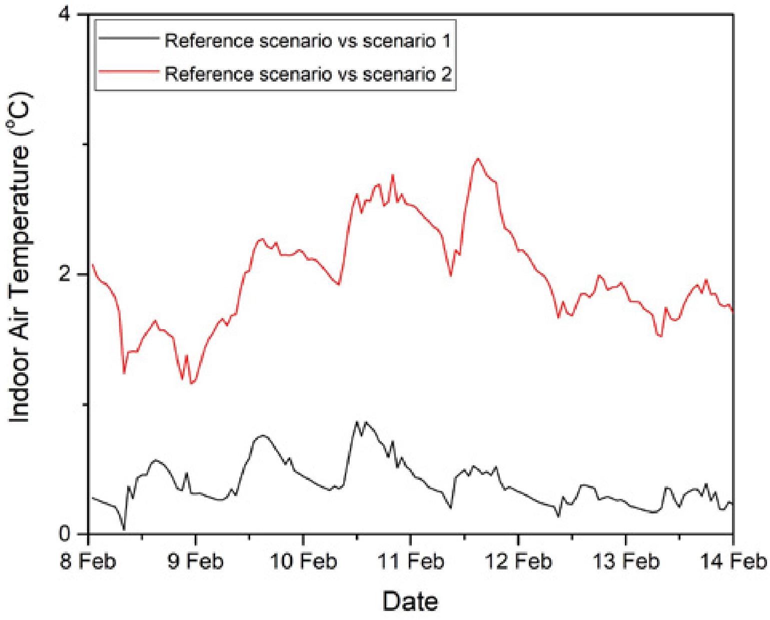

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.9 °C and 0.8 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.9 and 1.7 °C in Kuitpo and Roseworthy stations, respectively.

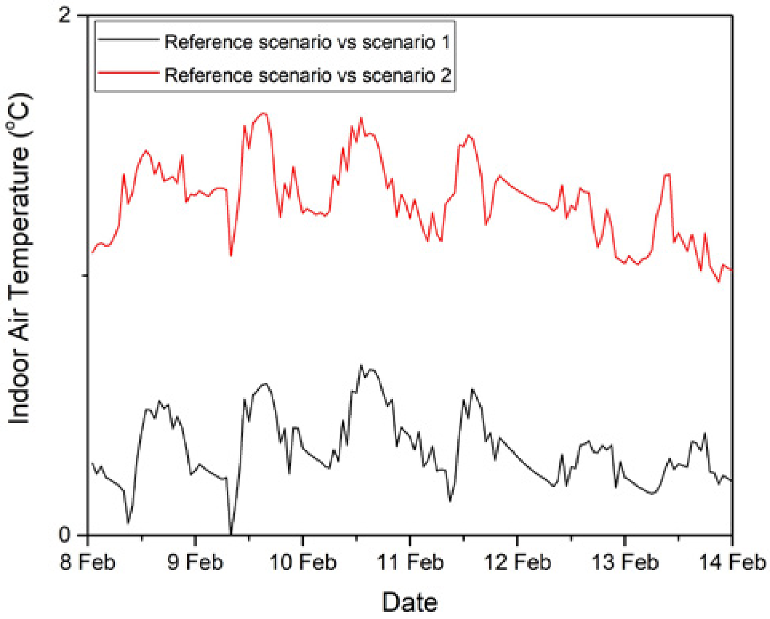

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 13.0 and 21.5 °C in reference scenario to a range between 12.9 and 21.3 °C in scenario 1 in Kuitpo station.

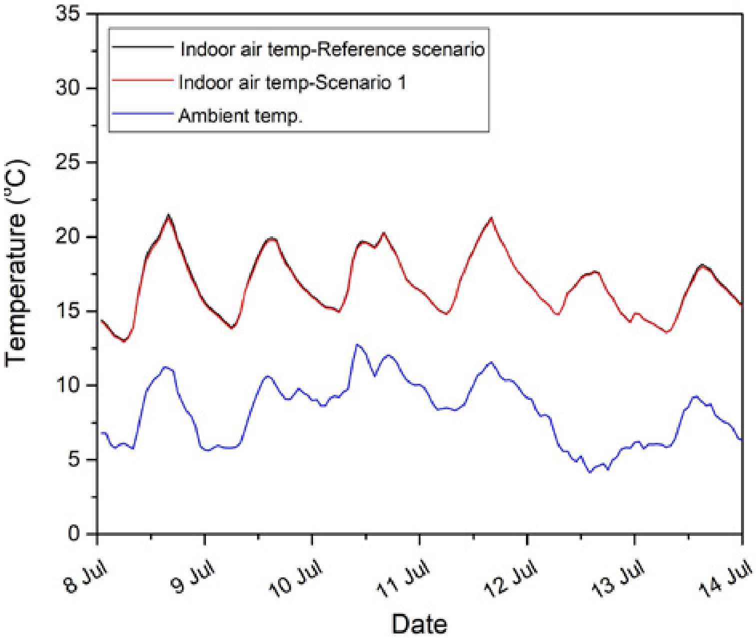

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range between 12.8 and 23.5 °C in reference scenario to a range between 12.7 and 23.4 °C in scenario 1 in Roseworthy station.

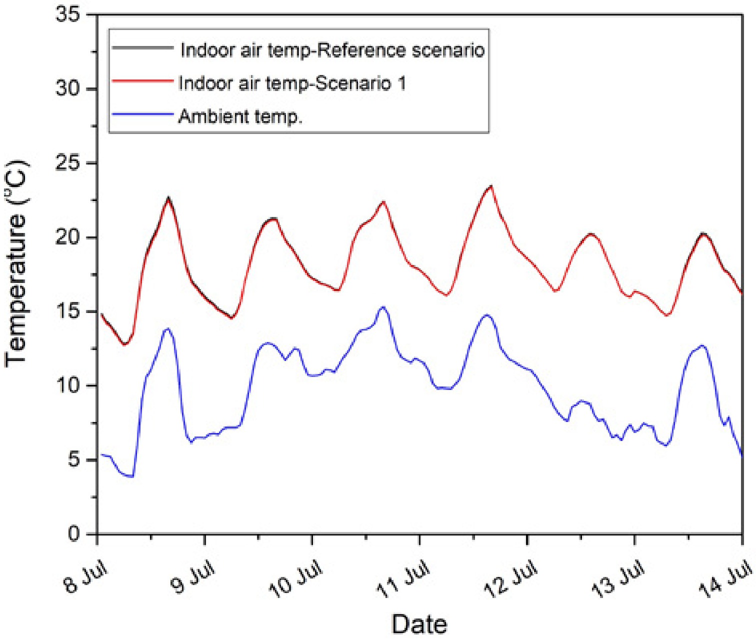

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C in Kuitpo and Roseworthy stations.

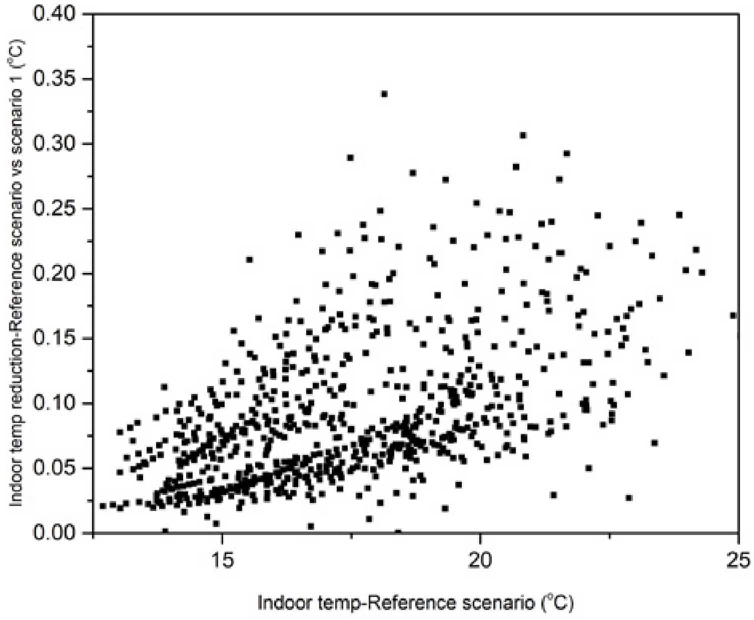

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

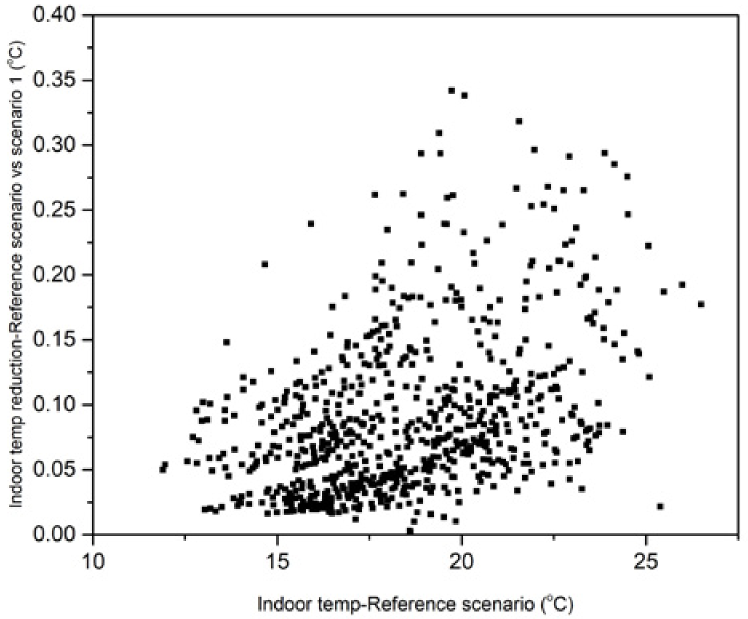

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 531 hours in reference scenario to 540 and hours and from 435 to 442 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 212 hours in reference scenario to 216 hours; and from 143 to 146 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	212	531	216	540
Roseworthy	143	435	146	442

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 518 hours in reference scenario to 501 and 412 hours under scenario 1 and 2, in Kuitpo station; and from 552 hours in reference scenario to 541 and 495 hours under scenario 1 and 2 in Roseworthy station, respectively.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	518	501	412
Roseworthy	552	541	495

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the fact that it is a high-rise office building with roof insulation, the 'Do Nothing' approach has clearly the higher cost over the building's life cycle, compared to the coating cool roof options.

The building and its energy performance

Building 14 is an existing, high-rise office building, with a total air-conditioned area of 12.000 m² distributed on ten levels. The 1.200 m² roof is insulated and, since it has a direct impact only on the last floor, it eventually results in limited energy losses and, consequently, in a respectively modest energy saving potential. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 14.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	89.8	158.9
Energy consumption after cool roof (MWh)	87.4	152.6
Energy savings (MWh)	2.4	6.3
Energy savings (%)	2.67%	3.96%
Area (m²)	1,200	1,200
Roof costs - Metal roof (AU$/m²)	38.0	38.0
Roof costs - Coating (AU$/m²)	22.75	22.75
Life expectancy - Metal roof (years)	28.5	28.5
Life expectancy - Coating (years)	22.5	22.5
HVACs COP	2.5	2.5
Existing roof's renovation costs (AU$/m²)	15.0	15.0

Building 14 is a good example of an existing, insulated, high-rise office building, with a limited energy conservation potential, where the coating cool roof is clearly a feasible and appealing investment under all conditions.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

The metal cool roof is only feasible for Roseworthy conditions, but due to its high initial investment cost it is less appealing as an investment.

Both options have the same energy efficiency, resulting in modest energy savings of 2,67% for the Kuitpo weather conditions and of 3,96% for the Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 21,5% for the low energy price scenario and for Kuitpo and 25,6% for the high energy scenario and for Roseworthy conditions.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

The metal cool roof is only feasible for Roseworthy conditions and marginally so for Kuitpo conditions and the high energy prices scenario.

