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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 7 – Brisbane: Analysis and Results of the Climatic and Energy Performance of Cool Roofs. Description and Results of Building Case Studies.

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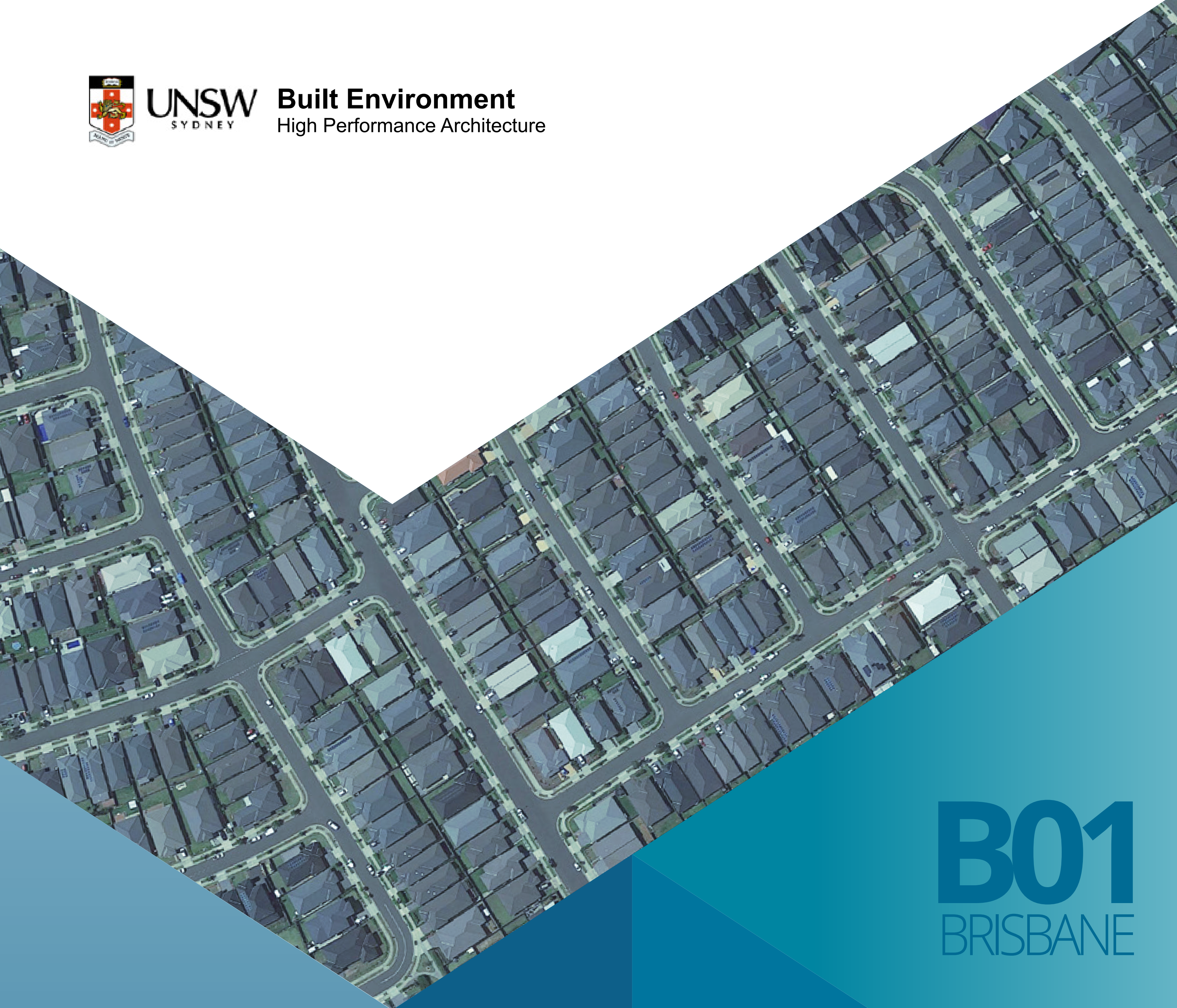

B01
BRISBANE

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.

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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 Brisbane using weather data simulated by WRF.

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 43.6-44.8 kWh/m² to 30.7-32.8 kWh/m².

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.

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)
Amberley	35.5	46.3	20.8	30.7	19.5	25.0
Archerfield	30.9	44.1	19.2	32.8	17.8	25.0
Brisbane Airport	30.8	44.4	19.0	31.4	17.2	23.9
Gold Coast - Seaway	29.3	43.6	18.4	31.2	16.9	24.6
Greenbank (Defence)	29.7	43.6	18.5	31.1	17.0	23.9
Redcliffe	31.6	44.8	19.1	31.0	17.5	24.2
Redland (Alexandra Hills)	30.3	43.6	18.7	30.7	17.4	24.9

For Scenario 1, the total cooling load saving is around 11.3-15.6 kWh/m² which is equivalent to 28.4-33.7 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 18.7-21.3 kWh/m² which is equivalent to 42.9-46.2 % of total cooling load reduction.

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.

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	%
Amberley	14.7	41.4	15.6	33.7	16	45.1	21.3	46.0
Archerfield	11.7	37.9	11.3	25.6	13.1	42.4	19.1	43.3
Brisbane Airport	11.8	38.3	13.0	29.3	13.6	44.2	20.5	46.2
Gold Coast - Seaway	10.9	37.2	12.4	28.4	12.4	42.3	19.0	43.6
Greenbank (Defence)	11.2	37.7	12.5	28.7	12.7	42.8	19.7	45.2
Redcliffe	12.5	39.6	13.8	30.8	14.1	44.6	20.6	46.0
Redland (Alexandra Hills)	11.6	38.3	12.9	29.6	12.9	42.6	18.7	42.9

In the eleven weather stations in Brisbane, 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.

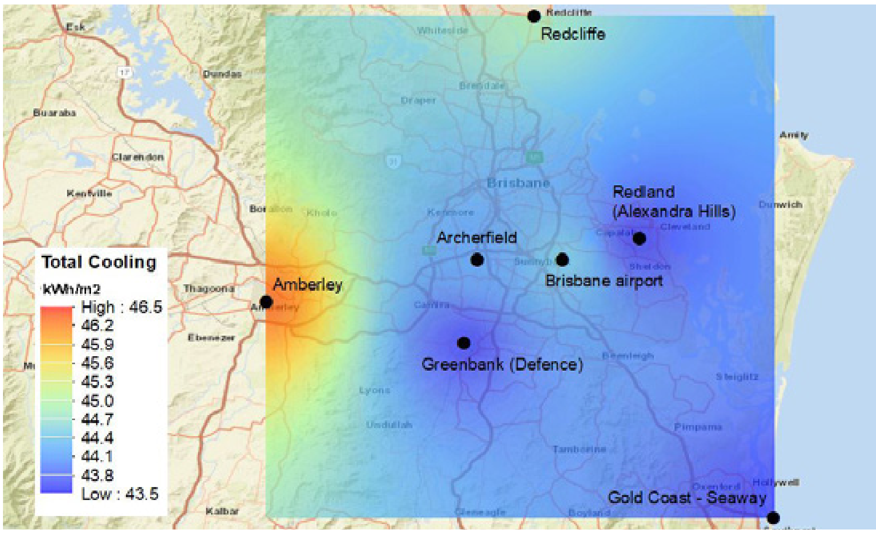

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

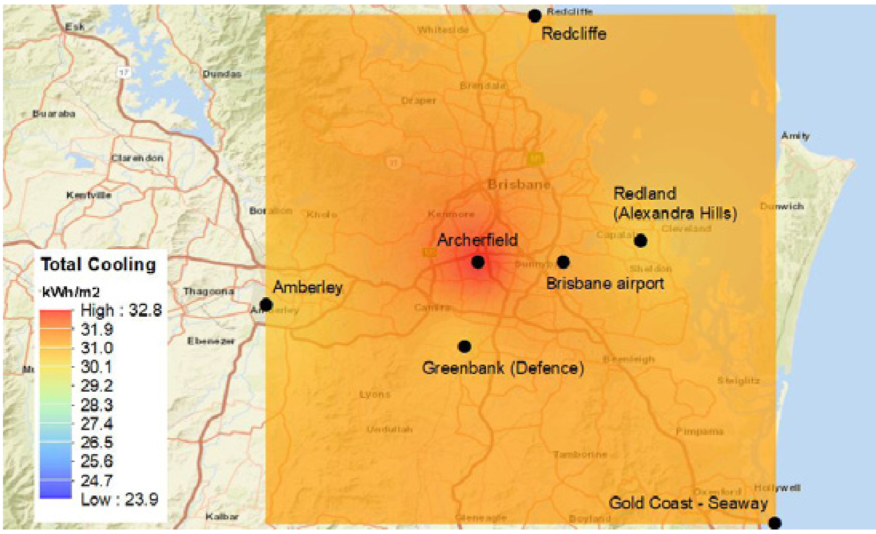

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

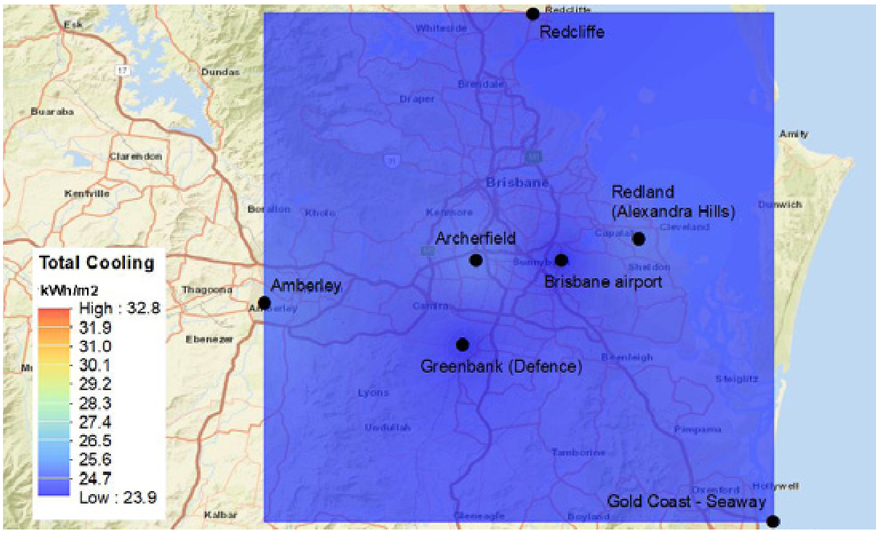

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.5-0.9 kWh/m²) is significantly lower than the annual cooling load reduction (41.2-52.7 kWh/m²).

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.

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
Amberley	113.8	114.6	1.1	2.0	61.2	71.4	1.7	2.9
Archerfield	110.2	113.5	0.7	1.2	62.1	73.2	1.1	1.8
Brisbane	129.1	131.6	0.4	0.8	66.6	78.9	0.7	1.3
Brisbane Airport	101.4	100.3	0.4	0.9	57.9	65.6	0.8	1.4
Redland (Alexandra Hills)	110.3	103.2	0.4	0.9	57.2	62.0	0.9	1.5

The annual cooling load saving by building-scale application of cool roofs is around 34.6-40.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 34.2-52.2 kWh/m² (~33.8-39.4 %).

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 a low-rise office building without roof insulation 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	%
Amberley	52.6	46.2	43.2	37.7	0.6	0.9	52.0	45.3	42.3	36.3
Archerfield	48.1	43.6	40.3	35.5	0.4	0.6	47.7	43.0	39.7	34.6
Brisbane	62.5	48.4	52.7	40.0	0.3	0.5	62.2	48.0	52.2	39.4
Brisbane Airport	43.5	42.9	34.7	34.6	0.4	0.5	43.1	42.3	34.2	33.8
Redland (Alexandra Hills)	53.1	48.1	41.2	39.9	0.5	0.6	52.6	47.5	40.6	39.0

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. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

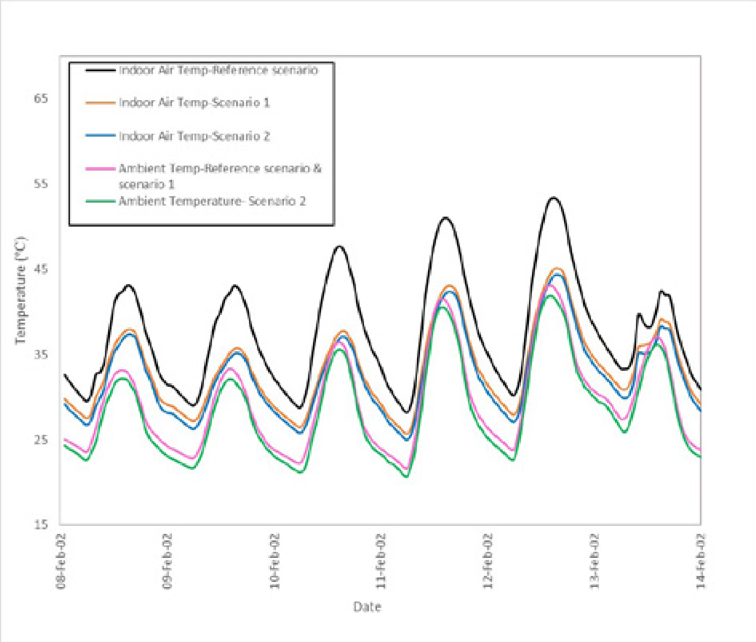

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

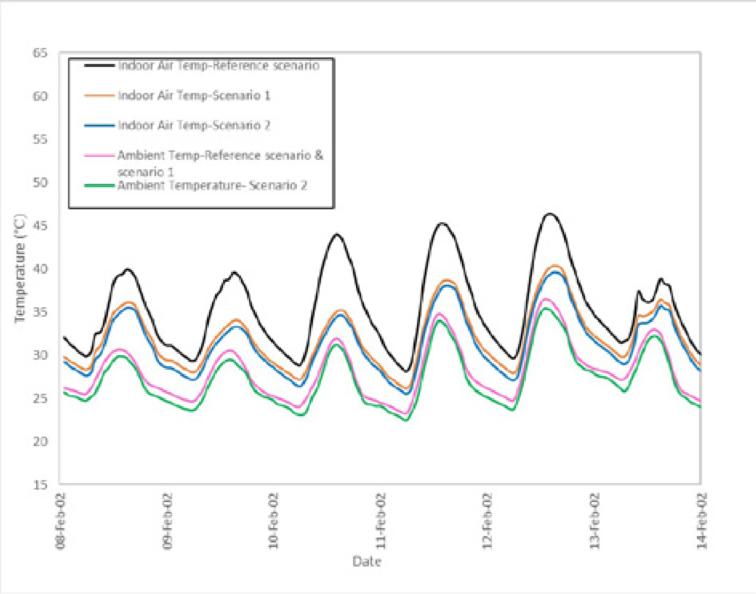

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.0-53.4 °C and 28.1-46.4 °C in Amberley and Redland stations, respectively.

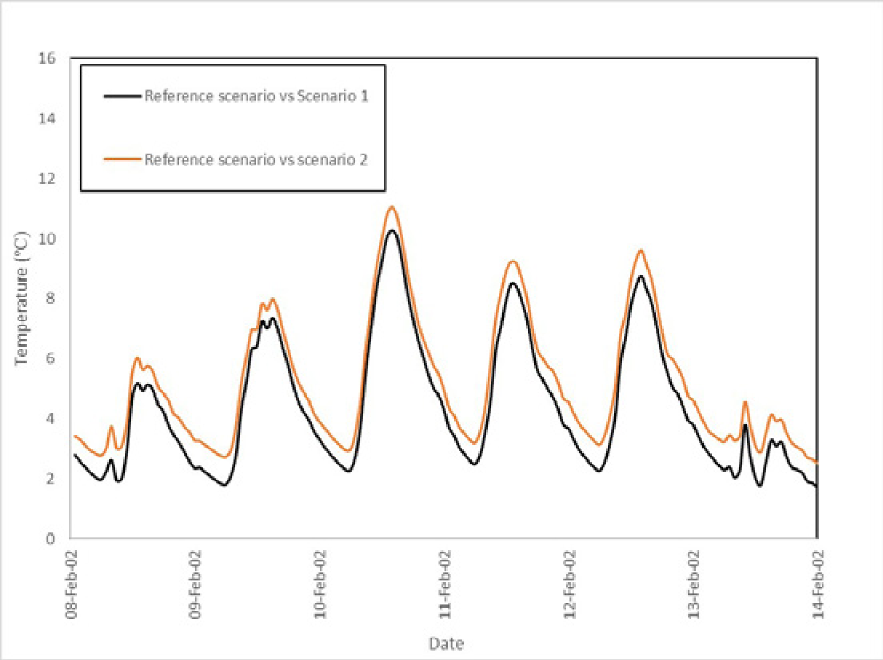

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 10.3 °C and 9.0 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 11.1 °C and 9.6 °C in Amberley and Redland stations, respectively.

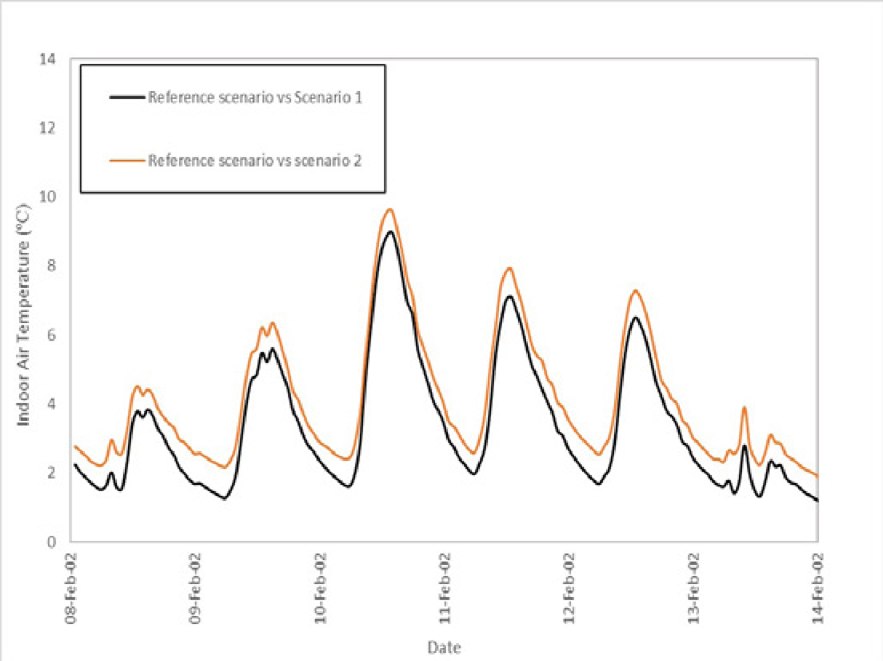

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 11.7-32.4 °C in reference scenario to a range 10.9-28.4 °C in scenario 1 in Amberley station.

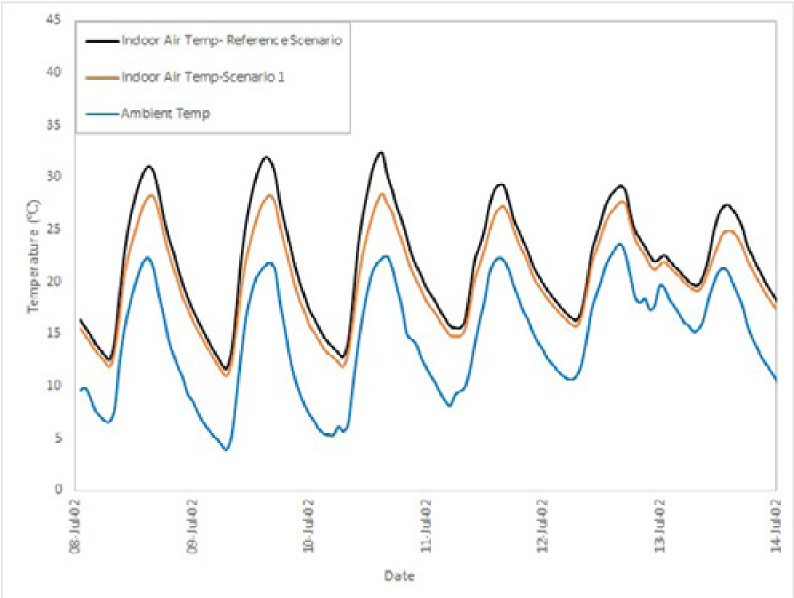

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Amberley station* using annual measured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

The indoor air temperature is predicted to reduce from a range 15.5-32.3 °C in reference scenario to a range 14.8-28.6 °C in scenario 1 in Redland station.

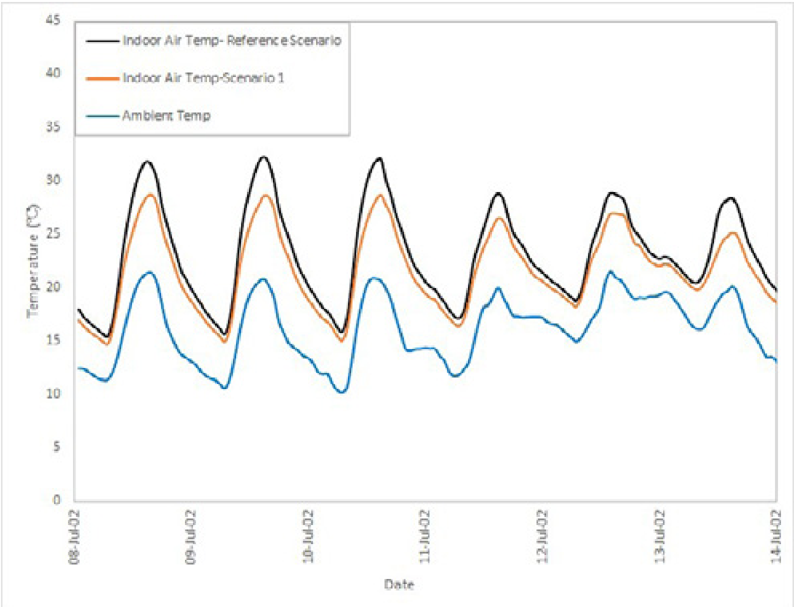

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Redland station* using annual measured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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 5.6 °C and 5.5 °C in Amberley and Redland stations, respectively.

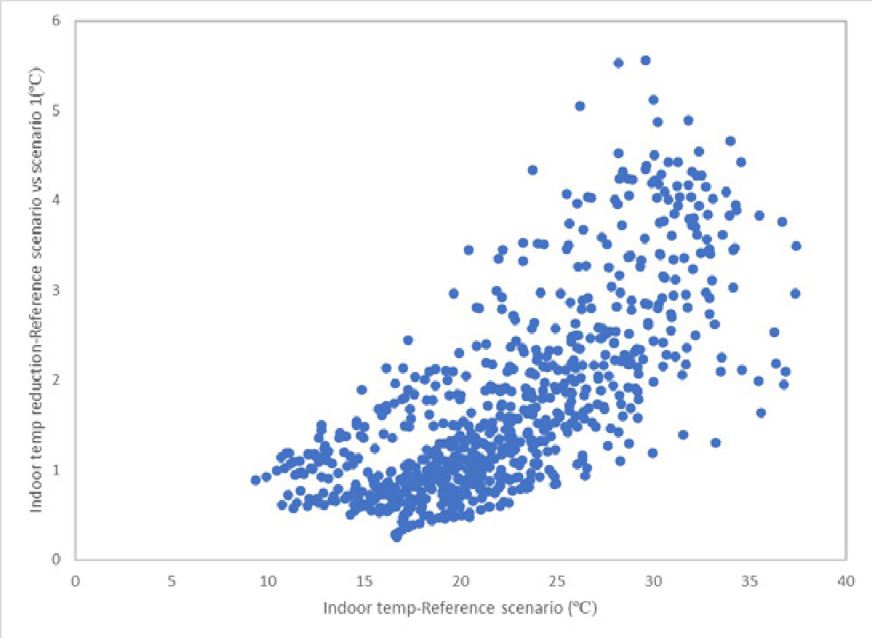

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

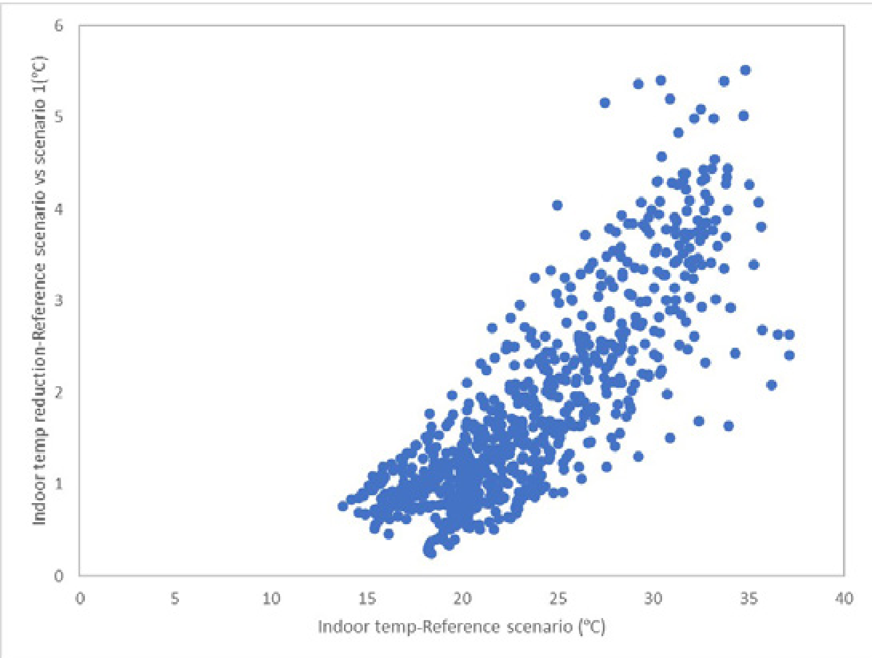

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 229 hours in reference scenario to 294 and hours and from 158 to 221 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to increase from 37 hours in reference scenario to 56 hours; and from 30 to 42 hours in scenario 1 in Amberley and Redland stations, respectively.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Amberley	37	229	56	294
Redland	30	158	42	221

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

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 significantly decreased from 649 hours in reference scenario to 591 and 558 hours under scenario 1 and 2 in Amberley station; and from 664 hours in reference scenario to 629 and 592 hours under scenario 1 and 2 in Redland station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Amberley	649	591	558
Redland	664	629	592

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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 01.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	111.9	99.9
Energy consumption after cool roof (MWh)	71.3	61.0
Energy savings (MWh)	40.6	38.9
Energy savings (%)	36.28%	38.94%
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 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.

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 36,28% for the Amberley weather conditions and of 38,94% for the Redland 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 29,6 and 47,3%, 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 Amberley and for Redland weather conditions respectively.

> *The coating cool roof achieves in all cases significant better results, although the metal cool roof is also a very feasible option. The weather conditions do not have a significant impact on the results.*

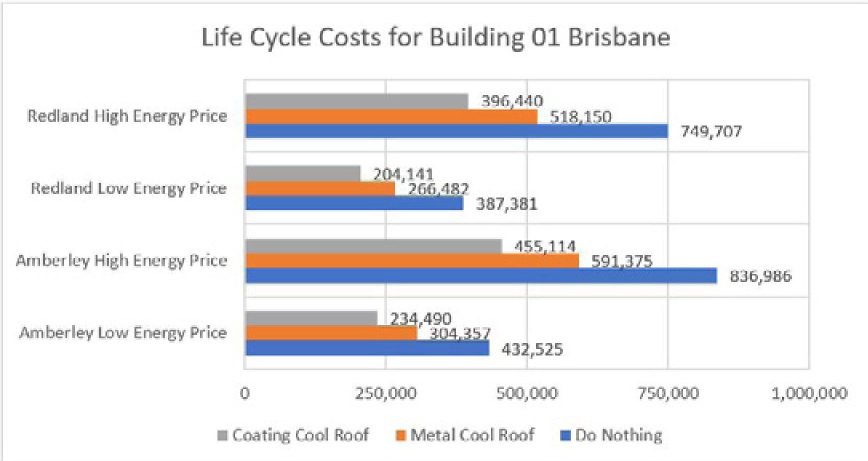

Figure 12. Life Cycle Costs for Building 01 for Amberley and Redland weather stations.

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	29.63 %	29.34 %	31.21 %	30.89 %
Coating Cool Roof	45.79 %	45.62 %	47.30 %	47.12 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 43.6-44.8 kWh/m^2 to 30.7-32.8 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 11.3-15.6 kWh/m^2. This is equivalent to approximately 28.4-33.7 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 8.3-11.7 kWh/m^2. This is equivalent to 42.9-46.2 % 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 (0.5-0.9 kWh/m^2) is significantly lower than the annual cooling load reduction (41.2-52.7 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 34.6-40.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 34.2-52.2 kWh/m^2 (~33.8-39.4 %) (Tables 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 28.0-53.4 °C and 28.1-46.4 °C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 10.3 and 9.0 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 11.1 and 9.6 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland 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 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 11.7-32.4 °C in reference scenario to a range between 10.9-28.4 °C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 15.5-

32.3 °C in reference scenario to a range between 14.8-28.6 °C in reference with cool roof scenario (scenario 1) in Redland 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 5.6 °C and 5.5 °C in Amberley and Redland 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 229 hours in reference scenario to 294 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland station also show a increase in total number of hours below 19 °C from 158 hours in reference scenario to 221 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 37 hours in reference scenario to 56 hours in reference with cool roof scenario (scenario 1) in Amberley station. Similarly, the calculation in Redland station shows a slightly increase of number of hours below 19 °C from 30 hours to 42 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 649 hours under the reference scenario in Amberley station, which significanlty decreases to 591and 558 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Redland station also illustrate a significant reduction in number of hours above 26 °C from 664 hours in reference scenario to 629 in reference with cool roof scenario (scenario 1) and 592 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 clearly 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 29,6 and 47,3%, depending on the weather and energy price scenarios, as it can be seen in Table 8. The coating cool roof achieves in all cases significant better results, although the metal cool roof is also a very feasible option. The weather conditions do not have a significant impact on the results.

B01

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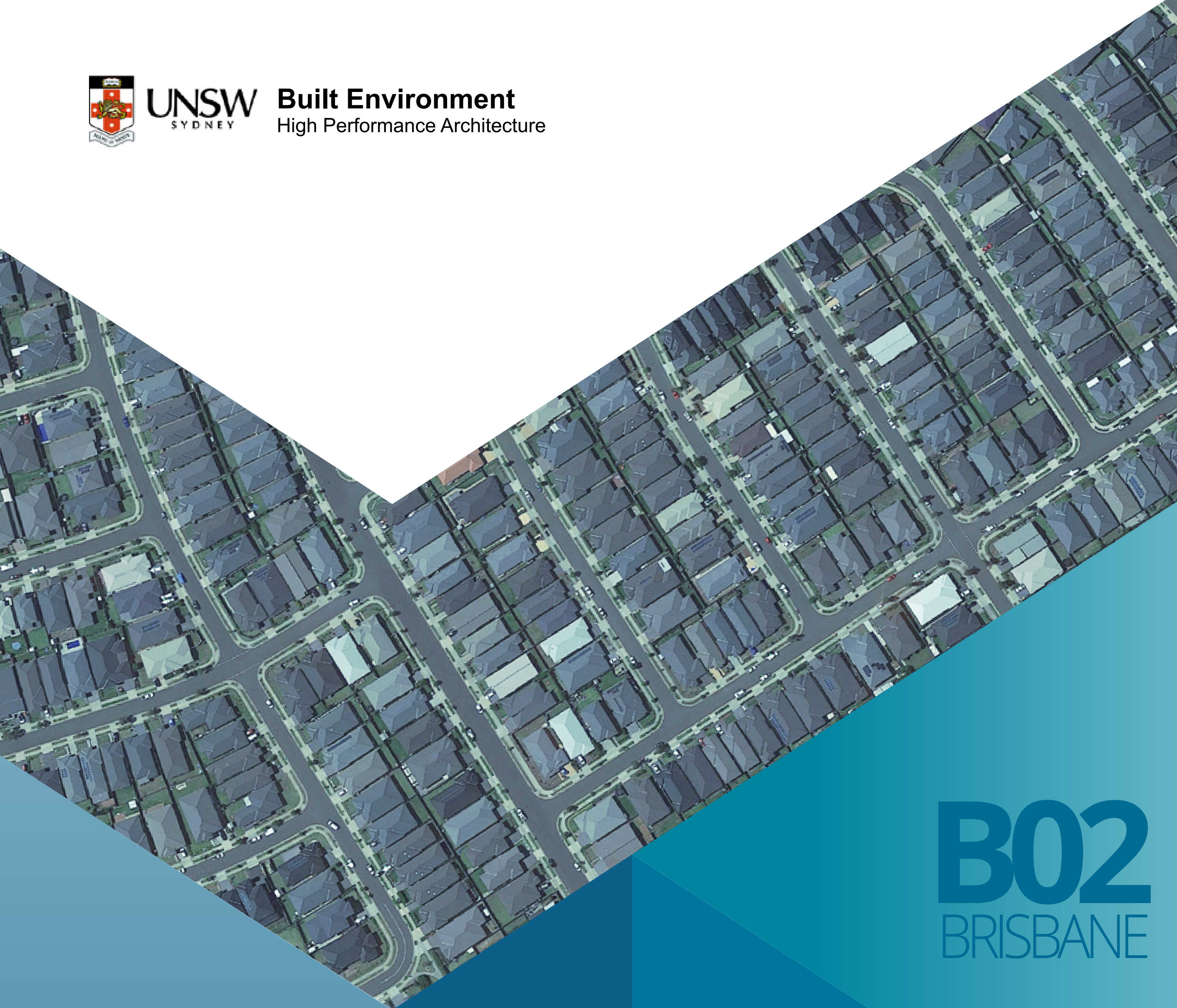

B02
BRISBANE

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

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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 Brisbane using weather data simulated by WRF.

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 34.2-35.2 kWh/m² to 31.2-33.0 kWh/m².

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.

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)
Amberley	23.7	34.2	21.0	31.2	19.7	25.2
Archerfield	21.8	35.1	19.8	32.8	18.6	25.9
Brisbane Airport	21.7	35.1	19.7	32.9	18.1	24.7
Gold Coast - Seaway	21.2	35.2	19.3	33.2	18.0	25.9
Greenbank (Defence)	21.3	35.1	19.4	33.0	17.9	25.1
Redcliffe	22.0	34.7	19.8	32.3	18.3	25.0
Redland (Alexandra Hills)	21.4	34.5	19.3	32.2	18.3	25.9

For Scenario 1, the total cooling load saving is around 2.0-3.0 kWh/m² which is equivalent to 5.7-8.8 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 8.6-10.4 kWh/m² which is equivalent to 24.9-29.6 % of total cooling load reduction.

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.

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	%
Amberley	2.7	11.4	3.0	8.8	4.0	16.9	9.0	26.3
Archerfield	2.0	9.2	2.3	6.6	3.2	14.7	9.2	26.2
Brisbane Airport	2.0	9.2	2.2	6.3	3.6	16.6	10.4	29.6
Gold Coast - Seaway	1.9	9.0	2.0	5.7	3.2	15.1	9.3	26.4
Greenbank (Defence)	1.9	8.9	2.1	6.0	3.4	16.0	10.0	28.5
Redcliffe	2.2	10.0	2.4	6.9	3.7	16.8	9.7	28.0
Redland (Alexandra Hills)	2.1	9.8	2.3	6.7	3.1	14.5	8.6	24.9

In the eleven weather stations in Brisbane, 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.

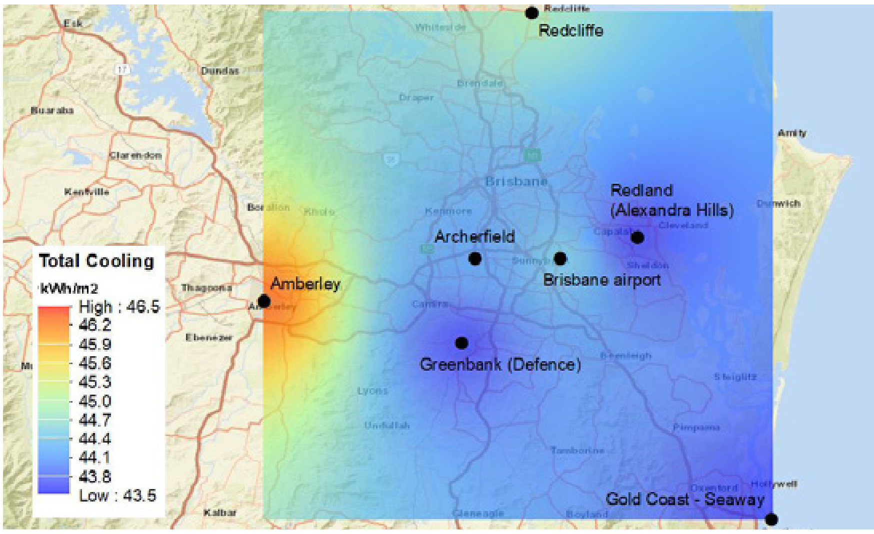

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

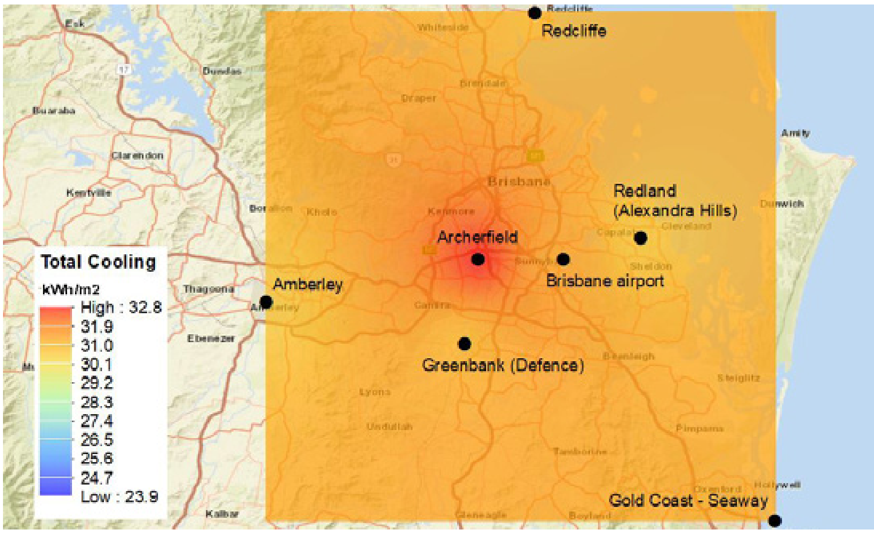

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

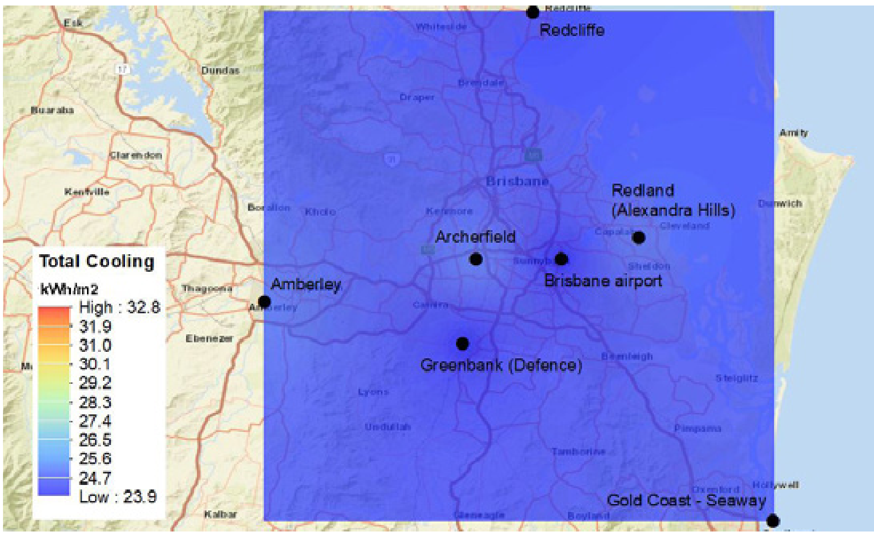

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 (0.0-0.2 kWh/m²) is significantly lower than the annual cooling load reduction (5.7-9.7 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
Amberley	75.8	80.3	0.3	0.8	65.5	72.7	0.4	1.0
Archerfield	77.7	82.9	0.1	0.3	69.9	76.1	0.2	0.4
Brisbane	85.7	91.3	0.1	0.2	74.3	81.6	0.1	0.2
Brisbane Airport	74.6	75.5	0.1	0.2	67.4	69.8	0.2	0.3
Redland (Alexandra Hills)	74.5	71.9	0.1	0.2	65.4	64.8	0.2	0.3

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 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 7.5-10.6 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.6-9.7 kWh/m² (~7.4-10.6 %).

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	%
Amberley	10.3	13.6	7.6	9.5	0.1	0.2	10.2	13.4	7.4	9.1
Archerfield	7.8	10.0	6.8	8.2	0.1	0.1	7.7	9.9	6.7	8.1
Brisbane	11.4	13.3	9.7	10.6	0.0	0.0	11.4	13.3	9.7	10.6
Brisbane Airport	7.2	9.7	5.7	7.5	0.1	0.1	7.1	9.5	5.6	7.4
Redland (Alexandra Hills)	9.1	12.2	7.1	9.9	0.1	0.1	9.0	12.1	7.0	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. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

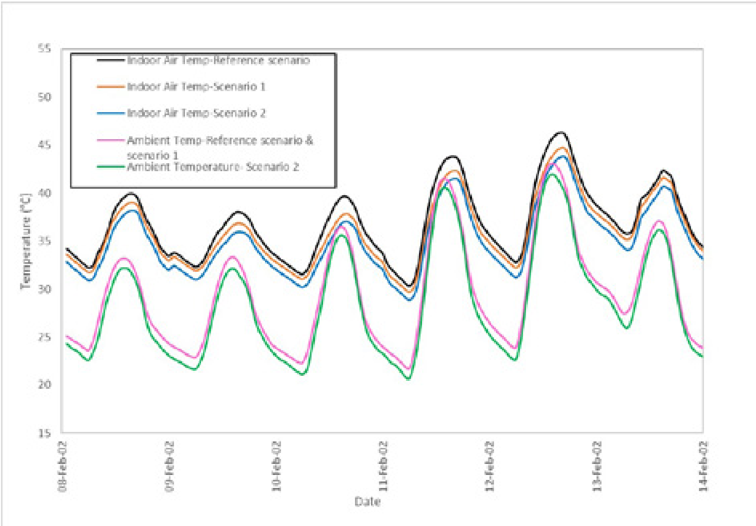

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

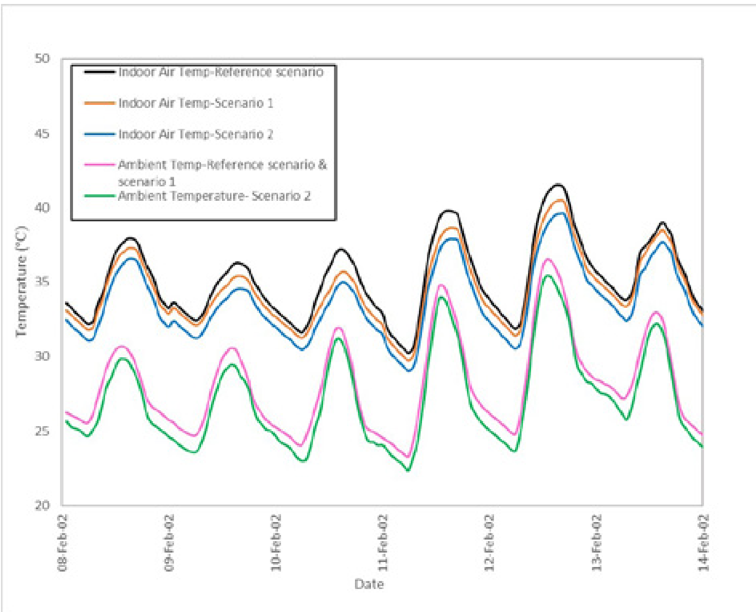

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 30.4-46.3 °C and 30.3-41.5 °C in Amberley and Redland stations, respectively.

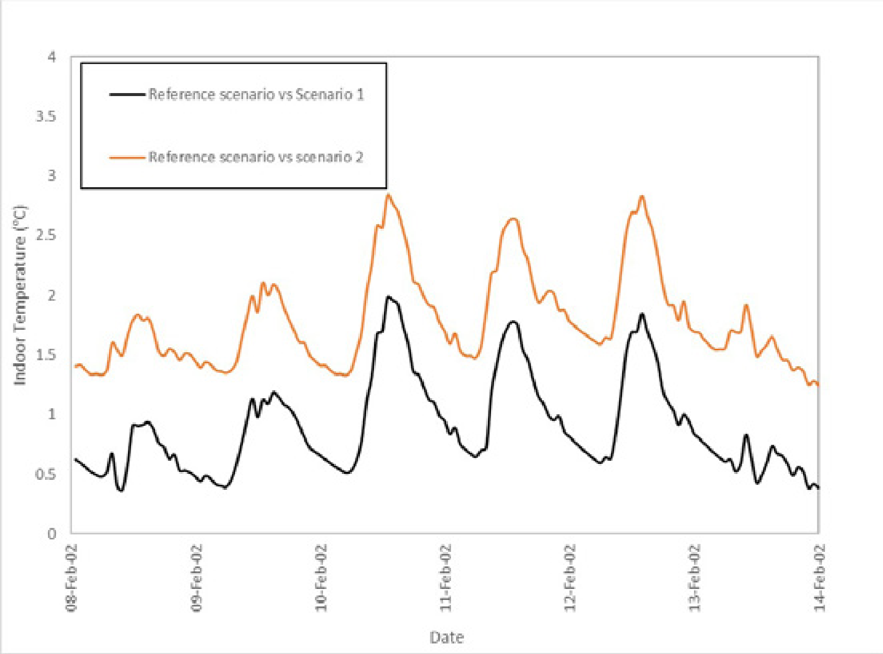

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.0 °C and 1.6 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.8 and 2.4 °C in Amberley and Redland stations, respectively.

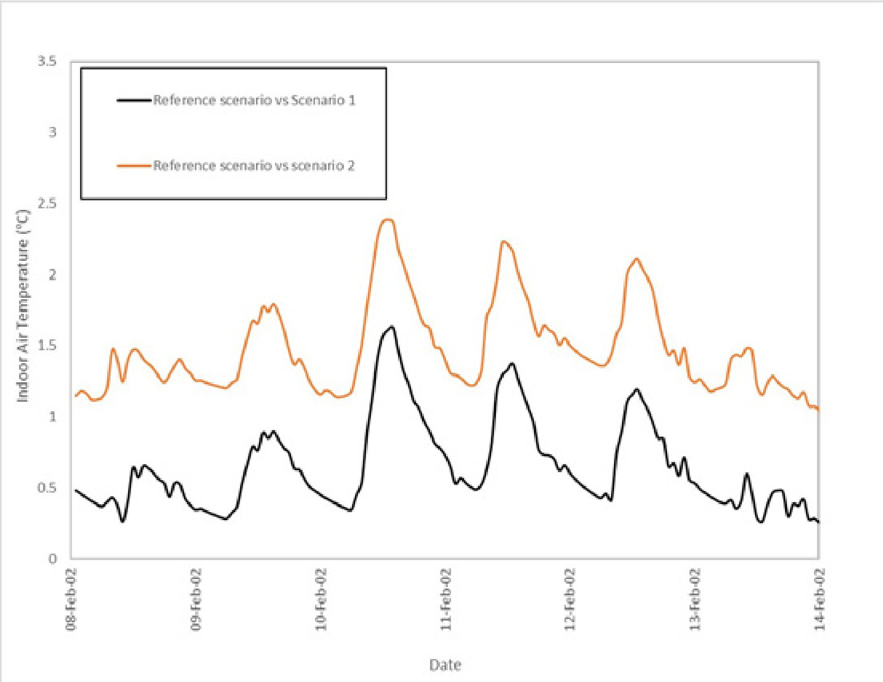

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 16.7 and 30.3 °C in reference scenario to a range between 16.5 and 29.7 °C in scenario 1 in Amberley station.

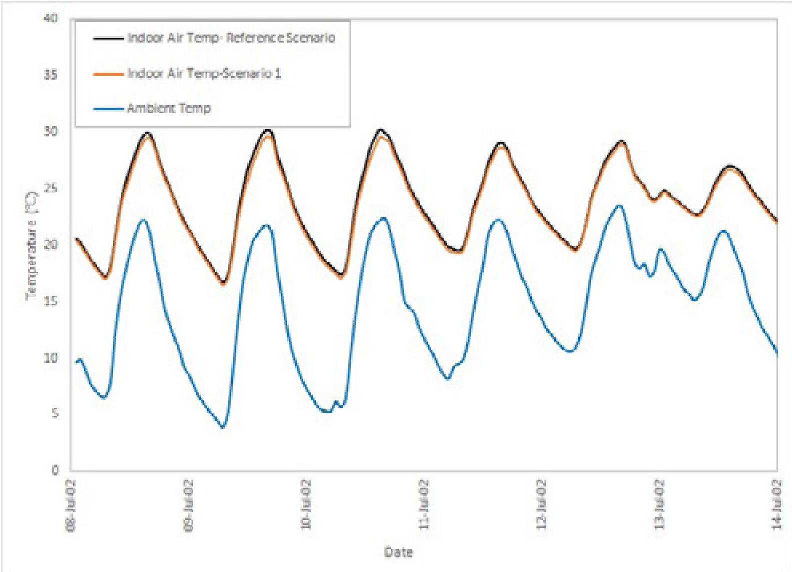

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Amberley station* using annual measured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

The indoor air temperature is predicted to slighly reduce from a range between 15.5 and 32.3 °C in reference scenario to a range between 14.8 and 28.6 °C in scenario 1 in Redland station.

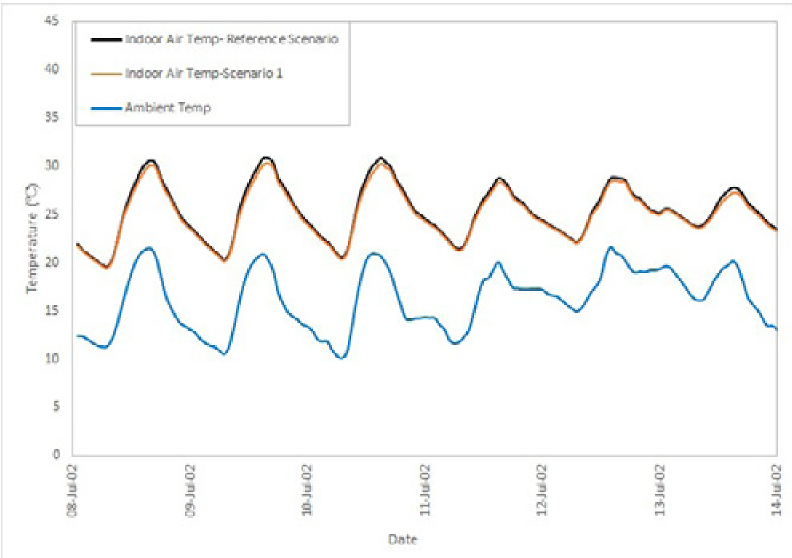

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Redland station* using annual measured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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.1 °C in Amberley and Redland stations.

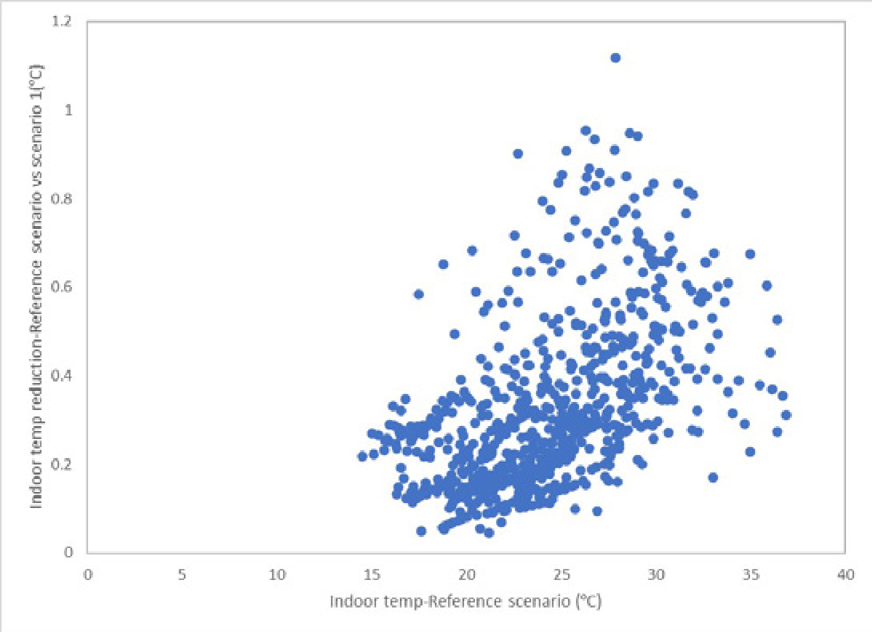

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

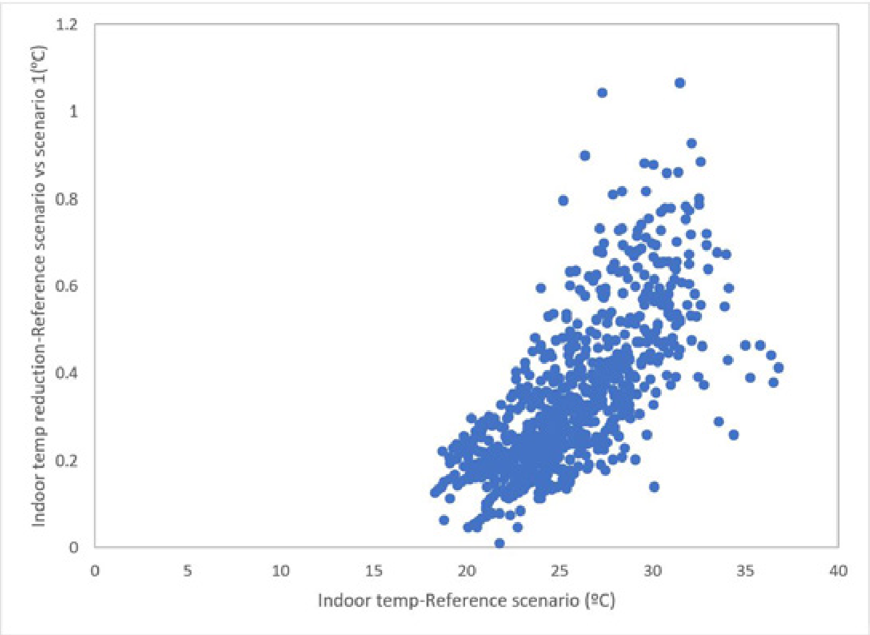

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Amberley	15	80	16	91
Redland	0	6	4	10

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

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 80 hours in reference scenario to 91 and hours and from 6 to 10 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 15 hours in reference scenario to 16 hours; and from 0 to 4 hours in scenario 1 in Amberley and Redland 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
Amberley	672	672	668
Redland	672	672	672

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 672 hours in reference scenario to 672 and 668 hours under scenario 1 and 2, in Amberley station, respectively; while oit remains the same in Redland station, with 672 hours under scenario 1 and 2.

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 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 Amberley and for Redland weather conditions, are presented in Table 7.

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.

Table 7. Energy performance features of Building 02.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	389.3	346.1
Energy consumption after cool roof (MWh)	353.8	312.5
Energy savings (MWh)	35.5	33.6
Energy savings (%)	9.12%	9.71%
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

The cool roof refurbishment options

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.

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 9,12% for the Amberley weather conditions and of 9,71% for the Redland 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 8,8 and 28,5%, 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 Amberley and for Redland weather conditions respectively.

The metal cool roof is due to its higher initial investment cost quite less attractive than the coating cool roof for all energy prices scenario.

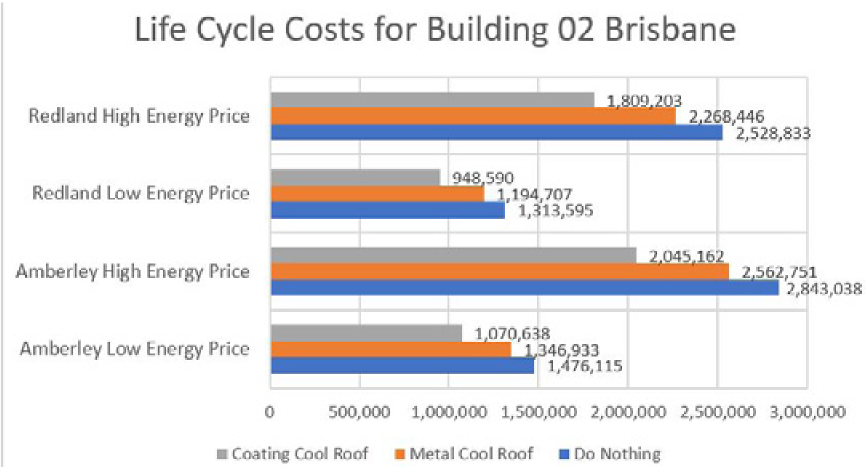

Figure 12. Life Cycle Costs for Building 02 for Amberley and Redland weather stations.

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	8.75 %	9.86 %	9.05 %	10.30 %
Coating Cool Roof	27.47 %	28.06 %	27.79 %	28.46 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 34.2-35.2kWh/m^2 to 31.2-33.0 kWh/m^2. As computed, the total cooling load saving by building-scale application of cool roofs is around 2.0-3.0 kWh/m^2 for a typical high rise office building without roof insulation. This is equal to 5.7-8.8 % 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 Brisbane, 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 8.6-10.4 kWh/m^2. This is equivalent to roughly 24.9-29.6 % 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 (0.0-0.2 kWh/m^2) is significantly lower than the annual cooling load reduction (5.7-9.7kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 7.5-10.6 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.6-9.7 kWh/m^2 (~7.4-10.6%) (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 30.4-46.3 °C and 30.3-41.5 °C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.0 and 1.6 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.8 and 2.4 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland 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 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 16.7 and 30.3 ^{o}C in reference scenario to a range between 16.5 and 29.7 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 15.5 and 32.3 °C in reference scenario to a range between 14.8 and 28.6 °C in reference with cool roof scenario (scenario 1) in Redland 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 1.1 °C in Amberley and Redland 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 80 hours in reference scenario to 91 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight increase in total number of hours below 19 °C from 6 hours in reference scenario to 10 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 15 hours in reference scenario to 16 hours in reference with cool roof scenario (scenario 1) in Amberley station. Similarly, the calculation in Redland station shows a slight increase of number of hours below 19 °C from 0 hours to 4 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 °C. As computed, the number of hours above 26 °C is 672 hours under the reference scenario in Amberley station, which remains the same under Scenario 1 and decreases to 668 under the modified urban temperature scenario (scenario 2). The simulations in Redland station show that the number of hours above 26 °C (672 hours) remain the same for all scenarios (See Table 6).

• As it can be deduced from the feasibility analysis, the 'Do Nothing' approach has clearly 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 8,8 and 28,5%, 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 quite less attractive than the coating cool roof for all energy prices scenario. 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. As a result, the coating cool roof is the advisable solution.

B02

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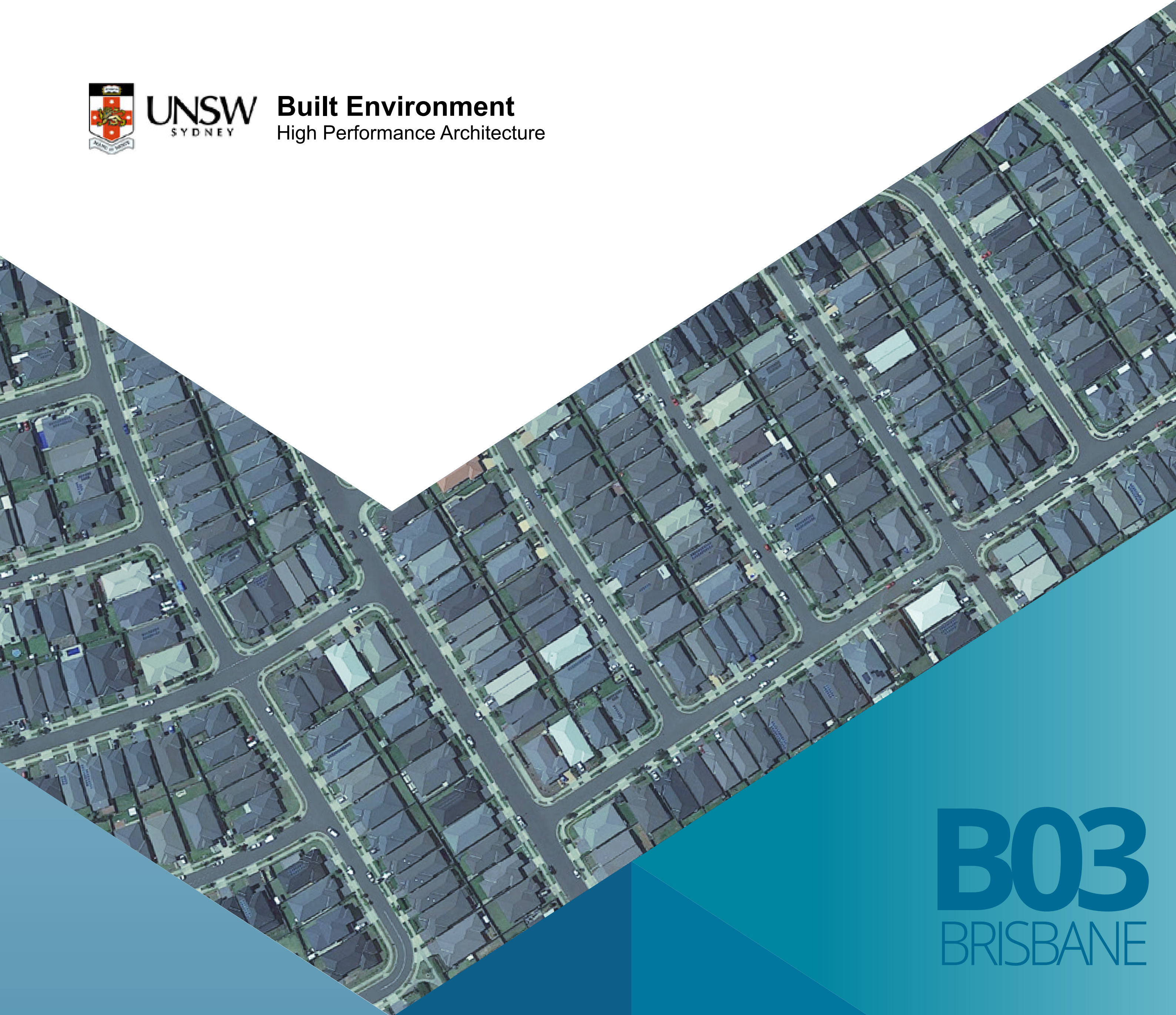

B03
BRISBANE

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 : 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

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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 Brisbane 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 low-rise office building with roof insulation from 32.1-33.7 kWh/m² to 30.5-32.4 kWh/m².

