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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 11 – Perth: Analysis and Results of the Climatic and Energy Performance of Cool Roofs. Description and Results of Building Case Studies.

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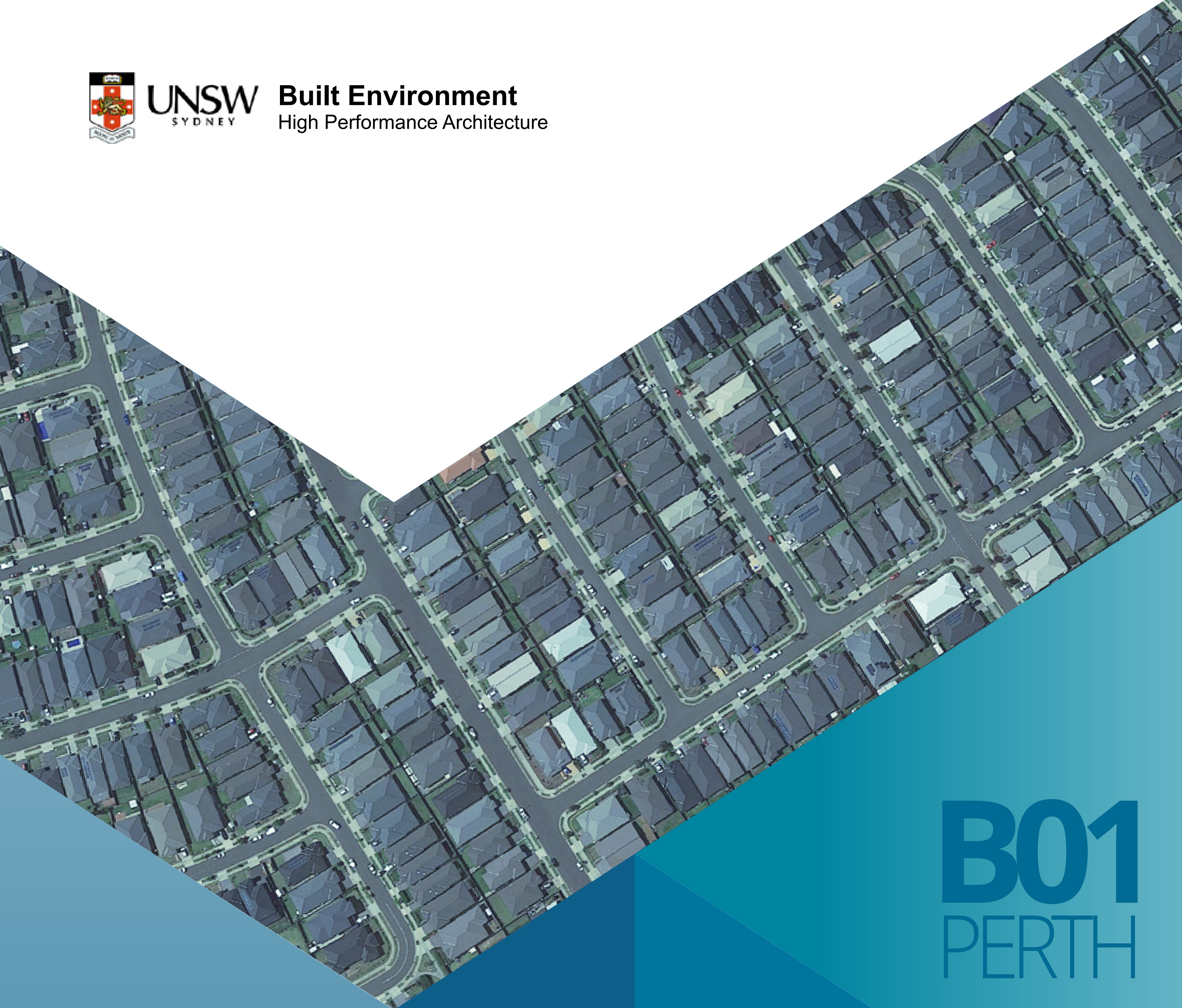

B01
PERTH

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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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 Perth 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 21.7-32.3 kWh/m² to 11.3-19.3 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)
Jandakot	23.6	26.1	12.4	14.4	10.4	11.2
Pearce	29.3	32.3	16.7	19.3	15.5	16.9
Perth Airport	28.0	30.9	15.7	18.1	13.8	14.7
Perth Metro	24.5	27.3	13.1	15.4	10.9	11.8
Swanbourne	19.4	21.7	9.6	11.3	7.4	8.1

For Scenario 1, the total cooling load saving is around 10.3-12.8 kWh/m² which is equivalent to 40.4-47.7 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 13.6-16.2 kWh/m² which is equivalent to 52.5-62.6 % 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	%
Jandakot	11.2	47.5	11.7	44.8	13.1	55.7	14.8	56.9
Pearce	12.6	42.9	13.0	40.4	13.8	47.1	15.4	47.5
Perth Airport	12.3	43.9	12.8	41.4	14.3	50.8	16.2	52.5
Perth Metro	11.4	46.6	11.9	43.5	13.6	55.5	15.6	57.0
Swanbourne	9.8	50.7	10.3	47.7	12.0	61.8	13.6	62.6

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

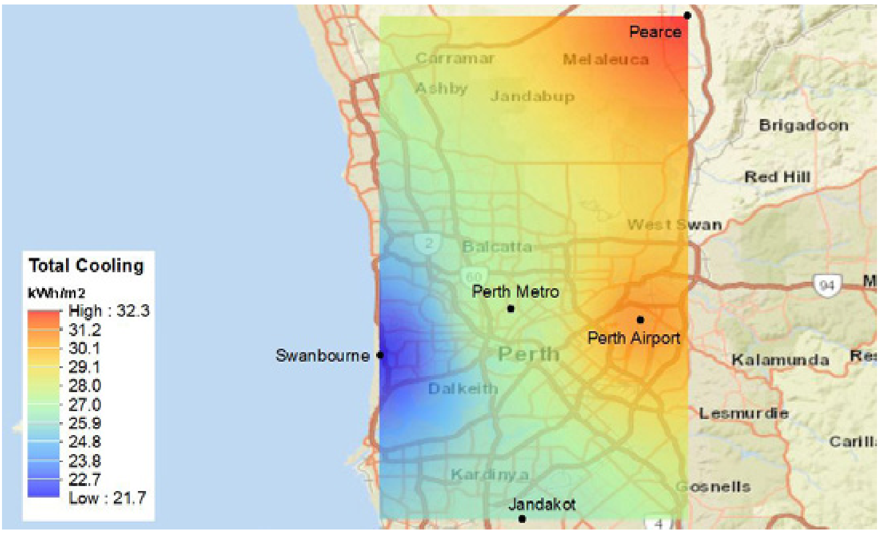

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

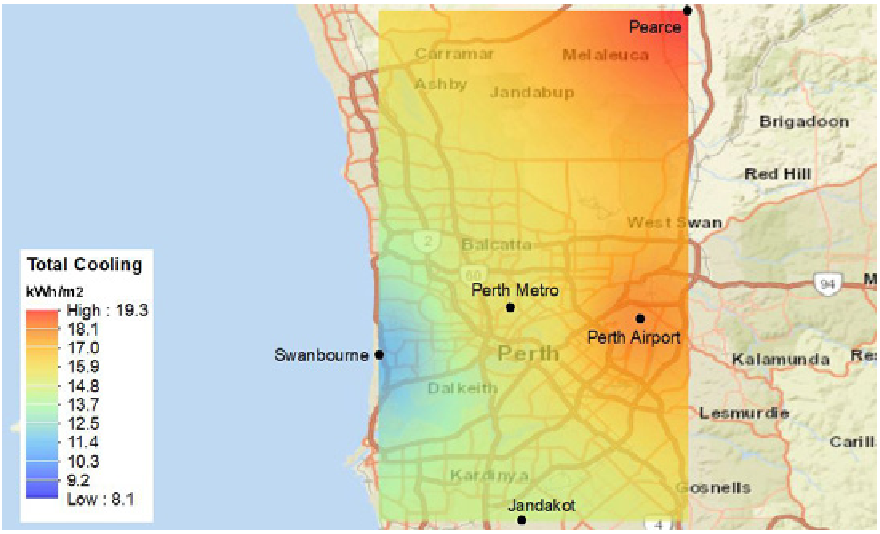

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

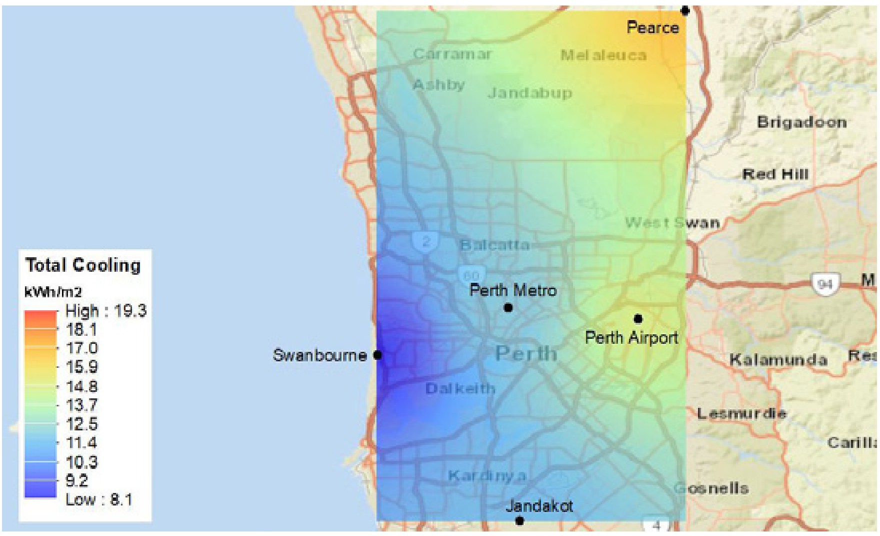

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (1.1-1.2 kWh/m²) is significantly lower than the annual cooling load reduction (17.8-26.8 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
Jandakot	46.6	49.6	3.6	6.6	25.9	28.3	4.1	7.6
Pearce	55.4	58.9	3.4	6.1	31.2	34.0	4.0	7.4
Perth Airport	51.1	53.7	3.5	6.4	29.0	31.1	4.0	7.5
Perth Metro	52.5	56.3	3.1	5.7	26.5	29.6	3.7	6.9
Swanbourne	33.4	36.9	2.6	4.7	16.2	19.1	3.2	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 a low-rise office building without roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 42.1-48.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 16.6-25.5 kWh/m² (~35.8-41.2 %).

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	%
Jandakot	20.7	44.3	21.2	42.8	0.5	1.1	20.1	40.2	20.2	35.9
Pearce	24.2	43.7	25.0	42.4	0.6	1.2	23.6	40.1	23.8	36.5
Perth Airport	22.1	43.2	22.6	42.1	0.6	1.1	21.5	39.4	21.5	35.8
Perth Metro	26.0	49.5	26.8	47.5	0.7	1.2	25.3	45.5	25.5	41.2
Swanbourne	17.2	51.5	17.8	48.2	0.6	1.2	16.6	46.0	16.6	39.9

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 (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

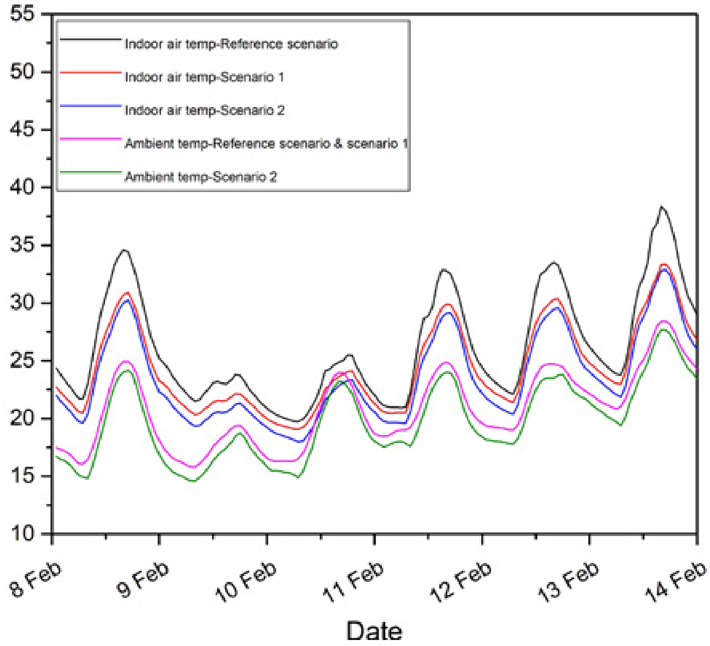

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

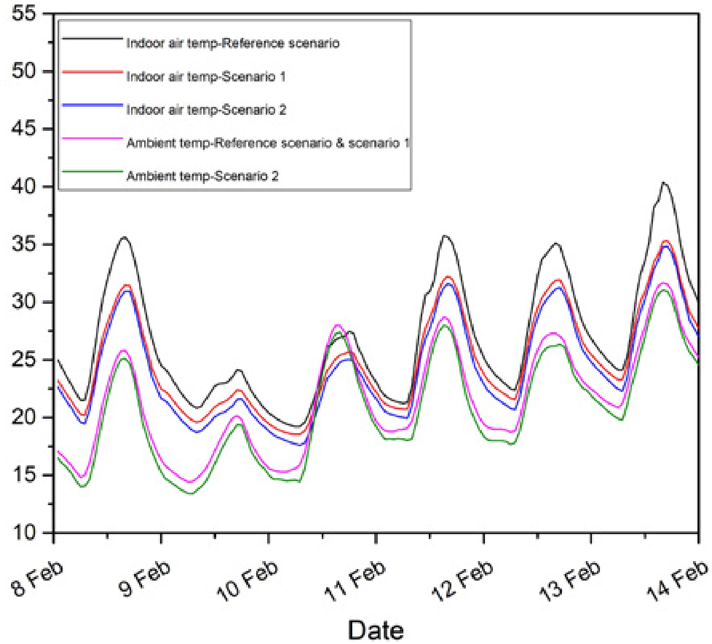

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.7-38.4 °C and 22.5-34.7 °C in Swanbourne and Pearce stations, respectively.

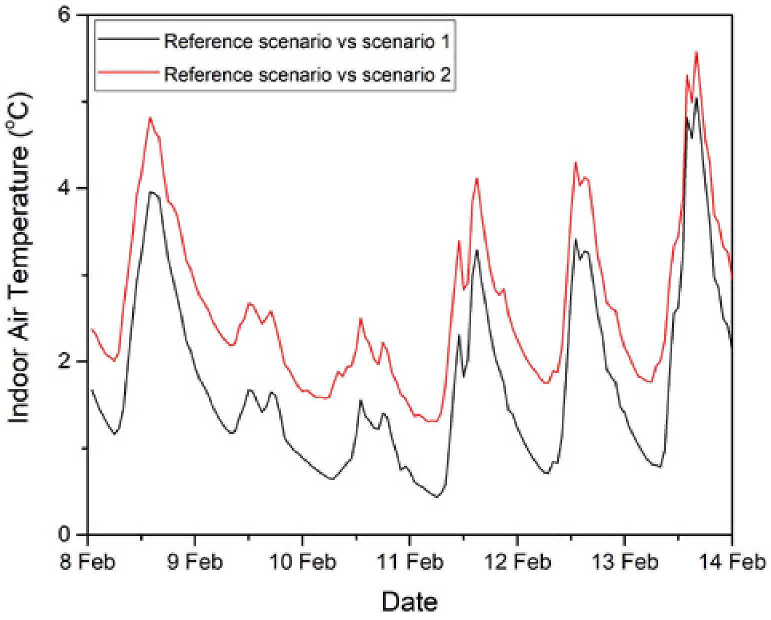

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 5.1°C and 0.9 °C in Swanbourne and Pearce stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 5.9 °C and 1.8 °C in Swanbourne and Pearce stations, respectively.

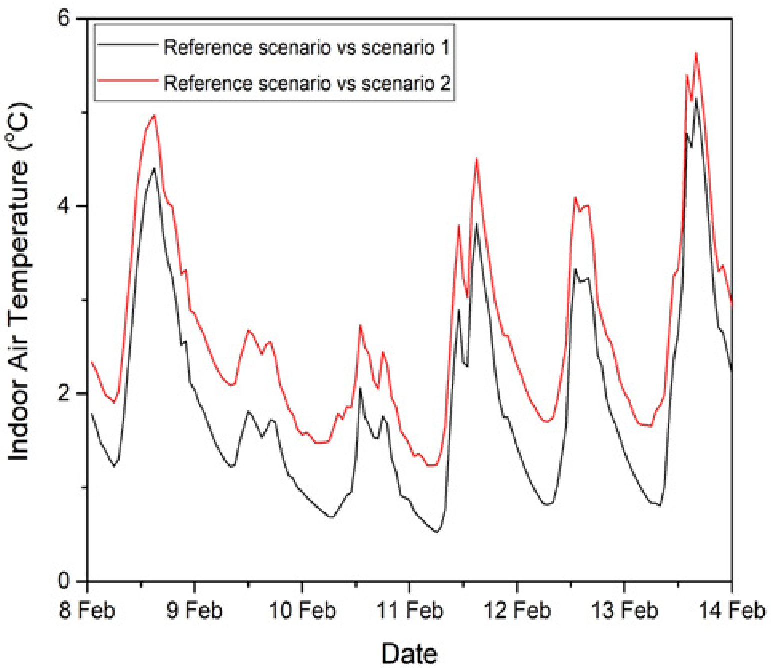

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 10.3-25.5 °C in reference scenario to a range 9.7-23.9 °C in scenario 1 in Swanbourne station.

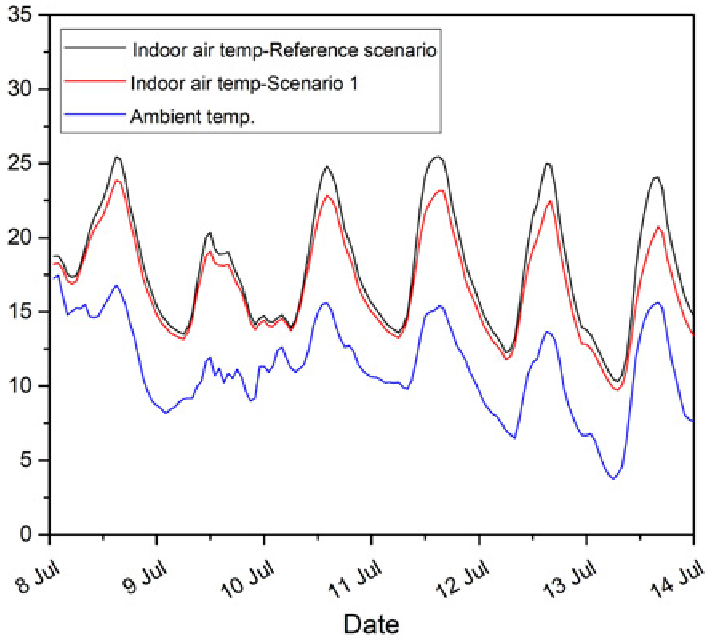

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Swanbourne station* using annual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

The indoor air temperature is predicted to reduce from a range 9.6-25.2 °C in reference scenario to a range 8.9-23.2 °C in scenario 1 in Pearce station.

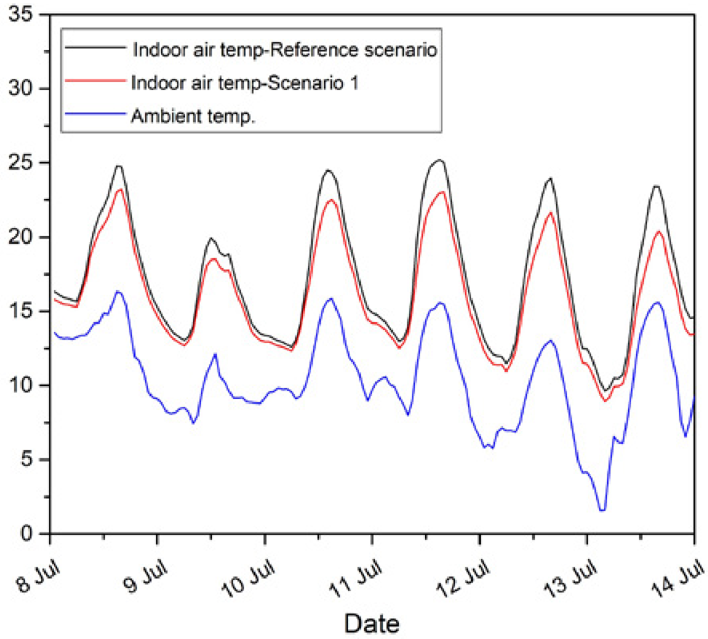

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Pearce station* using annual measured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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.2 °C in Swanbourne and Pearce stations, respectively.

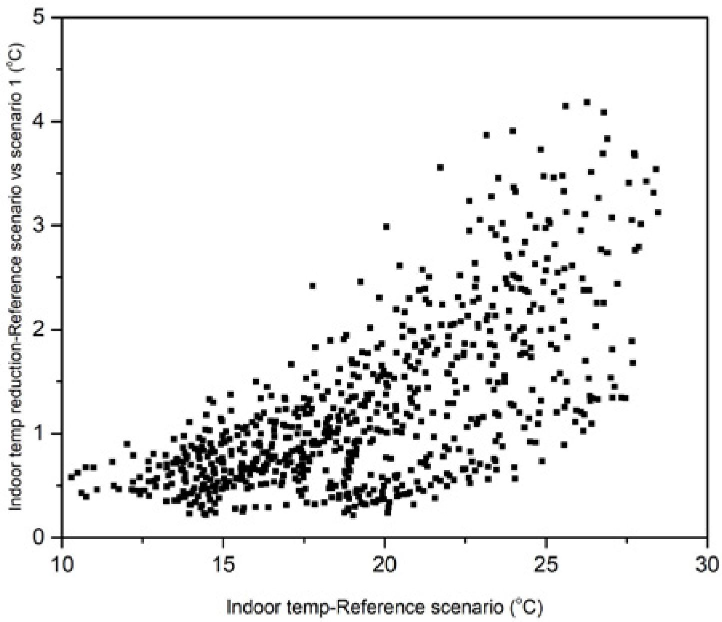

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

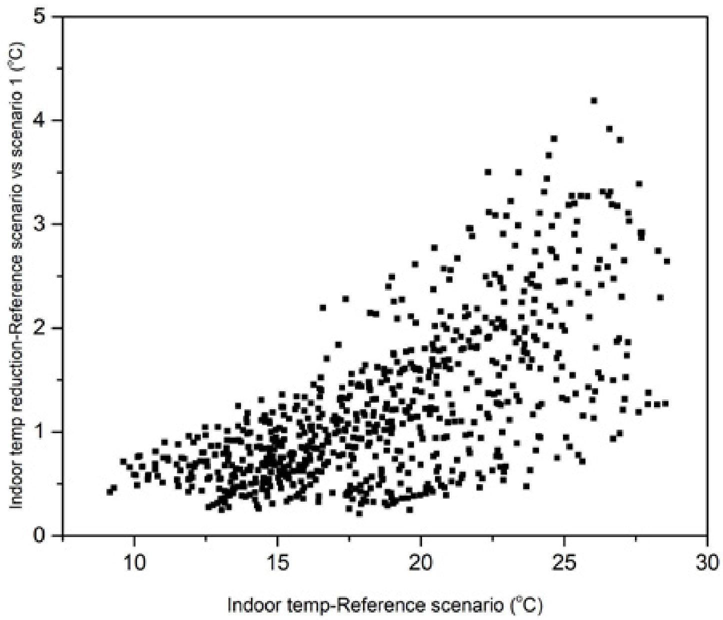

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 361 hours in reference scenario to 439 and hours and from 402 to 479 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to increase from 98 hours in reference scenario to 138 hours; and from 112 to 158 hours in scenario 1 in Swanbourne and Pearce 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
Swanbourne	98	361	138	439
Pearce	112	402	158	479

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

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decreased from 478 hours in reference scenario to 361 and 312 hours under scenario 1 and 2 in Swanbourne station; and from 498 hours in reference scenario to 393 and 358 hours under scenario 1 and 2 in Pearce 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
Swanbourne	478	361	312
Pearce	498	393	358

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	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	39,9	62,4
Energy consumption after cool roof (MWh)	24,0	39,7
Energy savings (MWh)	15,9	22,7
Energy savings (%)	39,85%	36,38%
Area (m^2)	1.200	1.200
Roof costs - Metal roof (AU$/$m^2$)	38,0	38,0
Roof costs - Coating (AU$/$m^2$)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/$m^2$)	15,0	15,0

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

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 39,85% for the Swanbourne weather conditions and of 36,38% for the Pearce 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 42,3 and 47,9%, 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 highly feasible option.

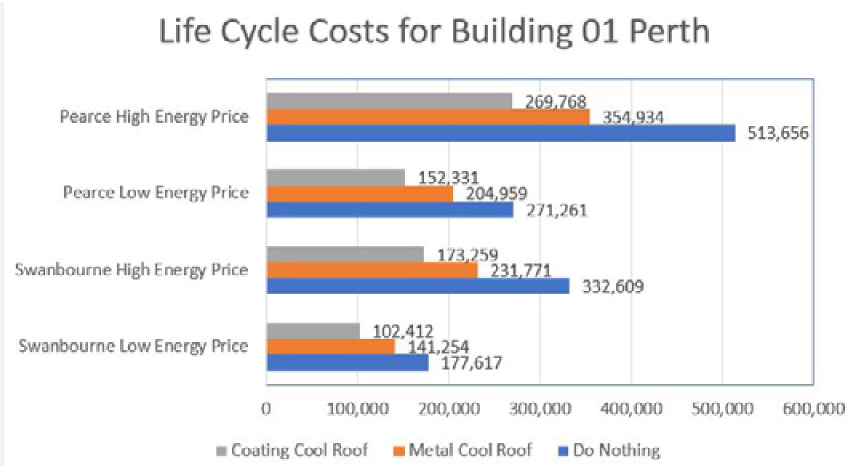

Figure 12. Life Cycle Costs for Building 01 for Swanbourne and Pearce weather stations.

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	20,47 %	30,32 %	24,44 %	30,90 %
Coating Cool Roof	42,34 %	47,91 %	43,84 %	47,48 %

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CONCLUSIONS

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

• In the eleven weather stations in Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 21.7-32.3 kWh/m^2 to 11.3-19.3 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 10.3-12.8 kWh/m^2. This is equivalent to approximately 40.4-47.7 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 13.6-16.2 kWh/m^2. This is equivalent to 52.5-62.6 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 & Table 2 and Figure 2 & Figure 3).

• The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (1.1-1.2 kWh/m^2) is significantly lower than the annual cooling load reduction (17.8-26.8 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 42.1-48.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 16.6-25.5 kWh/m^2 (~35.8-41.2 %) (Tables 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 19.7-38.4 °C and 22.5-34.7 °C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 5.1 and 0.9 °C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 5.9 and 1.8 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce 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 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce station (See Figure 4 and Figure 6).

• During a typical winter week and under free-floating condition, the indoor air temperature is expected to decrease slightly from a range between 10.3-25.5 °C in reference scenario to a range between 9.7-23.9 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 9.6-25.2 °C in reference scenario to a range between 8.9-23.2°C in reference with cool roof scenario (scenario 1) in Pearce 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 1.2 °C in Swanbourne and Pearce 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 361 hours in reference scenario to 439 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce station also show a increase in total number of hours below 19 °C from 402 hours in reference scenario to 479 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 98 hours in reference scenario to 138 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. Similarly, the calculation in Pearce station shows a slightly increase of number of hours below 19 °C from 112 hours to 158 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 478 hours under the reference scenario in Swanbourne station, which significanlty decreases to 361 and 312 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also illustrate a significant reduction in number of hours above 26 °C from 498 hours in reference scenario to 393 in reference with cool roof scenario (scenario 1) and 358 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 42,3 and 47,9%, 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 highly feasible option. Building 01 is in that sense a very good example of a cool roof's contribution to drastically reducing energy requirements and life cycle costs in low-rise buildings with poor energy performance. The higher initial cost of the metal cool roof leads to less attractive results than the coating cool roof, although they are still very positive.

B01

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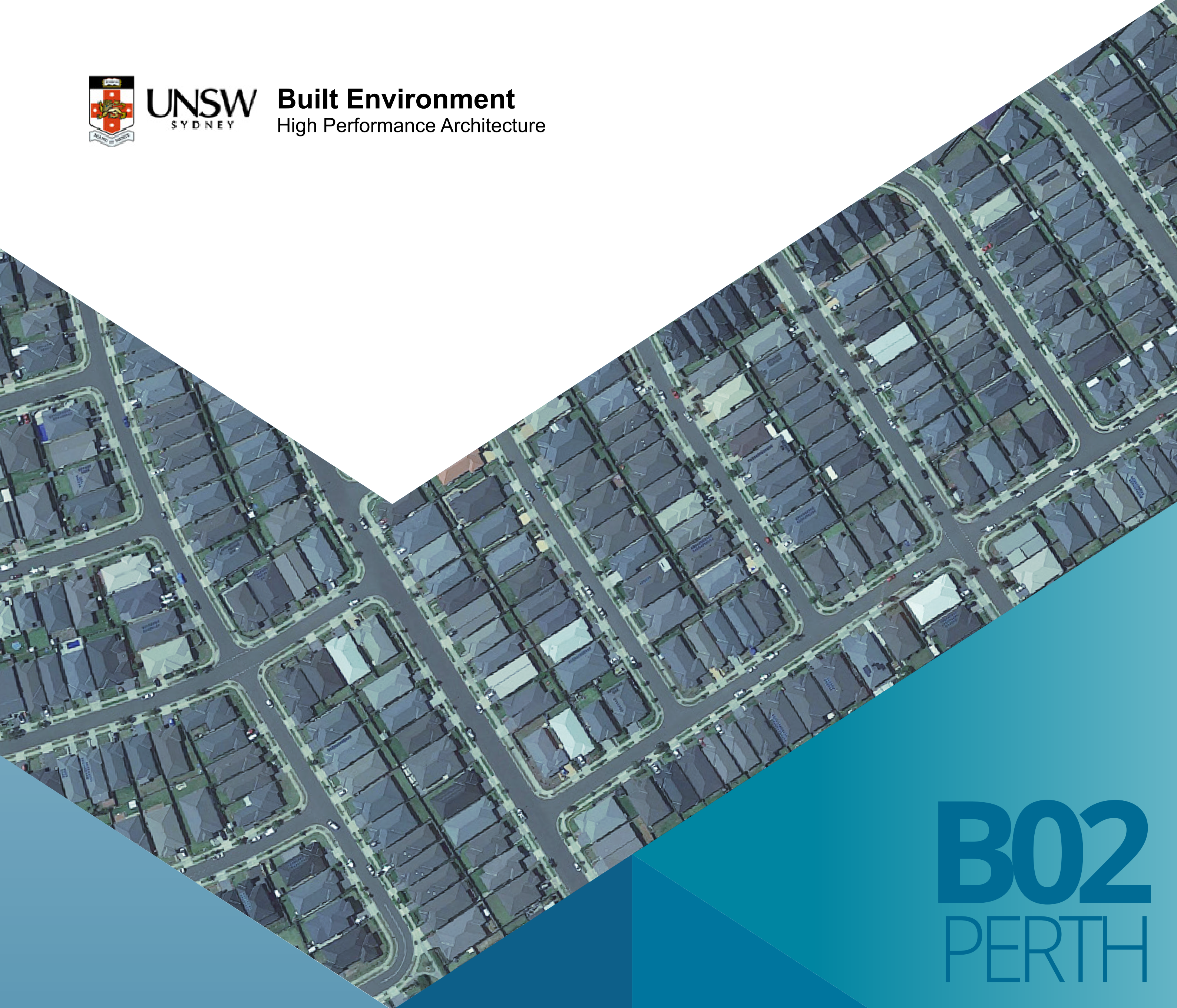

B02 PERTH

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 Perth 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 13.2-22.1 kWh/m² to 11.4-19.8 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)
Jandakot	14.5	16.7	12.6	14.6	10.3	11.1
Pearce	19.4	22.1	17.2	19.8	15.7	17.2
Perth Airport	18.3	20.8	16.1	18.6	13.8	14.7
Perth Metro	15.3	17.8	13.3	15.8	10.8	11.7
Swanbourne	11.4	13.2	9.7	11.4	7.2	7.9

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	%
Jandakot	1.9	13.3	2.0	12.0	4.2	29.0	5.5	33.3
Pearce	2.2	11.4	2.3	10.5	3.7	18.9	4.9	22.3
Perth Airport	2.2	11.9	2.3	10.8	4.5	24.7	6.1	29.5
Perth Metro	2.0	12.9	2.1	11.6	4.5	29.6	6.2	34.6
Swanbourne	1.7	15.1	1.8	13.6	4.2	37.0	5.3	40.5

For Scenario 1, the total cooling load saving is around 1.8-2.3 kWh/m² which is equivalent to 10.5-13.6 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.9-6.2 kWh/m² which is equivalent to 22.3-40.5 % of total cooling load reduction.

In the eleven weather stations in Perth, 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.

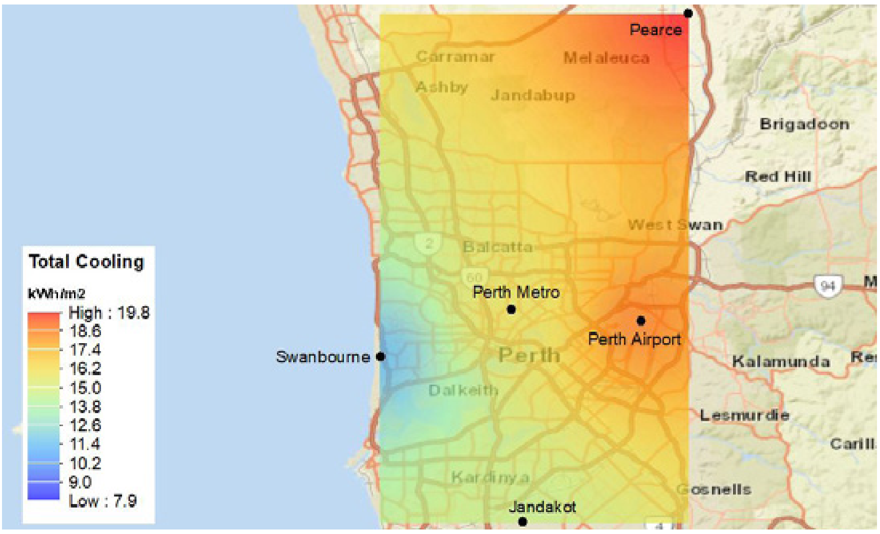

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

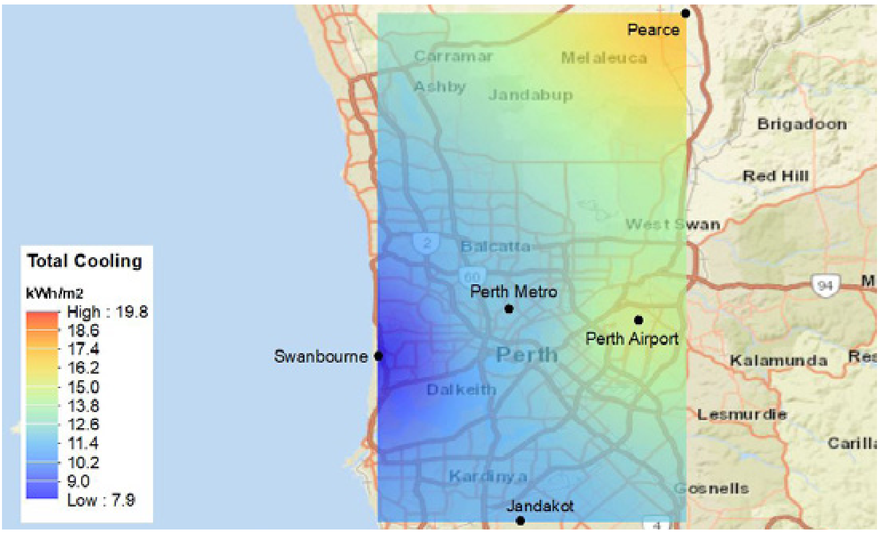

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

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 (0.3-0.4 kWh/m²) is significantly lower than the annual cooling load reduction (2.9-4.6 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
Jandakot	30.0	32.7	1.2	3.0	26.7	29.3	1.4	3.4
Pearce	36.1	39.3	1.0	2.6	32.2	35.1	1.2	2.9
Perth Airport	33.6	36.0	1.0	2.7	30.0	32.3	1.3	3.1
Perth Metro	31.6	35.0	0.9	2.3	27.2	30.4	1.1	2.7
Swanbourne	19.9	23.0	0.6	1.5	17.2	20.1	0.7	1.8

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a 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 10.3-13.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.6-4.2 kWh/m² (~8.6-11.3 %).