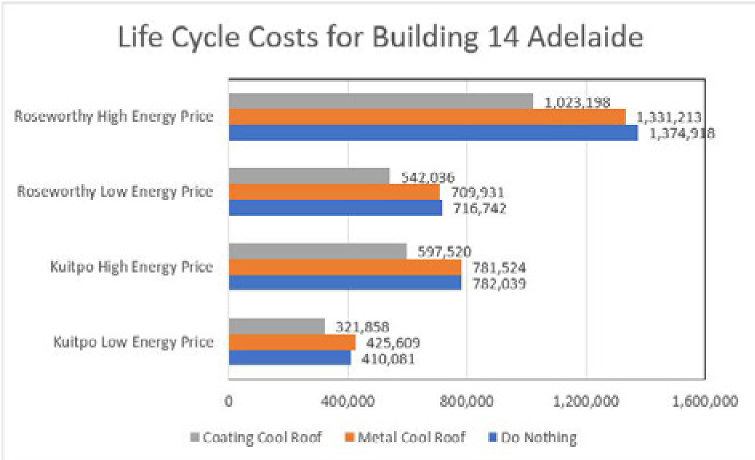

Figure 12. Life Cycle Costs for Building 14 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-3.79 %	0.07 %	0.95 %	3.18 %
Coating Cool Roof	21.51 %	23.59 %	24.38 %	25.58 %

7

CONCLUSIONS

• It is estimated that the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the existing high-rise office building with insulation during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building from 12.7-19.0 kWh/m^2 to 11.9-18.0 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.8-1.0 kWh/m^2. This is equivalent to approximately 5.3-6.3 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.5-4.2 kWh/m^2. This is equivalent to 18.5-33.2 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1-0.3 kWh/m^2) is significantly lower than the annual cooling load reduction (0.8-1.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.8-6.3 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.5-1.4 kWh/m^2 (~2.9-4.2 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 24.3-41.7 ^{o}C and 24.0-44.4 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.9 and 0.8 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.9 and 1.7 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 3.0 and 21.5 ^{o}C in reference scenario to a range between 12.9 and 21.3 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 12.8 and 23.5 °C in reference scenario to a range between 12.7 and 23.4 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C in Kuitpo and Roseworthy stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 531 hours in reference scenario to 540 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight increase in total number of hours below 19 °C from 435 hours in reference scenario to 442 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 212 hours in reference scenario to 216 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. Similarly, the calculation in Roseworthy station shows a slight increase of number of hours below 19 °C from 143 hours to 146 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 518 hours under the reference scenario in Observa-tory station, which significantly decreases to 501 and 412 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station also illustrate a significant reduc-tion in number of hours above 26 °C from 552 hours in reference scenario to 541 in ref-erence with cool roof scenario (scenario 1) and 495 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the fact that it is a high-rise office building with roof insulation, the 'Do Nothing' approach has clearly the higher cost over the building's life cycle, compared to the coating cool roof options, which leads to a reduction of life cycle costs, that varies between 21,5% for the low energy price scenario and for Kuitpo and 25,6% for the high energy scenario and for Roseworthy conditions. The metal cool roof is only feasible for Roseworthy conditions and marginally so for Kuitpo conditions and the high energy prices scenario. Building 14 is in that sense a good example of an existing, insulated, high-rise office building, with a limited energy conservation potential, where the coating cool roof is clearly a feasible and appealing investment under all conditions; the metal cool roof is only feasible for Roseworthy conditions, but due to its high initial investment cost it is less appealing as an investment.

B14

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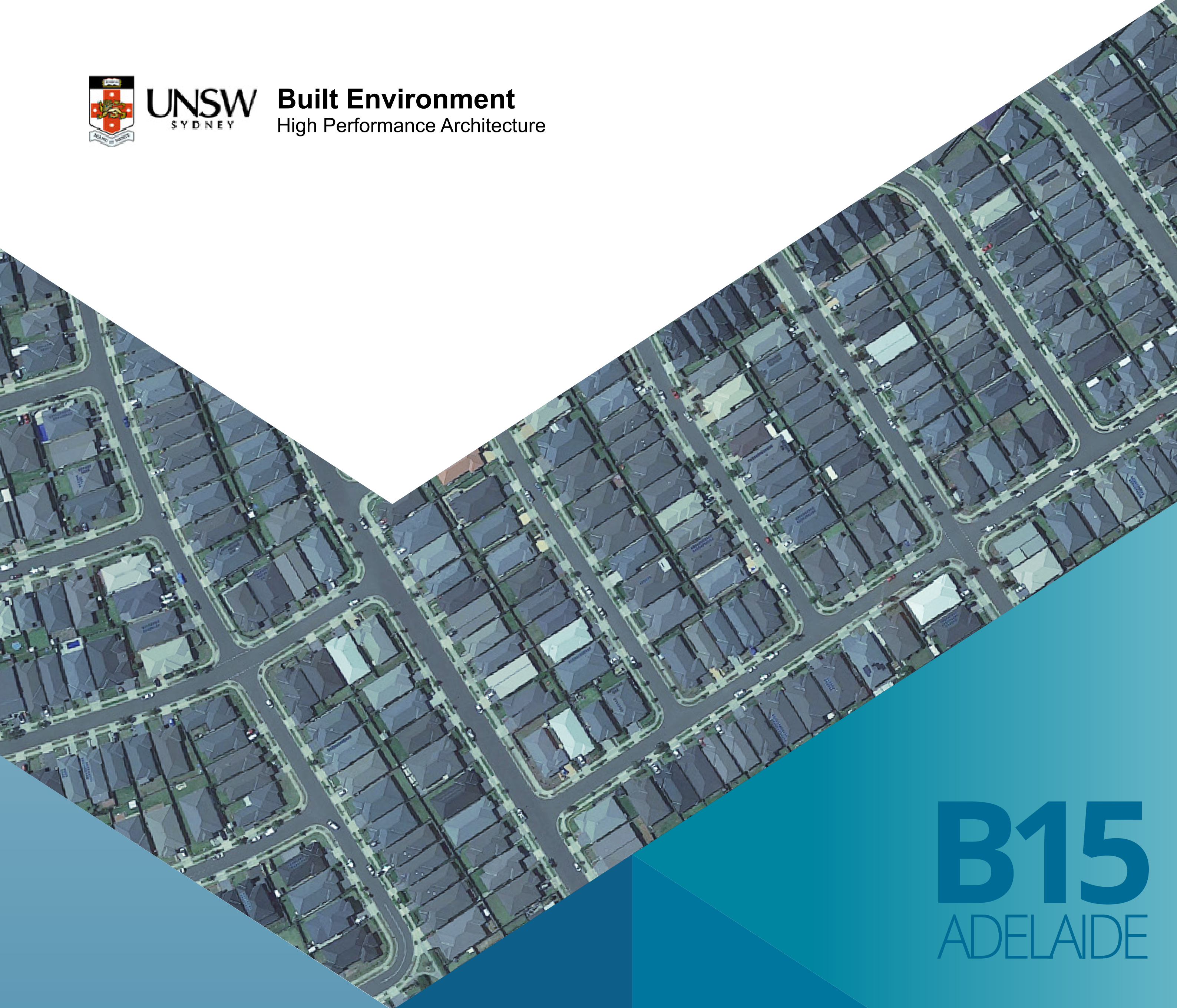

B15
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

Existing low-rise shopping mall centre
2021

BUILDING 15

EXISTING LOW-RISE SHOPPING MALL CENTRE

Floor area : 1100m^2
Number of stories : 2

Image source: Westfield Tea Tree Plaza, Tea Tree Plaza 976 North East Rd, Modbury, Tea Tree Gully, South Australia 5092, Australia

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise shopping mall centre from 60.3-70.5 kWh/m² to 52.3-62.5 kWh/m².

Table 1. Sensible and total cooling load for an existing low-rise shopping mall centre without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	60.8	65.2	52.7	57.0	49.0	50.6
Edinburgh	63.6	67.6	55.7	59.6	51.3	52.6
Kuitpo	54.9	60.3	47.0	52.3	42.3	44.1
Parafield	62.9	66.9	54.9	58.8	51.6	53.2
Roseworthy	67.6	70.5	59.7	62.5	56.0	57.1

For Scenario 1, the total cooling load saving is around 8.0-8.2 kWh/m² which is equivalent to 11.4-13.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 13.4-16.3 kWh/m² which is equivalent to 19.1-27.0 % total cooling load reduction.

Table 2. Sensible and total cooling load saving for an existing low-rise shopping mall centre without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	8.1	13.3	8.2	12.6	11.8	19.3	14.6	22.4
Edinburgh	7.9	12.4	8.0	11.8	12.3	19.3	15.0	22.2
Kuitpo	7.8	14.3	8.0	13.3	12.5	22.9	16.3	27.0
Parafield	8.0	12.7	8.1	12.2	11.3	17.9	13.7	20.5
Roseworthy	7.9	11.7	8.0	11.4	11.6	17.2	13.4	19.1

In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs can reduce the cooling load of the existing low-rise shopping mall centre with insulation during the summer season.

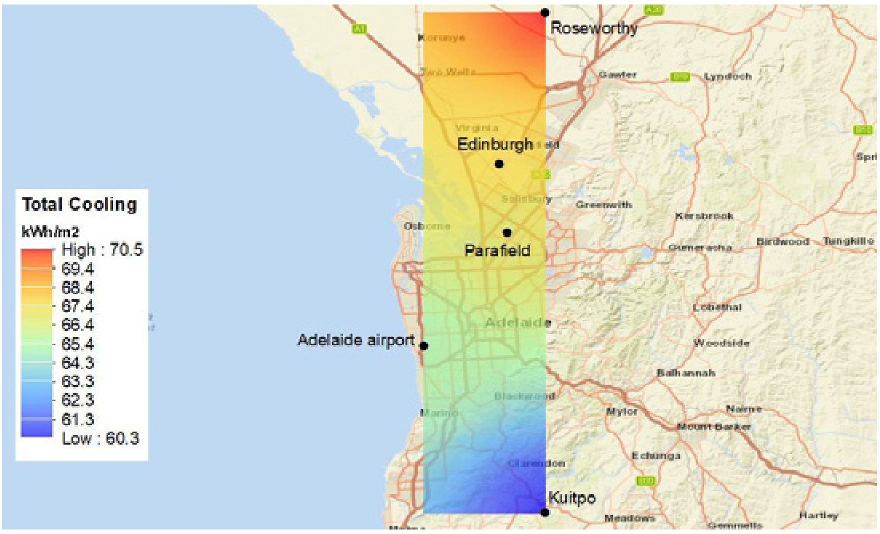

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

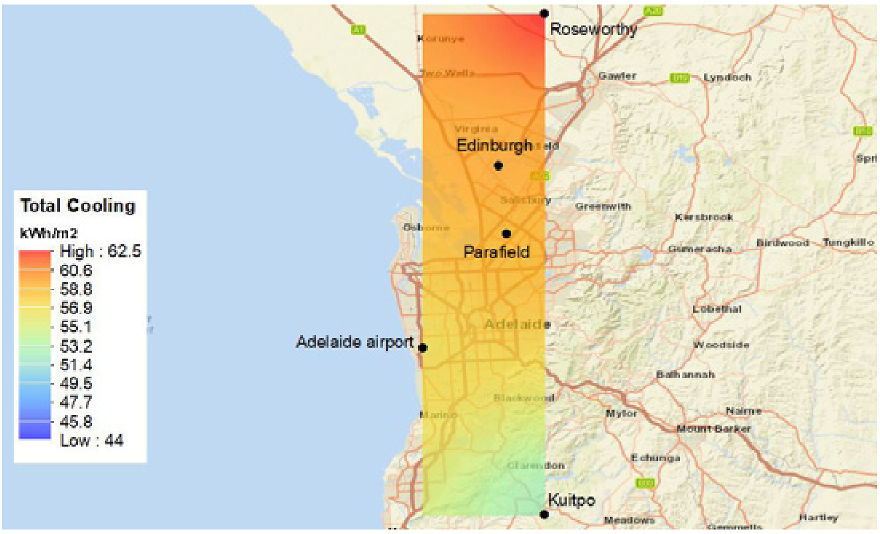

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

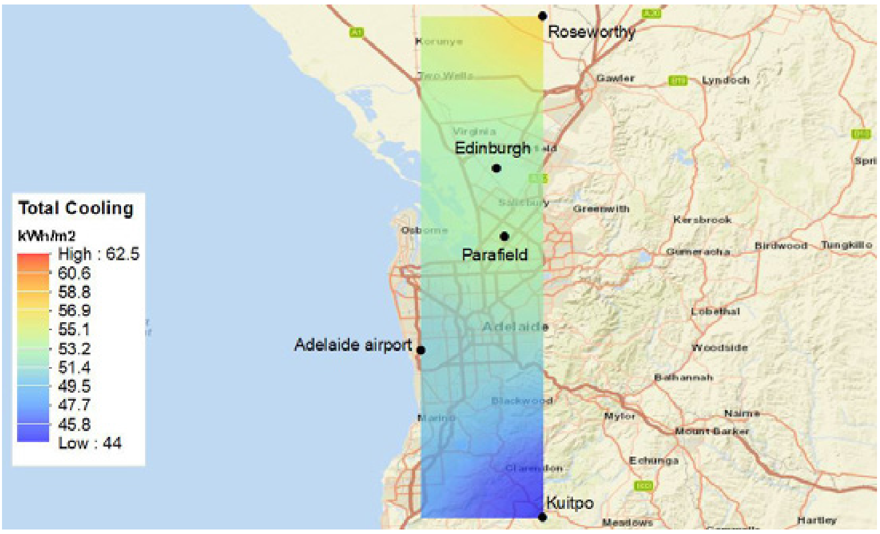

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

Table 3. Annual cooling and heating loads for an existing low-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.3-0.8 kWh/m²) is significantly lower than the annual cooling load reduction (18.2-22.0 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	137.6	151.3	1.5	4.3	118.3	131.7	1.6	4.6
Edinburgh	150.3	160.8	2.1	6.7	130.4	140.5	2.3	7.1
Kuitpo	98.1	107.7	2.7	9.4	80.3	89.4	2.9	10.2
Parafield	159.6	172.6	2.0	6.0	138.0	150.6	2.1	6.4
Roseworthy	150.4	159.5	2.9	8.7	131.0	139.8	3.0	9.2