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.

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)
Amberley	21.8	32.1	20.5	30.5	19.2	24.6
Archerfield	20.7	33.1	19.4	31.9	18.2	25.4
Brisbane Airport	20.4	33.5	19.3	32.2	17.7	24.3
Gold Coast - Seaway	20	33.7	19	32.4	17.7	25.4
Greenbank (Defence)	20.1	33.5	19.1	32.2	17.7	24.6
Redcliffe	20.6	32.9	19.4	31.5	17.9	24.5
Redland (Alexandra Hills)	20.2	32.7	19.1	31.4	17.9	25.4

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 1.2-1.6 kWh/m² which is equivalent to 3.6-5.0 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.3-9.2 kWh/m² which is equivalent to 22.3-27.5 % 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	%
Amberley	1.3	6.0	1.6	5.0	2.6	11.9	7.5	23.4
Archerfield	1.3	6.3	1.2	3.6	2.5	12.1	7.7	23.3
Brisbane Airport	1.1	5.4	1.3	3.9	2.7	13.2	9.2	27.5
Gold Coast - Seaway	1.0	5.0	1.3	3.9	2.3	11.5	8.3	24.6
Greenbank (Defence)	1.0	5.0	1.3	3.9	2.4	11.9	8.9	26.6
Redcliffe	1.2	5.8	1.4	4.3	2.7	13.1	8.4	25.5
Redland (Alexandra Hills)	1.1	5.4	1.3	4.0	2.3	11.4	7.3	22.3

In the eleven weather stations in Brisbane, 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.

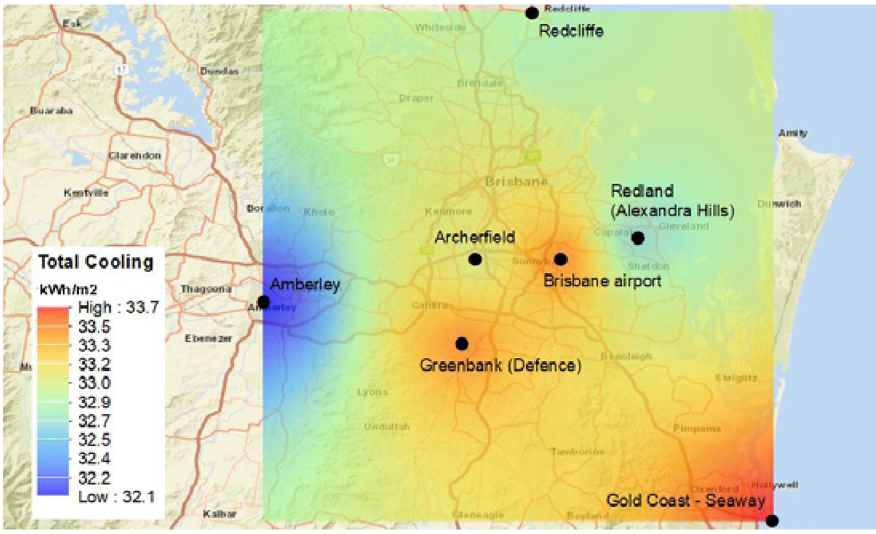

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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.

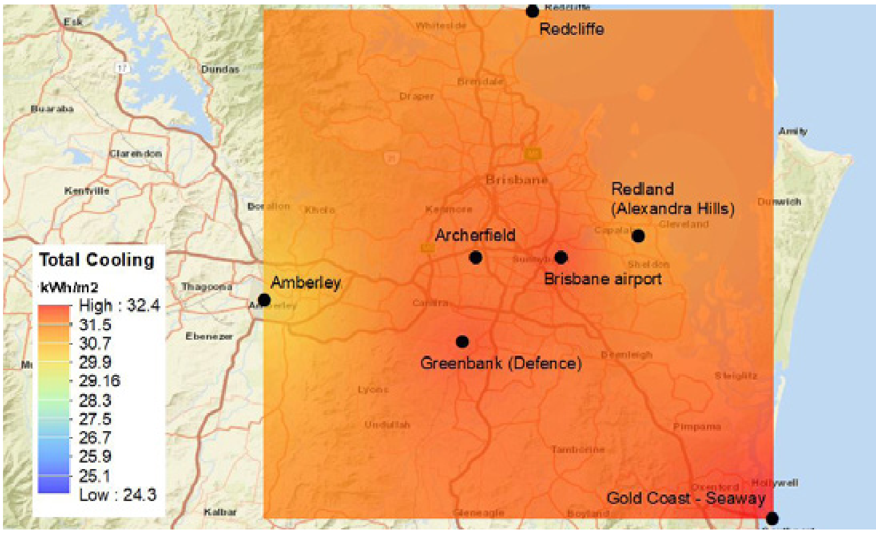

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

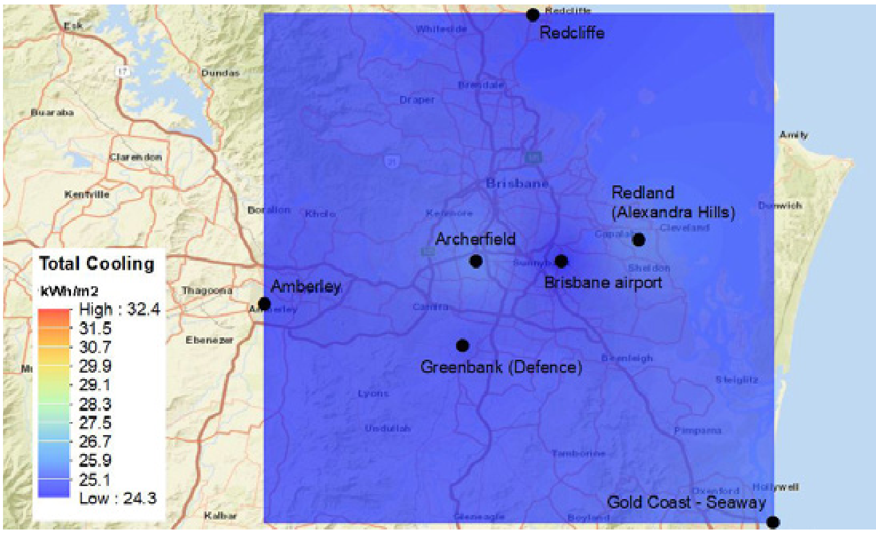

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

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 (73.0-81.0 kWh/m²) that is significantly higher than the annual cooling load reduction (0.1-0.5 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
Amberley	113.8	114.6	1.1	2.0	61.2	71.4	1.7	2.9
Archerfield	110.2	113.5	0.7	1.2	62.1	73.2	1.1	1.8
Brisbane	129.1	131.6	0.4	0.8	66.6	78.9	0.7	1.3
Brisbane Airport	101.4	100.3	0.4	0.9	57.9	65.6	0.8	1.4
Redland (Alexandra Hills)	110.3	103.2	0.4	0.9	57.2	62.0	0.9	1.5

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 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 0.2-1.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 73.6-81.4 kWh/m² (~73.2-86.2 %).

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	%
Amberley	73.6	77.2	0.5	1.0	68.4	73.0	0.5	1.1	73.6	77.2
Archerfield	76.1	80.2	0.2	0.4	71.2	76.2	0.2	0.5	76.1	80.2
Brisbane	81.4	86.2	0.1	0.2	75.2	81.0	0.1	0.2	81.4	86.2
Brisbane Airport	73.6	73.2	0.1	0.2	69.1	69.7	0.2	0.3	73.6	73.2
Redland (Alexandra Hills)	72.5	68.6	0.2	0.3	67.1	64.6	0.2	0.3	72.5	68.6

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 (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

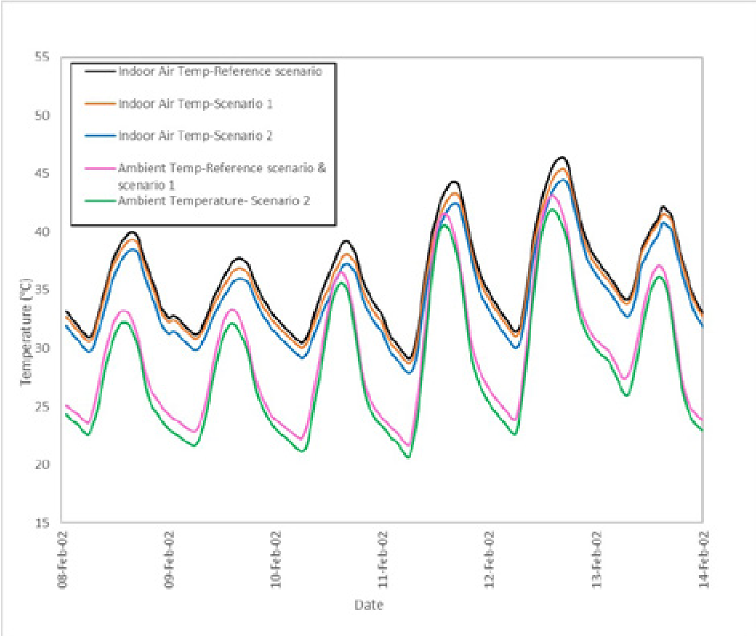

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

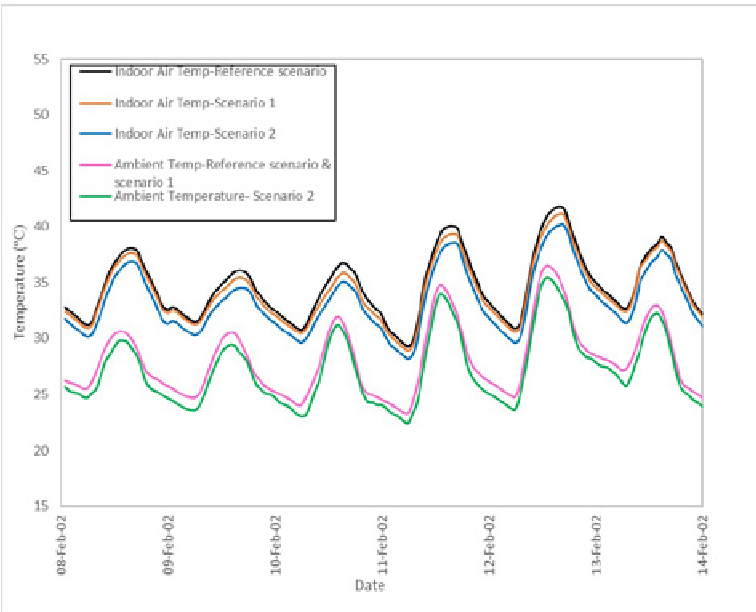

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 29.2-46.4 °C and 29.3-41.8 °C in Amberley and Redland stations, respectively.

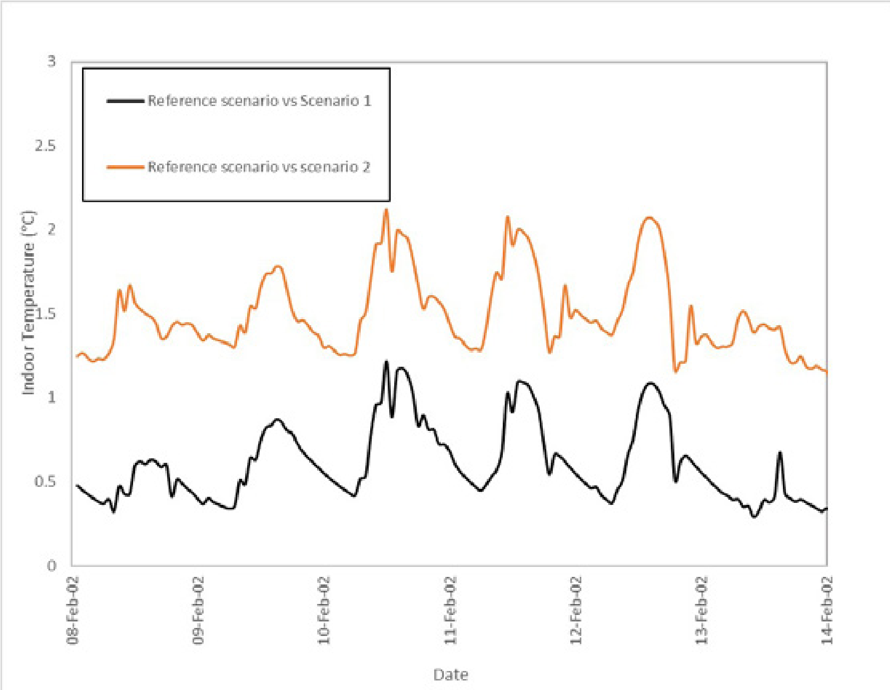

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.2 °C and 1.0 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.1 and 1.7 °C in Amberley and Redland stations, respectively.

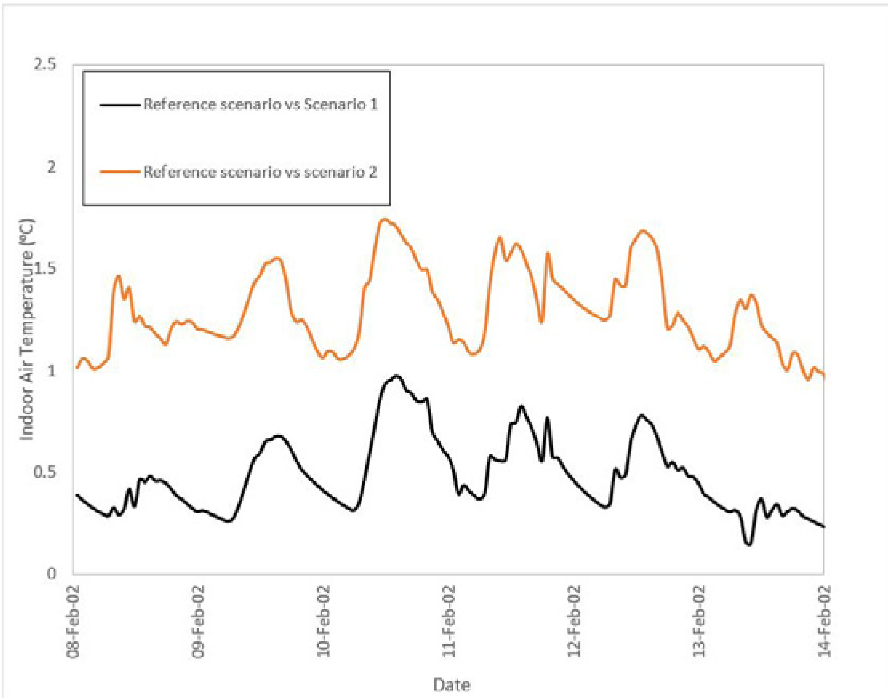

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 15.5 and 31.6 °C in reference scenario to a range between 15.3 and 31.1 °C in scenario 1 in Amberley station.

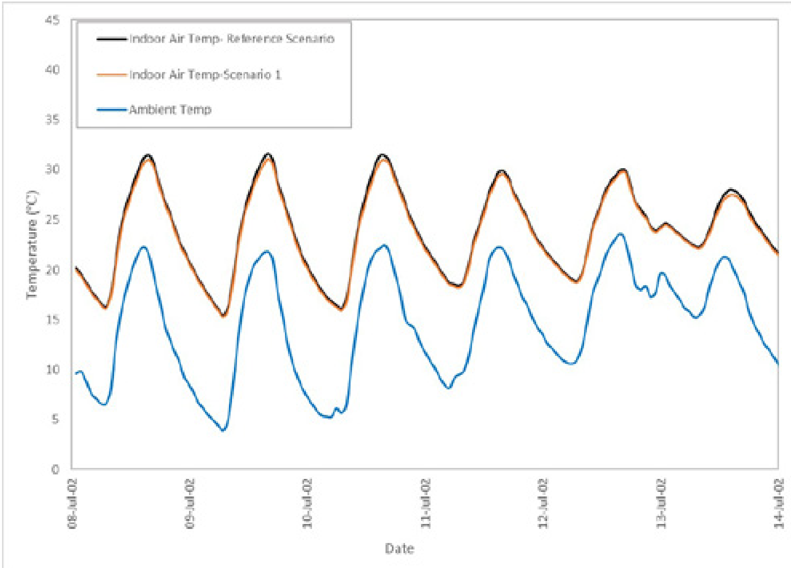

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Amberley station* using annual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

The indoor air temperature is predicted to reduce from a range between 18.9 and 32.1 °C in reference scenario to a range between 18.7 and 31.6 °C in scenario 1 in Redland station.

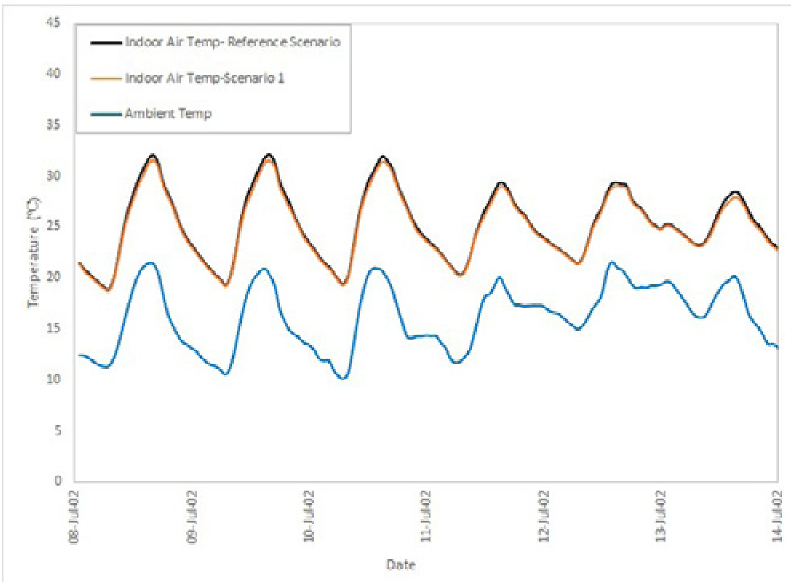

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Redland station* using annual 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 1.0 °C in Amberley and Redland stations.*

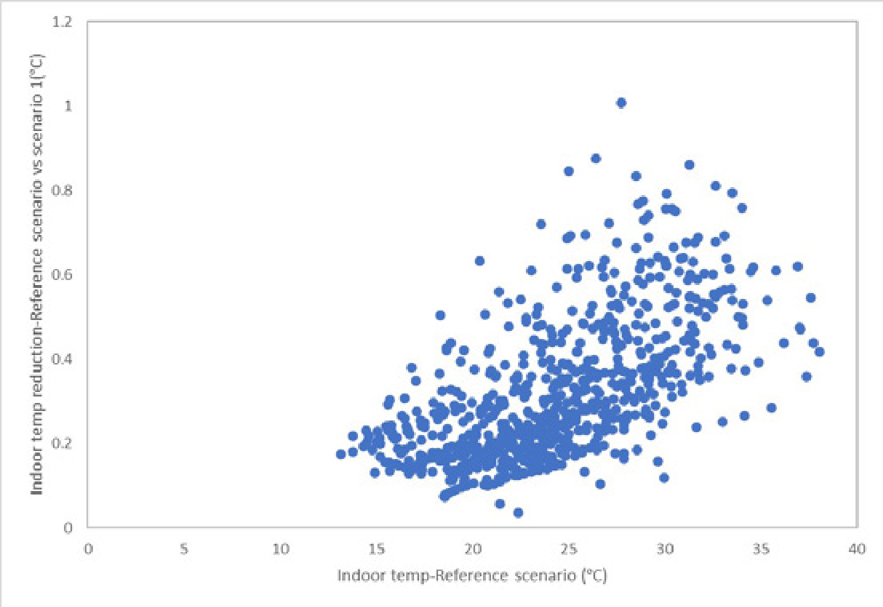

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

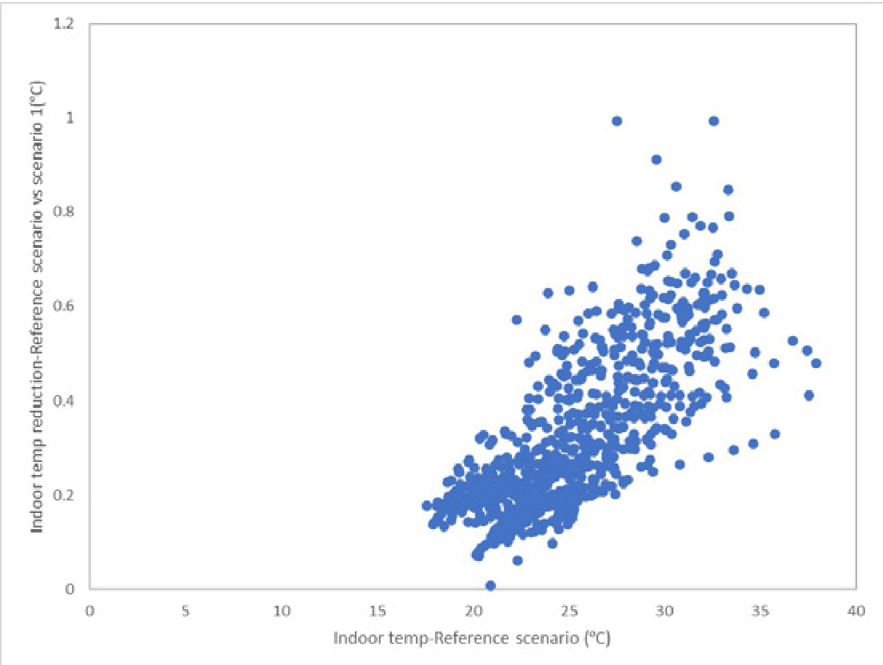

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Brisbane (i.e. Amberley and Redland) 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]

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase slightly from 109 hours in reference scenario to 116 hours, and from 21 to 24 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 24 hours in reference scenario to 27 hours; and from 7 to 15 hours in scenario 1 in Amberley and Redland 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
Amberley	24	109	27	116
Redland	7	21	15	24

** 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 670 hours in reference scenario to 668 and 662 hours under scenario 1 and 2, in Amberley station; while it remains the same with 672 hours in Redland 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
Amberley	670	668	662
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 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 Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 03.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	75.1	66.1
Energy consumption after cool roof (MWh)	71.1	62.3
Energy savings (MWh)	4.0	3.8
Energy savings (%)	5.33%	5.75%
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 5,33% for the Amberley weather conditions and of 5,75% for the Redland 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 19.1% for the low energy price scenario for Redland and 22,4% for the high energy scenario and for Redland 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 Amberley and for Redland weather conditions respectively.

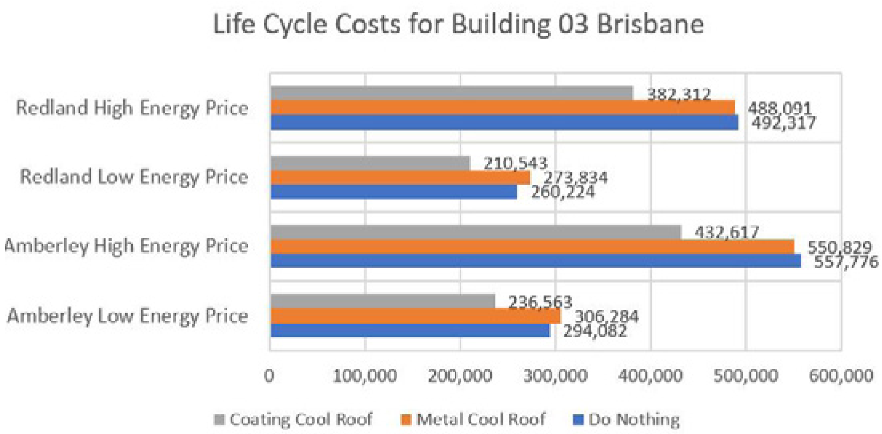

Figure 12. Life Cycle Costs for Building 03 for Amberley and Redland weather stations.

The metal cool roof is due to its higher initial investment cost marginally feasible for the high energy price scenario.

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	-4.15 %	1.25 %	-5.23 %	0.86 %
Coating Cool Roof	19.56 %	22.44 %	19.09 %	22.34 %

7

CONCLUSIONS

• In the eleven weather stations in Brisbane, 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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 32.1-33.7 kWh/m^2 to 30.5-32.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.2-1.6 kWh/m^2. This is equivalent to approximately 3.6-5.0 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.3-9.2 kWh/m^2. This is equivalent to 22.3-27.5 % 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 73.0-81.0 kWh/m^2) is significantly higher than the annual cooling load reduction (0.1-0.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.2-1.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 73.6-81.4 kWh/m^2 (~73.2-86.2 %) (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 Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.2 and 1.0 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.1 and 1.7 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland 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 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 115.5 and 31.6 °C in reference scenario to a range between 15.3 and 31.1 °C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 18.9 and 32.1 °C in reference scenario to a range between 18.7 and 31.6 °C in reference with cool roof scenario (scenario 1) in Redland 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 1.0 °C in Amberley and Redland stations. 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 109 hours in reference scenario to 116 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland station also show a increase in total number of hours below 19 °C from 21 hours in reference scenario to 24 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 24 hours in reference scenario to 27 hours in reference with cool roof scenario (scenario 1) in Amberley station. Similarly, the calculation in Redland station shows a slightly increase of number of hours below 19 °C from 7 hours to 15 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 670 hours under the reference scenario in Amberley station, which slightly decreases to 668 and 662 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Redland station also shows that the number of hours above 26 °C remain the same for all scenarios with 672 hours in total (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 19.1% for the low energy price scenario for Redland and 22,4% for the high energy scenario and for Redland conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost marginally feasible for the high energy price scenario. 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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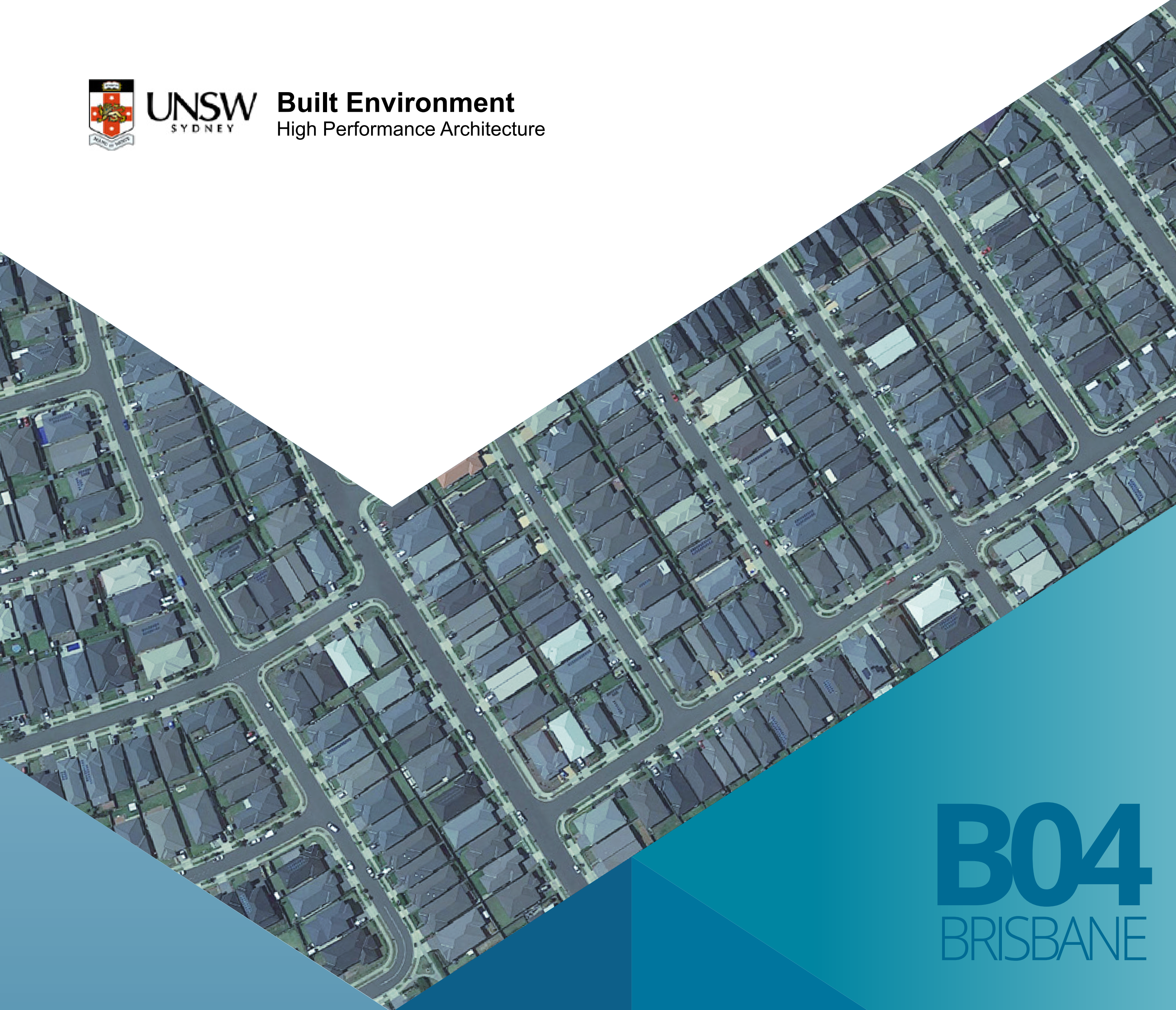

B04
BRISBANE

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	: 1200m²
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

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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 Brisbane using weather data simulated by WRF.

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.

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 31.6-33.8 kWh/m² to 31.3-33.6 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)
Amberley	21.3	31.6	21	31.3	19.8	25.3
Archerfield	20.2	33.3	20	33.1	18.8	26.2
Brisbane Airport	20.1	33.5	19.9	33.2	18.3	25
Gold Coast - Seaway	19.8	33.8	19.6	33.6	18.4	26.3
Greenbank (Defence)	19.9	33.6	19.7	33.4	18.3	25.5
Redcliffe	20.2	32.9	20	32.6	18.5	25.2
Redland (Alexandra Hills)	19.8	32.8	19.6	32.6	18.6	26.2

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 0.2-0.3 kWh/m² which is equivalent to 0.6-0.9 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.3-8.5 kWh/m² which is equivalent to 19.9-25.4 % 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	%
Amberley	0.3	1.4	0.3	0.9	1.5	7.0	6.3	19.9
Archerfield	0.2	1.0	0.2	0.6	1.4	6.9	7.1	21.3
Brisbane Airport	0.2	1.0	0.3	0.9	1.8	9.0	8.5	25.4
Gold Coast - Seaway	0.2	1.0	0.2	0.6	1.4	7.1	7.5	22.2
Greenbank (Defence)	0.2	1.0	0.2	0.6	1.6	8.0	8.1	24.1
Redcliffe	0.2	1.0	0.3	0.9	1.7	8.4	7.7	23.4
Redland (Alexandra Hills)	0.2	1.0	0.2	0.6	1.2	6.1	6.6	20.1

In the eleven weather stations in Brisbane, 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.

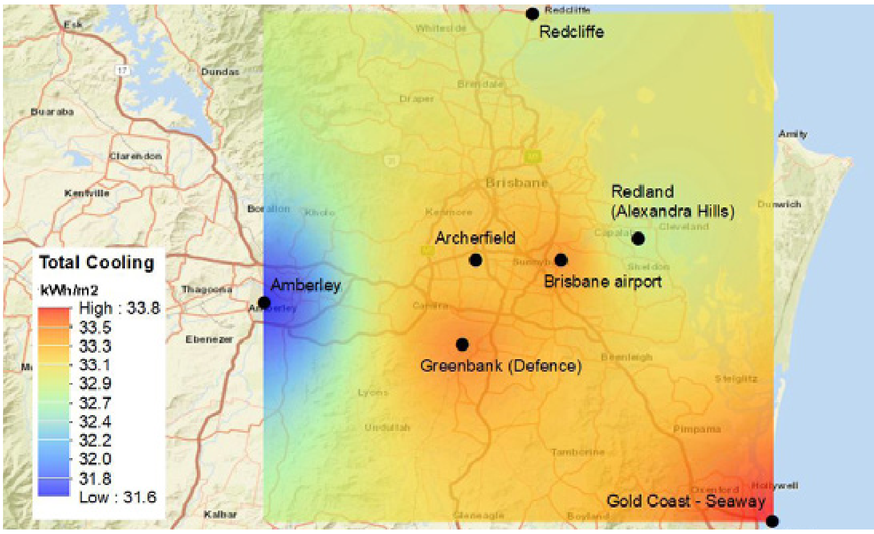

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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

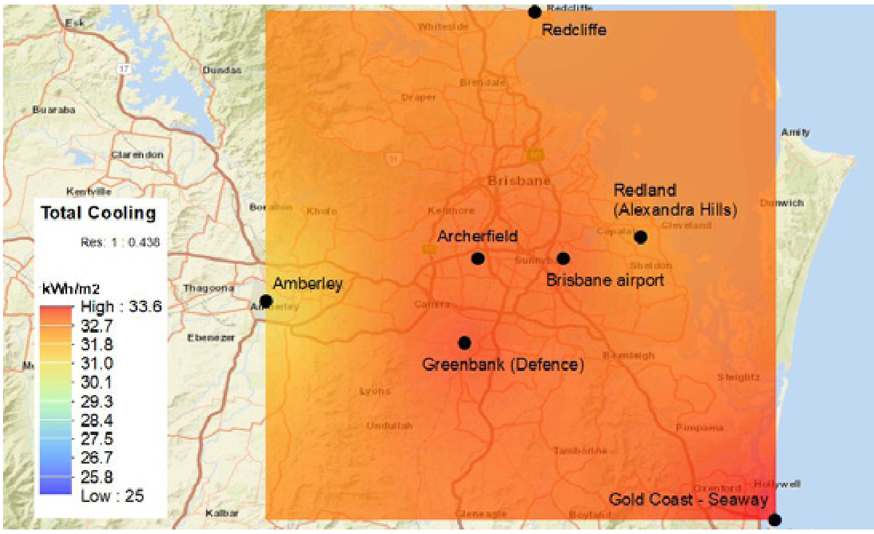

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

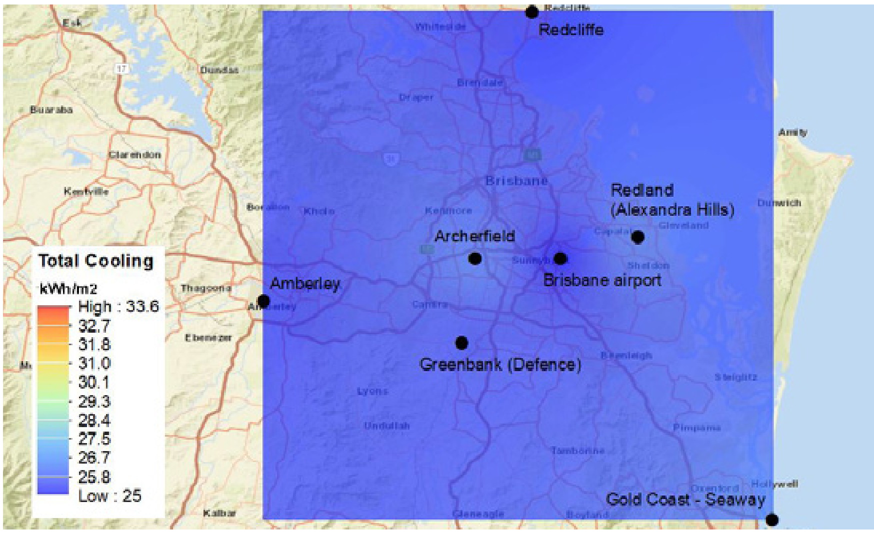

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

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 lower than the annual cooling load reduction (0.6-1.0 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
Amberley	69.9	74.5	0.2	0.6	68.9	73.7	0.2	0.7
Archerfield	73.2	78.1	0.1	0.2	72.4	77.4	0.1	0.2
Brisbane	78.2	83.7	0.0	0.1	77.1	82.7	0.0	0.1
Brisbane Airport	71.4	71.9	0.0	0.1	70.7	71.3	0.0	0.1
Redland (Alexandra Hills)	69.3	66.7	0.0	0.1	68.4	66	0.0	0.1

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 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 0.8-1.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6 and 1.0 kWh/m² (~0.8-1.2 %).

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	%
Amberley	1.0	1.4	0.8	1.1	0.0	0.1	1.0	1.4	0.7	0.9
Archerfield	0.8	1.1	0.7	0.9	0.0	0.0	0.8	1.1	0.7	0.9
Brisbane	1.1	1.4	1.0	1.2	0.0	0.0	1.1	1.4	1.0	1.2
Brisbane Airport	0.7	1.0	0.6	0.8	0.0	0.0	0.7	1.0	0.6	0.8
Redland (Alexandra Hills)	0.9	1.3	0.7	1.0	0.0	0.0	0.9	1.3	0.7	1.0

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. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

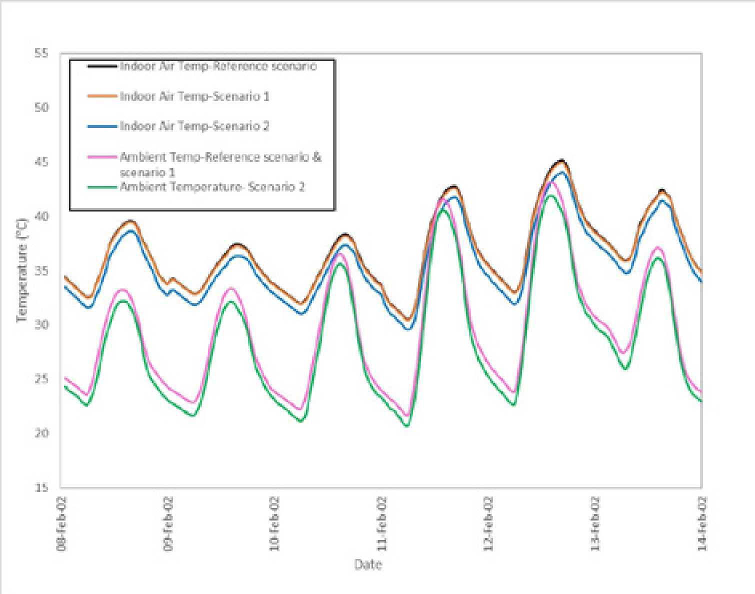

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

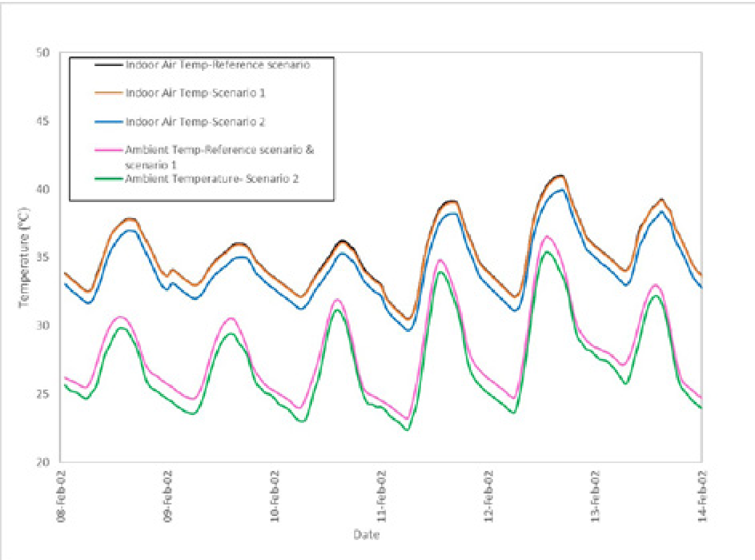

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 30.5-45.1 °C and 30.5-41.0 °C in Amberley and Redland stations, respectively.

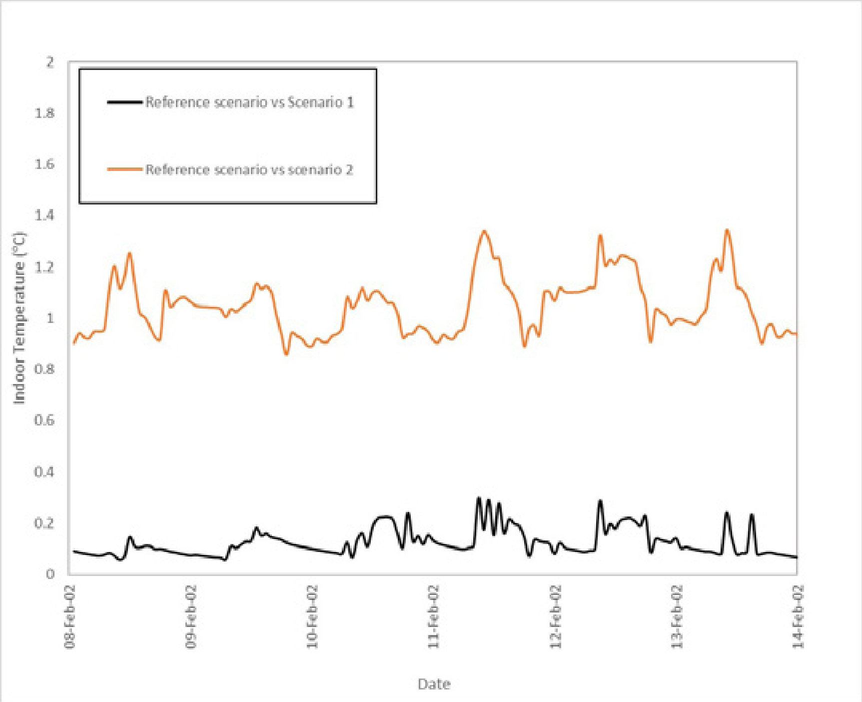

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during a typical summer week in *Amberley 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 0.2 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.3 and 1.2 °C in Amberley and Redland stations, respectively.

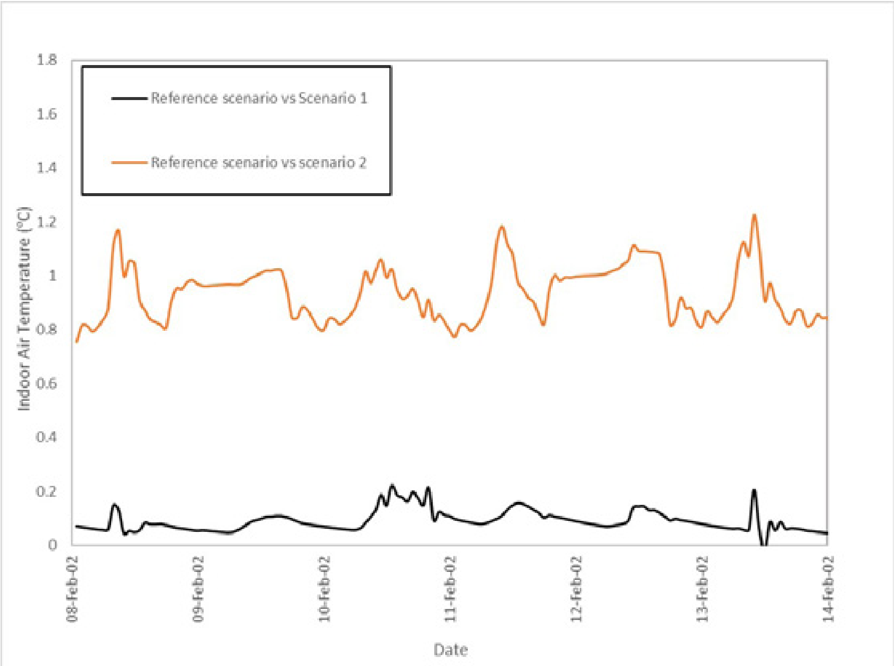

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) 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 Amberley and Redland stations, respectively.

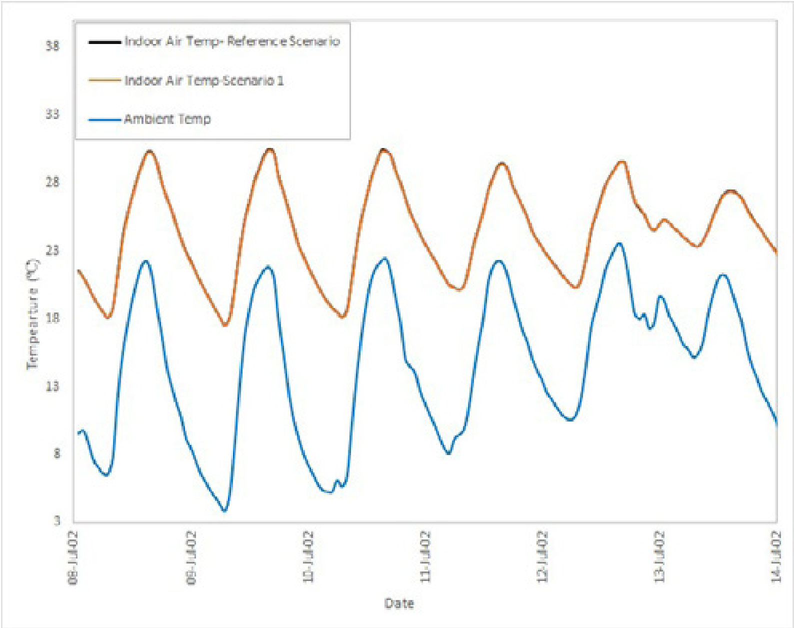

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Amberley station* using annual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

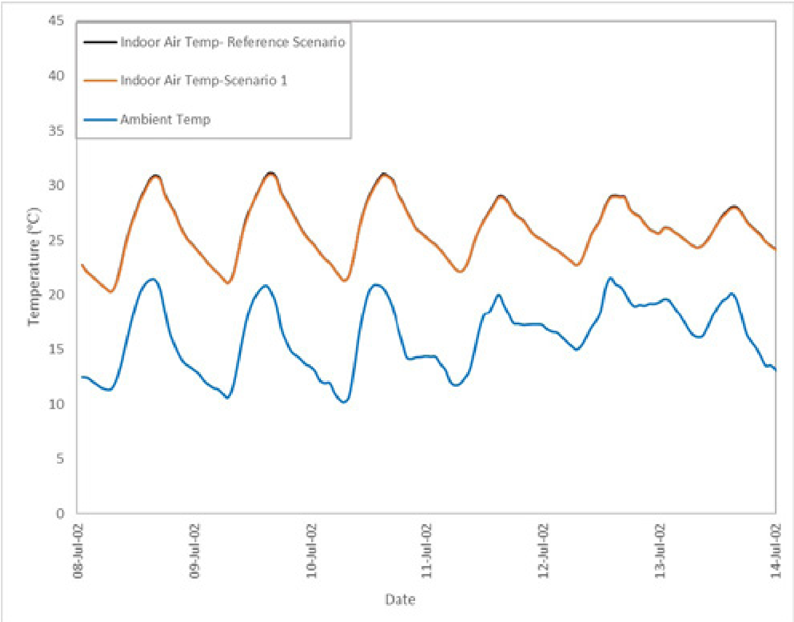

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Redland station* using annual measured 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 and 0.3 °C in Amberley and Redland stations, respectively.*

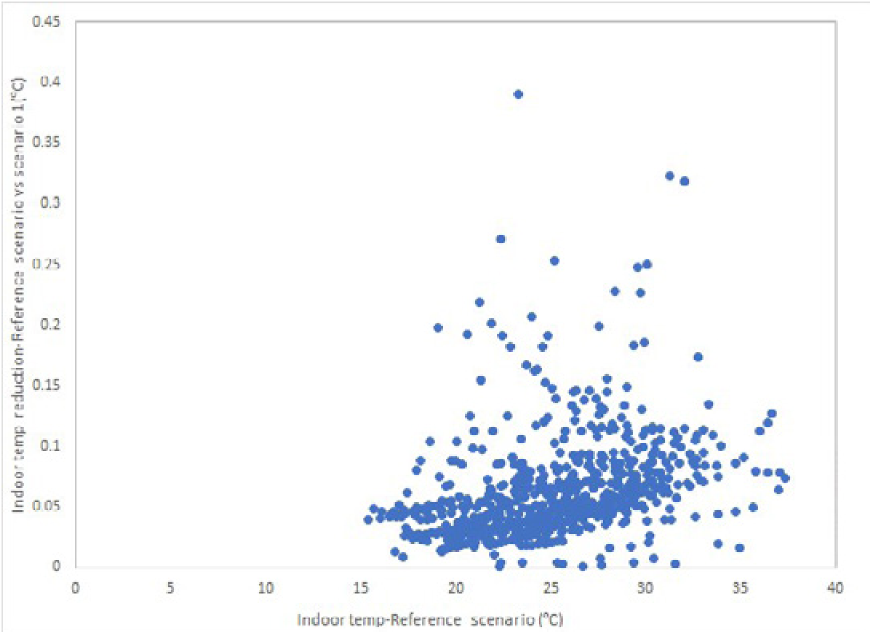

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

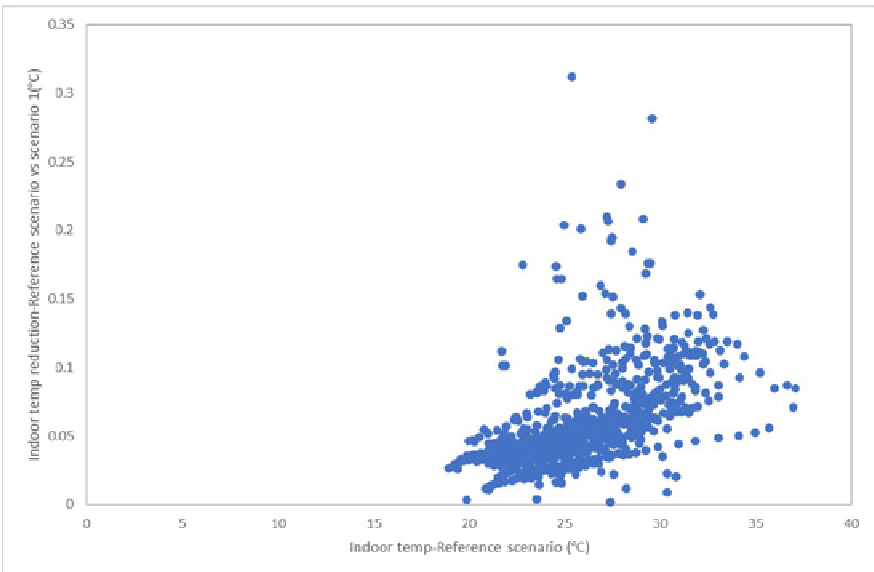

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 57 hours to 59 hours in reference scenario in Amberley station while remains the same for Redland station.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 10 to 14 hours in Amberley stations and remain the same for reference scenario and scenario 1 in Redland 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
Amberley	10	57	14	59
Redland	0	1	0	1

** 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 remain the same (672 hours) for all scenarios in Amberley and Redland stations.

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
Amberley	672	672	672
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 04.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	360.5	320.6
Energy consumption after cool roof (MWh)	357.1	317.3
Energy savings (MWh)	3.4	3.3
Energy savings (%)	0.94 %	1.03 %
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 energy savings of 0,94% for the Amberley weather conditions and of 1,03% for the Redland 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 20,8% for the low energy price scenario for both locations and 21,5% for the high energy scenario and for Amberley conditions.

The metal cool roof is due to its higher initial investment cost marginally feasible.

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 Frankston Beach and for Coldstream weather conditions respectively.

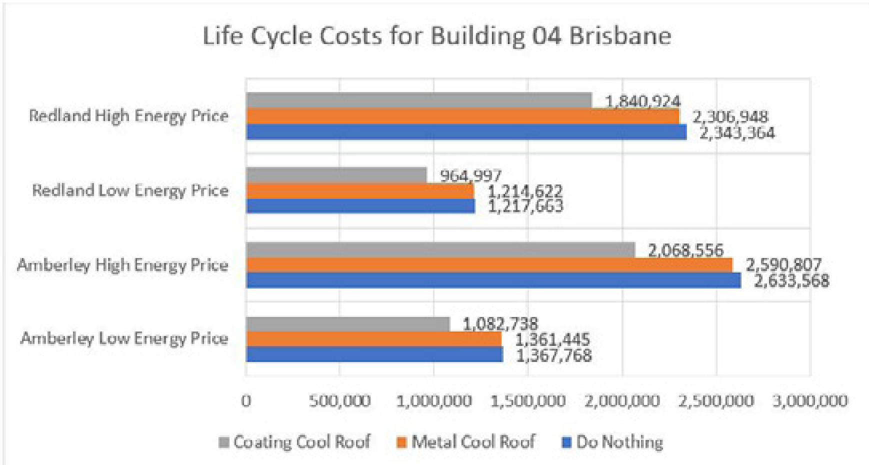

Figure 12. Life Cycle Costs for Building 04 for Amberley and Redland weather stations.

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	0.46 %	1.62 %	0.25 %	1.55 %
Coating Cool Roof	20.84 %	21.45 %	20.75 %	21.44 %

7

CONCLUSIONS

• In the eleven weather stations in Brisbane, 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 31.6-33.8 kWh/m^2 to 31.3-33.6 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 0.2-0.3 kWh/m^2 (~0.6-0.9 %) (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 6.3-8.5 kWh/m^2 (~19.9-25.4 %) 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 lower than the annual cooling load reduction (0.6-1.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.8-1.1%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6 and 1.0 kWh/m^2 (~0.8-1.2 %) (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 22.0-36.0 ^{o}C and 21.3-37.0 ^{o}C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.3 ^{o}C and 0.2 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.3 and 1.2 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 Amberley and Redland 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 0.4 °C and 0.3 °C in Amberley and Redland 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 57 hours in reference scenario to 59 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations show that the total number of hours below 19 °C remain the same for the reference scenario and scenario 1. Also, 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 10 to 14 hours in Amberley stations and remain the same for reference scenario and scenario 1 in Redland station. (See Table 5).

• During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to remain the same with 672 hours for all scenarios, in Amberley and Redland stations (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 20,8% for the low energy price scenario for both locations and 21,5% for the high energy scenario and for Amberley conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost marginally 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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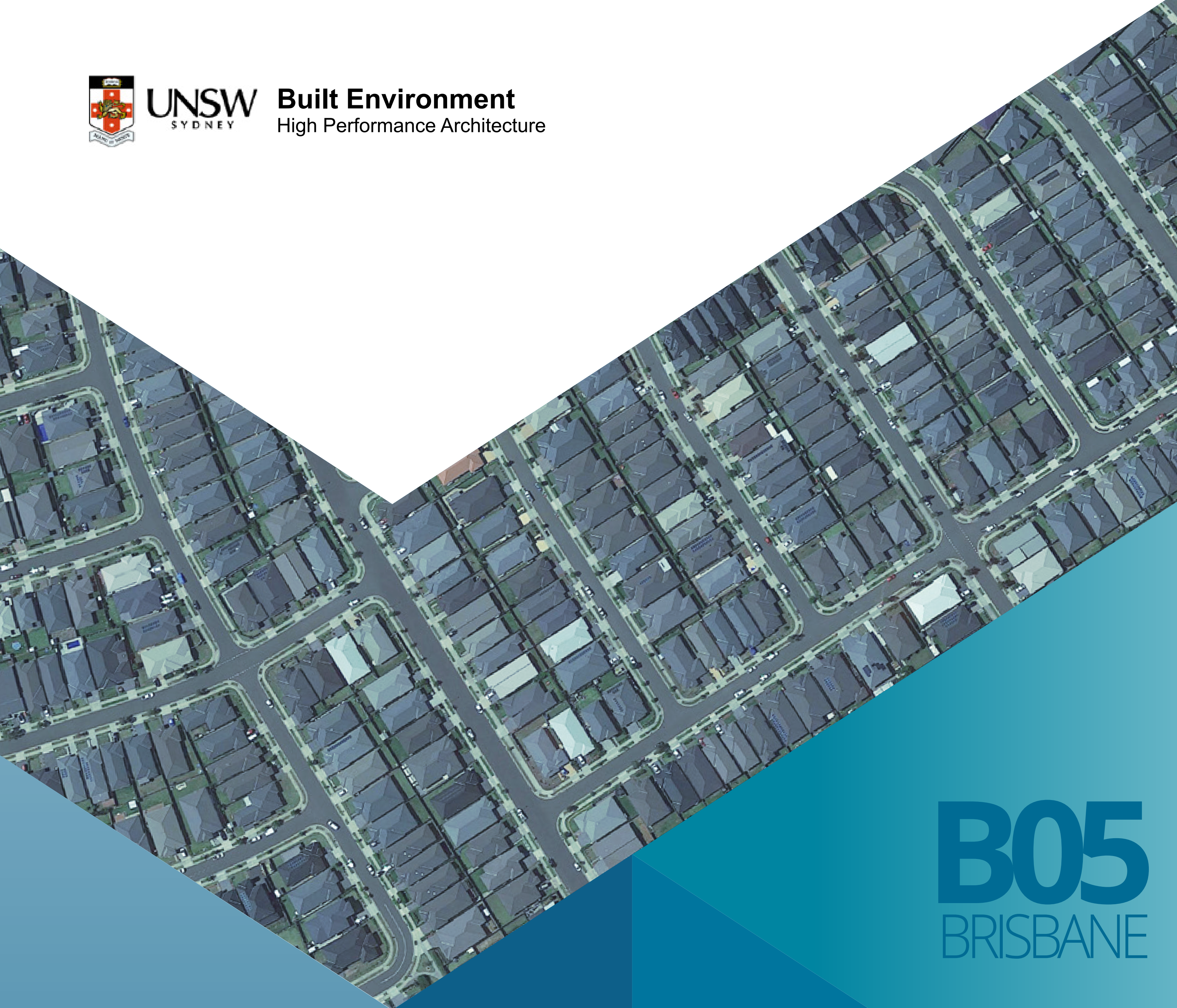

B05 BRISBANE

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise shopping mall centre
2021

BUILDING 05

NEW LOW-RISE SHOPPING MALL CENTRE

Floor area : 1100m²
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

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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 Brisbane 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 low-rise office building from 96.4-98.2 kWh/m² to 94.5-97.8 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)
Amberley	65.9	96.4	64.1	94.5	61.4	80.2
Archerfield	62.2	98.4	60.8	96.9	57.9	81.9
Brisbane Airport	61.9	99.1	60.5	97.5	56.8	79.7
Gold Coast - Seaway	60.5	99.4	59.2	97.8	56.3	82.7
Greenbank (Defence)	60.9	99.1	59.5	97.5	56.4	80.9
Redcliffe	61.9	98.2	60.4	96.9	57.3	80.1
Redland (Alexandra Hills)	61.1	97.7	59.7	96.2	57.2	82.3

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.