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	%
Jandakot	3.3	11.1	3.4	10.5	0.2	0.4	3.1	9.9	3.1	8.6
Pearce	4.0	10.9	4.2	10.6	0.2	0.4	3.7	10.1	3.8	9.1
Perth Airport	3.6	10.6	3.7	10.3	0.2	0.3	3.4	9.7	3.4	8.7
Perth Metro	4.4	13.9	4.6	13.1	0.2	0.4	4.2	12.9	4.2	11.3
Swanbourne	2.8	14.0	2.9	12.6	0.2	0.3	2.6	12.8	2.6	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 (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

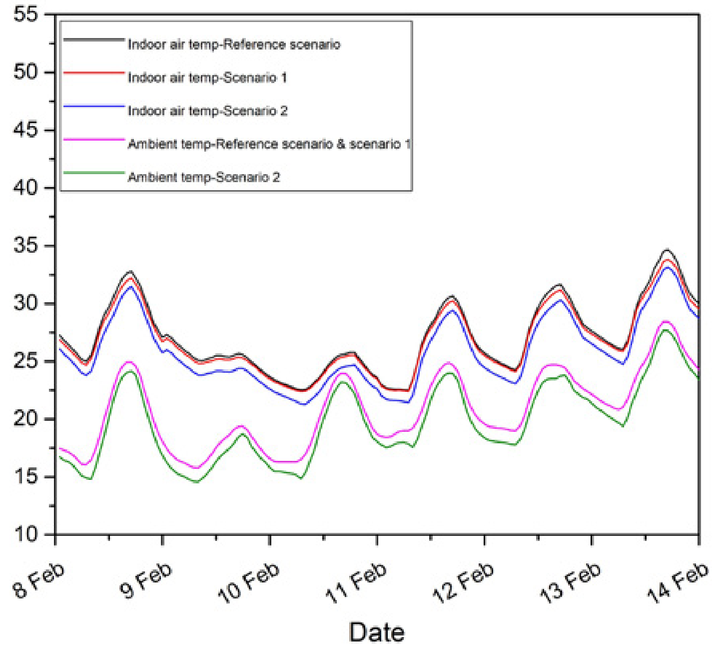

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

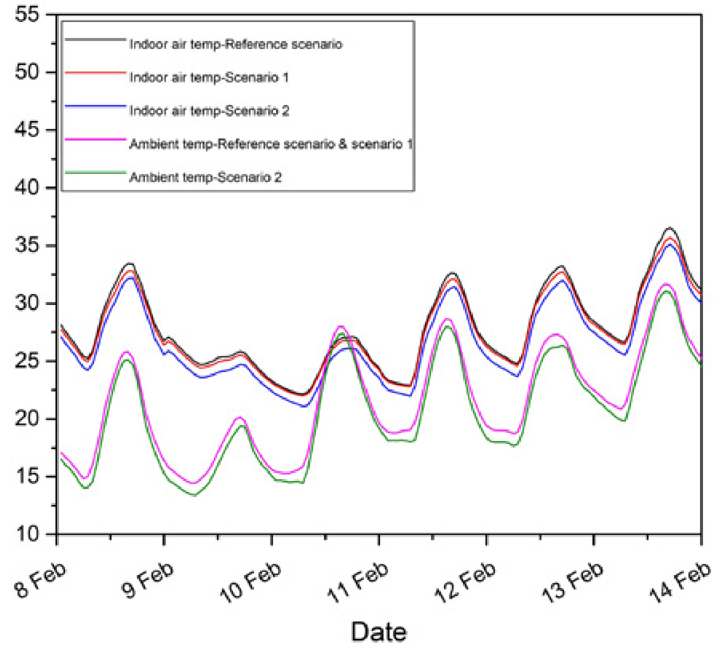

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.5-34.7 °C and 22.1-37.2 °C in Swanbourne and Pearce stations, respectively.

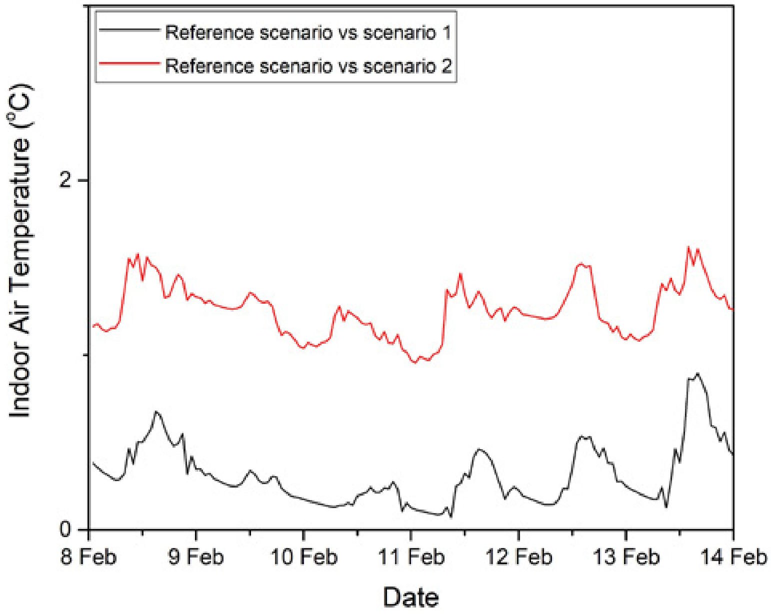

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.9 °C and 1.0 °C in Swanbourne and Pearce stations, respectively.

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

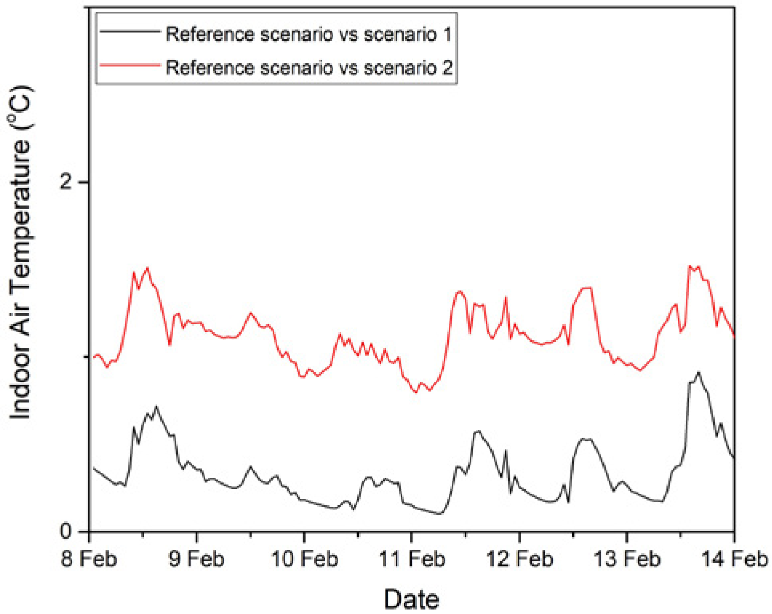

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 15.6 and 25.4 °C in reference scenario to a range between 15.4 and 25.1 °C in scenario 1 in Swanbourne station.

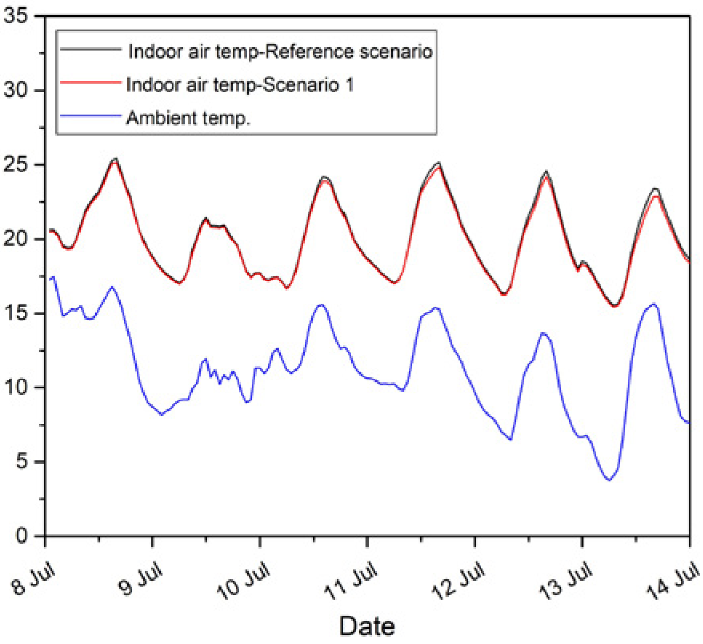

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Swanbourne station* using annual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

The indoor air temperature is predicted to slighly reduce from a range between 15.1 and 24.9 °C in reference scenario to a range between 15.0 and 24.6 °C in scenario 1 in Pearce station.

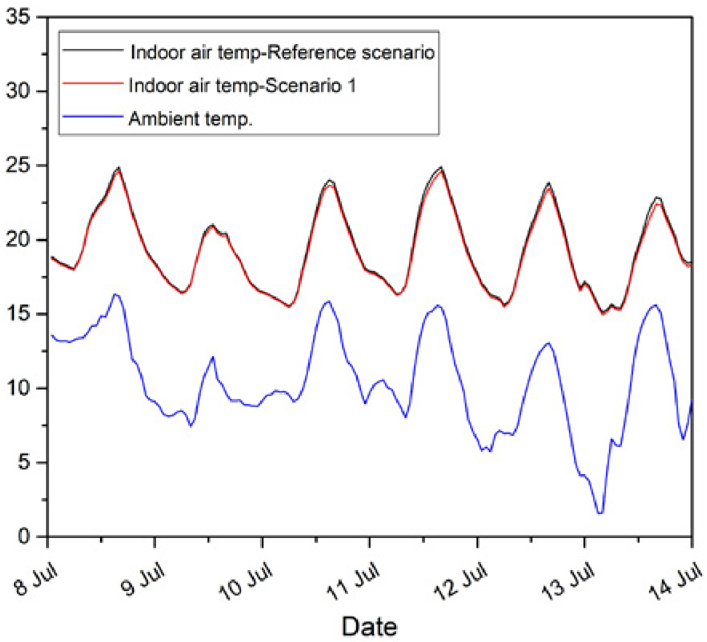

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Pearce station* using annual measured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

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

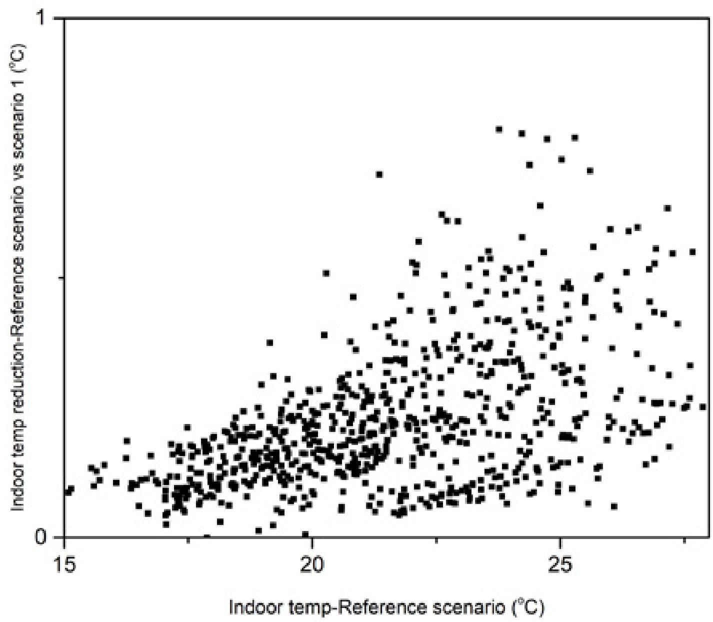

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

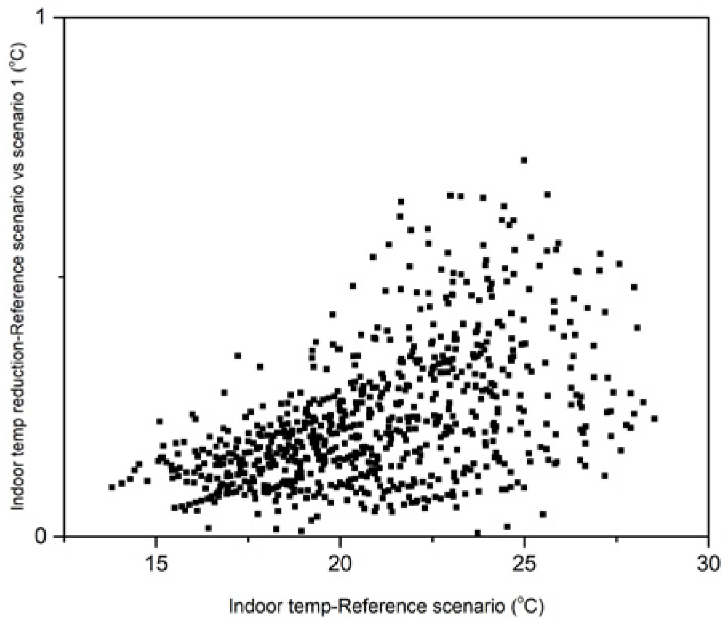

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 149 hours in reference scenario to 160 and hours and from 218 to 232 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 49 hours in reference scenario to 54 hours; and from 67 to 75 hours in scenario 1 in Swanbourne and Pearce 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
Swanbourne	49	149	54	160
Pearce	67	218	75	232

** 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 587 hours in reference scenario to 568 and 515 hours under scenario 1 and 2, in Swanbourne station, respectively; and from 596 to 583 and 545 in Pearce station under scenario 1 and 2, respectively.

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

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	587	568	515
Pearce	596	583	545

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 m^2 distributed on ten levels. The 1.200 m^2 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 Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 02.

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.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	117,6	201,1
Energy consumption after cool roof (MWh)	105,1	182,4
Energy savings (MWh)	12,5	18,7
Energy savings (%)	10,63%	9,30%
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 impact of the roof is not as big as in low-rise buildings, since it affects only to a limited extent the building's energy requirement, hence the impact of the initial cost of the refurbishment is bigger compared to the low-rise buildings. Still, cool roofs are feasible, the coating option being the advisable solution.

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 10,63% for the Swanbourne weather conditions and of 9,30% for the Pearce 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 27,53 and 29,3%, depending on the weather and energy price scenario.

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 Swanbourne and for Pearce weather conditions respectively.

The metal cool roof is due to its higher initial investment cost less attractive than the coating cool roof, but still strongly feasible for the high energy prices scenario.

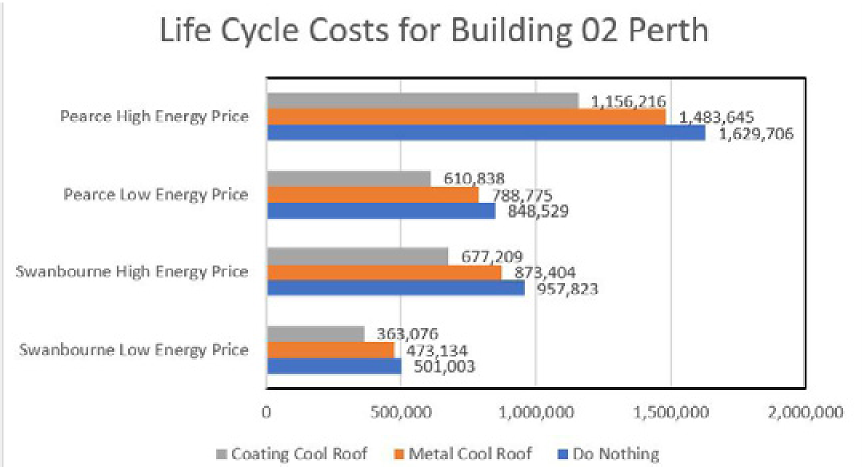

Figure 12. Life Cycle Costs for Building 02 for Swanbourne and Pearce weather stations.

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

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	5.56 %	8.81 %	7.04 %	8.96 %
Coating Cool Roof	27.53 %	29.30 %	28.01 %	29.05 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 13.2-22.1 kWh/m^2 to 11.4-19.8 kWh/m^2. As computed, the total cooling load saving by building-scale application of cool roofs is around 1.8-2.3 kWh/m^2 for a typical high rise office building without roof insulation. This is equal to 10.5-13.6 % cooling load reduction in reference with cool roof scenario (scenario 1) compared to reference scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Perth, the combined building-scale and urban-scale implementation of cool roofs can reduce the total cooling load of the high-rise office building without roof insulation by 4.9-6.2 kWh/m^2. This is equivalent to roughly 22.3-40.5 % 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 (0.3-0.4 kWh/m^2) is significantly lower than the annual cooling load reduction (2.9-4.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 10.3-13.1 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.6-4.2 kWh/m^2 (~8.6-11.3 %) (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 22.5-34.7 °C and 22.1-37.2 °C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.9 and 1.0 °C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 and 1.8 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce 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 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 15.6 and 25.4 ^{o}C in reference scenario to a range between 15.4 and 25.1 ^{o}C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 15.1 and 24.9 ^{o}C in reference scenario to a range between 15.0 and 24.6 ^{o}C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

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

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 149 hours in reference scenario to 160 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slight increase in total number of hours below 19 ^{o}C from 218 hours in reference scenario to 232 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 ^{o}C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 ^{o}C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to slightly increase from 49 hours in reference scenario to 54 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. Similarly, the calculation in Pearce station shows a slight increase of number of hours below 19 ^{o}C from 67 hours to 75 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to slightly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 587 hours under the reference scenario in Swanbourne station, which decreases to 568 under Scenario 1 and 515 under the modified urban temperature scenario (scenario 2). The simulations in Pearce station show that the number of hours above 26 ^{o}C (596 hours) decreases to 583 under Scenario 1 and 545 under Scenario 2 (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 27,53 and 29,3%, depending on the weather and energy price scenarios, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost less attractive than the coating cool roof, but still strongly feasible for the high 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. Still, cool roofs are feasible, the coating option being the advisable solution.

B02

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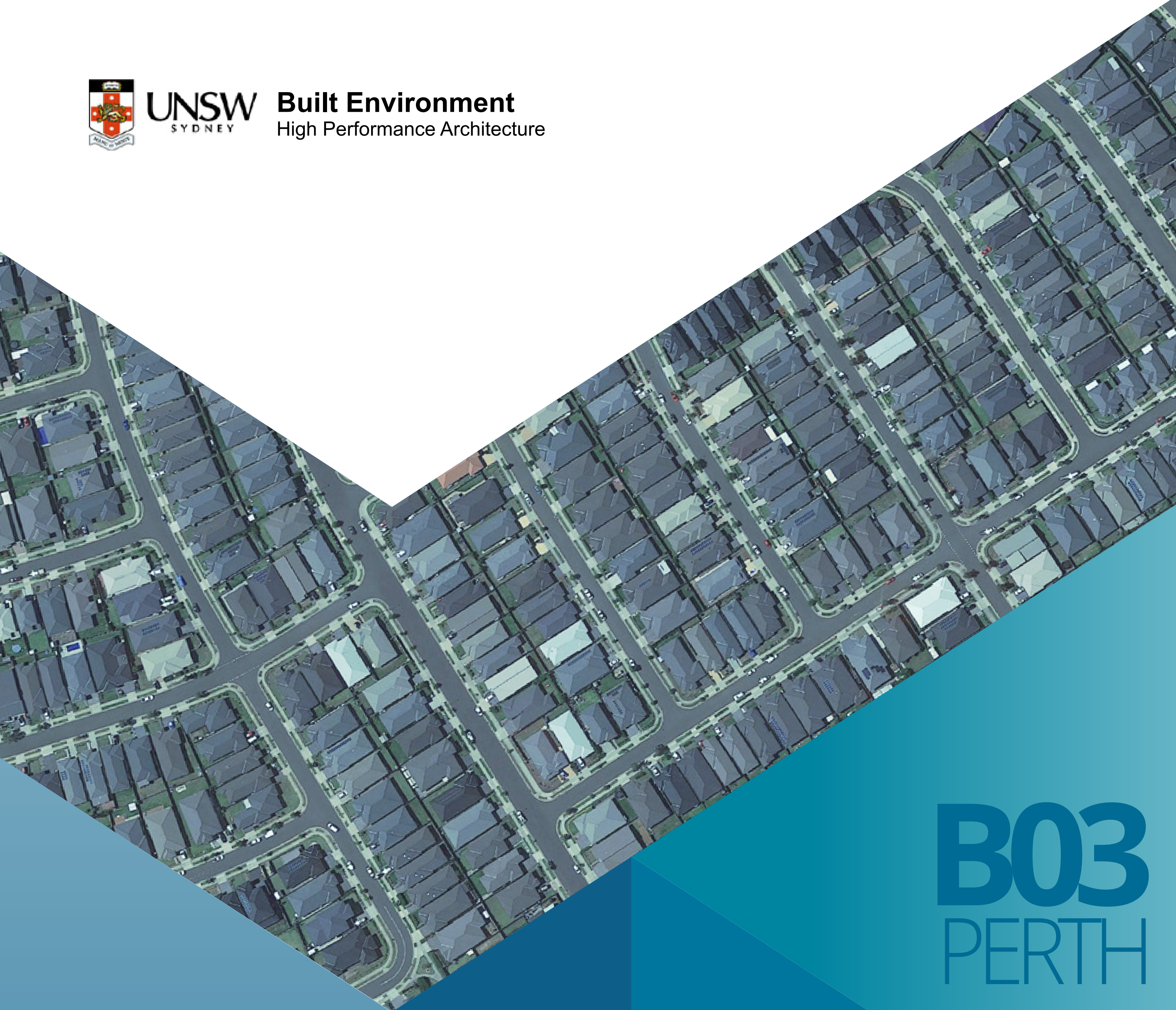

B03 PERTH

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 : $1200 m^2$
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 Perth 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 12.4-21.1 kWh/m² to 11.5-19.9 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)
Jandakot	13.6	15.8	12.6	14.7	10.3	11.2
Pearce	18.4	21.1	17.3	19.9	15.8	17.3
Perth Airport	17.3	19.8	16.2	18.6	13.8	14.8
Perth Metro	14.4	17.0	13.4	15.9	10.8	11.7
Swanbourne	10.6	12.4	9.7	11.5	7.2	7.9

For Scenario 1, the total cooling load saving is around 0.9-1.2 kWh/m² which is equivalent to 5.8-7.6 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.9-5.2 kWh/m² which is equivalent to 18.3-36.3 % of total cooling load reduction.

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.

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	%
Jandakot	1.0	7.5	1.1	6.8	3.3	24.2	4.6	29.3
Pearce	1.2	6.2	1.2	5.8	2.7	14.4	3.9	18.3
Perth Airport	1.1	6.6	1.2	6.0	3.5	20.0	5.1	25.6
Perth Metro	1.0	7.2	1.1	6.5	3.6	24.9	5.2	30.7
Swanbourne	0.9	8.4	0.9	7.6	3.4	31.9	4.5	36.3

In the eleven weather stations in Perth, 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.

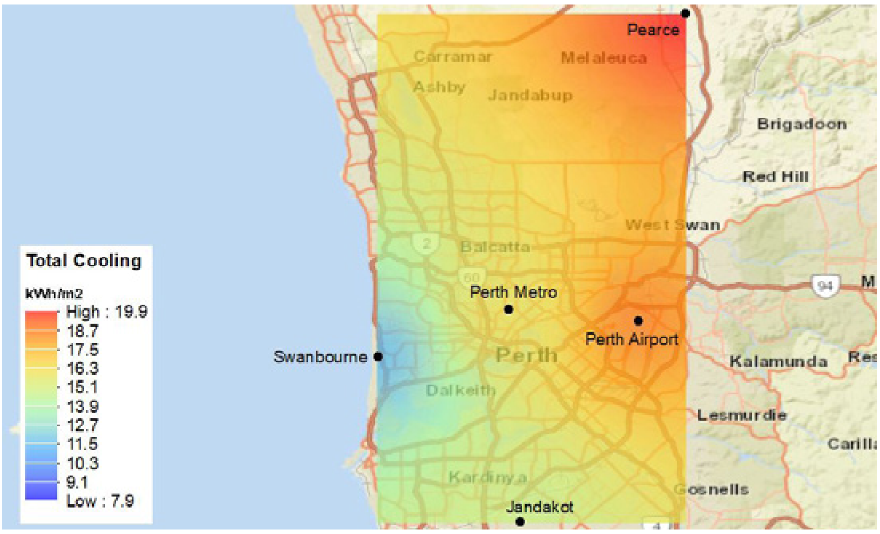

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

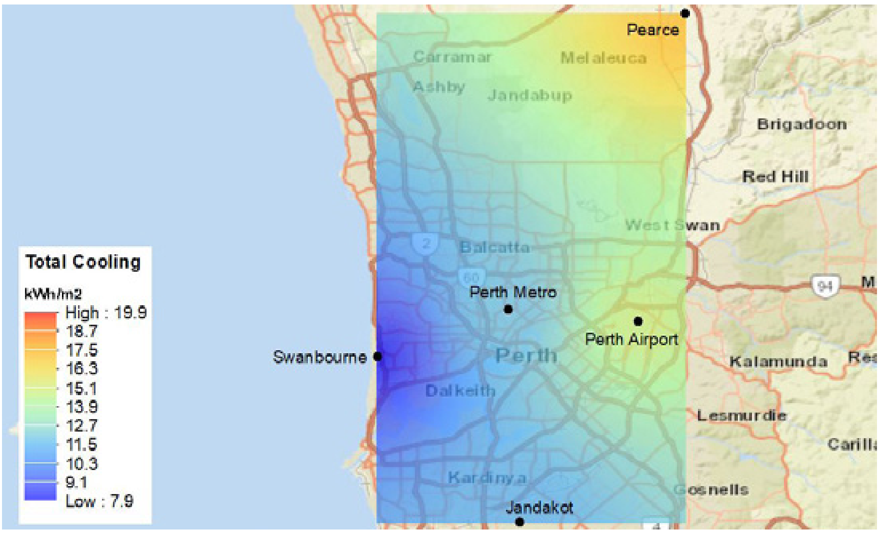

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data shows an annual heating penalty (0.1-0.2 kWh/m²) that is significantly lower than the annual cooling load reduction (1.5-2.4 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
Jandakot	29.1	31.8	1.5	3.5	27.2	29.9	1.6	3.7
Pearce	34.9	38.1	1.3	3.1	32.7	35.8	1.3	3.2
Perth Airport	32.5	34.9	1.4	3.2	30.5	32.8	1.4	3.4
Perth Metro	29.8	33.3	1.2	2.8	27.5	30.9	1.2	3.0
Swanbourne	18.9	21.9	0.7	1.8	17.4	20.4	0.7	1.9

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

The annual cooling load saving by building-scale application of cool roofs is around 5.9-7.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.4-2.2 kWh/m² (~5.0-6.1 %).

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	%
Jandakot	1.9	6.4	1.9	6.0	0.1	0.2	1.8	5.8	1.8	5.0
Pearce	2.2	6.3	2.3	6.0	0.1	0.2	2.1	5.9	2.1	5.2
Perth Airport	2.0	6.2	2.1	5.9	0.1	0.2	1.9	5.7	1.9	5.0
Perth Metro	2.3	7.6	2.4	7.1	0.1	0.1	2.2	7.1	2.2	6.1
Swanbourne	1.5	7.8	1.5	6.8	0.0	0.1	1.4	7.3	1.4	5.9

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 (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

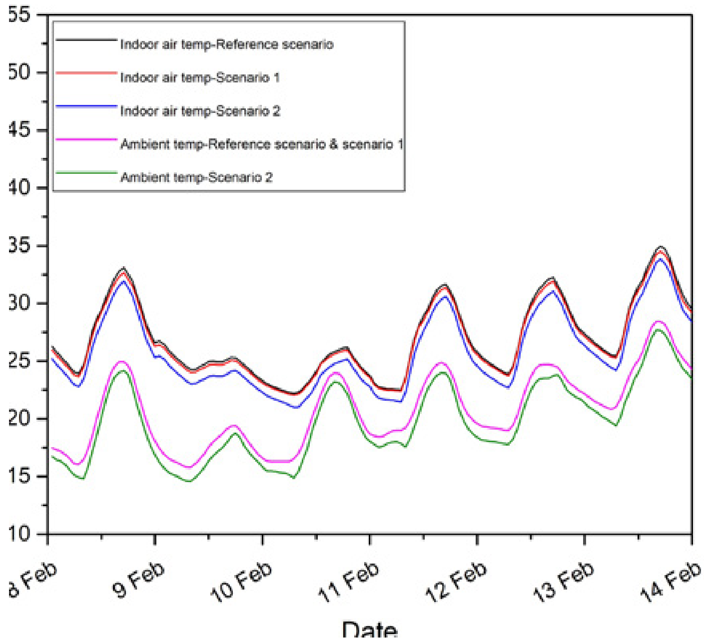

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

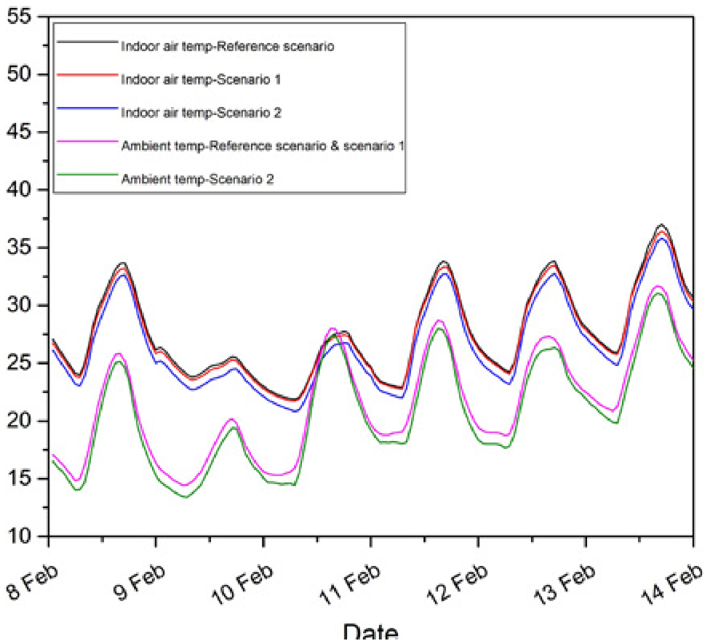

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.2-35.0 °C and 21.9-37.3 °C in Swanbourne and Pearce stations, respectively.

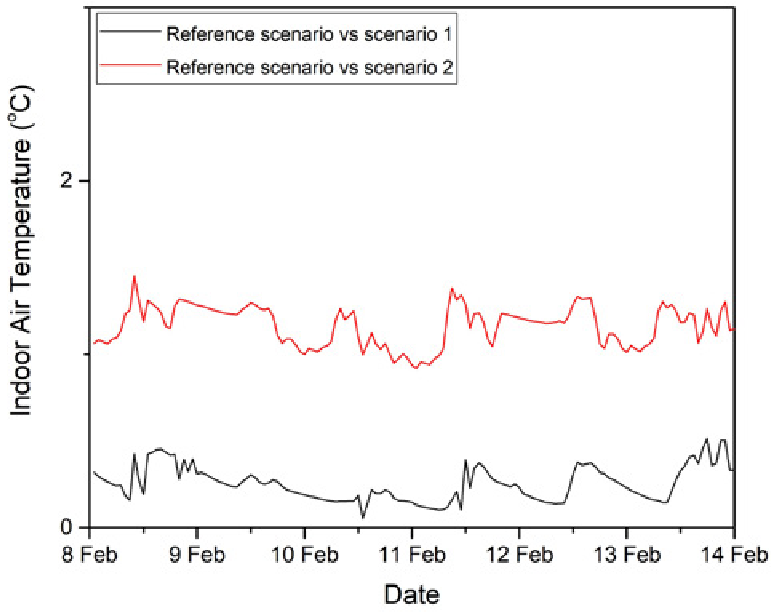

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.6 °C and 0.7 °C in Swanbourne and Pearce stations, respectively.

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

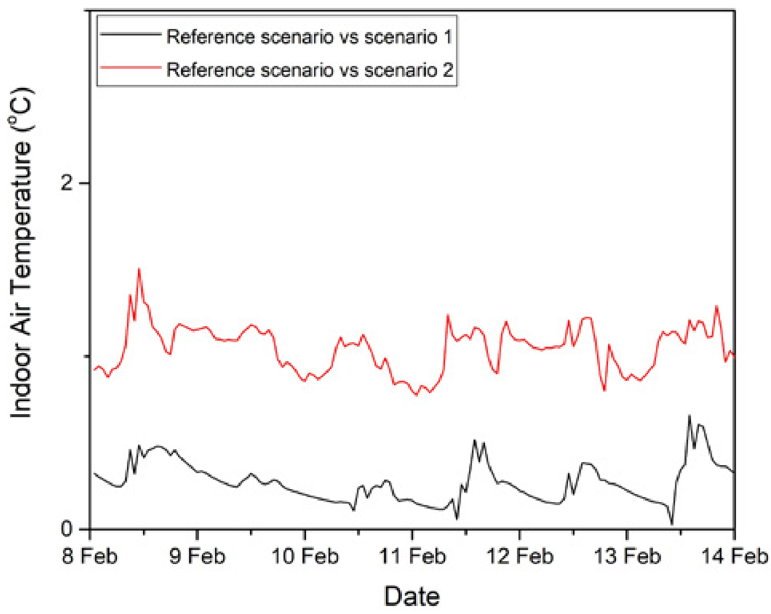

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 14.7 and 26.5 °C in reference scenario to a range between 14.6 and 26.2 °C in scenario 1 in Swanbourne station.

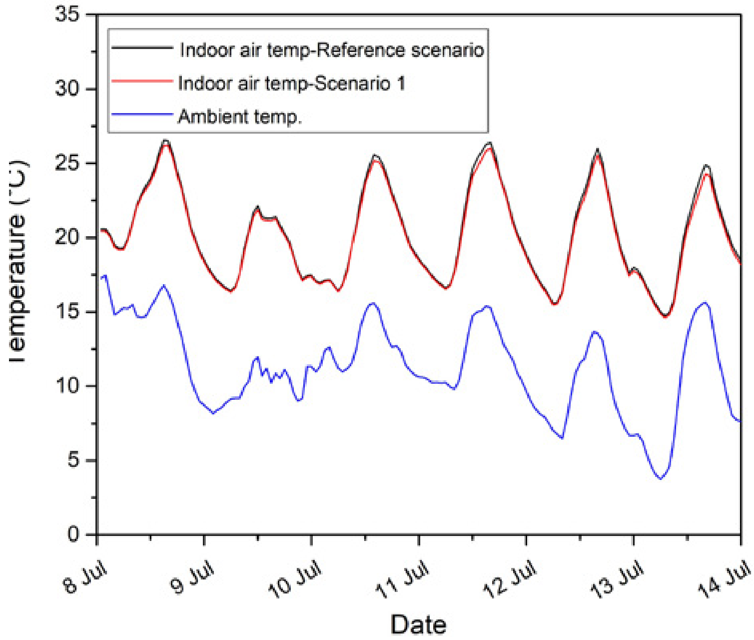

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Swanbourne station* using annual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

The indoor air temperature is predicted to reduce from a range between 14.3 and 26.2 °C in reference scenario to a range between 14.2 and 25.8 °C in scenario 1 in Pearce station.

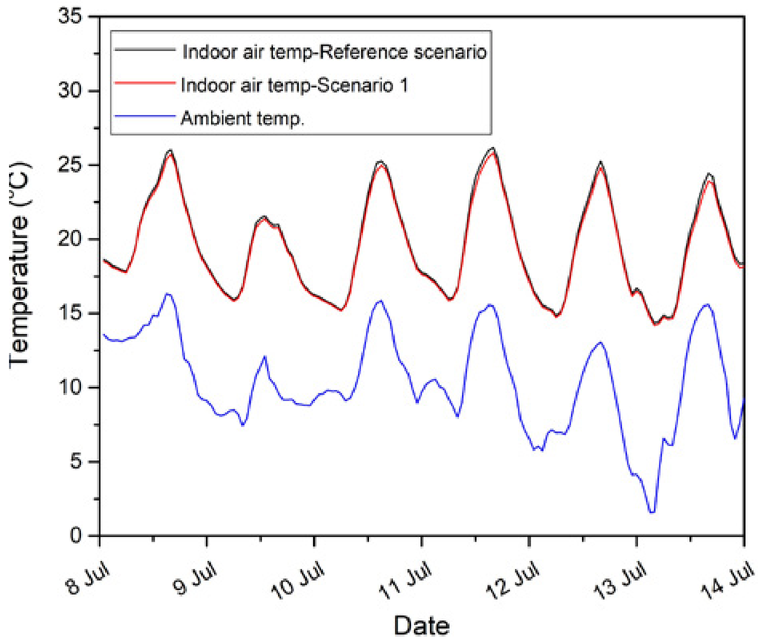

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Pearce station* using annual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

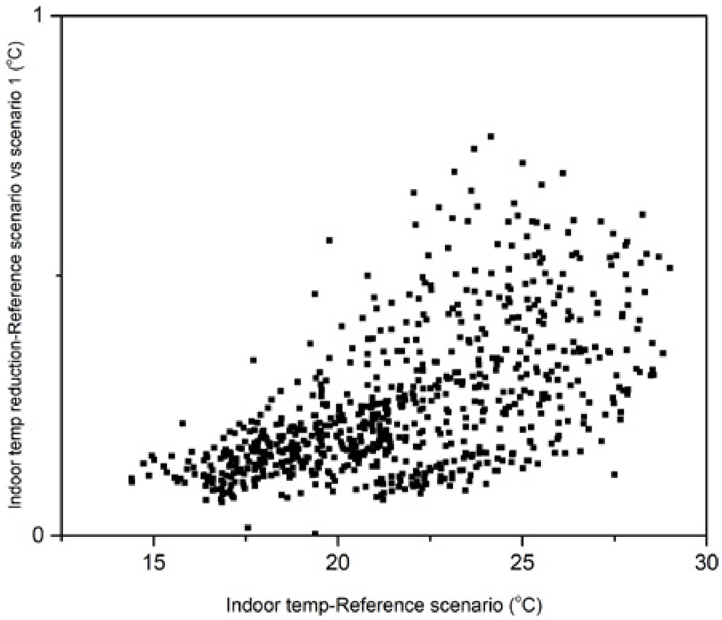

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

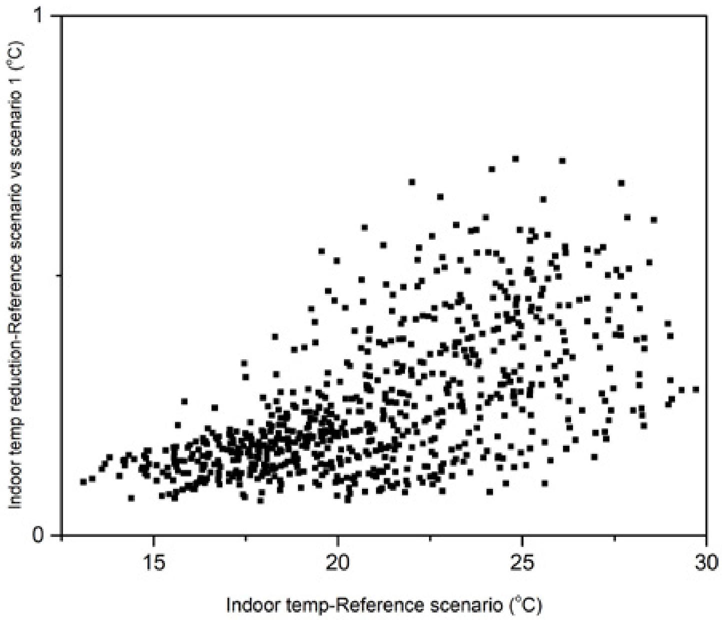

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 177 hours in reference scenario to 186 hours, and from 230 to 246 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 56 hours in reference scenario to 59 hours; and from 66 to 75 hours in scenario 1 in Swanbourne and Pearce 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
Swanbourne	56	177	59	186
Pearce	66	230	75	246

** 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 540 hours in reference scenario to 520 and 471 hours under scenario 1 and 2, in Swanbourne station; and from 556 to 543 and 507 under scenario 1 and 2 in Pearce 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
Swanbourne	540	520	471
Pearce	556	543	507

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 03 is a new, low-rise building, with a total air-conditioned area of 2.400 m^2 distributed on two levels. The 1.200 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 Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 03.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	22,8	39,6
Energy consumption after cool roof (MWh)	21,4	37,4
Energy savings (MWh)	1,4	2,2
Energy savings (%)	6,14%	5,56%
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 6,14% for the Swanbourne weather conditions and of 5,56% for the Pearce 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 10.6% for the low energy price scenario for Swanbourne and 21,8% for the high energy scenario for Pearce 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 Swanbourne and for Pearce weather conditions respectively.