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 12.3-16.9 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 17.4-21.6 kWh/m² (~11.4-14.9 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	19.3	14.0	19.7	13.0	0.1	0.3	19.2	13.8	19.4	12.5
Edinburgh	19.9	13.3	20.2	12.6	0.1	0.4	19.8	13.0	19.8	11.9
Kuitpo	17.8	18.1	18.2	16.9	0.2	0.8	17.6	17.5	17.4	14.9
Parafield	21.6	13.5	22.0	12.7	0.1	0.4	21.4	13.3	21.6	12.1
Roseworthy	19.4	12.9	19.7	12.3	0.2	0.5	19.2	12.5	19.2	11.4

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

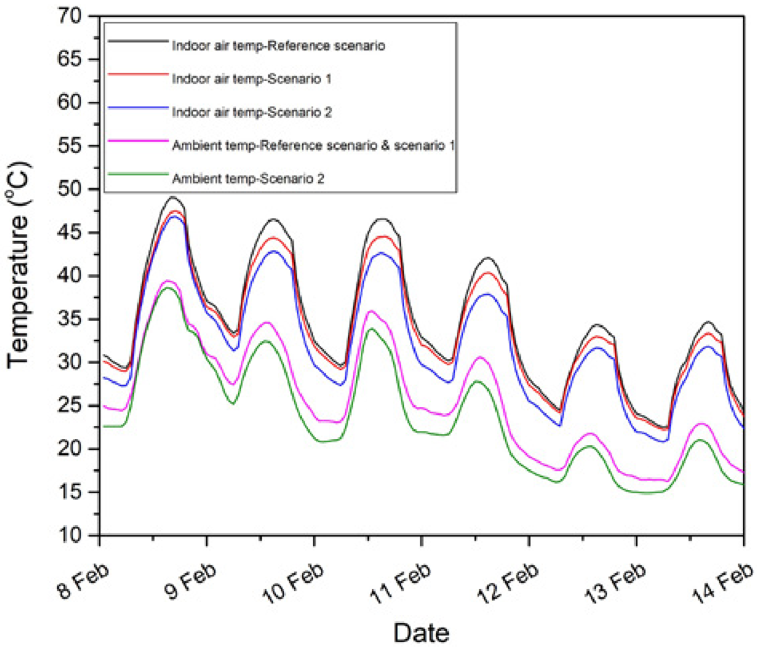

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

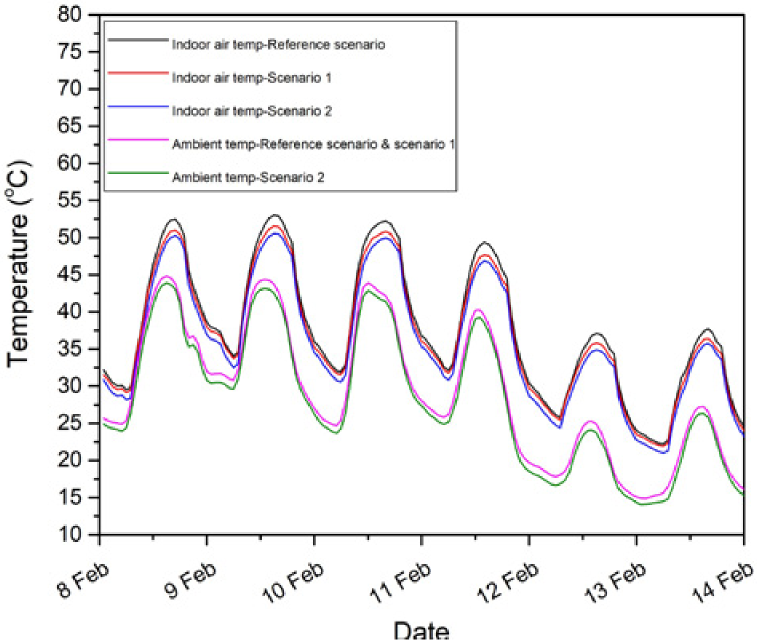

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.5-49.1 °C and 21.3-53.1 °C in Kuitpo and Roseworthy stations, respectively.

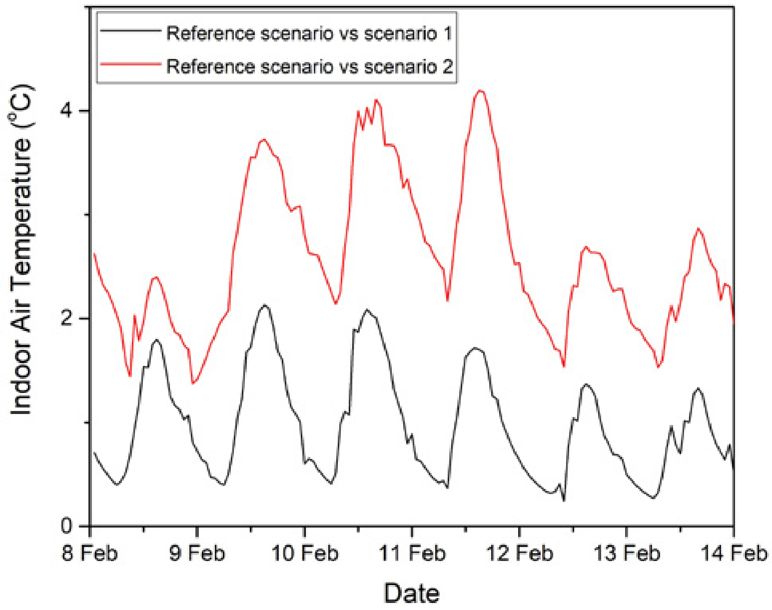

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.4 °C and 2.6 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 4.2 °C and 3.6 °C in Kuitpo and Roseworthy stations, respectively.

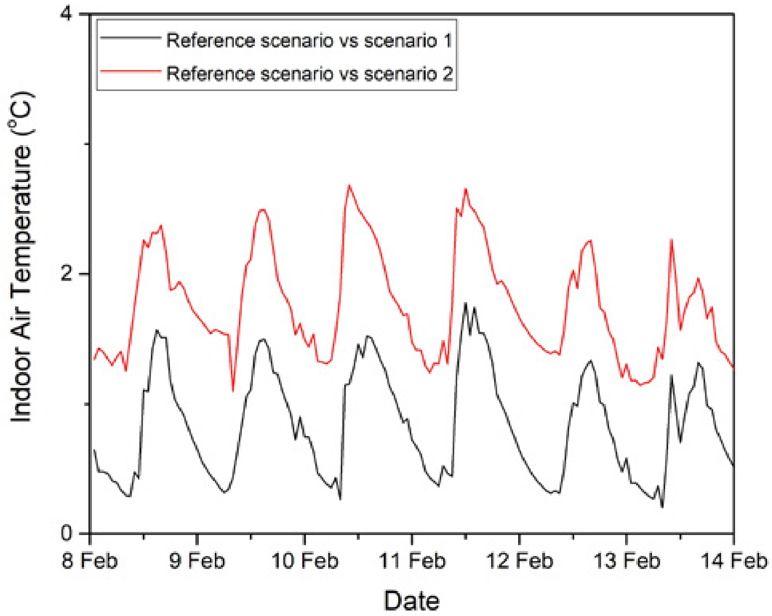

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) an existing new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 11.1-25.1 °C in reference scenario to a range 11.1-24.2 °C in scenario 1 in Kuitpo station.

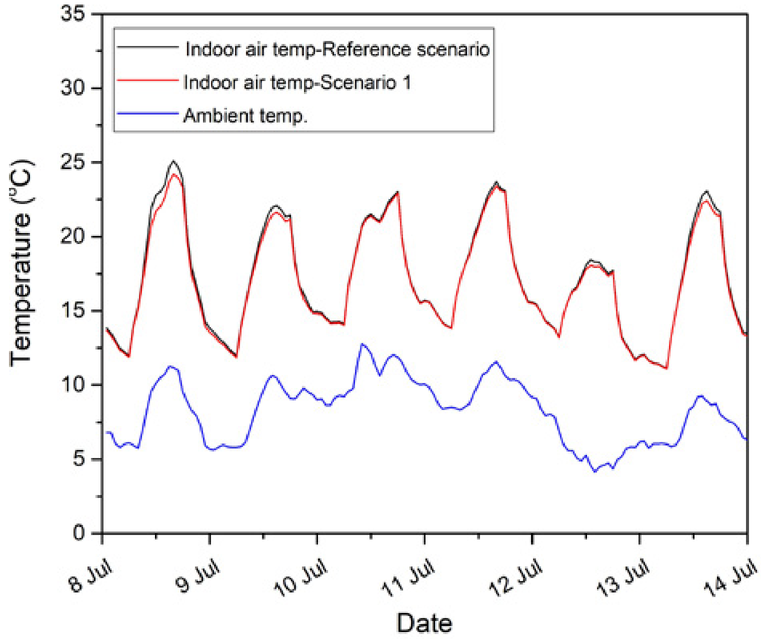

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 10.9-26.5 °C in reference scenario to a range 10.8-25.9 °C in scenario 1 in Roseworthy station.

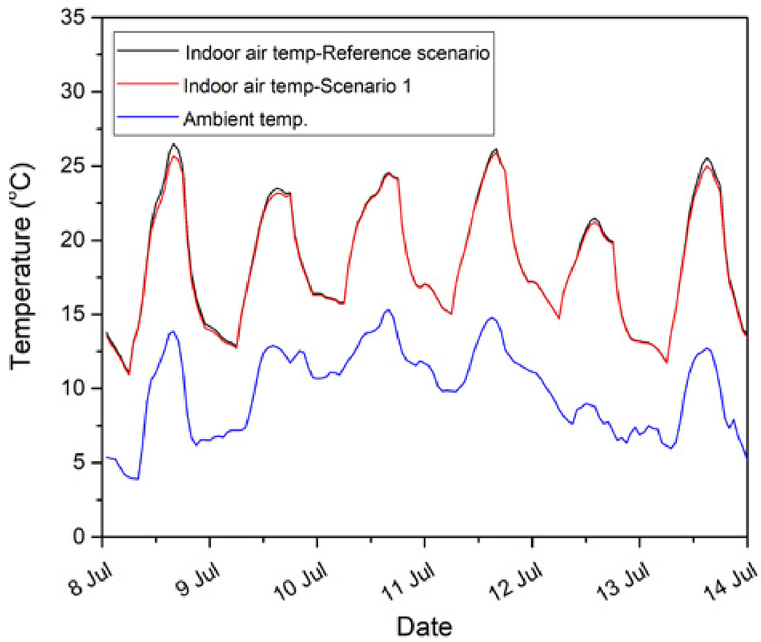

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.3 °C and 1.2 °C in Kuitpo and Roseworthy stations, respectively.

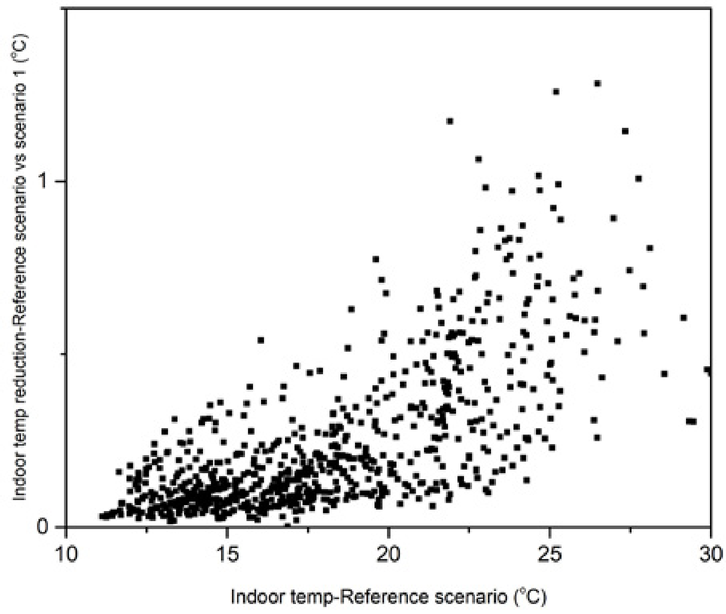

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

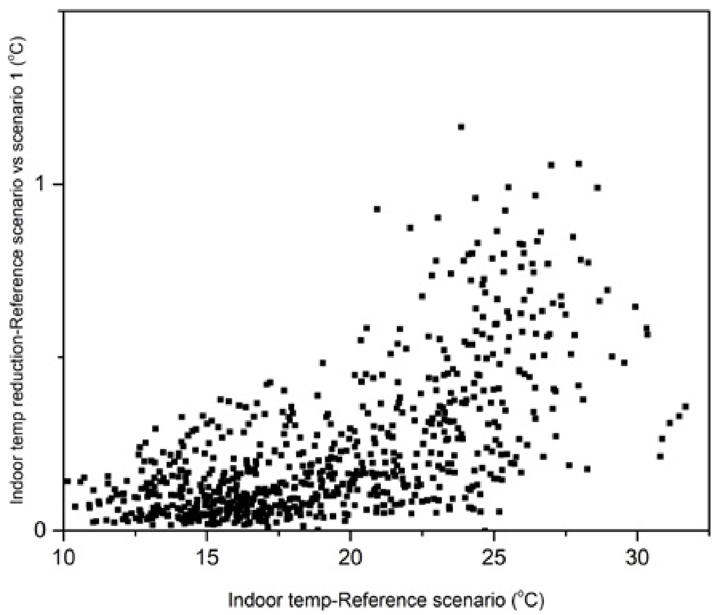

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 452 hours in reference scenario to 457 hours, and from 392 to 398 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 112 hours in reference scenario compared to 116 hours in scenario 1 in Kuitpo; and from 84 to 86 hours in Roseworthy station.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	112	452	116	457
Roseworthy	84	392	86	398

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 498 hours in reference scenario to 478 and 424 hours under scenario 1 and 2 in Kuitpo station; while decreases from 513 hours to 496 for scenario 1 and to 467 for scenario 2 in Roseworthy station.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	498	478	424
Roseworthy	513	496	467

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques.