For Scenario 1, the total cooling load saving is around 1.3-1.9 kWh/m² which is equivalent to 1.3-2.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 15.4-19.4 kWh/m² which is equivalent to 15.8-19.6 % 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	%
Amberley	1.8	2.7	1.9	2.0	4.5	6.8	16.2	16.8
Archerfield	1.4	2.3	1.5	1.5	4.3	6.9	16.5	16.8
Brisbane Airport	1.4	2.3	1.6	1.6	5.1	8.2	19.4	19.6
Gold Coast - Seaway	1.3	2.1	1.6	1.6	4.2	6.9	16.7	16.8
Greenbank (Defence)	1.4	2.3	1.6	1.6	4.5	7.4	18.2	18.4
Redcliffe	1.5	2.4	1.3	1.3	4.6	7.4	18.1	18.4
Redland (Alexandra Hills)	1.4	2.3	1.5	1.5	3.9	6.4	15.4	15.8

> *In the eleven weather stations in Brisbane, 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.*

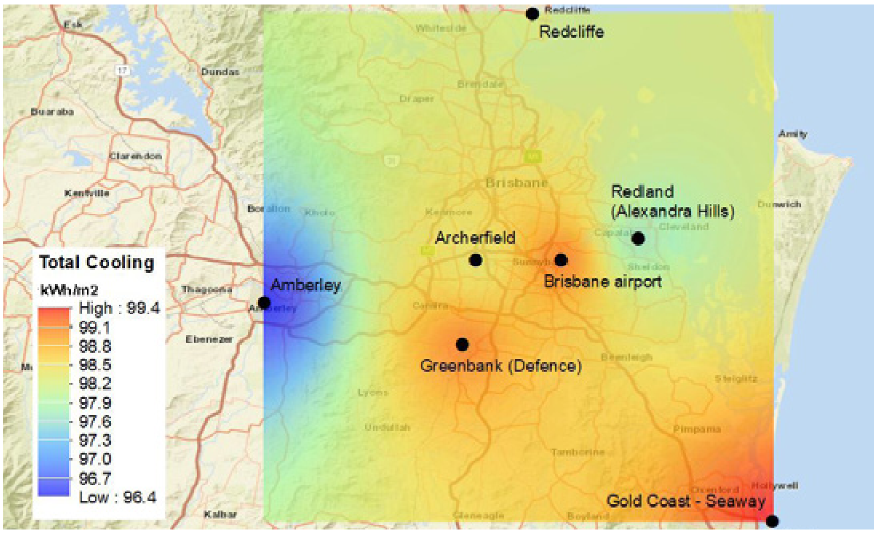

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

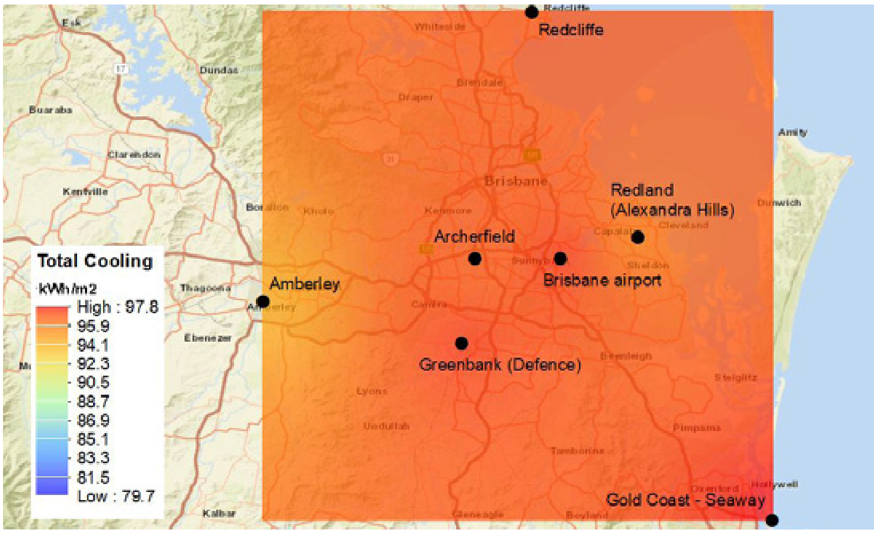

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

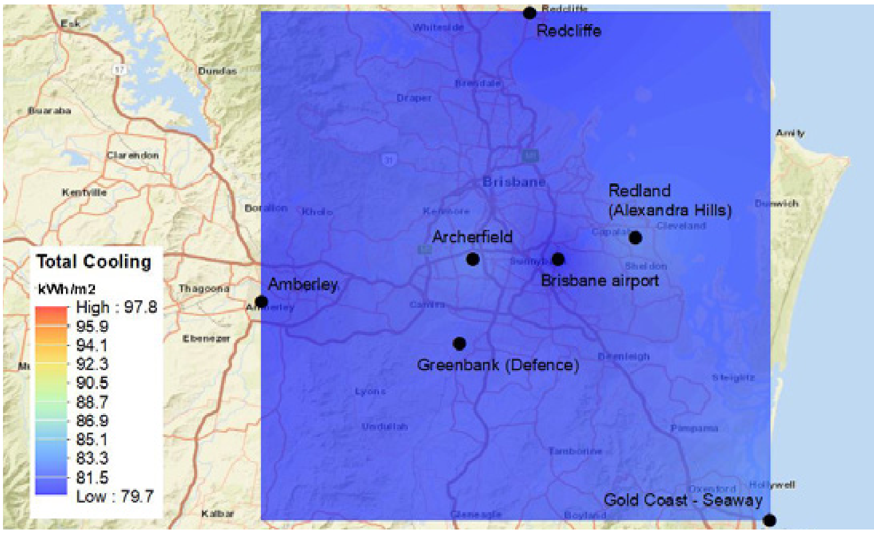

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 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 (7.2-9.2 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
Amberley	266.9	328.5	0.9	2.0	259.5	320.7	0.9	2.0
Archerfield	271.7	341.7	0.3	0.6	265.0	334.5	0.3	0.7
Brisbane	287.6	367.1	0.2	0.3	279.1	357.9	0.2	0.3
Brisbane Airport	264.5	344.9	0.2	0.4	258.5	338.3	0.3	0.4
Redland (Alexandra Hills)	263.9	342.9	0.2	0.4	256.5	334.9	0.3	0.4

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 new 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 1.9-2.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.6-9.2 kWh/m² (~1.9-2.5 %).

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	%
Amberley	7.4	2.8	7.8	2.4	0.0	0.0	7.4	2.8	7.8	2.4
Archerfield	6.7	2.5	7.2	2.1	0.0	0.1	6.7	2.5	7.1	2.1
Brisbane	8.5	3.0	9.2	2.5	0.0	0.0	8.5	3.0	9.2	2.5
Brisbane Airport	6.0	2.3	6.6	1.9	0.1	0.0	5.9	2.2	6.6	1.9
Redland (Alexandra Hills)	7.4	2.8	8.0	2.3	0.1	0.0	7.3	2.8	8.0	2.3

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

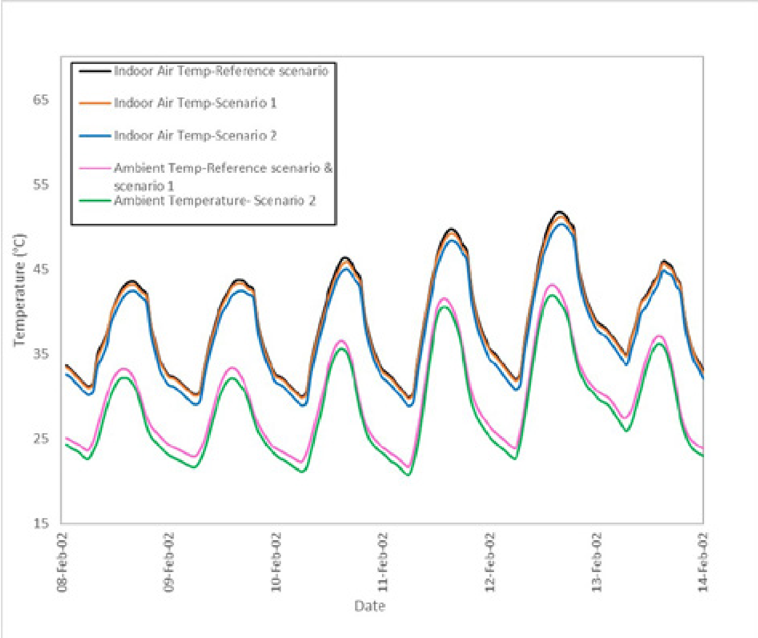

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new low-rise shopping mall centre under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

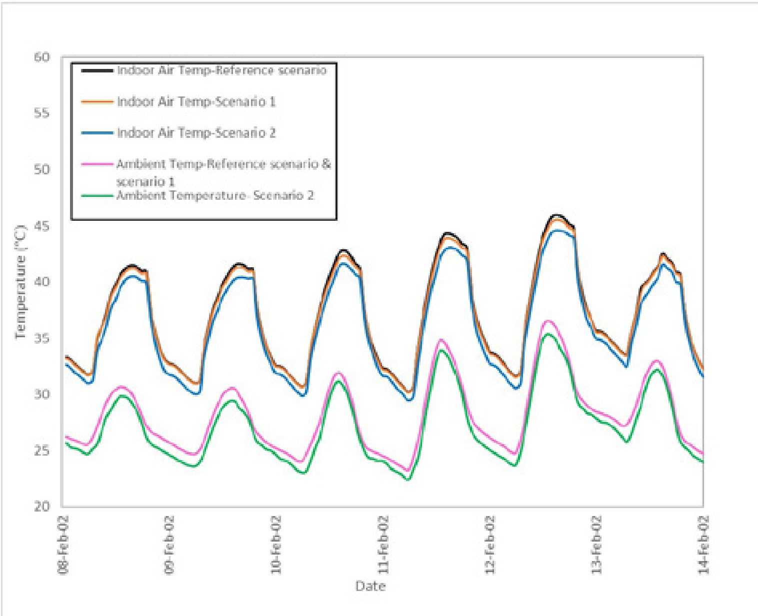

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 29.9-51.7 °C and 30.3-46.0 °C in Amberley and Redland stations, respectively.

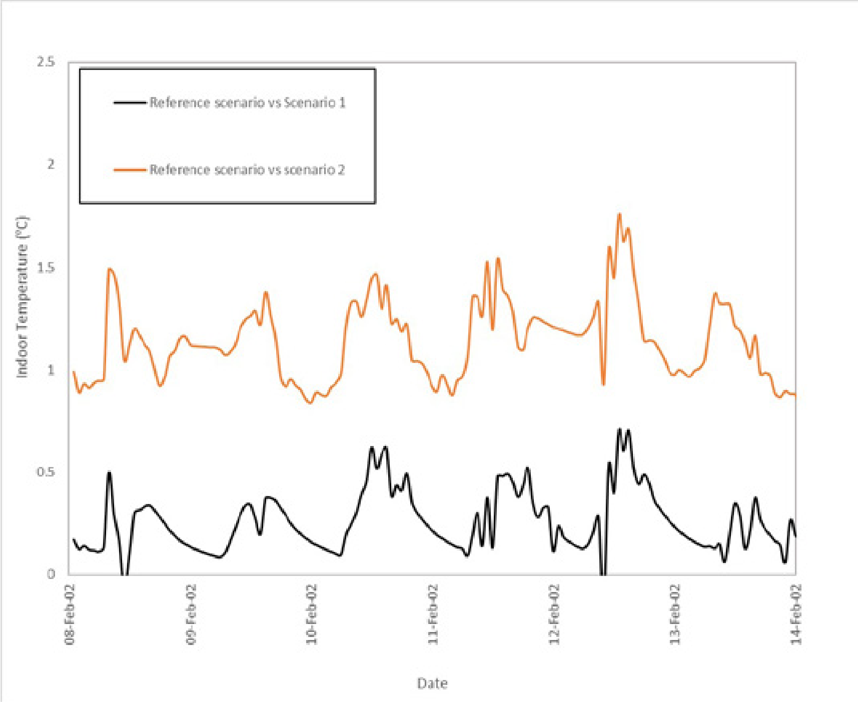

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Amberley 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 0.8 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.8 °C and 1.6 °C in Amberley and Redland stations, respectively.

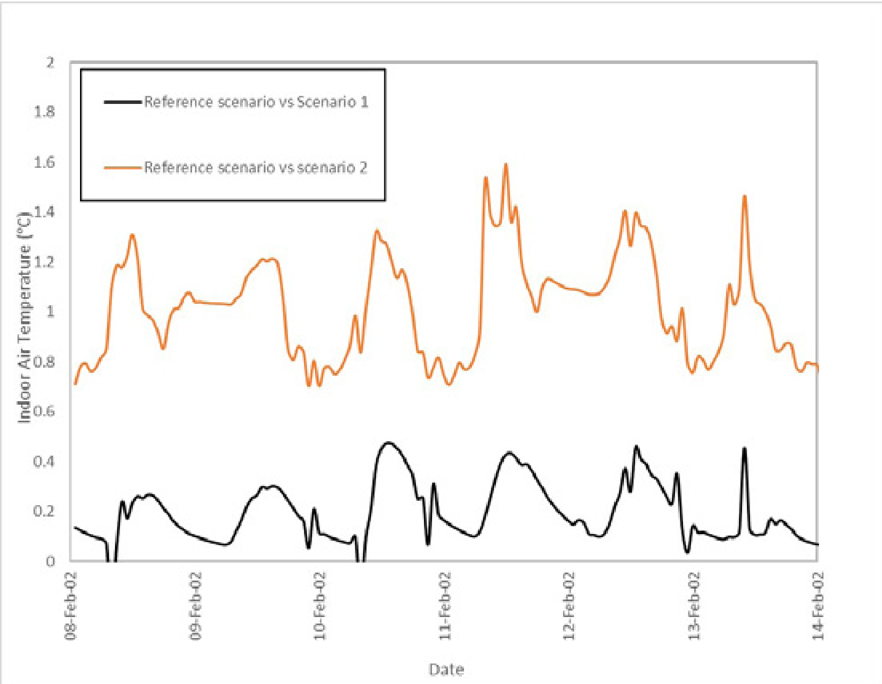

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical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

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

4

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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 14.0-34.9 °C in reference scenario to a range 17.5-30.4 °C in scenario 1 in Amberley station.

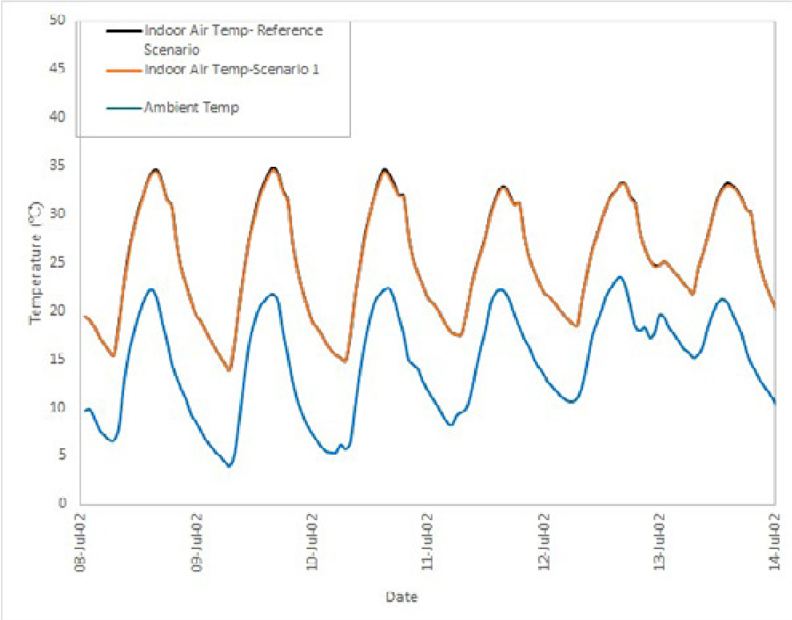

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Amberley station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 18.5-35.3 °C in reference scenario to a range 18.5-35.0 °C in scenario 1 in Redland station.

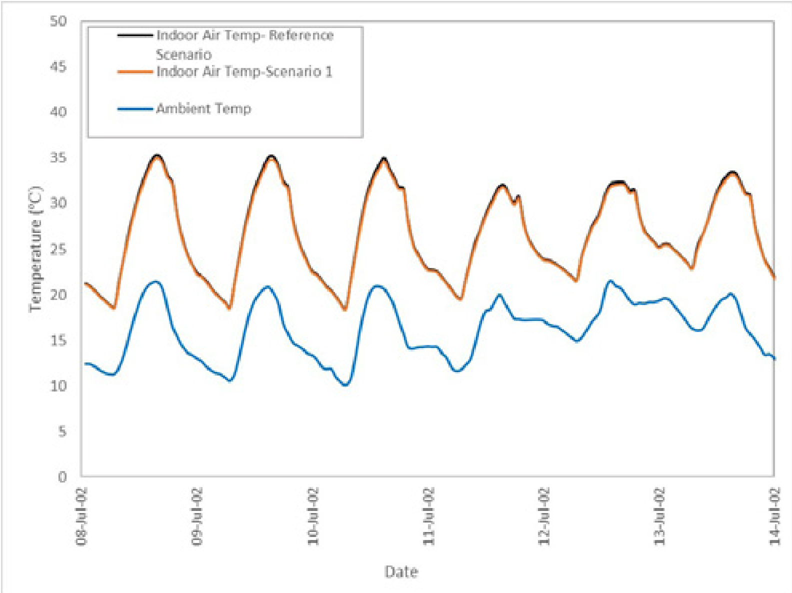

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Redland station* using annual measured weather 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 °C and 0.6 °C in Amberley and Redland stations, respectively.

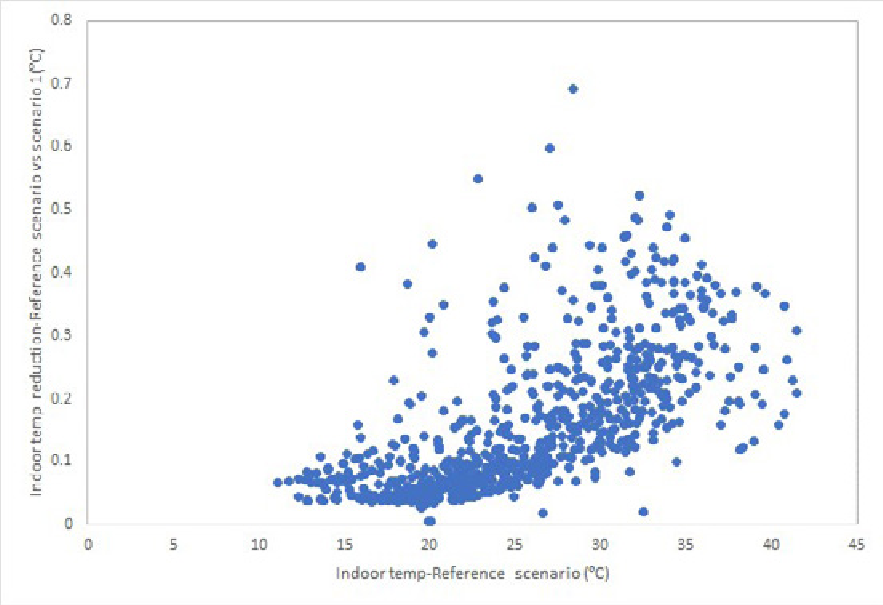

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

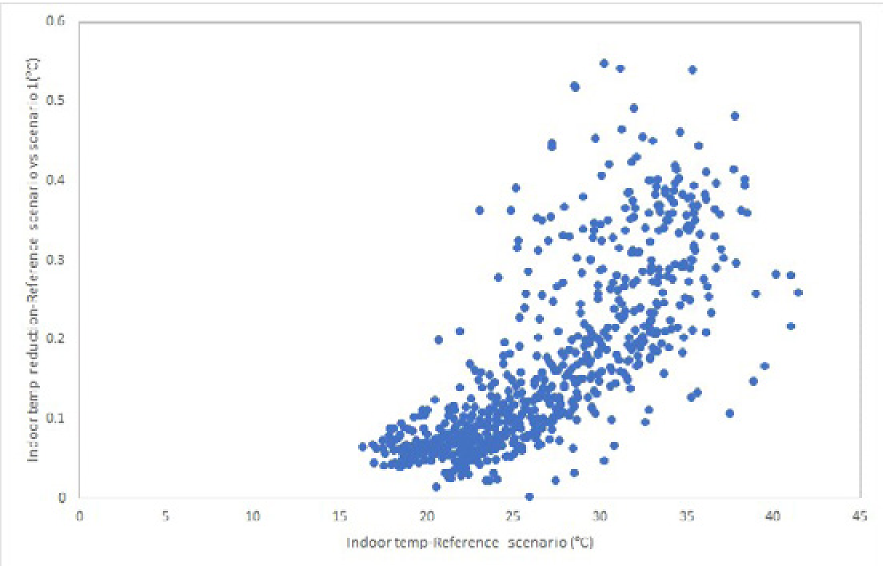

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 116 hours in reference scenario to 121 hours, and from 43 to 44 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 15 to 17 hours in scenario 1 in Redland station.

Stations	**Reference scenario**		**Scenario 1 Reference with cool roof scenario**	
	Operational hours*	**Total**	**Operational hours***	**Total**
Amberley	31	116	31	121
Redland	15	43	17	44

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

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 slightly decrease from 672 hours in reference scenario to 671 and 666 hours under scenario 1 and 2 in Amberley station; while remains the same (672 hours) in Redland station.

Stations	**Reference scenario**	**Scenario 1 Reference with cool roof scenario**	**Scenario 2 Cool roof with modified urban temperature scenario**
Amberley	672	671	666
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 05.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	290.8	302.1
Energy consumption after cool roof (MWh)	284.0	295.1
Energy savings (MWh)	6.8	7.0
Energy savings (%)	2.34 %	2.32 %
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 2,34% for the Amberley weather conditions and of 2,32% for the Coldstream 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 21,8% for the low energy price scenario and 22,5% for the high energy scenario for both locations.

The metal cool roof is due to its higher initial investment barely feasible, with reductions of between 1,5 and 2,9%.

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 Amberley and for Redland weather conditions respectively.

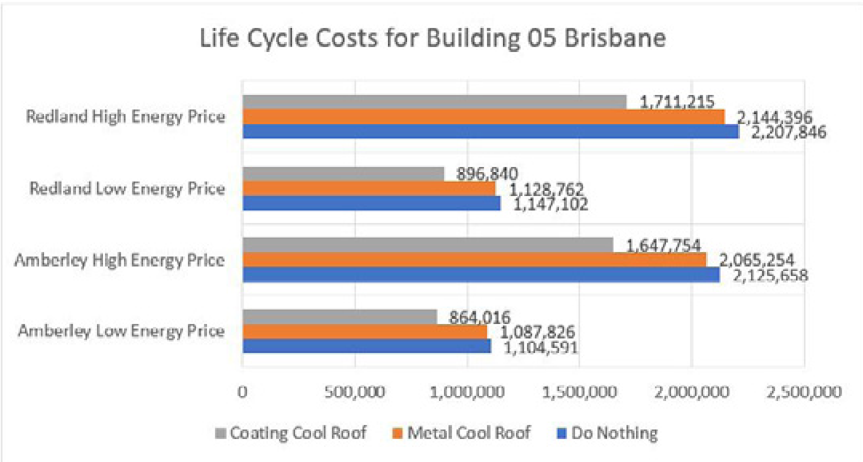

Figure 12. Life Cycle Costs for Building 05 for Amberley and Redland weather stations.

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	1.52 %	2.84 %	1.60 %	2.87 %
Coating Cool Roof	21.78 %	22.48 %	21.82 %	22.49 %

7

CONCLUSIONS

• In the eleven weather stations in Brisbane, 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 Brisbane, the total cooling load of a typical low-rise shopping mall centre under the reference scenario is approximately 96.4-98.2 kWh/m^2, which reduces to a range between 94.5-97.8 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 1.3-1.9 kWh/m^2 (~ 1.3-2.0 %) (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Brisbane, the total cooling load of low-rise shopping mall centre is estimated to be around 15.4-19.4 kWh/m^2 lower under cool roof with modified urban temperature scenario (scenario 2) compared to the reference scenario. This is equivalent to 15.8-19.6 % 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 (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (7.2-9.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.9-2.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.6-9.2 kWh/m^2 (~1.9-2.5 %) (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 29.9-51.7 °C and 30.3-46.0 °C in Amberley and Redland 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 0.8 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 °C and 1.6 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 14.0-34.9 °C in reference scenario to a range between 17.5-30.4 °C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 18.5-35.3 °C in reference scenario to a range between 18.5-35.0 °C in reference with cool roof scenario (scenario 1) in Redland 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 0.7 °C and 0.6 °C in Amberley and Redland 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 116 hours in reference scenario to 121 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight increase in total number of hours below 19 °C from 43 hours in reference scenario to 44 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 15 hours in reference scenario to 17 hours in Redland station.

• 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 672 hours under the reference scenario in Amberley station, which slightly decreases to 671 and 666 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Redland station shows that the total number of hours above 26 °C remains the same (672 hours) for all scenarios (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. The latter leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 21,8% for the low energy price scenario and 22,5% for the high energy scenario for both locations, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment barely feasible, with reductions of between 1,5 and 2,9%. 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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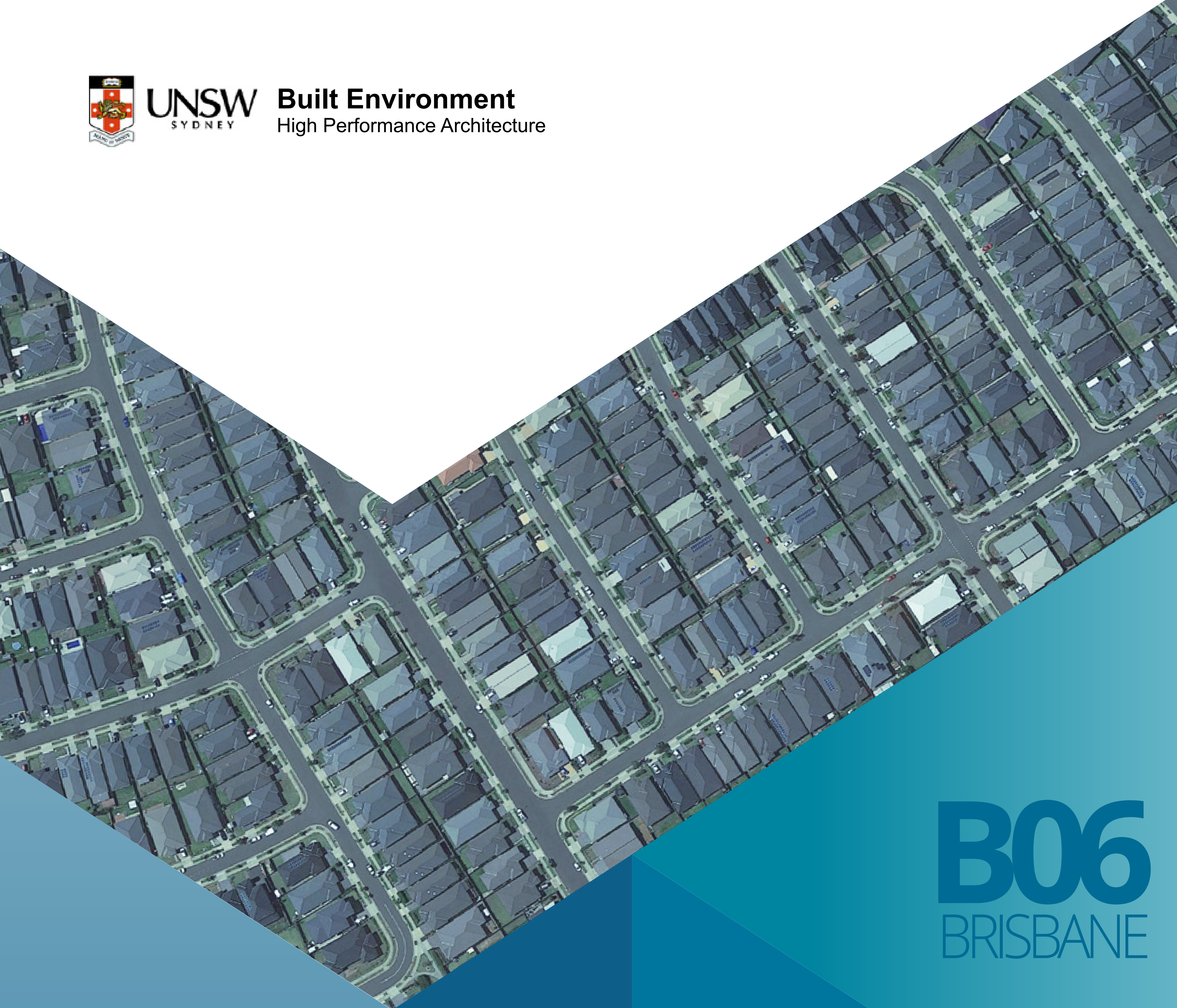

B06
BRISBANE

COOL ROOFS
COST BENEFIT ANALYSIS

New mid-rise shopping mall centre
2021

BUILDING 06

NEW MID-RISE SHOPPING MALL CENTRE

Floor area	: 1100m^2
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

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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 Brisbane 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 95.3-98.5 kWh/m² to 94.5-97.8 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/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)
Amberley	64.8	95.3	63.9	94.5	61.2	80.1
Archerfield	61.3	97.5	60.7	96.8	57.7	81.7
Brisbane Airport	61.1	98.2	60.4	97.4	56.6	79.5
Gold Coast - Seaway	59.8	98.5	59.2	97.8	56.2	82.6
Greenbank (Defence)	60.1	98.1	59.4	97.4	56.2	80.8
Redcliffe	61.1	97.2	60.3	96.4	57.1	80.0
Redland (Alexandra Hills)	60.3	96.7	59.6	96.0	57.0	82.1

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.

For Scenario 1, the total cooling load saving is around 0.7-0.8 kWh/m² which is equivalent to 0.7-0.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 14.6-18.7 kWh/m² which is equivalent to 15.1-19.0 % 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	%
Amberley	0.9	1.4	0.8	0.8	3.6	5.6	15.2	15.9
Archerfield	0.6	1.0	0.7	0.7	3.6	5.9	15.8	16.2
Brisbane Airport	0.7	1.1	0.8	0.8	4.5	7.4	18.7	19.0
Gold Coast - Seaway	0.6	1.0	0.7	0.7	3.6	6.0	15.9	16.1
Greenbank (Defence)	0.7	1.2	0.7	0.7	3.9	6.5	17.3	17.6
Redcliffe	0.8	1.3	0.8	0.8	4	6.5	17.2	17.7
Redland (Alexandra Hills)	0.7	1.2	0.7	0.7	3.3	5.5	14.6	15.1

In the eleven weather stations in Brisbane, 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.

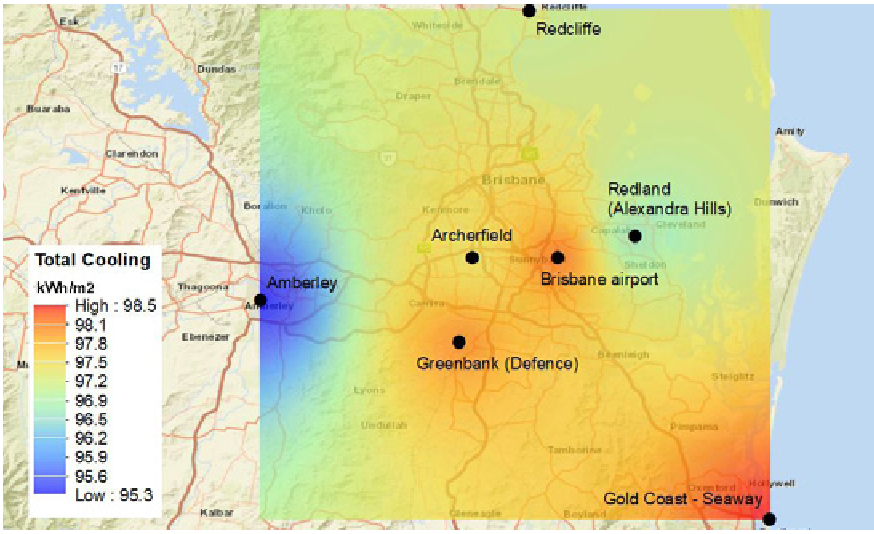

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

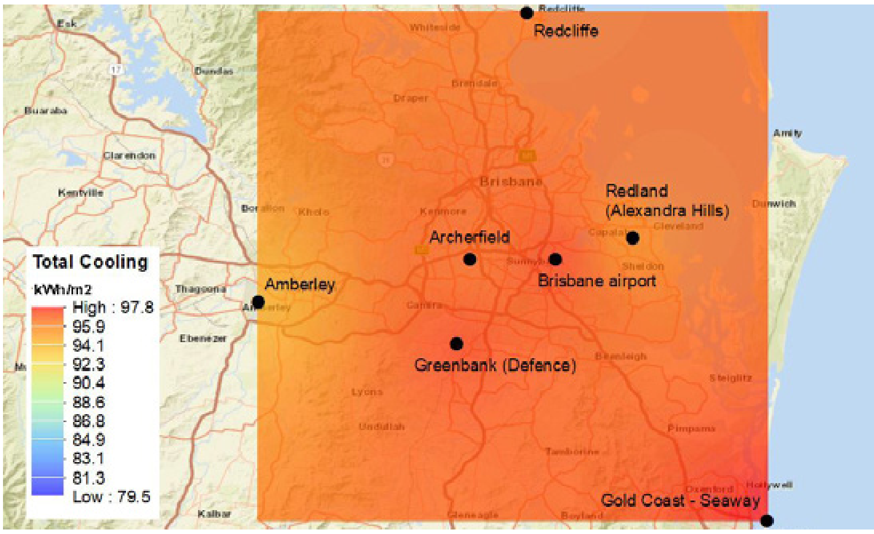

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

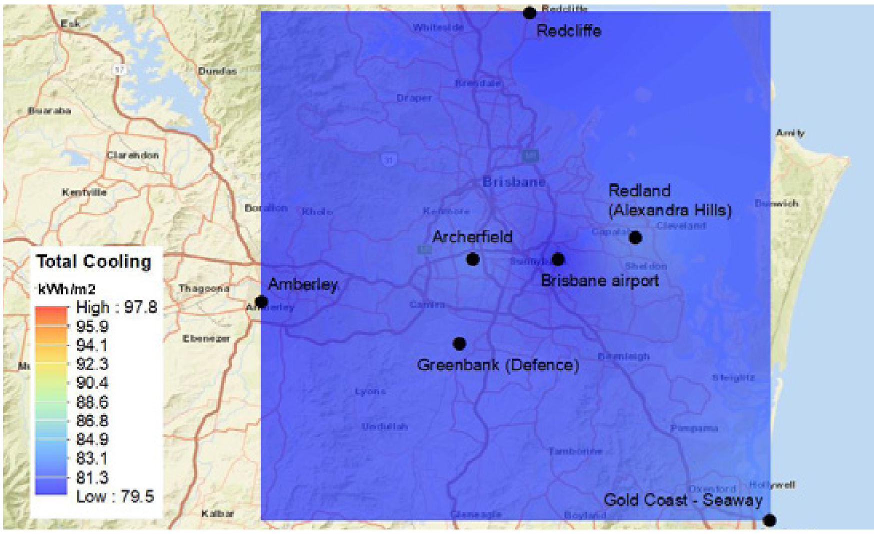

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 kWh/m²) is significantly lower than the annual cooling load reduction (3.0-4.4 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
Amberley	257.9	319.3	0.7	1.7	254.5	315.7	0.7	1.7
Archerfield	264.0	333.6	0.2	0.5	260.9	330.2	0.2	0.5
Brisbane	280.0	358.9	0.1	0.2	275.8	354.5	0.1	0.2
Brisbane Airport	257.7	337.6	0.2	0.3	254.9	334.6	0.2	0.3
Redland (Alexandra Hills)	256.1	334.6	0.2	0.3	252.7	330.8	0.2	0.3

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 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 1.0-1.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.0-4.4 kWh/m² (~0.9-1.2 %).

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	%
Amberley	3.4	1.3	3.6	1.1	0.0	0.0	3.4	1.3	3.6	1.1
Archerfield	3.1	1.2	3.4	1.0	0.0	0.0	3.1	1.2	3.4	1.0
Brisbane	4.2	1.5	4.4	1.2	0.0	0.0	4.2	1.5	4.4	1.2
Brisbane Airport	2.8	1.1	3.0	0.9	0.0	0.0	2.8	1.1	3.0	0.9
Redland (Alexandra Hills)	3.4	1.3	3.8	1.1	0.0	0.0	3.4	1.3	3.8	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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

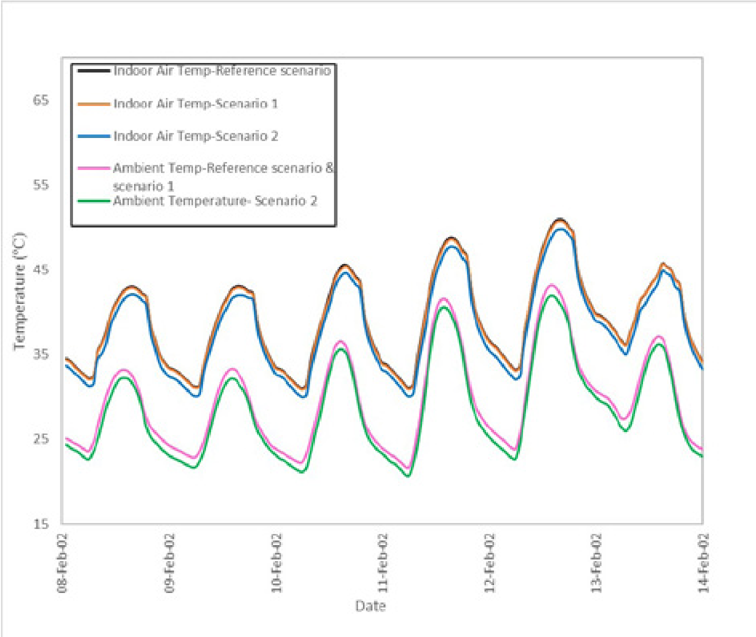

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new mid-rise shopping mall centre under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

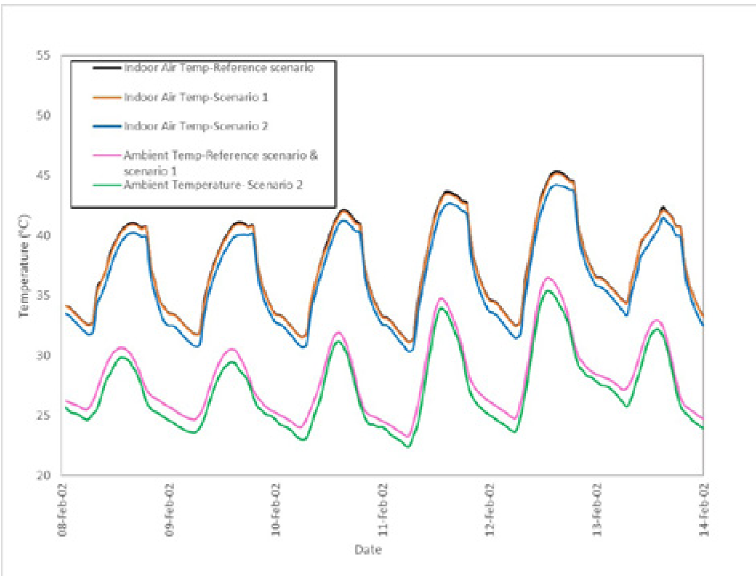

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 30.9-50.9 °C and 31.2-45.3 °C in Amberley and Redland stations, respectively.

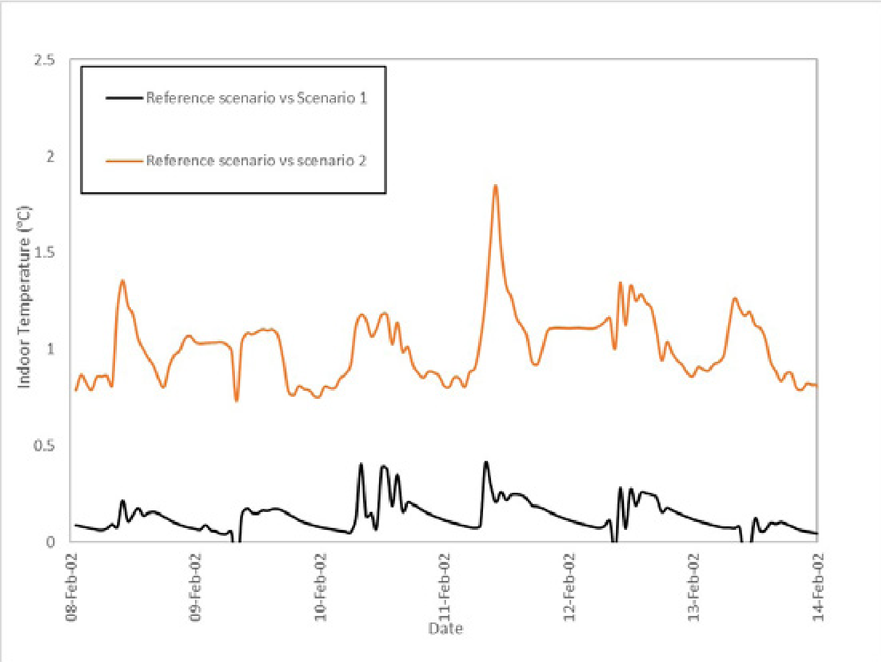

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical summer week in *Amberley 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 0.4 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.9 °C and 1.4 °C in Amberley and Redland stations, respectively.

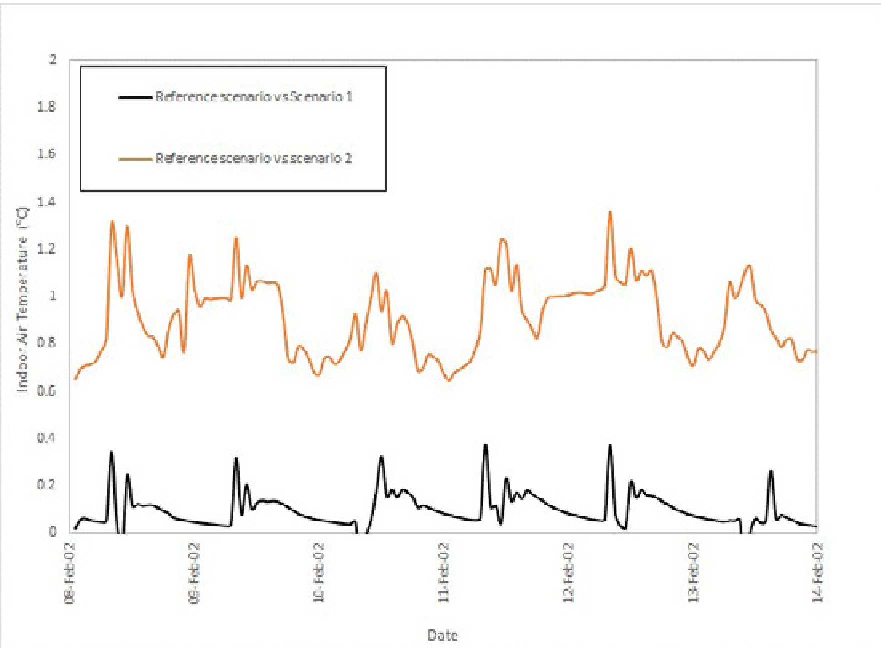

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly reduce from a range 15.2-33.8 °C in reference scenario to a range 13.9-34.5 °C in scenario 1 in Amberley station.

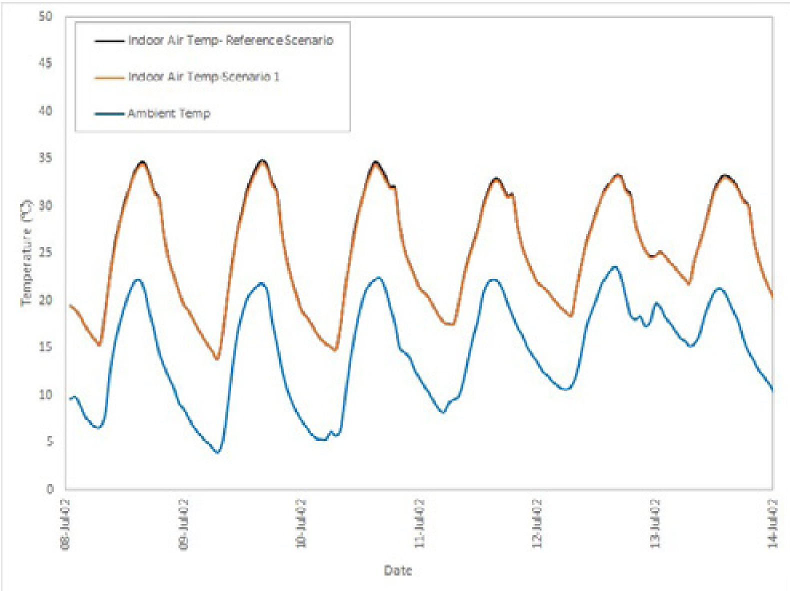

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Amberley station* using annual measured weather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

The indoor air temperature is predicted to slightly reduce from a range 19.5-34.4 °C in reference scenario to a range 19.5-34.2 °C in scenario 1 in Redland station.

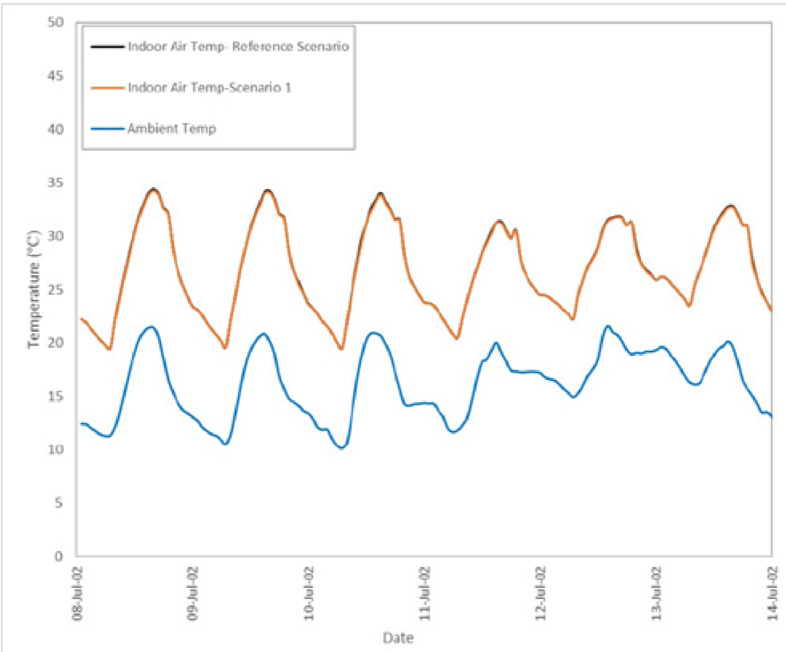

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Redland station* using annual measured weather 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 and 0.5 °C in Amberley and Redland stations, respectively.

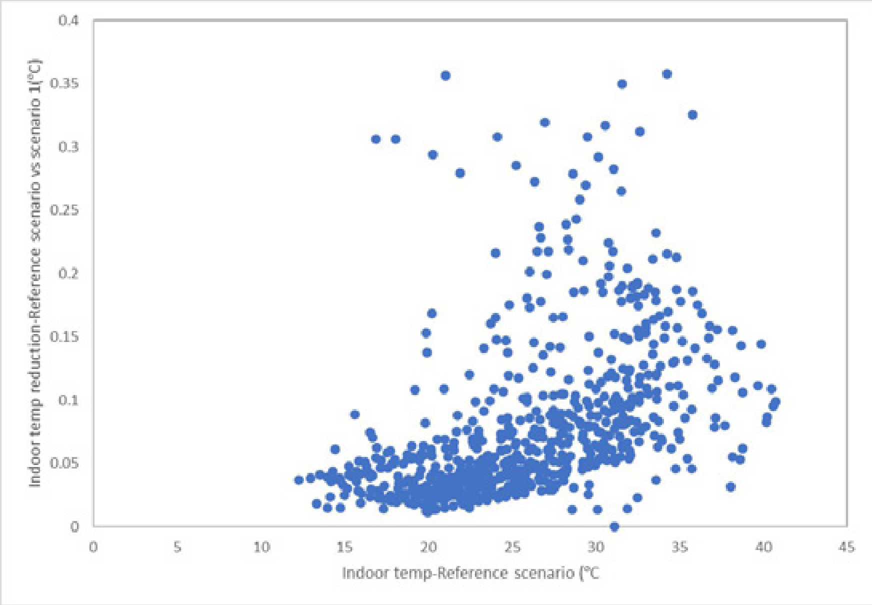

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

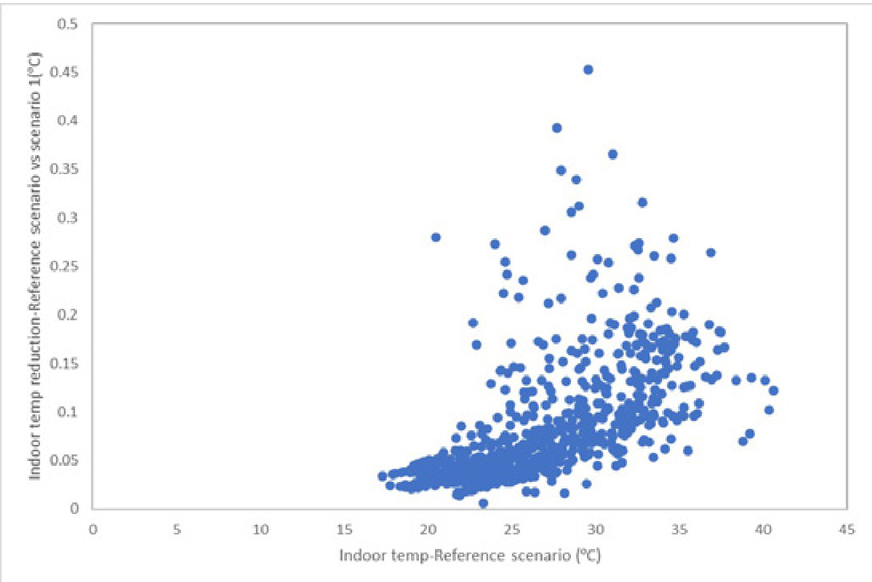

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 87 hours in reference scenario to 89 hours, and from 15 to 16 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 25 hours in reference scenario to 26 hours; and from 8 to 9 hours in scenario 1 in Amberley and Redland 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
Amberley	25	87	26	89
Redland	8	15	9	16

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

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 remain the same (672 hours) for all scenarios in Amberley and Redland stations.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Amberley	672	672	672
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due 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 06 is a new, mid-rise commercial building, with a total air-conditioned area of 4.400 m² distributed on four levels. The 1.100 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 Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 06.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	565.0	589.4
Energy consumption after cool roof (MWh)	558.6	582.7
Energy savings (MWh)	6.4	6.7
Energy savings (%)	1.13 %	1.14 %
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 06 is 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.

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 1,13% for the Amberley weather conditions and of 1,14% for the Redland 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 1,7% for the low energy price scenario for Amberley and 21,9% for the high energy scenario for both locations.

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 Amberley and for Redland weather conditions respectively.

The metal cool roof is due to its higher initial investment cost not feasible, or only marginally so.

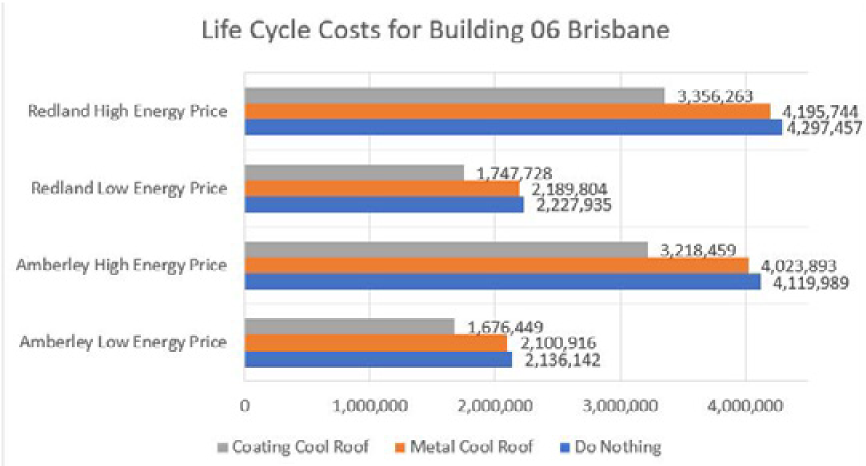

Figure 12. Life Cycle Costs for Building 06 for Amberley and Redland weather stations.

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	1.65 %	2.33 %	1.71 %	2.37 %
Coating Cool Roof	21.52 %	21.88 %	21.55 %	21.90 %

7

CONCLUSIONS

• In the eleven weather stations in Brisbane, 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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of the mid-rise shopping mall centre from 95.3-98.5 kWh/m^2 to 94.5-97.8 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.7-0.8 kWh/m^2. This is equivalent to approximately 0.7-0.8 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 14.6-18.7 kWh/m^2. This is equivalent to 15.1-19.0 % 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 (0.0 kWh/m^2) is significantly lower than the annual cooling load reduction (3.0-4.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.0-1.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.0-4.4 kWh/m^2 (~0.9-1.2%) (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 30.9-50.9 °C and 31.2-45.3 °C in Amberley and Redland 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 0.4 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.9 °C and 1.4 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 15.2-33.8 °C in reference scenario to a range between 13.9-34.5 °C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce between 19.5-34.4 °C in reference scenario to a range between 19.5-34.2 °C in reference with cool roof scenario (scenario 1) in Redland 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 and 0.5 °C in Amberley and Redland 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 87 hours in reference scenario to 89 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight increase in total number of hours below 19 °C from 15 hours in reference scenario to 16 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 25 hours in reference scenario to 26 hours; and from 8 to 9 hours in scenario 1 in Amberley and Redland stations, respectively.

• During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to remain the same with 672 hours for all scenarios, in Amberley and Redland stations (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. The latter leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 1,7% for the low energy price scenario for Amberley and 21,9% for the high energy scenario for both locations, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible, or only marginally so. 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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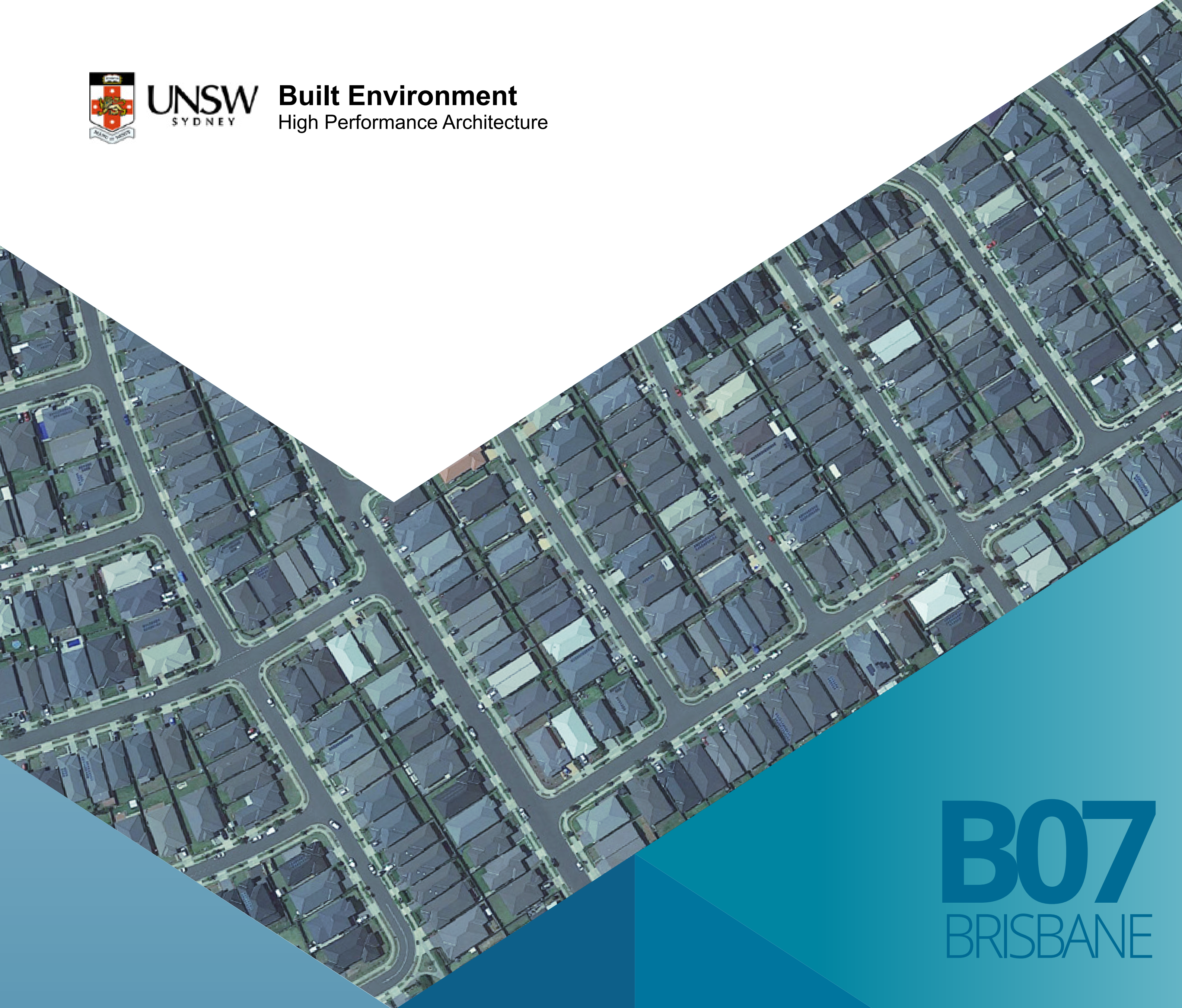

B07
BRISBANE

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

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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 Brisbane 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 94.8-98.1 kWh/m² to 94.2-97.7 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)
Amberley	64.3	94.8	63.7	94.2	61.1	79.9
Archerfield	60.9	97.1	60.6	96.6	56.7	81.5
Brisbane Airport	60.7	97.8	60.3	97.3	56.5	79.4
Gold Coast - Seaway	59.5	98.1	59.1	97.7	56.1	82.4
Greenbank (Defence)	59.8	97.7	59.4	97.3	56.1	80.6
Redcliffe	60.7	96.8	60.2	96.2	57	79.8
Redland (Alexandra Hills)	59.9	96.3	59.5	95.9	56.9	81.9

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 0.4-0.6 kWh/m² which is equivalent to 0.4-0.6 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 14.4-18.4 kWh/m² which is equivalent to 15.0-18.8 % 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	%
Amberley	0.6	0.9	0.6	0.6	3.2	5.0	14.9	15.7
Archerfield	0.3	0.5	0.5	0.5	4.2	6.9	15.6	16.1
Brisbane Airport	0.4	0.7	0.5	0.5	4.2	6.9	18.4	18.8
Gold Coast - Seaway	0.4	0.7	0.4	0.4	3.4	5.7	15.7	16.0
Greenbank (Defence)	0.4	0.7	0.4	0.4	3.7	6.2	17.1	17.5
Redcliffe	0.5	0.8	0.6	0.6	3.7	6.1	17.0	17.6
Redland (Alexandra Hills)	0.4	0.7	0.4	0.4	3.0	5.0	14.4	15.0

In the eleven weather stations in Brisbane, 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.

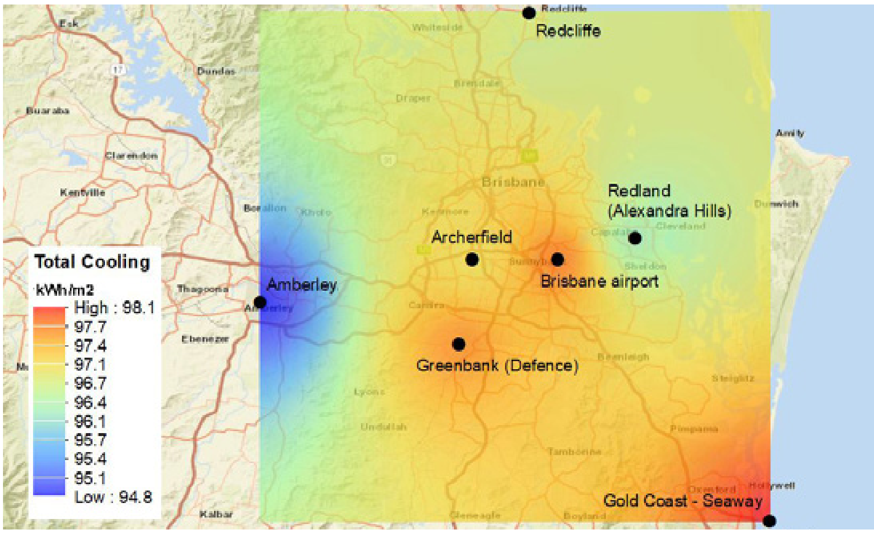

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

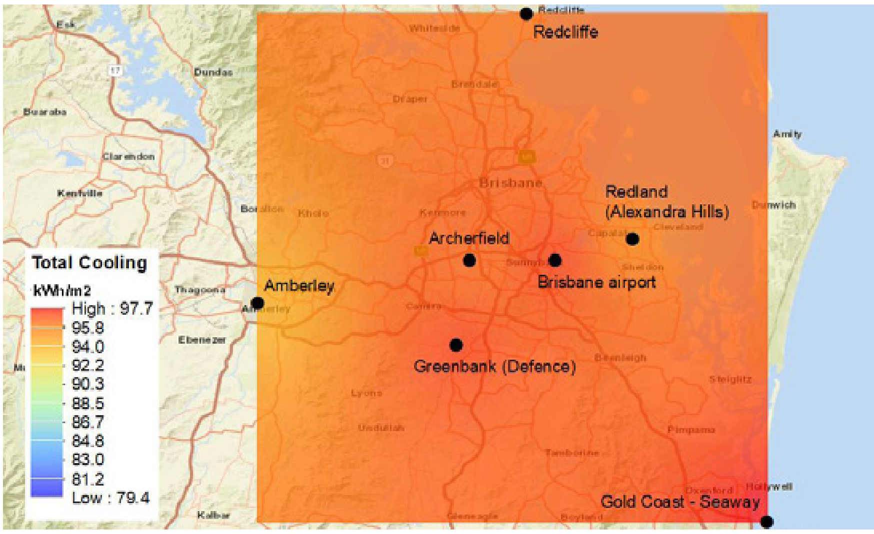

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

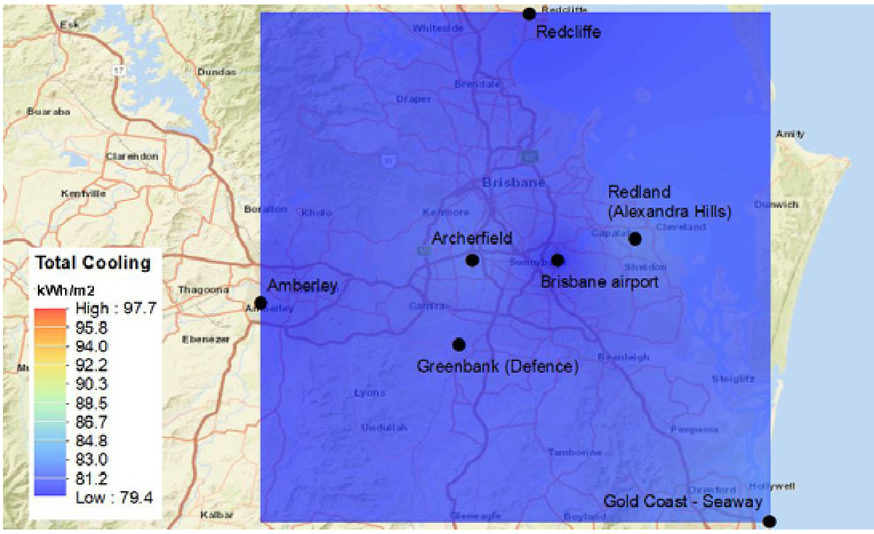

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 kWh/m²) is significantly lower than the annual cooling load reduction (2.0-2.8 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
Amberley	254.9	315.7	0.6	1.7	252.4	313.4	0.6	1.7
Archerfield	260.9	330.3	0.2	0.4	258.9	328.2	0.2	0.4
Brisbane	276.9	355.7	0.1	0.2	274.2	352.9	0.1	0.2
Brisbane Airport	254.9	334.6	0.1	0.2	253.1	332.6	0.1	0.2
Redland (Alexandra Hills)	248.9	331.2	0.1	0.2	246.8	328.8	0.1	0.2

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 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 0.6-0.8 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.0-2.8 kWh/m² (~0.6-0.8 %).