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

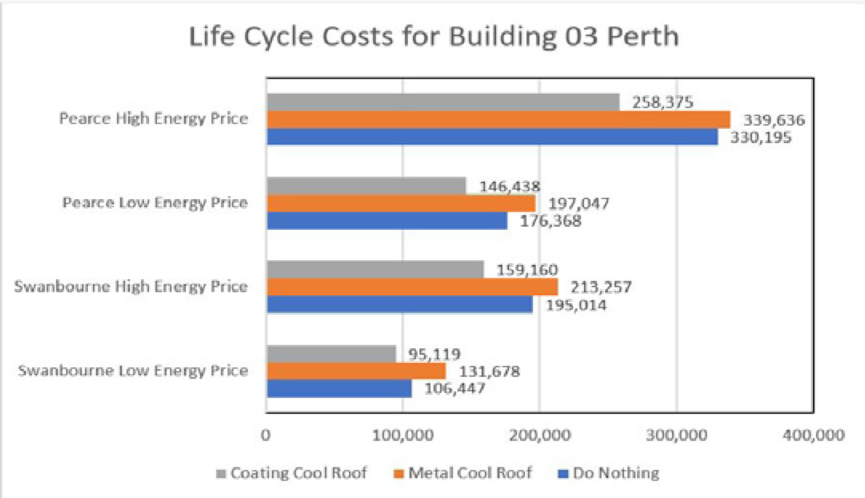

Figure 12. Life Cycle Costs for Building 03 for Swanbourne and Pearce weather stations.

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	-23.70 %	-9.35 %	-11.72 %	-2.86 %
Coating Cool Roof	10.64 %	18.39 %	16.97 %	21.75 %

7

CONCLUSIONS

• In the eleven weather stations in Perth, 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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 12.4-21.1 kWh/m^2 to 11.5-19.9 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.9-1.2 kWh/m^2. This is equivalent to approximately 5.8-7.6 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.9-5.2 kWh/m^2. This is equivalent to 18.3-36.3 % 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 0.1-0.2 kWh/m^2) is significantly lower than the annual cooling load reduction (1.5-2.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 5.9-7.1 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.4-2.2 kWh/m^2 (~5.0-6.1 %) (Tables 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 22.2-35.0 °C and 21.9-37.3 °C in Swanbourne and Pearce 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 Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.5 and 1.5 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce 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 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 14.7 and 26.5 °C in reference scenario to a range between 14.6 and 26.2 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 14.3 and 26.2 °C in reference scenario to a range between 14.2 and 25.8 °C in reference with cool roof scenario (scenario 1) in Pearce station (See Figure 8 and Figure 9).

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

• During a typical winter month and under free-floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 177 hours in reference scenario to 186 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce station also show a increase in total number of hours below 19 °C from 230 hours in reference scenario to 246 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 56 hours in reference scenario to 59 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. Similarly, the calculation in Pearce station shows a slightly increase of number of hours below 19 °C from 66 hours to 75 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 540 hours under the reference scenario in Swanbourne station, which decreases to 520 and 471 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also shows that the number of hours above 26 °C decreases from 556 to 543 and 507 under Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 10.6% for the low energy price scenario for Swanbourne and 21,8% for the high energy scenario for Pearce conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible. Building 03 is in that sense a very good example of building with limited energy conservation potential. However, even in this case, a coating cool roof is a feasible investment, due its comparatively low initial investment cost and to the reasonable savings it achieves.

B03

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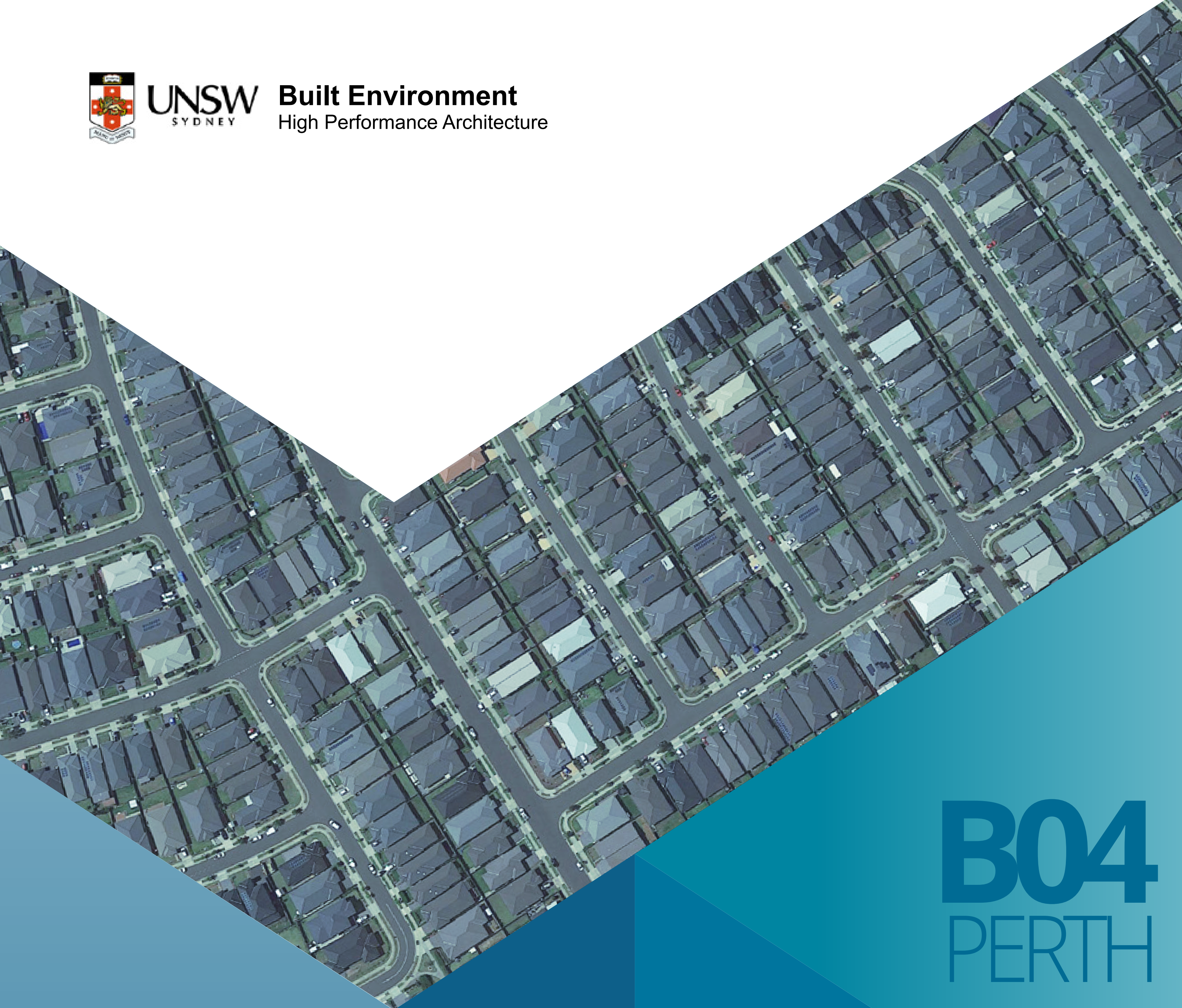

B04 PERTH

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise office building with roof insulation
2021

BUILDING 04

NEW HIGH-RISE OFFICE BUILDING WITH ROOF INSULATION

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

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

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

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

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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 Perth using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new high-rise office building with roof insulation from 11.7-20.3 kWh/m² to 11.6-20.1 kWh/m².

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

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Jandakot	12.9	15.0	12.7	14.8	10.4	11.2
Pearce	17.6	20.3	17.4	20.1	15.9	17.4
Perth Airport	16.6	19.1	16.4	18.8	13.9	14.8
Perth Metro	13.7	16.2	13.5	16.0	10.9	11.8
Swanbourne	10.0	11.7	9.8	11.6	7.2	7.9

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

For Scenario 1, the total cooling load saving is around 0.2 kWh/m² which is equivalent to 1.2-1.4 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.9-4.4 kWh/m² which is equivalent to 14.3-32.5 % 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	%
Jandakot	0.2	1.4	0.2	1.2	2.5	19.4	3.8	25.2
Pearce	0.2	1.4	0.2	1.0	1.7	9.7	2.9	14.3
Perth Airport	0.2	1.2	0.2	1.1	2.6	16.0	4.2	22.1
Perth Metro	0.2	1.4	0.2	1.1	2.8	20.5	4.4	27.1
Swanbourne	0.2	1.6	0.2	1.4	2.7	27.5	3.8	32.5

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

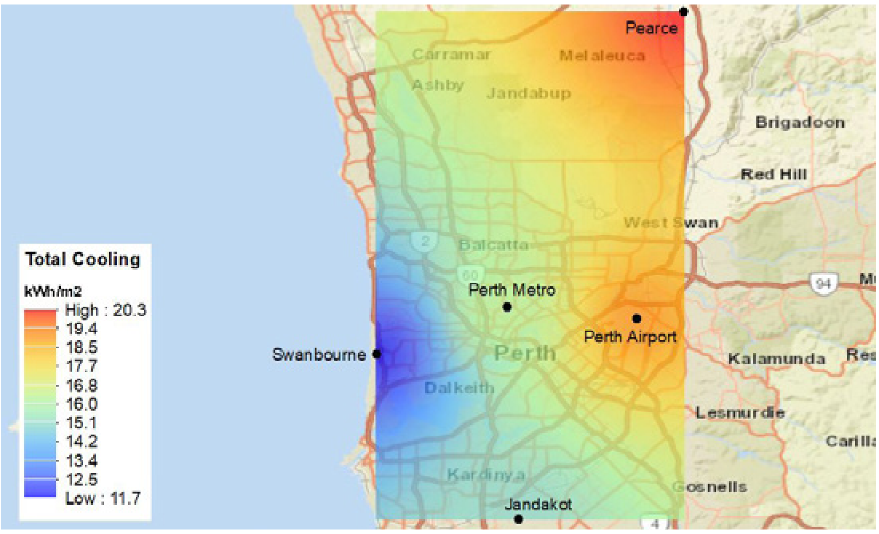

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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

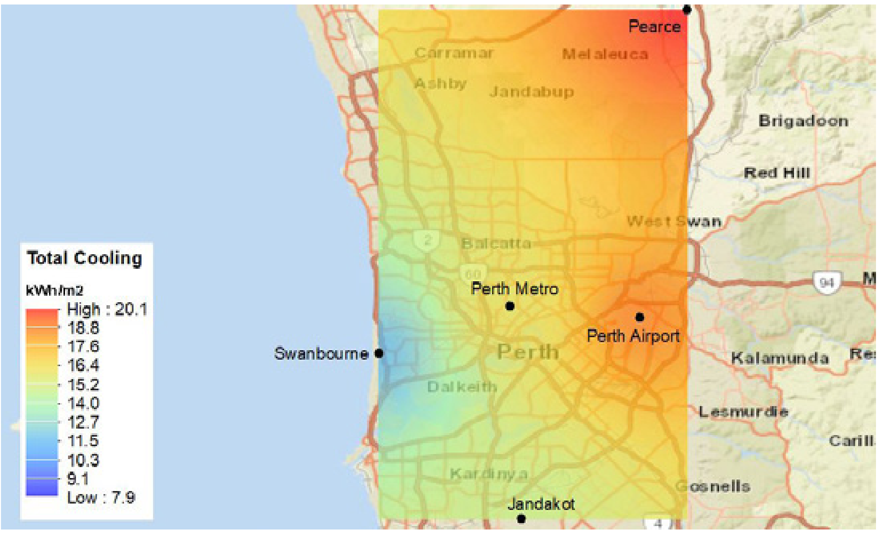

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

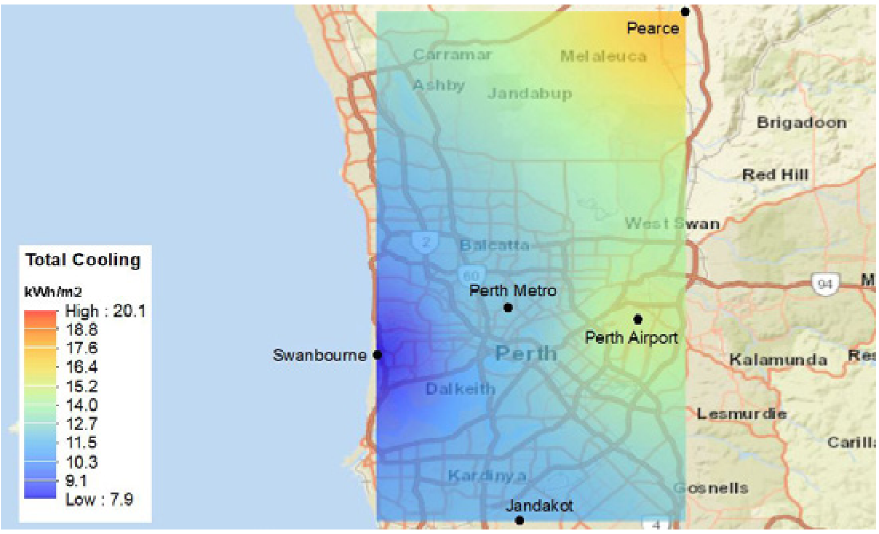

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0 kWh/m²) is neraly the same that the annual cooling load reduction (0.3-0.4 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
Jandakot	27.6	30.2	0.8	2.4	27.3	29.9	0.9	2.5
Pearce	33.1	36.3	0.6	1.9	32.7	35.9	0.6	2.0
Perth Airport	31.0	33.3	0.7	2.1	30.6	33.0	0.7	2.1
Perth Metro	28.1	31.5	0.6	1.8	27.7	31.0	0.6	1.8
Swanbourne	17.9	20.9	0.3	1.0	17.6	20.6	0.3	1.0

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

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

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.2 and 0.4 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	%
Jandakot	0.3	1.2	0.3	1.1	0.0	0.0	0.3	1.1	0.3	0.9
Pearce	0.4	1.2	0.4	1.1	0.0	0.0	0.4	1.2	0.4	0.9
Perth Airport	0.3	1.1	0.3	1.0	0.0	0.0	0.3	1.0	0.3	0.9
Perth Metro	0.4	1.4	0.4	1.3	0.0	0.0	0.4	1.3	0.4	1.2
Swanbourne	0.3	1.4	0.3	1.3	0.0	0.0	0.3	1.4	0.2	1.1

3

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

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

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

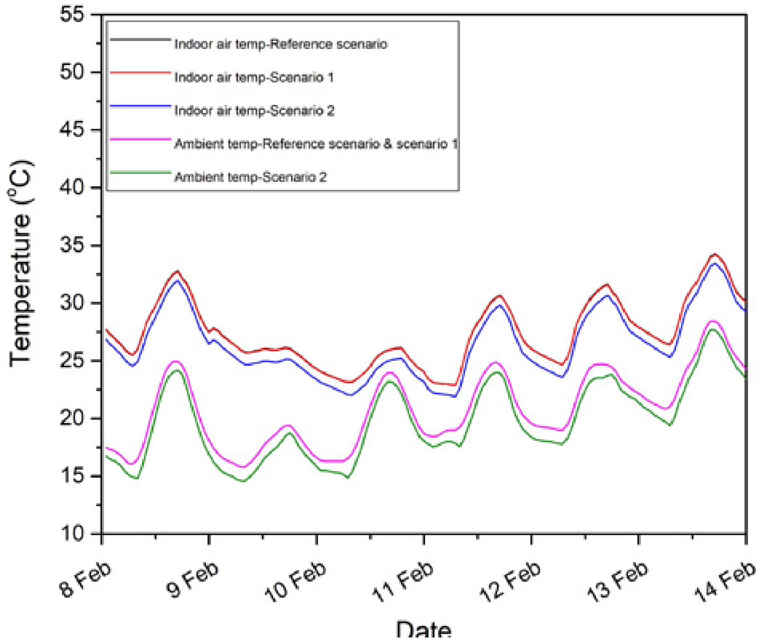

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

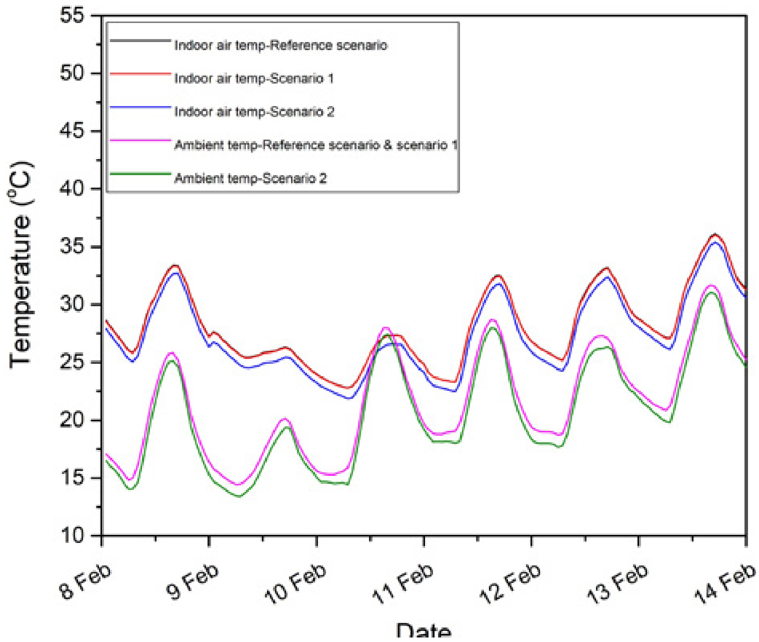

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.9-34.3 °C and 22.8-36.8 °C in Swanbourne and Pearce stations, respectively.

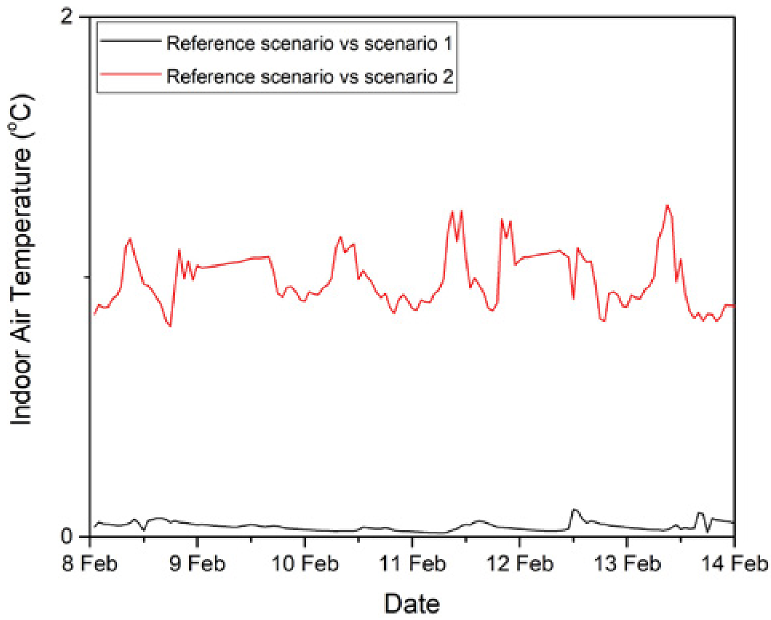

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.1 °C and 0.2 °C in Swanbourne and Pearce stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.3 and 1.1 °C in Swanbourne and Pearce stations, respectively.

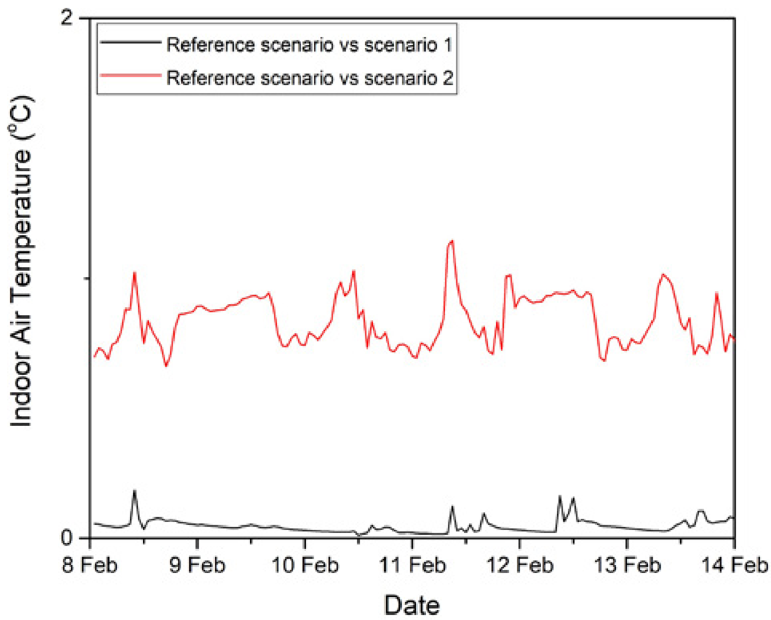

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during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

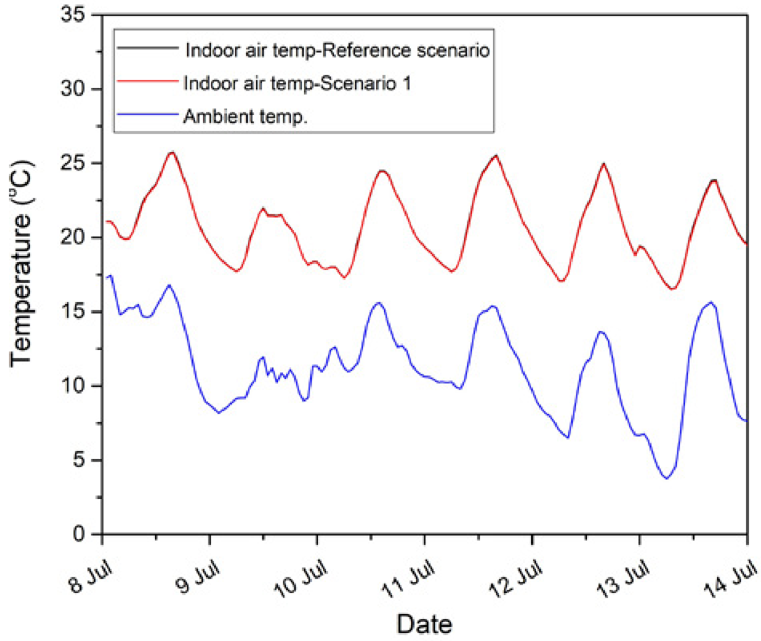

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Swanbourne station* using annual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

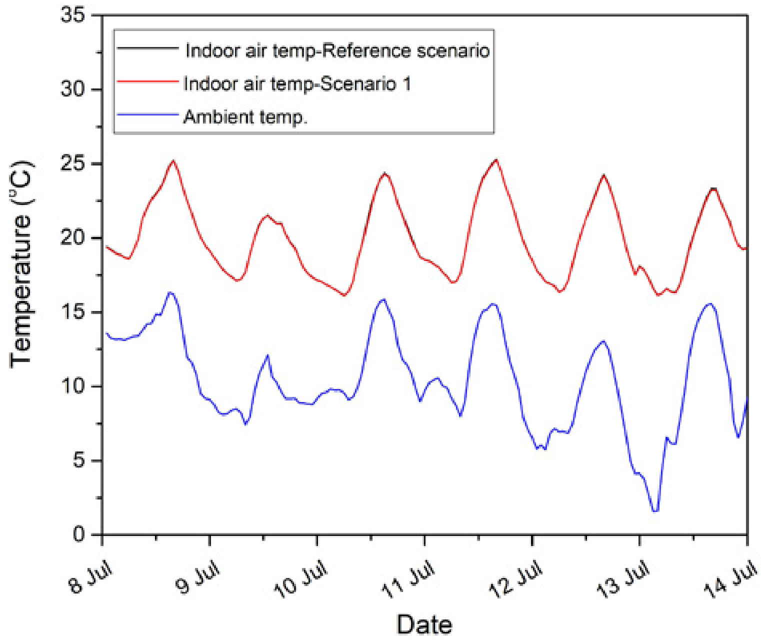

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Pearce station* using annual measured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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne station.

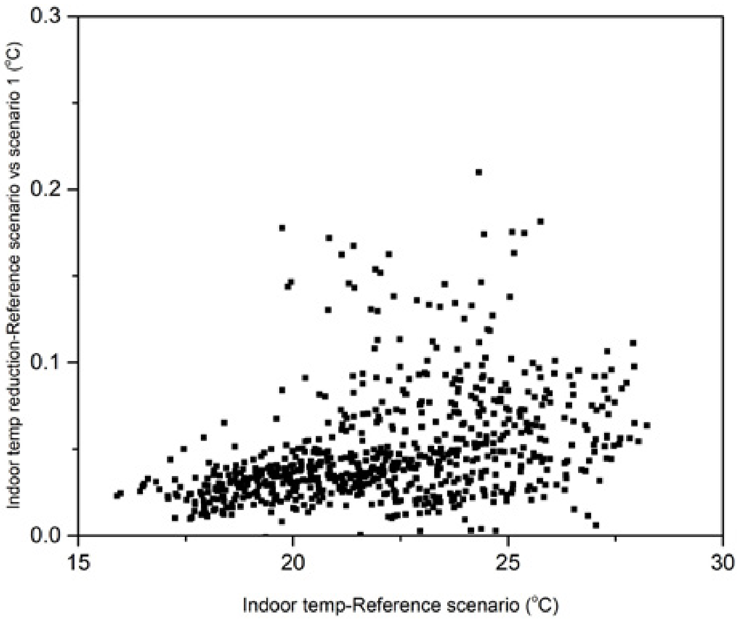

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

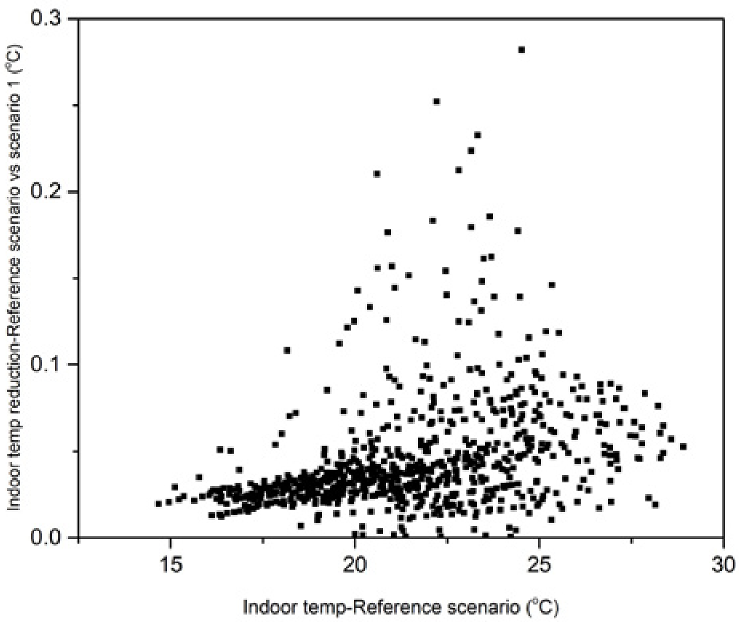

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 (100 hours) in Swanbourne station while remains almost the same (157-159) for Pearce station.

The number operational hours with air temperature <19 °C during is expected to remain the same (136- for reference scenario and scenario 1 in Swanbourne and Pearce 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
Swanbourne	34	100	34	100
Pearce	51	157	51	159

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

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 606 hours to 600 and 555 for scanerio 1 and 2 in Swanbourne station, and from 612 hours to 609 and 583 hours for Scenario 1 and 2 in Pearce station.

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

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	606	600	555
Pearce	612	609	583

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

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

Table 7. Energy performance features of Building 04.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	105,1	183,4
Energy consumption after cool roof (MWh)	103,7	181,9
Energy savings (MWh)	1,4	1,5
Energy savings (%)	1,33%	0,82%
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 1,33% for the Swanbourne and of 0,82% for the Pearce weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 20,0% for Swanbourne and 22,3% for Pearce 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 Swanbourne and for Pearce weather conditions respectively.

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

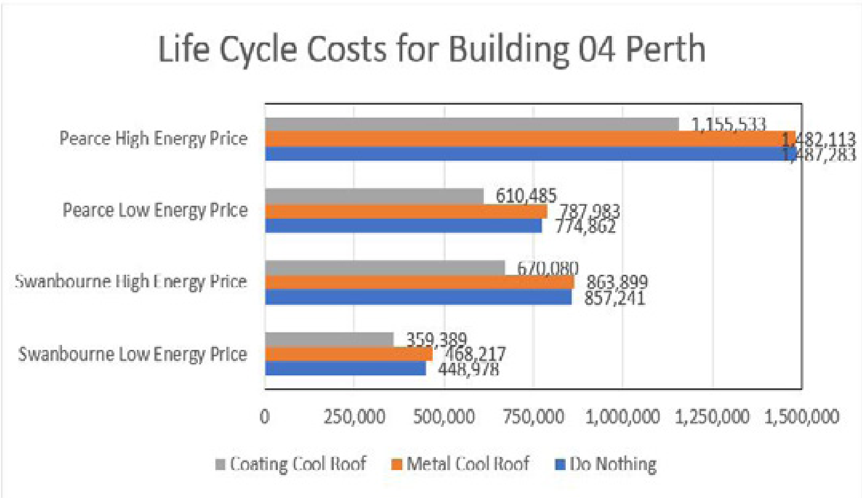

Figure 12. Life Cycle Costs for Building 04 for Swanbourne and Pearce weather stations.

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	-4.28 %	-0.78 %	-1.69 %	0.35 %
Coating Cool Roof	19.95 %	21.83 %	21.21 %	22.31 %

7

CONCLUSIONS

• In the eleven weather stations in Perth, 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 11.7-20.3 kWh/m^2 to 11.6-20.1 kWh/m^2. As computed, the building-scale application of cool roofs is predicted to reduce the cooling load of new high-rise office building with roof insulation by 0.2 kWh/m^2 (~1.2-1.4 %) (See Table 1 and 2 and Figures 1 and 2). The combined building-scale and urban-scale application of cool roofs is foreseen to have a significant contribution to cooling load reduction. It is estimated that the cooling load of cool roof with modified urban temperature scenario (scenario 2) is around 2.9-4.4 kWh/m^2 (~14.3-32.5 %) 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 kWh/m^2) is neraly the same that the annual cooling load reduction (0.3-0.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.0-1.3%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.2 and 0.4 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 22.9-34.3 ^{o}C and 22.8-36.8 ^{o}C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.1 ^{o}C and 0.2 ^{o}C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.3 and 1.1 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 Swanbourne and Pearce 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 0.1 ^{o}C in Swanbourne station. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to remain the same (100 hours) in reference scenario and scenario 1 in Swanbourne station. The estimations for Pearce station show that the total number of hours below 19 ^{o}C remain almost the same (157-159) for the reference scenario and scenario 1. Also, the number of hours below 19 ^{o}C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to remain the samefor reference scenario and scenario 1 in Swanbourne and Pearce stations. (See Table 5).

• During a typical summer month, the total number of hours with an indoor air temperature (>26 ^{o}C) is predicted to slightly decreased from 606 hours to 600 and 555 for scanerio 1 and 2 in Swanbourne station, and from 612 hours to 609 and 583 hours for Scenario 1 and 2 in Pearce station. (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a significantly higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 20,0% for Swanbourne and 22,3% for Pearce conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible or marginally so. 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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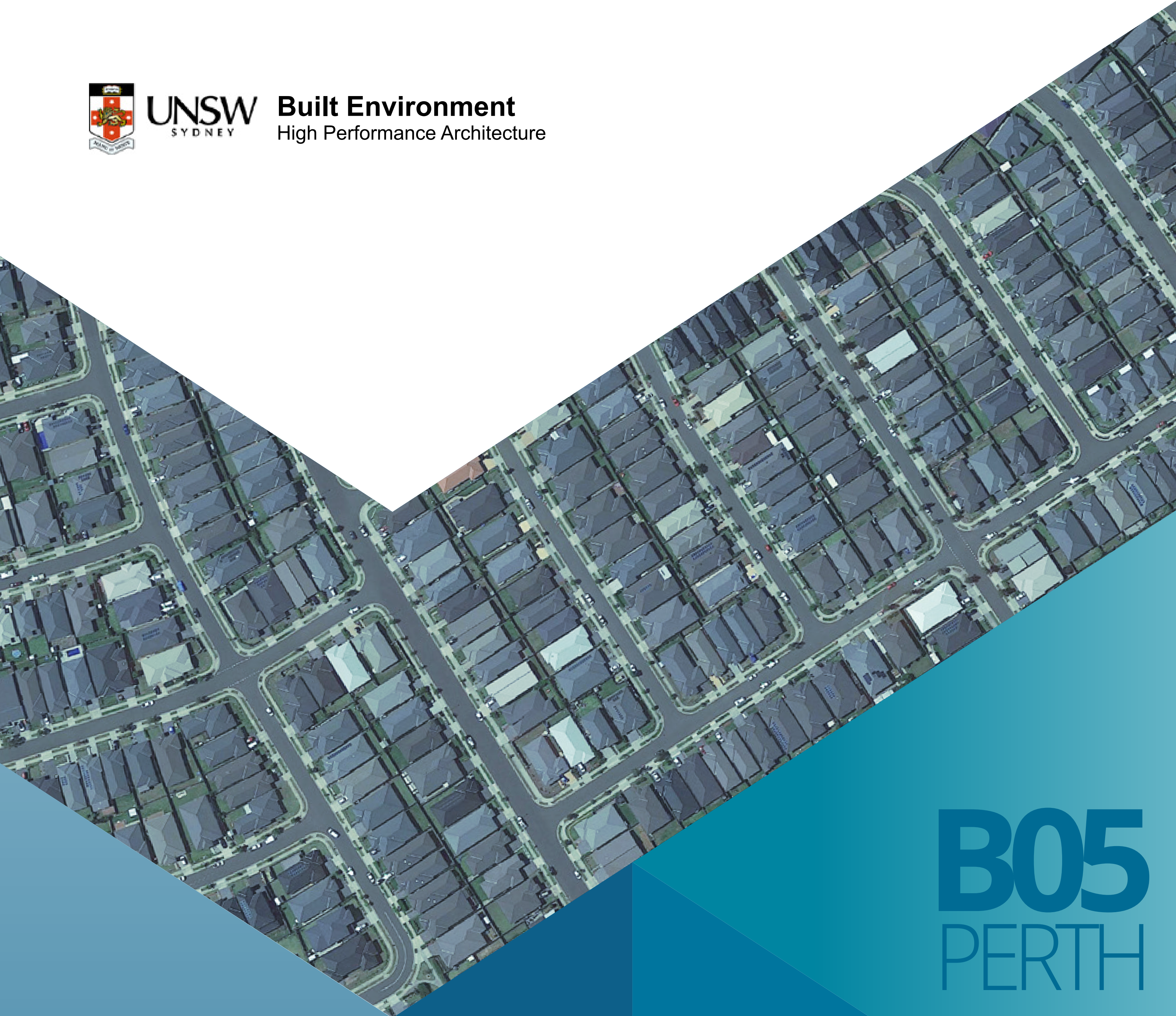

B05
PERTH

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise shopping mall centre
2021

BUILDING 05

NEW LOW-RISE SHOPPING MALL CENTRE

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

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

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

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

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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 Perth using weather data simulated by WRF.