The building and its energy performance

Building 15 is an existing, low-rise commercial building, with a total air-conditioned area of 2.200 m^2 distributed on two levels. The 1.100 m^2 roof is insulated, but given its impact on half of the building's air-conditioned space, there are important energy losses and, consequently, an important energy saving potential. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 15.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	103.0	148.0
Energy consumption after cool roof (MWh)	87.6	131.1
Energy savings (MWh)	15.4	16.9
Energy savings (%)	14.95%	11.42%
Area (m^2)	1,100	1,100
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

Building 15 is a very good example of a how in a low-rise building, even if its roof is insulated, the energy conservation potential makes both cool roof techniques feasible investment, the coating roof being the more appealing investment over the building's life cycle.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in significant energy savings for both locations, namely 14,95% for Kuitpo and 11,42% for the Roseworthy weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

> *The coating cool roof option leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 9,8% for the metal roof, the low energy price scenario and 33,5% for the cool coating for Kuitpo conditions.*

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

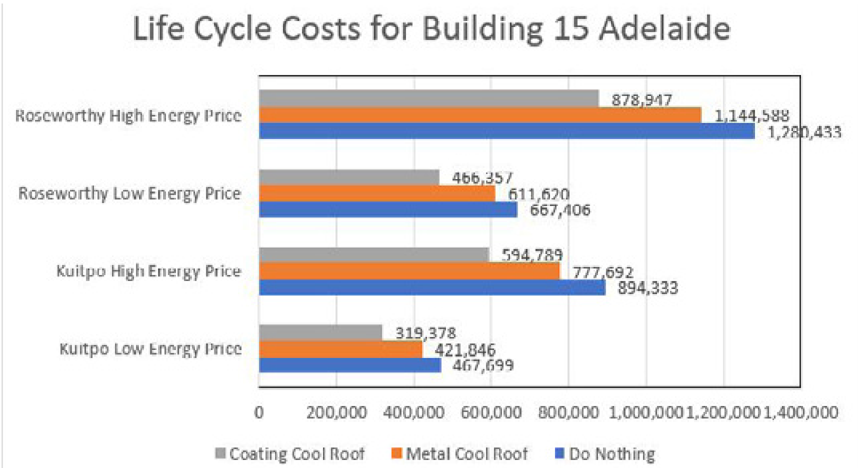

Figure 12. Life Cycle Costs for Building 15 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	9.80 %	13.04 %	8.36 %	10.61 %
Coating Cool Roof	31.71 %	33.49 %	30.12 %	31.36 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the existing low-rise shopping mall centre during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise shopping mall centre from 60.3-70.5 kWh/m^2 to 52.3-62.5 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 8.0-8.2 kWh/m^2. This is equivalent to approximately 11.4-13.3 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 13.4-16.3 kWh/m^2. This is equivalent to 19.1-27.0 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.3-0.8 kWh/m^2) is significantly lower than the annual cooling load reduction (18.2-22.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 12.3-16.9 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 17.4-21.6 kWh/m^2 (~11.4-14.9 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 22.5-49.1 ^{o}C and 21.3-53.1 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.4 and 2.6 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 4.2 and 3.6 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 11.1-25.1 ^{o}C in reference scenario to a range between 11.1-24.2 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 10.9-26.5 °C in reference scenario to a range between 10.8-25.9 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.3 °C and 1.2 °C in Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 452 hours in reference scenario to 457 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight increase in total number of hours below 19 °C from 392 hours in reference scenario to 398 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. 7 am-6 pm) is expected to increase from 112 hours in reference scenario to 116 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. Similarly, the calculation in Roseworthy station shows a slight increase of number of hours below 19 °C from 84 hours to 86 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 498 hours under the reference scenario in Kuitpo station, which decreases to 478 and 424 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Roseworthy station show that the number of hours above 26 °C decreases from 513 to 496 and 467 hours for scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques, which lead to a significant reduction of life cycle costs over the building's life cycle, that varies between 9,8% for the metal roof, the low energy price scenario and 33,5% for the cool coating for Kuitpo conditions, as it can be seen in Table 8. Building 15 is in that sense a very good example of a how in a low-rise building, even if its roof is insulated, the energy conservation potential makes both cool roof techniques feasible investment, the coating roof being the more appealing investment over the building's life cycle.

B15

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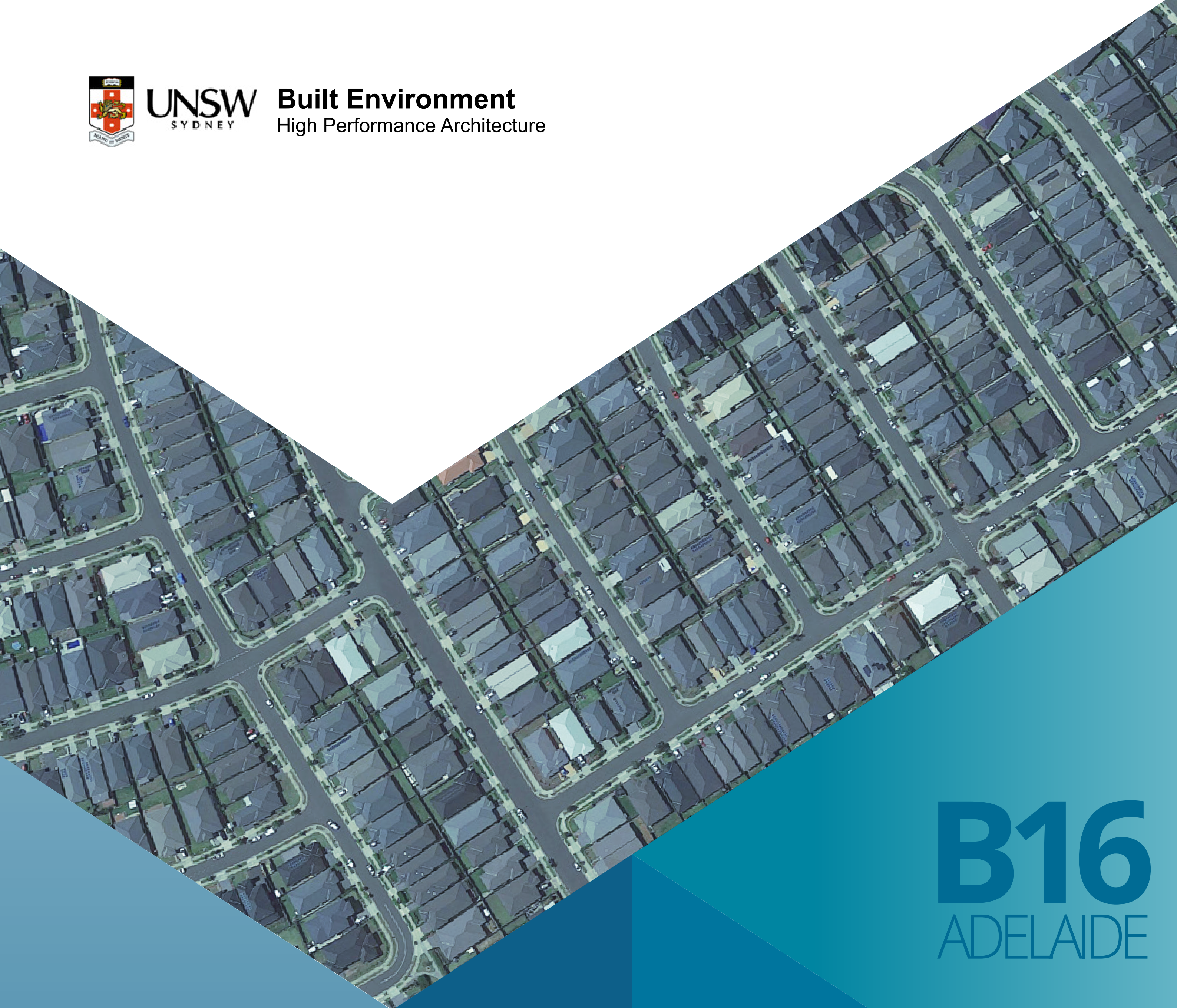

B16
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

Existing high-rise shopping mall centre
2021

BUILDING 16

EXISTING HIGH-RISE SHOPPING MALL CENTRE

Floor area : 1100m^2
Number of stories : 6

Image source: Mall of America, Minneapolis

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing high-rise shopping mall centre from 55.2-65.1 kWh/m² to 52.8-62.7 kWh/m².

Table 1. Sensible and total cooling load for an existing high-rise shopping mall centre for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	55.6	60.0	53.1	57.5	49.4	51.0
Edinburgh	58.4	62.4	56.1	60.0	51.6	53.0
Kuitpo	49.8	55.2	47.5	52.8	42.4	44.2
Parafield	57.7	61.7	55.3	59.2	52.0	53.6
Roseworthy	62.2	65.1	59.8	62.7	56.1	57.2

For Scenario 1, the total cooling load saving is around 2.4-2.5 kWh/m² which is equivalent to 3.7-4.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.9-11.0 kWh/m² which is equivalent to 12.1-19.9 % total cooling load reduction.

Table 2. Sensible and total cooling load saving for an existing high-rise shopping mall centre for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	2.4	4.4	2.5	4.1	6.2	11.1	8.9	14.9
Edinburgh	2.4	4.0	2.4	3.8	6.8	11.7	9.5	15.1
Kuitpo	2.3	4.7	2.4	4.3	7.4	14.8	11.0	19.9
Parafield	2.4	4.2	2.4	4.0	5.7	9.9	8.1	13.1
Roseworthy	2.4	3.8	2.4	3.7	6.1	9.8	7.9	12.1

In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of an existing high-rise shopping mall centre during the summer season.