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	%
Amberley	2.5	1.0	2.3	0.7	0.0	0.0	2.5	1.0	2.3	0.7
Archerfield	2	0.8	2.1	0.6	0.0	0.0	2.0	0.8	2.1	0.6
Brisbane	2.7	1.0	2.8	0.8	0.0	0.0	2.7	1.0	2.8	0.8
Brisbane Airport	1.8	0.7	2.0	0.6	0.0	0.0	1.8	0.7	2.0	0.6
Redland (Alexandra Hills)	2.1	0.8	2.4	0.7	0.0	0.0	2.1	0.8	2.4	0.7

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

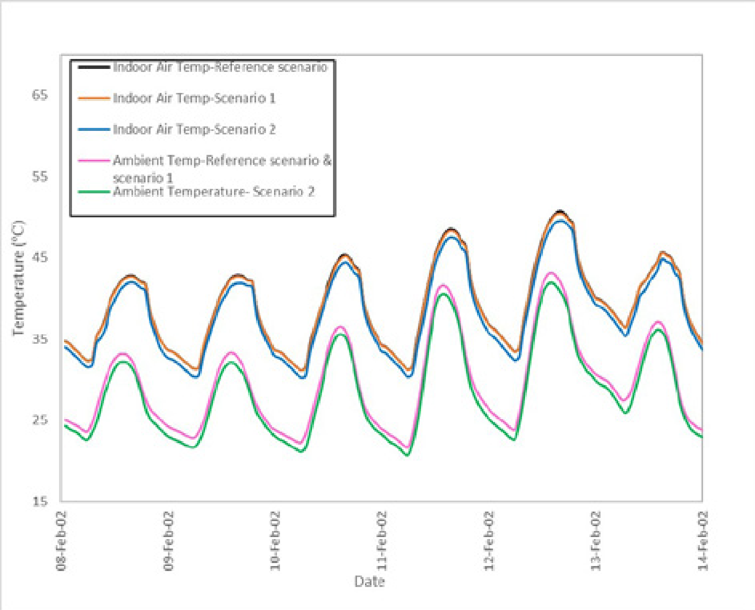

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

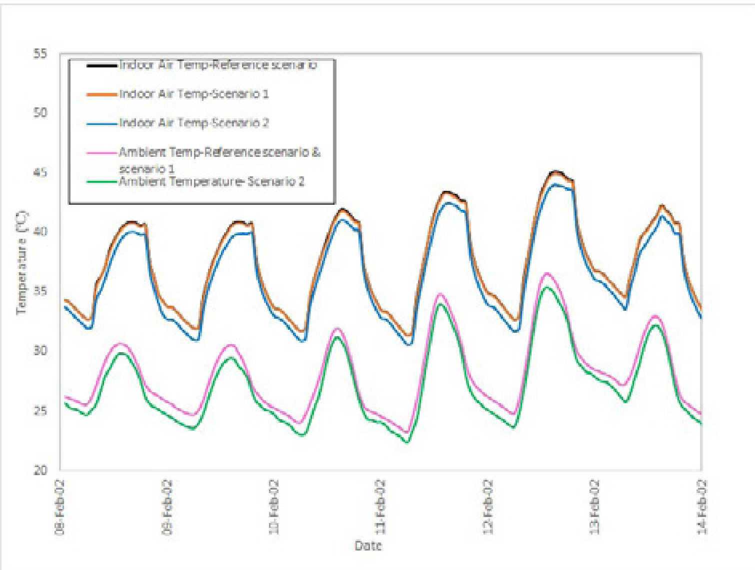

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 31.2-50.7 °C and 31.4-45.1 °C in Amberley and Redland stations, respectively.

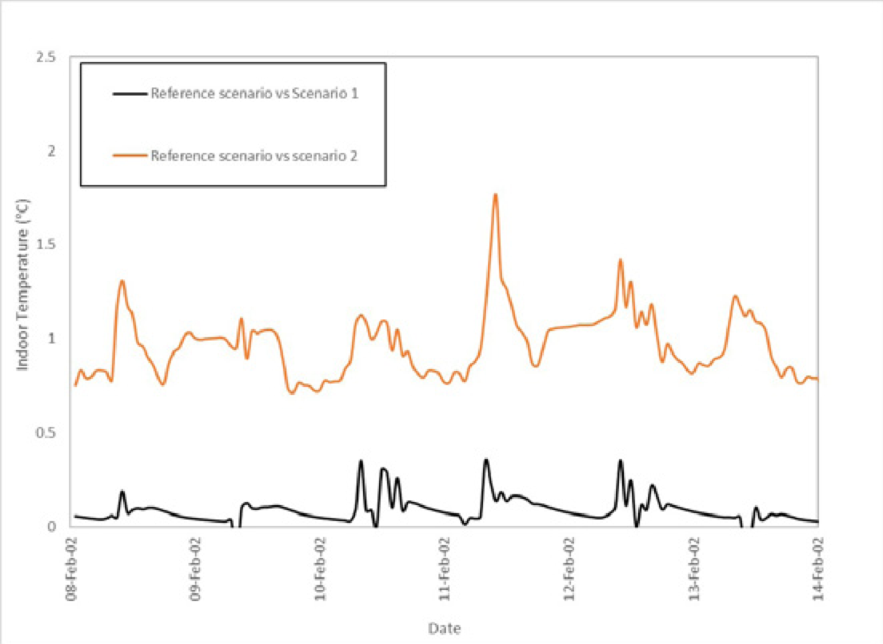

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free-floating conditions during a typical summer week in *Amberley 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 0.3 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.8 °C and 1.3 °C in Amberley and Redland stations, respectively.

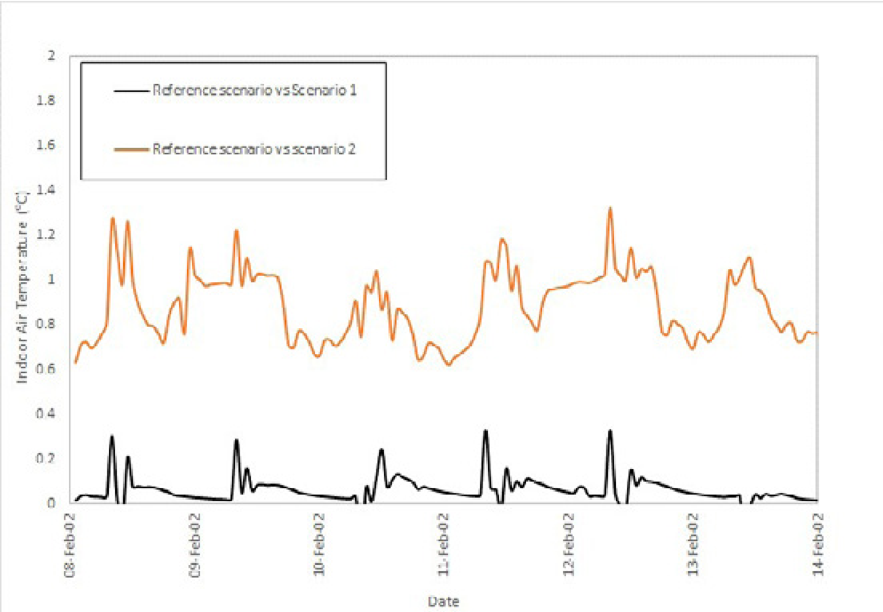

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new highrise shopping mall centre under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 15.5-33.5 °C in reference scenario to a range15.1-33.6 °C in scenario 1 in Amberley station.

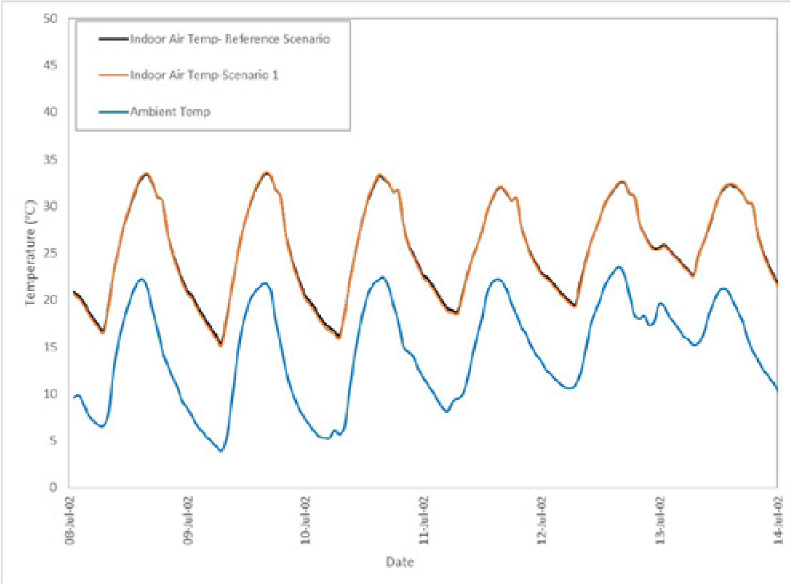

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Amberley station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 19.8-34.1 °C in reference scenario to a range 19.7-34.0 °C in scenario 1 in Redland station.

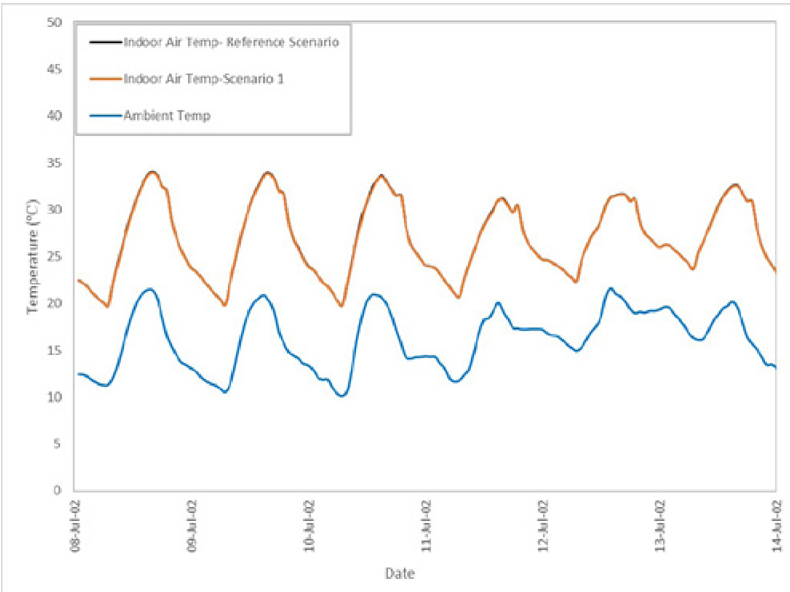

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Redland station* using annual measured weather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

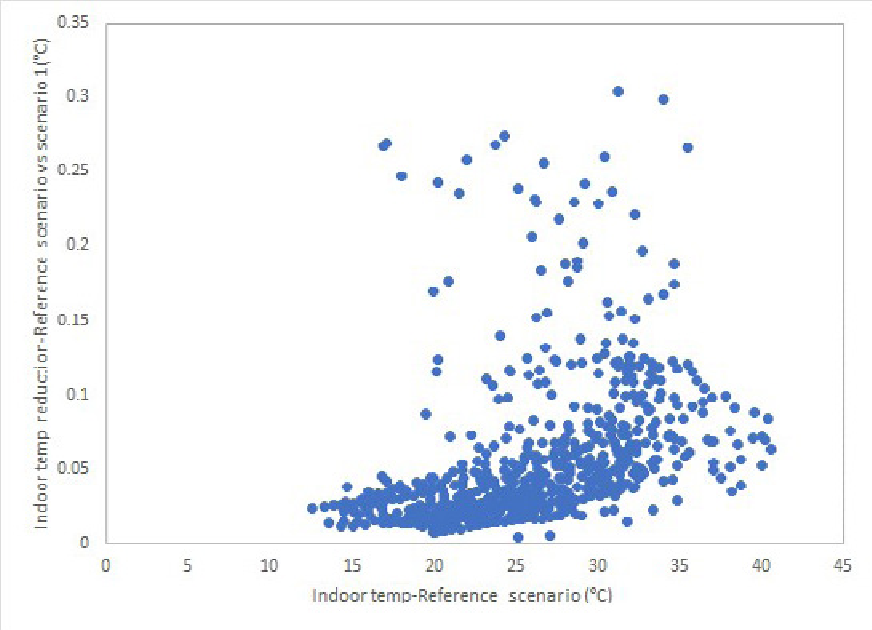

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

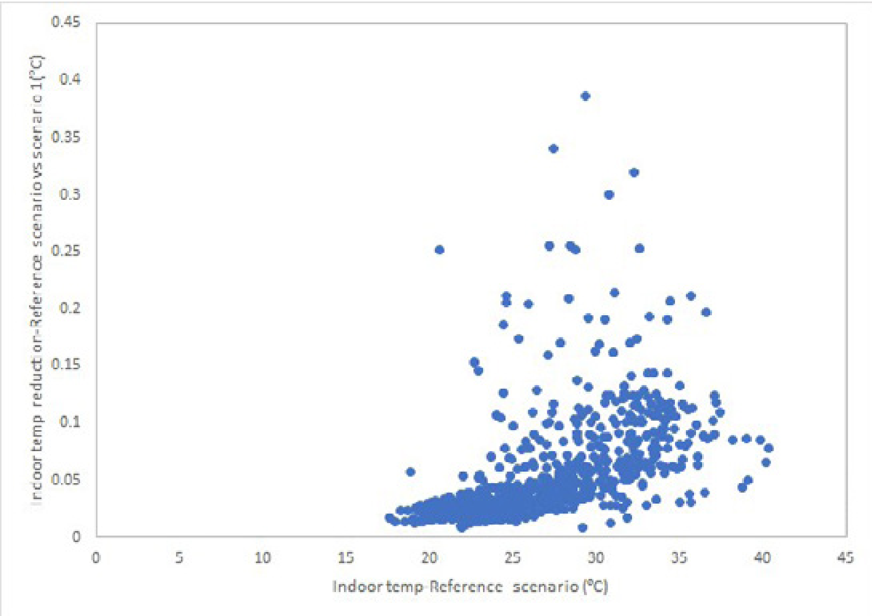

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 with 83-84 hours in Amberley and 9 hours in Redland stations, respectively.

The number operational hours with air temperature <19 °C during remain the same in reference scenario compared to scenario 1 in Amberley and Redland stations.

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
Amberley	25	83	25	84
Redland	5	9	5	9

** 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 remain the same (672 hours) for all scenarios in Amberley and Redland stations.

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
Amberley	672	672	672
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due the building's existing roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to both cool roof options.

The building and its energy performance

Building 07 is a new, 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 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 07.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	837.9	874.9
Energy consumption after cool roof (MWh)	831.9	868.6
Energy savings (MWh)	6.0	6.3
Energy savings (%)	0.72 %	0.72 %
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 07 is 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 feasible investment, over the building's life cycle, due to the large 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 0,72% for both 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 reduction of life cycle costs over the building's life cycle, varies between 1,7% and 2,0% for the metal cool roof for all energy price scenarios and both locations and between 21,5% and 24% for the high energy scenario for Amberley and Redland 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 Amberley and for Redland weather conditions respectively.

> *The metal cool roof is due to its higher initial investment cost only marginally feasible.*

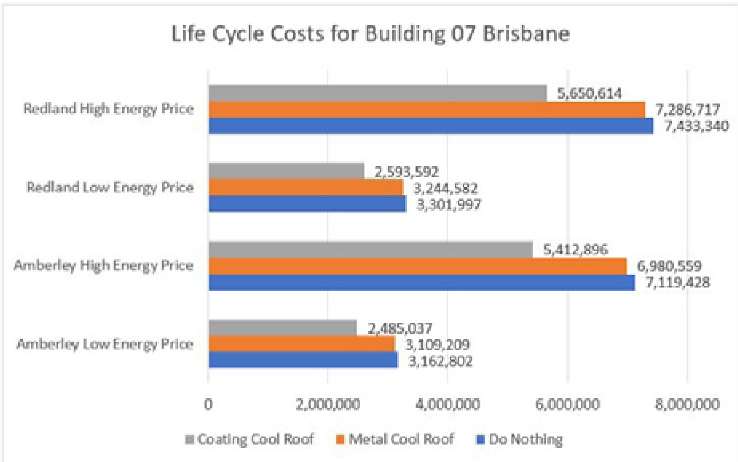

Figure 12. Life Cycle Costs for Building 07 for Amberley and Redland weather stations.

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	1.69 %	1.95 %	1.74 %	1.97 %
Coating Cool Roof	21.43 %	23.97 %	21.45 %	23.98 %

6

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 Brisbane, 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 94.8-98.1 kWh/m^2 to 94.2-97.7 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.4-0.6 kWh/m^2. This is equivalent to approximately 0.4-0.6 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 14.4-18.4 kWh/m^2. This is equivalent to 15.0-18.8 % 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 (2.0-2.8 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.6-0.8 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.0-2.8 kWh/m^2 (~0.6-0.8 %) (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 31.2-50.7 ^{o}C and 31.4-45.1 ^{o}C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.4 ^{o}C and 0.3 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 and 1.3 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 15.5-33.5 ^{o}C in reference scenario to a range between 15.1-33.6 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 19.8-34.1 °C in reference scenario to a range between 19.7-34.0 °C in reference with cool roof scenario (scenario 1) in Redland 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 Amberley and Redland 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 remain the same with 83-84 hours in Amberley station and 9 hours in Redland station. The estimations for Redland stations also show the same number of hours below 19 °C with 25 for both scenarios. The results show no significant 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, 7am-6 pm) also remain the same between reference scenario and cool roof scenario (scenario 1) with 25 hours in Amberley station and 5 hours in Redland station (See Table 5).

• During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to remain the same with 672 hours for all scenarios, in Amberley and Redland stations (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's existing roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to both cool roof options. The reduction of life cycle costs over the building's life cycle, varies between 1,7% and 2,0% for the metal cool roof for all energy price scenarios and both locations and between 21,5% and 24% for the high energy scenario for Amberley and Redland conditions, 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 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.

B07

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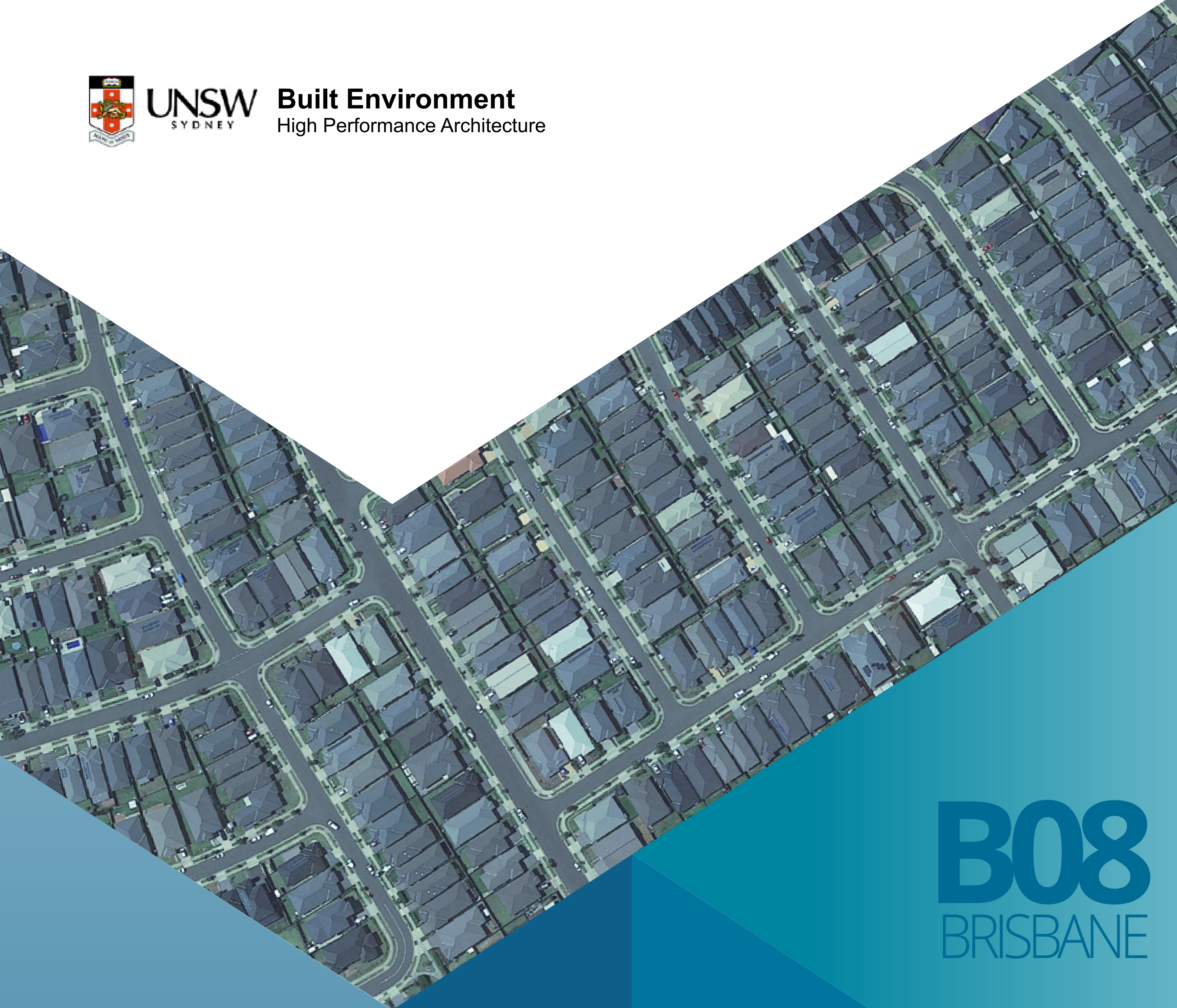

B08 BRISBANE

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

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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 Brisbane using weather data simulated by WRF.

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.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment building from 25.5-27.0 kWh/m² to 23.9-25.7 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)
Amberley	15.9	25.5	14.7	23.9	12.9	17.8
Archerfield	14.2	26.3	13.2	25.0	11.2	18.0
Brisbane Airport	14.2	26.7	13.2	25.3	10.6	16.8
Gold Coast - Seaway	13.7	27.0	12.7	25.7	10.6	18.3
Greenbank (Defence)	13.8	26.8	12.8	25.5	10.5	17.5
Redcliffe	14.2	26.3	13.1	24.8	10.9	17.2
Redland (Alexandra Hills)	13.6	25.7	12.6	24.3	10.8	17.9

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 1.3-1.6 kWh/m² which is equivalent to 4.8-6.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.7-9.9 kWh/m² which is equivalent to 30.2-37.1 % 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	%
Amberley	1.2	7.5	1.6	6.3	3.0	18.9	7.7	30.2
Archerfield	1.0	7.0	1.3	4.9	3.0	21.1	8.3	31.6
Brisbane Airport	1.0	7.0	1.4	5.2	3.6	25.4	9.9	37.1
Gold Coast - Seaway	1.0	7.3	1.3	4.8	3.1	22.6	8.7	32.2
Greenbank (Defence)	1.0	7.2	1.3	4.9	3.3	23.9	9.3	34.7
Redcliffe	1.1	7.7	1.5	5.7	3.3	23.2	9.1	34.6
Redland (Alexandra Hills)	1.0	7.4	1.4	5.4	2.8	20.6	7.8	30.4

In the eleven weather stations in Brisbane, 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.

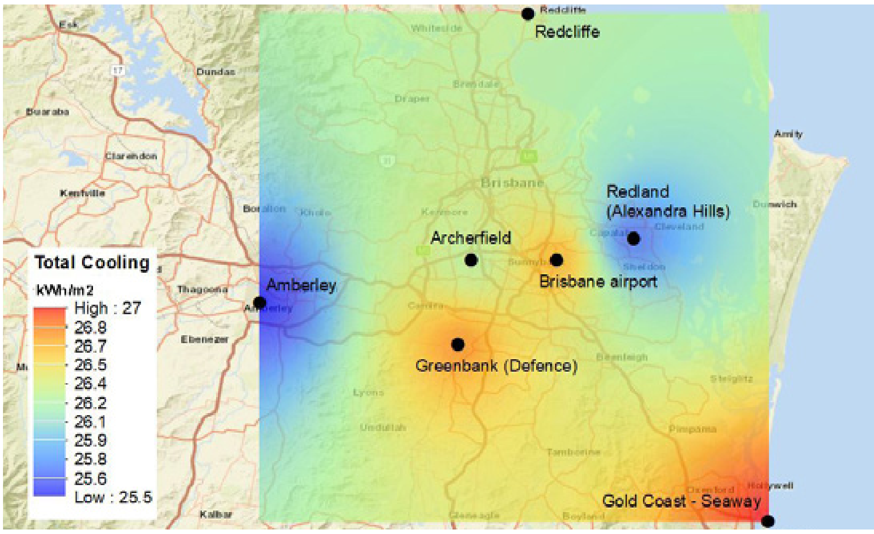

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

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.

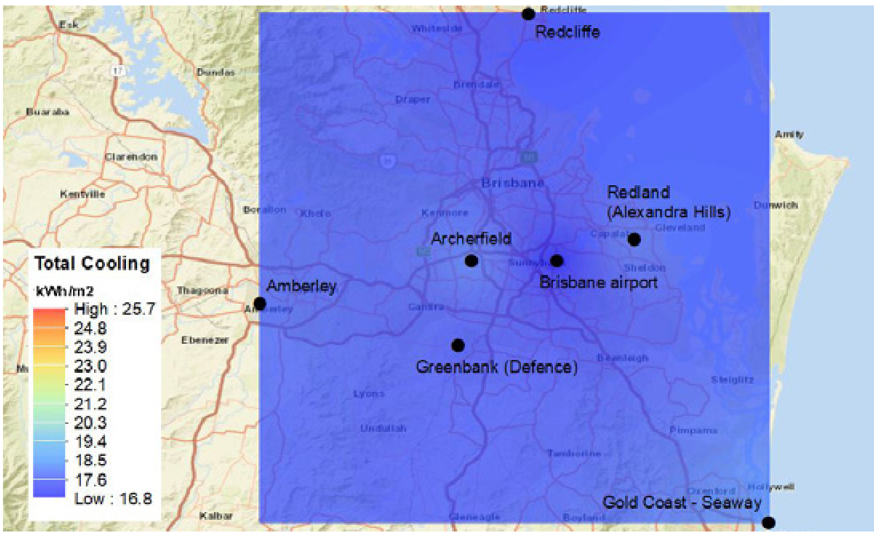

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 (0.2-0.4 kWh/m²) is lower than the annual cooling load reduction (3.8-5.6 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
Amberley	36.9	51.4	4.5	8.3	33.3	47.1	4.8	8.7
Archerfield	37.2	53.7	2.3	4.4	33.9	49.7	2.5	4.7
Brisbane	43.2	63.4	1.1	2.2	38.6	57.8	1.2	2.4
Brisbane Airport	33.4	51.6	1.6	3.0	30.5	47.8	1.7	3.2
Redland (Alexandra Hills)	33.1	49.4	1.7	3.2	29.6	44.7	1.8	3.4

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 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 7.4-9.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.7 and 5.4 kWh/m² (~ 6.4-8.6 %).

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	%
Amberley	3.6	9.8	4.3	8.4	0.3	0.4	3.3	8.0	3.9	6.5
Archerfield	3.3	8.9	4.0	7.4	0.2	0.3	3.1	7.8	3.7	6.4
Brisbane	4.6	10.6	5.6	8.8	0.1	0.2	4.5	10.2	5.4	8.2
Brisbane Airport	2.9	8.7	3.8	7.4	0.1	0.2	2.8	8.0	3.6	6.6
Redland (Alexandra Hills)	3.5	10.6	4.7	9.5	0.1	0.2	3.4	9.8	4.5	8.6

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

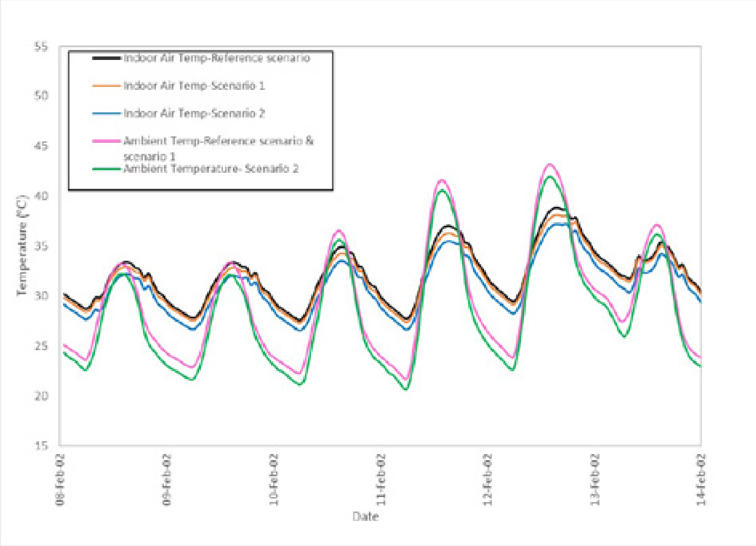

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

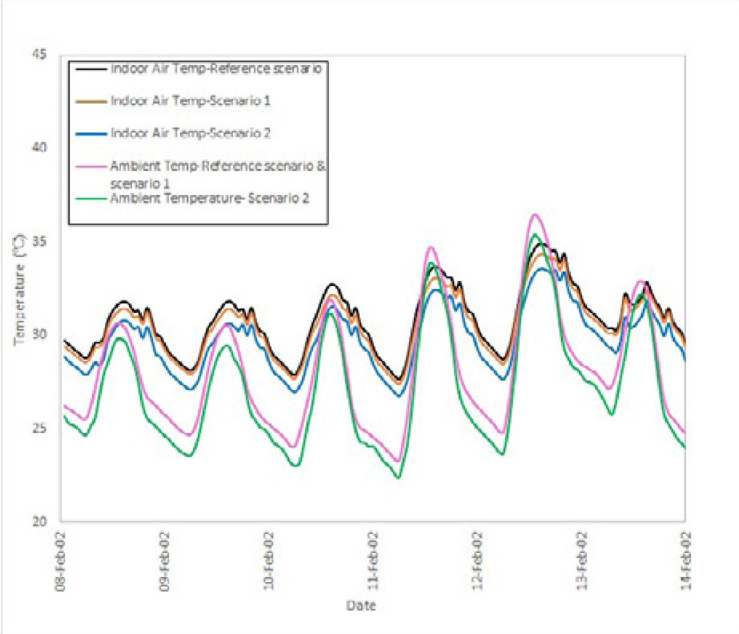

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 27.6-38.9 °C and 27.7-34.9 °C in Amberley and Redland stations, respectively.

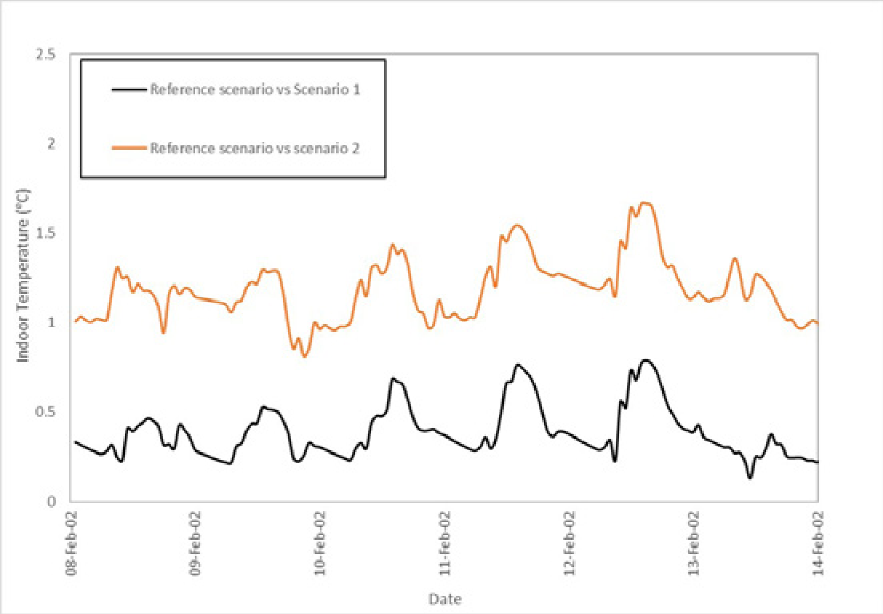

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical summer week in *Amberley 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 0.6 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.7 °C and 1.4 °C in Amberley and Redland stations, respectively.

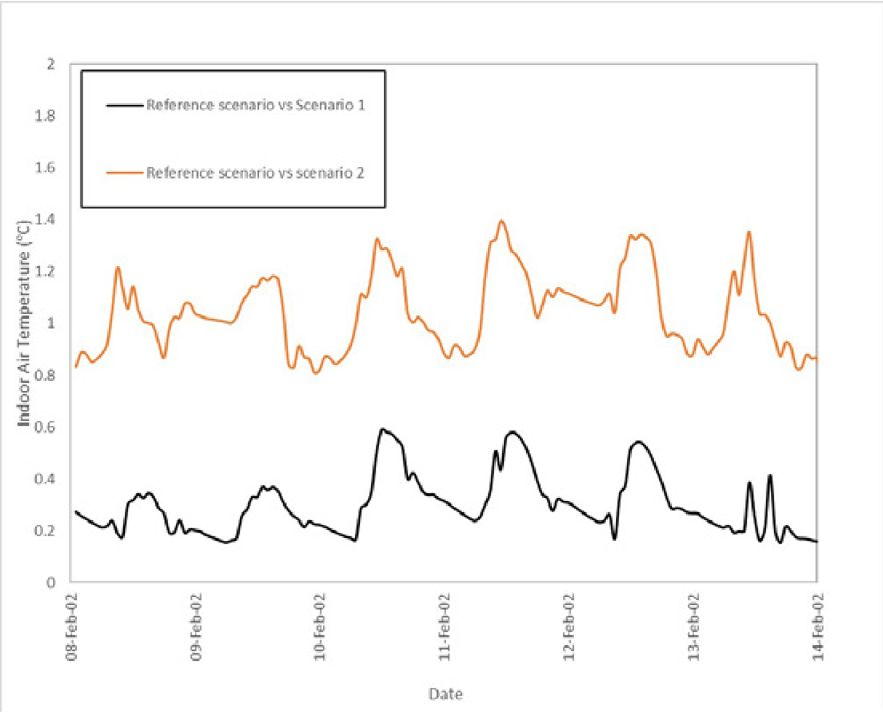

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical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

d Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Brisbane (i.e. Amberley and Redland) using annual measured weather data.

4

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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 14.4-24.9 °C in reference scenario to a range 14.3-24.5 °C in scenario 1 in Amberley station.

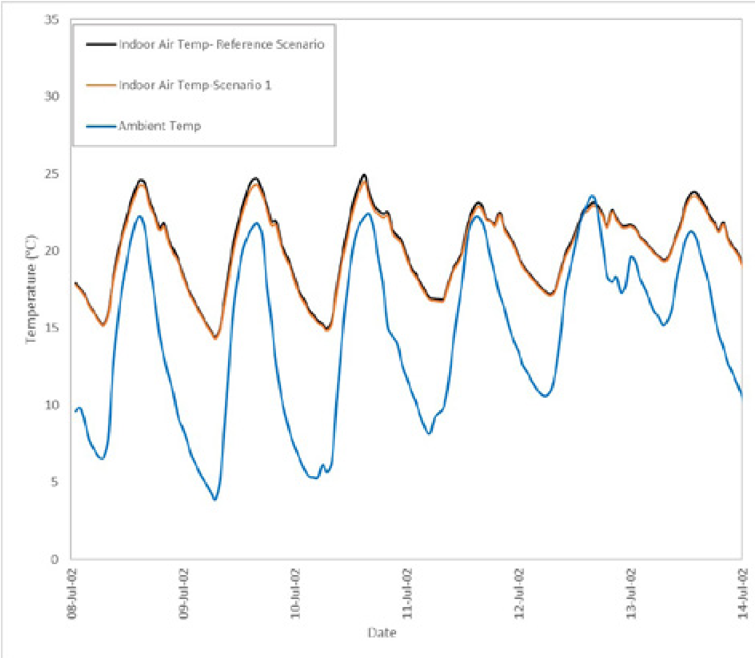

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Amberley station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 17.5-25.6 °C in reference scenario to a range 17.4-25.2 °C in scenario 1 in Redland station.

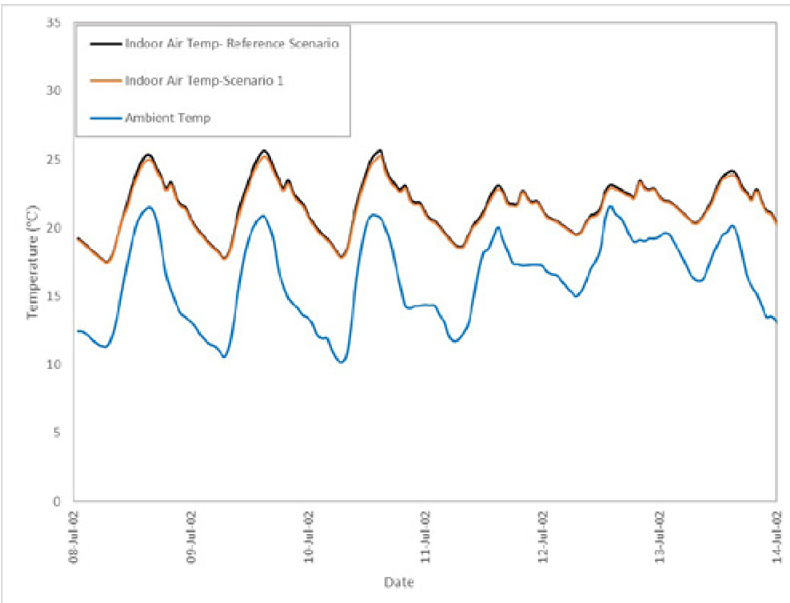

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Redland station* using annual measured weather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

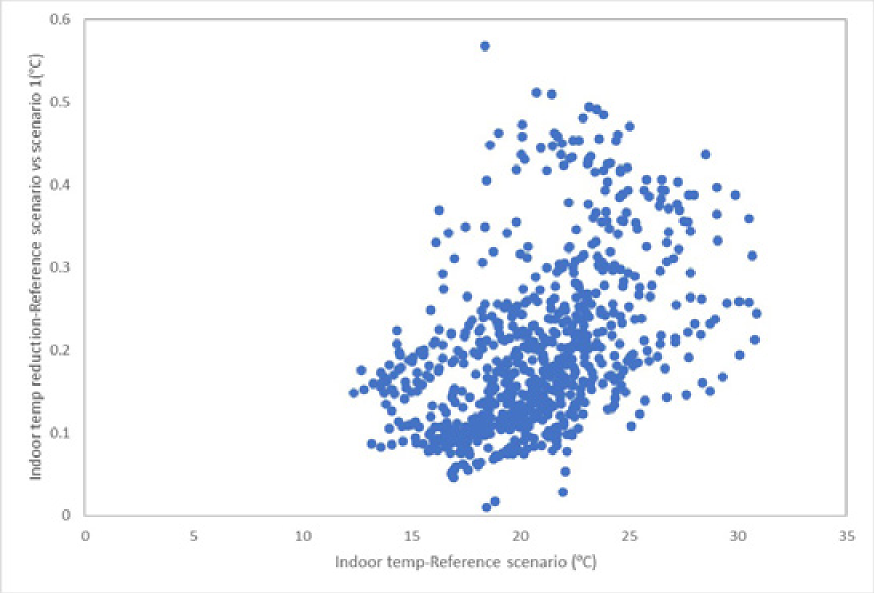

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

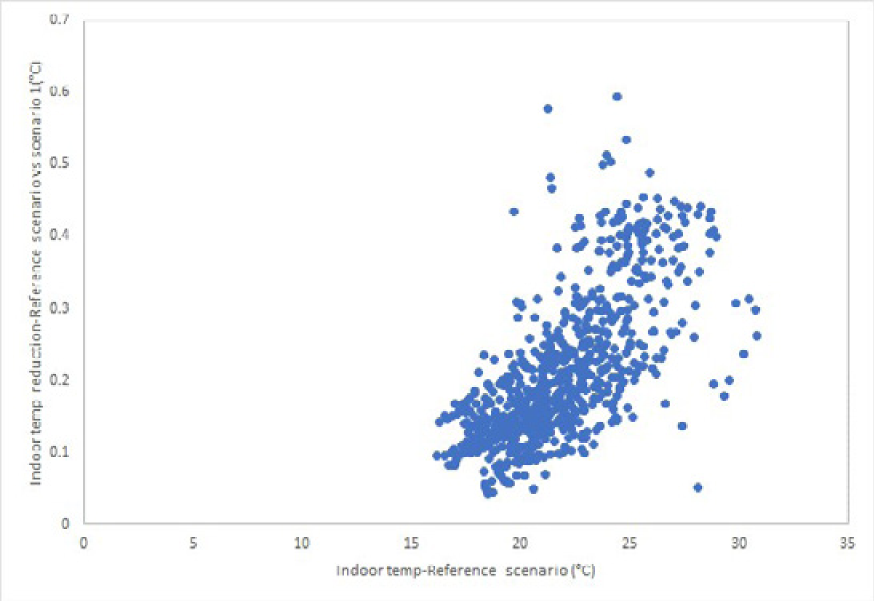

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 240 hours in reference scenario to 248 and hours and from 120 to 129 hours in scenario 1 in Amberley and Redland 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
Amberley	240	248
Redland	120	129

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 635 hours in reference scenario to 624 and 581 hours under scenario 1 and 2 in Amberley station; and from 656 hours in reference scenario to 651 and 614 hours under scenario 1 and 2 in Redland 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
Amberley	635	624	581
Redland	656	651	614

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 08.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	44.7	39.4
Energy consumption after cool roof (MWh)	41.8	36.0
Energy savings (MWh)	2.9	3.4
Energy savings (%)	6.49 %	8.63 %
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 a very 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, whilst the metal cool roof is feasible only for high energy prices.

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 6,49% for the Amberley weather conditions and of 8,63% for the Redland conditions. Given the margin of error of simulations, in practice one can deduce that the energy requirements remain practically unaltered.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 vary between 21,2% for the low energy price scenario for Amberley and 25,1% for the high energy scenario and for Redland 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 Amberley and for Redland weather conditions respectively.

The metal cool roof is due to its higher initial investment cost only marginally feasible.

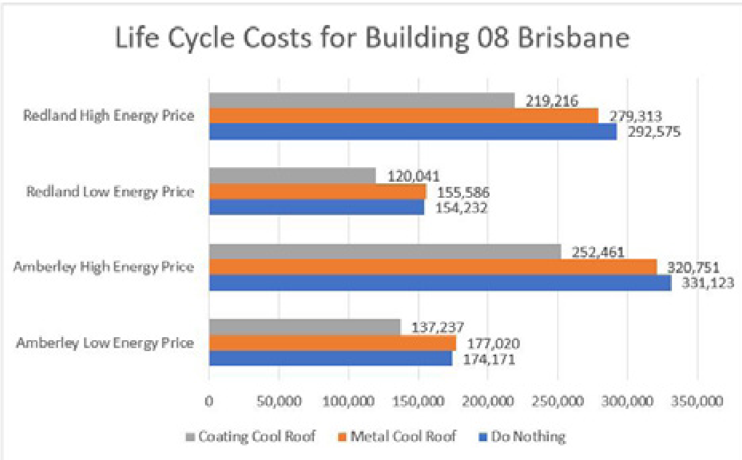

Figure 12. Life Cycle Costs for Building 08 for Amberley and Redland weather stations.

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	-1.64 %	3.13 %	-0.88 %	4.53 %
Coating Cool Roof	21.21 %	23.76 %	22.17 %	25.07 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment from 25.5-27.0 kWh/m^2 to 23.9-25.7 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.3-1.6 kWh/m^2. This is equivalent to approximately 4.8-6.3 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.7-9.9 kWh/m^2. This is equivalent to 30.2-37.1 % 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 (0.2-0.7 kWh/m^2) is similar to the annual cooling load reduction (3.8-5.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 7.4-9.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.7 and 5.4 kWh/m^2 (~ 6.4-8.6 %) (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 27.6-38.9 ^{o}C and 27.7-34.9 ^{o}C in Amberley and Redland 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 0.6 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.7 and 1.4 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 14.4-24.9 ^{o}C in reference scenario to a range between 14.3-24.5 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 17.5-25.6 °C in reference scenario to a range between 17.4-25.2°C in reference with cool roof scenario (scenario 1) in Redland 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 0.6 °C for both Amberley and Redland 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 240 hours in reference scenario to 248 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slightly increase in total number of hours below 19 °C from 120 hours in reference scenario to 129 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 635 hours under the reference scenario in Amberley station, which decreases to 624 and 581 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Redland station also illustrate a significant reduction in number of hours above 26 °C from 656 hours in reference scenario to 651 in reference with cool roof scenario (scenario 1) and 614 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 vary between 21,2% for the low energy price scenario for Amberley and 25,1% for the high energy scenario and for Redland conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost, feasible only for the high energy price scenario for both locations. Building 08 is in that sense a very 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, whilst the metal cool roof is feasible only for high energy prices.

B08

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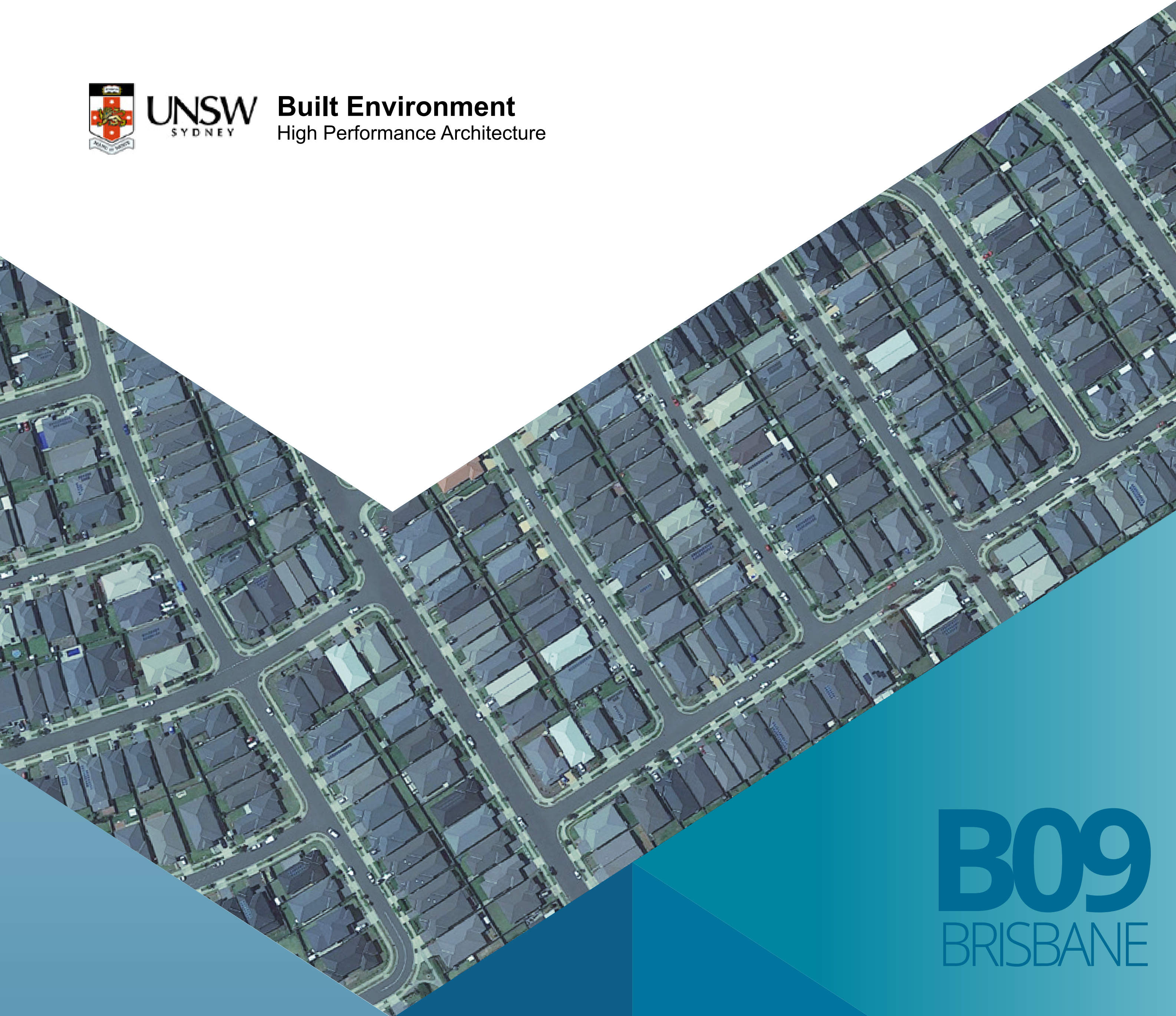

B09 BRISBANE

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

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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 Brisbane 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 apartment building from 25.2-26.9 kWh/m² to 24.3-26.1 kWh/m².

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.

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)
Amberley	15.6	25.2	14.9	24.3	13.1	18.1
Archerfield	13.9	26.1	13.4	25.3	11.4	18.3
Brisbane Airport	13.8	26.5	13.3	25.7	10.7	17.1
Gold Coast - Seaway	13.4	26.9	12.9	26.1	10.8	18.7
Greenbank (Defence)	13.5	26.6	13.0	25.9	10.7	17.9
Redcliffe	13.9	26.0	13.3	25.2	11.1	17.5
Redland (Alexandra Hills)	13.4	25.5	12.8	24.6	11.0	18.3

For Scenario 1, the total cooling load saving is around 0.7-0.9 kWh/m² which is equivalent to 3.0-3.6 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.1-9.4 kWh/m² which is equivalent to 28.2-35.5 % total cooling load reduction.

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.

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	%
Amberley	0.7	4.5	0.9	3.6	2.5	16.0	7.1	28.2
Archerfield	0.5	3.6	0.8	3.1	2.5	18.0	7.8	29.9
Brisbane Airport	0.5	3.6	0.8	3.0	3.1	22.5	9.4	35.5
Gold Coast - Seaway	0.5	3.7	0.8	3.0	2.6	19.4	8.2	30.5
Greenbank (Defence)	0.5	3.7	0.7	2.6	2.8	20.7	8.7	32.7
Redcliffe	0.6	4.3	0.8	3.1	2.8	20.1	8.5	32.7
Redland (Alexandra Hills)	0.6	4.5	0.9	3.5	2.4	17.9	7.2	28.2

In the eleven weather stations in Brisbane, 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.

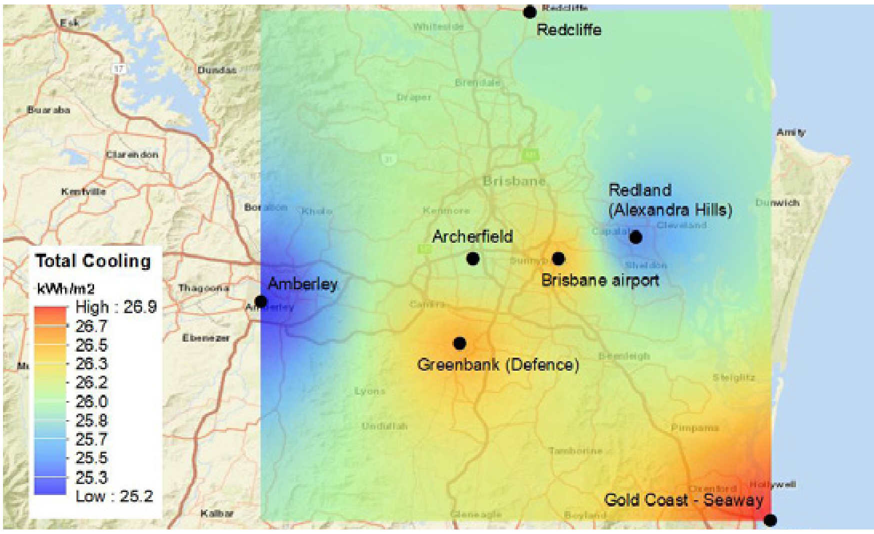

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

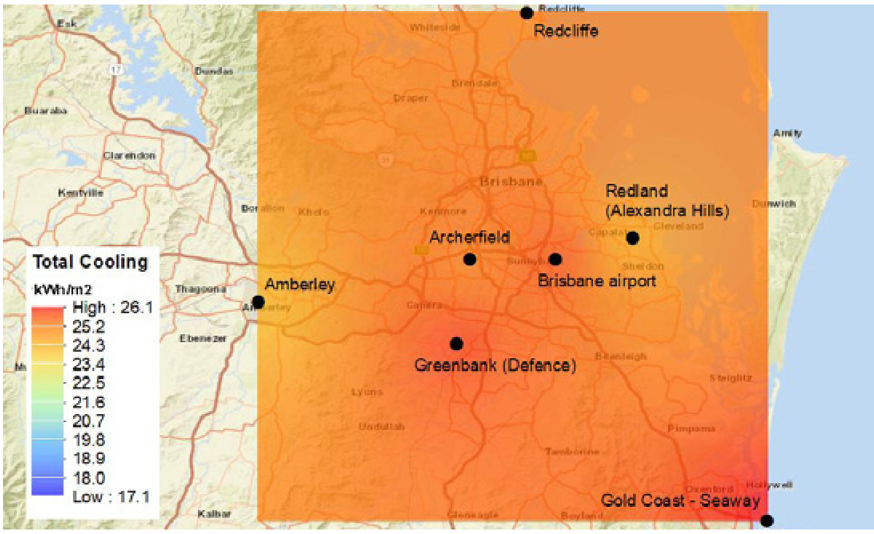

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

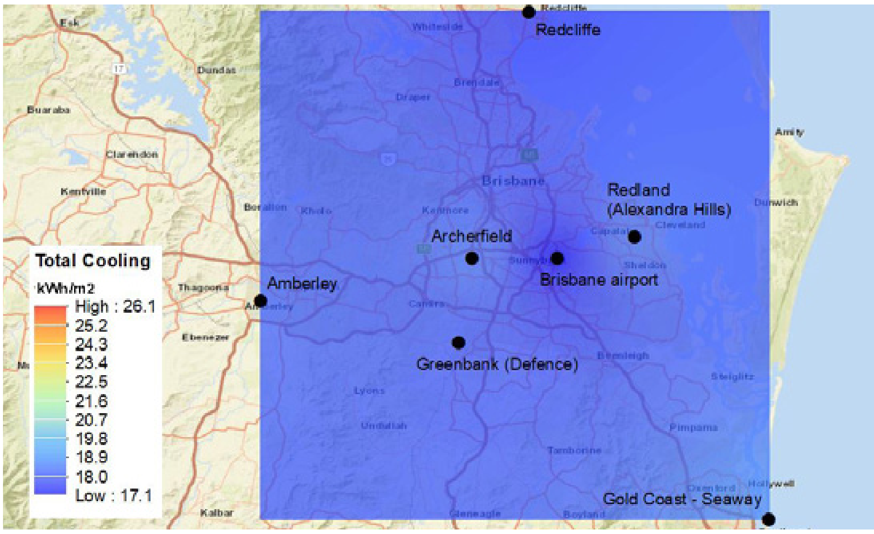

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (1.6-2.6 kWh/m²) is lower than the annual cooling load reduction (4.3-5.6 kWh/m²).

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.

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
Amberley	35.6	49.8	4.0	7.5	33.5	47.4	4.1	7.7
Archerfield	36.1	52.4	2.0	3.8	34.2	50.1	2.0	4.0
Brisbane	41.9	61.9	0.9	1.8	39.2	58.6	1.0	1.9
Brisbane Airport	32.6	50.6	1.3	2.6	30.9	48.4	1.4	2.7
Redland (Alexandra Hills)	32.0	47.9	1.3	2.7	30.0	45.2	1.5	2.8

The annual cooling load saving by building-scale application of cool roofs is around 0.0-0.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.7 and 5.1 kWh/m² (~ 5.2 to 6.4 %).

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 a new mid-rise apartment building 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	%
Amberley	5.9	2.4	4.8	0.1	0.2	2.0	5.1	2.2	3.8	5.9
Archerfield	5.3	2.3	4.4	0.0	0.2	1.9	5.0	2.1	3.7	5.3
Brisbane	6.4	3.3	5.3	0.1	0.1	2.6	6.1	3.2	5.0	6.4
Brisbane Airport	5.2	2.2	4.3	0.1	0.1	1.6	4.7	2.1	3.9	5.2
Redland (Alexandra Hills)	6.3	2.7	5.6	0.2	0.1	1.8	5.4	2.6	5.1	6.3

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

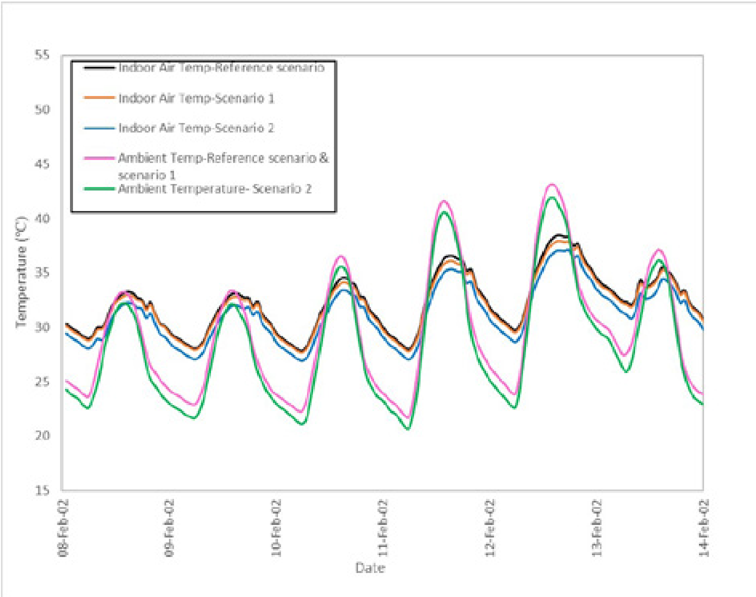

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

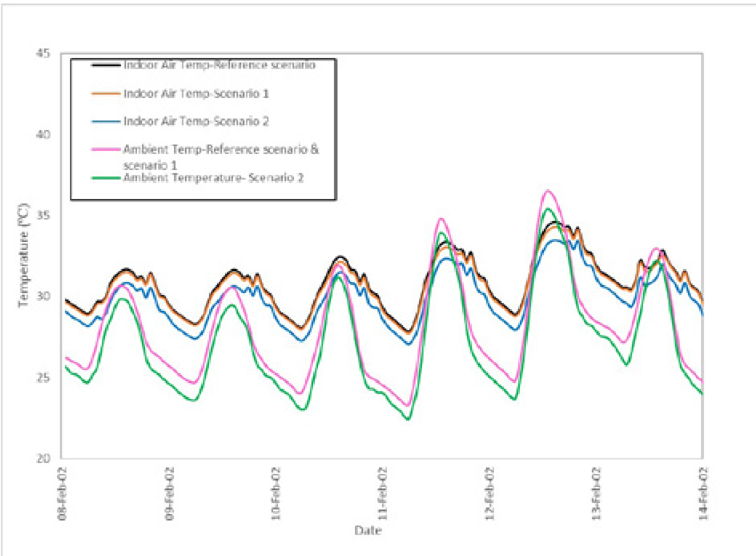

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 27.9-38.4 °C and 27.9-34.6 °C in Amberley and Redland stations, respectively.

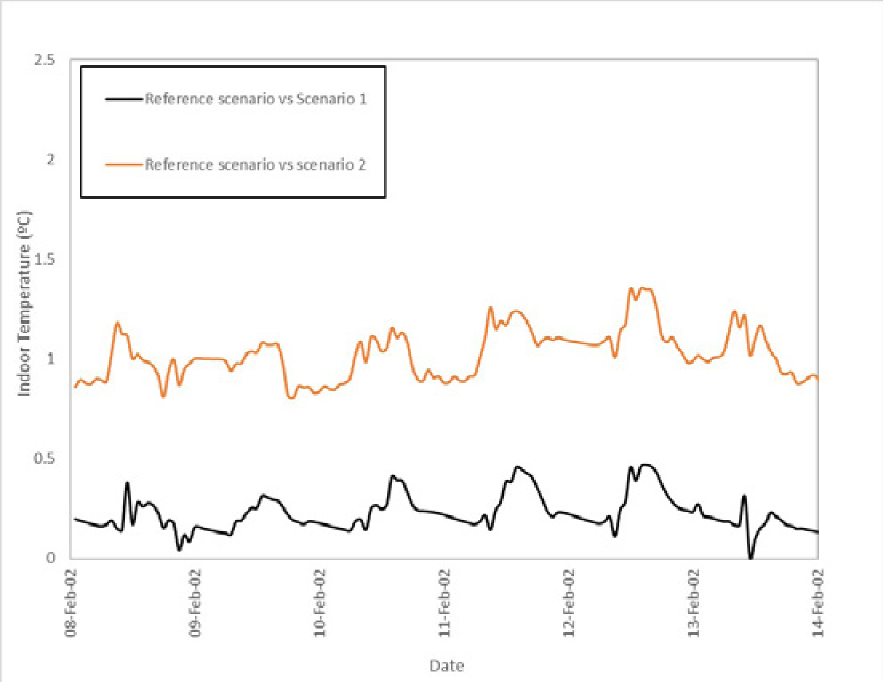

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical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

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

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.4 °C and 1.2 °C in Amberley and Redland stations, respectively.