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.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new low-rise office building from 58.3-69.1 kWh/m² to 56.7-67.4 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)
Jandakot	51.2	60.1	49.7	58.5	45.6	49.9
Pearce	60.2	69.1	58.6	67.4	55.4	60.7
Perth Airport	57.6	66.2	56.1	64.6	51.4	55.2
Perth Metro	52.6	62.2	51.1	60.6	46.5	51.1
Swanbourne	47.0	58.3	45.5	56.7	41.4	47.1

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 0.2-1.6 kWh/m² which is equivalent to 1.4-2.6 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.8-11.1 kWh/m² which is equivalent to 12.2-32.5 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Jandakot	1.5	3.0	1.6	2.6	5.6	10.9	10.1	16.9
Pearce	1.6	2.6	1.6	2.4	4.7	7.9	8.4	12.2
Perth Airport	1.6	2.7	1.6	2.5	6.3	10.9	11.0	16.6
Perth Metro	1.5	2.9	1.6	2.6	6.0	11.5	11.1	17.8
Swanbourne	0.2	1.6	0.2	1.4	2.7	27.5	3.8	32.5

In the eleven weather stations in Perth, 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.

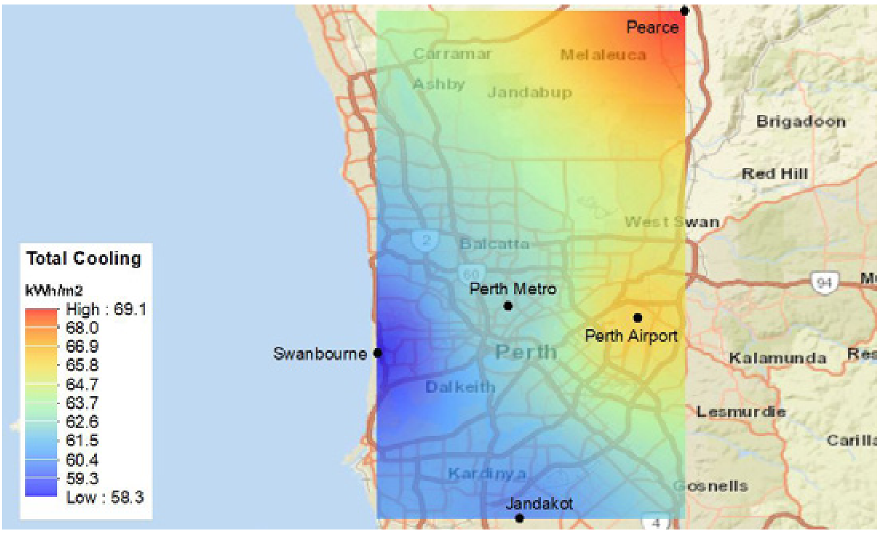

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

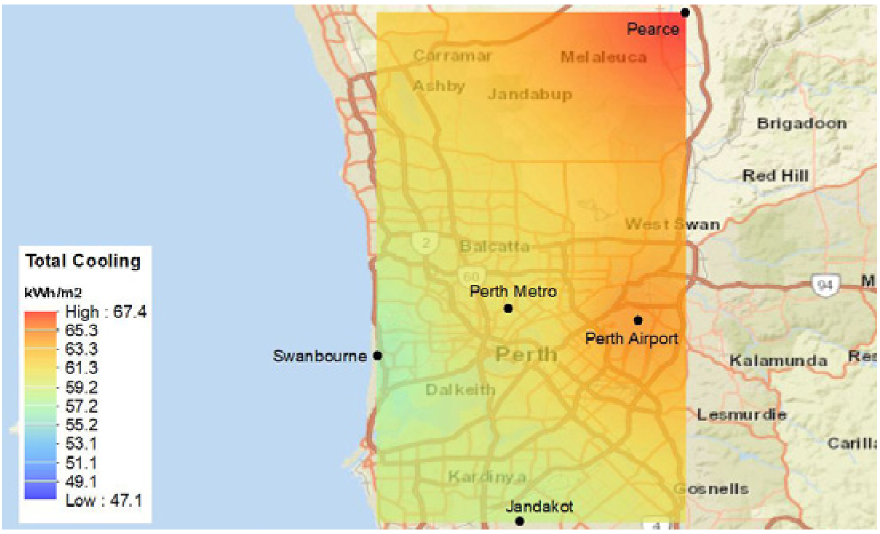

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

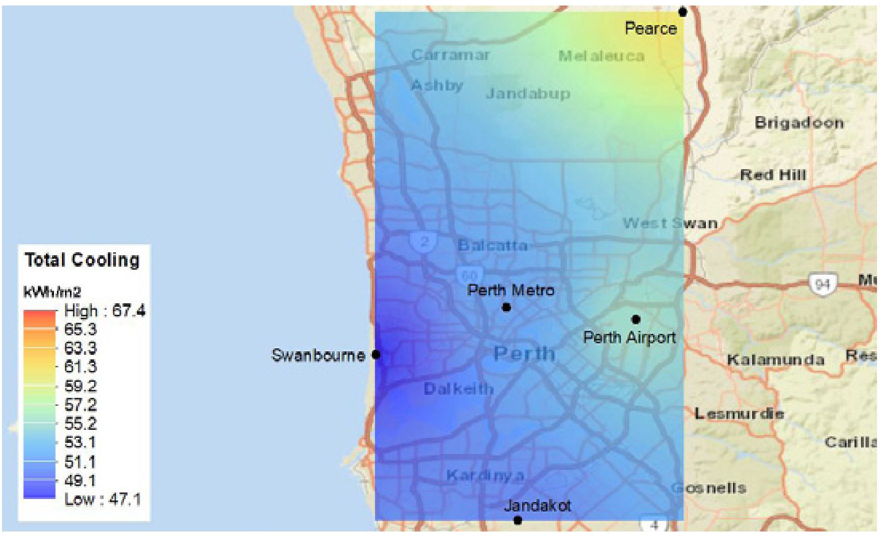

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

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 (0.1 kWh/m²) is significantly lower than the annual cooling load reduction (5.2-6.7 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
Jandakot	161.6	174.5	2.1	5.6	156.4	169.2	2.1	5.7
Pearce	174.6	190.7	1.7	4.4	169.1	185.1	1.7	4.5
Perth Airport	170.1	181.8	1.8	4.7	164.9	176.5	1.8	4.8
Perth Metro	172.8	190.1	1.6	4.1	166.3	183.4	1.6	4.2
Swanbourne	152.8	177.4	1.0	2.4	147.2	171.6	1.0	2.4

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 2.9-3.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.1-6.6 kWh/m² (~2.8-3.4 %).

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	%
Jandakot	5.1	3.2	5.2	3.0	0.0	0.1	5.1	3.1	5.1	2.8
Pearce	5.5	3.2	5.6	2.9	0.0	0.1	5.5	3.1	5.5	2.8
Perth Airport	5.2	3.1	5.3	2.9	0.0	0.1	5.2	3.0	5.2	2.8
Perth Metro	6.5	3.8	6.7	3.5	0.0	0.1	6.5	3.7	6.6	3.4
Swanbourne	5.6	3.7	5.8	3.3	0.0	0.1	5.6	3.6	5.8	3.2

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

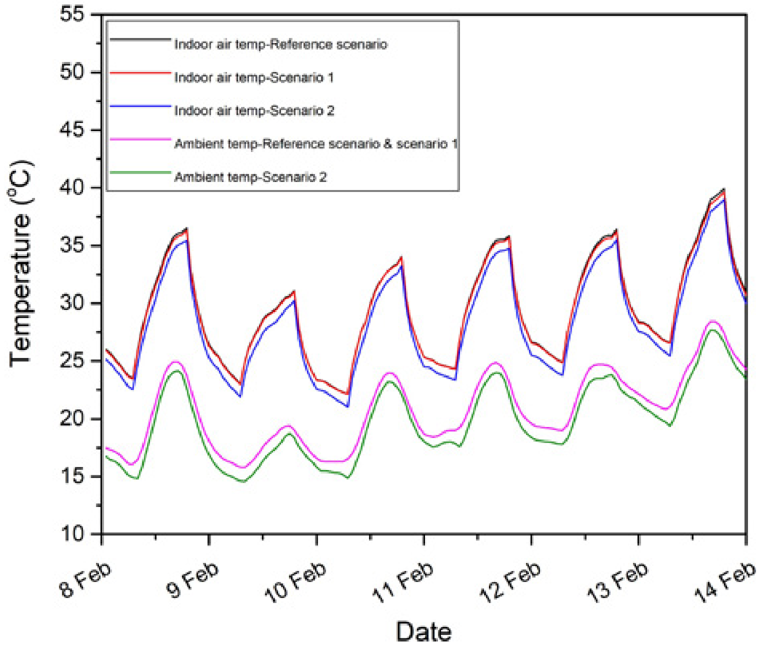

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new low-rise shopping mall centre under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

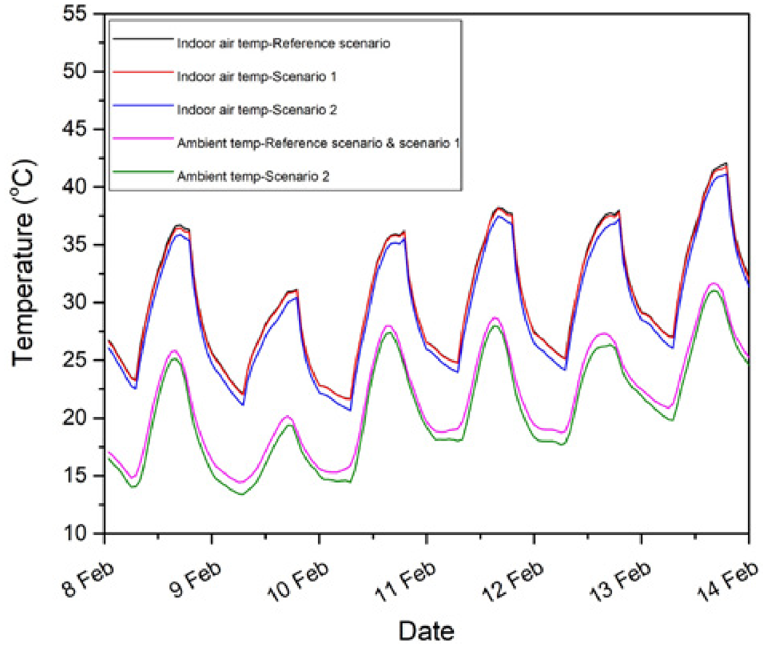

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.2-39.94 °C and 21.7-42.1 °C in Swanbourne and Pearce stations, respectively.

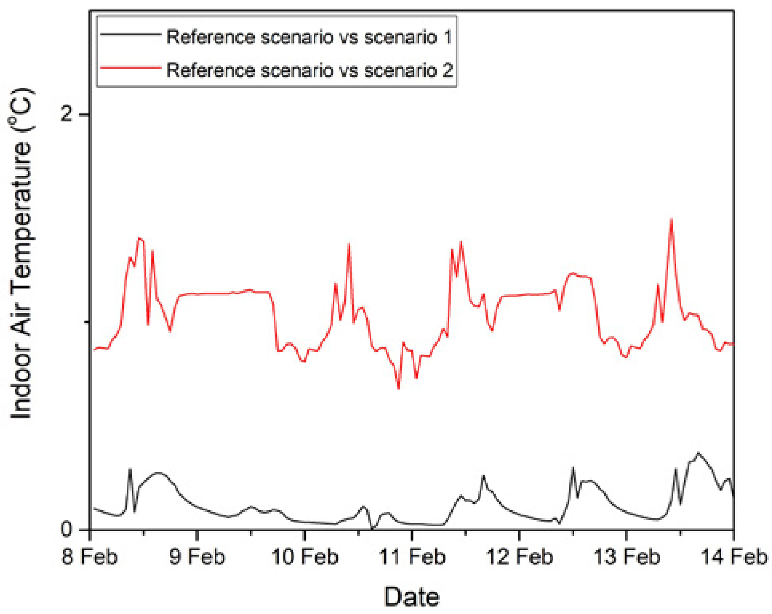

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical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

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.5 °C and 1.3 °C in Swanbourne and Pearce stations, respectively.

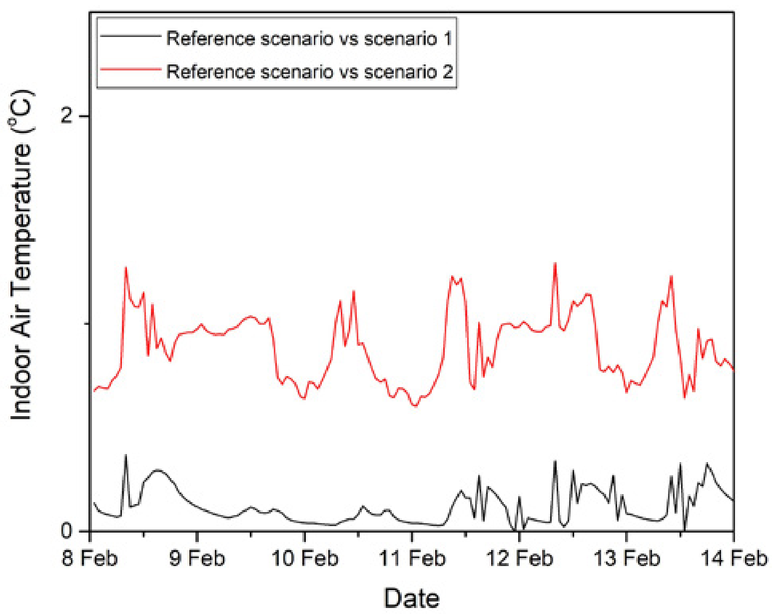

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.3-30.8 °C in reference scenario to a range 12.3-30.5 °C in scenario 1 in Swanbourne station.

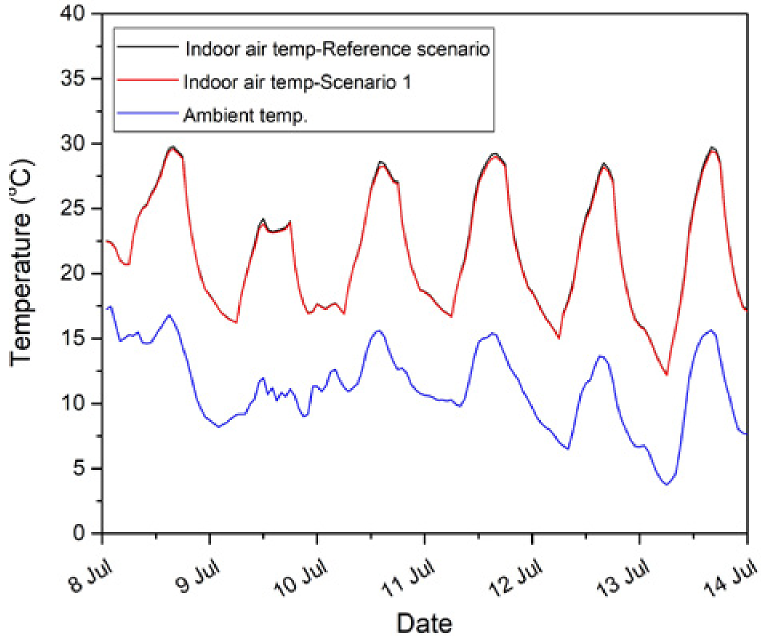

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Swanbourne station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 11.3-30.3 °C in reference scenario to a range 11.2-30.1 °C in scenario 1 in Pearce station.

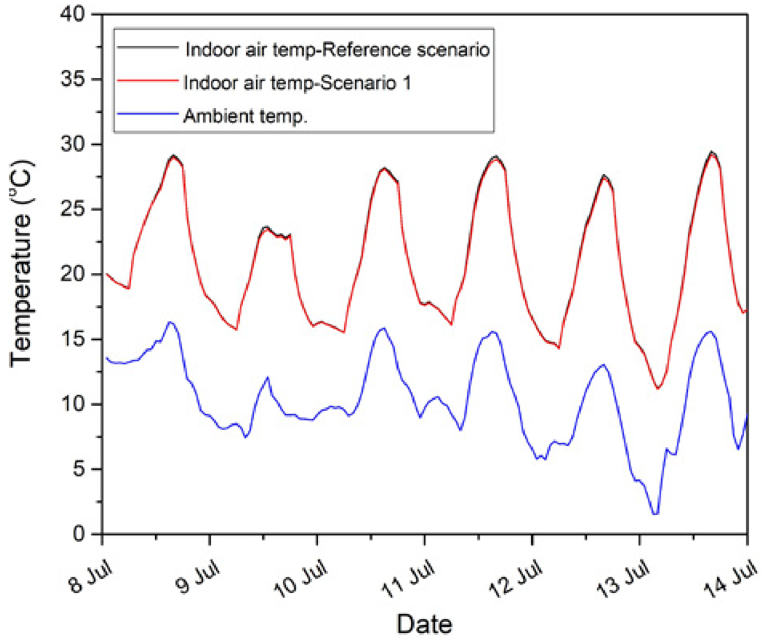

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Pearce station* using annual measured weather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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce stations.

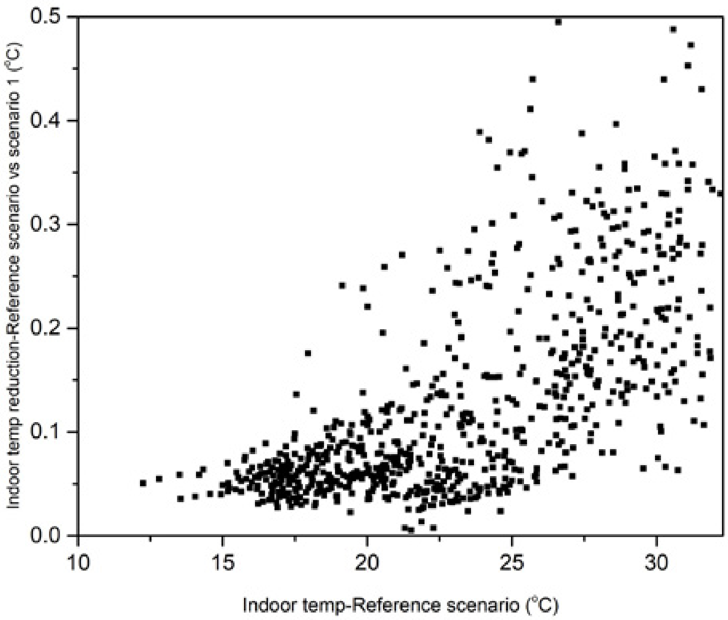

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

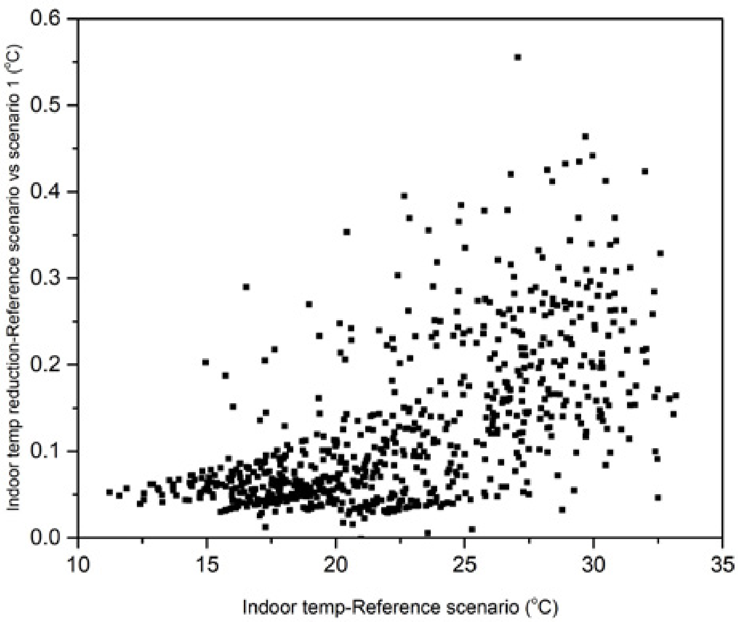

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 172 hours in reference scenario to 176 hours, and from 217 to 221 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Swanbourne	28	172	29	176
Pearce	38	217	40	221

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

The number operational hours with air temperature <19 °C during is expected to slightly increase from 28 to 29 hours and from 38 to 40 hours in scenario 1 in Swanbourne and Pearce 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.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 594 hours in reference scenario to 593 and from 595 hours to 586 and 564 hours under scenario 1 and 2 in Swanbourne and Pearce stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	594	593	551
Pearce	595	586	564

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 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 Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 05.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	158,2	171,7
Energy consumption after cool roof (MWh)	153,1	166,8
Energy savings (MWh)	5,1	4,9
Energy savings (%)	3,22%	2,85%
Area (m^2)	1.100	1.100
Roof costs - Metal roof (AU$/m^2)	38,0	38,0
Roof costs - Coating (AU$/m^2)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m^2)	15,0	15,0

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

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 3,22% for the Swanbourne and of 2,85% for the Pearce weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,9% for the low energy price scenario for Pearce and 30,7% for the low energy scenario for Swanbourne.

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 Swanbourne and for Pearce weather conditions respectively.

The metal cool roof is due to its higher initial investment marginally feasible for both locations and energy prices' scenarios, with reductions of life cycle costs around 2%.

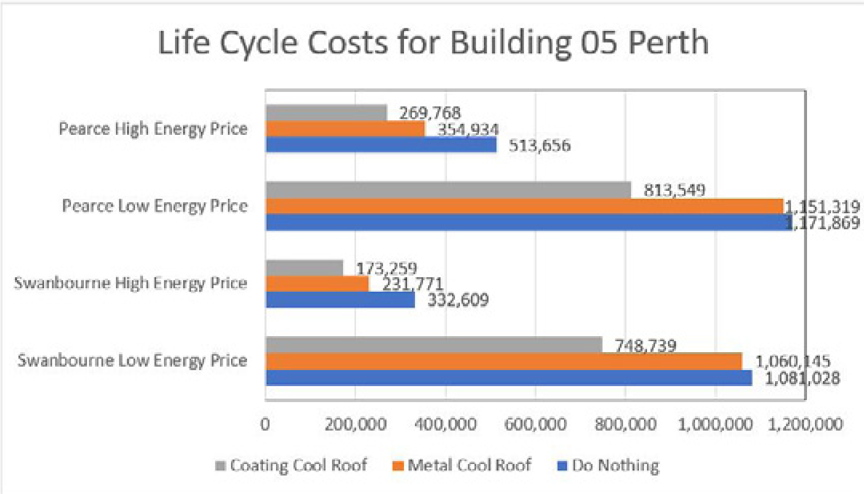

Figure 12. Life Cycle Costs for Building 05 for Swanbourne and Pearce weather stations.

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	1.93 %	2.60 %	1.75 %	2.41 %
Coating Cool Roof	30.74 %	24.11 %	30.58 %	23.92 %

7

CONCLUSIONS

• In the eleven weather stations in Perth, 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 Perth, the total cooling load of a typical low-rise shopping mall centre under the reference scenario is approximately 58.3-69.1 kWh/m^2, which reduces to a range between 56.7-67.4 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 0.2-1.6 kWh/m^2 (~1.4-2.6 %) (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Perth, the total cooling load of low-rise shopping mall centre is estimated to be around 3.8-11.1 kWh/m^2 lower under cool roof with modified urban temperature scenario (scenario 2) compared to the reference scenario. This is equivalent to 12.2-32.5 % total cooling load saving by combined building-scale and urban-scale application of cool roof.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (5.2-6.7 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 2.9-3.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.1-6.6 kWh/m^2 (~2.8-3.4 %) (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 22.2-39.94 °C and 21.7-42.1 °C in Swanbourne and Pearce 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 Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.5 °C and 1.3 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 12.3-30.8 °C in reference scenario to a range between 12.3-30.5 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 11.3-30.3 °C in reference scenario to a range between 11.2-30.1 °C in reference with cool roof scenario (scenario 1) in Pearce 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 0.1 °C in Swanbourne and Pearce 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 172 hours in reference scenario to 176 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slight increase in total number of hours below 19 °C from 217 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 operational hours with air temperature <19 °C during is expected to slightly increase from 28hours in reference scenario to 29 hours and from 38 to 40 hours in Swanbourne and in Pearce stations, respectively.

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 594 hours under the reference scenario in Swanbourne station, which slightly decreases to 593 and 551 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station shows that the total number of hours above 26 °C decreases from 595 hours to 586 and 564 hours for Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to both cool roof options. The coating cool roof leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,9% for the low energy price scenario for Pearce and 30,7% for the low energy scenario for Swanbourne, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment marginally feasible for both locations and energy prices' scenarios, with reductions of life cycle costs around 2%. 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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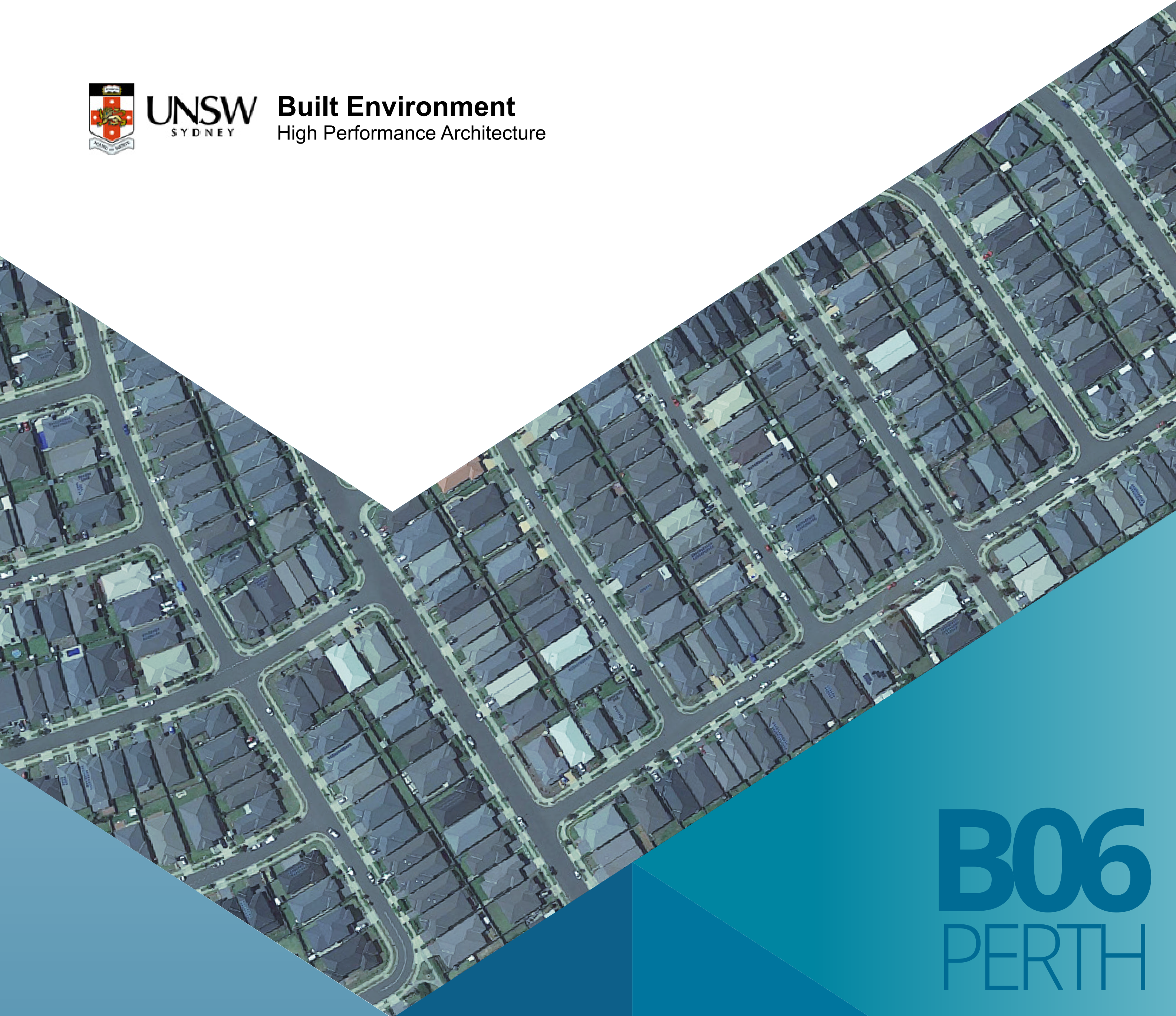

B06
PERTH

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 Perth using weather data simulated by WRF.

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.

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 56.9-67.6 kWh/m² to 56.2-66.8 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Jandakot	49.8	58.7	49.1	57.9	45.0	49.3
Pearce	58.8	67.6	58.0	66.8	54.8	60.1
Perth Airport	56.3	64.8	55.5	64.0	50.7	54.6
Perth Metro	51.2	60.7	50.5	60.0	45.9	50.5
Swanbourne	45.7	56.9	45.0	56.2	40.8	46.5

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 1.1-1.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.5-10.5 kWh/m² which is equivalent to 11.1-16.9 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Jandakot	0.7	1.4	0.7	1.3	4.9	9.8	9.4	16.0
Pearce	0.7	1.3	0.8	1.1	3.9	6.7	7.5	11.1
Perth Airport	0.7	1.3	0.8	1.2	5.5	9.8	10.2	15.7
Perth Metro	0.7	1.4	0.7	1.2	5.3	10.4	10.3	16.9
Swanbourne	0.7	1.5	0.7	1.3	4.9	10.7	10.5	18.4

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

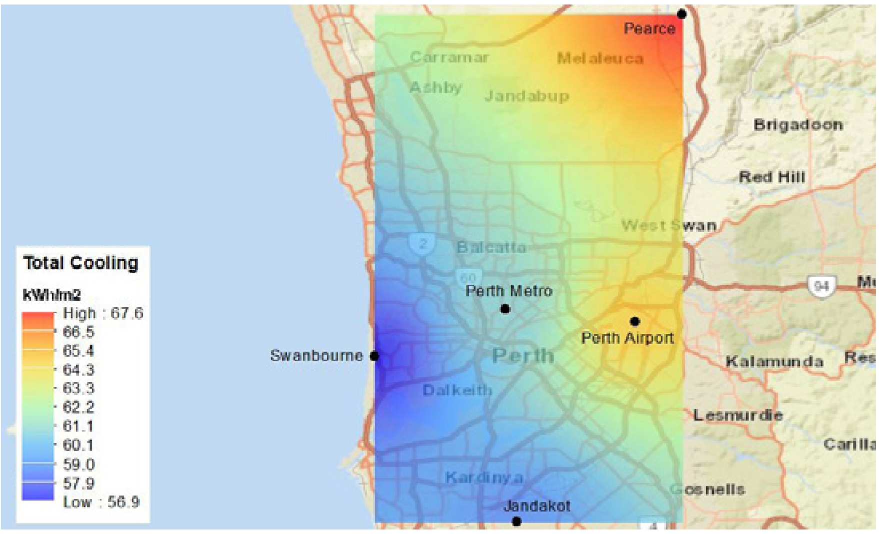

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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.

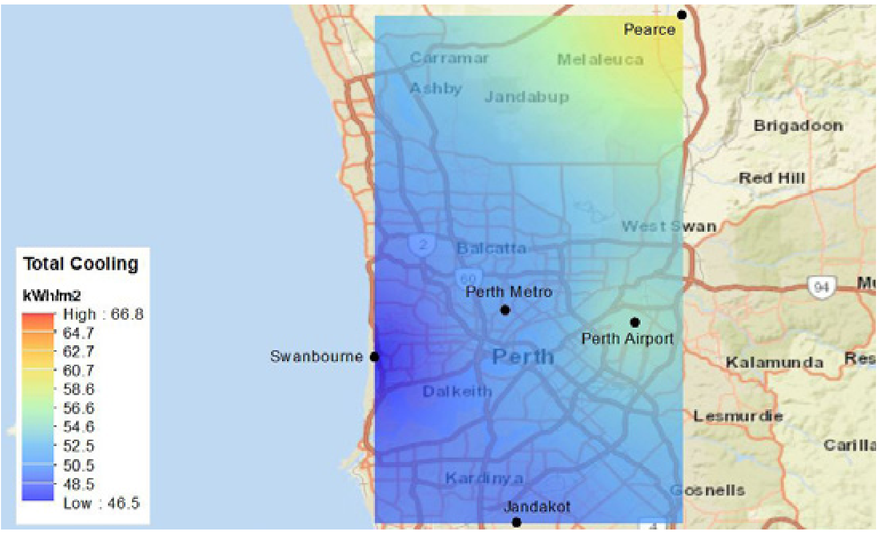

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Perth 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 lower than the annual cooling load reduction (2.4-3.1 kWh/m²).

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.

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
Jandakot	153.0	165.8	1.6	4.8	150.7	163.4	1.6	4.9
Pearce	166.0	181.9	1.3	3.7	163.4	179.3	1.3	3.7
Perth Airport	161.7	173.3	1.3	4.0	159.3	170.9	1.4	4.0
Perth Metro	163.9	181.1	1.1	3.4	160.9	178.0	1.2	3.5
Swanbourne	144.7	169.2	0.7	1.8	142.1	166.5	0.7	1.9

The annual cooling load saving by building-scale application of cool roofs is around 1.4-1.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.3-3.1 kWh/m² (~1.3-1.7 %).

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

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	%
Jandakot	2.3	1.5	2.4	1.4	0.0	0.1	2.3	1.5	2.3	1.4
Pearce	2.5	1.5	2.6	1.4	0.0	0.1	2.5	1.5	2.6	1.4
Perth Airport	2.4	1.5	2.4	1.4	0.0	0.1	2.4	1.5	2.4	1.3
Perth Metro	3.0	1.9	3.1	1.7	0.0	0.0	3.0	1.8	3.1	1.7
Swanbourne	2.6	1.8	2.7	1.6	0.0	0.0	2.6	1.8	2.7	1.6

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

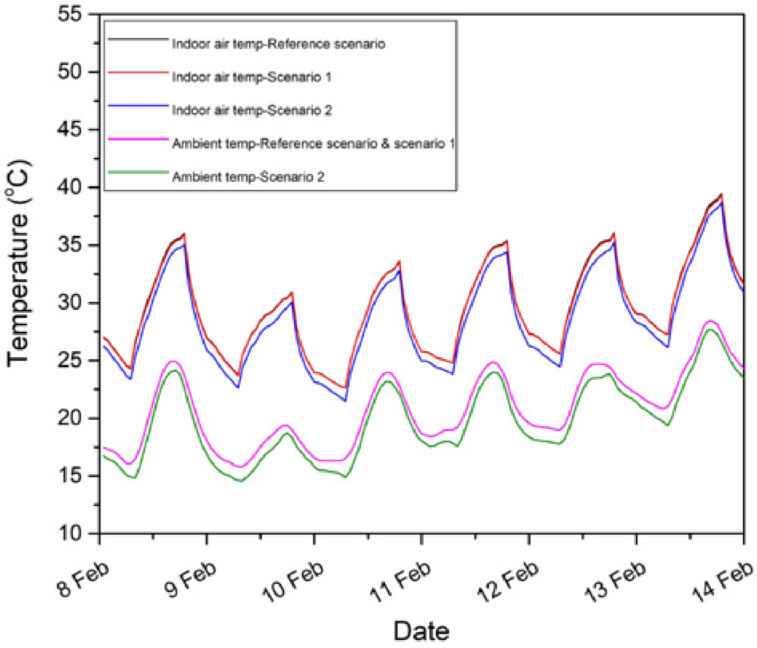

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new mid-rise shopping mall centre under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

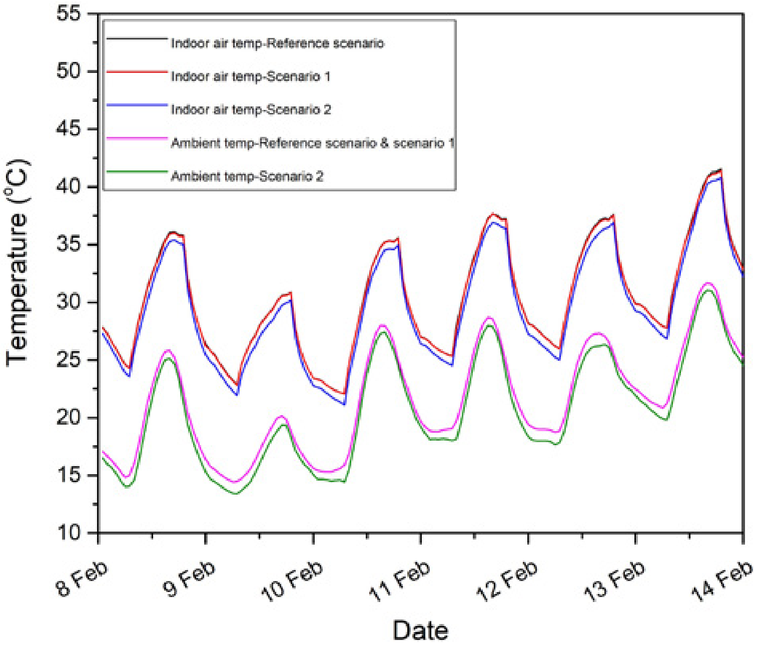

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.6-39.5 °C and 22.6-41.6 °C in Swanbourne and Pearce stations, respectively.

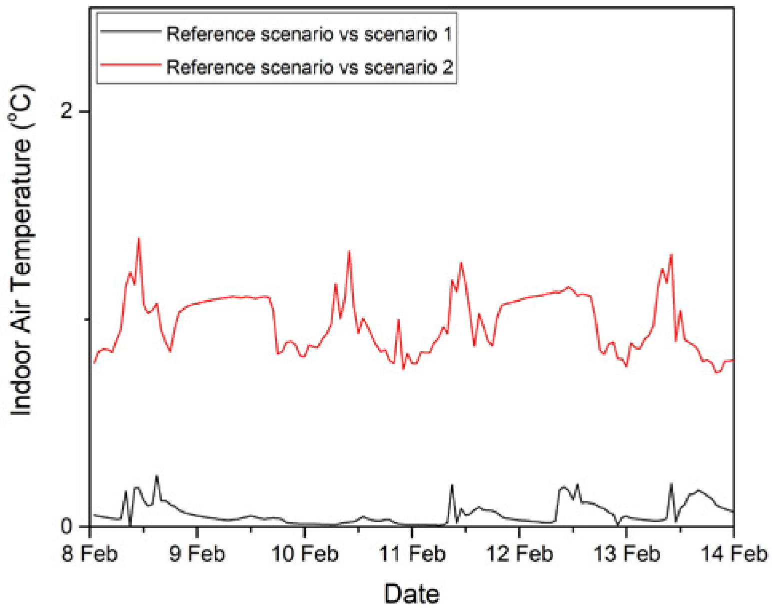

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical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

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.4 °C and 1.1 °C in Swanbourne and Pearce stations, respectively.