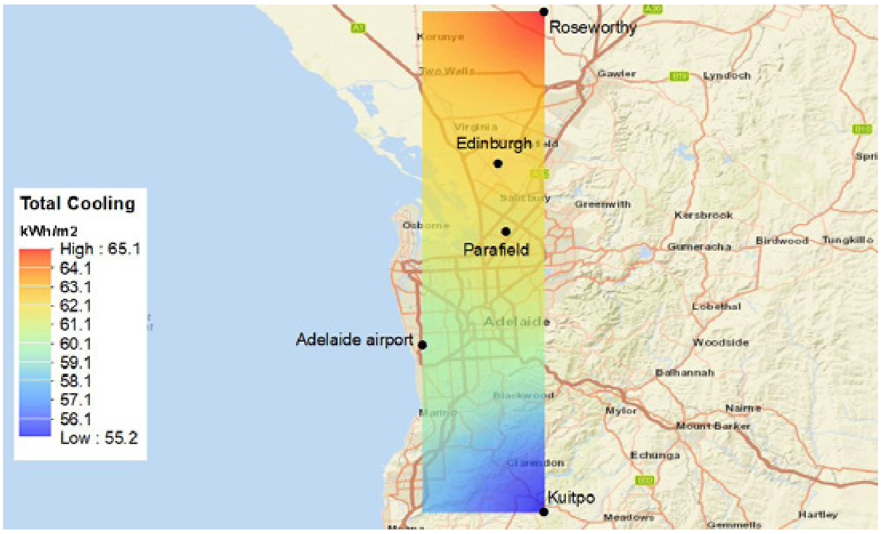

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

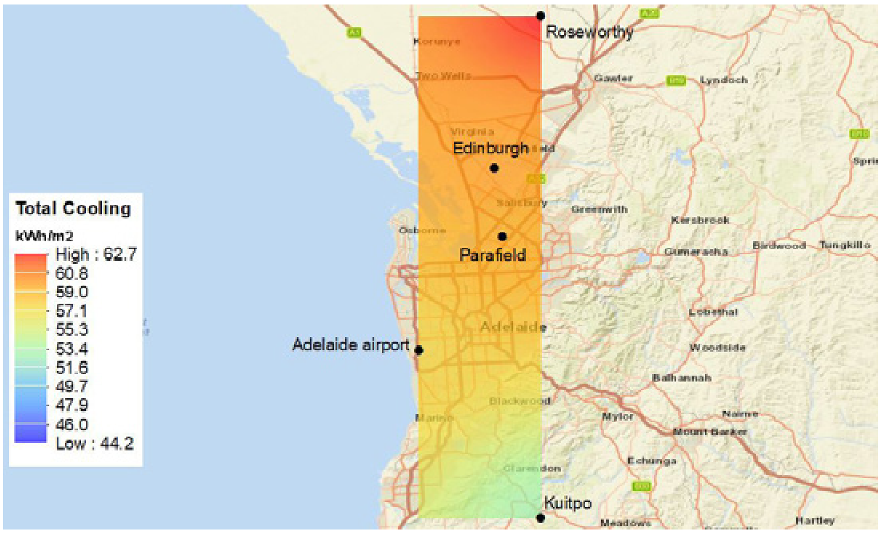

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

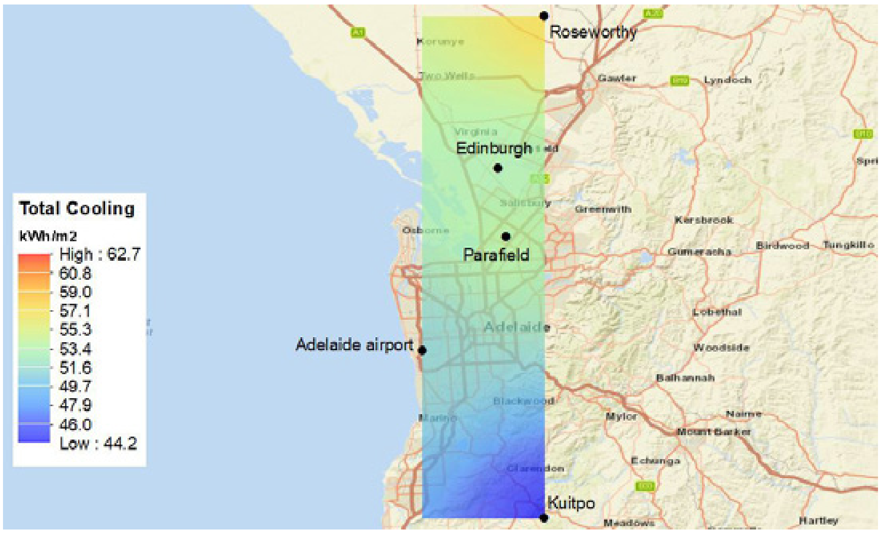

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

b Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing high-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1-0.2 kWh/m²) is significantly lower than the annual cooling load reduction (5.1-6.3 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	126.7	140.5	0.9	3.0	121.3	135.0	1.0	3.1
Edinburgh	137.7	148.2	1.4	4.9	132.1	142.4	1.5	5.1
Kuitpo	85.9	95.4	1.9	7.4	80.9	90.2	2.0	7.6
Parafield	145.6	158.6	1.4	4.5	139.5	152.3	1.4	4.6
Roseworthy	136.3	145.4	2.1	7.0	130.8	139.9	2.2	7.1

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 3.8-5.4 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.9-6.2 kWh/m² (~3.5-4.8 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	5.4	4.3	5.5	3.9	0.0	0.1	5.4	4.2	5.4	3.8
Edinburgh	5.6	4.1	5.7	3.9	0.0	0.1	5.6	4.0	5.6	3.7
Kuitpo	5.0	5.8	5.1	5.4	0.1	0.2	5.0	5.6	4.9	4.8
Parafield	6.2	4.2	6.3	4.0	0.0	0.1	6.1	4.2	6.2	3.8
Roseworthy	5.5	4.0	5.5	3.8	0.0	0.1	5.4	3.9	5.4	3.5

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

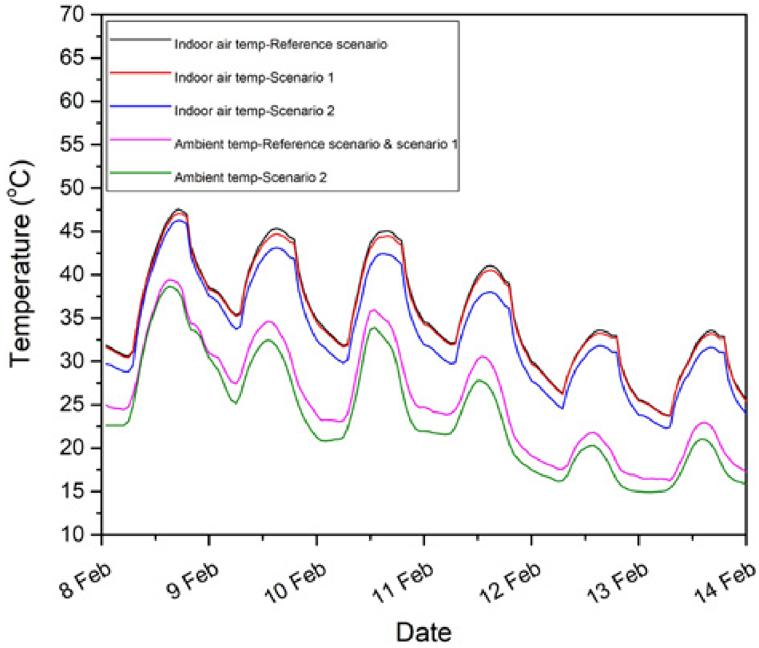

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

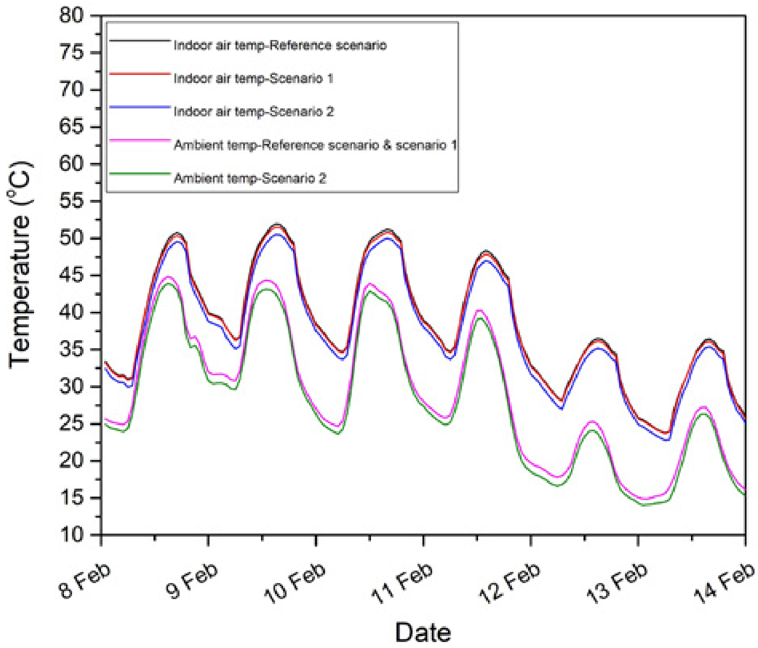

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 23.8-47.6 °C and 22.9-51.9 °C in Kuitpo and Roseworthy stations, respectively.

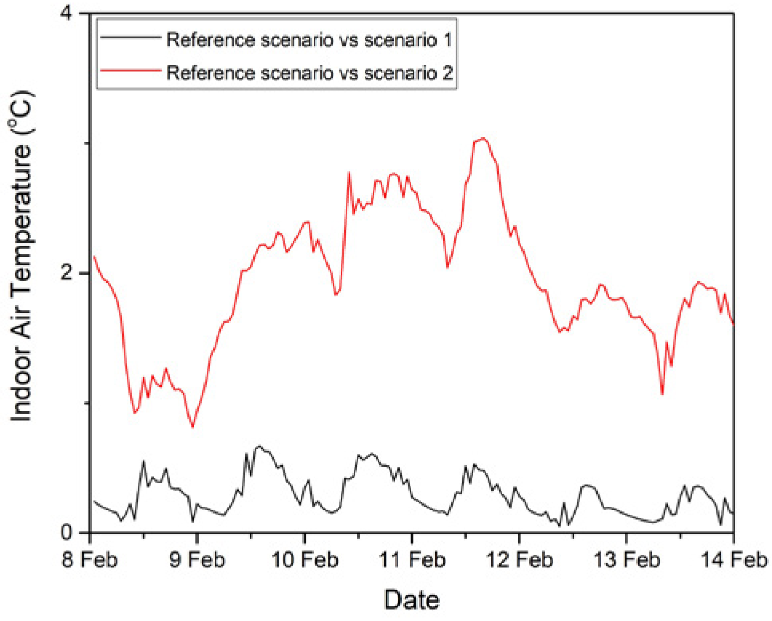

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.8 °C and 0.8 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.0 °C and 1.8 °C in Kuitpo and Roseworthy stations, respectively.

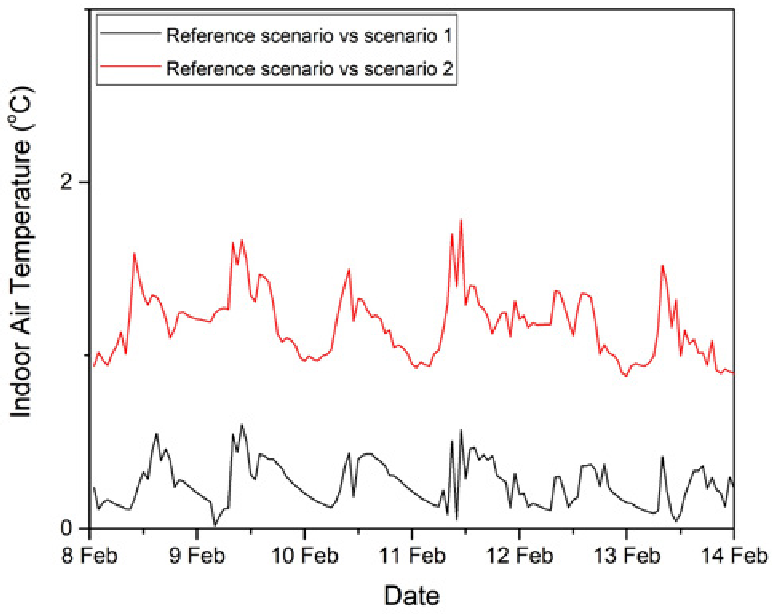

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing highrise shopping mall centre under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 12.3-24.5 °C in reference scenario to a range 12.3-24.3 °C in scenario 1 in Kuitpo station.

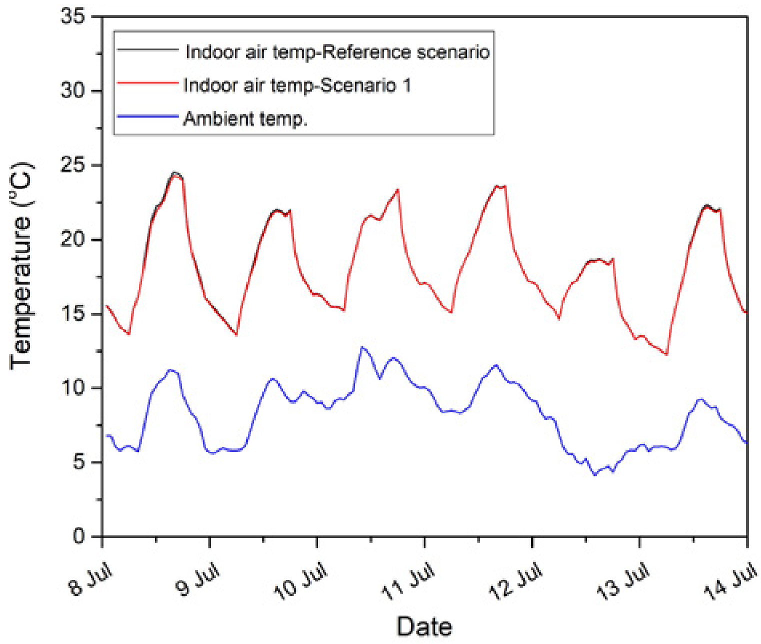

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 12.6-26.0 °C in reference scenario to a range 12.6-25.9 °C in scenario 1 in Roseworthy station.