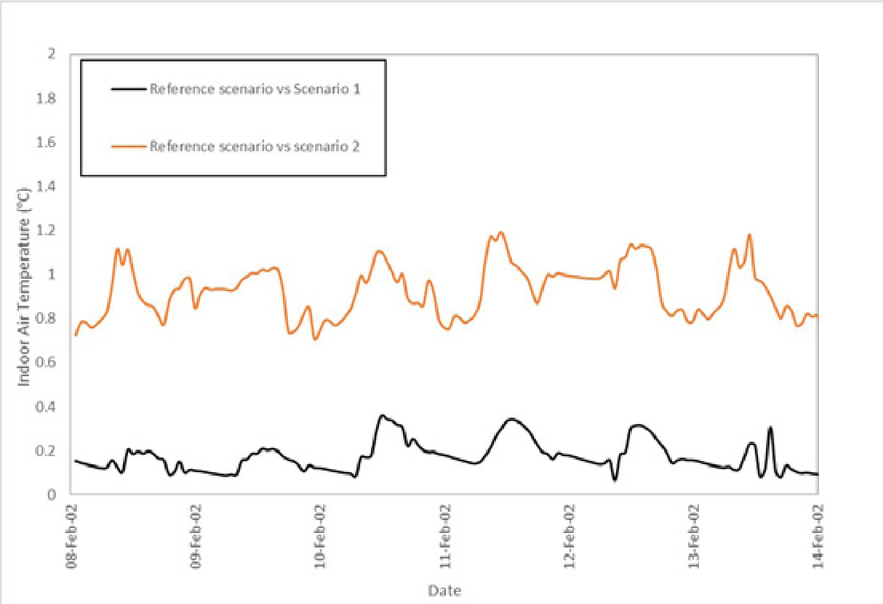

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 14.8-24.5 °C in reference scenario to a range 14.8-24.3 °C in scenario 1 in Amberley station.

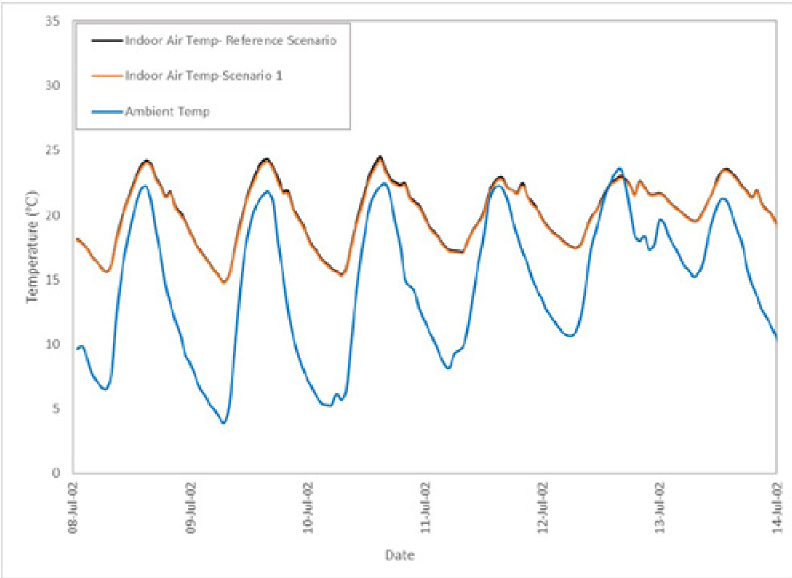

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Amberley station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 17.8-25.3 °C in reference scenario to a range 17.7-25.1 °C in scenario 1 in Redland station.

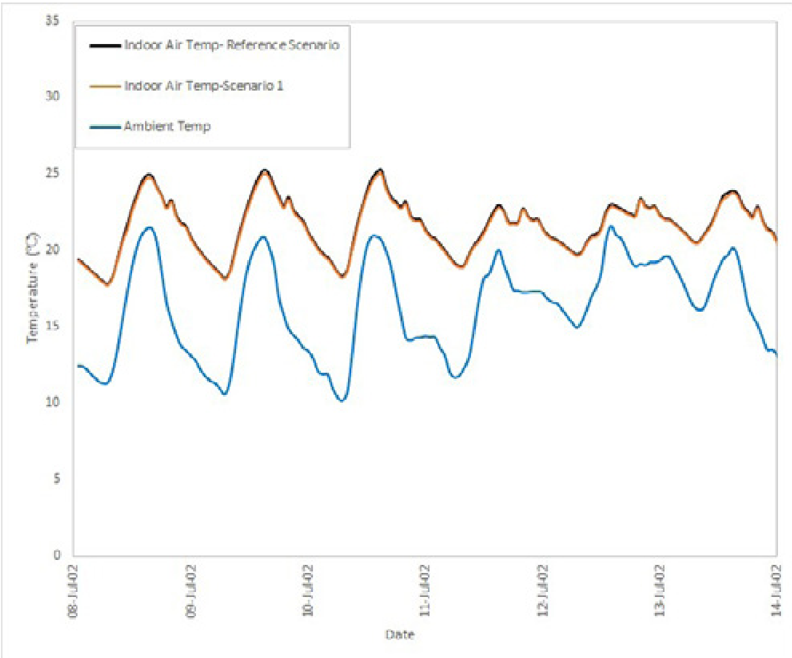

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Redland station* using annual measured weather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

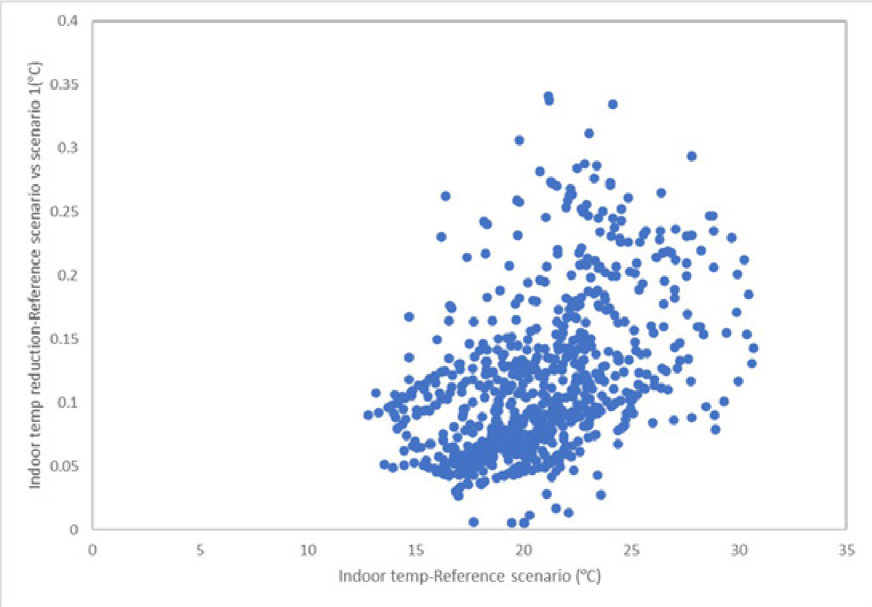

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

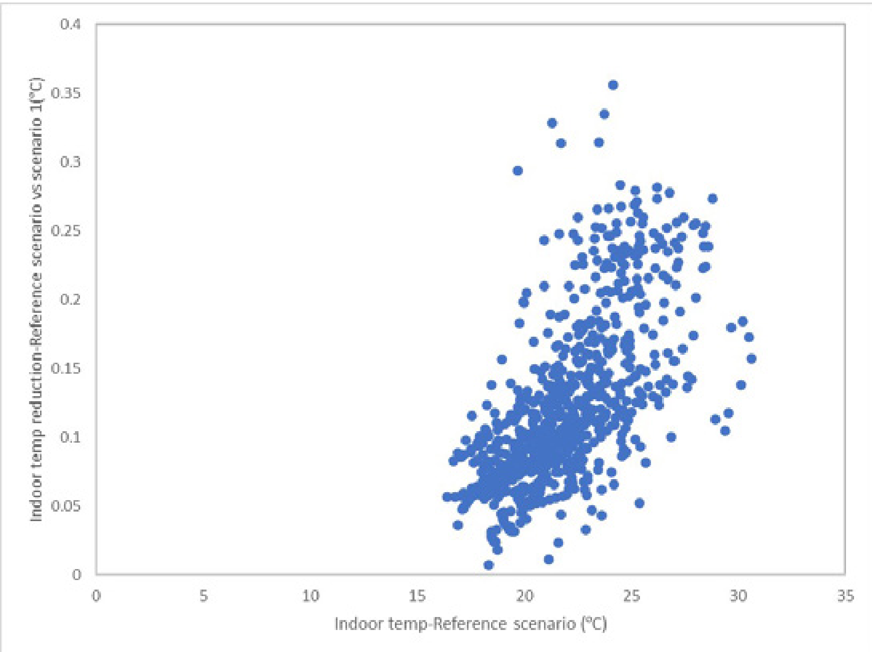

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 236 hours to 242 in Amberley station and from 108 hours to 112 hours in Redland 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
Amberley	236	242
Redland	108	112

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 639 hours in reference scenario to 637 and 598 hours under scenario 1 and 2 in Amberley station; and from 664 hours in reference scenario to 660 and 631 hours under scenario 1 and 2 in Redland 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
Amberley	639	637	598
Redland	664	660	631

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 09.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	71.5	63.1
Energy consumption after cool roof (MWh)	68.8	59.9
Energy savings (MWh)	2.7	3.2
Energy savings (%)	3.78 %	5.07 %
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' reduction of 3,78% for the Amberley weather conditions and of 5,07% for the Redland 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 21,0% for the low energy price scenario for Amberley and 23,4% for the high energy scenario and for Redland condition.*

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 Amberley and for Redland weather conditions respectively.

> *The metal cool roof is, due to its higher initial investment cost, only feasible for the high energy prices scenario for both locations.*

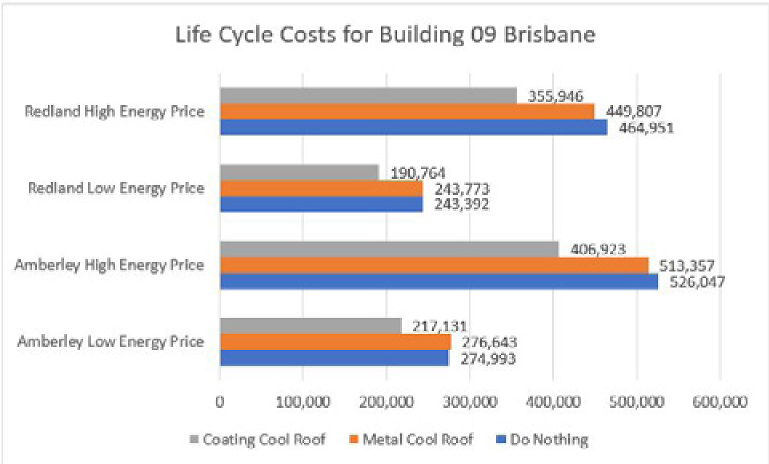

Figure 12. Life Cycle Costs for Building 09 for Amberley and Redland weather stations.

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	-0.60 %	2.41 %	-0.16 %	3.26 %
Coating Cool Roof	21.04 %	22.65 %	21.62 %	23.44 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise apartment from 25.2-26.9kWh/m^2 to 24.3-26.1 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 3.0-3.6 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.1-9.4 kWh/m^2 . This is equivalent to 28.2-35.5 % 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 (1.6-2.6 kWh/m^2) is slightly lower than the annual cooling load reduction (4.3-5.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.0-0.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.7 and 5.1 kWh/m^2 (~ 5.2 to 6.4 %) (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 27.9-38.4 ^{o}C and 27.9-34.6 ^{o}C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.5 and 0.4 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.4 and 1.2 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 14.8-24.5 ^{o}C in reference scenario to a range between 14.8-24.3 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 17.8-25.3 °C in reference scenario to a range between 17.7-25.1 °C in reference with cool roof scenario (scenario 1) in Redland 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 oC and 0.4 oC in Amberley and Redland 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 slightly increase from 236 hours to 242 in Amberley station and from 108 hours to 112 hours in Redland 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 639 hours under the reference scenario in Amberley station, which decreases to 637 and 598 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Redland station also illustrate a significant reduction in number of hours above 26 °C from 664 hours in reference scenario to 660 in reference with cool roof scenario (scenario 1) and 631 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 21,0% for the low energy price scenario for Amberley and 23,4% for the high energy scenario and for Redland conditions, as it can be seen in Table8. The metal cool roof is, due to its higher initial investment cost, only feasible for the high energy prices scenario for both 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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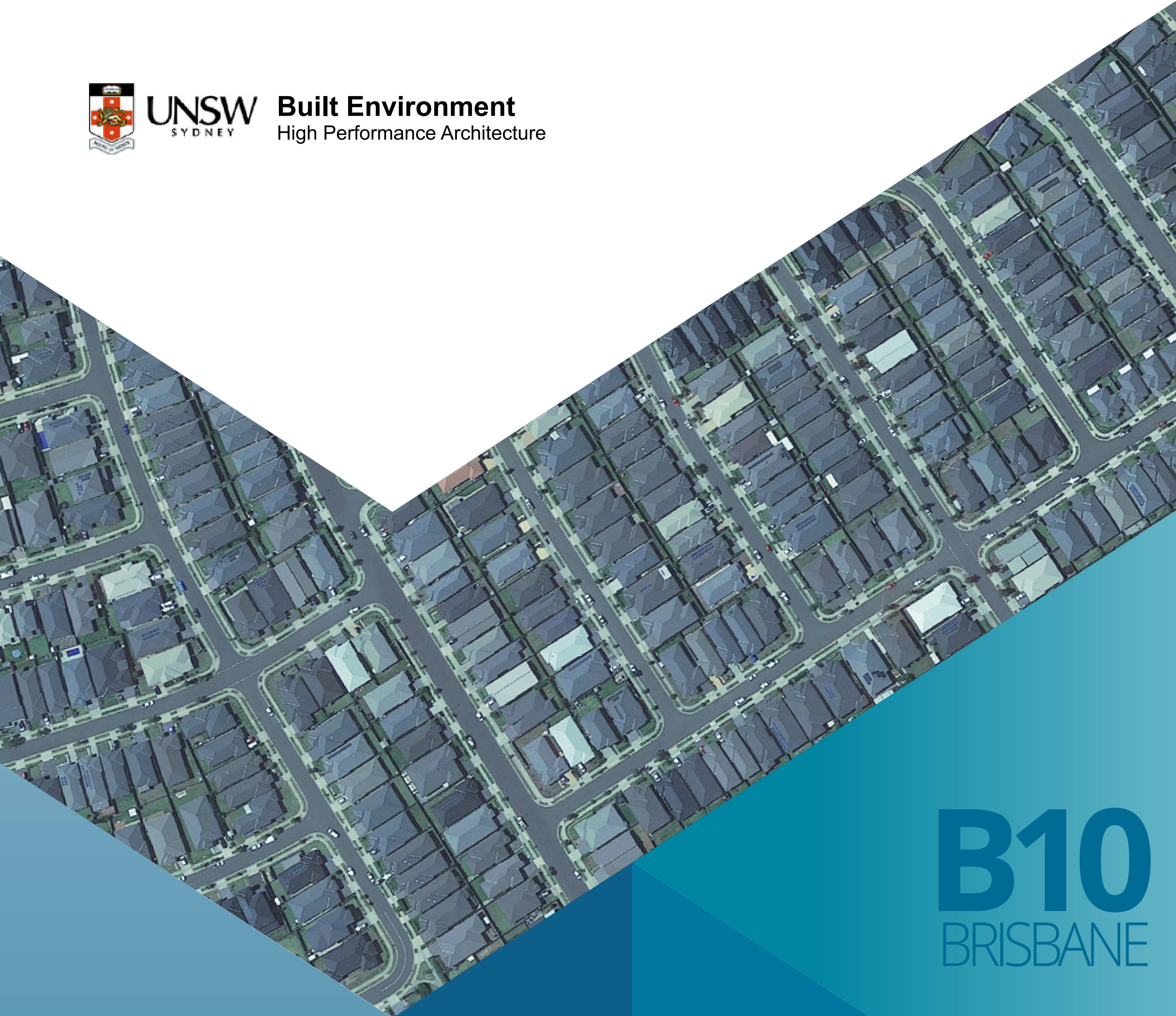

B10
BRISBANE

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

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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 Brisbane 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 24.9-26.7 kWh/m² to 24.4-26.2 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)
Amberley	15.3	24.9	14.9	24.4	13.1	18.2
Archerfield	13.8	25.9	13.4	25.4	11.4	18.4
Brisbane Airport	13.7	26.3	13.3	25.8	10.7	17.2
Gold Coast - Seaway	13.2	26.7	12.9	26.2	10.8	18.8
Greenbank (Defence)	13.3	26.4	12.9	26.0	10.7	18.0
Redcliffe	13.7	25.8	13.3	25.3	11.1	17.6
Redland (Alexandra Hills)	13.1	25.2	12.8	24.8	11.0	18.4

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 0.4-0.5 kWh/m² which is equivalent to 1.5-2.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.7-9.1 kWh/m² which is equivalent to 26.9-34.9 % 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	%
Amberley	0.4	2.6	0.5	2.0	2.2	14.4	6.7	26.9
Archerfield	0.4	2.9	0.5	1.9	2.4	17.4	7.5	29.0
Brisbane Airport	0.4	2.9	0.5	1.9	3	21.9	9.1	34.6
Gold Coast - Seaway	0.3	2.3	0.5	1.9	2.4	18.2	7.9	29.6
Greenbank (Defence)	0.4	3.0	0.4	1.5	2.6	19.5	8.4	31.8
Redcliffe	0.4	2.9	0.5	1.9	2.6	19.0	8.2	31.8
Redland (Alexandra Hills)	0.3	2.3	0.4	1.6	2.1	16.0	6.8	27.0

In the eleven weather stations in Brisbane, 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.

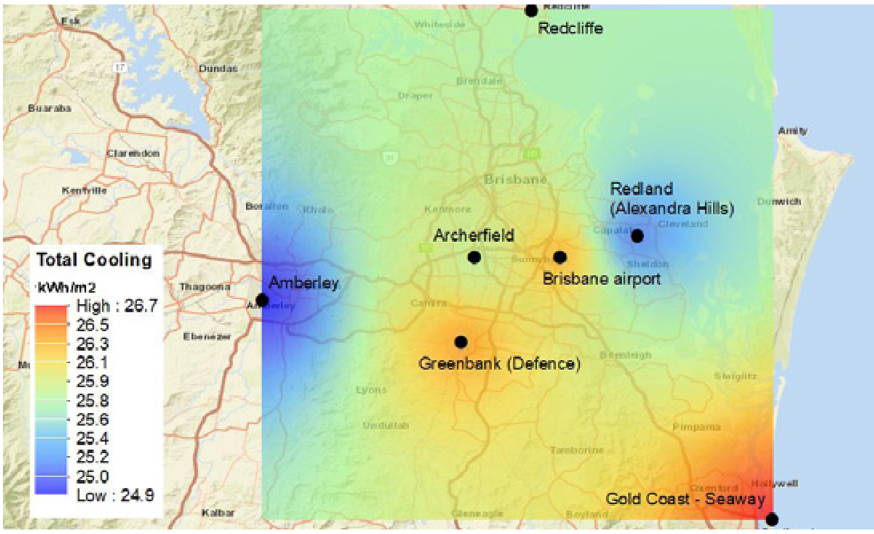

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

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

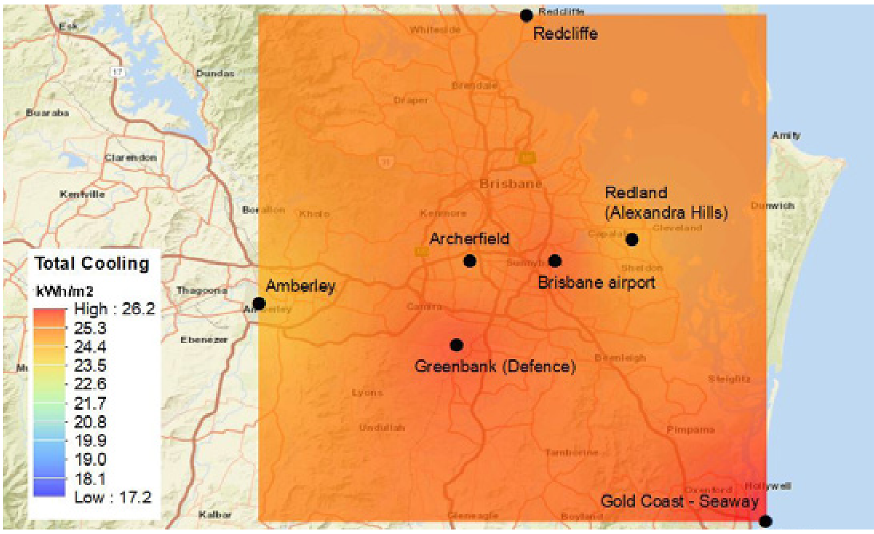

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

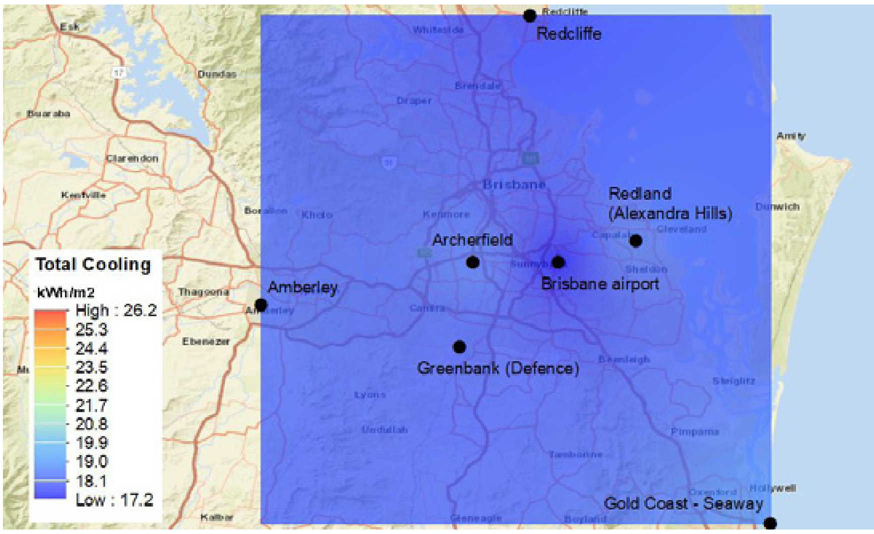

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 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 (0.1 kWh/m²) is significantly lower than the annual cooling load reduction (1.2-2.0 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
Amberley	34.6	48.7	3.7	7.1	33.4	47.3	3.8	7.2
Archerfield	35.2	51.4	1.8	3.6	34.1	50.0	1.9	3.7
Brisbane	40.9	60.7	0.8	1.6	39.3	58.7	0.9	1.7
Brisbane Airport	31.7	49.6	1.2	2.4	30.9	48.4	1.3	2.5
Redland (Alexandra Hills)	31.1	46.8	1.3	2.5	29.9	45.2	1.4	2.6

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 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 2.4-3.4 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.1 and 1.9 kWh/m² (~2.1-3.0 %).

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	%
Amberley	1.2	3.5	1.4	2.9	0.1	0.1	1.1	2.9	1.3	2.3
Archerfield	1.1	3.1	1.4	2.7	0.1	0.1	1.0	2.7	1.3	2.4
Brisbane	1.6	3.9	2.0	3.3	0.1	0.1	1.5	3.6	1.9	3.0
Brisbane Airport	0.8	2.5	1.2	2.4	0.1	0.1	0.7	2.1	1.1	2.1
Redland (Alexandra Hills)	1.2	3.9	1.6	3.4	0.1	0.1	1.1	3.4	1.5	3.0

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

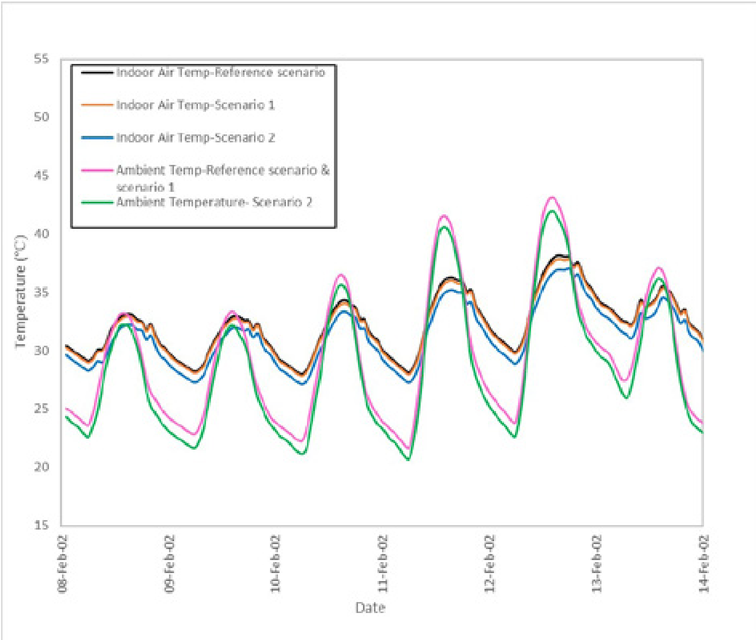

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

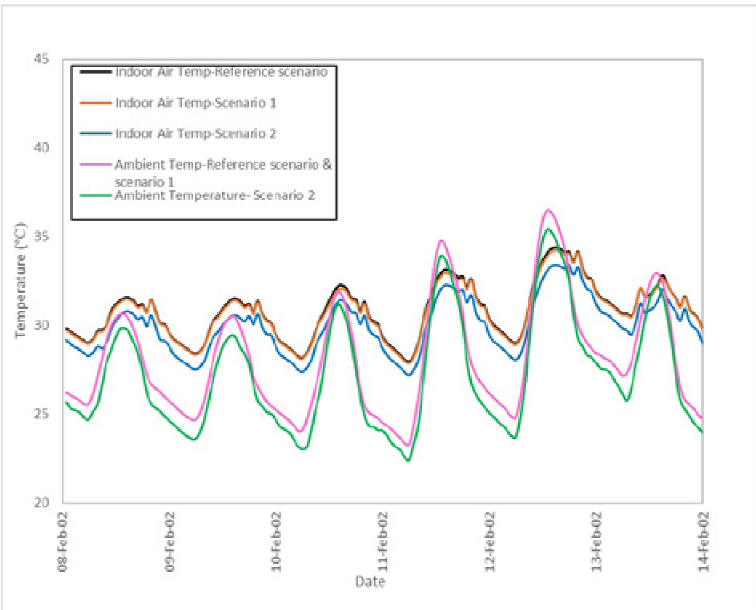

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.0-38.1 °C and 28.0-34.4 °C in Amberley and Redland stations, respectively.

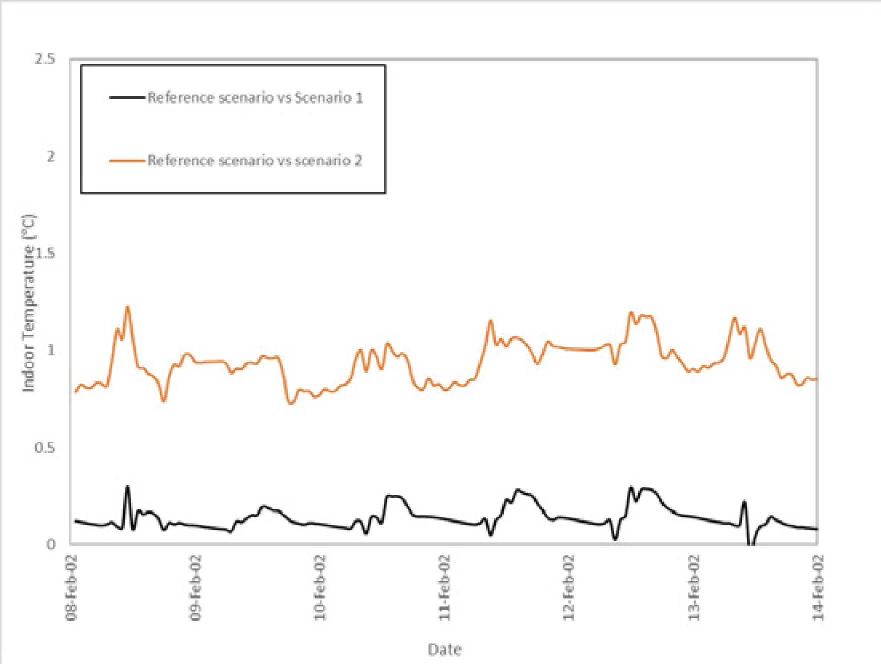

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical summer week in *Amberley 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 0.2 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.2 °C and 1.1 °C in Amberley and Redland stations, respectively.

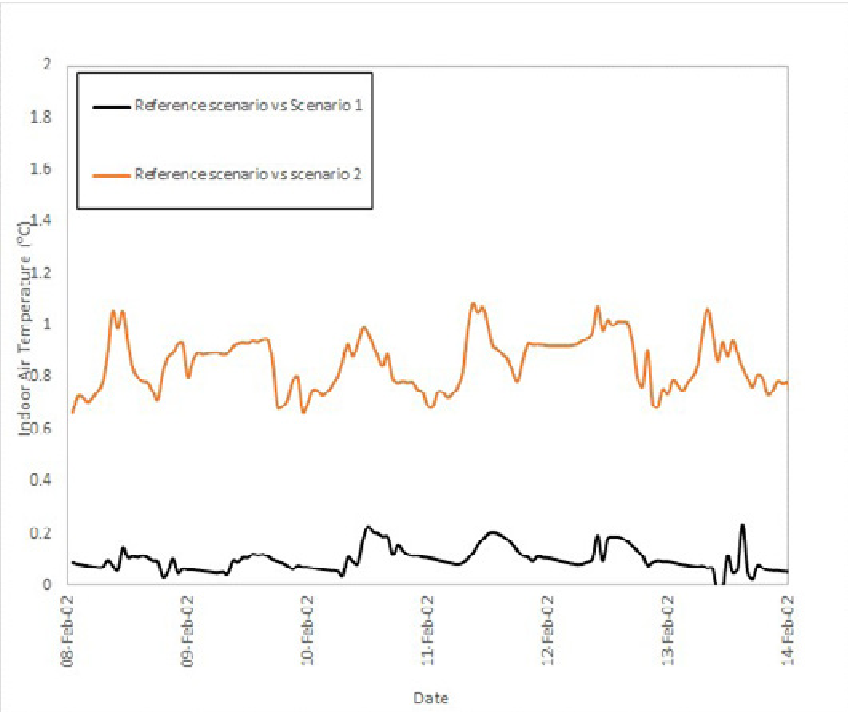

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 15.0-24.3 °C in reference scenario to a range 14.9-24.1 °C in scenario 1 in Amberley station.

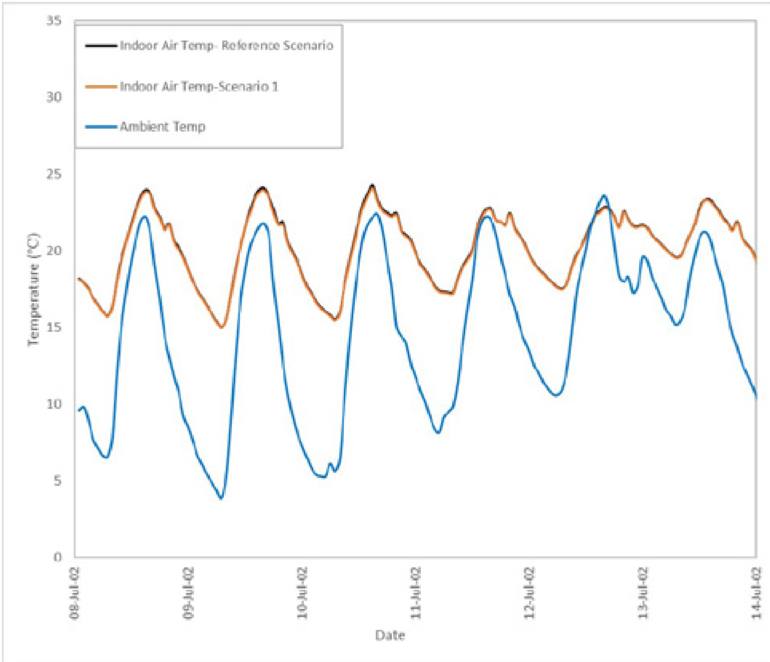

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Amberley station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 17.9-25.1 °C in reference scenario to a range 17.9-24.9 °C in scenario 1 in Redland station.

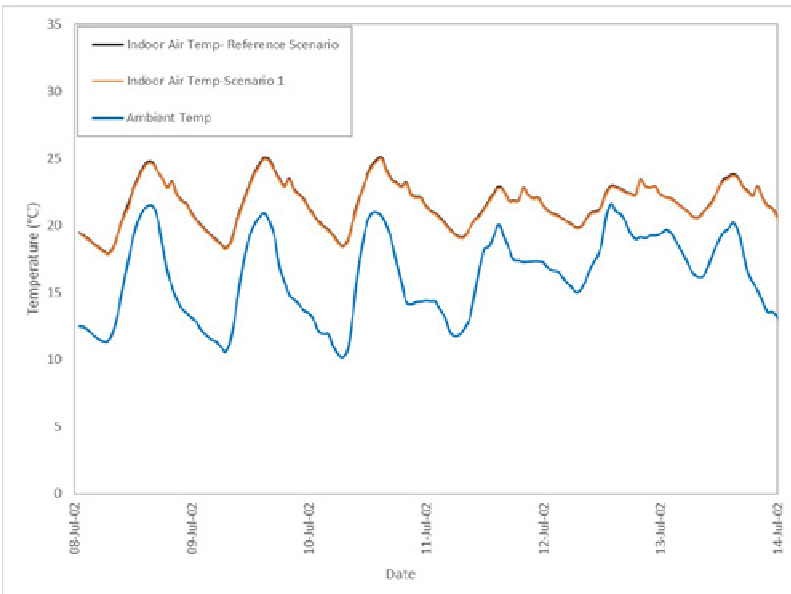

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Redland station* using annual measured weather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

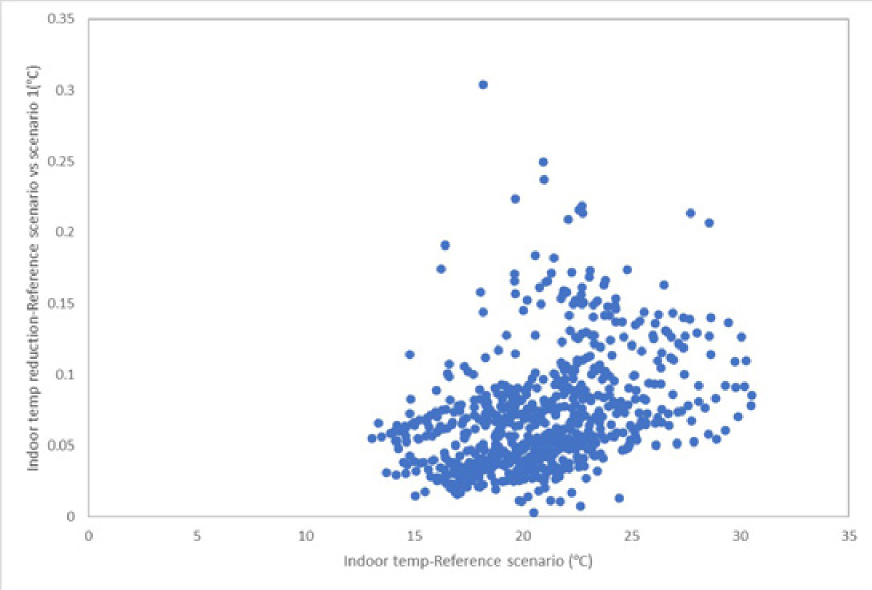

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

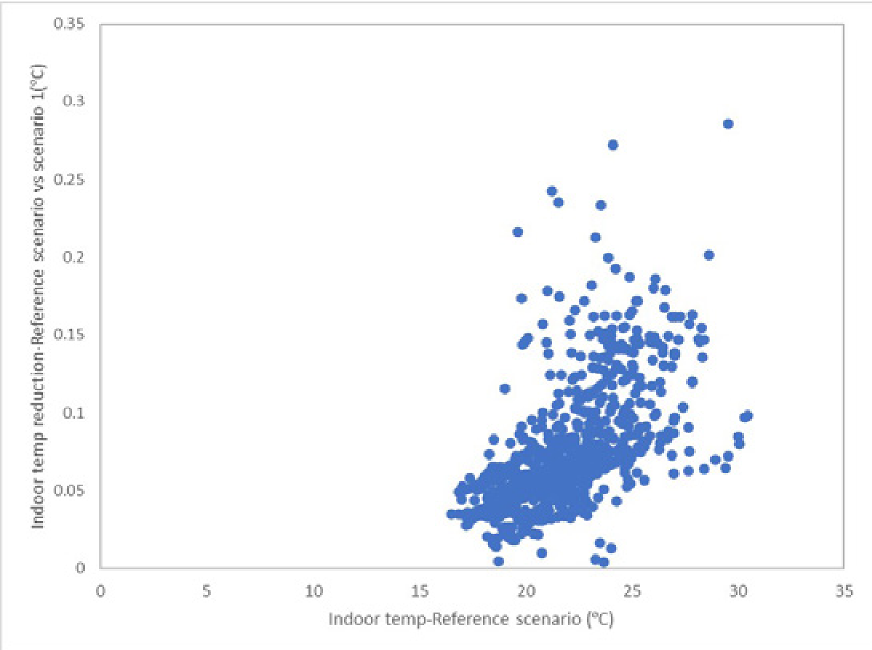

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 234 hours in reference scenario to 238 hours, and from 102 hours to 107 hours in scenario 1 in Amberley and Redland 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
Amberley	234	238
Redland	102	107

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 642 hours in reference scenario to 640 and 606 hours under scenario 1 and 2 in Amberley station; and from 665 hours in reference scenario to 664 and 637 hours under scenario 1 and 2 in Redland 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
Amberley	642	640	606
Redland	665	664	637

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due 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 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 10.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	111.4	98.4
Energy consumption after cool roof (MWh)	108.8	95.4
Energy savings (MWh)	2.6	3.0
Energy savings (%)	2.33 %	3.05 %
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 10 is an interesting example of a new, high-rise residential building, where the energy conservation potential is in modest. However, even so, the application of a coating cool technology emerges as a very 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 2,33% for the Amberley weather conditions and of 3,05% for the Redland 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, that varies between 21,1% for the low energy price scenario for Amberley and 22,5% for the high energy scenario and for Redland 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 Amberley and for Redland weather conditions respectively.

The metal cool roof is, due to its higher initial investment cost and the modest energy savings, feasible for the high energy prices scenario.

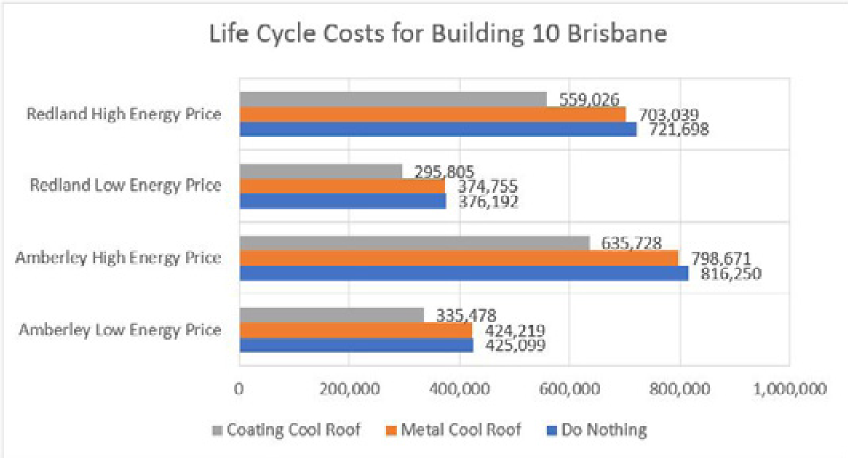

Figure 12. Life Cycle Costs for Building 10 for Amberley and Redland weather stations.

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	0.21 %	2.15 %	0.38 %	2.59 %
Coating Cool Roof	21.08 %	22.12 %	21.37 %	22.54 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 24.9-26.7 kWh/m^2 to 24.4-26.2 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.4-0.5 kWh/m^2. This is equivalent to approximately 1.5-2.0 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 6.7-9.1 kWh/m^2. This is equivalent to 26.9-34.9 % 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 kWh/m^2) is significantly lower than the annual cooling load reduction (1.2-2.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 2.4-3.4 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.1 and 1.9 kWh/m^2 (~2.1-3.0 %) (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 28.0-38.1 ^{o}C and 28.0-34.4 ^{o}C in Amberley and Redland 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 0.2 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.2 and 1.1 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 15.0-24.3 ^{o}C in reference scenario to a range between 14.9-24.1 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8). Similarly, the indoor air temperature is predicted to slightly reduce from a range between 17.9-25.1 °C in reference scenario to a range between 17.9-24.9 °C in reference with cool roof scenario (scenario 1) in Redland 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 for Amberley and Redland 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 234 hours in reference scenario to 238 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations show that the total number of hours below 19 °C slightly increased from 102 hours in reference scenario to 107 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 642 hours under the reference scenario in Amberley station, which decreases to 640 and 606 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Redland station also illustrate a significant reduction in number of hours above 26 °C from 665 hours in reference scenario to 664 in reference with cool roof scenario (scenario 1) and 637 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 21,1% for the low energy price scenario for Amberley and 22,5% for the high energy scenario and for Redland 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, feasible for the high energy prices scenario. Building 10 is in that sense an interesting example of a new, high-rise residential building, where the energy conservation potential is in modest. However, even so, the application of a coating cool technology emerges as a very meaningful investment.

B10

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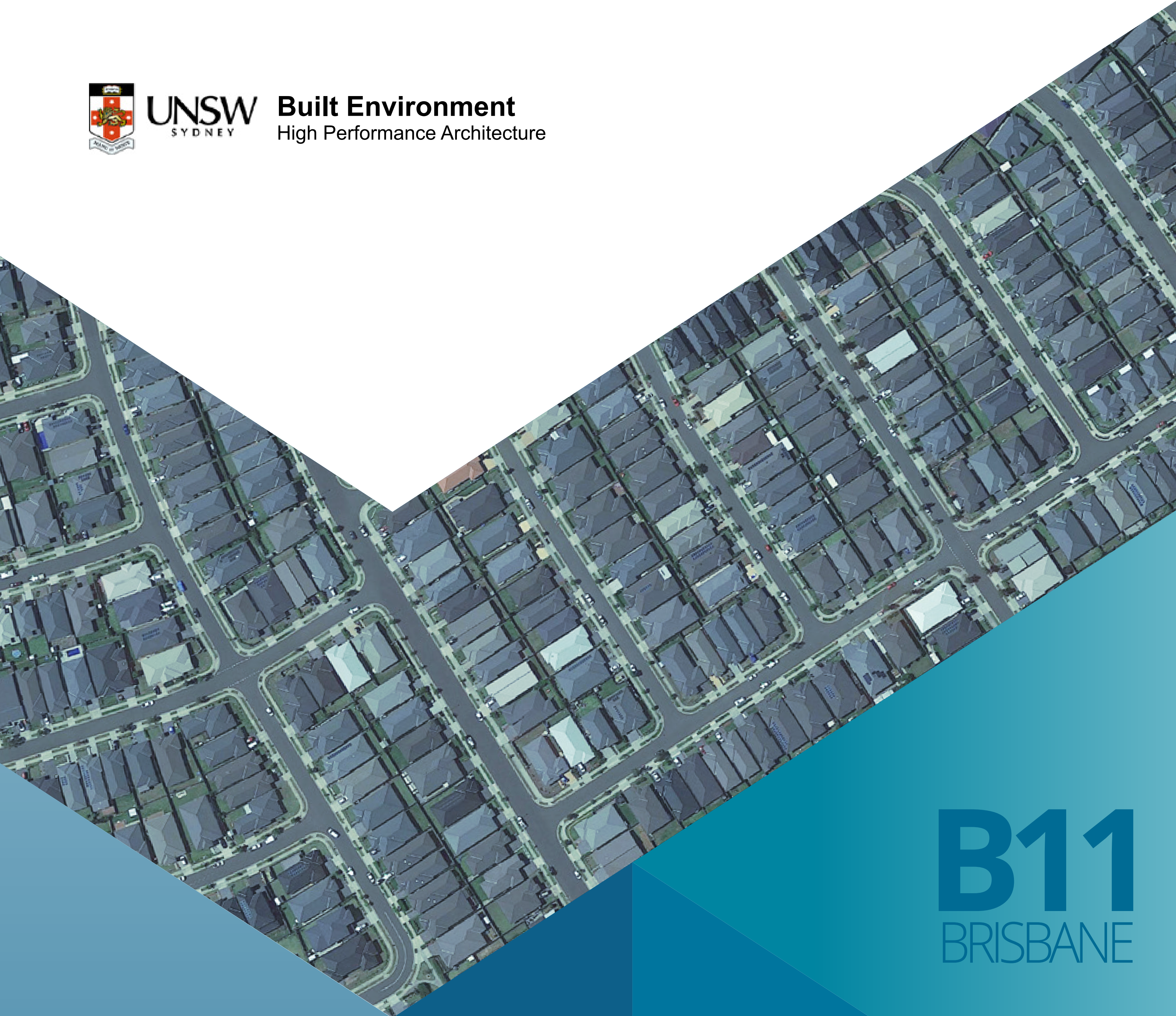

B11
BRISBANE

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

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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 Brisbane 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 22.3-22.6 kWh/m² to 17.8-18.7 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)
Amberley	15.5	22.4	12	18.2	10.4	13.7
Archerfield	13.4	22.3	10.4	18.4	8.7	13.4
Brisbane Airport	13.2	22.5	10.3	18.6	8.1	12.4
Gold Coast - Seaway	12.6	22.6	9.8	18.7	8.0	13.3
Greenbank (Defence)	12.7	22.5	9.9	18.5	7.9	12.8
Redcliffe	13.4	22.4	10.3	18.3	8.4	12.8
Redland (Alexandra Hills)	12.8	21.8	9.9	17.8	8.5	13.2

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 3.9-4.2 kWh/m² which is equivalent to 17.3-18.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 8.6-10.1 kWh/m² which is equivalent to 38.8-44.9 % 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	%
Amberley	3.5	22.6	4.2	18.8	5.1	32.9	8.7	38.8
Archerfield	3.0	22.4	3.9	17.5	4.7	35.1	8.9	39.9
Brisbane Airport	2.9	22.0	3.9	17.3	5.1	38.6	10.1	44.9
Gold Coast - Seaway	2.8	22.2	3.9	17.3	4.6	36.5	9.3	41.2
Greenbank (Defence)	2.8	22.0	4.0	17.8	4.8	37.8	9.7	43.1
Redcliffe	3.1	23.1	4.1	18.3	5.0	37.3	9.6	42.9
Redland (Alexandra Hills)	2.9	22.7	4.0	18.3	4.3	33.6	8.6	39.4

In the eleven weather stations in Brisbane, 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.

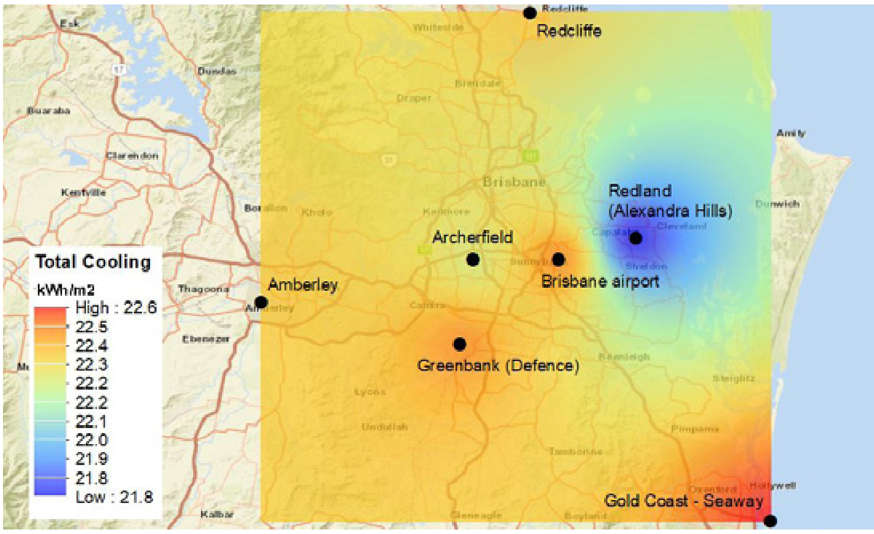

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

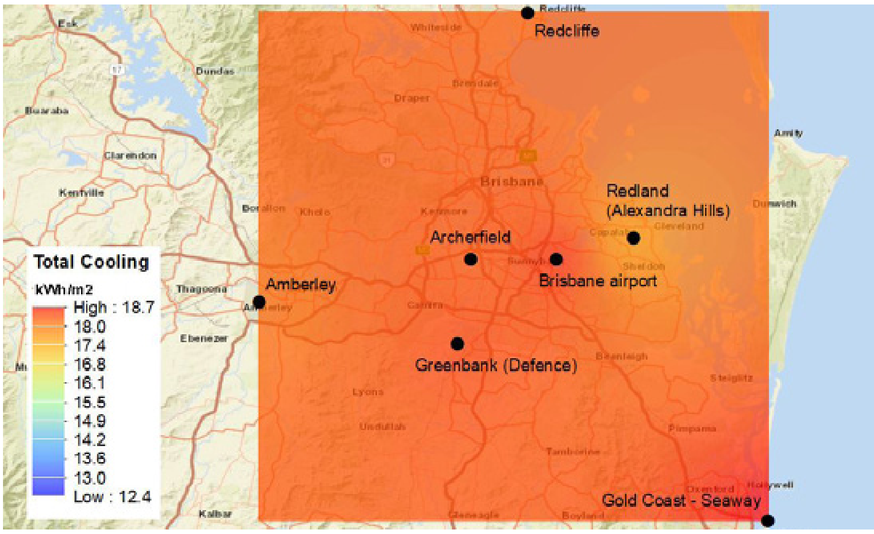

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

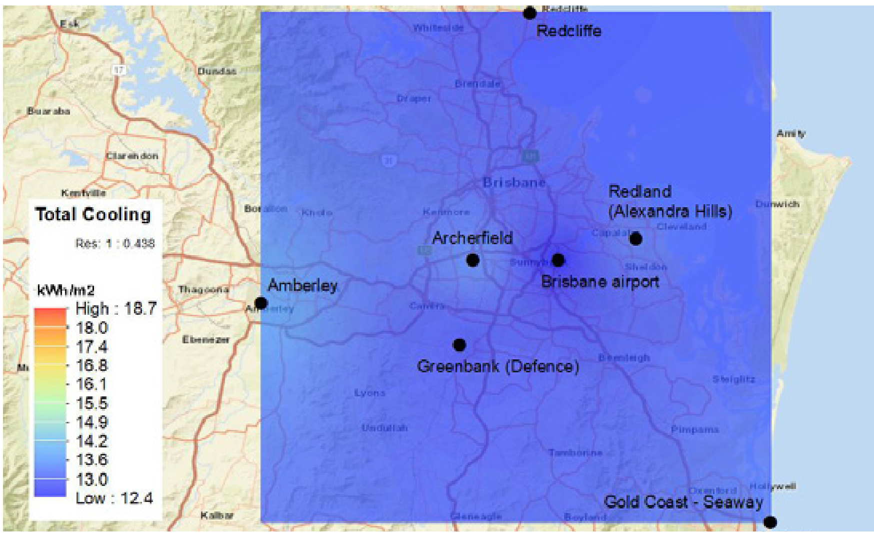

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.4-0.6 kWh/m²) is significantly lower than the annual cooling load reduction (11.5-13.6 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
Amberley	35.2	48.7	7.1	9.5	24.8	36.4	7.6	10.1
Archerfield	34.4	49.5	4.7	6.3	24.6	37.6	5.1	6.8
Brisbane	40.2	58.1	3.5	4.7	27.3	45.5	3.7	5.1
Brisbane Airport	29.8	46.3	3.9	5.1	21.0	34.8	4.1	5.5
Redland (Alexandra Hills)	30.5	46.4	4.1	5.4	20.0	32.8	4.4	5.9

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 an existing 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 21.7-29.3 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 11.1 and 13.1 kWh/m² (~19.4-25.3 %).

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	%
Amberley	10.4	29.5	12.3	25.3	0.5	0.6	9.9	23.4	11.7	20.1
Archerfield	9.8	28.5	11.9	24.0	0.4	0.5	9.4	24.0	11.4	20.4
Brisbane	12.9	32.1	12.6	21.7	0.2	0.4	12.7	29.1	12.2	19.4
Brisbane Airport	8.8	29.5	11.5	24.8	0.2	0.4	8.6	25.5	11.1	21.6
Redland (Alexandra Hills)	10.5	34.4	13.6	29.3	0.3	0.5	10.2	29.5	13.1	25.3

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

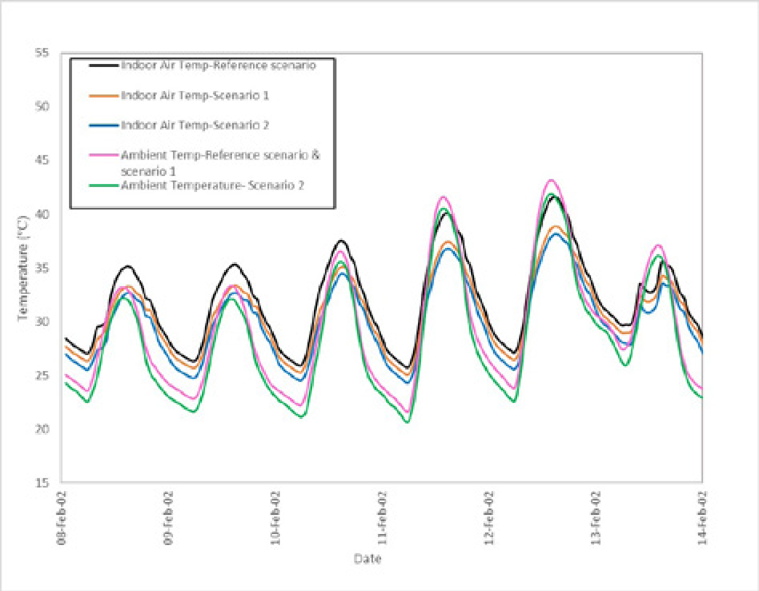

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical summer week in *Amberley station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

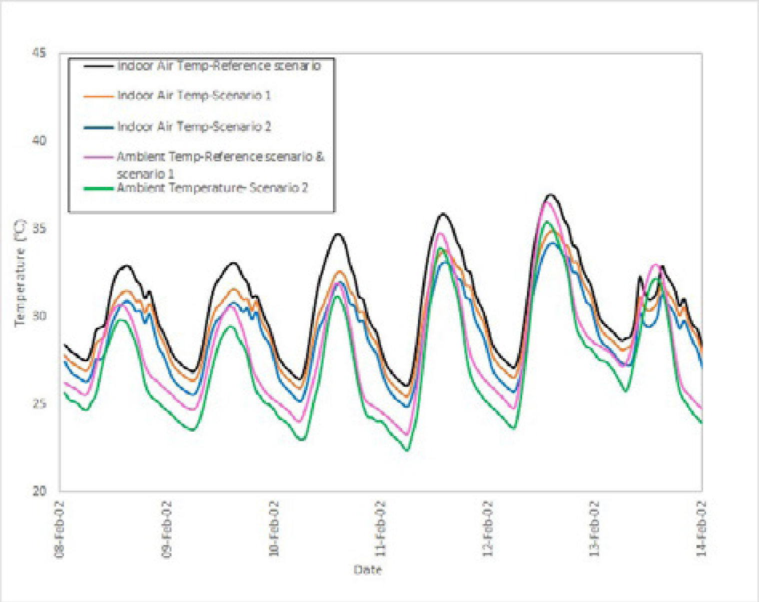

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical summer week in *Redland station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 25.8-41.6 °C and 26.1- 37.0 °C in Amberley and Redland stations, respectively.

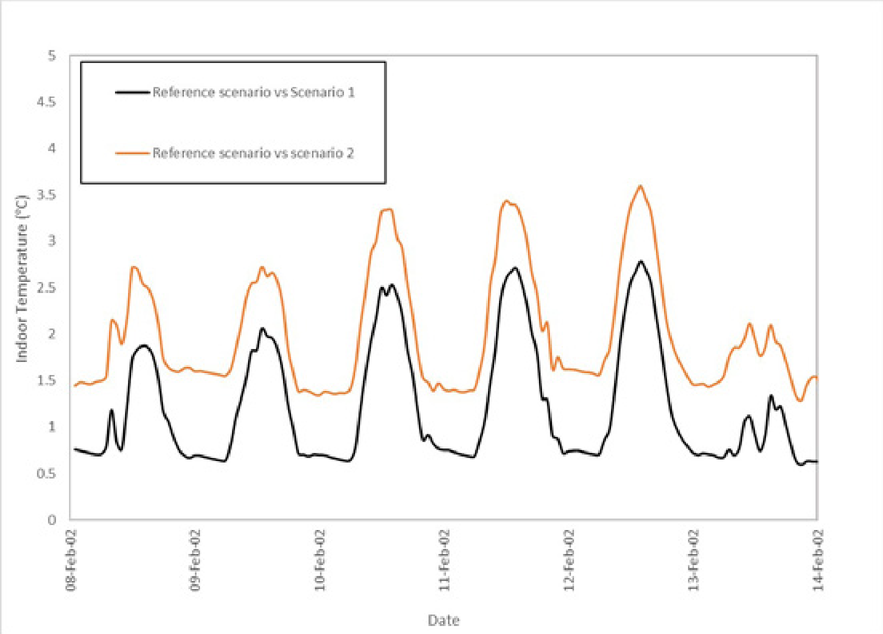

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer week in *Amberley station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.8 °C and 2.4 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.6 °C and 3.2 °C in Amberley and Redland stations, respectively.

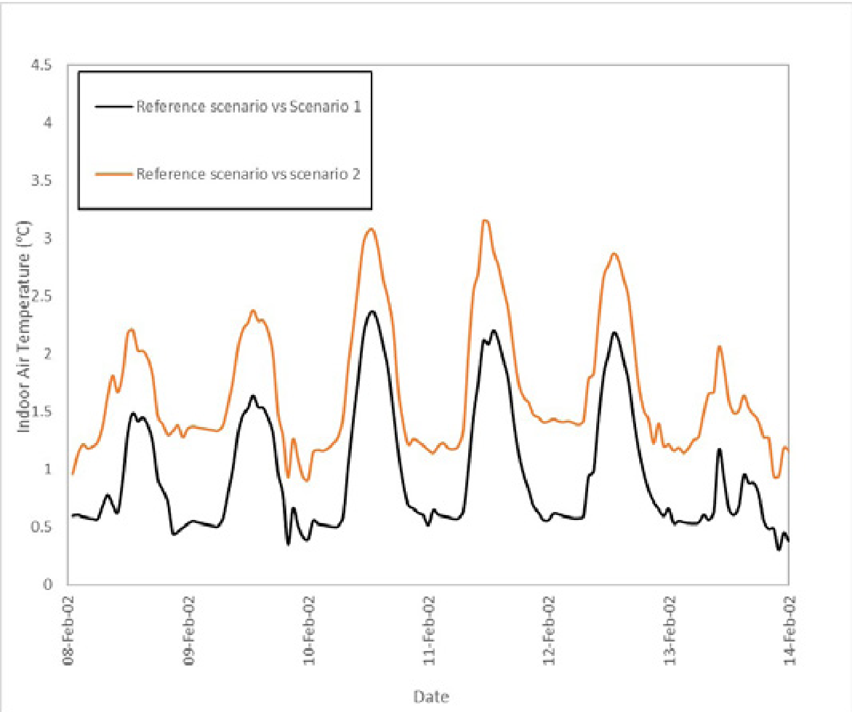

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 11.8-27.0 °C in reference scenario to a range 11.5-25.5 °C in scenario 1 in Amberley station.

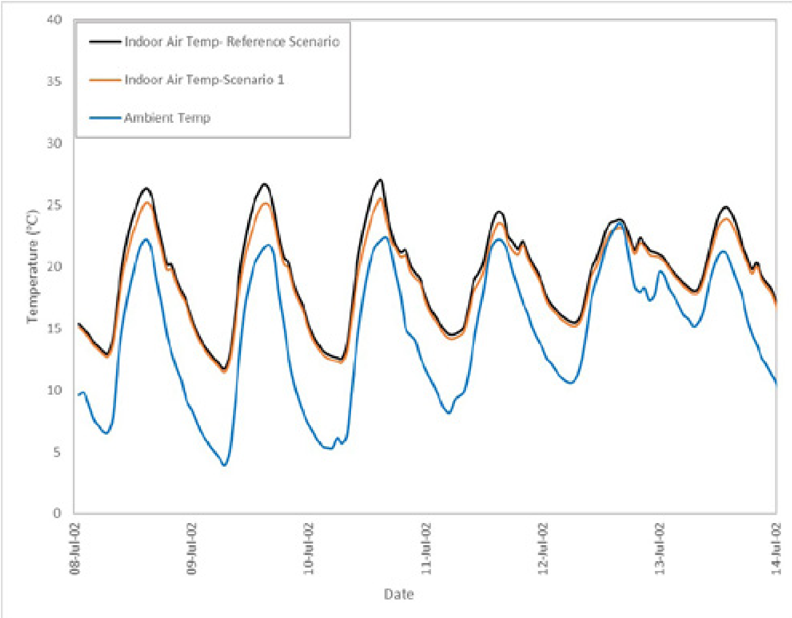

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Amberley station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 15.6-27.1 °C in reference scenario to a range 15.3-25.6 °C in scenario 1 in Redland station.