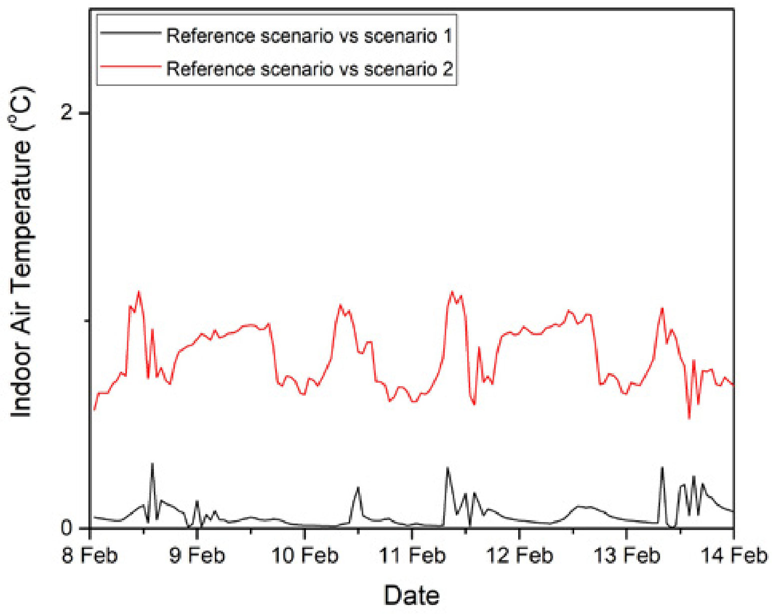

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to slightly reduce from a range 13.2-29.9 °C in reference scenario to a range 13.2-29.8 °C in scenario 1 in Swanbourne station.

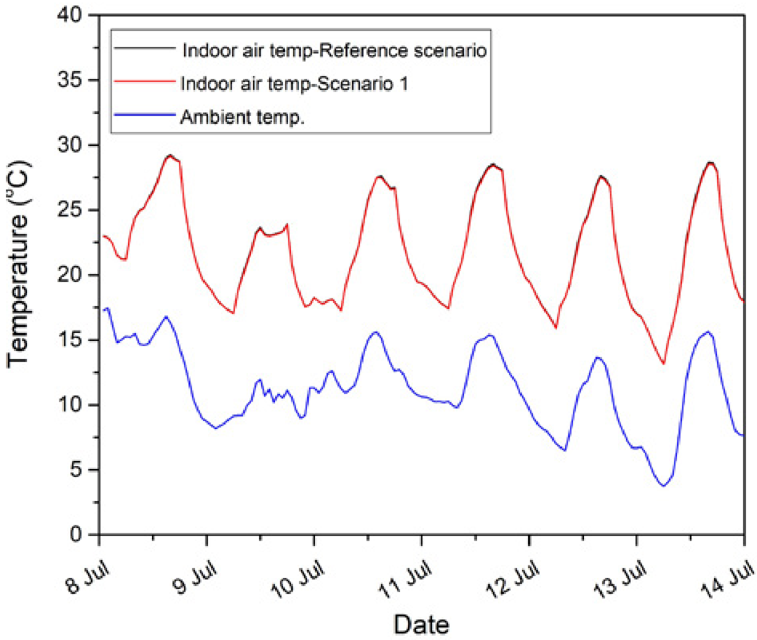

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Swanbourne station* using annual measured weather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

The indoor air temperature is predicted to slightly reduce from a range 12.3-29.7 °C in reference scenario to a range 12.3-29.6 °C in scenario 1 in Pearce station.

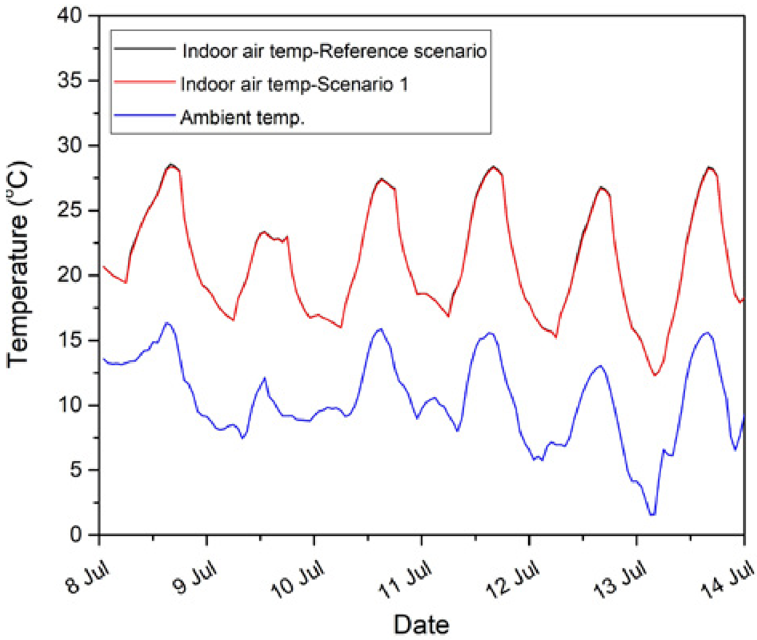

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Pearce station* using annual measured weather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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce stations, respectively.

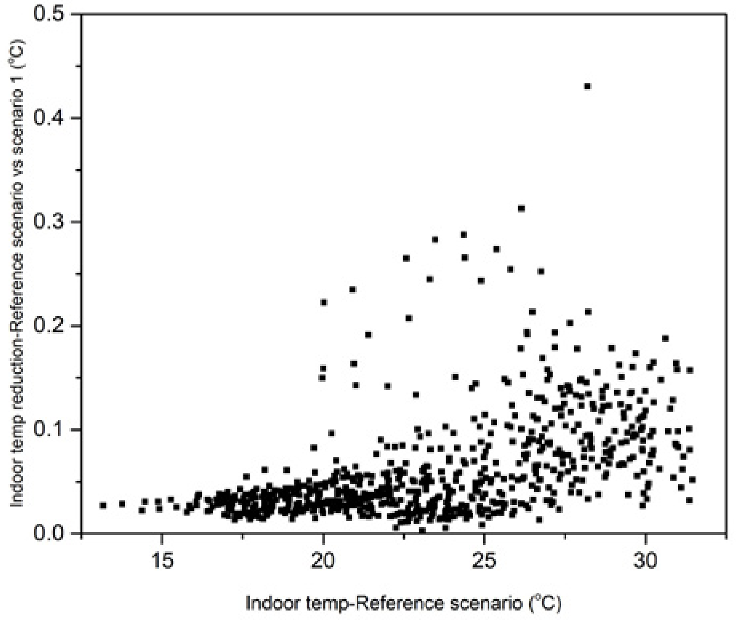

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

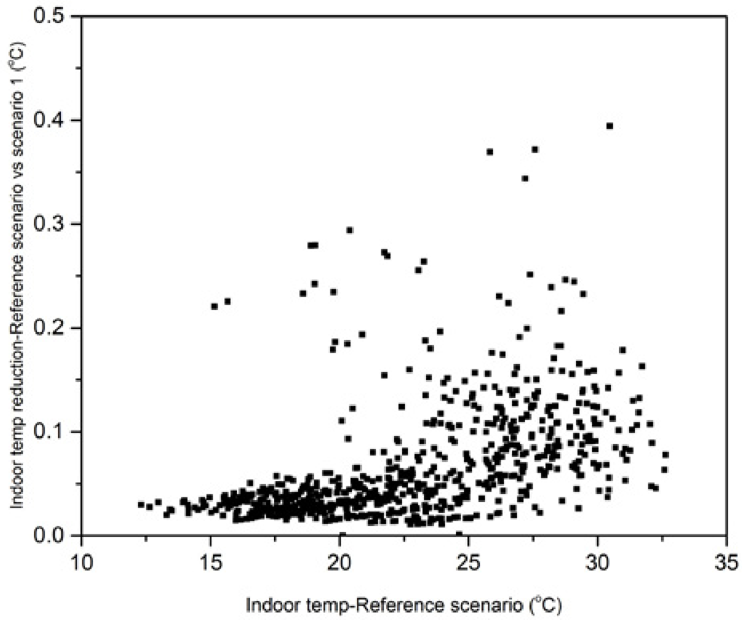

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 almost the same in reference scenario and scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from from 32 to 34 hours in scenario 1 in Pearce 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
Swanbourne	23	132	23	132
Pearce	32	181	34	183

** 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 623 hours in reference scenario to 586 hours under scenario 2, in Swanbourne station; and from 618 to 616 and 592 under scenario 1 and 2 in Pearce 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
Swanbourne	623	623	586
Pearce	618	616	592

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

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

Table 7. Energy performance features of Building 06.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	301,0	326,7
Energy consumption after cool roof (MWh)	296,4	322,1
Energy savings (MWh)	4,6	4,6
Energy savings (%)	1,53%	1,41%
Area (m^2)	1.100	1.100
Roof costs - Metal roof (AU$/$m^2$)	38,0	38,0
Roof costs - Coating (AU$/$m^2$)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/$m^2$)	15,0	15,0

Building 06 is an interesting example of a new, insulated, mid-rise commercial building where, despite its rather limited energy conservation potential, the 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 1,53% for the Swanbourne and of 1,41% for the Pearce 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 leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 22,8% for the low energy price scenario for both locations and 23,4% for the high energy scenario also for both locations.

The metal cool roof is due to its higher initial investment only marginally feasible with reductions between 1 and 2%, depending on the location and the energy prices.

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 Swanbourne and for Pearce weather conditions respectively.

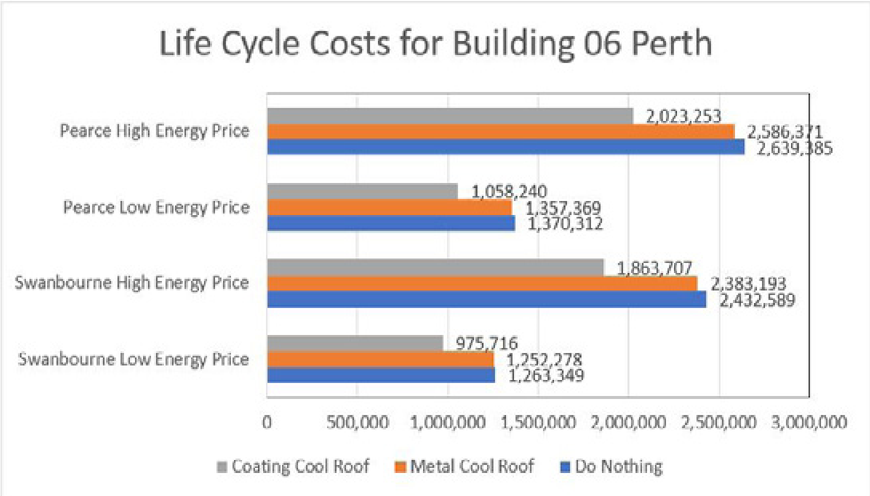

Figure 12. Life Cycle Costs for Building 06 for Swanbourne and Pearce weather stations.

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	0.88 %	2.03 %	0.94 %	2.01 %
Coating Cool Roof	22.77 %	23.39 %	22.77 %	23.34 %

7

CONCLUSIONS

• In the eleven weather stations in Perth, 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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the mid-rise shopping mall centre from 56.9-67.6 kWh/m^2 to 56.2-66.8 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 1.1-1.3 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.5-10.5 kWh/m^2. This is equivalent to 11.1-16.9 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (2.4-3.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.4-1.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.3-3.1 kWh/m^2 (~1.3-1.7 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 22.6-39.5 °C and 22.6-41.6 °C in Swanbourne and Pearce 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 0.3 °C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.4 °C and 1.1 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 13.2-29.9 °C in reference scenario to a range between 13.2-29.8 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce between 12.3-29.7 ^{o}C in reference scenario to a range between 12.3-29.6 ^{o}C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 ^{o}C in Swanbourne and Pearce stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to iremain the same in reference scenario compared to scenario 1 in Swanbourne station. The estimations for Pearce stations also show a slight increase in total number of hours below 19 ^{o}C from 181 hours in reference scenario to 183 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 operational hours with air temperature <19 ^{o}C during is expected to slightly increase from 32 hours in reference scenario to 34 hours; in Pearce 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 623 hours under the reference scenario in Swanbourne station, which decreases to 586 under the cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also shows that the number of hours above 26 °C decreases from 618 to 616 and 592 under Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to both cool roof options. The coating cool roof leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 22,8% for the low energy price scenario for both locations and 23,4% for the high energy scenario also for both locations, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment only marginally feasible with reductions between 1 and 2%, depending on the location and the energy prices. 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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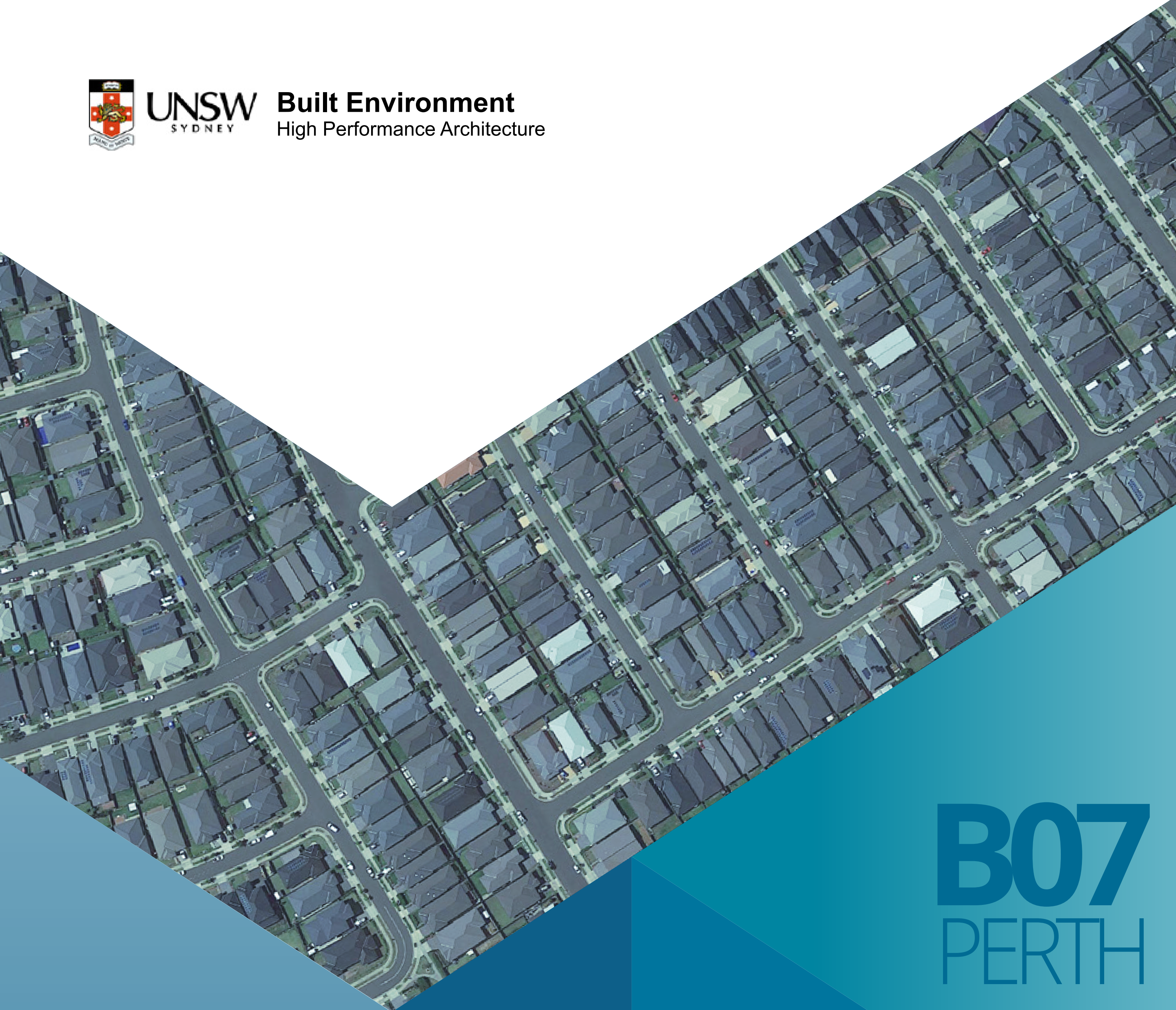

B07 PERTH

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.

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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 Perth 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 high-rise shopping mall centre from 56.3-67.0 kWh/m² to 55.9-66.6 kWh/m².

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.

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)
Jandakot	49.3	58.1	48.8	57.6	44.7	49.0
Pearce	58.2	67.0	57.7	66.6	54.5	59.7
Perth Airport	55.7	64.2	55.2	63.7	50.4	54.2
Perth Metro	50.6	60.1	50.2	59.7	45.6	50.1
Swanbourne	45.1	56.3	44.7	55.9	40.5	46.1

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

For Scenario 1, the total cooling load saving is around 0.5 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 7.3-10.2 kWh/m² which is equivalent to10.9-18.1 % 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	%
Jandakot	0.4	0.9	0.5	0.8	4.6	9.4	9.1	15.7
Pearce	0.5	0.8	0.5	0.7	3.7	6.3	7.3	10.9
Perth Airport	0.5	0.8	0.5	0.8	5.3	9.5	9.9	15.5
Perth Metro	0.5	0.9	0.5	0.8	5.1	10.0	10.0	16.6
Swanbourne	0.4	1.0	0.5	0.8	4.7	10.3	10.2	18.1

In the eleven weather stations in Perth, 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.

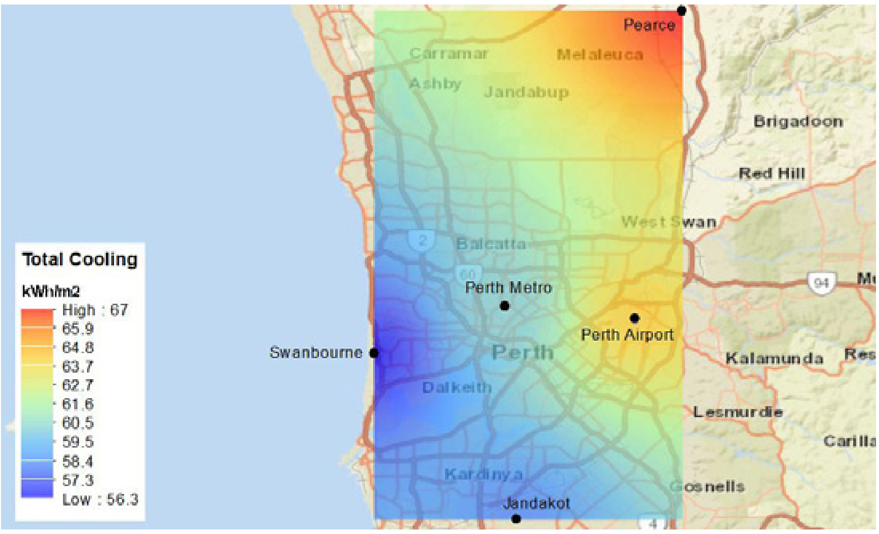

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

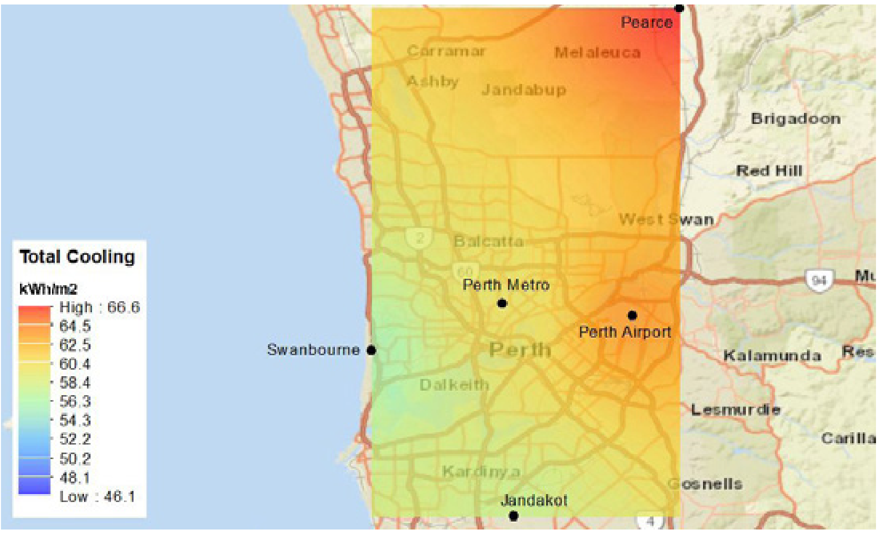

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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 Perth 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 (1.5-2.0 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
Jandakot	149.8	162.6	1.5	4.6	148.4	161.1	1.5	4.7
Pearce	162.8	178.7	1.2	3.5	161.1	177.0	1.2	3.5
Perth Airport	158.5	170.2	1.2	3.8	157.0	168.6	1.2	3.8
Perth Metro	160.6	177.7	1.0	3.2	158.6	175.7	1.1	3.3
Swanbourne	141.6	165.9	0.6	1.7	140.0	164.2	0.6	1.7

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

The annual cooling load saving by building-scale application of cool roofs is around 0.9-1.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.5-1.9 kWh/m² (~0.9-1.1 %).

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	%
Jandakot	1.5	1.0	1.5	0.9	0.0	0.0	1.5	1.0	1.5	0.9
Pearce	1.6	1.0	1.7	0.9	0.0	0.0	1.6	1.0	1.6	0.9
Perth Airport	1.5	1.0	1.5	0.9	0.0	0.0	1.5	0.9	1.5	0.9
Perth Metro	1.9	1.2	2.0	1.1	0.0	0.0	1.9	1.2	1.9	1.1
Swanbourne	1.6	1.1	1.7	1.0	0.0	0.0	1.6	1.1	1.7	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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

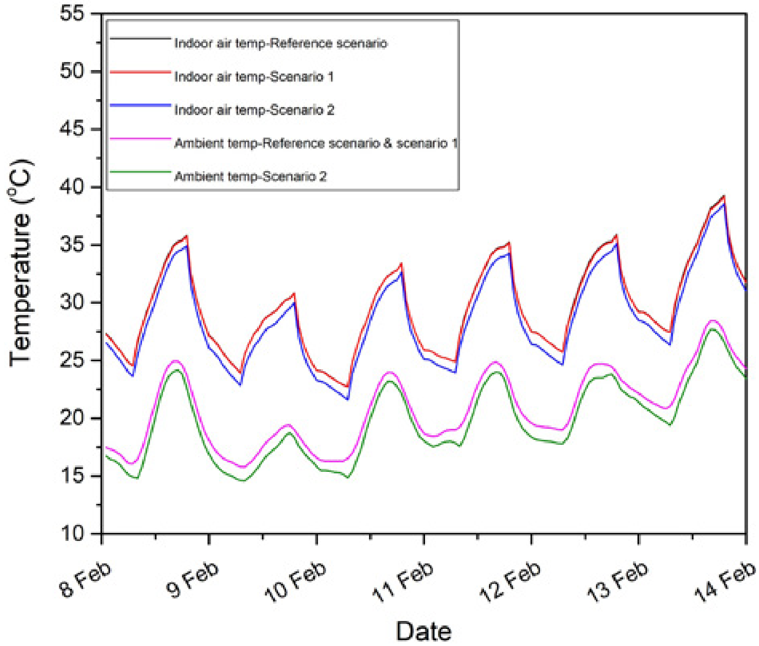

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

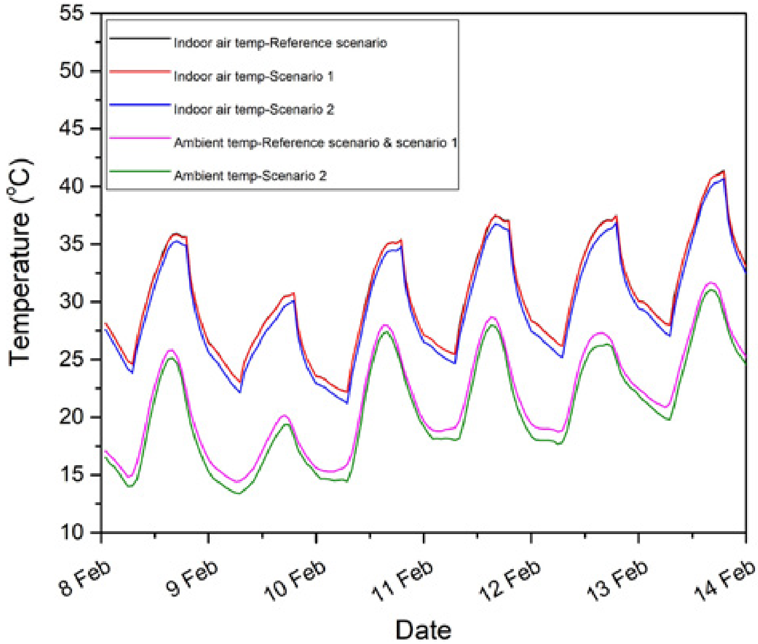

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.8-39.3 °C and 22.2-41.4 °C in Swanbourne and Pearce stations, respectively.

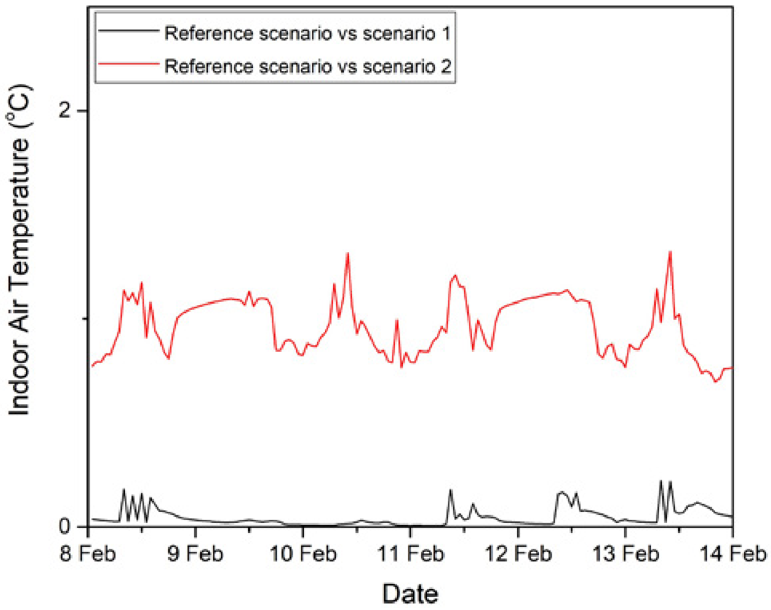

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free-floating conditions during a typical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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.2 °C and 0.3 °C in Swanbourne and Pearce stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.3 °C and 1.1 °C in Swanbourne and Pearce stations, respectively.

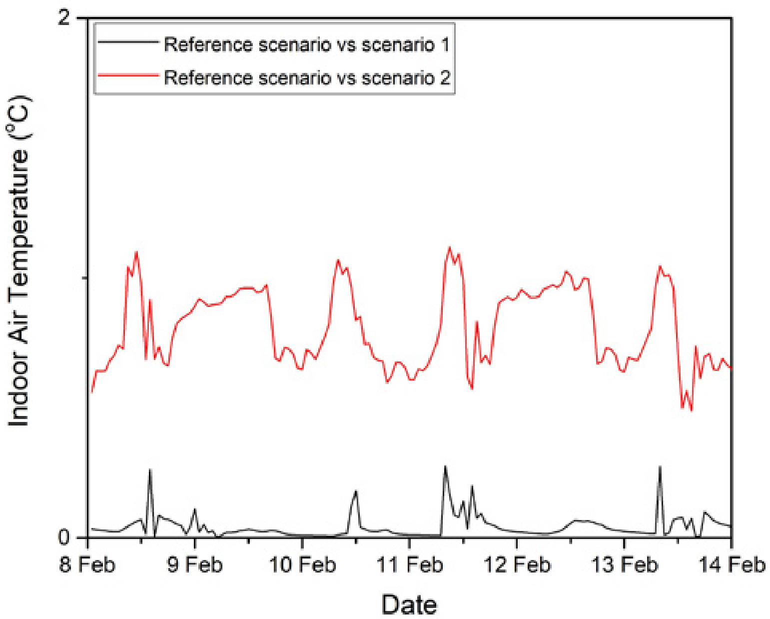

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new highrise shopping mall centre under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 13.4-29.8 °C in reference scenario to a range13.4-29.7 °C in scenario 1 in Swanbourne station.

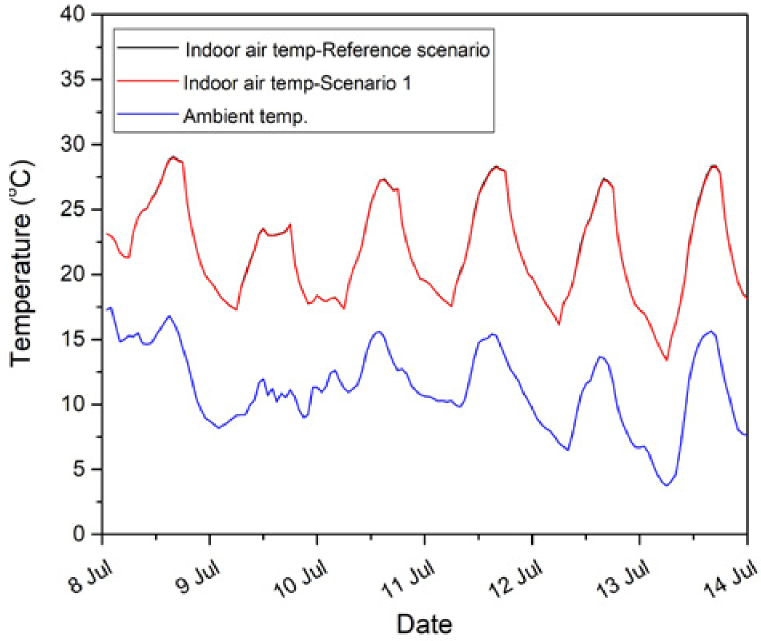

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Swanbourne station* using annual measured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

The indoor air temperature is predicted to reduce from a range 12.6-29.4 °C in reference scenario to a range 12.6-29.3 °C in scenario 1 in Pearce station.

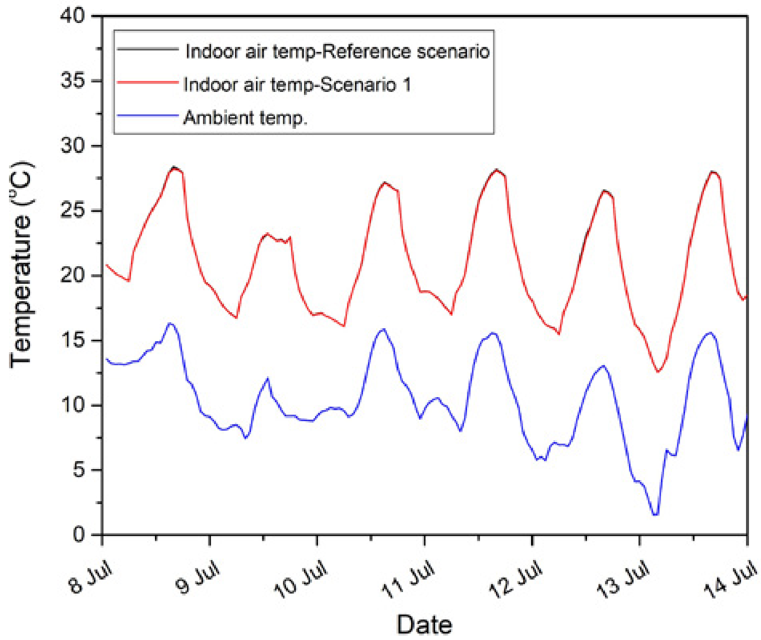

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Pearce station* using annual measured weather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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.04 °C in Swanbourne and Pearce stations, respectively.

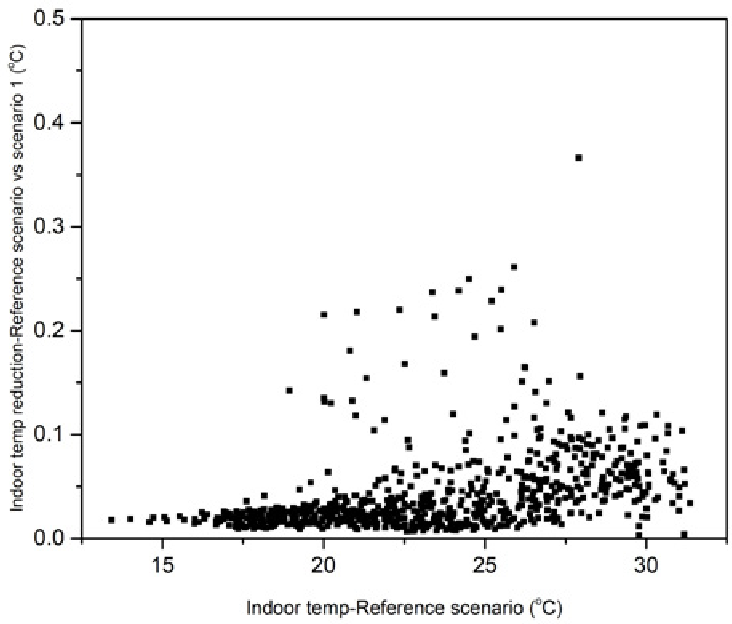

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

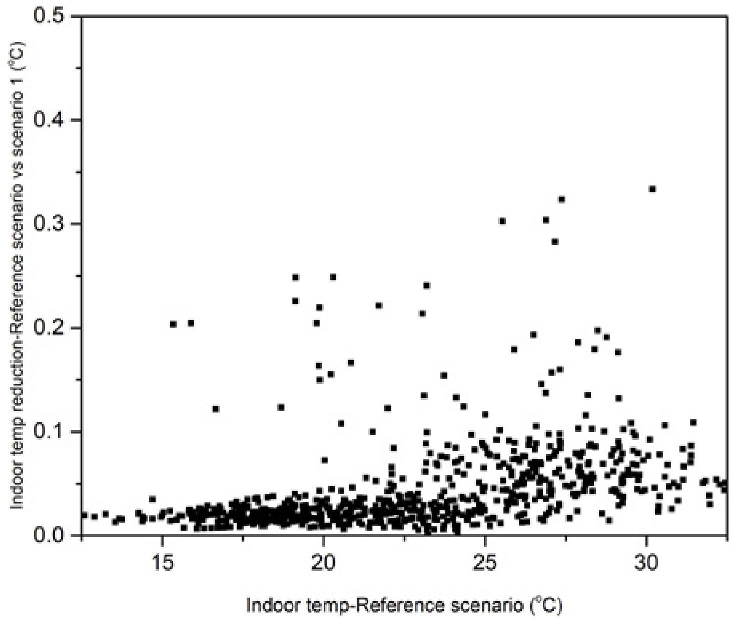

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 117 hours in reference scenario to 118 hours, and from 165 to 174 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 19 to 20 hours, and from 31 to 35 hours in scenario 1 in Swanbourne and Pearce 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
Swanbourne	19	117	20	118
Pearce	31	165	35	174

** 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 625 hours in reference scenario to 594 hours under scenario 2, in Swanbourne station; and from 627 to 625 and 603 under scenario 1 and 2 in Pearce 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
Swanbourne	625	625	594
Pearce	627	625	603

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's roof insulation, the 'Do Nothing' approach has the higher cost over the building's life cycle compared to 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 m² distributed on six levels. The 1.100 m² roof is insulated, resulting in low energy losses and, consequently, in a very limited energy saving potential, also given the small impact of the roof on the overall building's energy demand. The main features of the building's energy performance both for Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 07.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	442,5	481,0
Energy consumption after cool roof (MWh)	438,0	476,5
Energy savings (MWh)	4,5	4,5
Energy savings (%)	1,02%	0,94%
Area (m²)	1.100	1.100
Roof costs - Metal roof (AU$/m²)	38,0	38,0
Roof costs - Coating (AU$/m²)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m²)	15,0	15,0

Building 07 is 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.

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 1,1% and 1,9% for the metal cool roof for all energy price scenarios and both locations and between 22,8% and 23,2% for the high energy scenario for Swanbourne and Redland Pearce.

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 Swanbourne and for Pearce weather conditions respectively.

Due to the large impact of the roof on the building's cooling loads. The metal cool roof is due to its higher initial investment cost only marginally feasible. The feasibility results are practically identical for both locations.

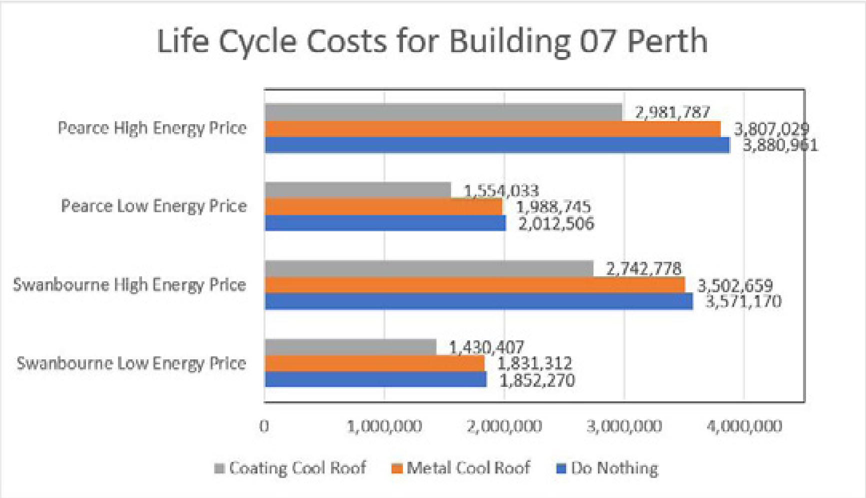

Figure 12. Life Cycle Costs for Building 07 for Swanbourne and Pearce weather stations.