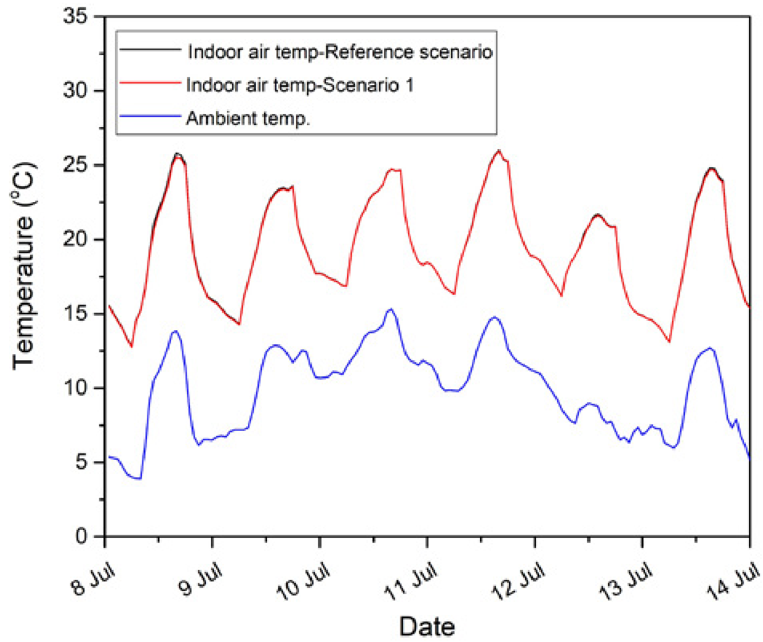

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.5 °C in Kuitpo and Roseworthy stations.

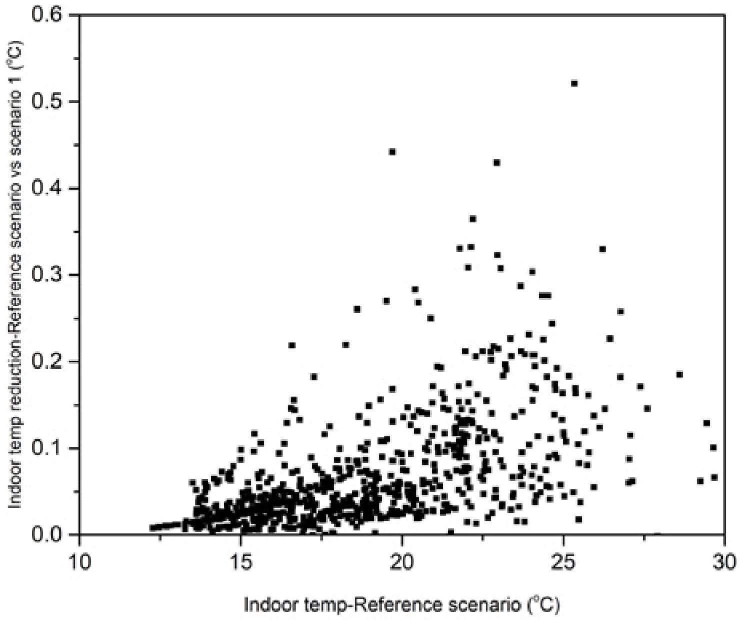

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

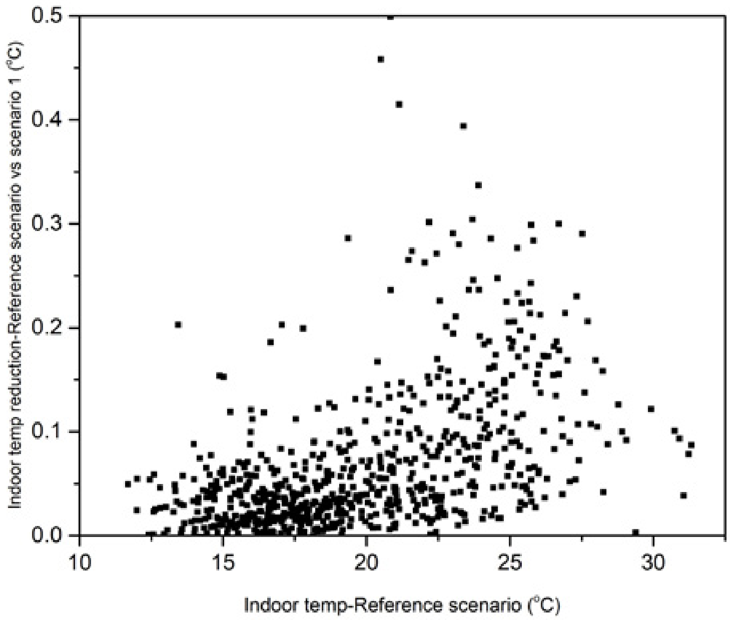

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase slightly from 404 in the reference scenario to 405 hours in Scenario 1 in Kuitpo; and from 340 to 342 hours in Roseworthy stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 70 hours in reference scenario compared to 71 hours in scenario 1 in Roseworthy station.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Kuitpo	104	404	104	405
Roseworthy	70	340	71	342

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 538 hours in reference scenario to 485 hours under scenario 2 in Kuitpo station; while decreases from 546 hours to 541 for scenario 1 and to 525 for scenario 2 in Roseworthy station.

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	538	538	485
Roseworthy	546	541	525

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques.

The building and its energy performance

Building 16 is an existing, high-rise commercial building, with a total air-conditioned area of 6.600 m^2 distributed on six levels. The 1.100 m^2 roof is not insulated, resulting in energy losses which have a direct impact on the building's last floor only and, consequently, lead to a modest energy saving potential. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 16.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	271.4	402.3
Energy consumption after cool roof (MWh)	258.2	388.1
Energy savings (MWh)	13.2	14.2
Energy savings (%)	4.86%	3.53%
Area (m^2)	1,100	1,100
Roof costs - Metal roof (AU$/m^2)	38.0	38.0
Roof costs - Coating (AU$/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

Building 16 is a good example of an existing, insulated, high-rise commercial building where, despite the moderate energy conservation potential, the coating cool roof is a highly feasible investment over the building's life cycle.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Furthermore, one can notice that it the case of the specific building, due to its typology and operational patterns, the impact of the different weather conditions is negligible.

Both options have the same energy efficiency, resulting in similar, modest energy savings for both locations, namely of 4,86% for Kuitpo and of 3,53% for the Roseworthy weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

There is a reduction of life cycle costs over the building's life cycle, that varies for the coating cool roof between 3,5% for the low energy price scenario, the metal cool roof and the Roseworthy conditions and 26,2% for the high energy scenario, the coating cool roof and Kuitpo.

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

Figure 12. Life Cycle Costs for Building 16 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	3.98 %	4.44 %	3.47 %	3.52 %
Coating Cool Roof	26.23 %	26.30 %	25.64 %	25.69 %

The metal cool roof is feasible, although less appealing as an investment.

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of an existing high-rise shopping mall centre during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 55.2-65.1 kWh/m^2 to 52.8-62.7 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 2.4-2.5 kWh/m^2. This is equivalent to approximately 3.7-4.3 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.9-11.0 kWh/m^2. This is equivalent to 12.1-19.9 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1-0.2 kWh/m^2) is significantly lower than the annual cooling load reduction (5.1-6.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.8-5.4 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.9-6.2 kWh/m2 (~3.5-4.8 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 23.8-47.6 ^{o}C and 22.9-51.9 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.8 and 0.8 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.0 and 1.8 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 12.3-24.5 ^{o}C in reference scenario to a range between 12.3-24.3 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 12.6-26.0 °C in reference scenario to a range between 12.6-25.9 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.5 °C in Kuitpo and Roseworthy stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 404 hours in reference scenario to 405 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slight increase in total number of hours below 19 °C from 340 hours in reference scenario to 342 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. 7 am-6 pm) is expected to increase from 70 hours in reference scenario to 71 hours in reference with cool roof scenario (scenario 1) in Roseworthy station (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 538 hours under the reference scenario in Kuitpo station, which decreases to 485 hours under the modified urban temperature scenario (scenario 2). The simulations in Roseworthy station show that the number of hours above 26 °C decreases from 546 to 541 and 525 hours for scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques. These lead to a reduction of life cycle costs over the building's life cycle, that varies for the coating cool roof between 3,5% for the low energy price scenario, the metal cool roof and the Roseworthy conditions and 26,2% for the high energy scenario, the coating cool roof and Kuitpo, as it can be seen in Table 8. Building 16 is in that sense a good example of an existing, insulated, high-rise commercial building where, despite the rather moderate energy conservation potential, the coating cool roof is a highly feasible investment over the building's life cycle. The metal cool roof is feasible, although less appealing as an investment. Furthermore, one can notice that it the case of the specific building, due to its typology and operational patterns, the impact of the different weather conditions is negligible.

B16

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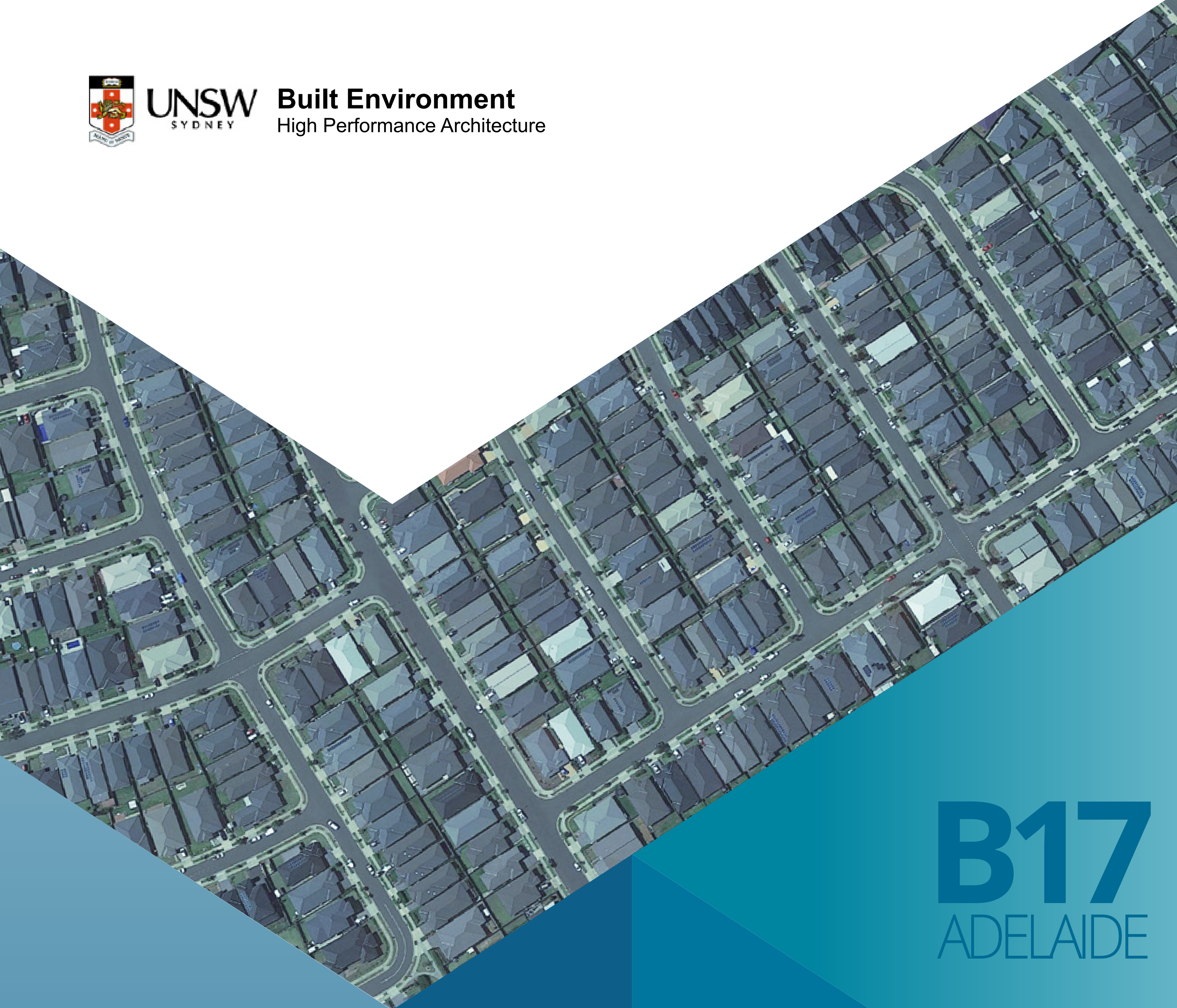

B17
ADELAIDE

COOL ROOFS
COST BENEFIT ANALYSIS

New standalone house
2021

BUILDING 17

NEW STANDALONE HOUSE

Floor area : 242m^2
Number of stories : 1

Image source: https://www.newhomesguide.com.au/builders/long-island-homes/homes/new-homes/moonbi-240

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Adelaide using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new stand-alone house for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new standalone house from 9.0-12.3 kWh/m² to 6.0-9.4 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Adelaide Airport	9.7	10.7	6.6	7.5	5.5	5.8
Edinburgh	10.7	11.7	7.6	8.4	6.2	6.4
Kuitpo	7.9	9.0	5.1	6.0	3.9	4.1
Parafield	10.4	11.4	7.3	8.1	6.2	6.5
Roseworthy	11.6	12.3	8.8	9.4	7.6	7.7

Table 2. Sensible and total cooling load saving for a new stand-alone house for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 2.9-3.3 kWh/m² which is equivalent to 23.7-33.9 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.6-5.2 kWh/m² which is equivalent to 37.1-54.9 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Adelaide Airport	3.1	31.9	3.3	30.4	4.2	43.5	5.0	46.5
Edinburgh	3.1	29.2	3.3	27.9	4.5	42.1	5.2	45.0
Kuitpo	2.8	35.7	3.0	33.9	4.0	51.0	4.9	54.9
Parafield	3.1	30.0	3.3	28.8	4.2	40.2	4.9	42.8
Roseworthy	2.8	24.5	2.9	23.7	4.1	34.9	4.6	37.1

In the eleven weather stations in Adelaide, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new standalone house during the summer season.