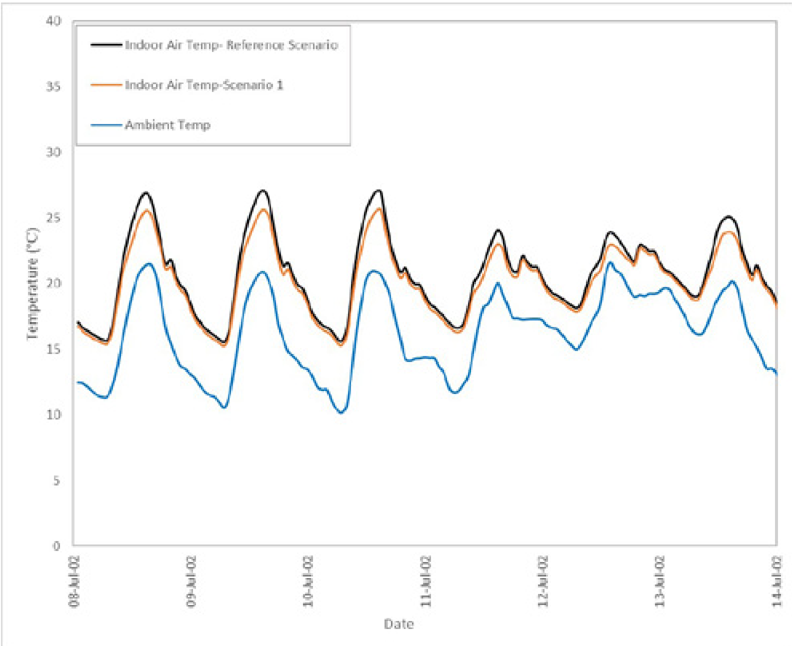

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Redland station* using annual measured weather data.

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 1.8 °C in Amberley and Redland stations, respectively.

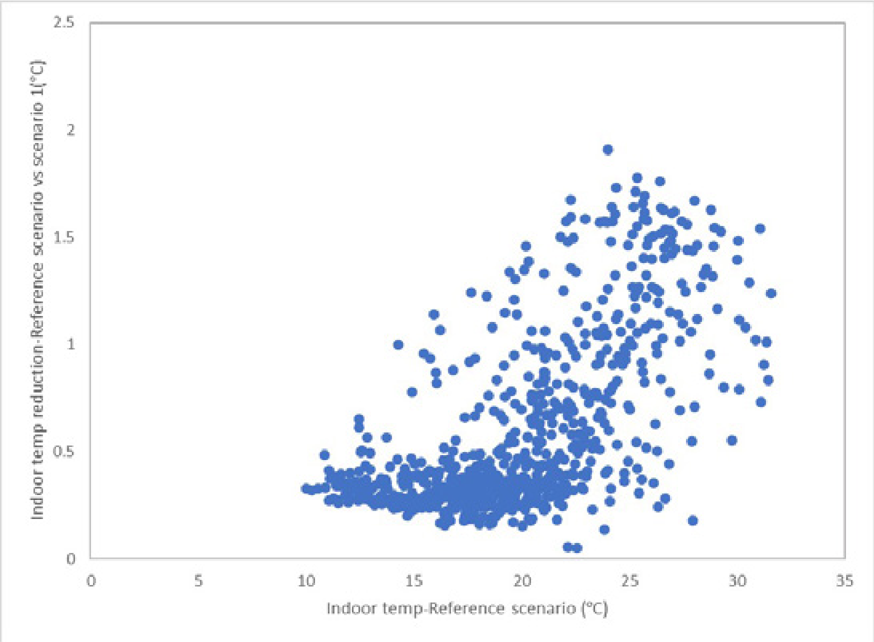

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

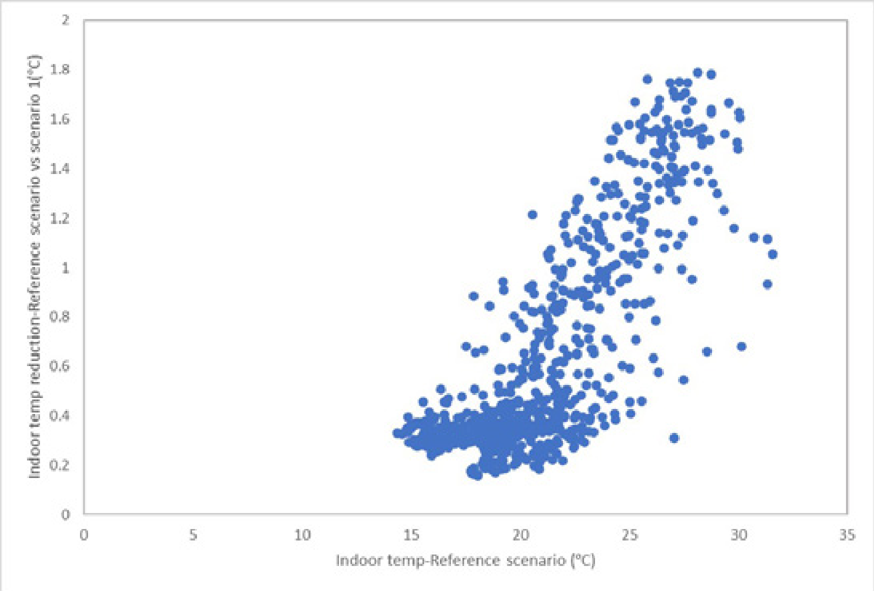

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 330 hours in reference scenario to 360 hours; and from 235 to 270 hours in scenario 1 in Amberley and Redland stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Amberley	330	360
Redland	235	270

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 573 hours in reference scenario to 530 and 463 hours under scenario 1 and 2 in Amberley station; and from 592 hours in reference scenario to 565 and 490 hours under scenario 1 and 2 in Redland station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Amberley	573	530	463
Redland	592	565	490

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 11 is an existing, stand-alone residential building, with a total air-conditioned area of 242 m^2 distributed on one level. Despite the fact that the 242 m^2 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 11.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	5.6	5.0
Energy consumption after cool roof (MWh)	4.5	3.7
Energy savings (MWh)	1.1	1.3
Energy savings (%)	19.64 %	26.00 %
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

The cool roof refurbishment options

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.

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 19,64% for the Amberley weather conditions and of 26,00% for the Redland 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, that varies between 20,6% for the low energy price scenario for Amberley and 32,0% for the high energy scenario and for Redland 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 Amberley and for Redland weather conditions respectively.

Given the low in absolute terms energy expenditure and the high initial cost of the metal cool roof, this is only feasible for high energy prices. On the contrary, the coating cool technology emerges as an appealing investment under all conditions.

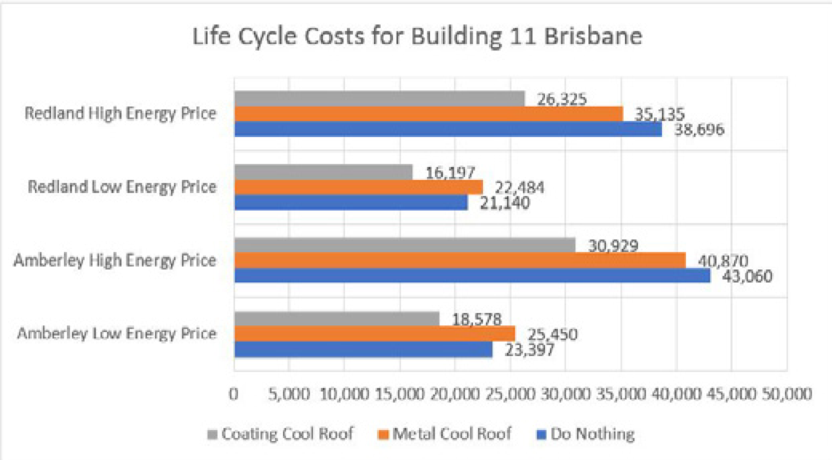

Figure 12. Life Cycle Costs for Building 11 for Amberley and Redland weather stations.

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	-8.77 %	5.09 %	-6.36 %	9.20 %
Coating Cool Roof	20.60 %	28.17 %	23.38 %	31.97 %

The metal cool roof is, due to its higher initial investment cost, only feasible for the high energy prices scenario for both locations.

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 22.3-22.6 kWh/m^2 to 17.8-18.7 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 3.9-4.2 kWh/m^2. This is equivalent to approximately 17.3-18.8 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 8.6-10.1 kWh/m^2. This is equivalent to 38.8-44.9 % 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 (0.4-0.6 kWh/m2) is relatively similar to the annual cooling load reduction (11.5-13.6 kWh/m2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 21.7-29.3 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 11.1 and 13.1 kWh/m^2 (~19.4-25.3 %) (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 25.8-41.6 °C and 26.1- 37.0 °C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 4.2 and 4.7 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 5.0 and 5.6 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 11.8-27.0 °C in reference scenario to a range between 11.5-25.5 °C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 15.6-27.1 °C in reference scenario to a range between 15.3-25.6 °C in reference with cool roof scenario (scenario 1) in Redland 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 and 1.8 °C for Amberley and Redland 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 330 hours in reference scenario to 360 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slightly increase in total number of hours below 19 °C from 235 hours in reference scenario to 270 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 573 hours under the reference scenario in Amberley station, which significantly decreases to 530 and 463 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Redland station also illustrate a significant reduction in number of hours above 26 °C from 592 hours in reference scenario to 565 in reference with cool roof scenario (scenario 1) and 490 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 20,6% for the low energy price scenario for Amberley and 32,0% for the high energy scenario and for Redland conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost, only feasible for the high energy prices scenario for both 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 only feasible for high energy prices. On the contrary, the coating cool technology emerges as an appealing investment under all conditions.

B11

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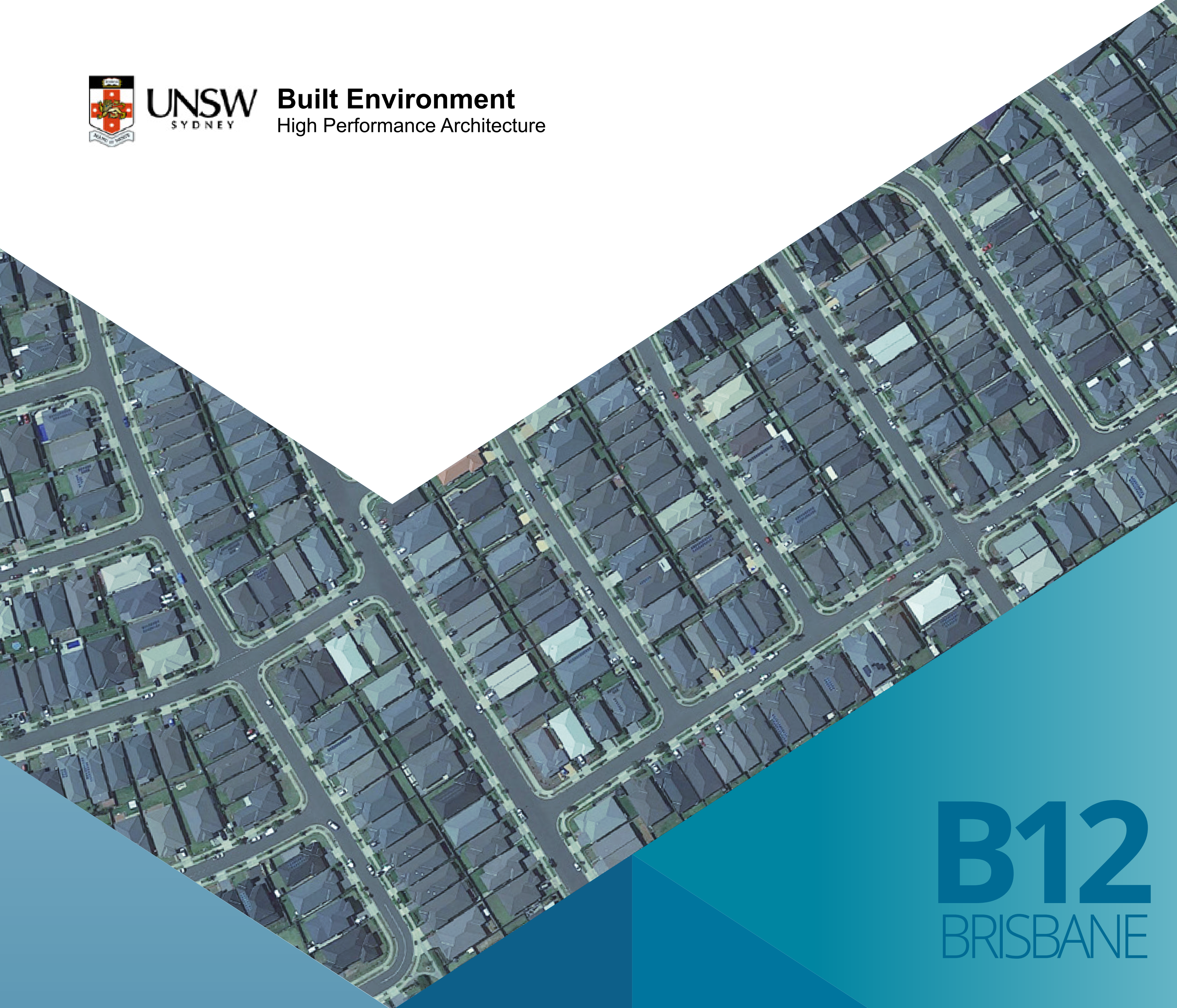

B12
BRISBANE

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

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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 Brisbane 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 44.4-46.0 kWh/m² to 42.8-44.4 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)
Amberley	20.7	45.1	19.9	43.5	18.6	32.5
Archerfield	19.4	45.5	18.8	44.0	17.4	30.7
Brisbane Airport	19.3	46.0	18.7	44.4	16.9	28.5
Gold Coast - Seaway	18.9	45.7	18.3	44.1	16.9	30.1
Greenbank (Defence)	19.0	45.4	18.4	43.9	16.9	28.9
Redcliffe	19.3	45.0	18.6	43.3	17.1	28.8
Redland (Alexandra Hills)	19.0	44.4	18.3	42.8	17.1	30.4

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 1.5-1.7 kWh/m² which is equivalent to 3.3-3.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 12.6-17.5 kWh/m² which is equivalent to 27.9-38.0 % 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	%
Amberley	0.8	3.9	1.6	3.5	2.1	10.1	12.6	27.9
Archerfield	0.6	3.1	1.5	3.3	2.0	10.3	14.8	32.5
Brisbane Airport	0.6	3.1	1.6	3.5	2.4	12.4	17.5	38.0
Gold Coast - Seaway	0.6	3.2	1.6	3.5	2.0	10.6	15.6	34.1
Greenbank (Defence)	0.6	3.2	1.5	3.3	2.1	11.1	16.5	36.3
Redcliffe	0.7	3.6	1.7	3.8	2.2	11.4	16.2	36.0
Redland (Alexandra Hills)	0.7	3.7	1.6	3.6	1.9	10.0	14.0	31.5

In the eleven weather stations in Brisbane, 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.

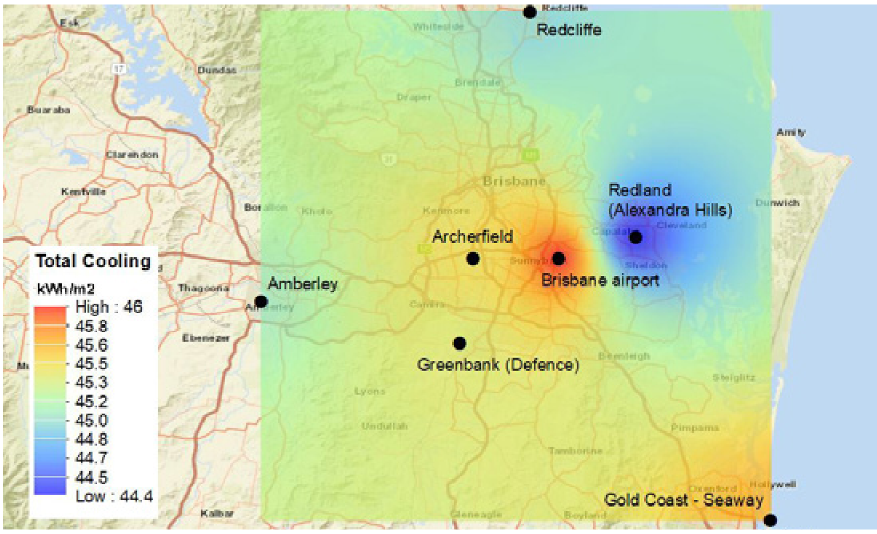

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for aan existing school with weather data simulated by WRF for COP=1 for heating and cooling.

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

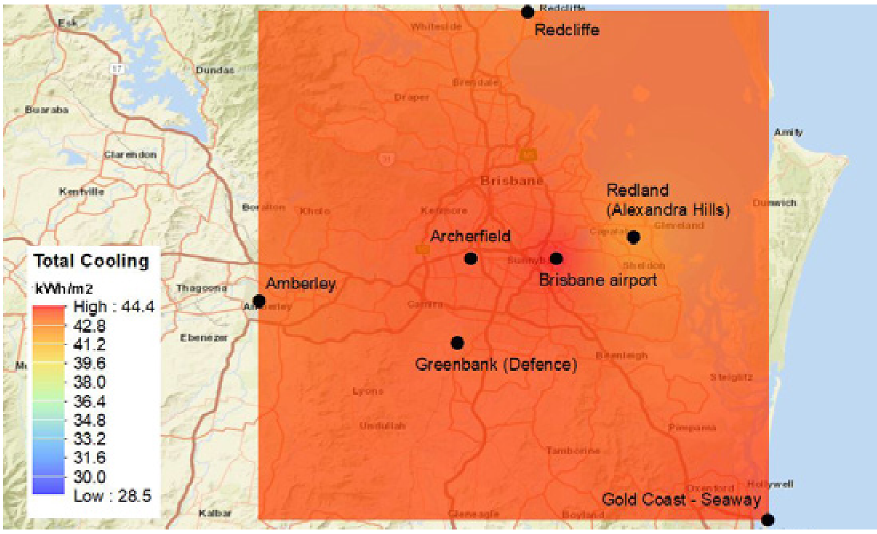

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

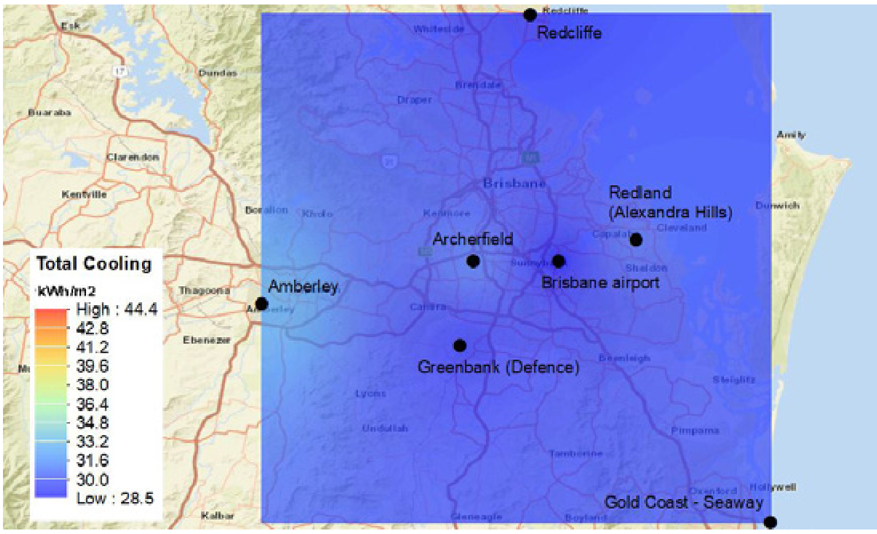

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 (0.0-0.1 kWh/m²) is significantly slower than the annual cooling load reduction (4.1-5.8 kWh/m²).

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.

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
Amberley	75.1	102.7	1.6	6.9	72.2	98.3	1.7	7.0
Archerfield	77.4	106.6	0.8	3.8	74.7	102.3	0.8	3.9
Brisbane	81.9	116.9	0.4	2.5	78.4	111.1	0.5	2.6
Brisbane Airport	74.8	100.6	0.5	2.8	72.4	96.5	0.6	2.8
Redland (Alexandra Hills)	74.1	94.7	0.7	3.1	71.1	89.7	0.9	3.2

The annual cooling load saving by building-scale application of cool roofs is around 4.0-5.3 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.1-5.7 kWh/m² (~3.8-5.0 %).

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 an existing school 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	%
Amberley	2.9	3.9	4.4	4.3	0.1	0.1	2.8	3.7	4.3	3.9
Archerfield	2.7	3.5	4.3	4.0	0.0	0.1	2.7	3.5	4.2	3.8
Brisbane	3.5	4.3	5.8	5.0	0.1	0.1	3.4	4.1	5.7	4.8
Brisbane Airport	2.4	3.2	4.1	4.1	0.1	0.0	2.3	3.1	4.1	4.0
Redland (Alexandra Hills)	3.0	4.0	5.0	5.3	0.2	0.1	2.8	3.7	4.9	5.0

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

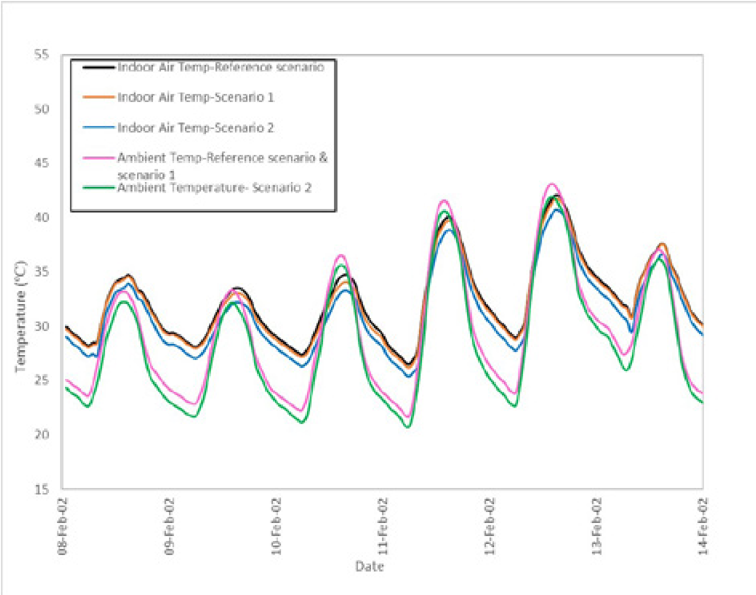

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer week in *Amberley station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

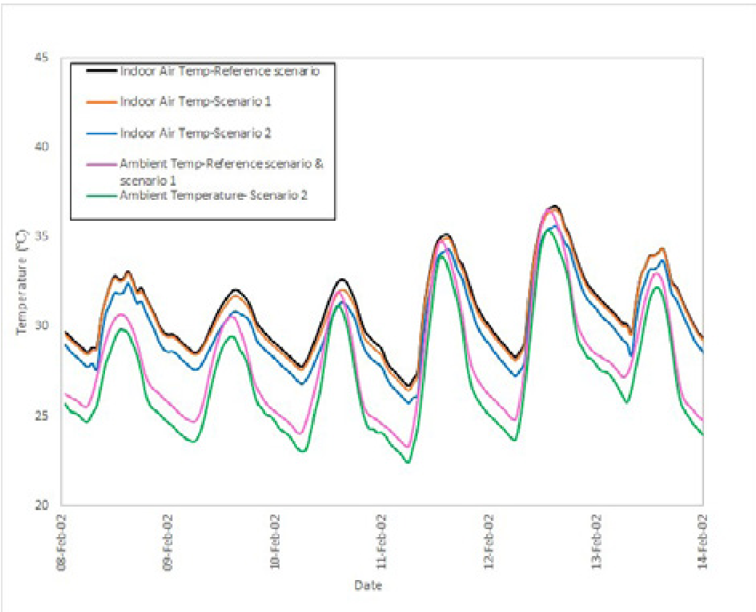

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer week in *Redland station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 26.5-42.1 °C and 26.7-36.7 °C in Amberley and Redland stations, respectively.

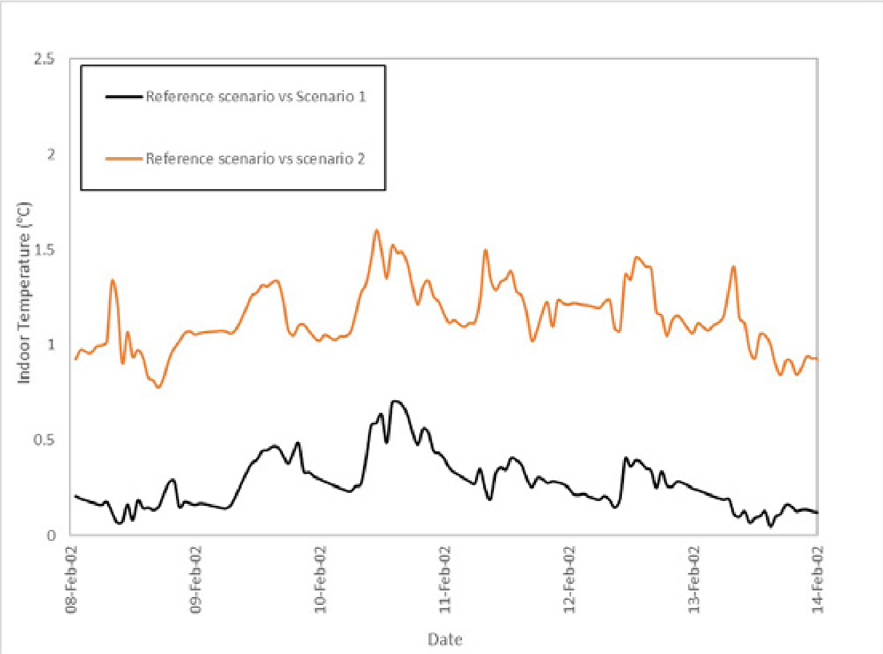

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in *Amberley 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 0.6 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.6 °C and 1.4 °C in Amberley and Redland stations, respectively.

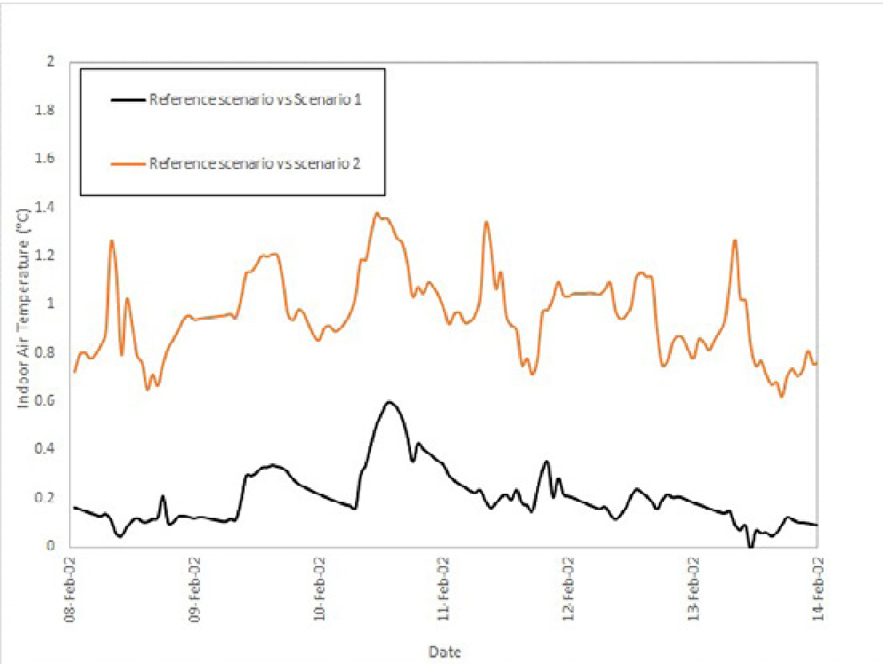

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 11.2-26.7 °C in reference scenario to a range 11.1-26.5 °C in scenario 1 in Amberley station.

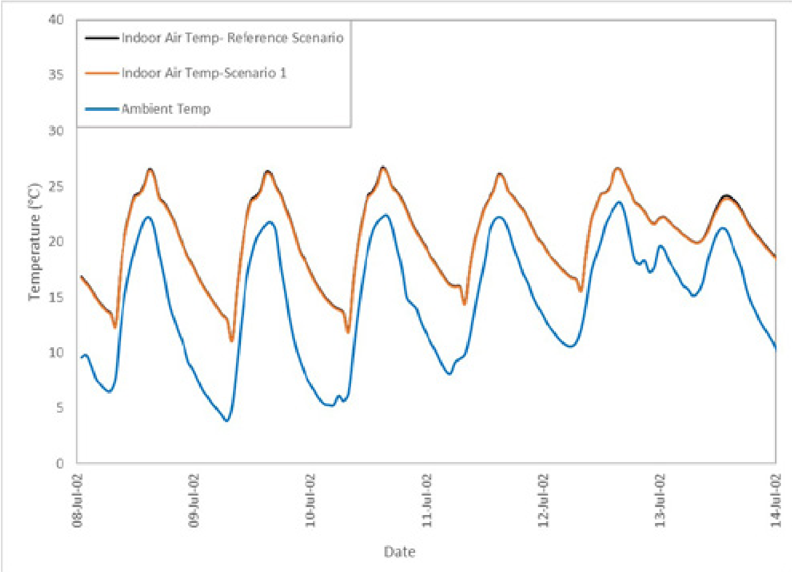

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Amberley station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 15.5-26.5 °C in reference scenario to a range 15.4-26.4 °C in scenario 1 in Redland station.

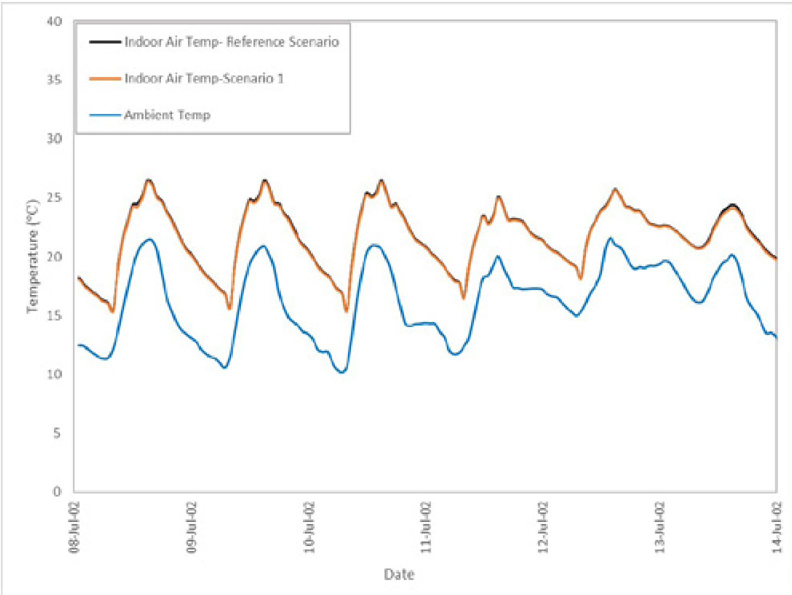

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Redland station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.6 °C and 0.5 °C in Amberley and Redland stations, respectively.

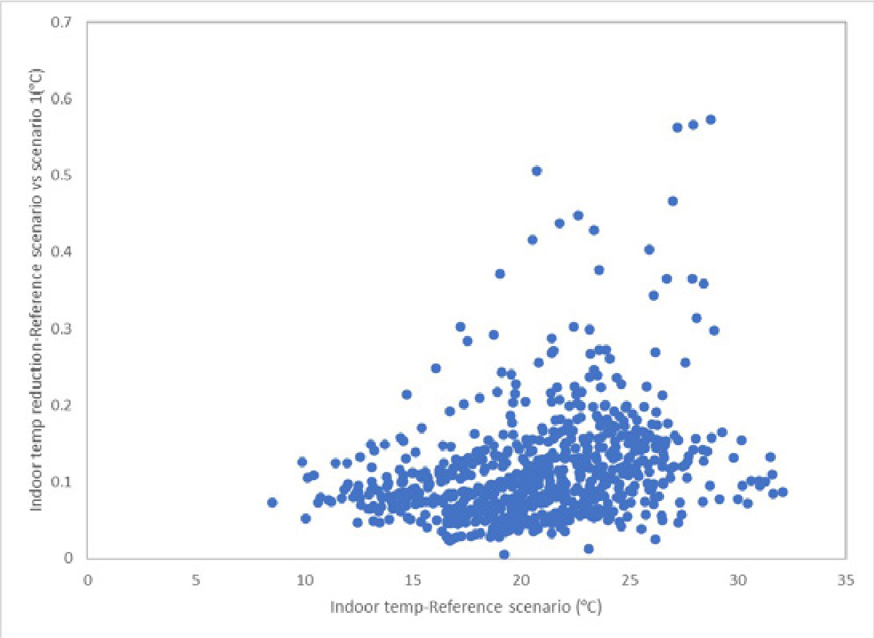

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

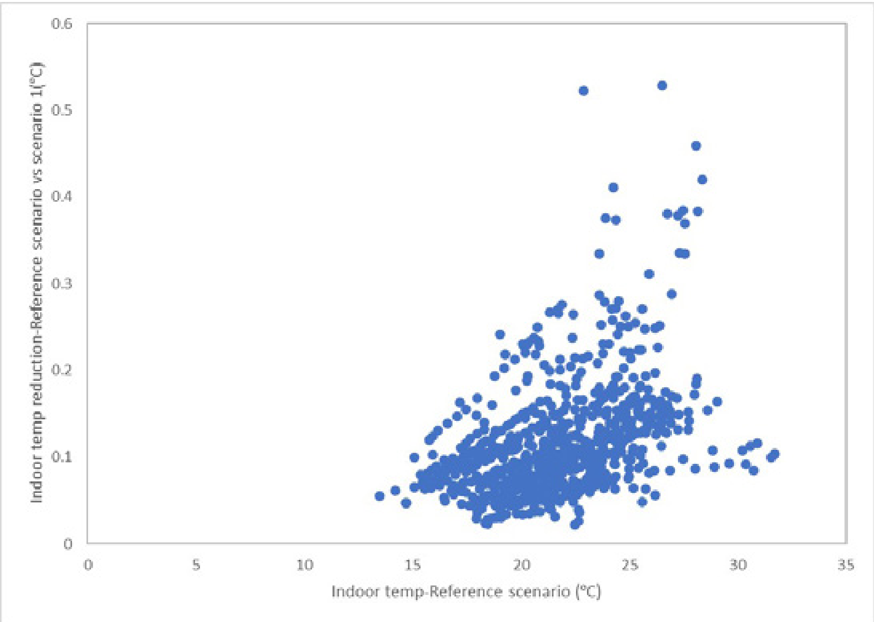

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Amberley	50	248	52	253
Redland	35	156	37	165

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

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 248 hours in reference scenario to 253 hours; and from 156 to 165 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 50 hours in reference scenario to 52 hours; and from 35 to 37 hours in scenario 1 in Amberley and Redland 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
Amberley	623	616	569
Redland	650	645	607

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 623 hours in reference scenario to 616 and 569 hours under scenario 1 and 2, in Amberley station; and from 650 hours in reference scenario to 645 and 607 hours under scenario 1 and 2 in Redland station, respectively.

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 12.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	144.7	129.1
Energy consumption after cool roof (MWh)	139.0	122.6
Energy savings (MWh)	5.7	6.5
Energy savings (%)	3.94 %	5.03 %
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 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, whilst the metal cool roof is feasible for the high energy prices scenario.

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 a modest energy requirements' reduction of 3,94% for the Amberley weather conditions and of 5,03% for the Redland 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 21,6% for the low energy price scenario for Amberley and 23,7% for the high energy scenario and for Redland 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 Amberley and for Redland weather conditions respectively.

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 both weather conditions.

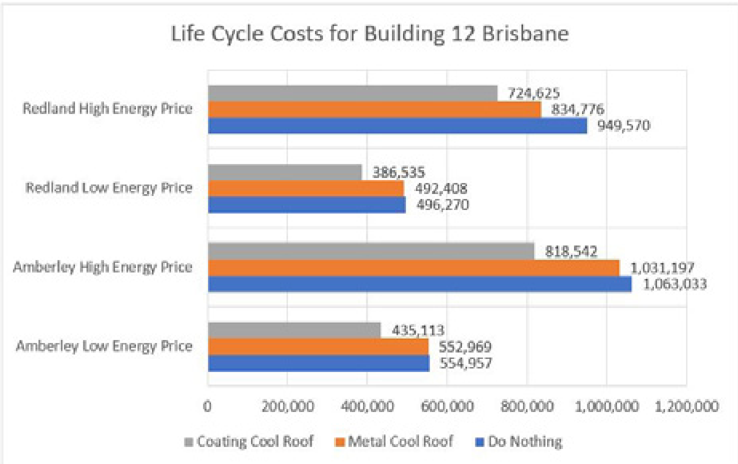

Figure 12. Life Cycle Costs for Building 12 for Amberley and Redland weather stations.

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	0.36 %	2.99 %	0.78 %	12.09 %
Coating Cool Roof	21.60 %	23.00 %	22.11 %	23.69 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing school from 44.4-46.0 kWh/m2 to 42.8-44.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.5-1.7 kWh/m^2. This is equivalent to approximately 3.3-3.8 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 12.6-17.5 kWh/m^2. This is equivalent to 27.9-38.0 % 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 (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (4.1-5.8 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.0-5.3 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.1-5.7 kWh/m^2 (~3.8-5.0 %) (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 26.5-42.1°C and 26.7-36.7 °C in Amberley and Redland 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 0.7 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 and 1.7 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 11.2-26.7 °C in reference scenario to a range between 11.1-26.5 °C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 15.5-26.5 °C in reference scenario to a range between 15.4-26.4 °C in reference with cool roof scenario (scenario 1) in Redland 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 0.6 °C and 0.5 °C in Amberley and Redland 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 248 hours in reference scenario to 253 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight increase in total number of hours below 19 °C from 156 hours in reference scenario to 165 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 50 hours in reference scenario to 52 hours in reference with cool roof scenario (scenario 1) in Amberley station. Similarly, the calculation in Redland station shows a slight increase of number of hours below 19 °C from 35 hours to 37 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 623 hours under the reference scenario in Amberley station, which slightly decreases to 616 and 569 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Redland station also illustrate a significant reduction in number of hours above 26 °C from 650 hours in reference scenario to 645 in reference with cool roof scenario (scenario 1) and 607 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 21,6% for the low energy price scenario for Amberley and 23,7% for the high energy scenario and for Redland 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, feasible only for the high energy prices scenario for both weather conditions. 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, whilst the metal cool roof is feasible for the high energy prices scenario.

B12

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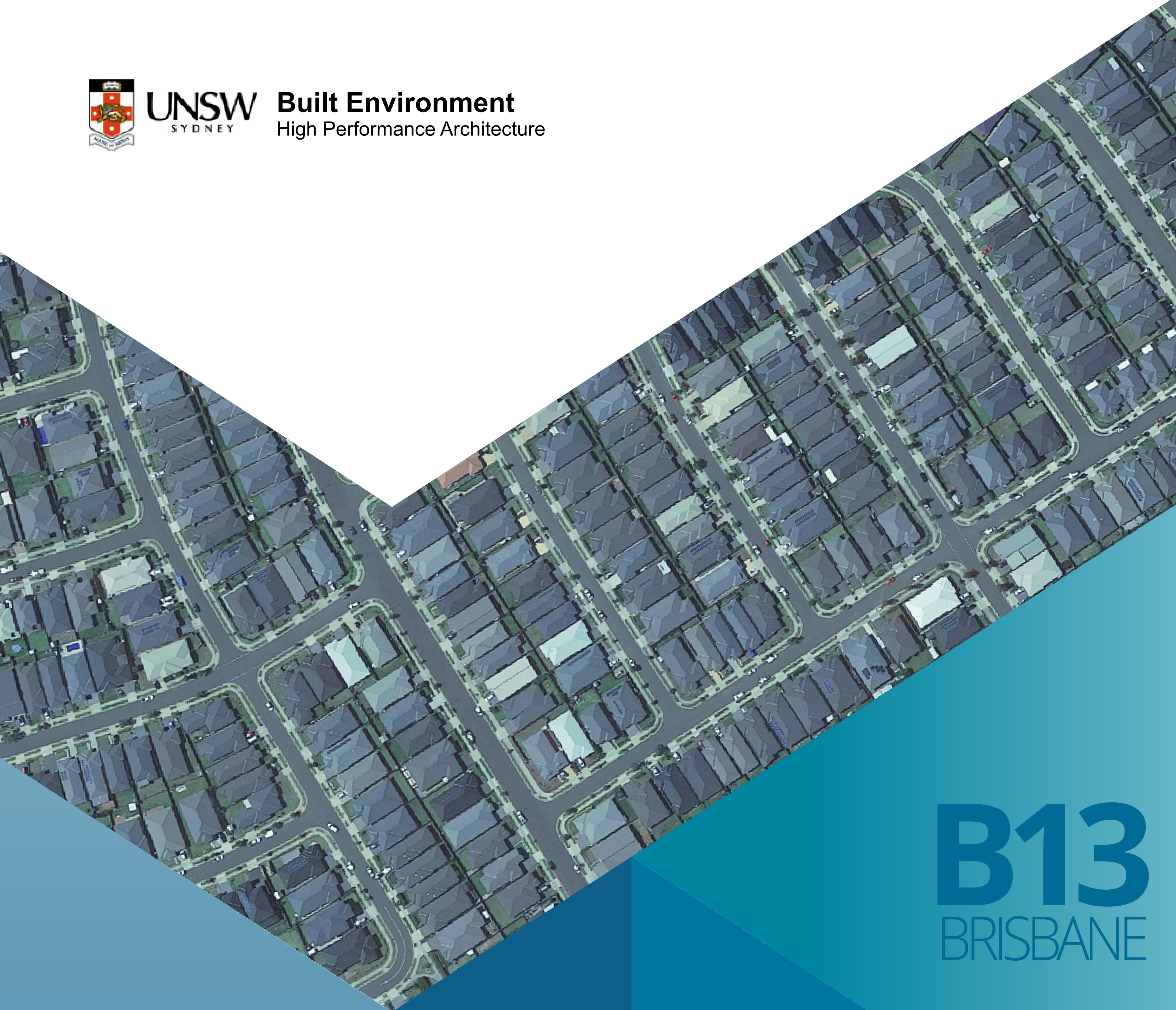

B13
BRISBANE

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

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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 Brisbane 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 office building with roof insulation from 37.1-37.8 kWh/m² to 30.3-31.7 kWh/m².

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.

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)
Amberley	27.3	37.8	20.4	30.3	19.1	24.5
Archerfield	24.8	37.5	19.2	31.2	17.8	25.0
Brisbane Airport	24.6	37.8	19.1	31.4	17.2	23.8
Gold Coast - Seaway	23.8	37.7	18.5	31.7	17.1	24.7
Greenbank (Defence)	23.9	37.6	18.6	31.4	17.1	24.1
Redcliffe	25.0	37.8	19.0	31.0	17.5	24.2
Redland (Alexandra Hills)	24.3	37.1	18.7	30.7	17.5	24.9

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 6.0-7.5 kWh/m² which is equivalent to 15.9-19.8 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 12.2-14.0 kWh/m² which is equivalent to 32.9-37.0 % 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/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Amberley	6.9	25.3	7.5	19.8	8.2	30.0	13.3	35.2
Archerfield	5.6	22.6	6.3	16.8	7.0	28.2	12.5	33.3
Brisbane Airport	5.5	22.4	6.4	16.9	7.4	30.1	14.0	37.0
Gold Coast - Seaway	5.3	22.3	6.0	15.9	6.7	28.2	13.0	34.5
Greenbank (Defence)	5.3	22.2	6.2	16.5	6.8	28.5	13.5	35.9
Redcliffe	6.0	24.0	6.8	18.0	7.5	30.0	13.6	36.0
Redland (Alexandra Hills)	5.6	23.0	6.4	17.3	6.8	28.0	12.2	32.9

In the eleven weather stations in Brisbane, 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.

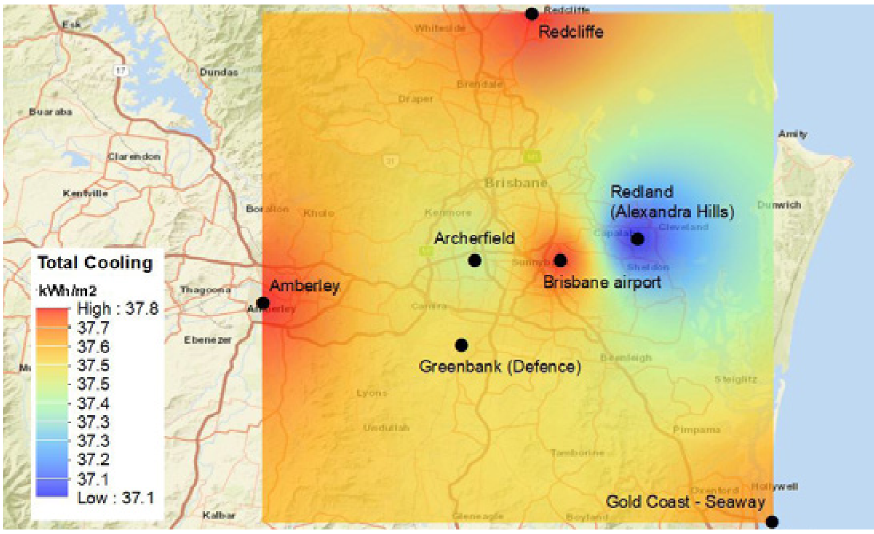

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

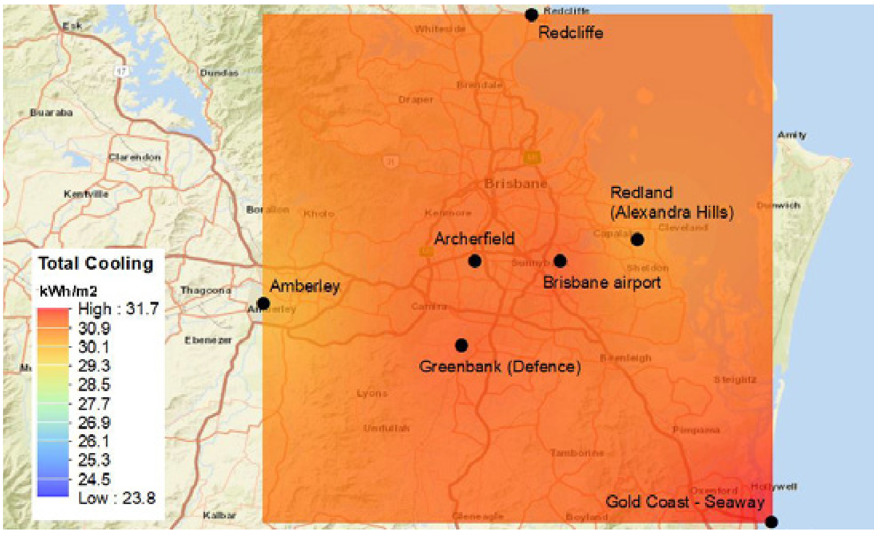

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

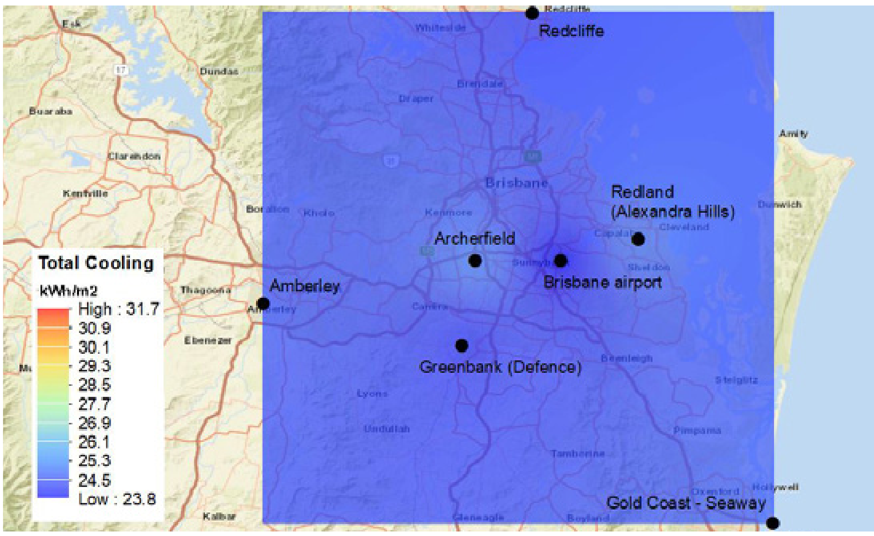

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 (0.1-0.4 kWh/m²) is significantly lower than the annual cooling load reduction (16.6-25.1 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
Amberley	89.1	92	0.8	1.6	63.6	71.4	1.0	2.0
Archerfield	89.0	93.3	0.4	0.8	65.6	74.0	0.5	1.0
Brisbane	100.0	104.2	0.2	0.5	69.9	79.1	0.3	0.7
Brisbane Airport	83.9	83.7	0.3	0.6	62.6	67.1	0.4	0.7
Redland (Alexandra Hills)	86.4	82.4	0.3	0.6	61.1	62.6	0.5	0.8

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 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 19.8-24.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 16.5-24.9 kWh/m² (~19.6-23.8 %).

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	%
Amberley	25.5	28.6	20.6	22.4	0.2	0.4	25.3	28.1	20.2	21.6
Archerfield	23.4	26.3	19.3	20.7	0.1	0.2	23.3	26.1	19.1	20.3
Brisbane	30.1	30.1	25.1	24.1	0.1	0.2	30	29.9	24.9	23.8
Brisbane Airport	21.3	25.4	16.6	19.8	0.1	0.1	21.2	25.2	16.5	19.6
Redland (Alexandra Hills)	25.3	29.3	19.8	24.0	0.2	0.2	25.1	29.0	19.6	23.6

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

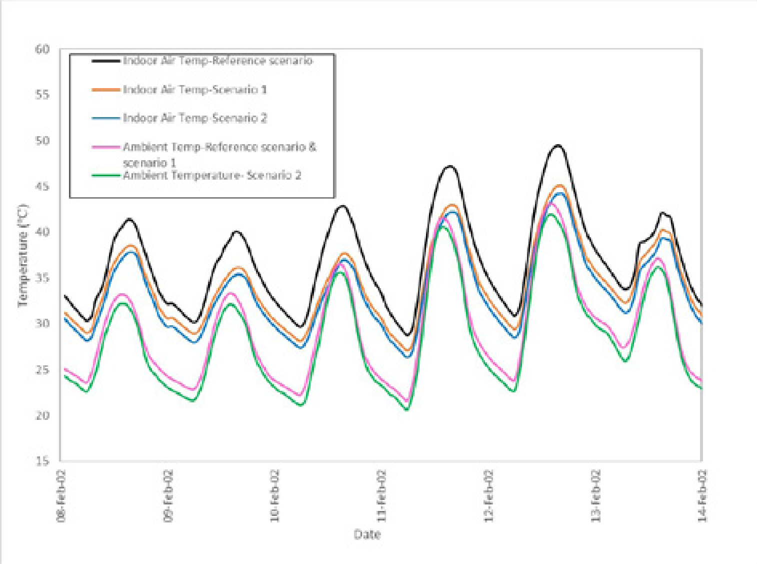

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

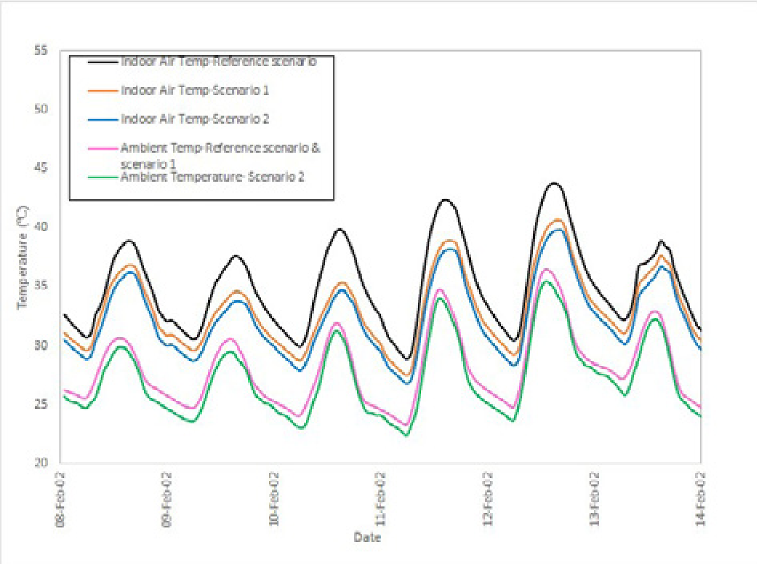

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.8-49.4 °C and 28.9-43.7 °C in Amberley and Redland stations, respectively.

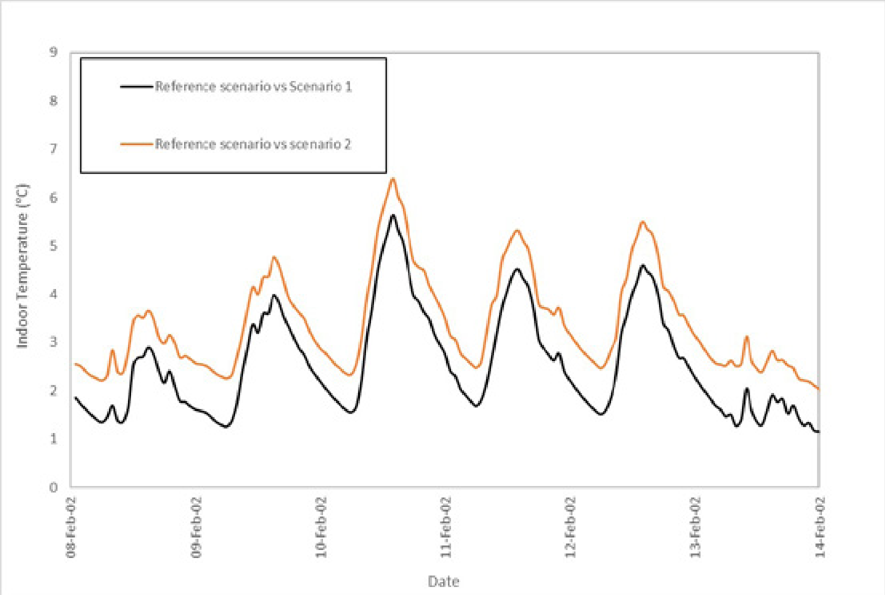

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 5.6 °C and 4.6 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 6.4 and 5.3 °C in Amberley and Redland stations, respectively.

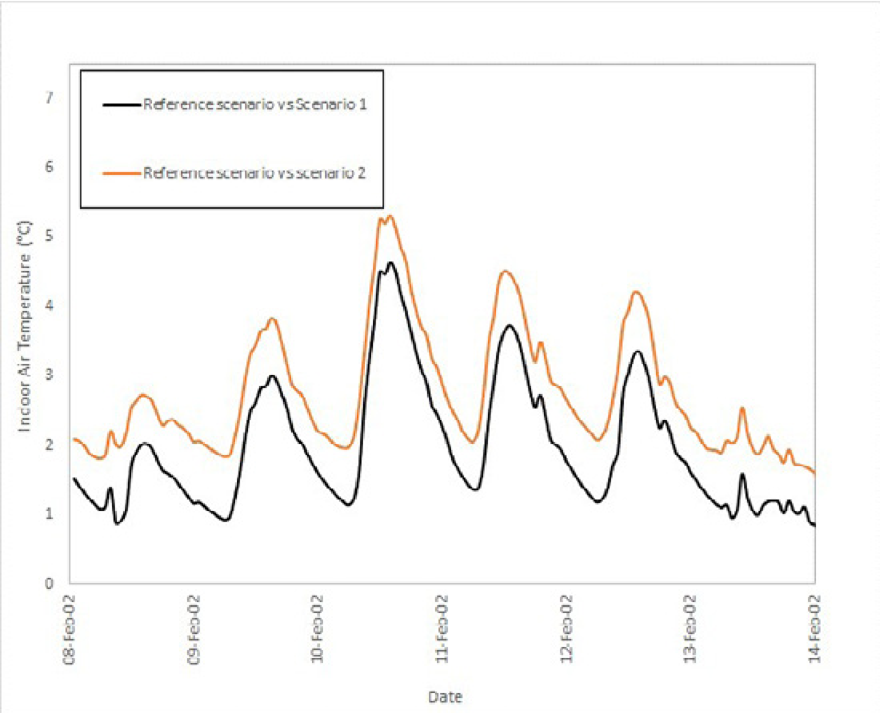

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 13.4 and 31.7 °C in reference scenario to a range between 12.9 and 29.6 °C in scenario 1 in Amberley station.

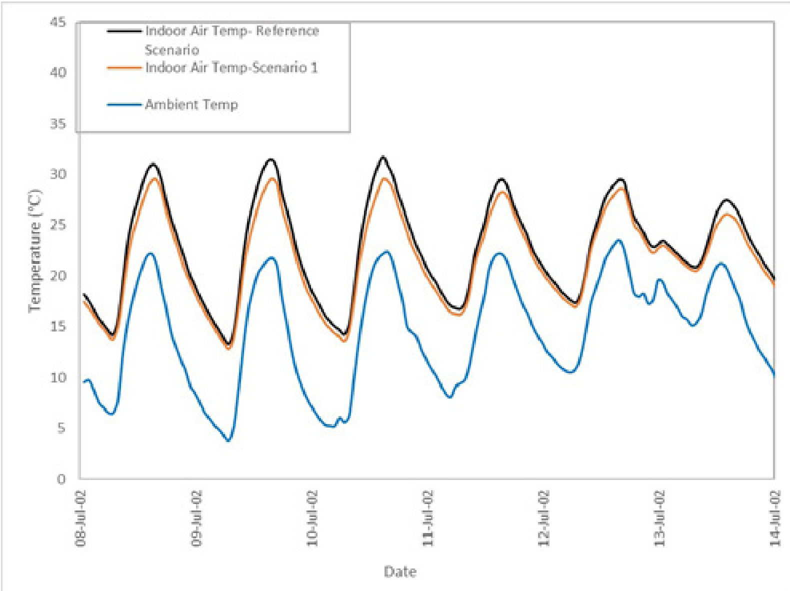

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Amberley station* using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

The indoor air temperature is predicted to reduce from a range between 17.1 and 32.0 °C in reference scenario to a range between 16.6 and 30.0 °C in scenario 1 in Redland station.

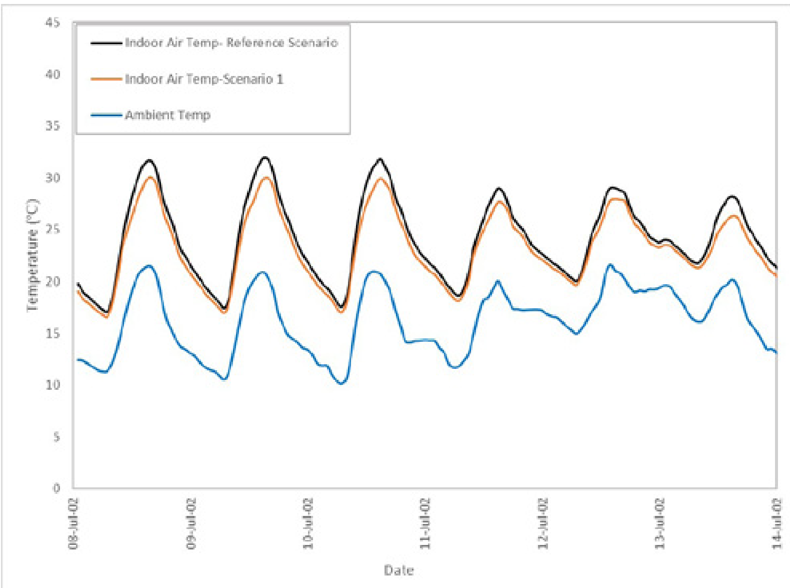

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Redland station* using 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 3.4 °C in Amberley and Redland stations, respectively.