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	1,13 %	1,92 %	1,18 %	1,90 %
Coating Cool Roof	22,78 %	23,20 %	22,78 %	23,17 %

7

CONCLUSIONS

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

• In the eleven weather stations in Perth, 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 56.3-67.0 kWh/m^2 to 55.9-66.6 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.3-10.2 kWh/m^2. This is equivalent to 10.9-18.1 % 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 (0.0 kWh/m^2) is significantly lower than the annual cooling load reduction (1.5-2.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.9-1.1 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.5-1.9 kWh/m^2 (~0.9-1.1 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 22.8-39.3 °C and 22.2-41.4 °C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.2 °C and 0.3 °C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.3 and 1.1 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 13.4-29.8 °C in reference scenario to a range between 13.4-29.7 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 12.6-29.4 ^{o}C in reference scenario to a range between 12.6-29.3 ^{o}C in reference with cool roof scenario (scenario 1) in Pearce 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 0.04 ^{o}C ^{o}C in Swanbourne and Pearce 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 117 hours in reference scenario to 118 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce station also show a increase in total number of hours below 19 °C from 165 hours in reference scenario to 174 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 19 hours in reference scenario to 20 hours in reference with cool roof scenario (scenario 1) in Swanbourne station.

However, the calculation in Pearce station shows is expected to slightly increase from 31 hours in reference scenario to 35 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 625 hours under the reference scenario in Swanbourne station, which decreases to 594 hours under cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also shows that the number of hours above 26 °C decreases from 627 to 625 and 603 under Scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's existing roof insulation, the 'Do Nothing' approach has 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 1,1% and 1,9% for the metal cool roof for all energy price scenarios and both locations and between 22,8% and 23,2% for the high energy scenario for Swanbourne and Redland Pearce, 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. The feasibility results are practically identical for both locations.

B07

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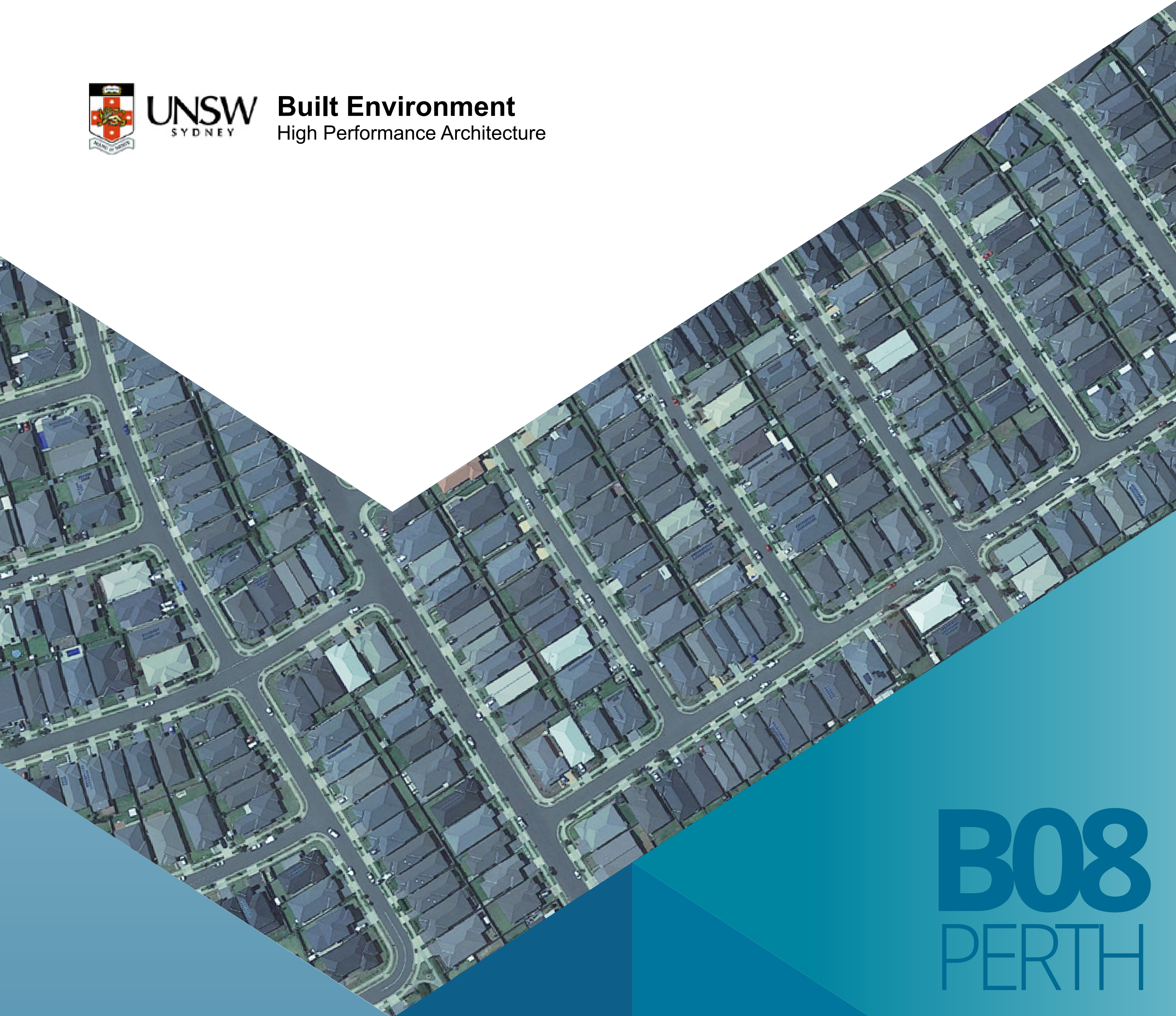

B08
PERTH

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 Perth using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise aparment building from 7.5-13.2 kWh/m² to 6.4-12.1 kWh/m².

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

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Jandakot	7.3	9.0	6.4	7.9	4.9	5.5
Pearce	11.1	13.2	10.1	12.1	8.7	9.7
Perth Airport	10.0	12.0	9.0	10.8	7.1	7.7
Perth Metro	7.8	9.8	6.9	8.7	5.2	5.8
Swanbourne	5.6	7.5	4.7	6.4	3.5	4.1

For Scenario 1, the total cooling load saving is around 1.1 kWh/m² which is equivalent to 8.6-14.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.4-4.3 kWh/m² which is equivalent to 26.7-45.2 % total cooling load reduction.

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.

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	%
Jandakot	0.9	12.3	1.1	11.8	2.3	32.2	3.5	38.6
Pearce	1.0	9.2	1.1	8.6	2.4	21.8	3.5	26.7
Perth Airport	1.0	10.0	1.1	9.4	2.9	29.4	4.3	35.6
Perth Metro	0.9	11.7	1.1	11.2	2.6	33.2	3.9	40.1
Swanbourne	0.8	14.7	1.1	14.3	2.1	37.6	3.4	45.2

In the eleven weather stations in Perth, 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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

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 (0.8-0.9 kWh/m²) is slightly lower than the annual cooling load reduction (1.7-2.3 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Jandakot	14.9	17.5	14.8	23.4	13.4	15.8	15.4	24.3
Pearce	19.0	22.3	13.8	21.9	17.1	20.3	14.5	22.8
Perth Airport	17.8	20.5	14.0	22.1	16.1	18.6	14.6	22.9
Perth Metro	17.0	20.6	11.8	18.8	14.9	18.3	12.4	19.7
Swanbourne	10.2	13.5	9.9	15.7	8.8	11.7	10.5	16.5

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 apartment building using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 8.8-13.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8 and 1.4 kWh/m² (~ 1.9-3.6 %).

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	%
Jandakot	1.5	10.1	1.7	9.5	0.7	0.9	0.9	2.9	0.8	1.9
Pearce	1.8	9.7	2.0	9.0	0.7	0.9	1.2	3.6	1.1	2.5
Perth Airport	1.7	9.5	1.8	8.8	0.6	0.8	1.1	3.4	1.0	2.3
Perth Metro	2.1	12.2	2.3	11.3	0.7	0.9	1.4	4.9	1.4	3.6
Swanbourne	1.4	13.6	1.8	13.1	0.6	0.8	0.8	4.1	1.0	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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

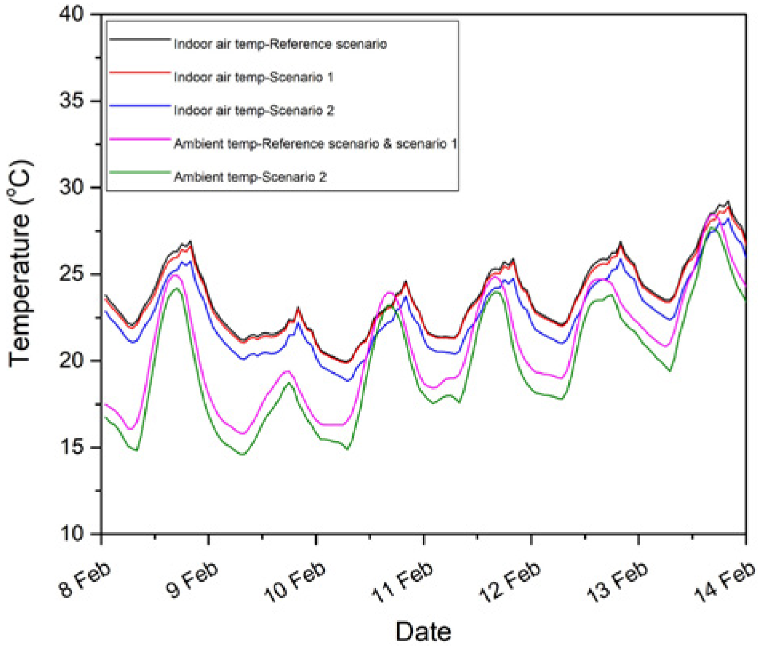

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

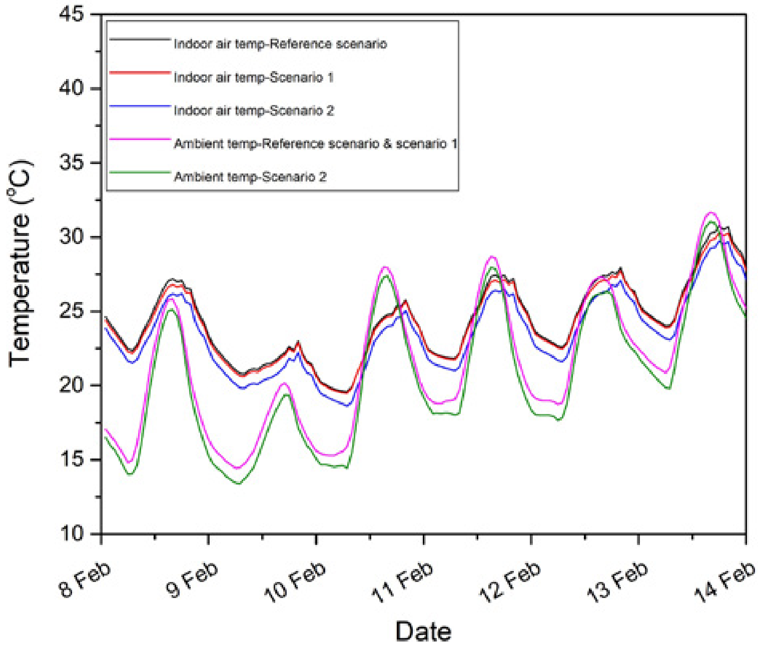

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 23.8-29.2 °C and 19.6-30.9 °C in Swanbourne and Pearce stations, respectively.

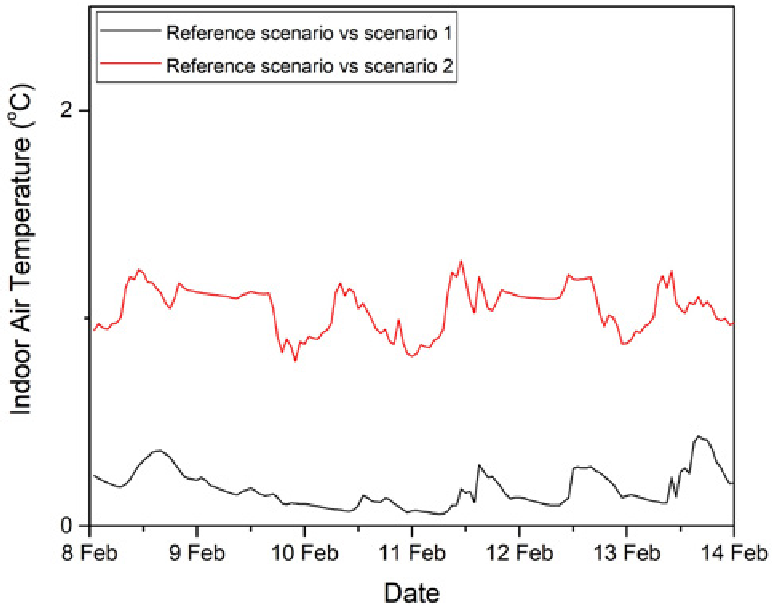

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical summer week in *Swanbourne 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 0.5 °C in Swanbourne and Pearce stations, respectively.

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

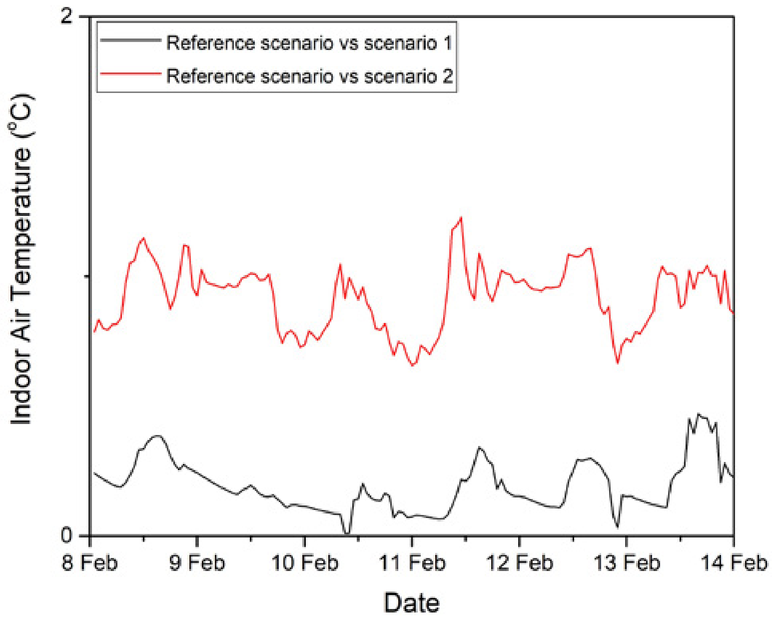

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.0-21.3 °C in reference scenario to a range 11.9-21.1 °C in scenario 1 in Swanbourne station.

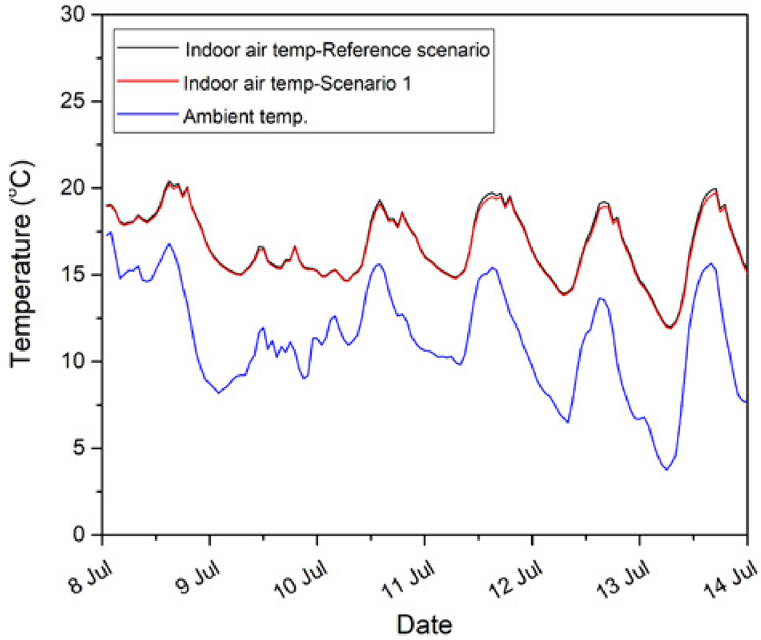

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Swanbourne station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 11.2-20.7 °C in reference scenario to a range 11.1-20.6 °C in scenario 1 in Pearce station.

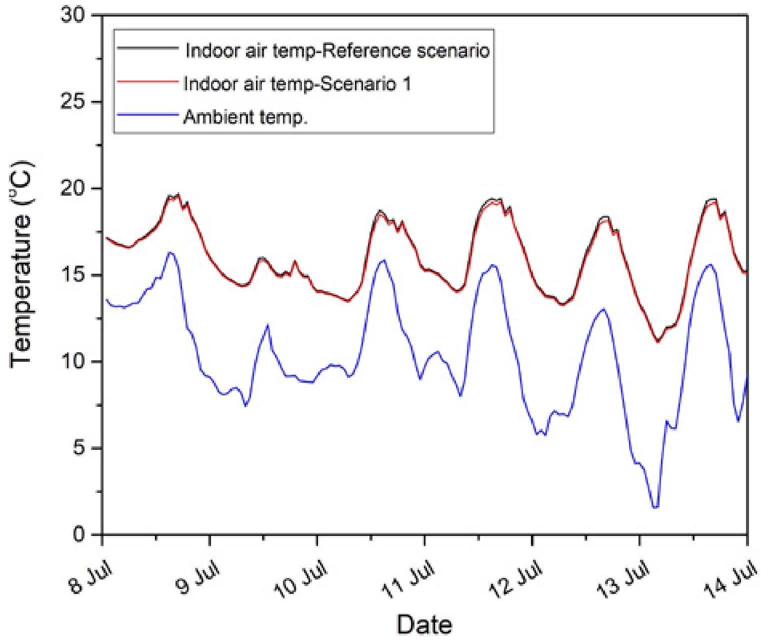

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Pearce station* using annual measured weather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

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

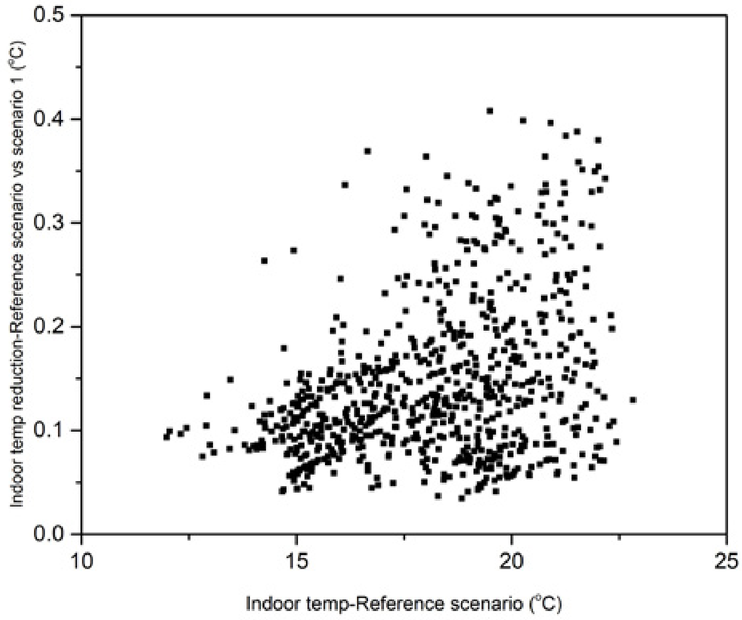

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

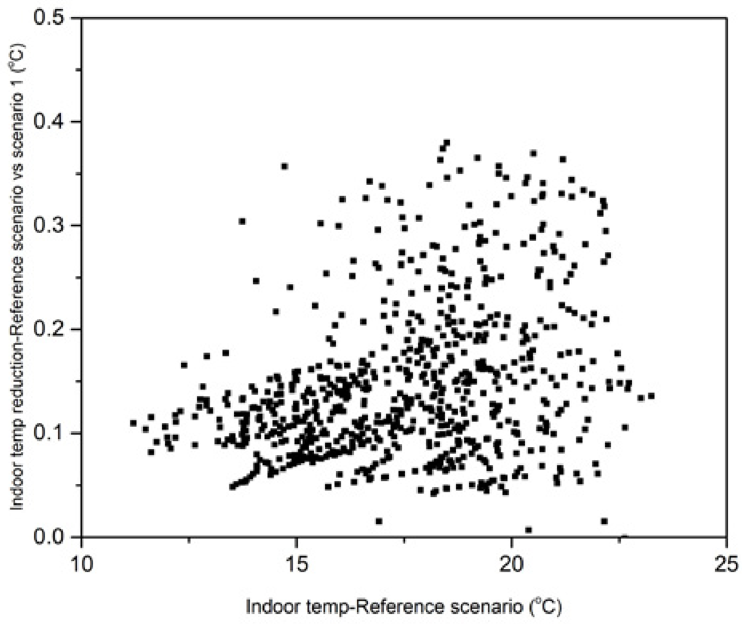

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 442 hours in reference scenario to 465 hours and from 524 to 540 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Swanbourne	442	465
Pearce	524	540

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 328 hours in reference scenario to 289 and 210 hours under scenario 1 and 2 in Swanbourne station; and from 408 hours in reference scenario to 388 and 328 hours under scenario 1 and 2 in Pearce station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	328	289	210
Pearce	408	388	328

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

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

Table 7. Energy performance features of Building 08.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	21,9	33,1
Energy consumption after cool roof (MWh)	21,1	32,3
Energy savings (MWh)	0,8	0,8
Energy savings (%)	3,65%	2,42%
Area (m^2)	624	624
Roof costs - Metal roof (AU$/m^2)	38,0	38,0
Roof costs - Coating (AU$/m^2)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m^2)	15,0	15,0

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

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in an energy requirements' decrease of 3,65% for the Swanbourne and 2,42% for the Pearce weather. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

> *The coating cool roof option leads to a reduction of life cycle costs, that vary between 16,1% for the low energy price scenario for Swanbourne and 21,4% for the high energy scenario and for Pearce 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 Swanbourne and for Pearce weather conditions respectively.

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

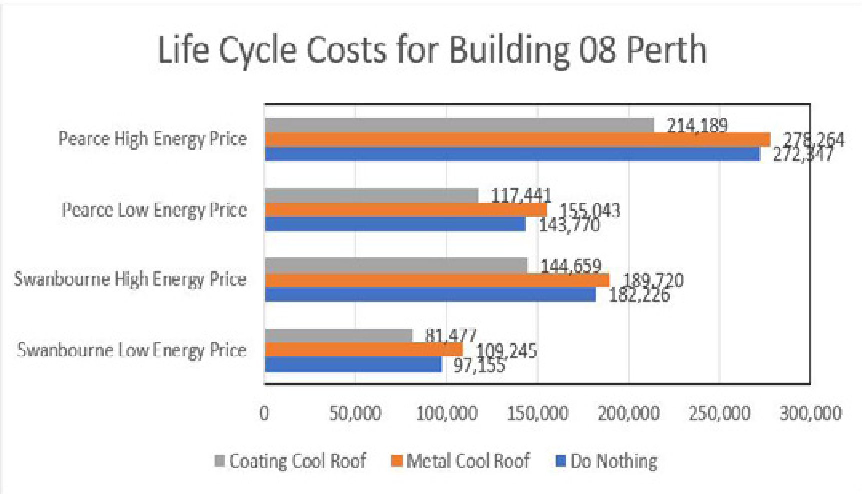

Figure 12. Life Cycle Costs for Building 08 for Swanbourne and Pearce weather stations.

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	-12,44 %	-4,11 %	-7,84 %	-2,17 %
Coating Cool Roof	16,14 %	20,62 %	18,31 %	21,35 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment from 7.5-13.2 kWh/m^2 to 6.4-12.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.1 kWh/m^2. This is equivalent to approximately 8.6-14.3 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.4-4.3 kWh/m^2. This is equivalent to 26.7-45.2 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.8-0.9 kWh/m^2) is slightly lower than the annual cooling load reduction (1.7-2.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 8.8-13.1 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8 and 1.4 kWh/m^2 (~ 1.9-3.6 %) (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 23.8-29.2 ^{o}C and 19.6-30.9 ^{o}C in Swanbourne and Pearce 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 0.5 ^{o}C in Swanbourne and Pearce 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 Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 12.0-21.3 ^{o}C in reference scenario to a range between 11.9-21.1 ^{o}C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.2-20.7 °C in reference scenario to a range between 11.2-20.6 °C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C for both Swanbourne and Pearce 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 442 hours in reference scenario to 465 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slightly increase in total number of hours below 19 °C from 524 hours in reference scenario to 465 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 328 hours under the reference scenario in Swanbourne station, which decreases to 289 and 210 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also illustrate a significant reduction in number of hours above 26 °C from 408 hours in reference scenario to 388 in reference with cool roof scenario (scenario 1) and 328 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 16,1% for the low energy price scenario for Swanbourne and 21,4% for the high energy scenario and for Pearce conditions, as it can be seen in Table . The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations. Building 08 is in that sense an interesting example of a new, low-rise residential building, where the energy conservation potential is rather limited. However, even so, the coating cool technology emerges as a meaningful investment.

B08

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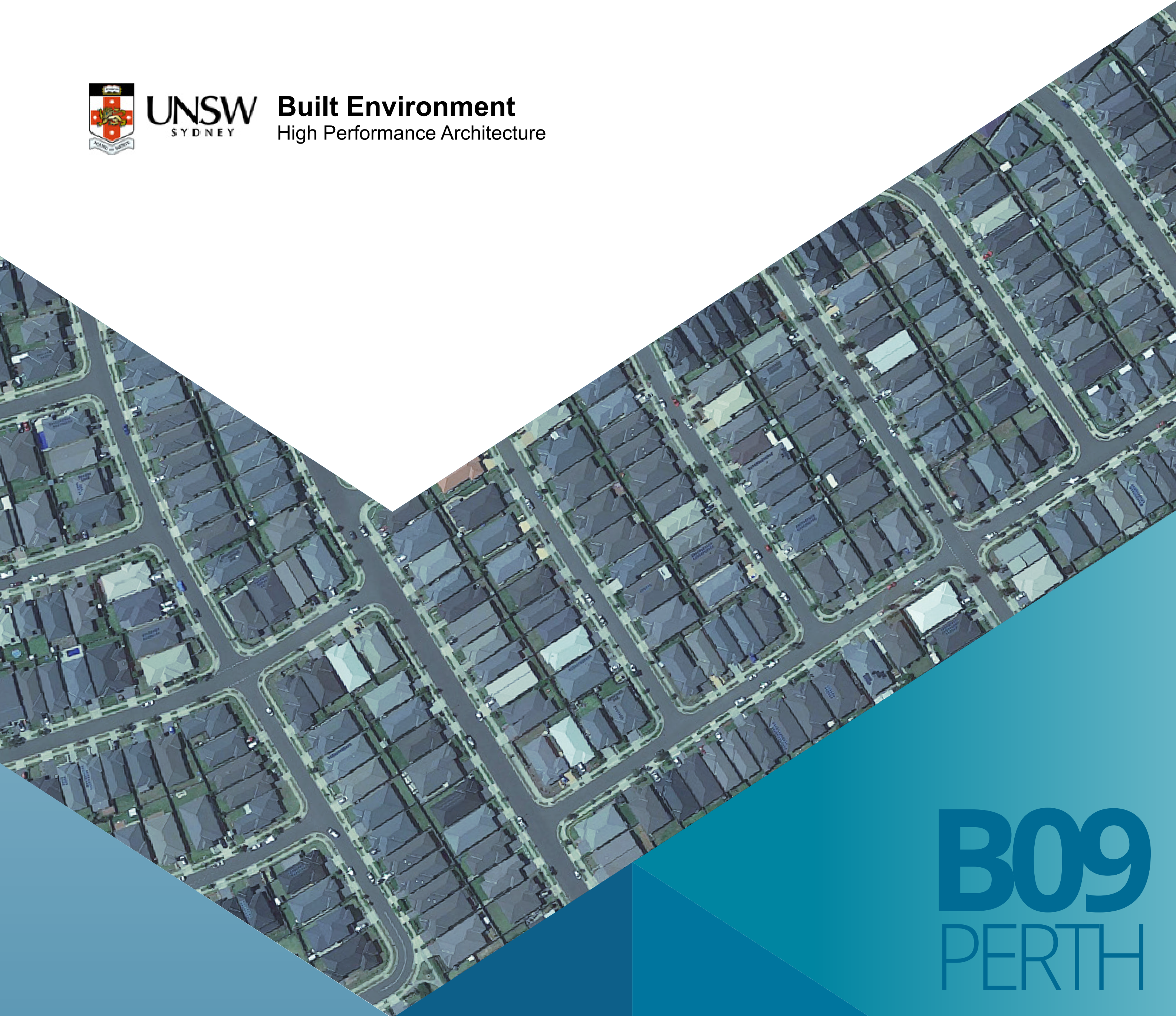

B09
PERTH

COOL ROOFS
COST BENEFIT ANALYSIS

New mid-rise apartment
2021

BUILDING 09

NEW MID-RISE APARTMENT

Floor area : 624m^2
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 Perth 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 aparment building from 7.1-12.8 kWh/m² to 6.5-12.2 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/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Jandakot	6.9	8.6	6.4	8.0	4.9	5.5
Pearce	10.7	12.8	10.1	12.2	8.7	9.7
Perth Airport	9.6	11.5	9.0	10.9	7.1	7.7
Perth Metro	7.4	9.3	6.9	8.7	5.2	5.8
Swanbourne	5.2	7.1	4.7	6.5	3.5	4.1

For Scenario 1, the total cooling load saving is around 0.6-0.7 kWh/m² which is equivalent to 5.1-8.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.1-3.8 kWh/m² which is equivalent to 24.1-42.0 % 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/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Jandakot	0.5	7.4	0.6	7.1	2.0	28.8	3.1	35.7
Pearce	0.6	5.5	0.7	5.1	2.0	18.8	3.1	24.1
Perth Airport	0.6	6.0	0.7	5.6	2.5	26.5	3.8	33.2
Perth Metro	0.5	7.1	0.6	6.7	2.2	30.1	3.5	37.5
Swanbourne	0.5	9.0	0.6	8.8	1.8	33.8	3.0	42.0

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

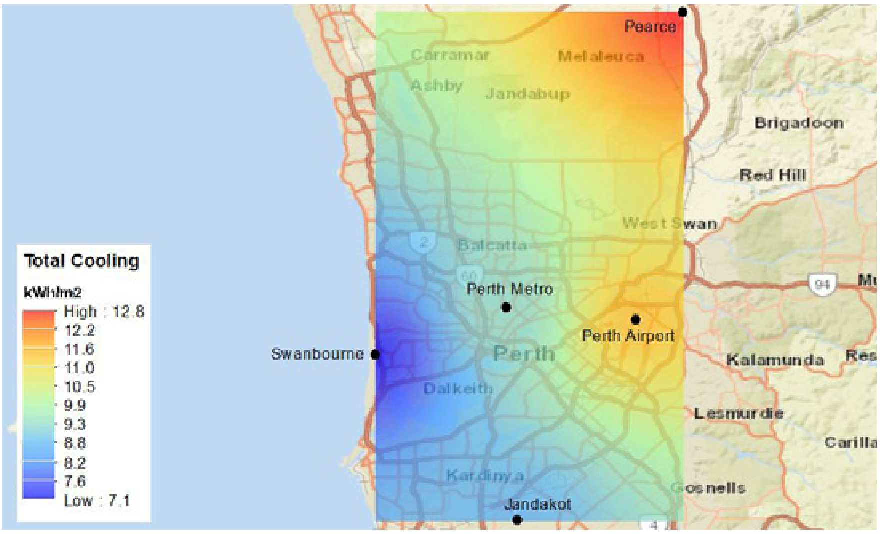

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

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

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

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.4-0.5 kWh/m²) is nearly the same that the annual cooling load reduction (0.9-1.3 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Jandakot	14.1	16.7	14.0	22.5	13.3	15.7	14.4	23.0
Pearce	18.1	21.3	13.0	20.9	17.0	20.2	13.3	21.5
Perth Airport	16.9	19.6	13.3	21.2	16.0	18.6	13.6	21.7
Perth Metro	16.1	19.6	11.0	17.8	14.9	18.3	11.3	18.4
Swanbourne	9.6	12.8	9.3	15.0	8.8	11.8	9.6	15.4

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.

The annual cooling load saving by building-scale application of cool roofs is around 5.1-7.9 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.5 and 0.8 kWh/m² (~ 1.1-2.1 %).

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	%
Jandakot	0.8	6.0	0.9	5.5	0.4	0.5	0.5	1.7	0.4	1.1
Pearce	1.0	5.7	1.1	5.2	0.4	0.5	0.7	2.1	0.6	1.4
Perth Airport	0.9	5.5	1.0	5.1	0.3	0.5	0.6	2.0	0.5	1.3
Perth Metro	1.2	7.4	1.3	6.7	0.4	0.5	0.8	3.0	0.8	2.1
Swanbourne	0.8	8.2	1.0	7.9	0.3	0.4	0.5	2.4	0.6	2.0

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

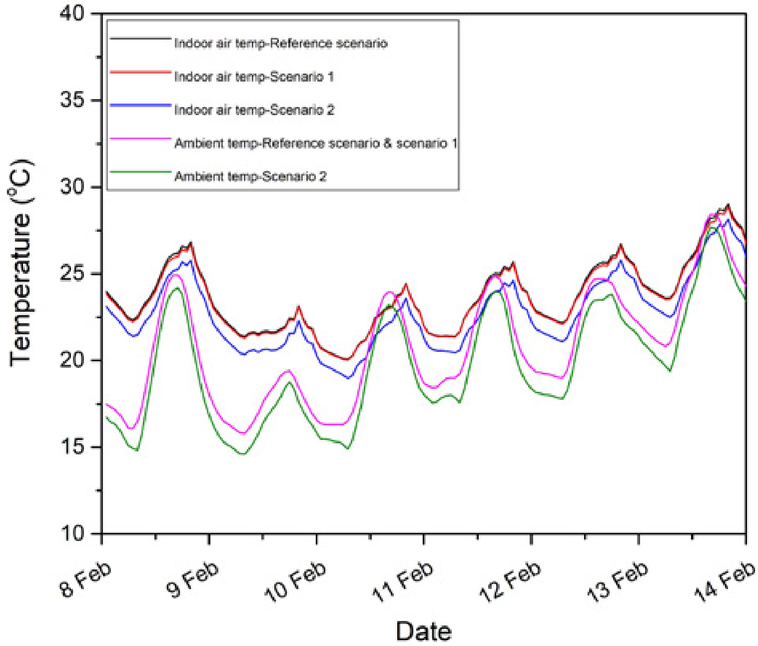

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

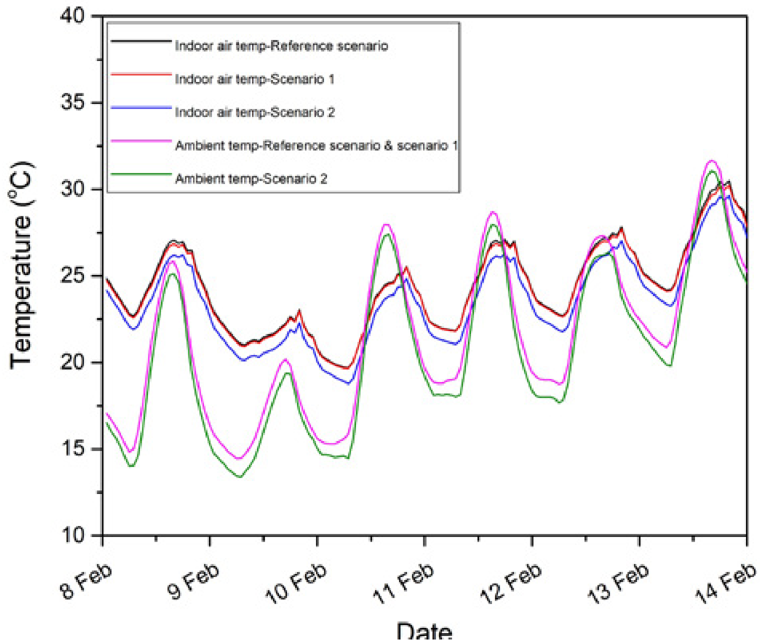

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 20.1-29.0 °C and 19.7-30.8 °C in Swanbourne and Pearce stations, respectively.