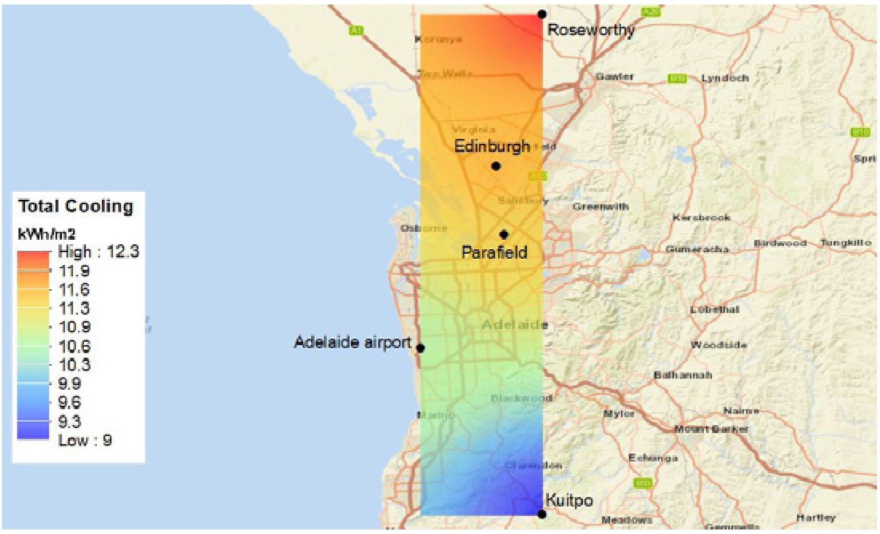

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

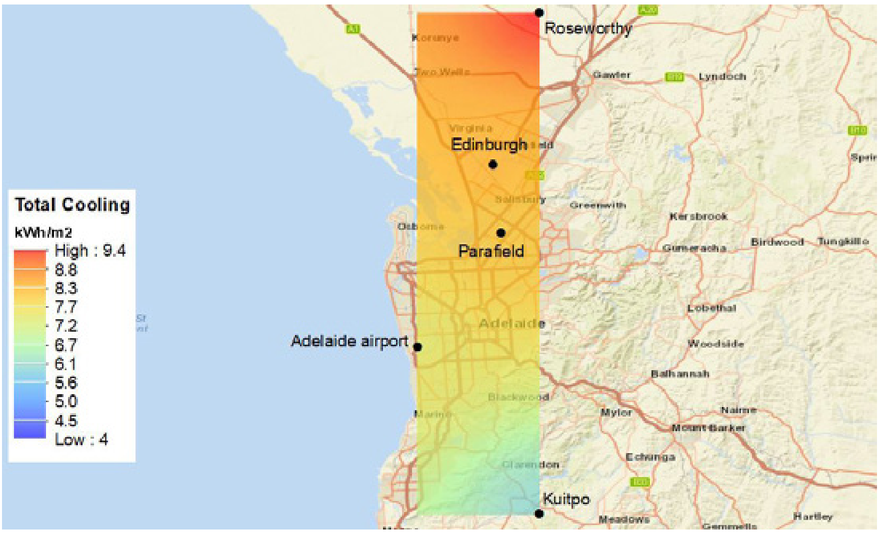

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

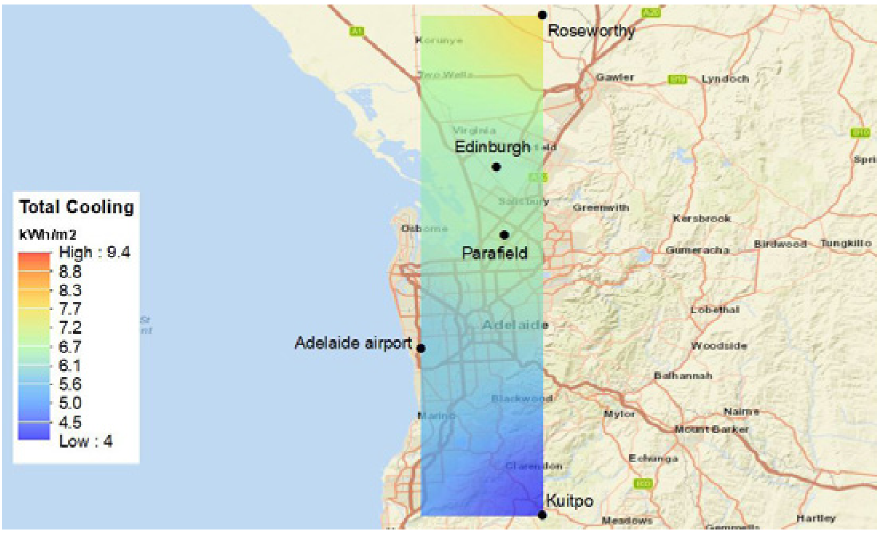

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Adelaide using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new stand-alone house for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (1.4-2.7 kWh/m²) is lower than the annual cooling load reduction (3.3-5.9 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Adelaide Airport	13.1	15.3	13.7	17.0	8.9	10.6	14.9	18.3
Edinburgh	17.0	18.9	17.4	21.4	12.0	13.5	18.8	23.0
Kuitpo	7.4	8.3	24.0	29.8	4.4	5.0	26.4	32.5
Parafield	18.4	20.9	16.4	20.2	12.9	15.0	17.8	21.8
Roseworthy	16.4	17.9	21.3	26.2	12.0	13.3	22.7	27.8

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 25.8-40.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6-4.3 kWh/m² (~1.7-10.5 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Adelaide Airport	4.2	32.0	4.7	30.7	1.2	1.4	3.0	11.2	3.3	10.3
Edinburgh	5.0	29.6	5.4	28.4	1.4	1.6	3.7	10.7	3.8	9.4
Kuitpo	3.0	40.3	3.3	40.0	2.4	2.7	0.6	2.0	0.6	1.7
Parafield	5.5	30.0	5.9	28.3	1.4	1.6	4.2	11.9	4.3	10.5
Roseworthy	4.4	26.8	4.6	25.8	1.4	1.6	3.0	8.0	3.0	6.9

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 16.3-39.4 °C in reference scenario to a range 14.9-38.6 °C in scenario 2 in Kuitpo station.

For Scenario 2, the estimated ambient temperature reduction is 0.3-3.2 °C compared to the reference scenario in Kuitpo station.

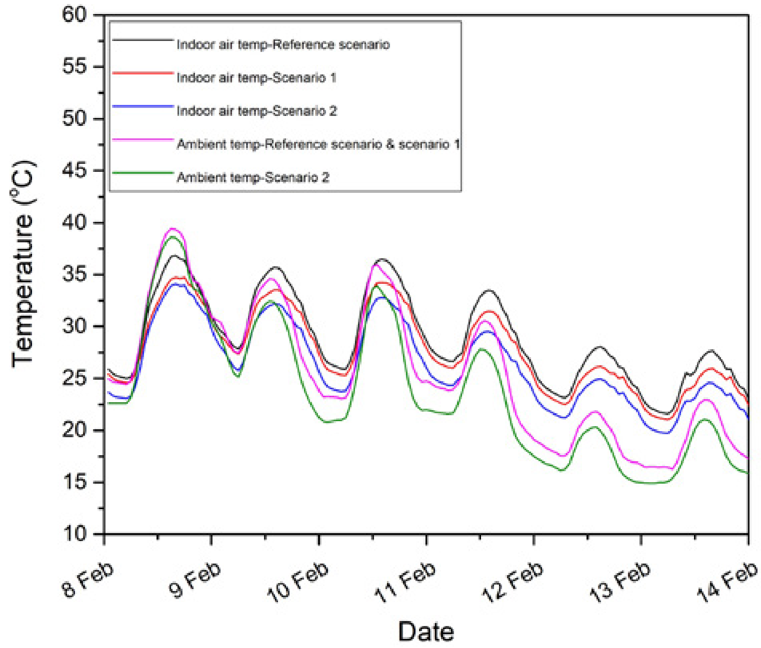

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in Roseworthy station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.7 °C compared to the reference scenario in Roseworthy station.

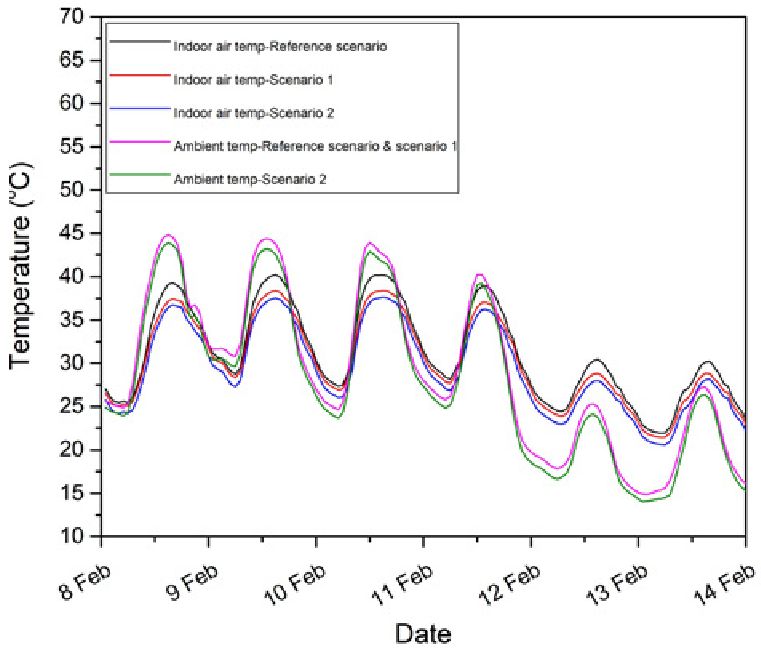

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.1-36.9 °C and 20.7-40.2 °C in Kuitpo and Roseworthy stations, respectively.

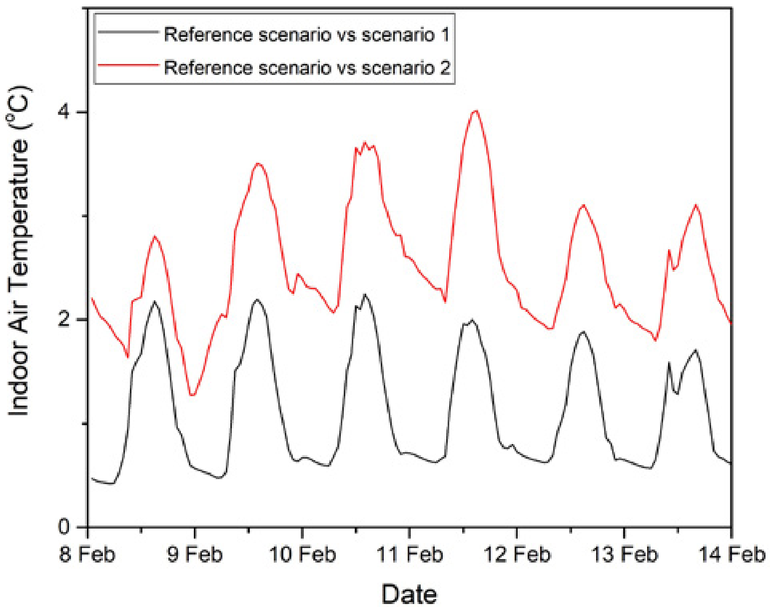

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week in *Kuitpo station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.4 °C and 2.2 °C in Kuitpo and Roseworthy stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 4.0 °C and 3.1 °C in Kuitpo and Roseworthy stations, respectively.

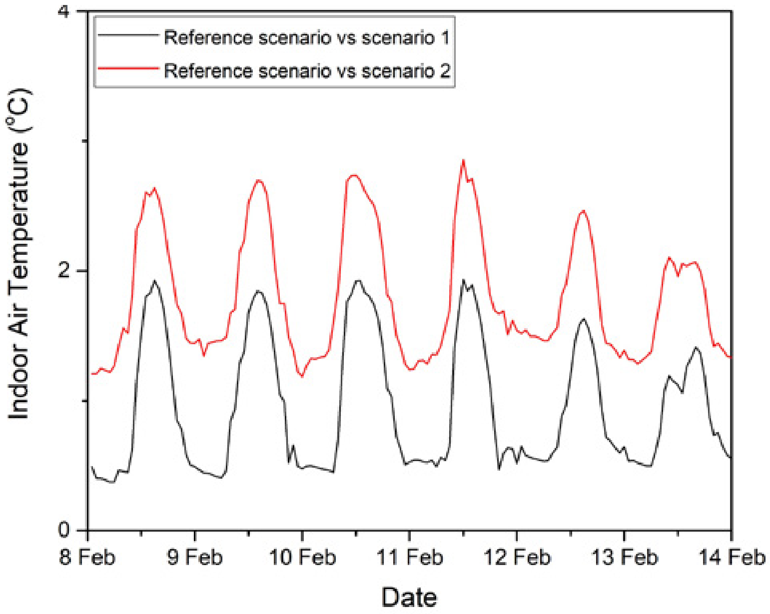

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week in *Roseworthy station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 10.4-18.0 °C in reference scenario to a range 10.3-17.0 °C in scenario 1 in Kuitpo station.