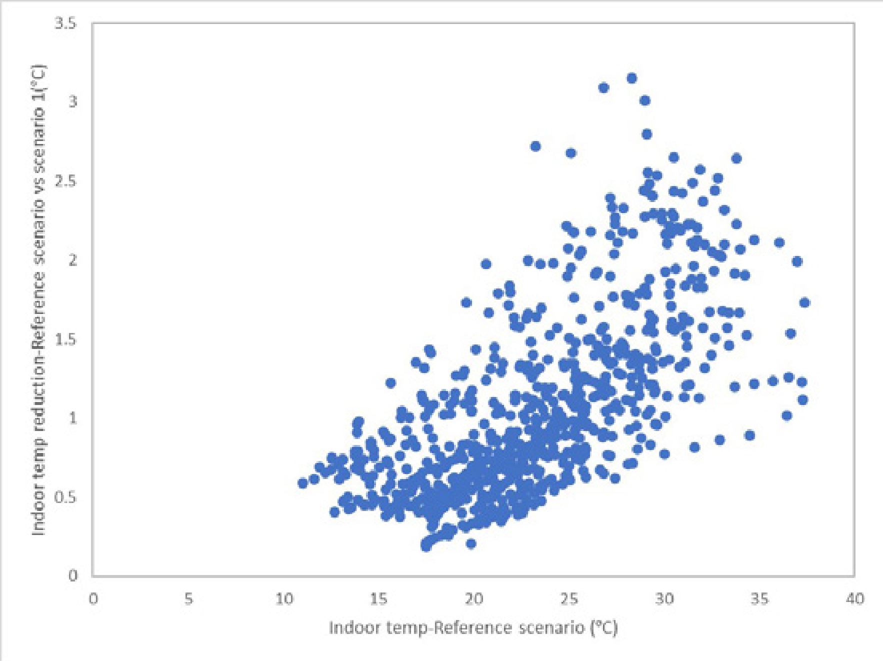

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather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

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

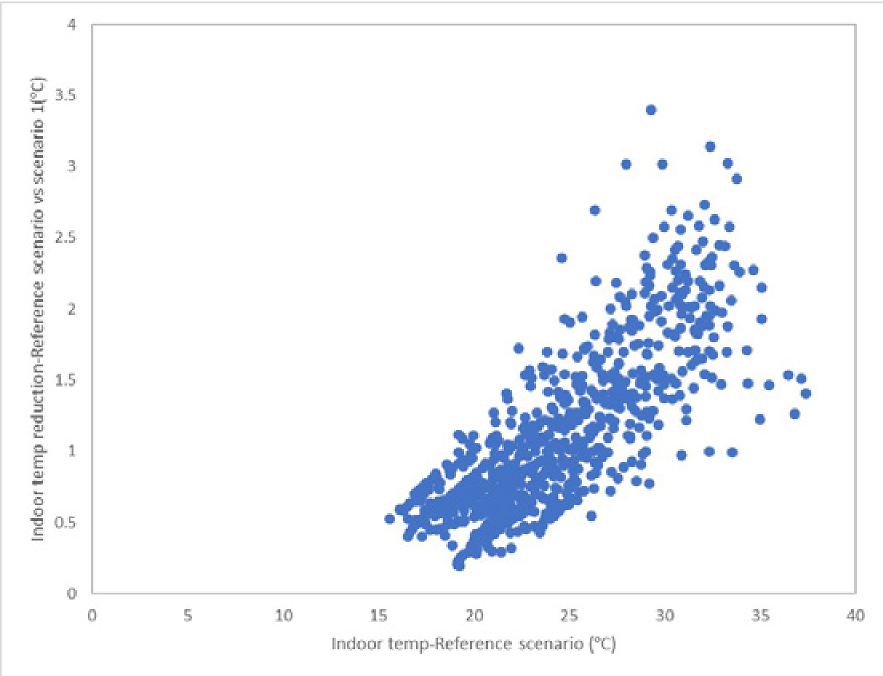

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Amberley	29	173	31	207
Redland	18	85	26	119

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

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 173 hours in reference scenario to 207 hours and from 85 to 119 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 29 hours in reference scenario to 31 hours; and from 18 to 26 hours in scenario 1 in Amberley and Redland 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
Amberley	664	644	617
Redland	672	666	657

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 664 hours in reference scenario to 644 and 617 hours under scenario 1 and 2, in Amberley station; and from 672 hours in reference scenario to 666 and 657 hours under scenario 1 and 2 in Redland station, respectively.

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to the fact that it is a low-rise building with roof insulation, the 'Do Nothing' approach has the higher costs over the building's life cycle, compared to both cool roof options.

The building and its energy performance

Building 13 is an existing, low-rise building, with a total air-conditioned area of 2.400 m² distributed on two levels. The 1.200 m² 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 13.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	89.9	79.7
Energy consumption after cool roof (MWh)	70.5	60.9
Energy savings (MWh)	19.4	18.8
Energy savings (%)	21.58 %	23.59 %
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 13 is a good example of an existing, low-rise office building, with a significant energy conservation potential, where both cool roof techniques lead to significant reductions of life cycle cost, with the coating cool roof being the more feasible 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 energy savings of 21,58% for the Amberley weather conditions and of 23,59% for the Redland 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.

> *Both cool roof option lead to a reduction of life cycle costs, that varies between 13,4% for the low energy price scenario for Amberley and 37,1% for the high energy scenario and for Redland condition.*

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 Amberley and for Redland weather conditions respectively.

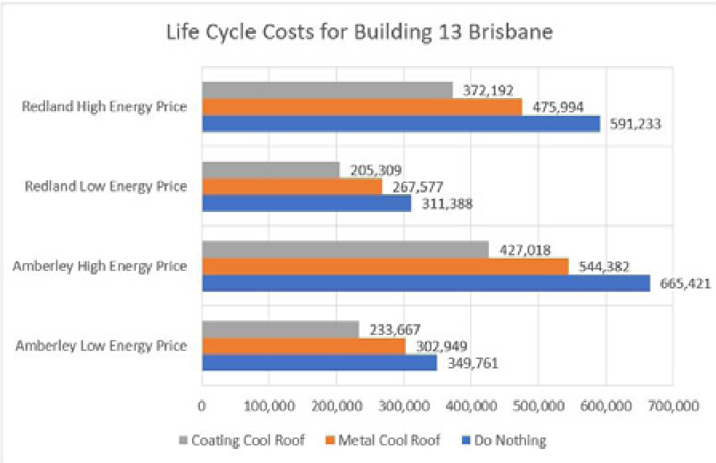

Figure 12. Life Cycle Costs for Building 13 for Amberley and Redland weather stations.

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	13.38 %	18.19 %	14.07 %	19.49 %
Coating Cool Roof	33.19 %	35.83 %	34.07 %	37.05 %

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 Brisbane, 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 37.1-37.8 kWh/m^2 to 30.3-31.7 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 6.0-7.5 kWh/m^2. This is equivalent to approximately 15.9-19.8 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 12.2-14.0 kWh/m^2. This is equivalent to 32.9-37.0 % 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 (0.1-0.4 kWh/m^2) is significantly lower than the annual cooling load reduction (16.6-25.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 19.8-24.1 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 16.5-24.9 kWh/m^2 (~19.6-23.8%) (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 28.8-49.4 ^{o}C and 28.9-43.7 ^{o}C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 5.6 and 4.6 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 6.4 and 5.3 ^{o}C by com-bined building-scale and urban-scale application of cool roofs (scenario 2) in Observato-ry and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 13.4 and 31.7 ^{o}C in reference scenario to a range between 12.9 and 29.6 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 17.1 and 32.0 ^{o}C in reference scenario to a range between 16.6 and 30.0 ^{o}C in reference with cool roof scenario (scenario 1) in Redland 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 3.2 ^{o}C and 3.4 ^{o}C in Amberley and Redland 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 ^{o}C is predicted to increase from 173 hours in reference scenario to 207 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight in-crease in total number of hours below 19 ^{o}C from 85 hours in reference scenario to 119 hours in reference with cool roof scenario (scenario 1). The results show less in-crease 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 increase from 29 hours in reference scenario to 31 hours in reference with cool roof scenario (scenario 1) in Amberley station. Similarly, the calculation in Redland station shows a slight increase of number of hours below 19 ^{o}C from 18 hours to 26 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 ^{o}C. As computed, the number of hours above 26 ^{o}C is 664 hours under the reference scenario in Observa-tory station, which significantly decreases to 644 and 617 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Redland station also illustrate a significant reduc-tion in number of hours above 26 ^{o}C from 672 hours in reference scenario to 666 in ref-erence with cool roof scenario (scenario 1) and 657 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 the higher costs over the building's life cycle, compared to both cool roof options. Their application leads to a reduction of life cycle costs, that varies between 13,4% for the low energy price scenario for Amberley and 37,1% for the high energy scenario and for Redland conditions, as it can be seen in Table 8. Building 13 is a good example of an existing, low-rise office building, with a significant energy conservation potential, where both cool roof techniques lead to significant reductions of life cycle cost, with the coating cool roof being the more feasible investment.

B13

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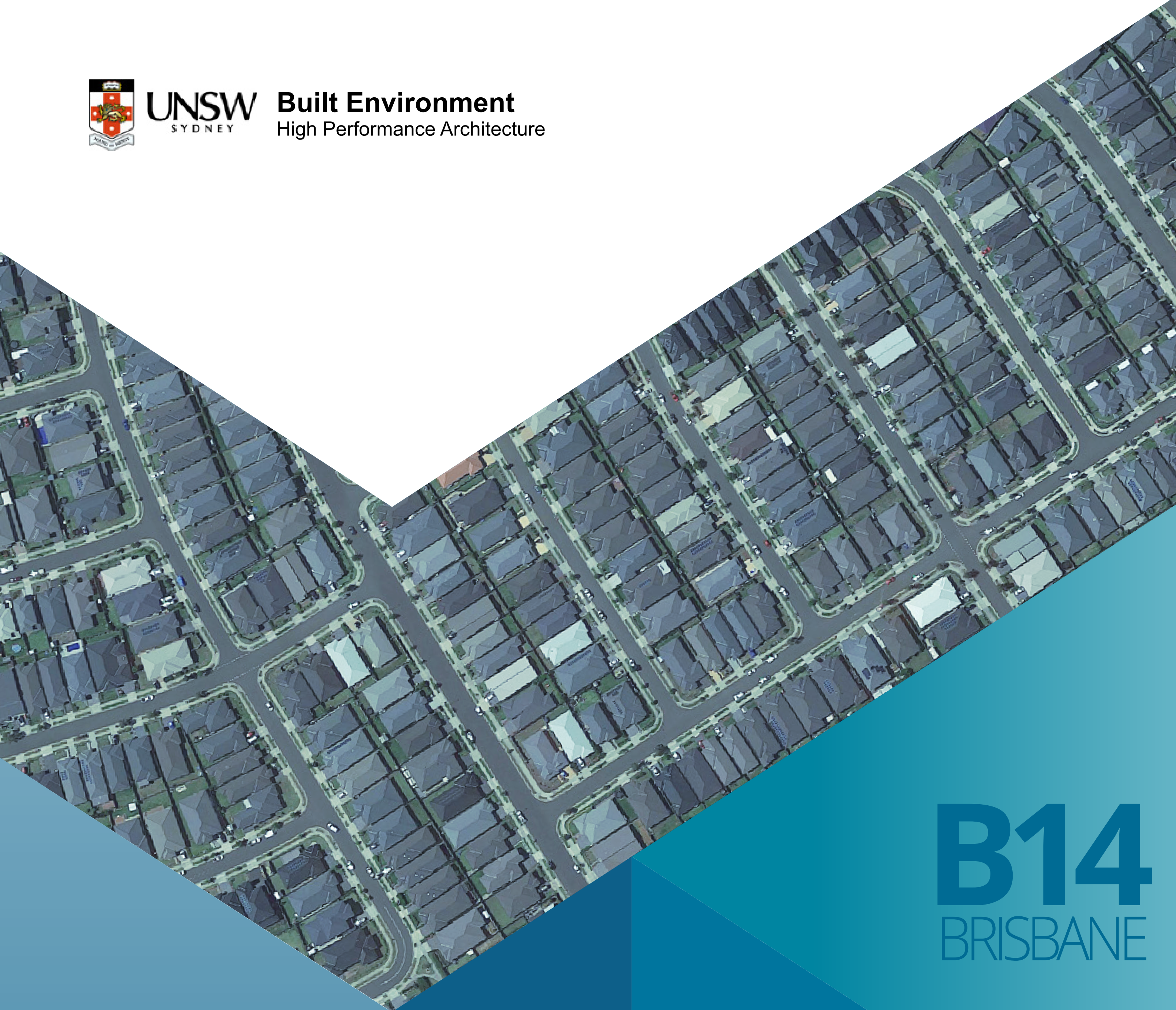

B14
BRISBANE

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

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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 Brisbane using weather data simulated by WRF.

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.

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 32.6-34.3 kWh/m² to 31.2-33.4 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)
Amberley	22.2	32.6	20.9	31.2	19.7	25.2
Archerfield	20.9	33.9	19.9	32.9	18.6	26
Brisbane Airport	20.7	34.1	19.7	33.0	18.2	24.8
Gold Coast - Seaway	20.3	34.3	19.5	33.4	18.1	26
Greenbank (Defence)	20.4	34.2	19.5	33.2	18.1	25.2
Redcliffe	20.9	33.7	19.9	32.4	18.4	25.1
Redland (Alexandra Hills)	20.4	33.5	19.4	32.4	18.4	26

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.

For Scenario 1, the total cooling load saving is around 1.0-1.4 kWh/m² which is equivalent to 2.6-4.3 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.4-9.3 kWh/m² which is equivalent to 22.7-27.3 % 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	%
Amberley	1.3	5.9	1.4	4.3	2.5	11.3	7.4	22.7
Archerfield	1.0	4.8	1.0	2.9	2.3	11.0	7.9	23.3
Brisbane Airport	1.0	4.8	1.1	3.2	2.5	12.1	9.3	27.3
Gold Coast - Seaway	0.8	3.9	0.9	2.6	2.2	10.8	8.3	24.2
Greenbank (Defence)	0.9	4.4	1.0	2.9	2.3	11.3	9.0	26.3
Redcliffe	1.0	4.8	1.3	3.9	2.5	12.0	8.6	25.5
Redland (Alexandra Hills)	1.0	4.9	1.1	3.3	2.0	9.8	7.5	22.4

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.

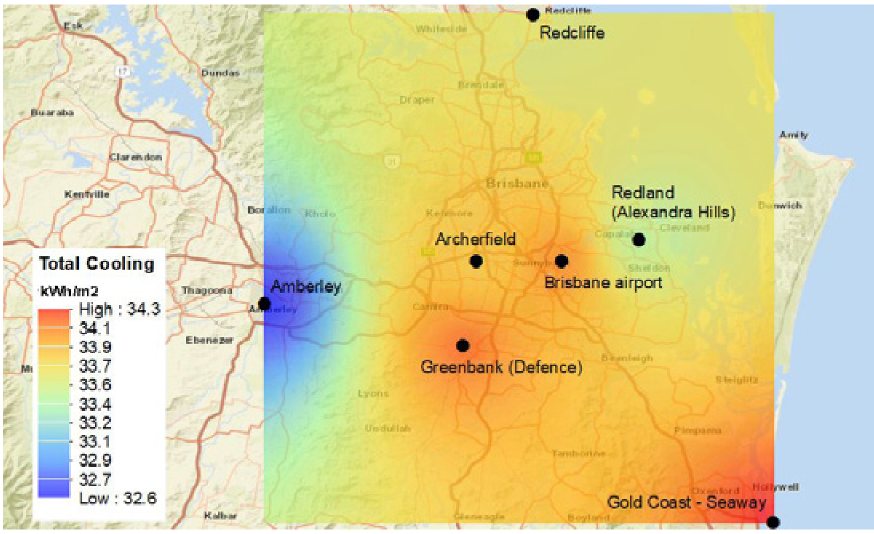

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

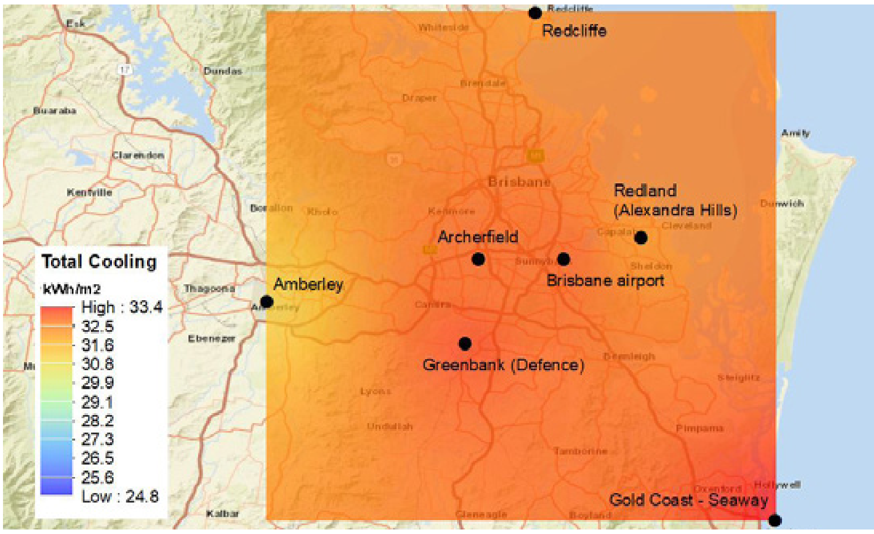

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

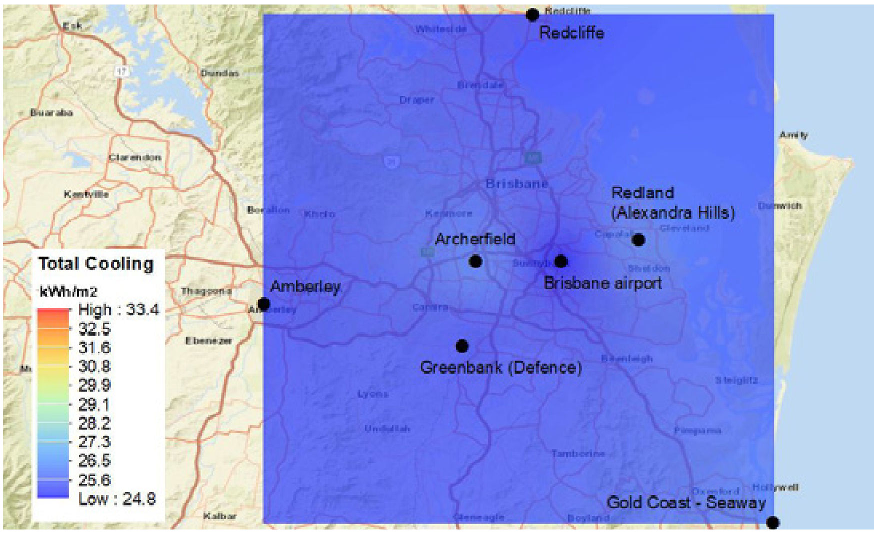

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 (0.0-0.1 kWh/m²) is lower than the annual cooling load reduction (2.8-4.6 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
Amberley	72.0	76.7	0.3	0.7	67.5	73.1	0.3	0.8
Archerfield	74.8	79.9	0.1	0.2	70.8	76.6	0.1	0.3
Brisbane	81.0	86.6	0.0	0.1	75.4	82.0	0.0	0.1
Brisbane Airport	72.4	73.3	0.0	0.1	68.9	70.5	0.0	0.1
Redland (Alexandra Hills)	71.6	68.7	0.0	0.1	66.7	65.3	0.0	0.1

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 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 4.1-5.3 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.8-4.6 kWh/m² (~3.8-5.3 %).

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	%
Amberley	4.5	6.3	3.6	4.7	0.0	0.1	4.5	6.2	3.5	4.5
Archerfield	4.0	5.3	3.3	4.1	0.0	0.1	4.0	5.3	3.2	4.0
Brisbane	5.6	6.9	4.6	5.3	0.0	0.0	5.6	6.9	4.6	5.3
Brisbane Airport	3.5	4.8	2.8	3.8	0.0	0.0	3.5	4.8	2.8	3.8
Redland (Alexandra Hills)	4.9	6.8	3.4	4.9	0.0	0.0	4.9	6.8	3.4	4.9

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

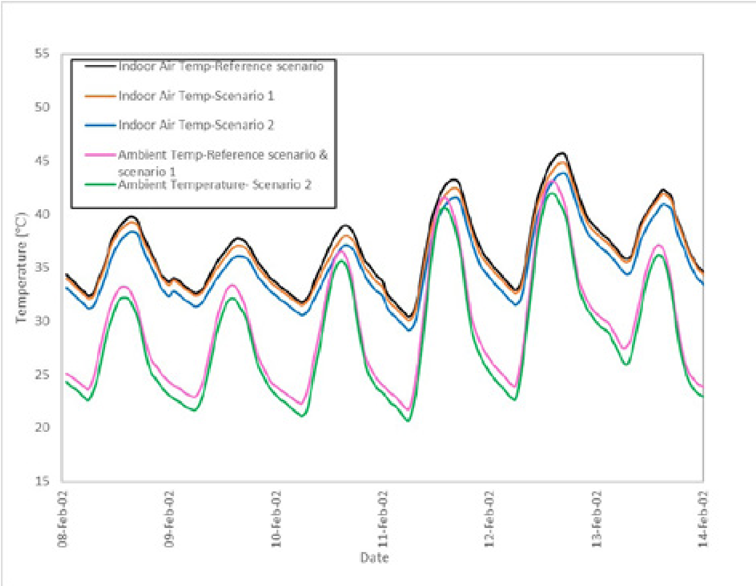

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

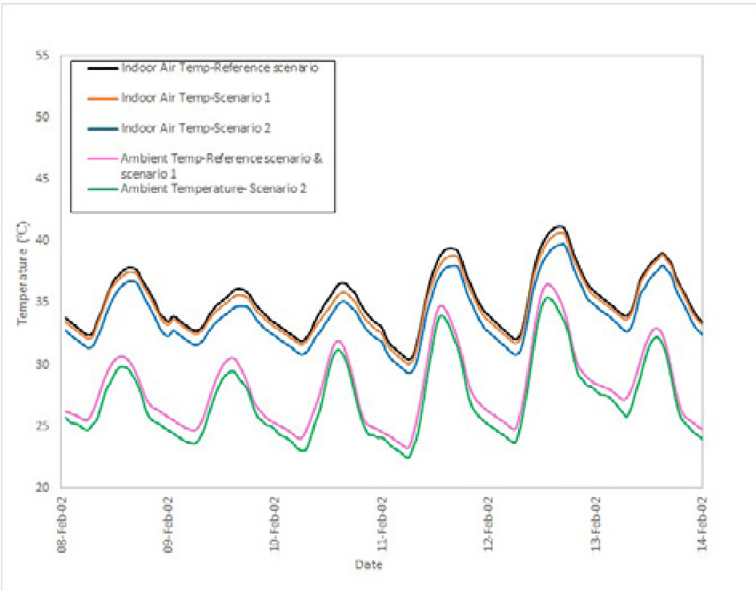

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 30.4-45.6 °C and 30.4-41.2 °C in Amberley and Redland stations, respectively.

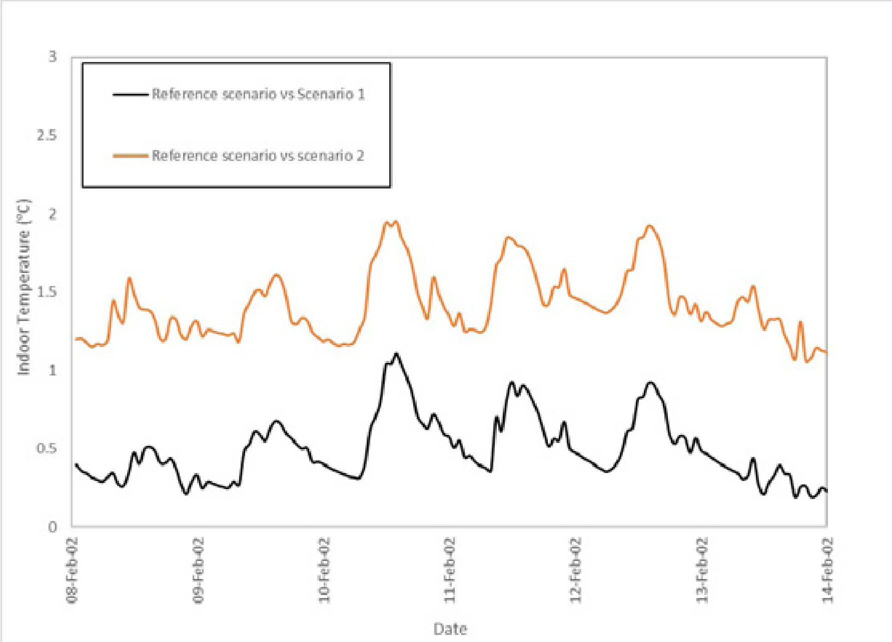

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.1 °C and 0.8 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.0 and 1.7 °C in Amberley and Redland stations, respectively.

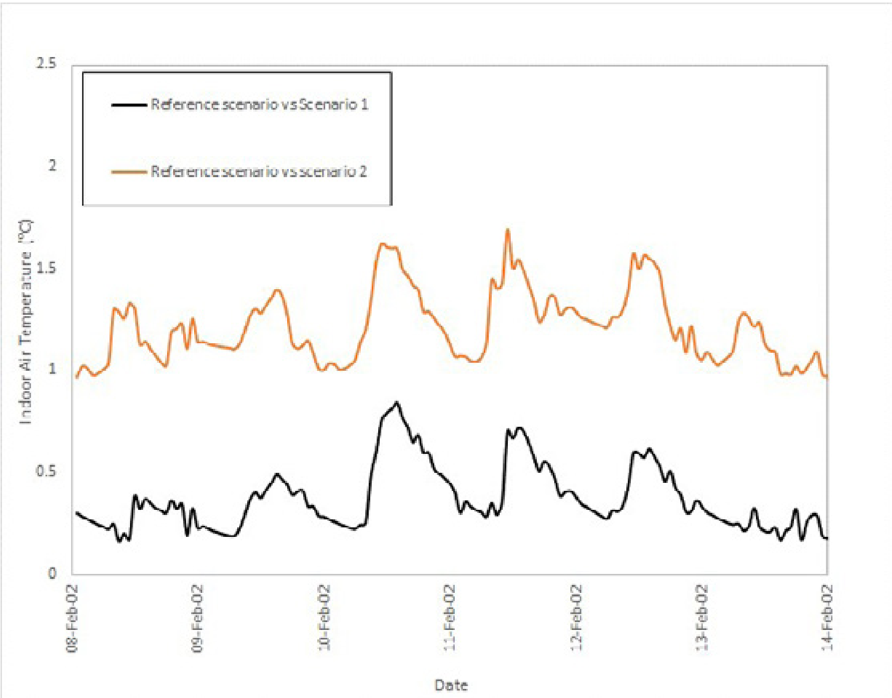

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 17.1 and 30.4 °C in reference scenario to a range between 17.0 and 30.0 °C in scenario 1 in Amberley station.

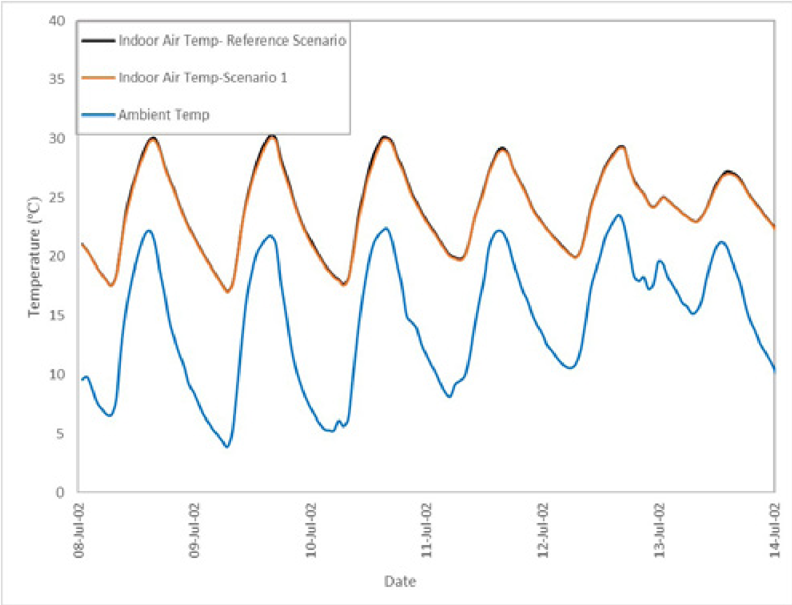

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Amberley station* using annual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

The indoor air temperature is predicted to reduce from a range between 19.9 and 31.0 °C in reference scenario to a range between 19.8 and 30.6 °C in scenario 1 in Redland station.

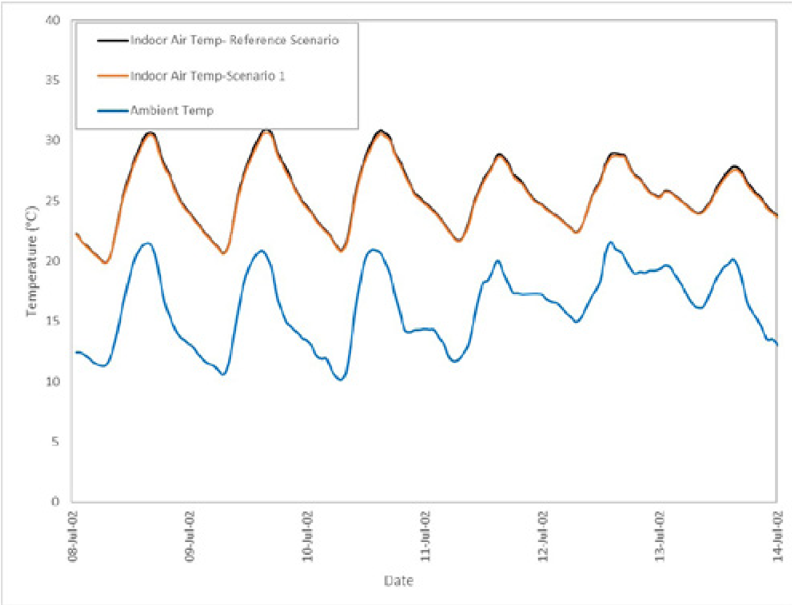

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Redland station* using annual 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 Amberley and Redland stations, respectively.

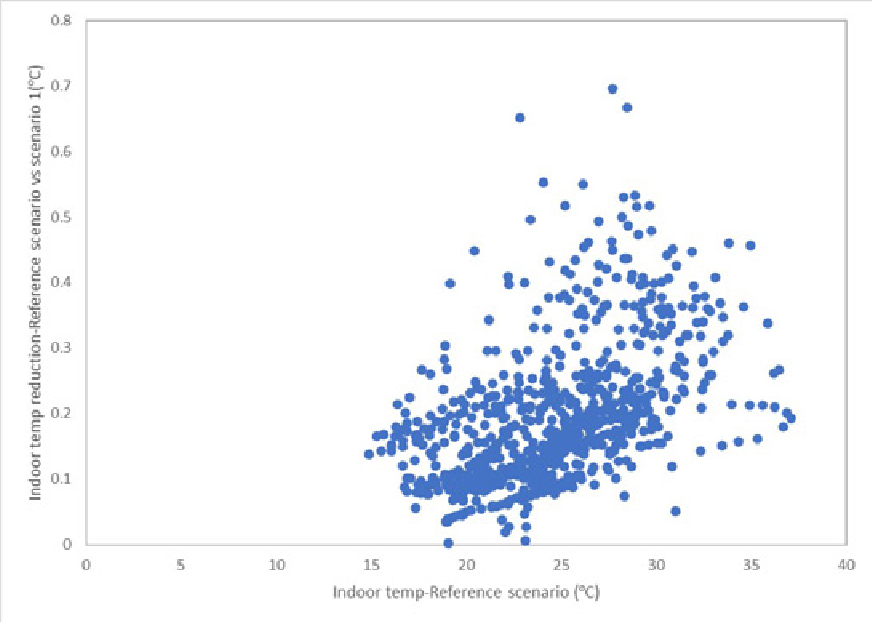

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

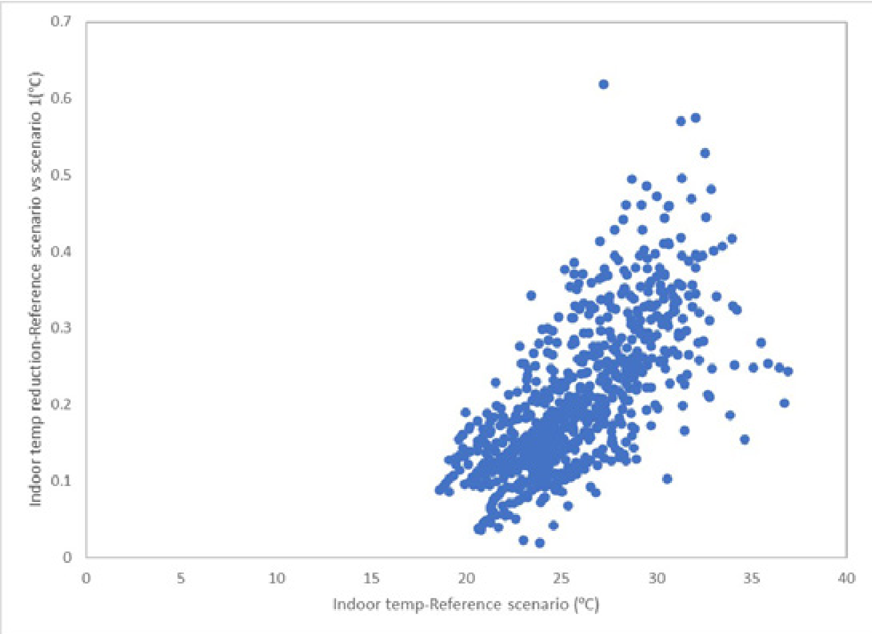

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 71 hours in reference scenario to 75 and hours and from 3 to 5 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 14 hours in reference scenario to 19 hours; and from 1 to 2 hours in scenario 1 in Amberley and Redland stations, respectively.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Amberley	14	71	19	75
Redland	1	3	2	5

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

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 remain the same (672 hours) for all scenarios in Amberley and Redland stations.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Amberley	672	672	672
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to the fact that it is a high-rise office building with roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle, compared to both 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 m^2 distributed on ten levels. The 1.200 m^2 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 14.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	371.5	330.2
Energy consumption after cool roof (MWh)	354.7	313.9
Energy savings (MWh)	16.8	16.3
Energy savings (%)	4.52 %	4.94 %
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 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

Both options have the same energy efficiency, resulting in energy savings of 4,52% for the Amberley weather conditions and of 4,94% for the Redland 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 4,08% for the metal cool roof, the low energy price scenario and for Amberley and 24,6% for coating cool roof, the high energy scenario and for Redland condition.

The metal cool roof is feasible, but due to its high initial investment cost it is less appealing as an investment.

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 Amberley and for Redland weather conditions respectively.

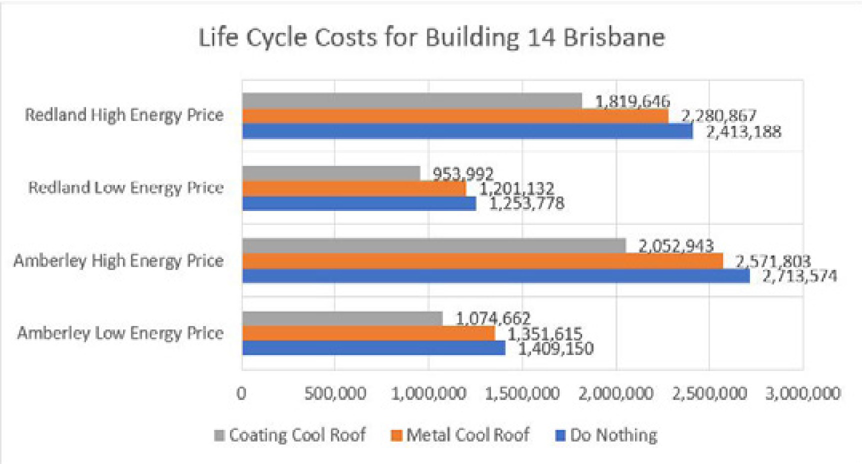

Figure 12. Life Cycle Costs for Building 14 for Amberley and Redland weather stations.

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	4.08 %	5.22 %	4.20 %	5.48 %
Coating Cool Roof	23.74 %	24.35 %	23.91 %	24.60 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building from 32.6-34.3 kWh/m^2 to 31.2-33.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.0-1.4 kWh/m^2. This is equivalent to approximately 2.6-4.3 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.4-9.3 kWh/m^2. This is equivalent to 22.7-27.3 % 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 (2.8-4.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.1-5.3 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.8-4.6 kWh/m^2 (~3.8-5.3 %) (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 30.4-45.6 ^oC and 30.4-41.2 ^oC in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.1 and 0.8 ^oC in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.0 and 1.7 ^oC by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 17.1 and 30.4 ^oC in reference scenario to a range between 17.0 and 30.0 ^oC in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 19.9 and 31.0 °C in reference scenario to a range between 19.8 and 30.6 °C in reference with cool roof scenario (scenario 1) in Redland 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 °C in Amberley and Redland 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 71 hours in reference scenario to 75 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight increase in total number of hours below 19 °C from 3 hours in reference scenario to 5 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 14 hours in reference scenario to 19 hours in reference with cool roof scenario (scenario 1) in Amberley station. Similarly, the calculation in Redland station shows a slight increase of number of hours below 19 °C from 1hours to 2 hours during the operational hours (See Table 5).

• During a typical summer month, the total number of hours with an indoor air temperature (>26 oC) is predicted to remain the same with 672 hours for all scenarios, in Amberley and Redland stations (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 the higher cost over the building's life cycle, compared to both cool roof options, which leads to a reduction of life cycle costs, that varies between 4,08% for the metal cool roof, the low energy price scenario and for Amberley and 24,6% for coating cool roof, the high energy scenario and for Redland condition. 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 feasible, but due to its high initial investment cost it is less appealing as an investment.

B14

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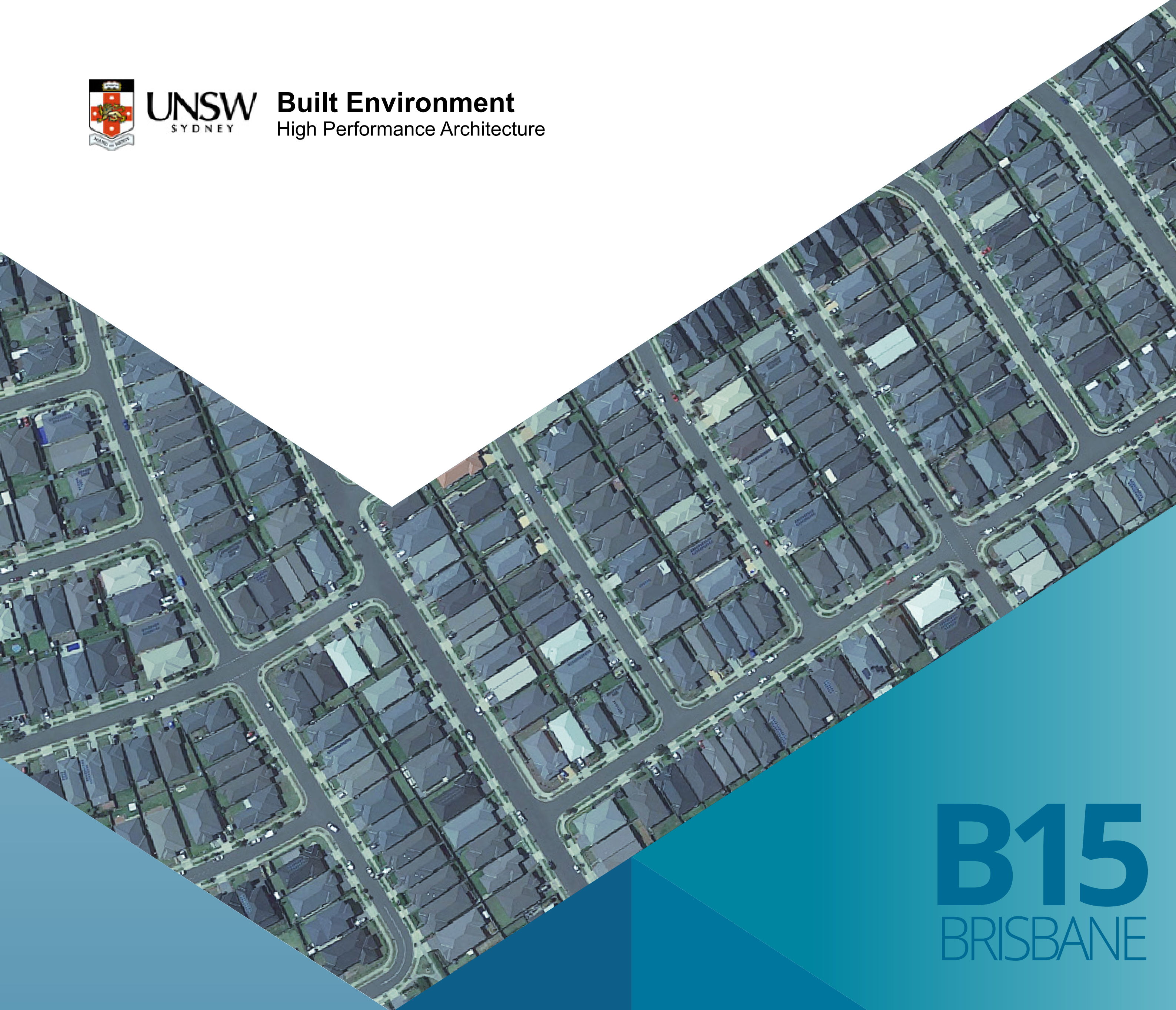

B15
BRISBANE

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

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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 Brisbane using weather data simulated by WRF.

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.

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 102.1-103.6 kWh/m² to 93.3-96.0 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)
Amberley	72.1	102.9	63.2	93.3	60.6	79.1
Archerfield	66.4	102.9	59.4	95.1	56.5	80.2
Brisbane Airport	66.1	103.6	59.1	95.8	55.4	78
Gold Coast - Seaway	64.2	103.4	57.7	96.0	54.7	80.8
Greenbank (Defence)	64.9	103.1	58.0	95.7	54.8	79.1
Redcliffe	66.6	103.2	59.1	94.9	55.9	78.5
Redland (Alexandra Hills)	65.2	102.1	58.3	94.3	55.7	80.5

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.

For Scenario 1, the total cooling load saving is around 7.4-9.6 kWh/m² which is equivalent to 7.2-9.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 21.6-25.6 kWh/m² which is equivalent to 25.8-32.4 % 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	%
Amberley	8.9	12.3	9.6	9.3	11.5	16.0	23.8	23.1
Archerfield	7.0	10.5	7.8	7.6	9.9	14.9	22.7	22.1
Brisbane Airport	7.0	10.6	7.8	7.5	10.7	16.2	25.6	24.7
Gold Coast - Seaway	6.5	10.1	7.4	7.2	9.5	14.8	22.6	21.9
Greenbank (Defence)	6.9	10.6	7.4	7.2	10.1	15.6	24.0	23.3
Redcliffe	7.5	11.3	8.3	8.0	10.7	16.1	24.7	23.9
Redland (Alexandra Hills)	6.9	10.6	7.8	7.6	9.5	14.6	21.6	21.2

In the eleven weather stations in Brisbane, 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.

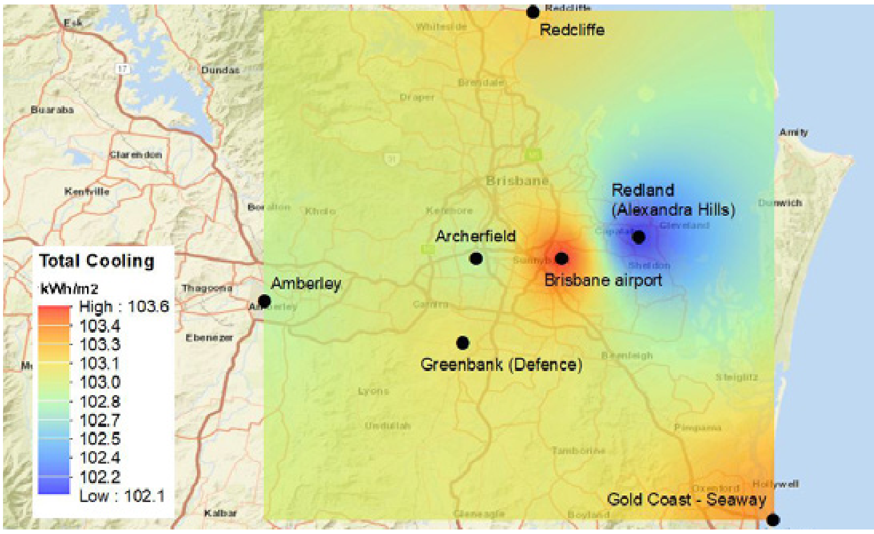

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

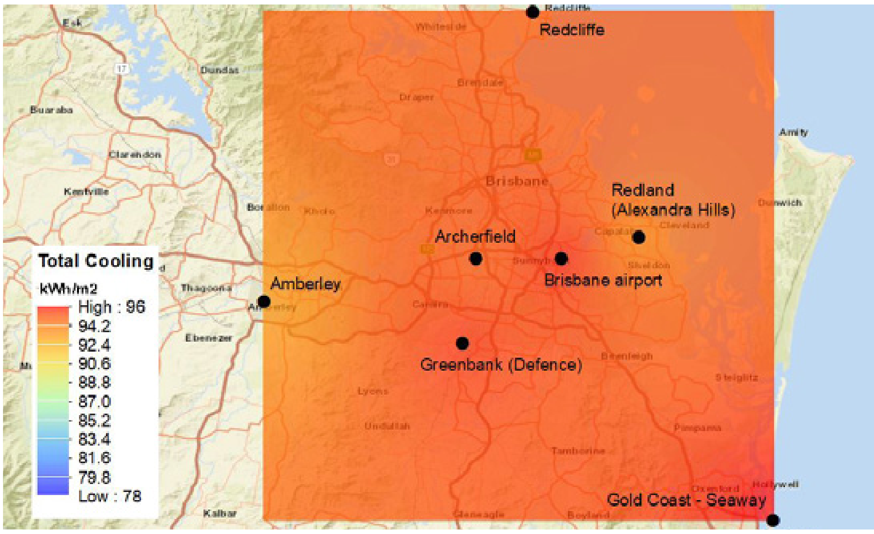

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

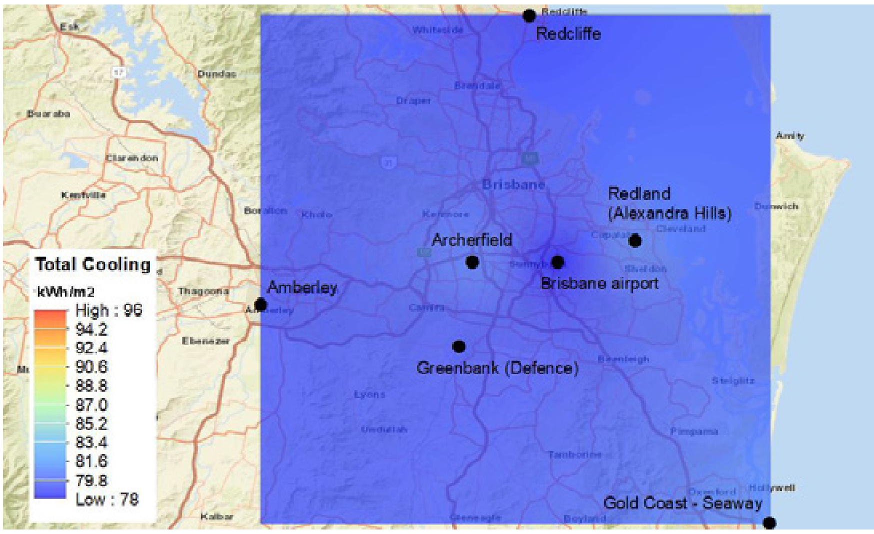

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 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 (0.0-0.2 kWh/m²) is significantly lower than the annual cooling load reduction (30.8-44.2 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
Amberley	280.3	342.7	1.1	2.6	245.4	306.1	1.3	2.8
Archerfield	281.3	351.9	0.5	1.0	249.7	318.2	0.5	1.1
Brisbane	305.1	385.8	0.3	0.5	263.7	341.6	0.4	0.6
Brisbane Airport	269.8	350.7	0.4	0.7	241.5	319.9	0.4	0.7
Redland (Alexandra Hills)	275.3	355.3	0.4	0.7	240.2	317.1	0.4	0.7

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 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 8.8-11.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 30.8-44.1 kWh/m² (~8.8-11.4 %).

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	%
Amberley	34.9	12.5	36.6	10.7	0.2	0.2	34.7	12.3	36.4	10.5
Archerfield	31.6	11.2	33.7	9.6	0.0	0.1	31.6	11.2	33.6	9.5
Brisbane	41.4	13.6	44.2	11.5	0.1	0.1	41.3	13.5	44.1	11.4
Brisbane Airport	28.3	10.5	30.8	8.8	0.0	0.0	28.3	10.5	30.8	8.8
Redland (Alexandra Hills)	35.1	12.7	38.2	10.8	0.0	0.0	35.1	12.7	38.2	10.7

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

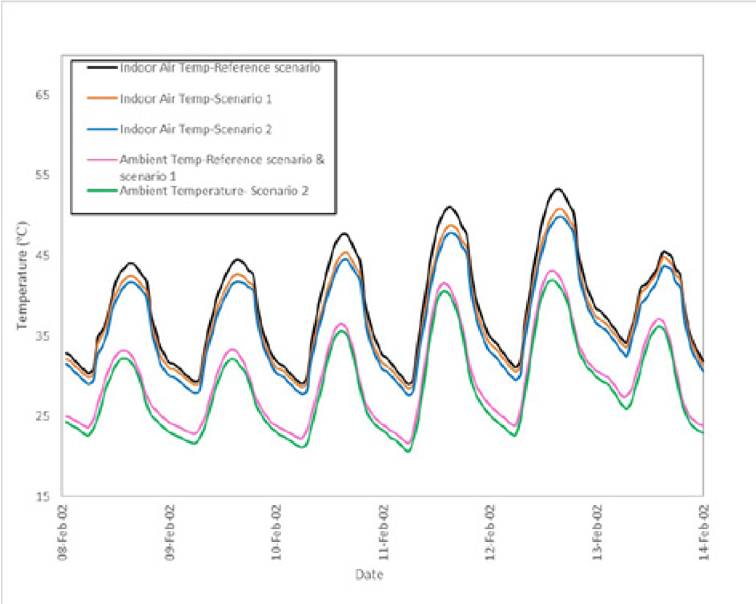

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

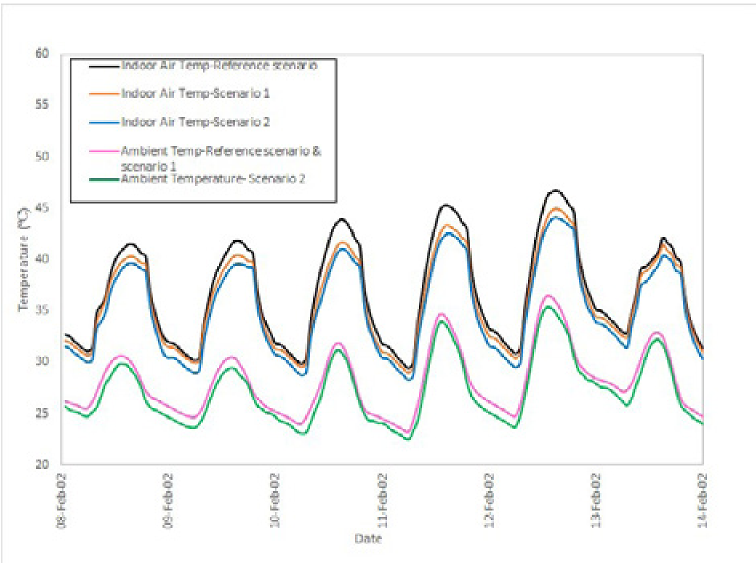

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 29.0-53.2 °C and 29.4-46.7 °C in Amberley and Redland stations, respectively.

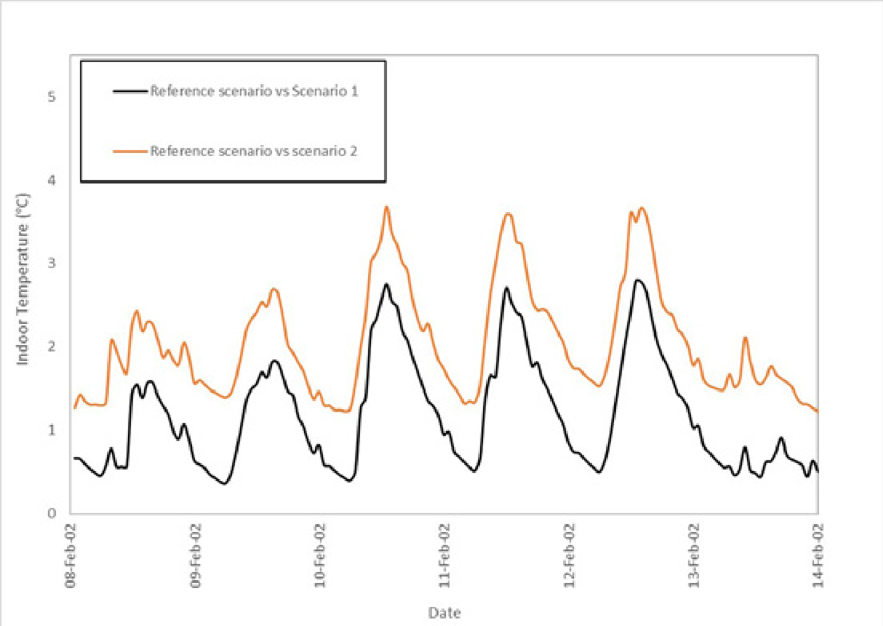

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free-floating conditions during a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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.8 °C and 2.5 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.7 °C and 3.3 °C in Amberley and Redland stations, respectively.

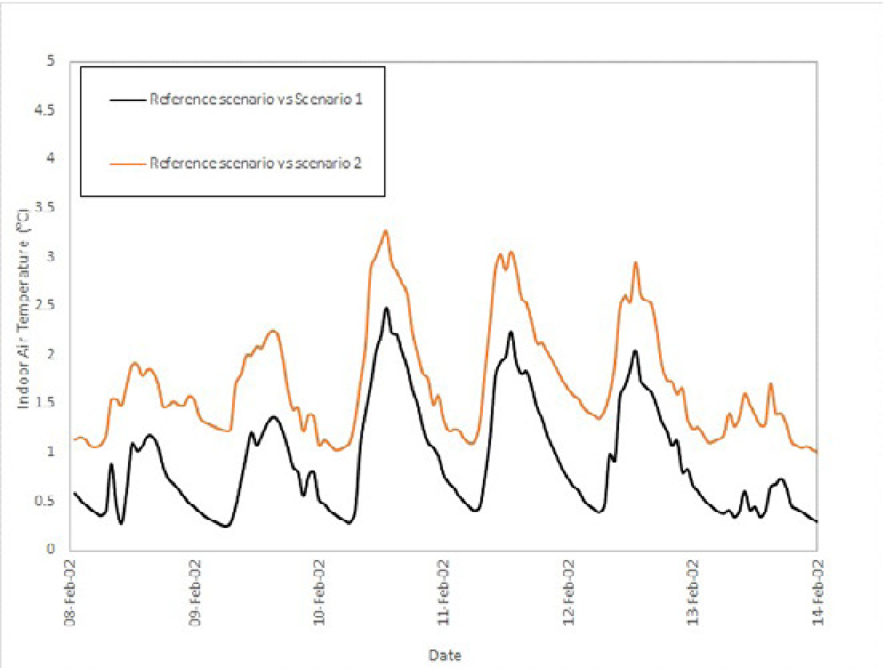

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) an existing new low-rise shopping mall centre under free-floating conditions during a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

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

4

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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.6-34.7 °C in reference scenario to a range 12.4-33.2 °C in scenario 1 in Amberley station.

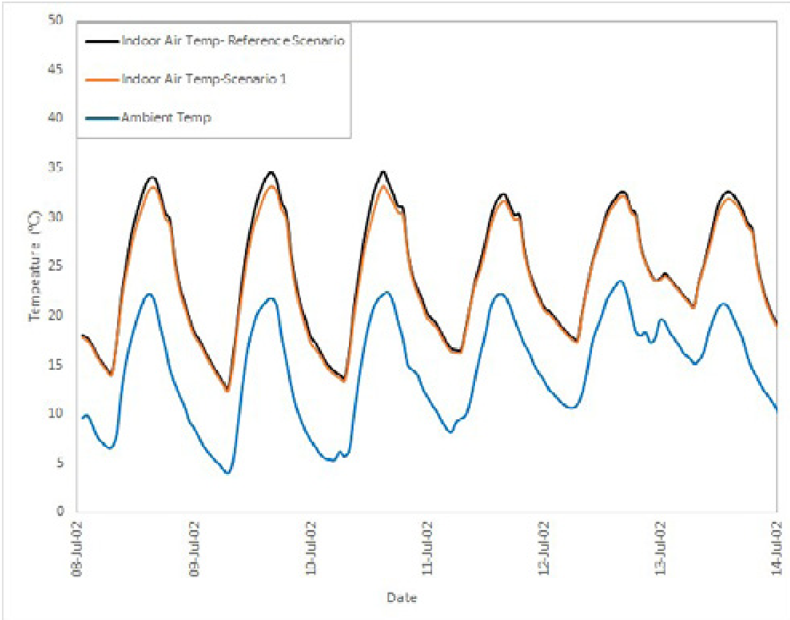

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Amberley station* using annual measured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

The indoor air temperature is predicted to reduce from a range 17.3-34.9 °C in reference scenario to a range 17.1-33.7 °C in scenario 1 in Redland station.

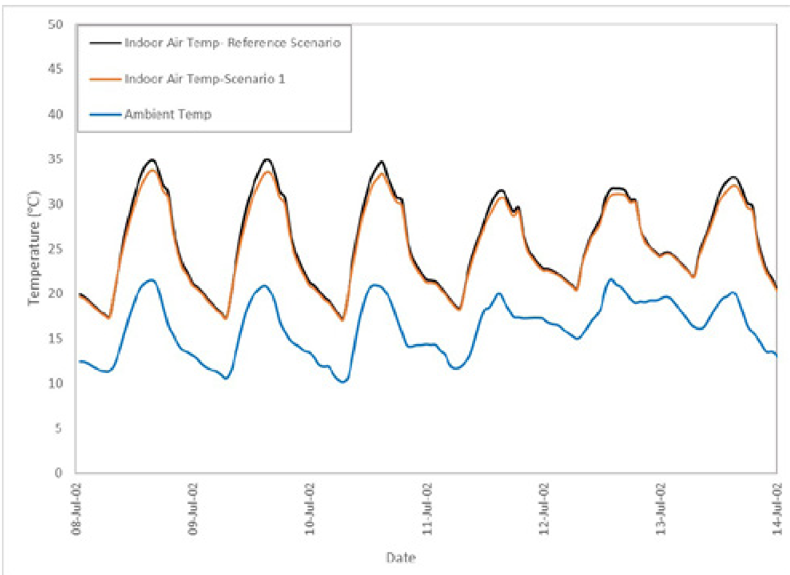

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Redland station* using annual measured 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 1.8 °C in Amberley and Redland stations, respectively.

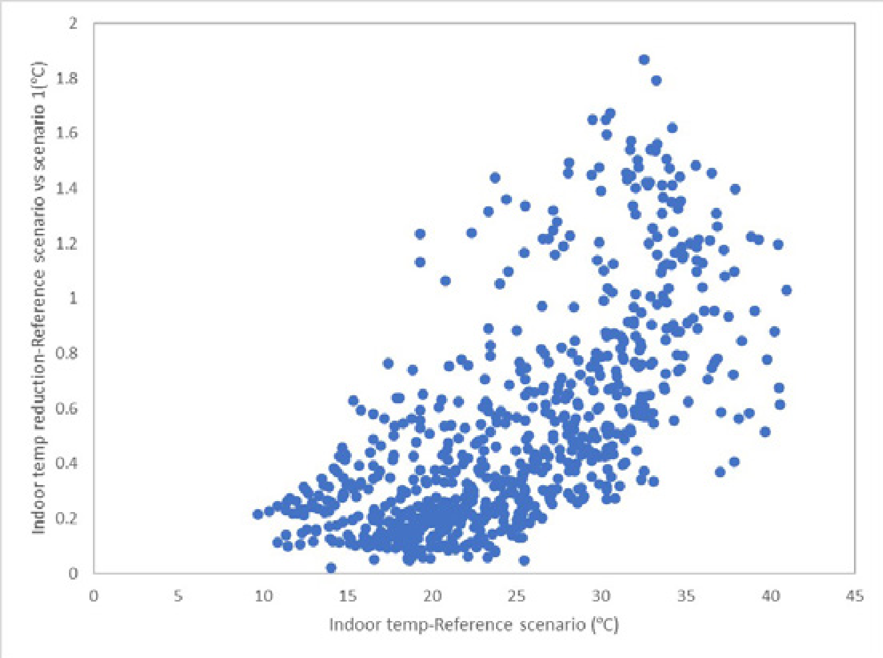

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

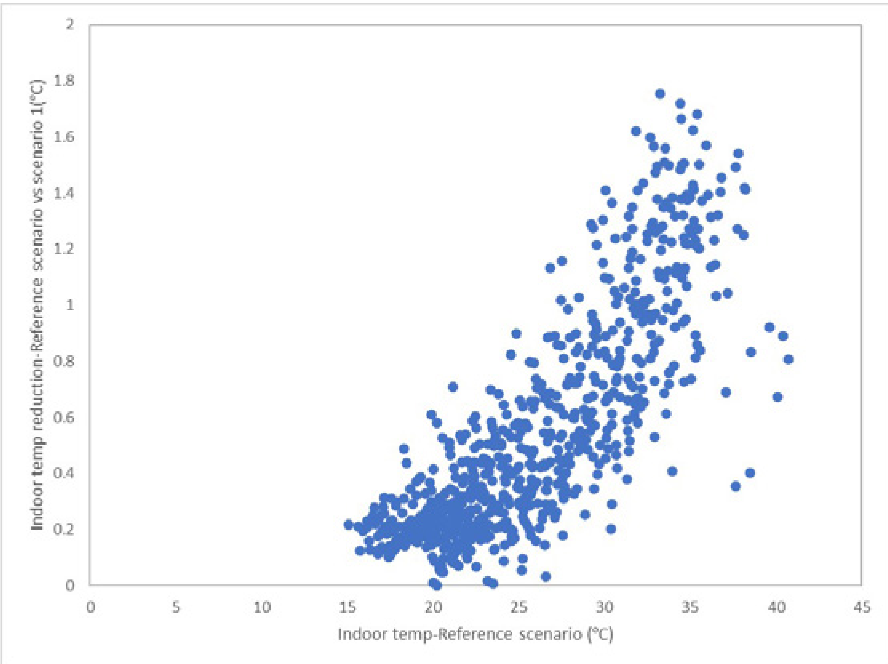

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 171 hours in reference scenario to 182 hours, and from 79 to 91 hours in scenario 1 in Amberley and Redland stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 42 hours in reference scenario compared to 45 hours in scenario 1 in Amberley; and from 20 to 25 hours in Redland 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
Amberley	42	171	45	182
Redland	20	79	25	91

** 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 664 hours in reference scenario to 662 and 648 hours under scenario 1 and 2 in Amberley station; while remains the same (672 hours) for scenario 1 and 2 in Redland 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
Amberley	664	662	648
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 15.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	303.9	313.3
Energy consumption after cool roof (MWh)	271.8	279.7
Energy savings (MWh)	32.1	33.6
Energy savings (%)	10.56 %	10.72 %
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

The cool roof refurbishment options

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 the use of cool roof techniques 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 practically identical energy savings for both locations, namely 10,56% for Amberley and 10,72% for the Redland 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.