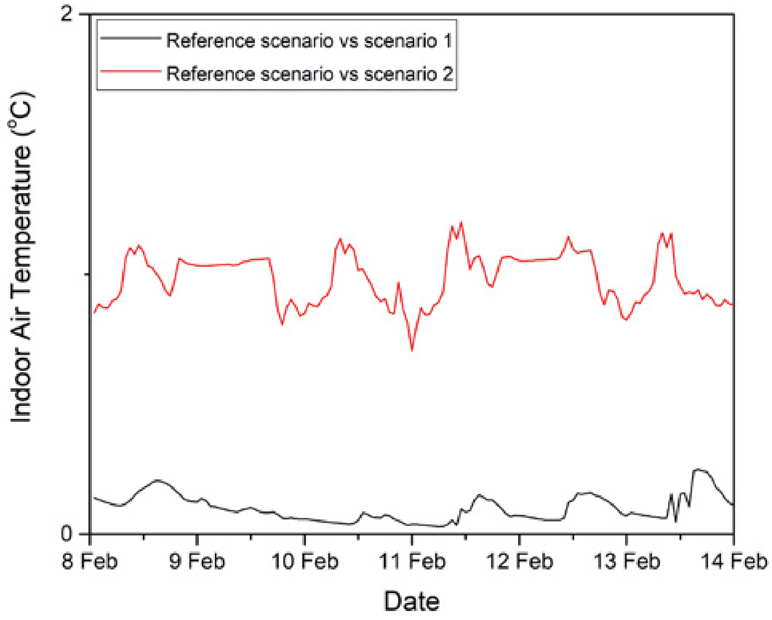

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical summer week in *Swanbourne 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 0.3 °C in Swanbourne and Pearce 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 Swanbourne and Pearce stations, respectively.

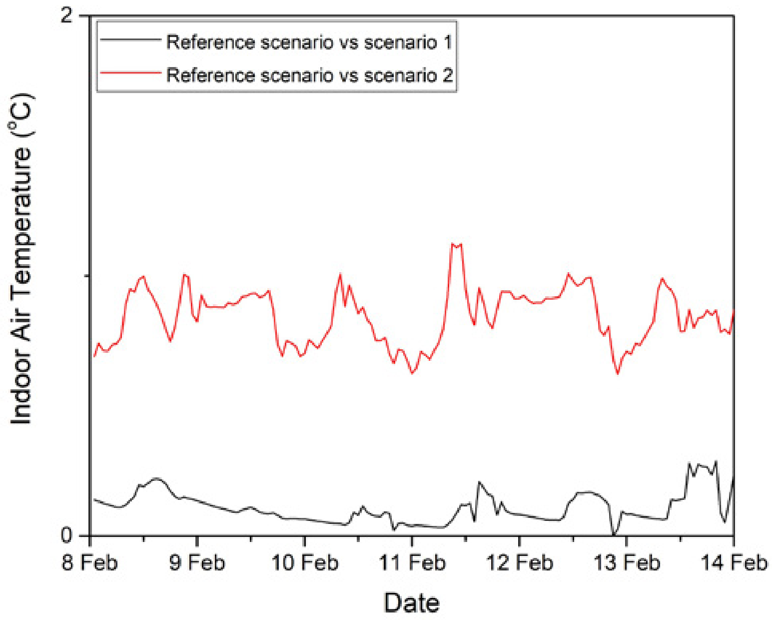

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 12.3-21.1 °C in reference scenario to a range 12.2-21.1 °C in scenario 1 in Swanbourne station.

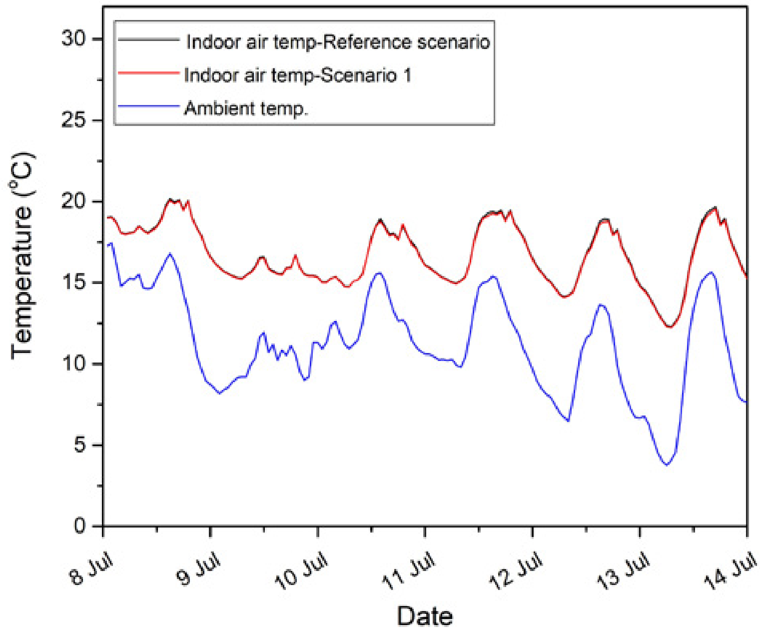

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Swanbourne station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 11.5-20.5 °C in reference scenario to a range 11.4-20.5 °C in scenario 1 in Pearce station.

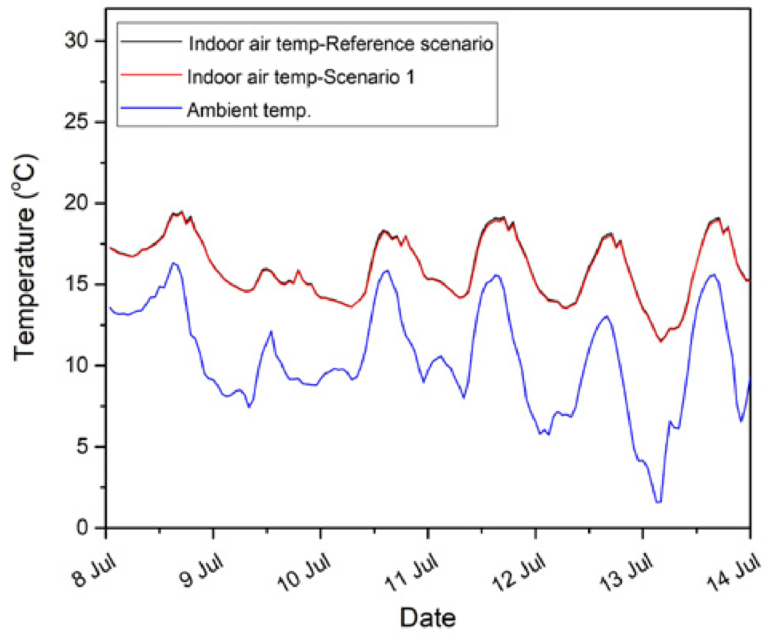

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Pearce station* using annual measured weather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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce stations.

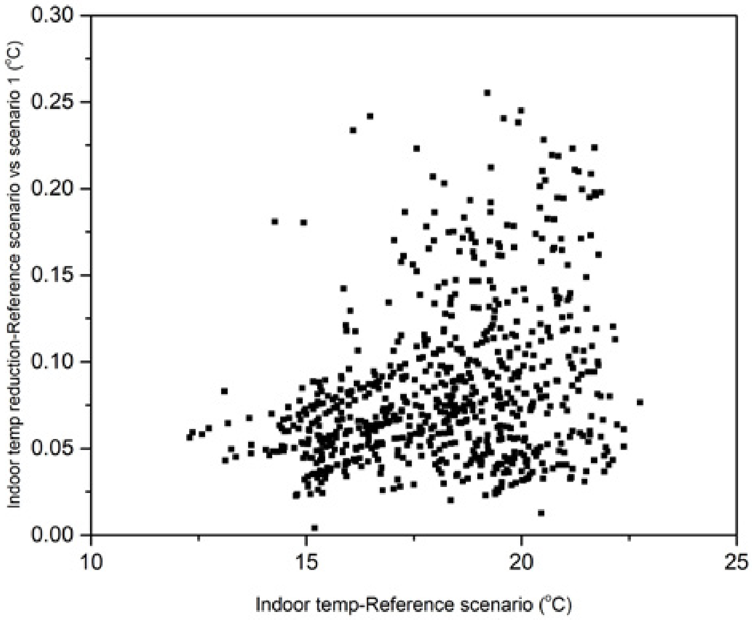

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

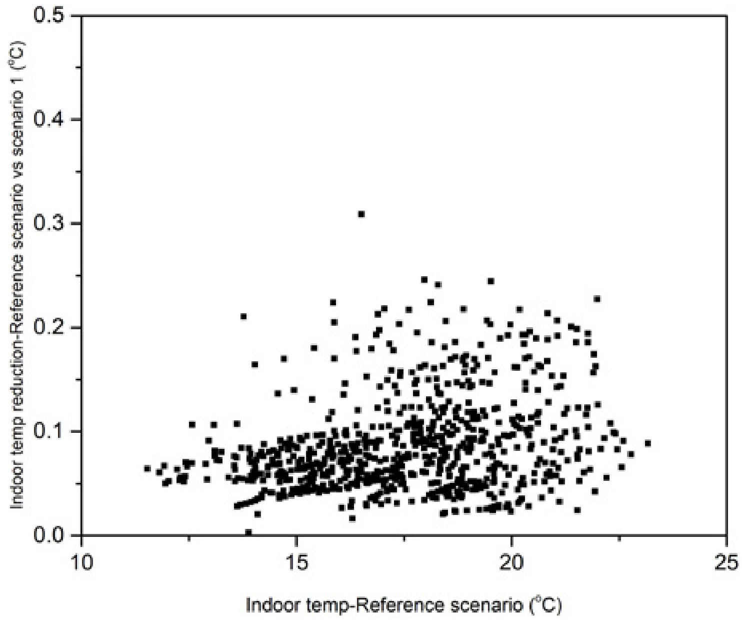

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 449 hours in reference scenario to 459 hours and from 532 to 546 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Swanbourne	449	459
Pearce	532	546

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 329 hours in reference scenario to 304 and 219 hours under scenario 1 and 2 in Swanbourne station; and from 412 hours in reference scenario to 403 and 346 hours under scenario 1 and 2 in Pearce station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	329	304	219
Pearce	412	403	346

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 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 Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 09.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	34,7	52,7
Energy consumption after cool roof (MWh)	33,9	52,0
Energy savings (MWh)	0,8	0,7
Energy savings (%)	2,31%	1,33%
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 2,31% for Swanbourne weather conditions and of 1,33% 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 18,5% for the low energy price scenario for Swanbourne and 21,8% for the high energy scenario and for Pearce 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 Swanbourne and for Pearce weather conditions respectively.

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

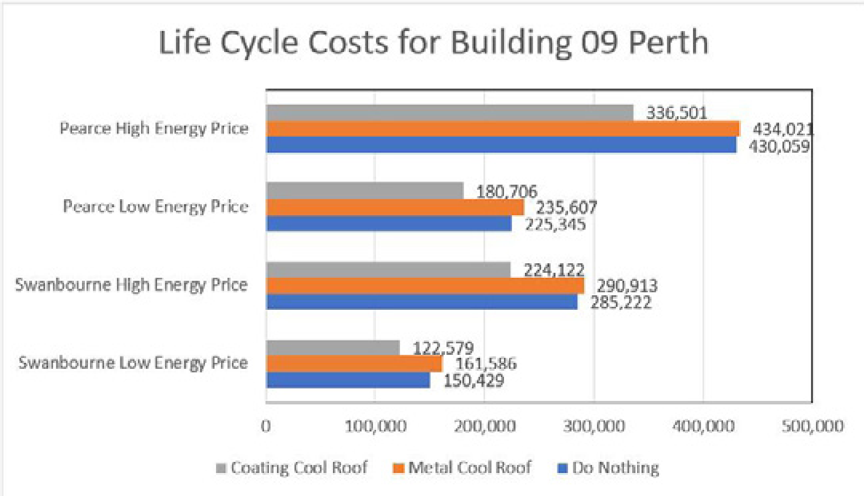

Figure 12. Life Cycle Costs for Building 09 for Swanbourne and Pearce weather stations.

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

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-7,42 %	-2,00 %	-4,55 %	-0,92 %
Coating Cool Roof	18,51 %	21,42 %	19,81 %	21,75 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise apartment from 7.1-12.8 kWh/m^2 to 6.5-12.2 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.6-0.7 kWh/m^2. This is equivalent to approximately 5.1-8.8 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.1-3.8 kWh/m^2 . This is equivalent to 24.1-42.0 % 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 (0.4-0.5 kWh/m^2) is nearly the same that the annual cooling load reduction (0.9-1.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 5.1-7.9 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.5 and 0.8 kWh/m^2 (~ 1.1-2.1 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 20.1-29.0 ^{o}C and 19.7-30.8 ^{o}C in Swanbourne and Pearce 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 0.3 ^{o}C in Swanbourne and Pearce 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 Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 12.3-21.1 ^{o}C in reference scenario to a range between 12.2-21.1 ^{o}C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.5-20.5 °C in reference scenario to a range between 11.4-20.5 °C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce 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 449 hours in reference scenario to 459 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slightly increase in total number of hours below 19 °C from 532 hours in reference scenario to 546 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 329 hours under the reference scenario in Swanbourne station, which decreases to 304 and 219 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also illustrate a significant reduction in number of hours above 26 °C from 412 hours in reference scenario to 403 in reference with cool roof scenario (scenario 1) and 346 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a clearly higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 18,5% for the low energy price scenario for Swanbourne and 21,8% for the high energy scenario and for Pearce conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations. Building 09 is in that sense an interesting example of a mid-rise residential building, where the energy conservation potential is not big. However, even so the application of a coating cool roof technology emerges as a meaningful investment.

B09

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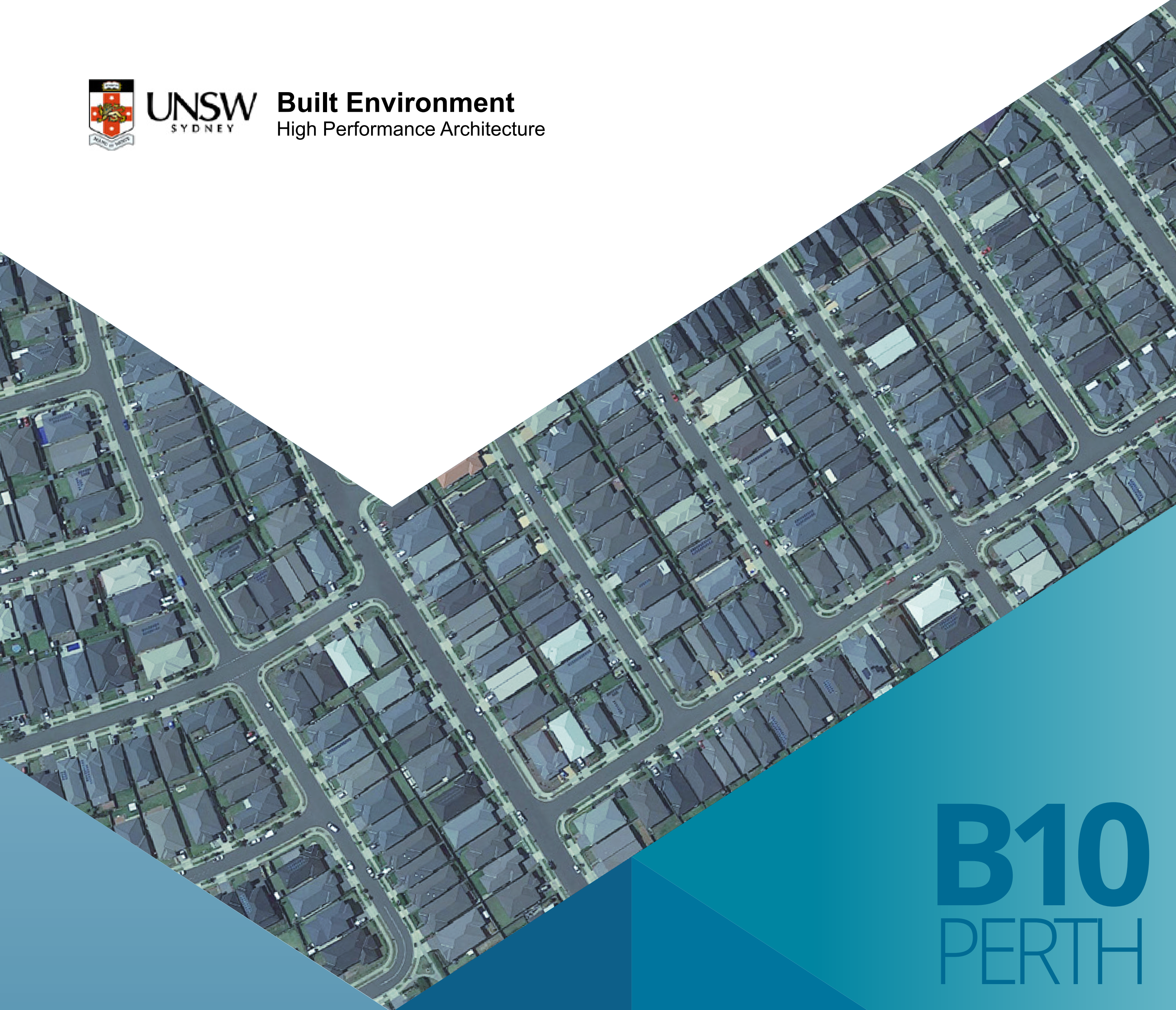

B10
PERTH

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 Perth 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 high-rise apartment building from 6.8-12.5 kWh/m² to 6.4-12.1 kWh/m².

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.

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)
Jandakot	6.6	8.3	6.3	7.9	4.9	5.5
Pearce	10.4	12.5	10.0	12.1	8.6	9.7
Perth Airport	9.3	11.2	9.0	10.8	7.0	7.7
Perth Metro	7.1	9.0	6.8	8.6	5.1	5.8
Swanbourne	5.0	6.8	4.7	6.4	3.4	4.0

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 kWh/m² which is equivalent to 3.1-5.4 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.7-3.6 kWh/m² which is equivalent to 22.6-40.1 % 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	%
Jandakot	0.3	4.6	0.4	4.4	1.8	26.8	2.8	34.0
Pearce	0.3	3.4	0.4	3.1	1.8	17.0	2.8	22.6
Perth Airport	0.3	3.6	0.4	3.4	2.3	24.9	3.6	31.8
Perth Metro	0.3	4.3	0.4	4.1	2.0	28.3	3.2	36.0
Swanbourne	0.3	5.6	0.4	5.4	1.6	31.6	2.7	40.1

In the eleven weather stations in Perth, 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.

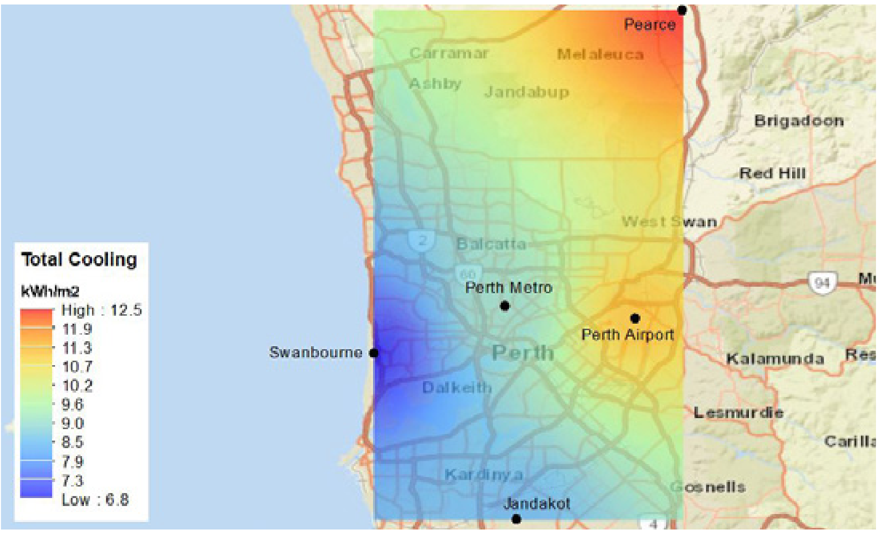

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

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

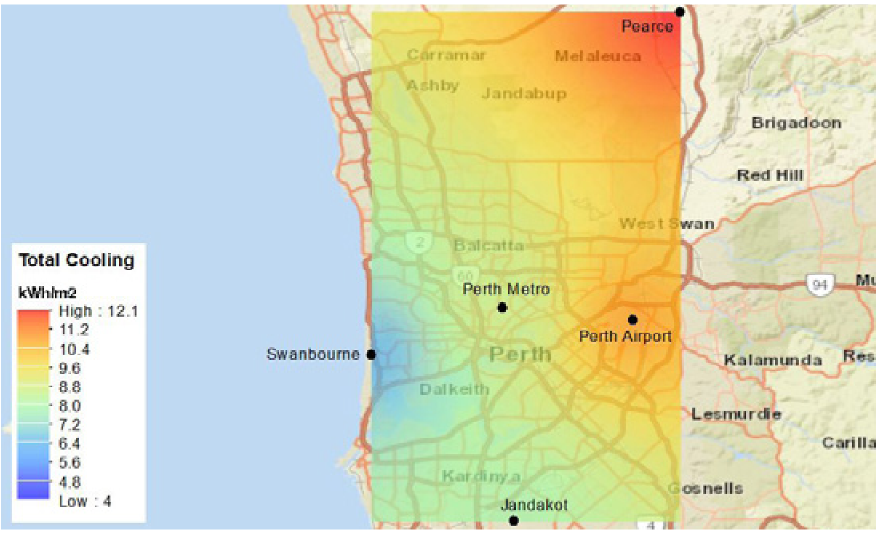

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

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 Perth 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 (0.3 kWh/m²) is slightly lower than the annual cooling load reduction (0.5-0.8 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
Jandakot	13.6	16.1	13.7	22.2	13.1	15.6	13.9	22.5
Pearce	17.4	20.7	12.7	20.6	16.8	20.0	12.9	20.9
Perth Airport	16.4	19.0	13.0	20.9	15.8	18.4	13.2	21.2
Perth Metro	15.4	18.9	10.6	17.5	14.7	18.2	10.9	17.8
Swanbourne	9.1	12.2	9.0	14.7	8.7	11.6	9.2	15.0

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

The annual cooling load saving by building-scale application of cool roofs is around 3.1-4.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.2 and 0.5 kWh/m² (~ 0.6-1.2 %).

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	%
Jandakot	0.5	3.6	0.5	3.3	0.2	0.3	0.3	0.9	0.2	0.6
Pearce	0.6	3.4	0.7	3.2	0.2	0.3	0.4	1.2	0.3	0.8
Perth Airport	0.5	3.3	0.6	3.1	0.2	0.3	0.3	1.2	0.3	0.8
Perth Metro	0.7	4.5	0.8	4.1	0.2	0.3	0.5	1.8	0.5	1.2
Swanbourne	0.4	4.9	0.6	4.7	0.2	0.3	0.3	1.4	0.3	1.2

3

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

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

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

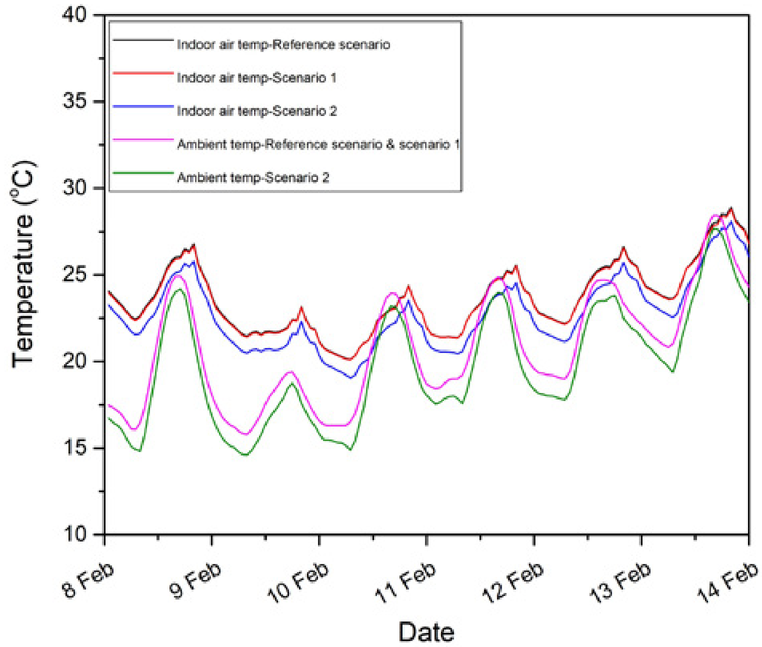

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

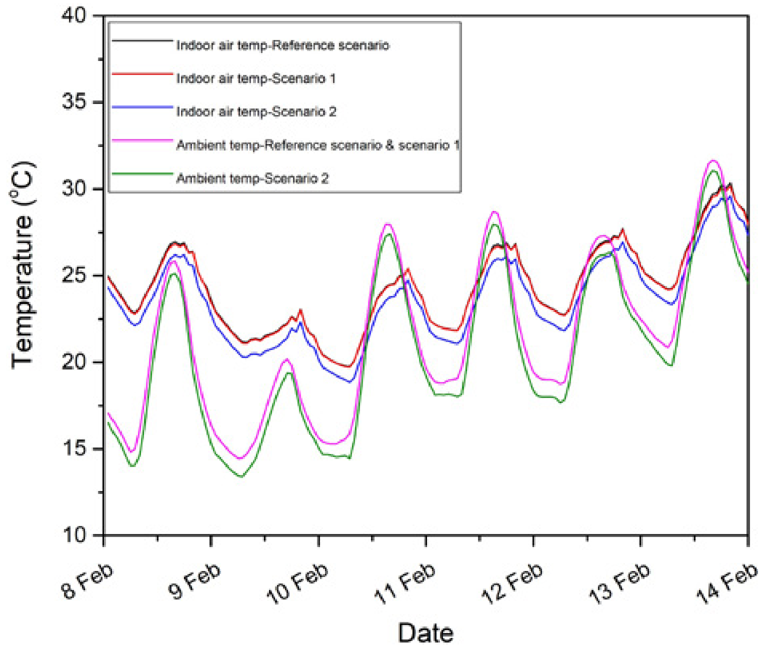

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.1-28.9 °C and 19.8-30.6 °C in Swanbourne and Pearce stations, respectively.

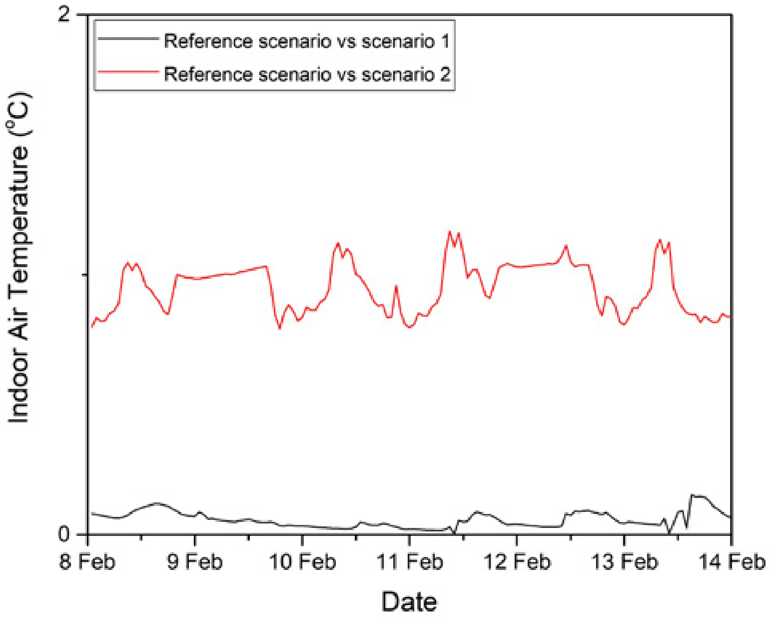

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical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

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

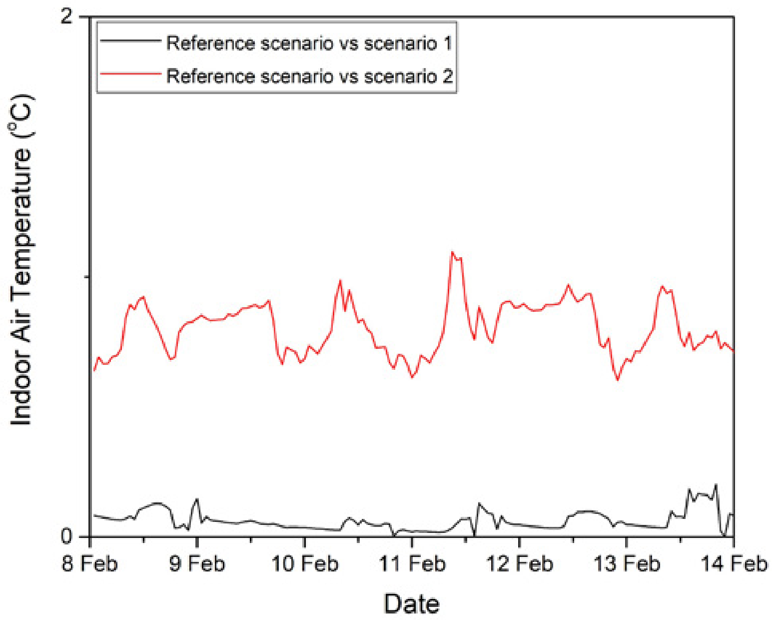

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.4-21.0 ºC in reference scenario to a range 12.4-21.0 ºC in scenario 1 in Swanbourne station.

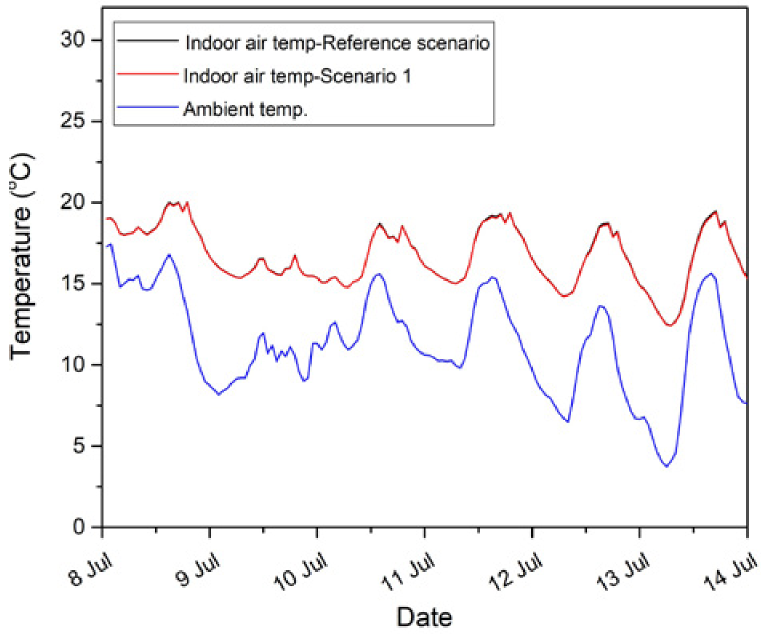

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Swanbourne station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 11.7-20.4 ºC in reference scenario to a range 11.6-20.4ºC in scenario 1 in Pearce station.

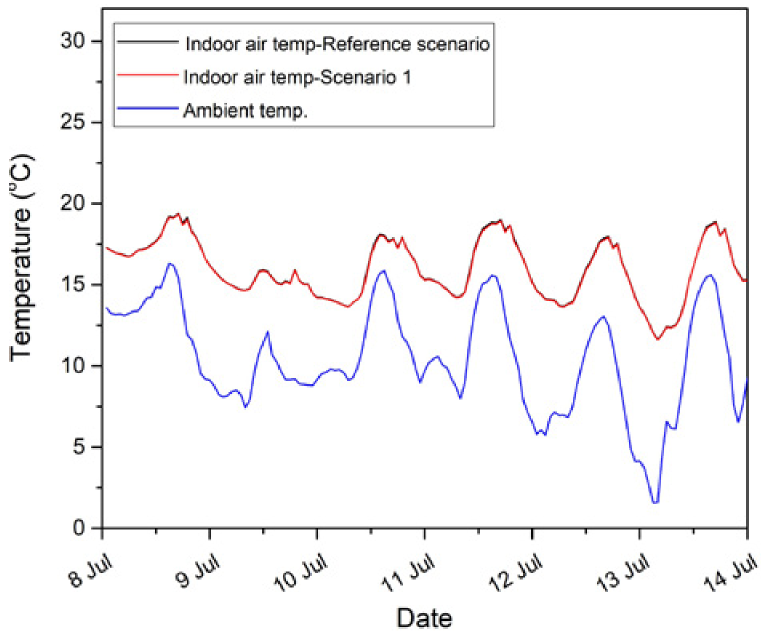

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Pearce station* using annual measured weather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

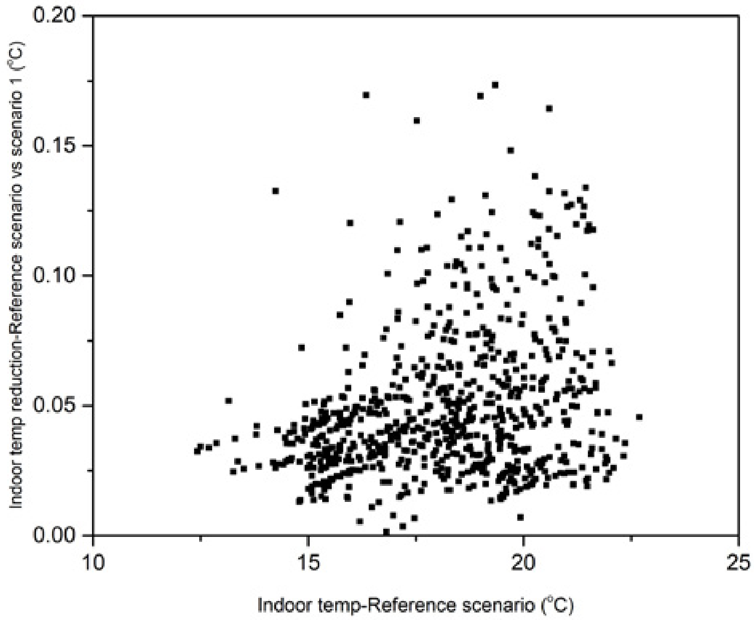

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

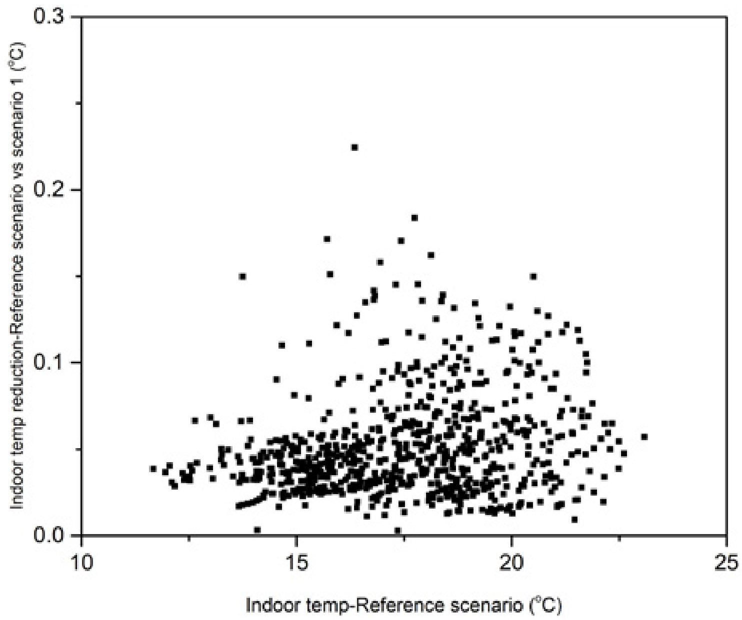

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 456 hours in reference scenario to 465 hours and from 540 to 550 hours in scenario 1 in Swanbourne and Pearce 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
Swanbourne	456	465
Pearce	540	550

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 327 hours in reference scenario to 314 and 216 hours under scenario 1 and 2 in Swanbourne station; and from 412 hours in reference scenario to 408 and 350 hours under scenario 1 and 2 in Pearce 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
Swanbourne	327	314	216
Pearce	412	408	350

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 10 is a new, high-rise apartment building, with a total air-conditioned area of 4.992 m^2 distributed on six levels. The 624 m^2 roof is insulated, resulting in modest energy savings. The main features of the building's energy performance both for Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 10.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	53,7	82,5
Energy consumption after cool roof (MWh)	53,1	81,7
Energy savings (MWh)	0,6	0,8
Energy savings (%)	1,12%	0,97%
Area (m^2)	624	624
Roof costs - Metal roof (AU\$/m^2)	38,0	38,0
Roof costs - Coating (AU\$/m^2)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU\$/m^2)	15,0	15,0

The cool roof refurbishment options

Building 10 is an interesting example of a new, high-rise residential building, where the energy conservation potential is truly modest. However, even so, the application of a coating cool technology emerges as a very meaningful investment.

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

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

Both options have the same energy efficiency, resulting in an energy requirements' decrease of 1,12% for the Swanbourne weather conditions and of 0,92% for the Pearce conditions. These savings are within the limits of simulative errors, but even so it is of interest to examine the feasibility The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a significant reduction of life cycle costs, that varies between 19,7% for the low energy price scenario for Swanbourne and 22,3% for the high energy scenario and for Pearce 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 Swanbourne and for Pearce weather conditions respectively.

The metal cool roof is, due to its higher initial investment cost and the modest energy savings, not feasible.

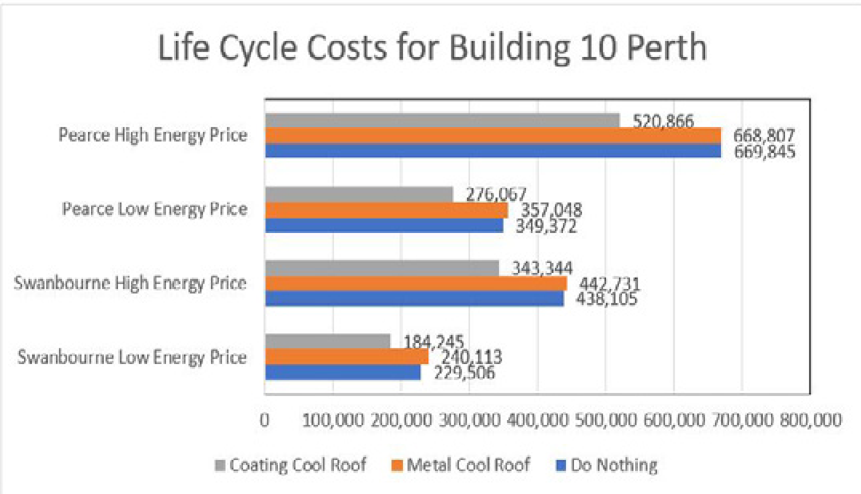

Figure 12. Life Cycle Costs for Building 10 for Swanbourne and Pearce weather stations.