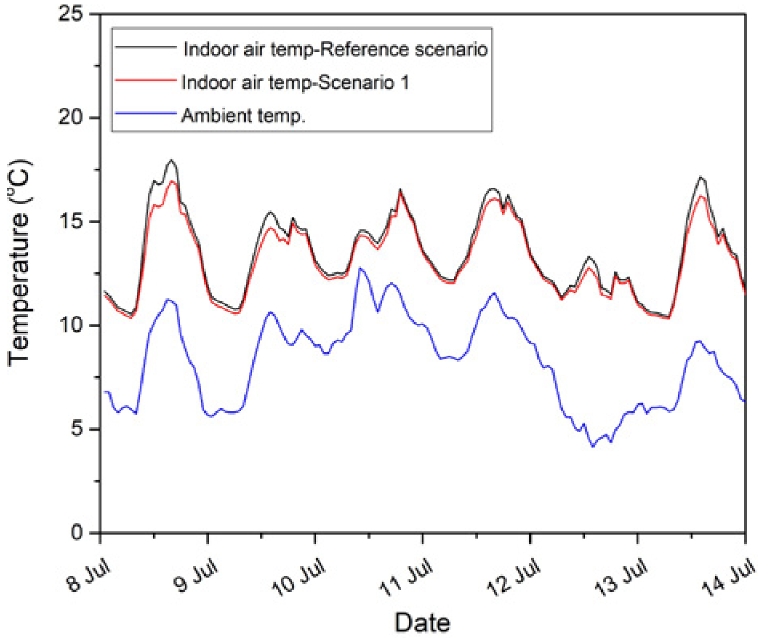

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Kuitpo station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 10.2-19.5 °C in reference scenario to a range 10.1-18.5 °C in scenario 1 in Roseworthy station.

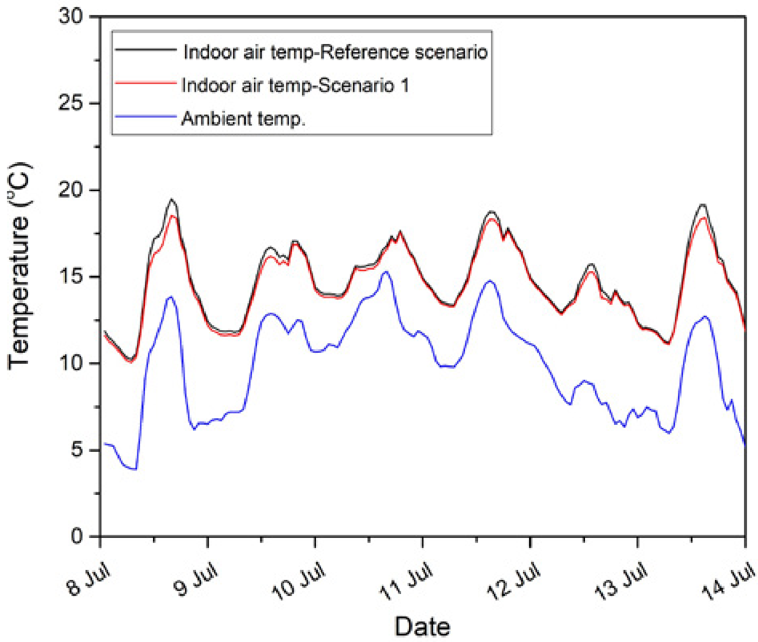

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Roseworthy station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.4 and 1.1 °C in Kuitpo and Roseworthy stations, respectively.

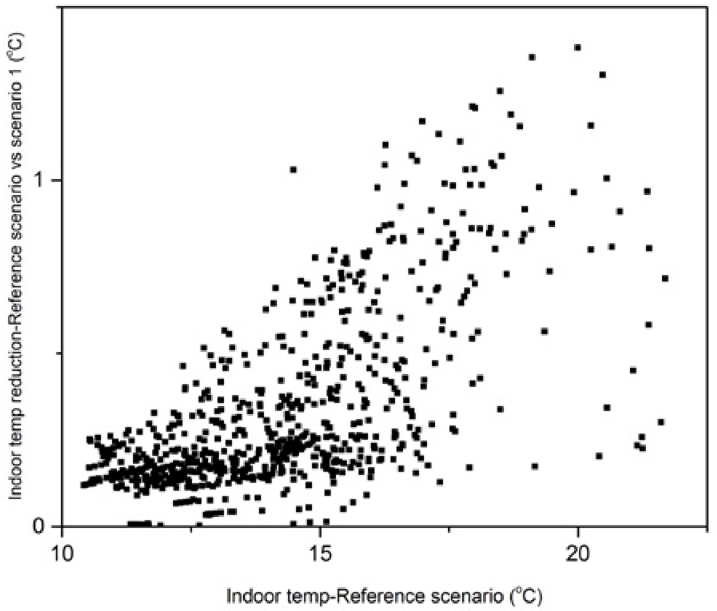

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Kuitpo station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

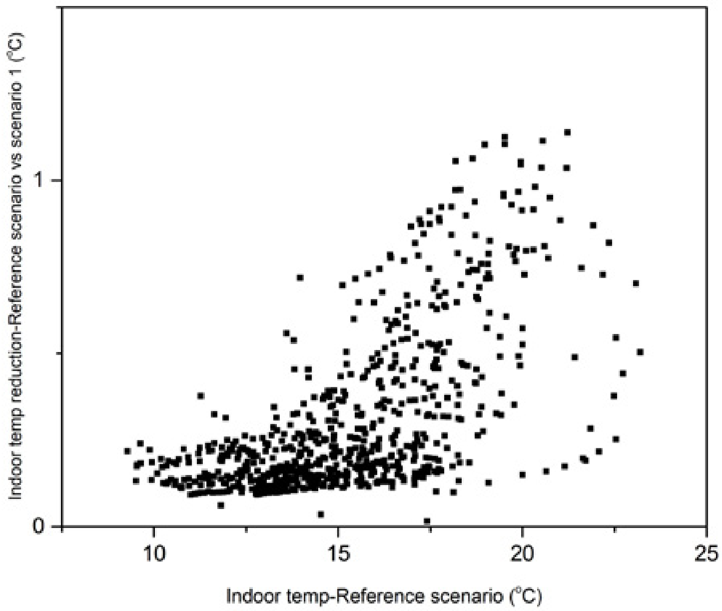

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Roseworthy station* using annual measured weather data.

5

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Adelaide (i.e. Kuitpo and Roseworthy) using annual measured weather data.

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 718 hours in reference scenario to 727 hours; and from 680 to 703 hours in scenario 1 in Kuitpo and Roseworthy stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Kuitpo	718	727
Roseworthy	680	703

Table 6. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month using weather data simulated by WRF.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease significantly from 284 hours in reference scenario to 203 and 139 hours under scenario 1 and 2 in Kuitpo station; and from 356 hours in reference scenario to 300 and 264 hours under scenario 1 and 2 in Roseworthy station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Kuitpo	284	203	139
Roseworthy	356	300	264

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option.

The building and its energy performance

Building 17 is an existing, stand-alone residential building, with a total air-conditioned area of 242 m^2 distributed on one level. The 242 m^2 roof is insulated, but given the fact that it affects the entire building are, the energy conservation potential is significant. The main features of the building's energy performance both for Kuitpo and for Roseworthy weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 17.

Energy performance features	Kuitpo	Roseworthy
Energy consumption prior cool roof (MWh)	3.7	4.3
Energy consumption after cool roof (MWh)	3.6	4.0
Energy savings (MWh)	0.1	0.3
Energy savings (%)	2.70%	6.98%
Area (m^2)	242	242
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	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

Building 17 is an interesting example of a new, stand-alone residential building, with a single ground floor and an insulated roof, where the energy conservation potential is important.

The cool roof refurbishment options

Two possible options are being considered for reducing energy loads by utilizing cool technologies on the roof:

- A metal roof with cool characteristics is installed on top of the existing roof
- A cool coating is applied on the existing roof

Both options have the same energy efficiency, resulting in an energy requirements' reduction of 2,70% for the Kuitpo weather conditions and of 6,98% for the Roseworthy conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The application of a coating cool technology emerges as a meaningful and appealing investment. On the other hand, given the low in absolute terms value of energy expenditures and the high initial investment cost of the metal cool roof, the latter is not feasible.

> *The coating cool roof option leads to a significant reduction of life cycle costs, that varies between 6,6% for the low energy price scenario for Kuitpo and 19,8% for the high energy scenario and for Roseworthy conditions.*

Feasibility analysis results

The feasibility analysis has been carried out by four methods, namely Net Present Value, Internal Rate of Return, Payback Period and Life Cycle Cost. Since the implementation of cool roofs techniques is not a revenue generating investment, the determining factor is the Life Cycle Cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining a retrofitting, the Life Cycle Cost of the "Do nothing" scenario does not consider the construction cost, but only a refurbishment of the existing roof after 15 years.

The analysis has been carried out for two electricity prices scenarios, one for a low initial price of 150 AU$/MWh and one for a high, of 290 AU$/MWh. The results of the Life Cycle Cost analysis are presented in Figure 12 for Kuitpo and for Roseworthy weather conditions, respectively.

> *The metal cool roof is, due to its higher initial investment cost and the limited in absolute terms energy savings, not feasible, for both scenarios and locations.*

Figure 12. Life Cycle Costs for Building 17 for Kuitpo and Roseworthy weather stations.

Table 8. Reduction of Life Cycle Costs, compared to the 'Do Nothing' approach.

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-31.39 %	-15.32 %	-23.13 %	-8.72 %
Coating Cool Roof	6.61 %	15.29 %	11.98 %	19.81 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new standalone house during the summer season.

• In the eleven weather stations in Adelaide, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 9.0-12.3 kWh/m^2 to 6.0-9.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 2.9-3.3 kWh/m^2. This is equivalent to approximately 23.7-33.9 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Adelaide, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 4.6-5.2 kWh/m^2. This is equivalent to 37.1-54.9 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (1.4-2.7 kWh/m^2) is lower than the annual cooling load reduction (3.3-5.9 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 25.8-40.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6-4.3 kWh/m^2 (~1.7-10.5 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 21.1-36.9 ^{o}C and 20.7-40.2 ^{o}C in Kuitpo and Roseworthy stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.4 and 2.2 ^{o}C in Kuitpo and Roseworthy stations, respectively. The indoor air temperature reduction is foreseen to increase further to 4.0 and 3.71^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Kuitpo and Roseworthy stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 16.3-39.4 °C in reference scenario to a range between 14.9-38.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Kuitpo station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.3-3.2 °C. Similarly, the ambient temperature is predicted to decrease from 14.0-44.9 °C in reference scenario to 13.4-43.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Roseworthy station. The estimated ambient temperature reduction is 0.6-1.7 °C in Roseworthy station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease from a range between 10.4-18.0 ^{o}C in reference scenario to a range between 10.3-17.0 ^{o}C in reference with cool roof scenario (scenario 1) in Kuitpo station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 10.2-19.5 °C in reference scenario to a range between 10.1-18.5 °C in reference with cool roof scenario (scenario 1) in Roseworthy station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.4 and 1.1 °C for both Kuitpo and Roseworthy stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase from 718 hours in reference scenario to 727 hours in reference with cool roof scenario (scenario 1) in Kuitpo station. The estimations for Roseworthy stations also show a slightly increase in total number of hours below 19 °C from 680 hours in reference scenario to 703 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 284 hours under the reference scenario in Kuitpo station, which slightly decreases to 203 and 139 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Roseworthy station also illustrate a significant reduction in number of hours above 26 °C from 356 hours in reference scenario to 300 in reference with cool roof scenario (scenario 1) and 264 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option, which leads to a significant reduction of life cycle costs, that varies between 6,6% for the low energy price scenario for Kuitpo and 19,8% for the high energy scenario and for Roseworthy conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the limited in absolute terms energy savings, not feasible, for both scenarios and locations. Building 17 is in that sense an interesting example of a new, stand-alone residential building, with a single ground floor and an insulated roof, where the energy conservation potential is important. The application of a coating cool technology emerges as a meaningful and appealing investment. On the other hand, given the low in absolute terms value of energy expenditures and the high initial investment cost of the metal cool roof, the latter is not feasible.

B17

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