Both cool roof options 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 for Amberley conditions and 29,3% for the cool coating, the high energy scenario and for Redland 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 Amberley and for Redland weather conditions respectively.

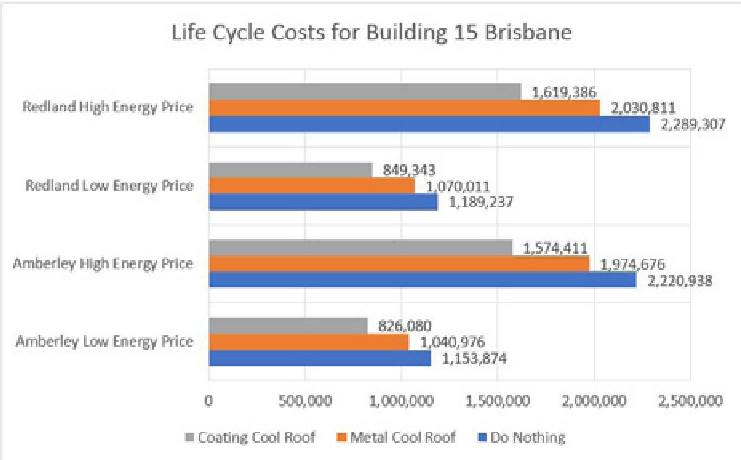

Figure 12. Life Cycle Costs for Building 15 for Amberley and Redland weather stations.

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	9.78 %	11.09 %	10.03 %	11.29 %
Coating Cool Roof	28.41 %	29.11 %	28.58 %	29.26 %

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 Brisbane, 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 102.1-103.6 kWh/m^2 to 93.3-96.0 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 7.4-9.6 kWh/m^2. This is equivalent to approximately 7.2-9.3 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 12.2-15.6 kWh/m^2. This is equivalent to 25.8-32.4 % 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 (0.0-0.2 kWh/m^2) is significantly lower than the annual cooling load reduction (30.8-44.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 8.8-11.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 30.8-44.1 kWh/m^2 (~8.8-11.4 %) (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 29.0-53.2 °C and 29.4-46.7 °C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.8 and 2.5 °C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.7 and 3.3 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 12.6-34.7 °C in reference scenario to a range between 12.4-33.2 °C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 17.3-34.9 °C in reference scenario to a range between 17.1-33.7 °C in reference with cool roof scenario (scenario 1) in Redland 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 1.8 °C in Amberley and Redland 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 171 hours in reference scenario to 182 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight increase in total number of hours below 19 °C from 79 hours in reference scenario to 91 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 42 hours in reference scenario to 45 hours in reference with cool roof scenario (scenario 1) in Amberley station. Similarly, the calculation in Redland station shows a slight increase of number of hours below 19 °C from 20 hours to 25 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 664 hours under the reference scenario in Amberley station, which decreases to 662 and 648 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Redland station show that the number of hours above 26 °C remain the same (672 hours) for all scenarios (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 for Amberley conditions and 29,3% for the cool coating, the high energy scenario and for Redland 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 the use of cool roof techniques a feasible investment over the building's life cycle.

B15

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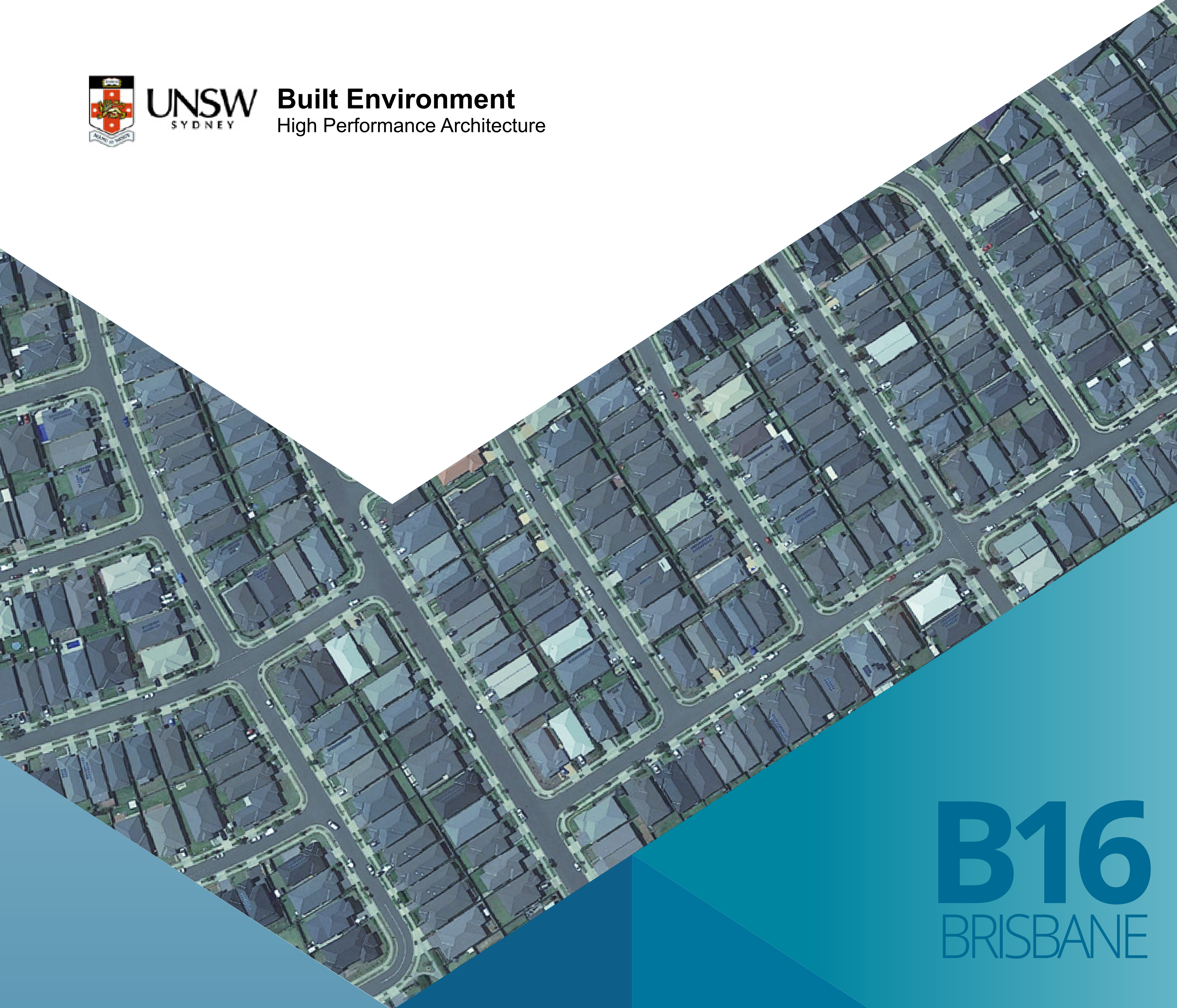

B16
BRISBANE

COOL ROOFS
COST BENEFIT ANALYSIS

Existing high-rise shopping mall centre
2021

BUILDING 16

EXISTING 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

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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 Brisbane 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 96.6-99.1 kWh/m² to 93.7-97.0 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)
Amberley	66.1	96.6	63.4	93.7	60.7	79.5
Archerfield	62.1	98.2	60.0	96.0	57.0	80.9
Brisbane Airport	61.8	98.9	59.7	96.6	55.9	78.7
Gold Coast - Seaway	60.4	99.1	58.5	97.0	55.4	81.7
Greenbank (Defence)	60.7	98.7	58.8	96.5	55.5	79.9
Redcliffe	61.9	98.1	59.7	95.6	56.4	79.2
Redland (Alexandra Hills)	61.0	97.4	58.9	95.2	56.3	81.2

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.

For Scenario 1, the total cooling load saving is around 2.1-3.0 kWh/m² which is equivalent to 2.1-3.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 16.2-20.2 kWh/m² which is equivalent to 16.6-20.4 % 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	%
Amberley	2.7	4.1	2.9	3.0	5.4	8.2	17.1	17.7
Archerfield	2.1	3.4	2.2	2.2	5.1	8.2	17.3	17.6
Brisbane Airport	2.1	3.4	2.3	2.3	5.9	9.5	20.2	20.4
Gold Coast - Seaway	1.9	3.1	2.1	2.1	5.0	8.3	17.4	17.6
Greenbank (Defence)	1.9	3.1	2.2	2.2	5.2	8.6	18.8	19.0
Redcliffe	2.2	3.6	2.5	2.5	5.5	8.9	18.9	19.3
Redland (Alexandra Hills)	2.1	3.4	2.2	2.3	4.7	7.7	16.2	16.6

In the eleven weather stations in Brisbane, 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.

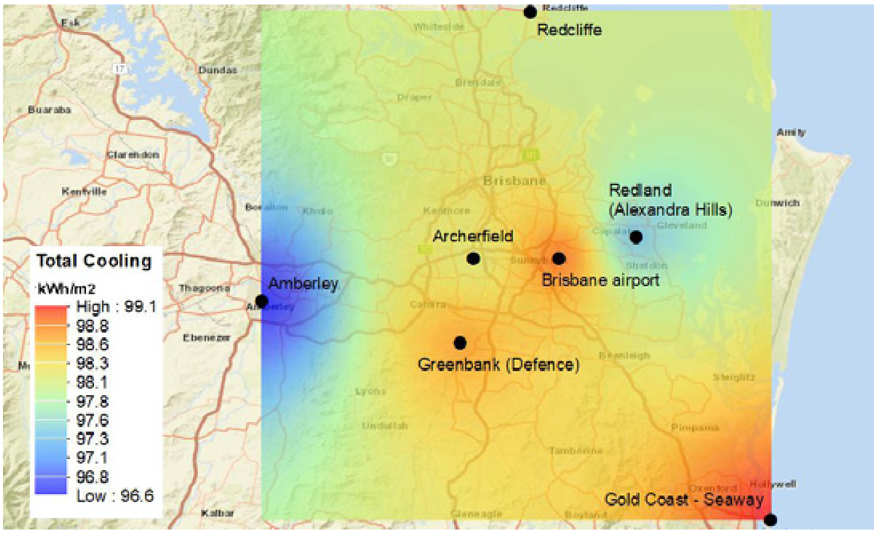

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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.

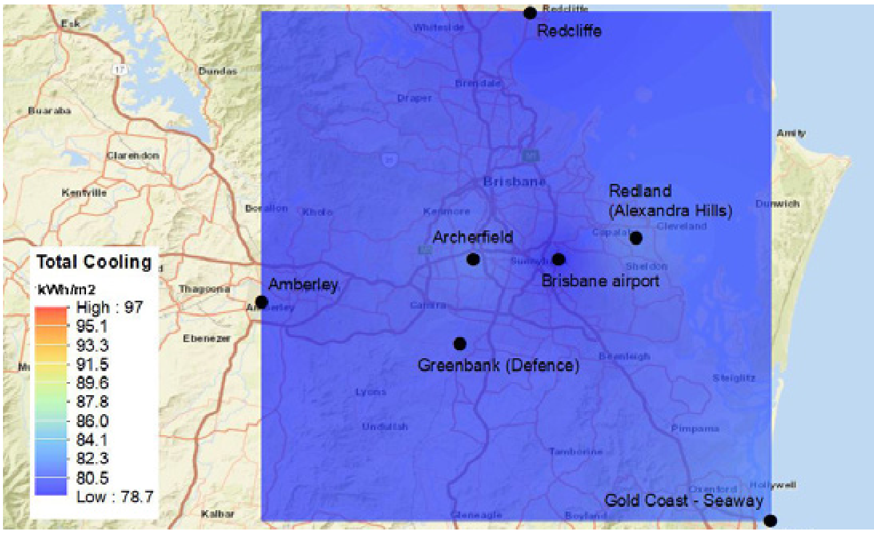

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Brisbane 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 (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (8.7-13.5 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
Amberley	257.4	318.8	0.7	1.7	247.1	307.8	0.8	1.8
Archerfield	262.3	331.8	0.3	0.5	253.2	322.1	0.3	0.6
Brisbane	271.1	360.2	0.1	0.2	268.5	346.7	0.1	0.2
Brisbane Airport	254.8	334.5	0.2	0.3	246.8	325.8	0.2	0.3
Redland (Alexandra Hills)	255.0	333.4	0.2	0.3	244.7	322.2	0.2	0.3

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 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 2.6-3.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 8.7-13.5 kWh/m² (~2.6-3.7 %).

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	%
Amberley	10.3	4.0	11.0	3.5	0.1	0.1	10.2	4.0	10.9	3.4
Archerfield	9.1	3.5	9.7	2.9	0.0	0.1	9.1	3.5	9.6	2.9
Brisbane	2.6	1.0	13.5	3.7	0.0	0.0	2.6	1.0	13.5	3.7
Brisbane Airport	8.0	3.1	8.7	2.6	0.0	0.0	8.0	3.1	8.7	2.6
Redland (Alexandra Hills)	10.3	4.0	11.2	3.4	0.0	0.0	10.3	4.0	11.2	3.4

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

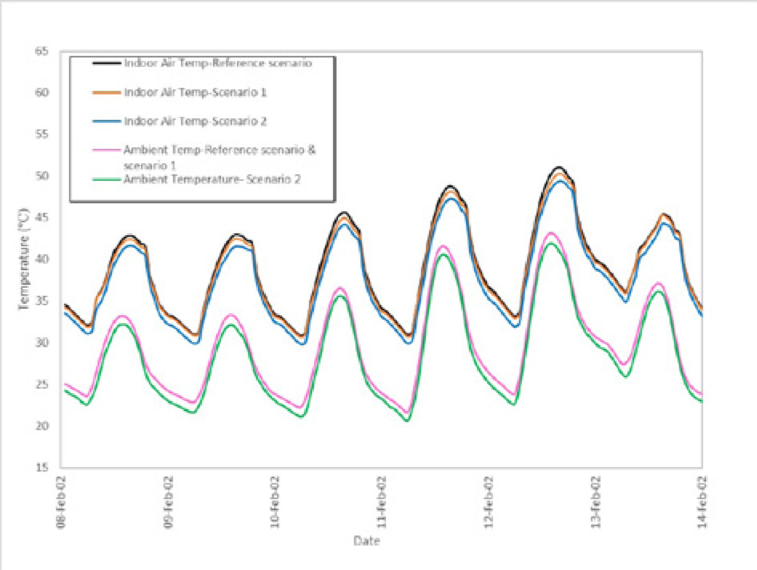

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

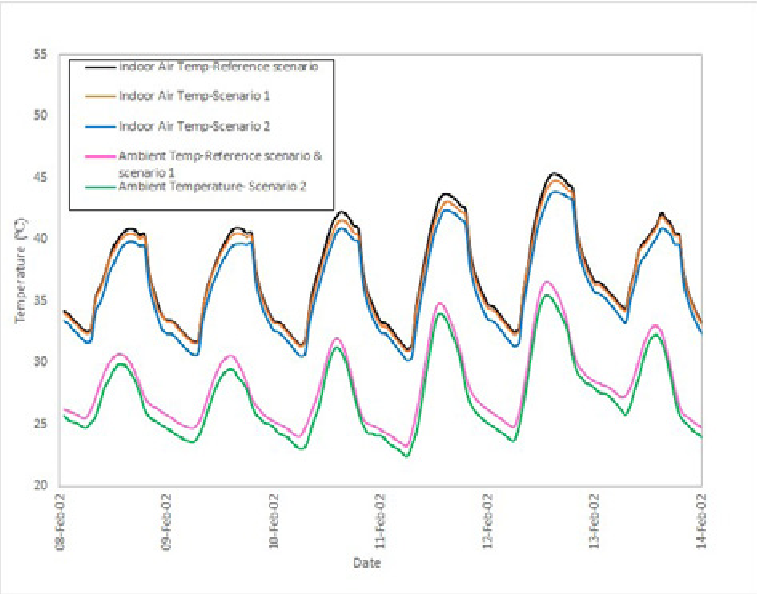

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 30.8-51.1 °C and 31.1-45.3 °C in Amberley and Redland stations, respectively.

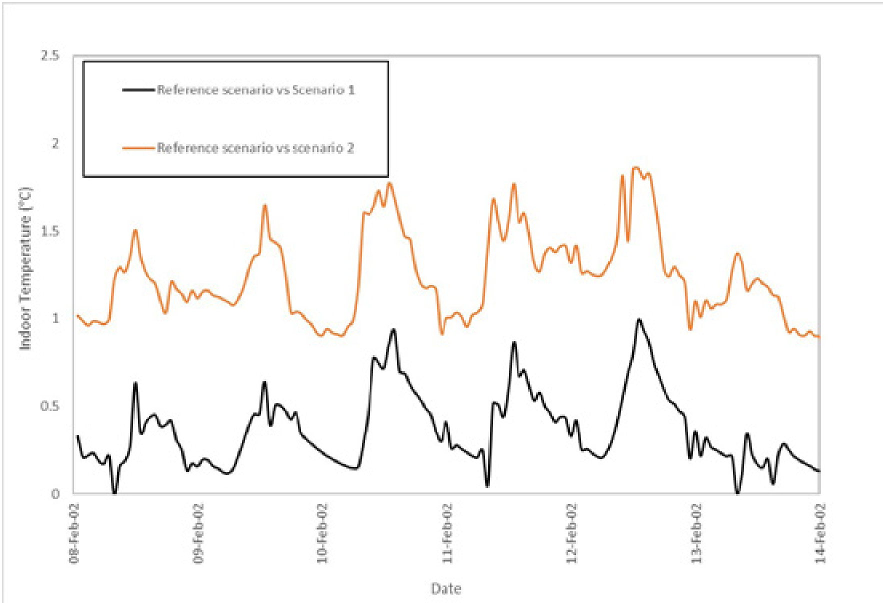

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free-floating conditions during a typical summer week in *Amberley 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 0.9 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.9 °C and 1.7 °C in Amberley and Redland stations, respectively.

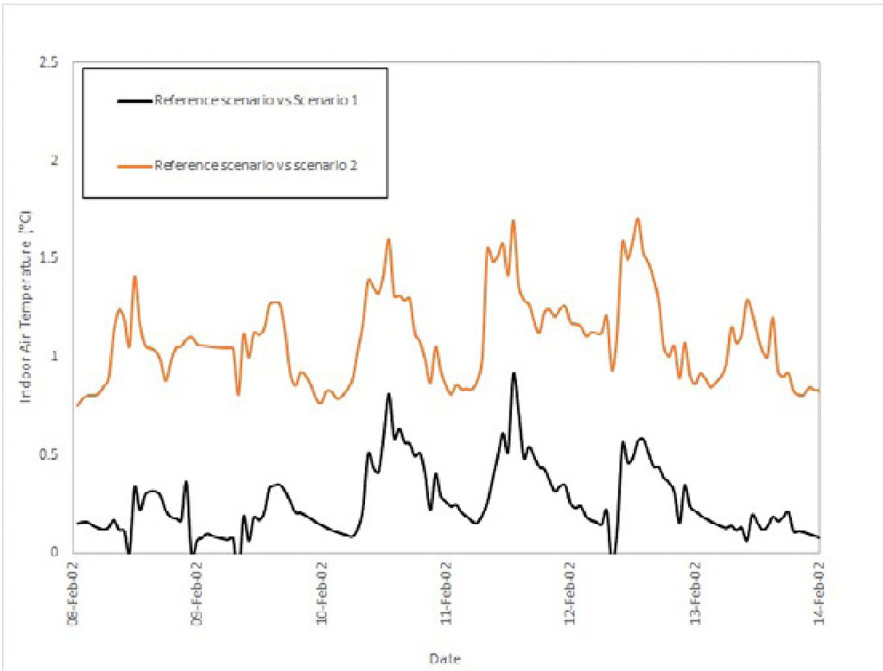

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing highrise shopping mall centre under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 15.0-33.4 °C in reference scenario to a range 14.9-33.0 °C in scenario 1 in Amberley station.

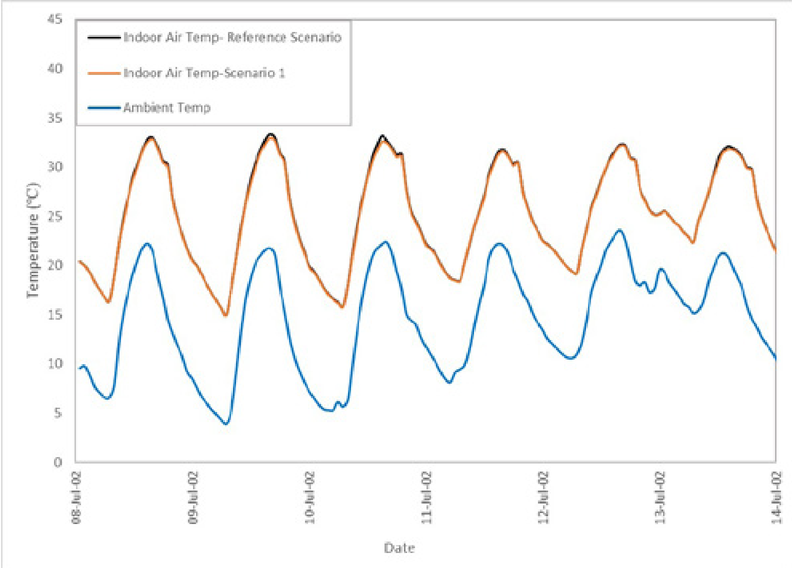

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Amberley station* using annual measured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

The indoor air temperature is predicted to reduce from a range 19.3-33.9 °C in reference scenario to a range 19.3-33.6 °C in scenario 1 in Redland station.

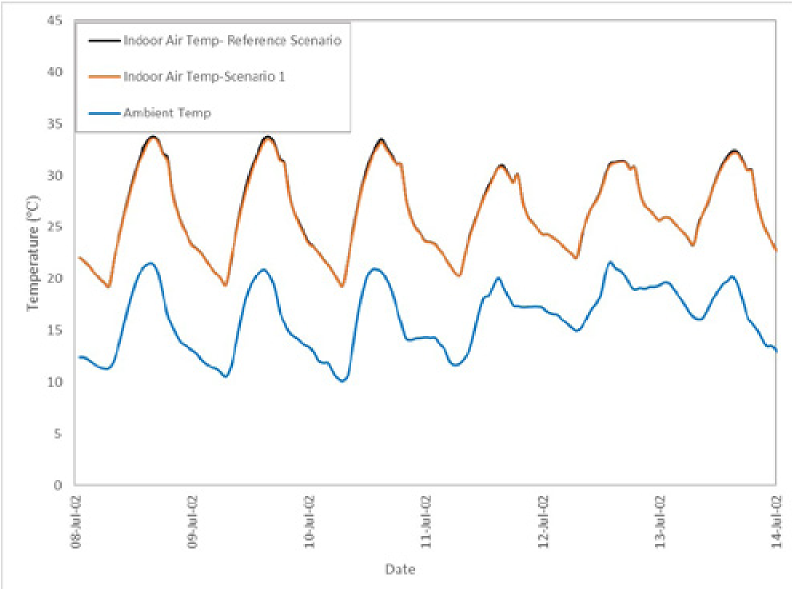

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Redland station* using annual measured 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 ^{o}C in Amberley and Redland stations.

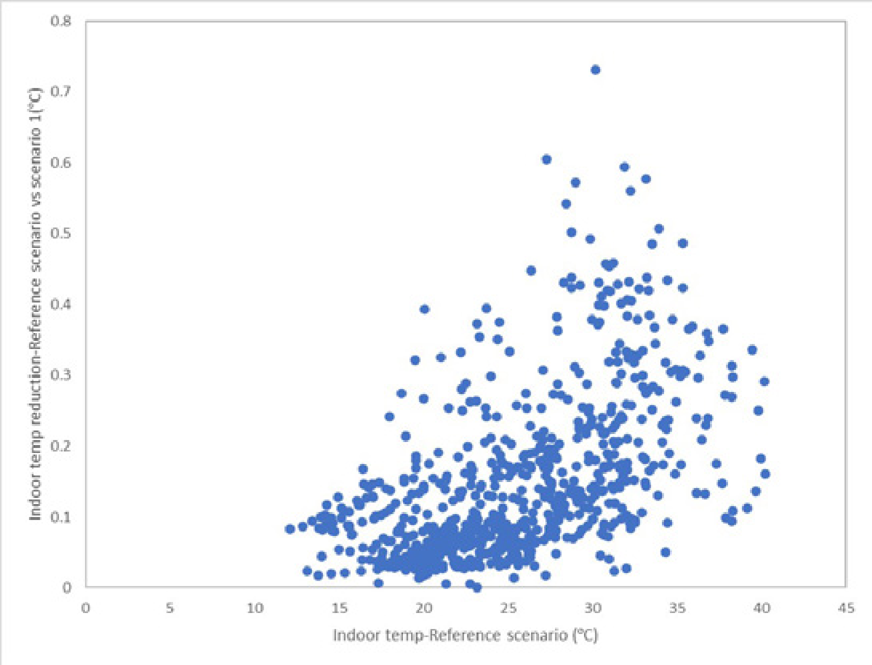

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

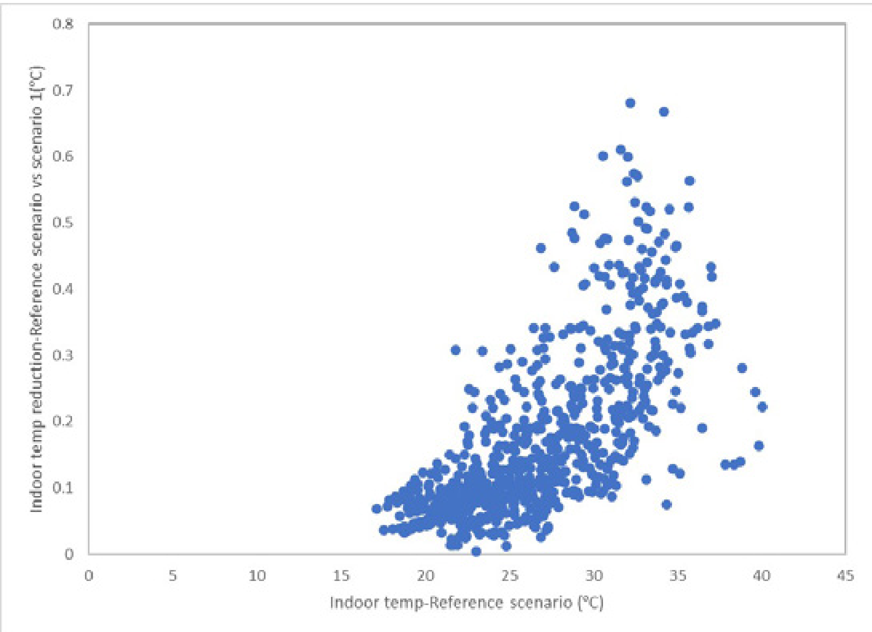

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 95 in the reference scenario to 97 hours in Scenario 1 in Amberley; and from 19 to 20 hours in Redland stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 29 hours in reference scenario compared to 30 hours in scenario 1 in Amberley; and from 9 to 11 hours in Redland 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
Amberley	29	95	30	97
Redland	9	19	11	20

** 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 remain the same (672 hours) for all scenarios in Amberley and Redland stations.

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
Amberley	672	672	672
Redland	672	672	672

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 16.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	846.1	881.0
Energy consumption after cool roof (MWh)	817.3	851.4
Energy savings (MWh)	28.8	29.6
Energy savings (%)	3.40 %	3.36 %
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 rather 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

Both options have the same energy efficiency, resulting in almost identical energy savings for both locations, namely of 3,40% for Amberley and of 3,36% for the Redland 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.

Both cool roof options lead to a reduction of life cycle costs over the building's life cycle, that varies for the coating cool roof between 4,4% for the low energy price scenario, the metal cool roof and the Amberley conditions and 23,7% for the high energy scenario, the coating cool roof and the Redland conditions.

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.

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 Amberley and for Redland weather conditions respectively.

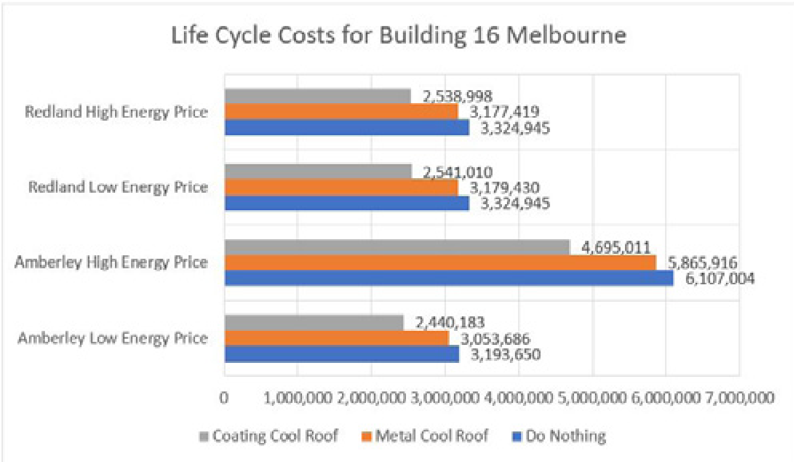

Figure 12. Life Cycle Costs for Building 16 for Amberley and Redland weather stations.

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	4.38 %	3.95 %	4.38 %	4.44 %
Coating Cool Roof	23.59 %	23.12 %	23.58 %	23.64 %

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 96.6-99.1 kWh/m^2 to 93.7-97.0 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 2.1-3.0 kWh/m^2. This is equivalent to approximately 2.1-3.0 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 16.2-20.2 kWh/m^2. This is equivalent to 16.6-20.4 % 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 (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (8.7-13.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 2.6-3.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 8.7-13.5 kWh/m2 (~2.6-3.7 %) (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 30.8-51.1 ^{o}C and 31.1-45.3 ^{o}C in Amberley and Redland 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 0.9 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.9 and 1.7 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 15.0-33.4 ^{o}C in reference scenario to a range between 14.9-33.0 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 19.3-33.9 ^{o}C in reference scenario to a range between 19.3-33.6^{o}C in reference with cool roof scenario (scenario 1) in Redland 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 ^{o}C in Amberley and Redland 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 269 hours in reference scenario to 275 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slight increase in total number of hours below 19 ^{o}C from 349 hours in reference scenario to 354 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. 7 am-6 pm) is expected to increase from 36 hours in reference scenario to 38 hours in reference with cool roof scenario (scenario 1) in Amberley station.

Similarly, the calculation in Redland station shows a slight increase of number of hours below 19 ^{o}C from 71 hours to 72 hours during the operational hours (See Table 5).

• During a typical summer month, the total number of hours with an indoor air temperature (>26 ^{o}C) is predicted to remain the same with 672 hours for all scenarios, in Amberley and Redland stations (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 4,4% for the low energy price scenario, the metal cool roof and the Amberley conditions and 23,7% for the high energy scenario, the coating cool roof and the Redland conditions, 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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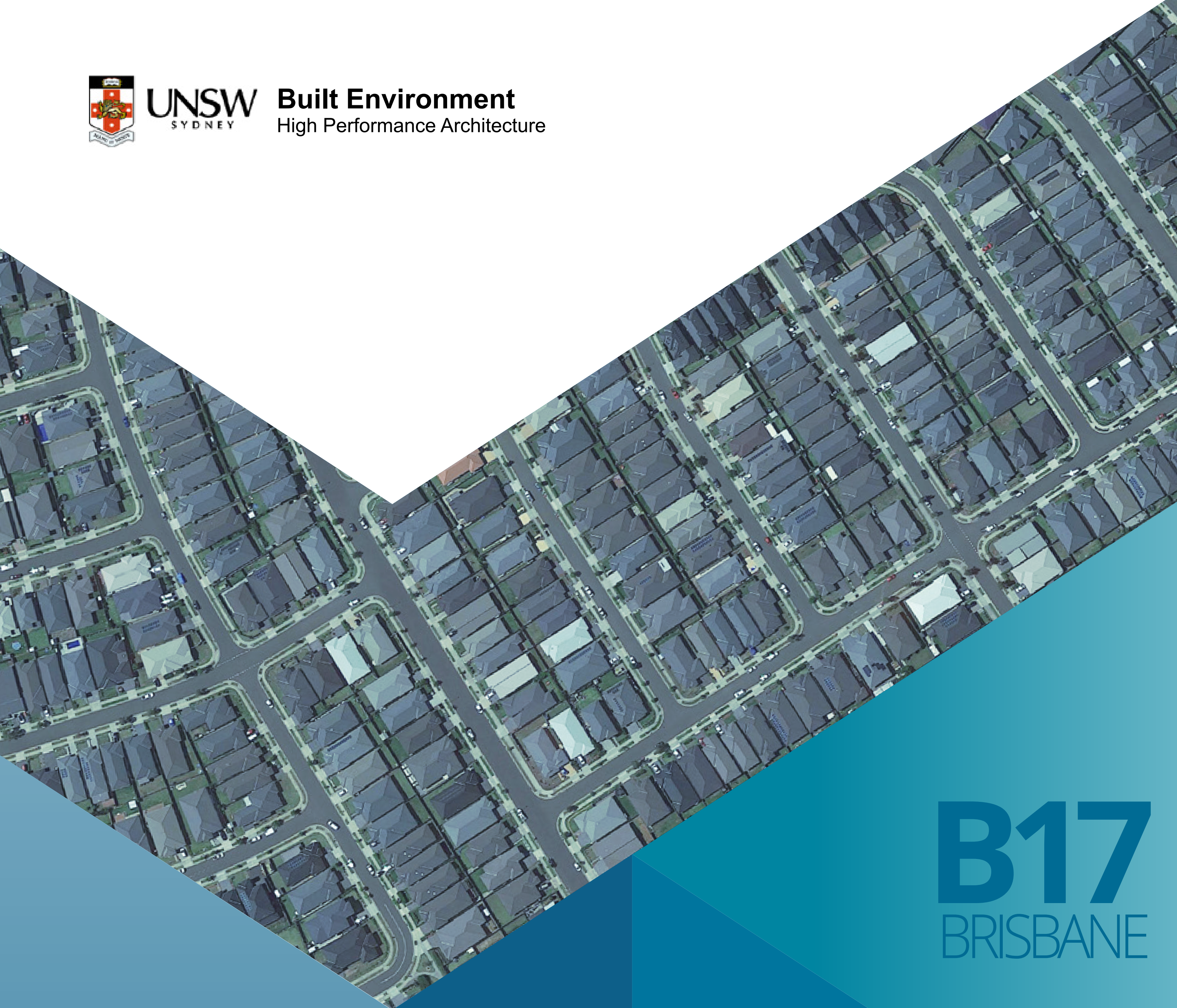

B17 BRISBANE

COOL ROOFS
COST BENEFIT ANALYSIS

New standalone house
2021

BUILDING 17

NEW STANDALONE HOUSE

Floor area : 242m²
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.

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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 Brisbane 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 22.5-23.5 kWh/m² to 18.4-19.4 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)
Amberley	15.3	22.8	11.7	18.4	10.2	13.8
Archerfield	13.5	23.1	10.4	19.0	8.8	13.8
Brisbane Airport	13.4	23.3	10.2	19.2	8.2	12.9
Gold Coast - Seaway	12.8	23.5	9.9	19.4	8.2	13.9
Greenbank (Defence)	12.9	23.3	10.0	19.2	8.1	13.3
Redcliffe	13.5	23.1	10.3	18.8	8.5	13.2
Redland (Alexandra Hills)	12.9	22.5	9.9	18.4	8.5	13.7

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 4.1-4.4 kWh/m² which is equivalent to 17.4-19.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 8.8-10.4 kWh/m² which is equivalent to 39.1-44.6 % 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	%
Amberley	3.6	23.5	4.4	19.3	5.1	33.3	9.0	39.5
Archerfield	3.1	23.0	4.1	17.7	4.7	34.8	9.3	40.3
Brisbane Airport	3.2	23.9	4.1	17.6	5.2	38.8	10.4	44.6
Gold Coast - Seaway	2.9	22.7	4.1	17.4	4.6	35.9	9.6	40.9
Greenbank (Defence)	2.9	22.5	4.1	17.6	4.8	37.2	10.0	42.9
Redcliffe	3.2	23.7	4.3	18.6	5.0	37.0	9.9	42.9
Redland (Alexandra Hills)	3.0	23.3	4.1	18.2	4.4	34.1	8.8	39.1

In the eleven weather stations in Brisbane, 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.

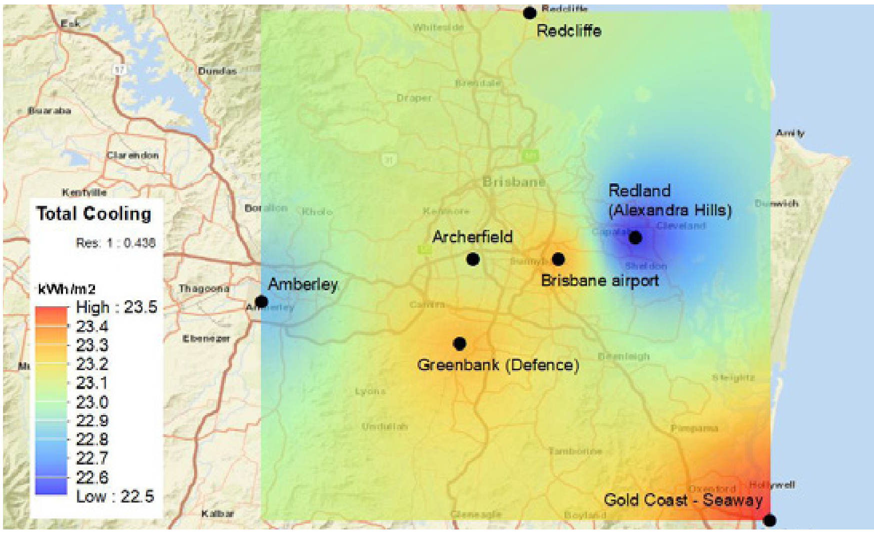

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

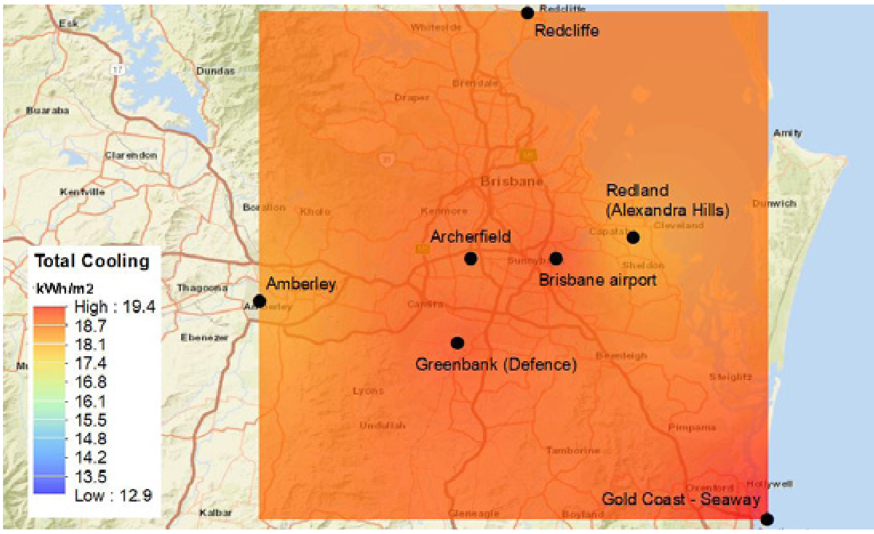

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

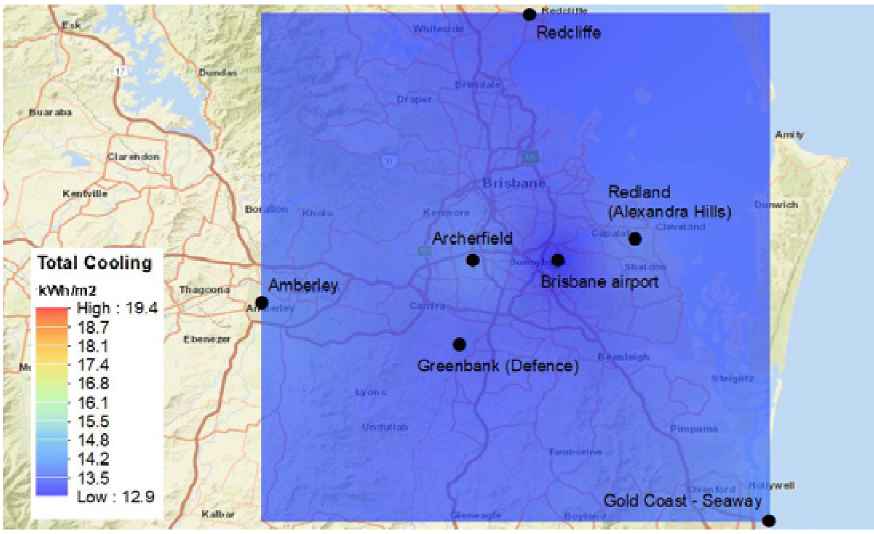

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.4-0.7 kWh/m²) is significantly lower than the annual cooling load reduction (12.3-16.4 kWh/m²).

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.

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
Amberley	36.5	50.1	6.9	9.9	25.5	37.2	7.5	10.6
Archerfield	35.9	51.3	4.4	6.3	25.5	38.7	4.8	6.8
Brisbane	41.3	59.6	3.1	4.4	27.8	43.2	3.4	4.9
Brisbane Airport	31.8	48.7	3.3	4.8	22.3	36.4	3.6	5.2
Redland (Alexandra Hills)	32.2	48.4	3.5	5.1	21.1	33.8	4.0	5.7

The annual cooling load saving by building-scale application of cool roofs is around 24.6-30.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 11.9-15.9 kWh/m² (~21.0-26.2 %).

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 a new 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	%
Amberley	11.0	30.1	12.9	25.7	0.6	0.7	10.4	24.0	12.2	20.3
Archerfield	10.4	29.0	12.6	24.6	0.4	0.5	10.0	24.8	12.1	21.0
Brisbane	13.5	32.7	16.4	27.5	0.3	0.5	13.2	29.7	15.9	24.8
Brisbane Airport	9.5	29.9	12.3	25.3	0.3	0.4	9.2	26.2	11.9	22.2
Redland (Alexandra Hills)	11.1	34.5	14.6	30.2	0.5	0.6	10.6	29.7	14.0	26.2

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 Brisbane (i.e. Amberley and Redland) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 21.7-43.1 °C in reference scenario to a range 20.8-41.9 °C in scenario 2 in Amberley station.

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

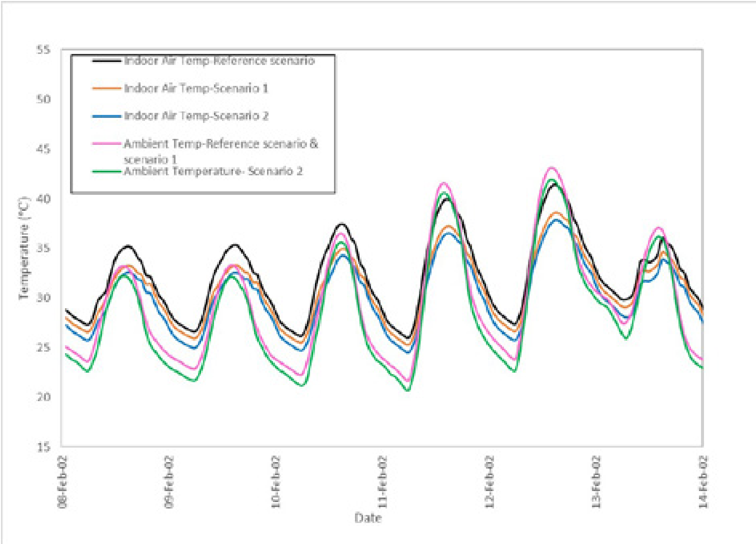

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer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

For scenario 2, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in Redland station.

For Scenario 2, the estimated ambient temperature reduction is 0.5-1.6 °C compared to the reference scenario in Redland station.

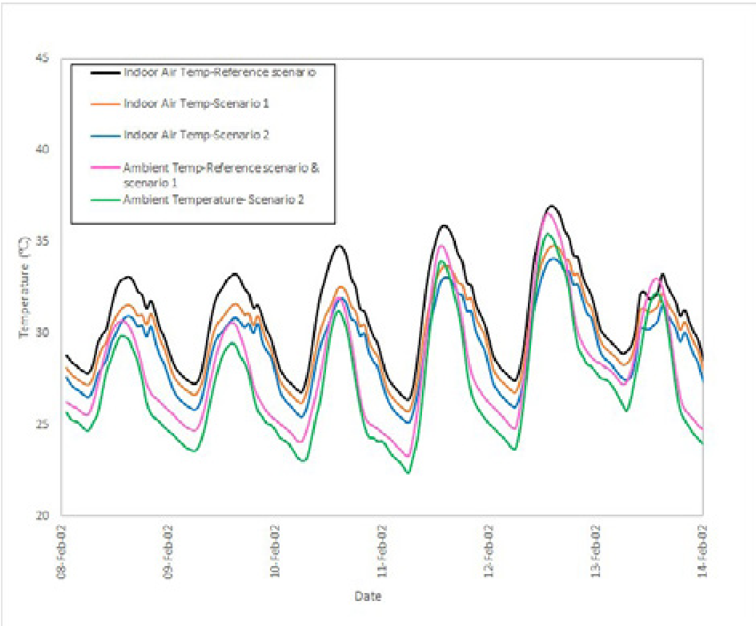

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 20.1-41.4 °C and 26.4-36.9 °C in Amberley and Redland stations, respectively.

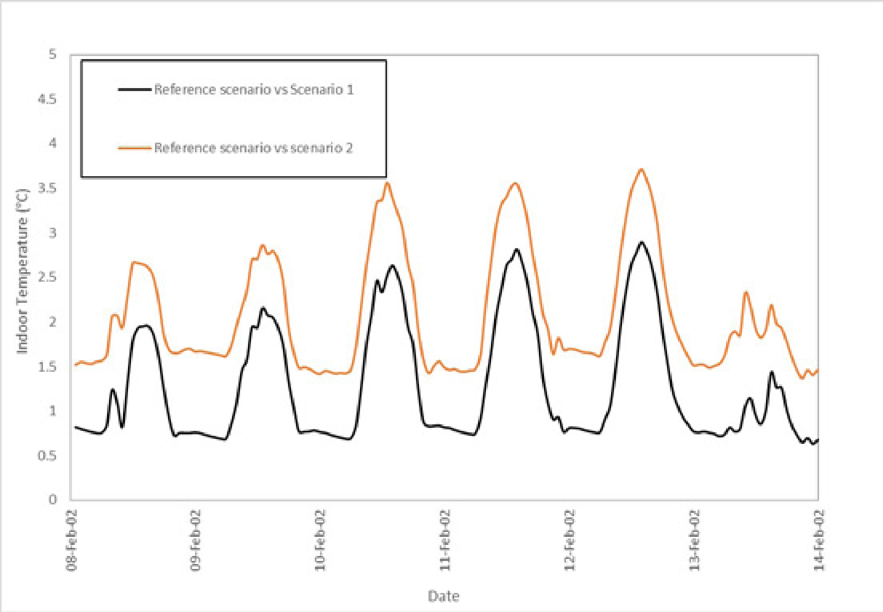

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.9 °C and 2.5 °C in Amberley and Redland stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.7 °C and 3.2 °C in Amberley and Redland stations, respectively.

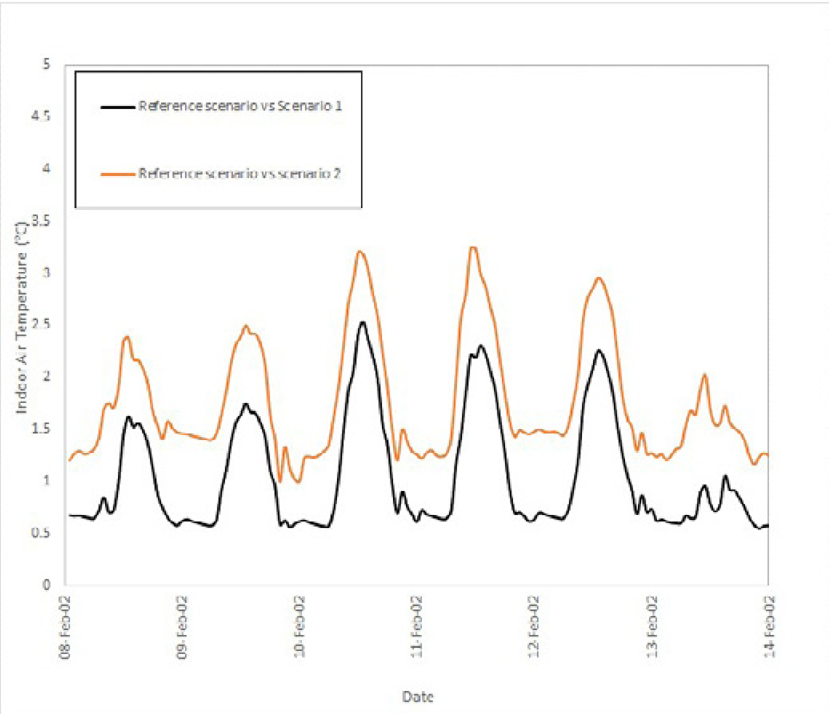

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week in *Redland 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 Brisbane (i.e. Amberley and Redland) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 12.4-27.4 °C in reference scenario to a range 12.0-25.8 °C in scenario 1 in Amberley station.

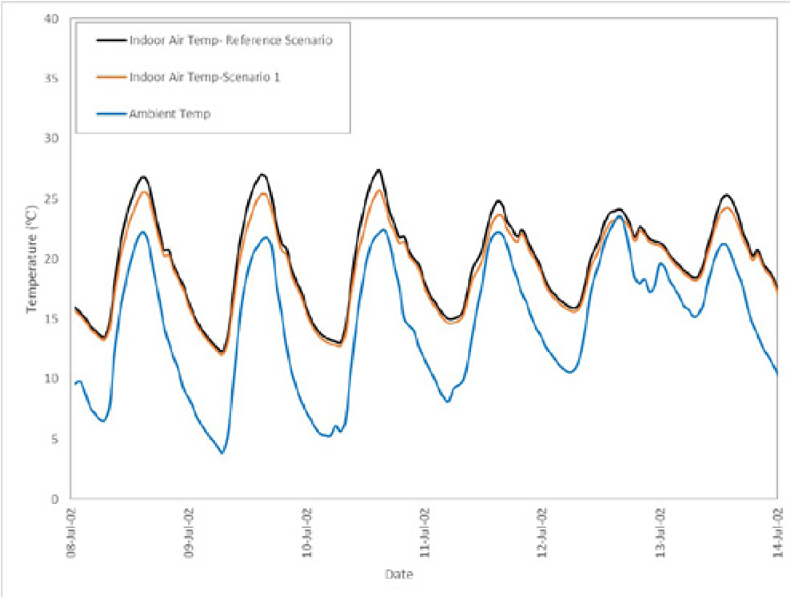

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Amberley station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 16.1-27.5 °C in reference scenario to a range 15.8-26.0 °C in scenario 1 in Redland station.

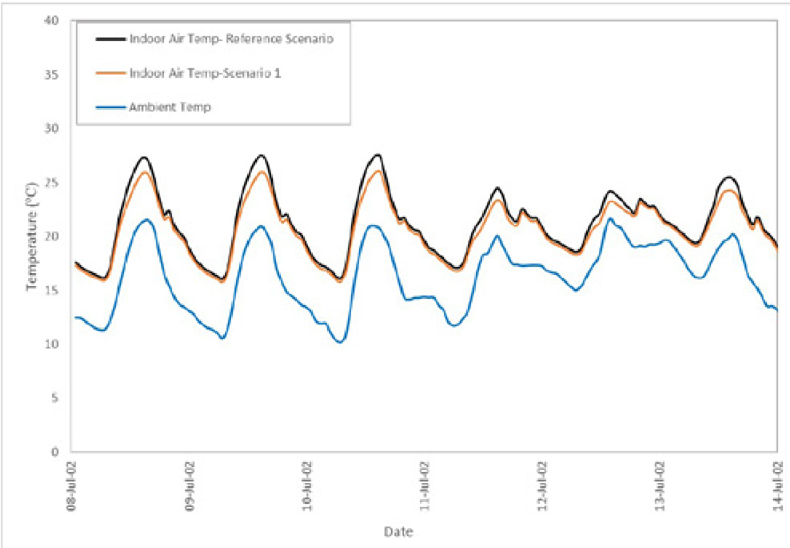

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Redland station* using annual measured weather data.

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 in Amberley and Redland stations.

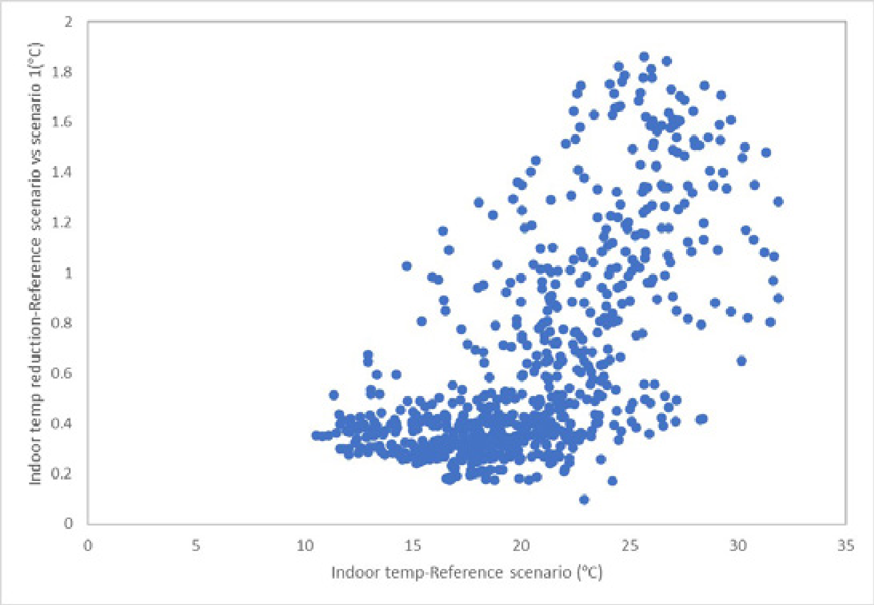

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Amberley station* using annual measured weather data.

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

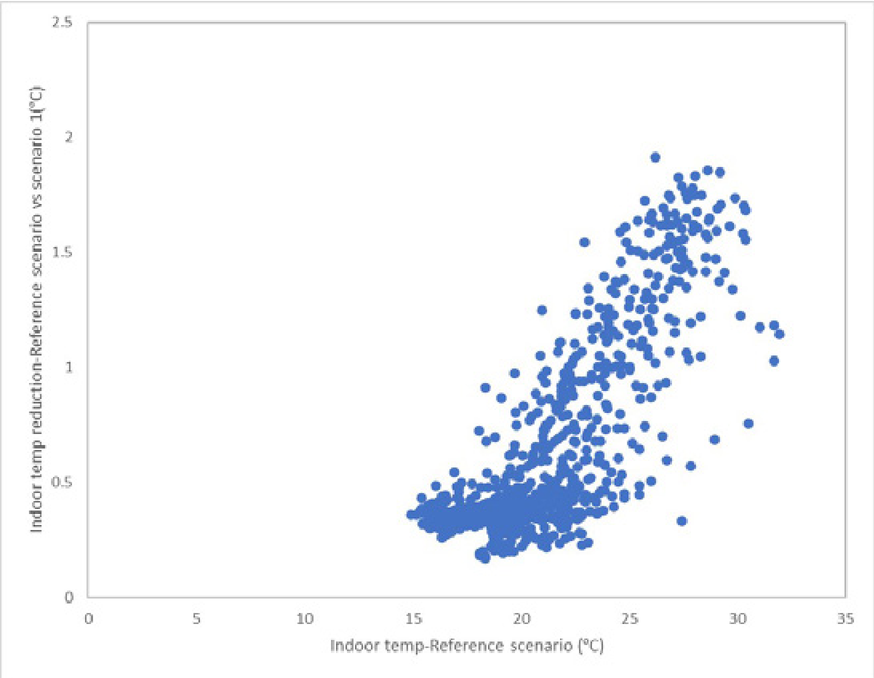

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Redland station* using annual measured weather data.

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 Brisbane (i.e. Amberley and Redland) 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 296 hours in reference scenario to 333 hours; and from 189 to 234 hours in scenario 1 in Amberley and Redland stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Amberley	296	333
Redland	189	234

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 slightly decrease from 558 hours in reference scenario to 552 and 485 hours under scenario 1 and 2 in Amberley station; and from 618 hours in reference scenario to 583 and 566 hours under scenario 1 and 2 in Redland station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Amberley	558	552	485
Redland	618	583	566

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Due to 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 Amberley and for Redland weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 17.

Energy performance features	Amberley	Redland
Energy consumption prior cool roof (MWh)	5.8	5.2
Energy consumption after cool roof (MWh)	4.6	3.8
Energy savings (MWh)	1.2	1.4
Energy savings (%)	20.69 %	26.92 %
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 application of a coating cool technology emerges as a meaningful and appealing 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' reduction of 20,69% for the Amberley weather conditions and of 26,92% for the Coldstream 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, that varies between 21,9% for the low energy price scenario for Amberley and 33,0% for the high energy scenario and for Redland condition.

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 Amberley and for Redland weather conditions respectively.

Given the low in absolute terms value of energy expenditures and the high initial investment cost of the metal cool roof, the latter is only feasible for the high energy prices scenario.

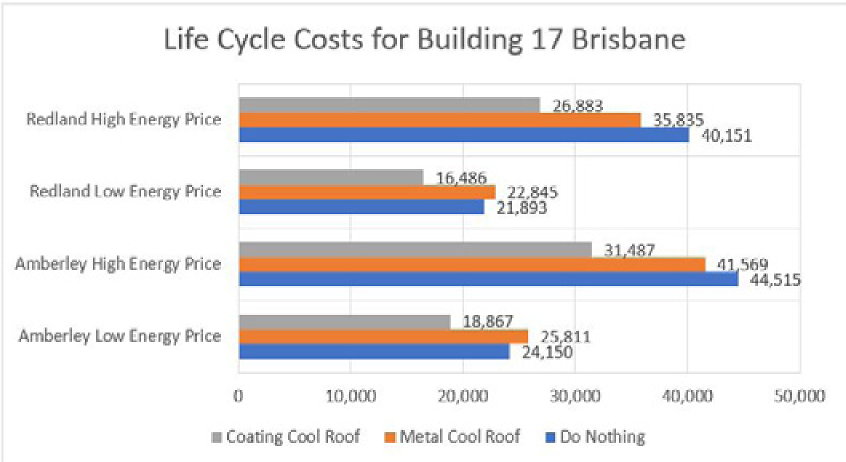

Figure 12. Life Cycle Costs for Building 17 for Amberley and Redland weather stations.

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	-6.88 %	6.62 %	-4.35 %	10.75 %
Coating Cool Roof	21.88 %	29.27 %	24.70 %	33.04 %

The metal cool roof is, due to its higher initial investment cost and the limited in absolute terms energy savings, is feasible only for the high energy prices scenario for both locations.

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 Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 22.5-23.5 kWh/m^2 to 18.4-19.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 4.1-4.4 kWh/m^2. This is equivalent to approximately 17.4-19.3 % 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 Brisbane, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 8.8-10.4 kWh/m^2. This is equivalent to 39.1-44.6 % 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 (0.4-0.7 kWh/m^2) is lower than the annual cooling load reduction (12.3-16.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 24.6-30.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 11.9-15.9 kWh/m^2 (~21.0-26.2 %) (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 20.1-41.4 ^{o}C and 26.4-36.9 ^{o}C in Amberley and Redland stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.3 and 2.8 ^{o}C in Amberley and Redland stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.3 and 3.7 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Amberley and Redland stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 21.7-43.1 °C in reference scenario to a range between 20.8-41.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Amberley station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.7 °C. Similarly, the ambient temperature is predicted to decrease from 23.3-36.5 °C in reference scenario to 22.4-35.4 °C in cool roof and modified urban temperature scenario (scenario 2) in Redland station. The estimated ambient temperature reduction is 0.5-1.6 °C in Redland 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 12.4-27.4 ^{o}C in reference scenario to a range between 12.0-25.8 ^{o}C in reference with cool roof scenario (scenario 1) in Amberley station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 16.1-27.5 °C in reference scenario to a range between 15.8-26.0 °C in reference with cool roof scenario (scenario 1) in Redland 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 for both Amberley and Redland 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 from 296 hours in reference scenario to 333 hours in reference with cool roof scenario (scenario 1) in Amberley station. The estimations for Redland stations also show a slightly increase in total number of hours below 19 °C from 189 hours in reference scenario to 234 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 558 hours under the reference scenario in Amberley station, which slightly decreases to 552 and 485 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Redland station also illustrate a significant reduction in number of hours above 26 °C from 618 hours in reference scenario to 583 in reference with cool roof scenario (scenario 1) and 566 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 21,9% for the low energy price scenario for Amberley and 33,0% for the high energy scenario and for Redland 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, is feasible only for the high energy prices scenario for both 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 only feasible for the high energy prices scenario.

B17

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