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	-4,62 %	-1,06 %	-2,20 %	0,15 %
Coating Cool Roof	19,72 %	21,63 %	20,98 %	22,24 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 6.8-12.5 kWh/m^2 to 6.4-12.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.4 kWh/m^2. This is equivalent to approximately 3.1-5.4 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 2.7-3.6 kWh/m^2. This is equivalent to 22.6-40.1 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.3 KWh/m^2) is slightly lower than the annual cooling load reduction (0.5-0.8 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.1-4.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.2 and 0.5 kWh/m^2 (~ 0.6-1.2 %) (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 21.1-28.9 °C and 19.8-30.6 °C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.2 and 0.2 °C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.2 and 1.1 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 12.4-21.0 °C in reference scenario to a range between 12.4-21.0 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8). Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.7-20.4 °C in reference scenario to a range between 11.6-20.4°C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 and 0.1 °C for Swanbourne and Pearce 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 456 hours in reference scenario to 465 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slightly increase in total number of hours below 19 °C from 540 hours in reference scenario to 550 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 327 hours under the reference scenario in Swanbourne station, which decreases to 314 and 216 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Pearce station also illustrate a significant reduction in number of hours above 26 °C from 412 hours in reference scenario to 408 in reference with cool roof scenario (scenario 1) and 350 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 19,7% for the low energy price scenario for Swanbourne and 22,3% for the high energy scenario and for Pearce conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the modest energy savings, not feasible. Building 10 is in that sense an interesting example of a new, high-rise residential building, where the energy conservation potential is truly modest. However, even so, the application of a coating cool technology emerges as a very meaningful investment.

B10

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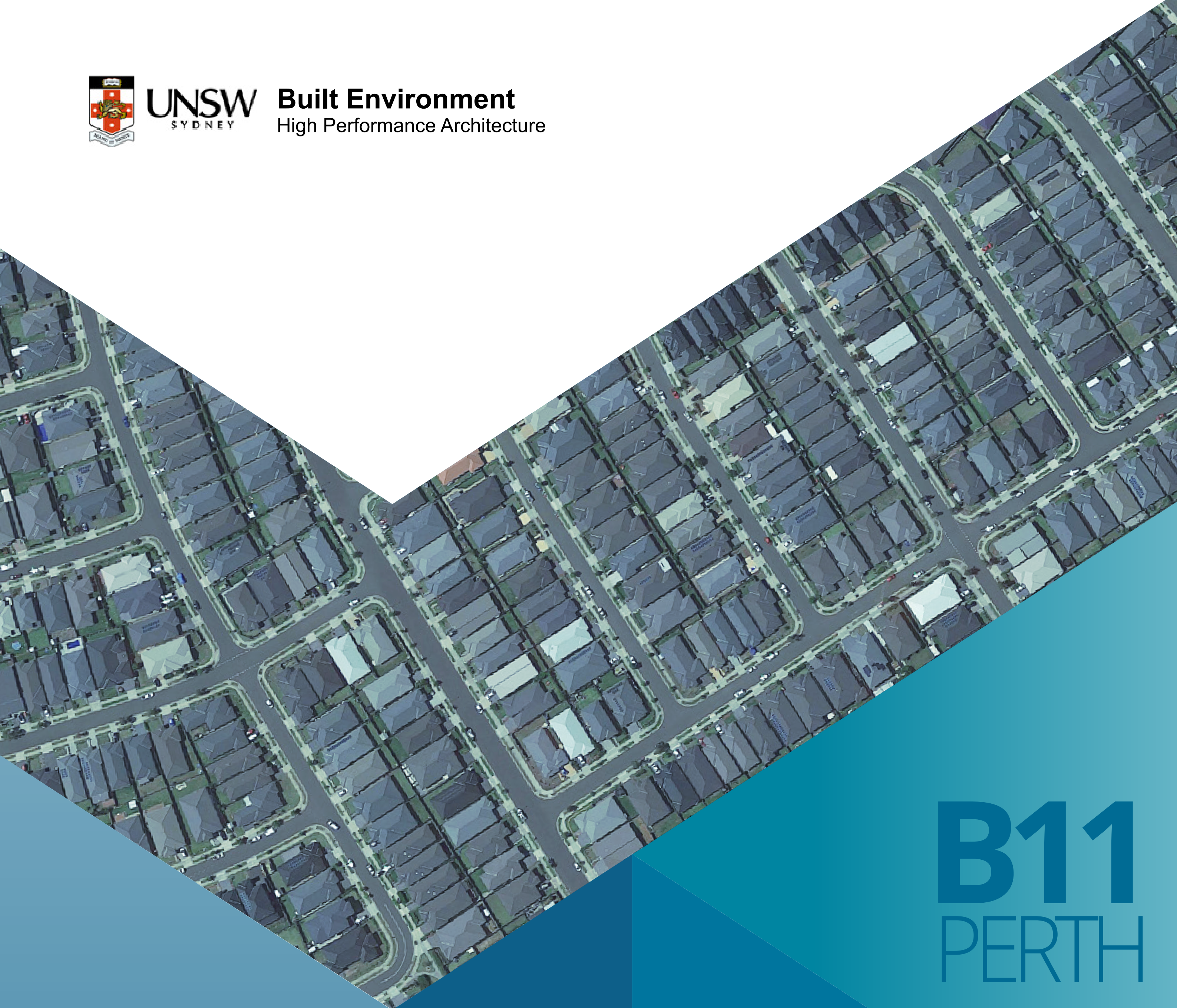

B11
PERTH

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 Perth using weather data simulated by WRF.

Table 1. Sensible and total cooling load for an existing stand-alone house for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing standalone house from 11.4-16.4 kWh/m² to 6.7-9.9 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Jandakot	11.0	12.7	5.5	6.7	4.5	4.9
Pearce	14.4	16.4	8.4	9.9	7.4	8.2
Perth Airport	13.5	15.4	7.6	8.9	6.2	6.7
Perth Metro	11.4	13.4	5.9	7.2	4.7	5.2
Swanbourne	9.2	11.4	4.1	5.3	3.2	3.6

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 6.1-6.6 kWh/m² which is equivalent to 41.9-53.5 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.7-8.7 kWh/m² which is equivalent to 50.3-67.9 % 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	%
Jandakot	5.5	49.7	6.1	47.8	6.5	59.1	7.8	61.5
Pearce	6.1	42.0	6.6	39.9	7.0	48.6	8.3	50.3
Perth Airport	5.9	43.8	6.4	41.9	7.3	53.9	8.7	56.4
Perth Metro	5.5	48.4	6.2	46.3	6.7	58.8	8.2	61.3
Swanbourne	5.2	55.8	6.1	53.5	6.0	65.3	7.7	67.9

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

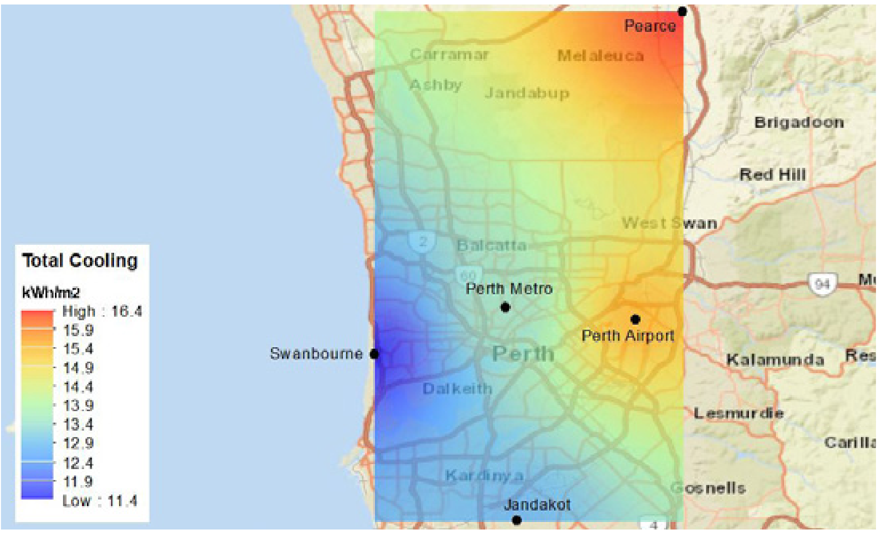

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

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.

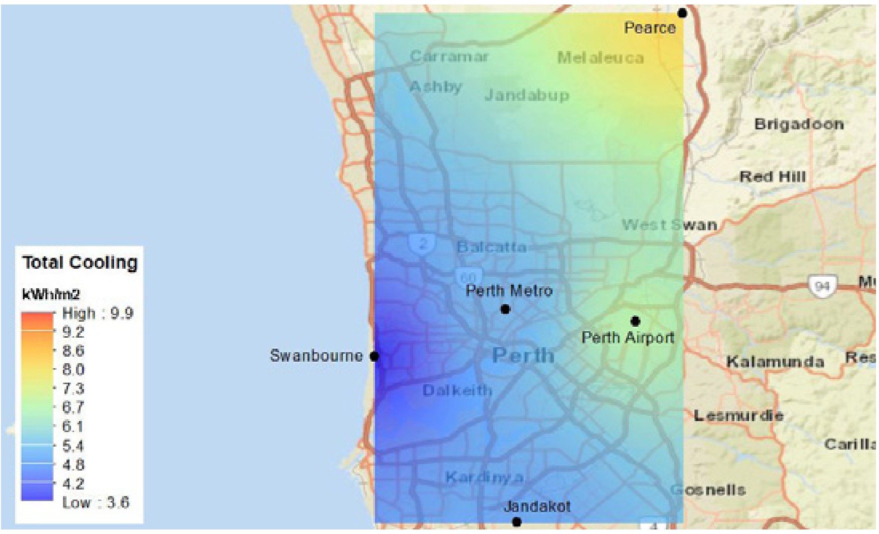

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

b Reference scenario and scenario 1; estimated for eleven weather stations in Perth 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 (4.8-5.2 kWh/m²) is lower than the annual cooling load reduction (11.3-15.0 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
Jandakot	22.7	24.9	22.0	26.5	12.0	13.6	26.7	31.6
Pearce	27.4	30.3	21.5	25.8	15.0	17.2	26.2	30.9
Perth Airport	25.6	27.9	21.0	25.2	14.1	15.9	25.4	30.0
Perth Metro	27.0	30.3	19.7	23.5	12.9	15.2	24.3	28.6
Swanbourne	17.8	21.5	17.3	20.7	7.4	9.5	21.4	25.2

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing 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 43.1-55.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.2-10.0 kWh/m² (~ 12.0-18.6 %).

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	%
Jandakot	10.7	47.3	11.3	45.3	4.7	5.1	6.1	13.6	6.2	12.0
Pearce	12.4	45.2	13.1	43.2	4.7	5.2	7.7	15.7	7.9	14.1
Perth Airport	11.5	44.9	12.0	43.1	4.4	4.8	7.1	15.3	7.2	13.6
Perth Metro	14.1	52.2	15.0	49.7	4.6	5.1	9.5	20.3	10.0	18.6
Swanbourne	10.4	58.2	11.9	55.5	4.1	4.5	6.3	18.0	7.4	17.6

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

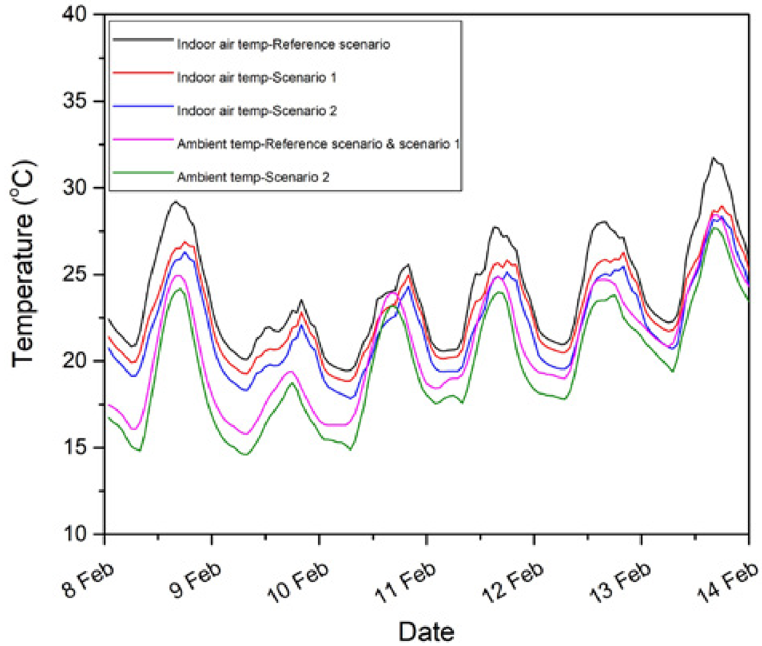

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

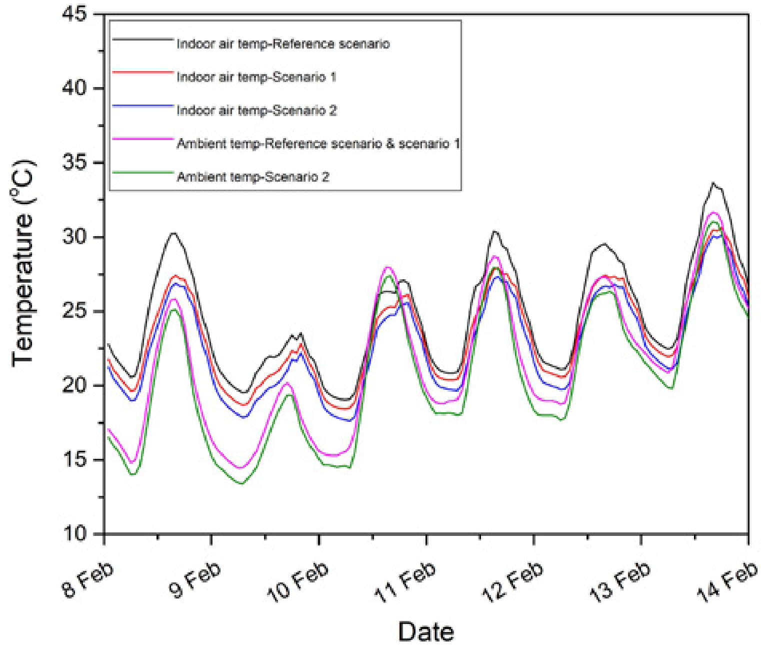

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.4-31.7 °C and 19.1-34.0 °C in Swanbourne and Pearce stations, respectively.

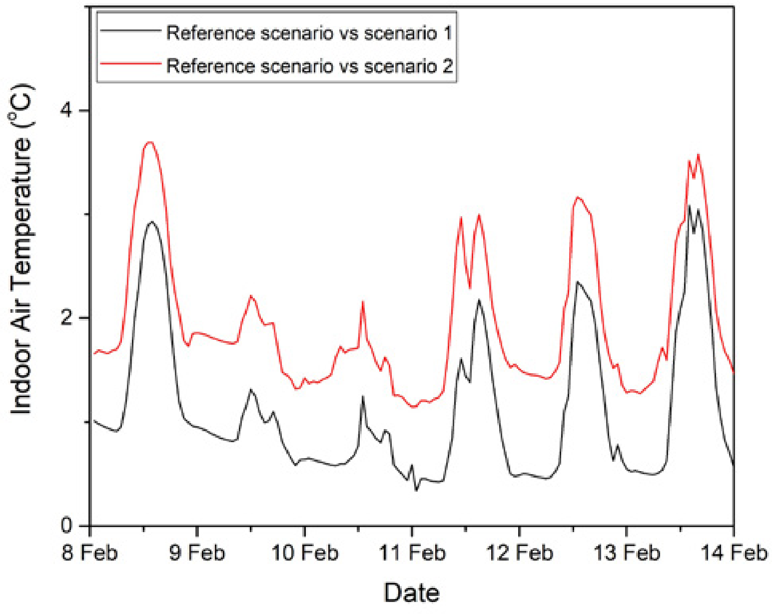

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 3.6 °C and 3.6 °C in Swanbourne and Pearce stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 4.3 °C and 4.2 °C in Swanbourne and Pearce stations, respectively.

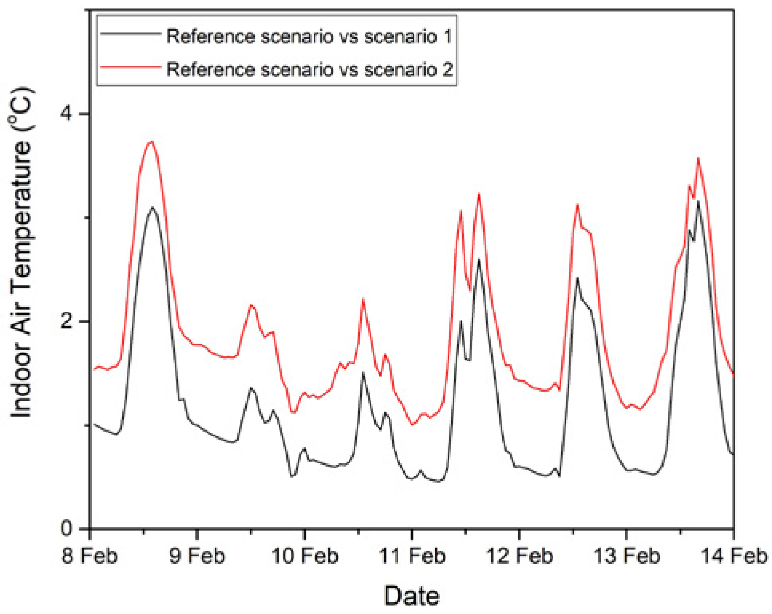

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer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

During a typical winter week, the indoor air temperature is expected to decrease from a range 9.6-22.4 °C in reference scenario to a range 9.2-20.8 °C in scenario 1 in Swanbourne station.

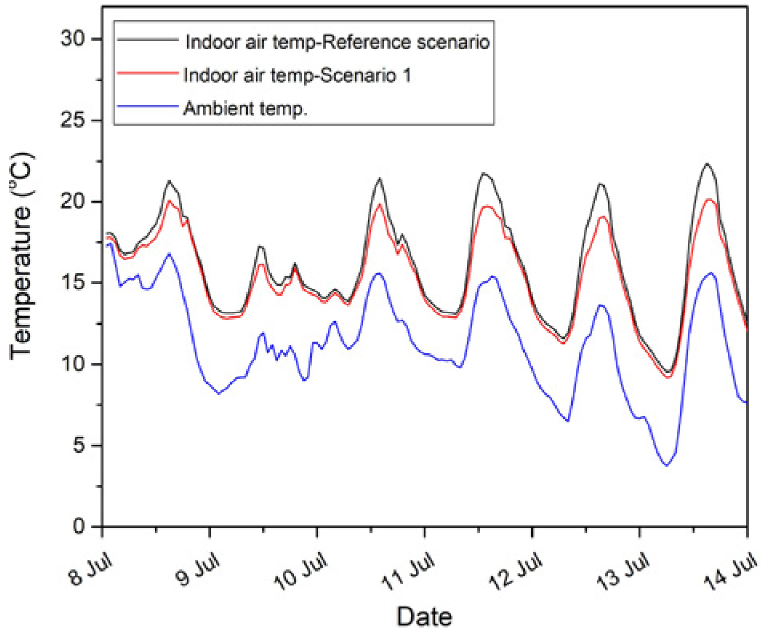

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Swanbourne station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 8.2-21.8 °C in reference scenario to a range 7.8-20.3 °C in scenario 1 in Pearce station.

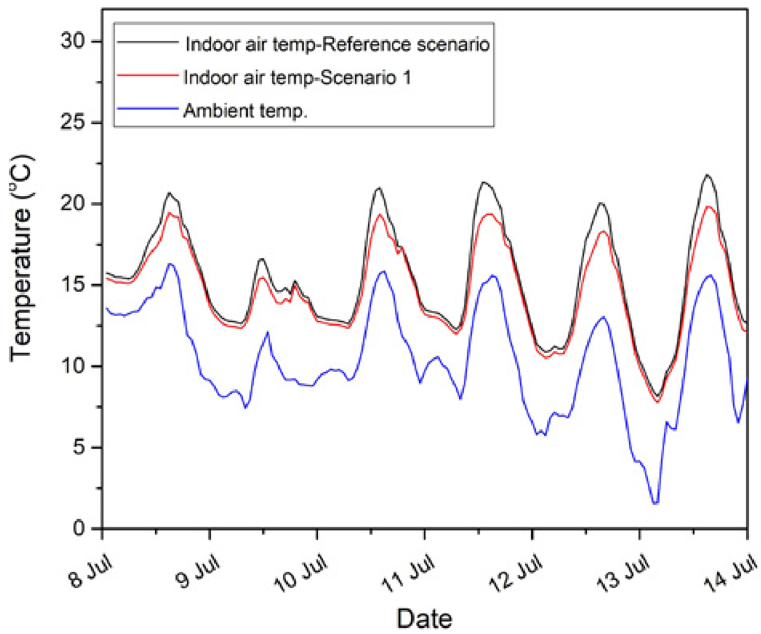

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Pearce station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.8 °C in Swanbourne and Pearce stations, respectively.

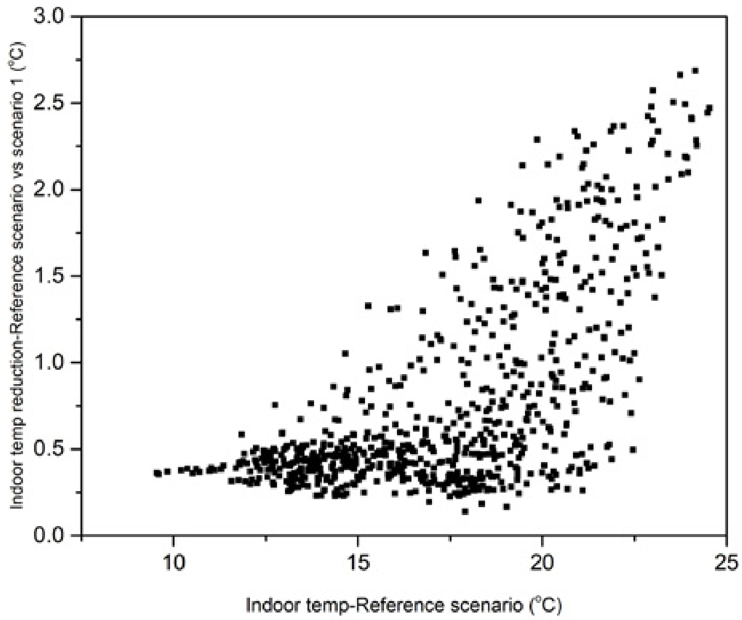

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

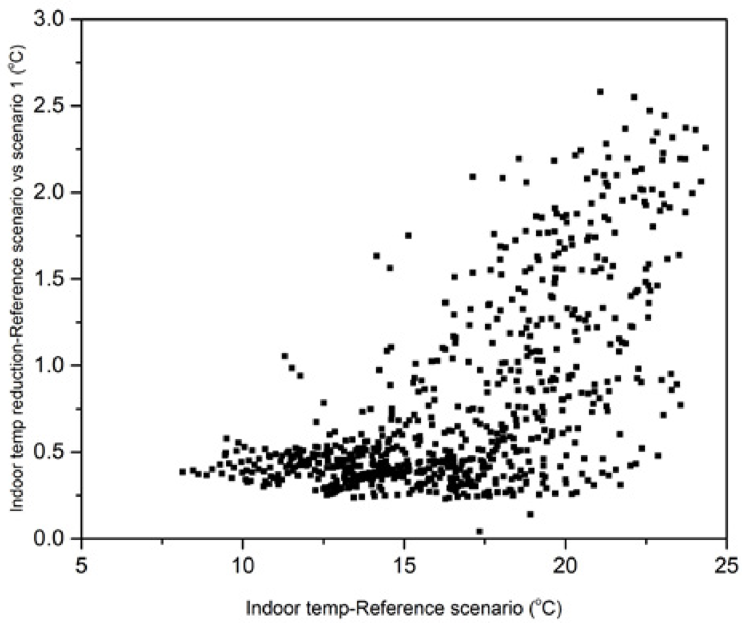

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 496 hours in reference scenario to 576 hours; and from 532 to 607 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Swanbourne	496	576
Pearce	532	607

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 332 hours in reference scenario to 226 and 170 hours under scenario 1 and 2 in Swanbourne station; and from 371 hours in reference scenario to 300 and 268 hours under scenario 1 and 2 in Pearce station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	332	226	170
Pearce	371	300	268

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 11 is an existing, stand-alone residential building, with a total air-conditioned area of 242 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 Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 11.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	4,1	5,4
Energy consumption after cool roof (MWh)	3,4	4,7
Energy savings (MWh)	0,7	0,7
Energy savings (%)	17,07%	12,96%
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 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.

The cool roof refurbishment options

Given the low in absolute terms energy expenditure and the high initial cost of the metal cool roof, this is not feasible. On the contrary, the coating cool technology emerges as an appealing investment under all conditions.

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' decrease of 17,07% for the Swanbourne and of 12,96% for the Pearce weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a significant reduction of life cycle costs, that varies between 16,4% for the low energy price scenario and 25,4% for the high energy scenario for Swanbourne conditions.

The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and 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 Swanbourne and for Pearce weather conditions respectively.

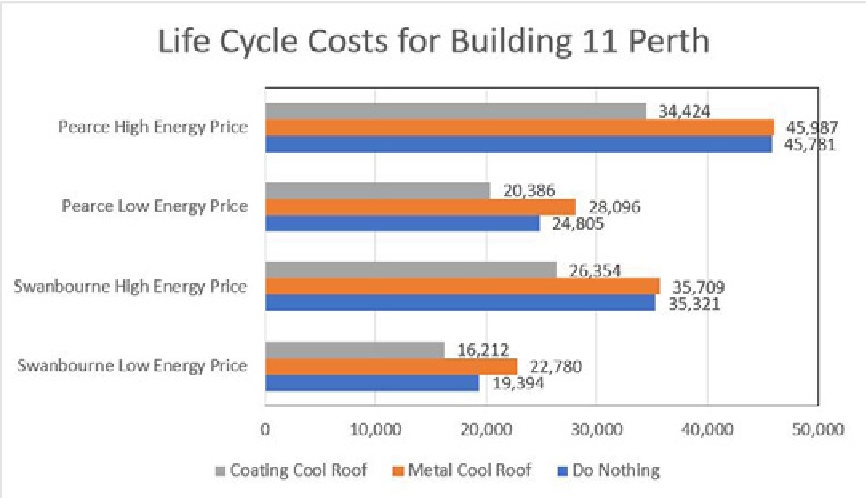

Figure 12. Life Cycle Costs for Building 11 for Swanbourne and Pearce weather stations.

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	-17,46 %	-1,10 %	-13,27 %	-0,45 %
Coating Cool Roof	16,41 %	25,39 %	17,81 %	24,81 %

7

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of an existing standalone house during the summer season.

• In the eleven weather stations in Brisbane, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 11.4-16.4 kWh/m^2 to 6.7-9.9 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 6.1-6.6 kWh/m^2. This is equivalent to approximately 41.9-53.5 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.7-8.7 kWh/m^2. This is equivalent to 50.3-67.9 % 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 (4.8-5.2 kWh/m^2) is lower than the annual cooling load reduction (11.3-15.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 43.1-55.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.2-10.0 kWh/m^2 (~ 12.0-18.6 %) (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 19.4-31.7 °C and 19.1-34.0 °C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 3.6 and 3.6 °C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 4.3 and 4.2 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease from a range between 9.6-22.4 °C in reference scenario to a range between 9.2-20.8 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 8.2-21.8 °C in reference scenario to a range between 7.8-20.3 °C in reference with cool roof scenario (scenario 1) in Pearce 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 0.8 °C for Swanbourne and Pearce 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 496 hours in reference scenario to 576 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slightly increase in total number of hours below 19 °C from 532 hours in reference scenario to 607 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 332 hours under the reference scenario in Swanbourne station, which significantly decreases to 226 and 170 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Pearce station also illustrate a significant reduction in number of hours above 26 °C from 371 hours in reference scenario to 300 in reference with cool roof scenario (scenario 1) and 268 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 16,4% for the low energy price scenario and 25,4% for the high energy scenario for Swanbourne conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost not feasible for both scenarios and locations. Building 11 is in that sense an interesting example of a new, stand-alone residential building, with a single floor and an insulated roof, where the energy conservation potential is significant. However, given the low in absolute terms energy expenditure and the high initial cost of the metal cool roof, this is not feasible. On the contrary, the coating cool technology emerges as an appealing investment under all conditions.

B11

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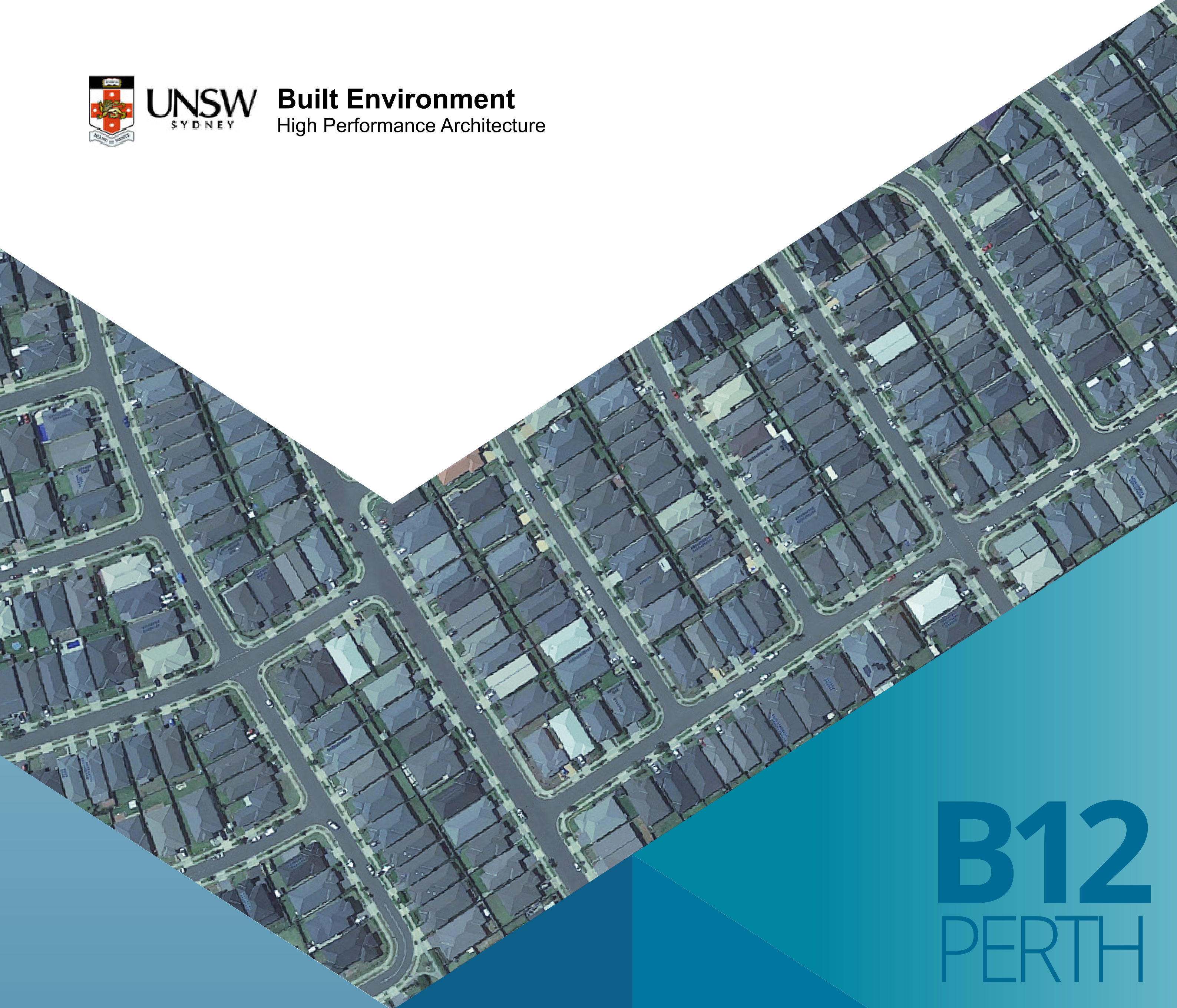

B12 PERTH

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 Perth 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 16.0-27.9 kWh/m² to 15.0-27.0 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/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)
Jandakot	17.3	19.5	16.6	18.6	13.8	14.2
Pearce	24.0	27.9	23.3	27.0	21.5	22.8
Perth Airport	22.2	25.4	21.5	24.5	18.4	19.0
Perth Metro	18.2	21.1	17.6	20.1	14.6	15.1
Swanbourne	13.7	16.0	13.1	15.0	10.4	10.8

Table 2. Sensible and total cooling load saving for an existing school for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.9-1.0 kWh/m² which is equivalent to 3.5-6.2 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 5.1-6.5 kWh/m² which is equivalent to 18.4-32.7 % 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	%
Jandakot	0.6	3.7	0.9	4.8	3.4	19.9	5.2	26.9
Pearce	0.7	3.0	1.0	3.5	2.6	10.7	5.1	18.4
Perth Airport	0.7	3.1	1.0	3.8	3.7	16.9	6.5	25.4
Perth Metro	0.7	3.7	1.0	4.6	3.7	20.0	6.0	28.5
Swanbourne	0.6	4.4	1.0	6.2	3.3	24.2	5.2	32.7

In the eleven weather stations in Perth, 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.

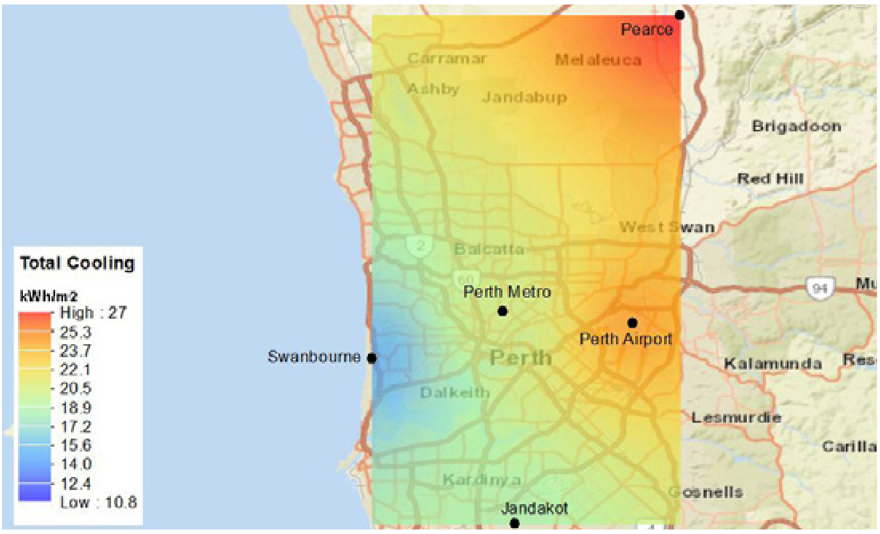

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

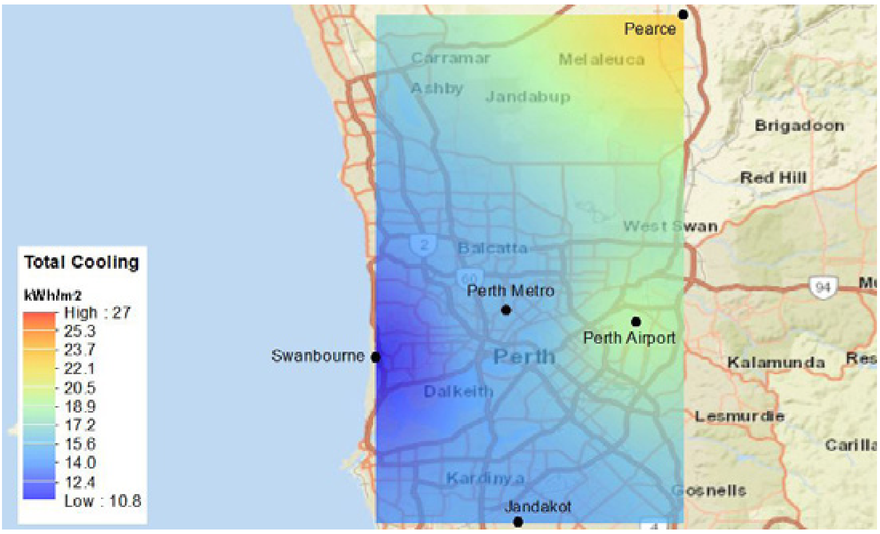

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing school for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.3 kWh/m²) is significantly slower than the annual cooling load reduction (1.6-2.1 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Jandakot	39.5	42.7	3.5	18.5	38.1	41.1	3.6	18.8
Pearce	46.6	51.5	3.3	17.4	45.1	49.7	3.3	17.7
Perth Airport	43.5	46.8	3.3	17.6	42.1	45.2	3.4	17.9
Perth Metro	40.5	45.3	2.9	15.9	38.8	43.2	3.0	16.3
Swanbourne	27.7	32.3	2.2	12.7	26.4	30.5	2.3	13.0

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.

The annual cooling load saving by building-scale application of cool roofs is around 3.5-4.6 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2-1.7 kWh/m² (~2.0-3.4 %).

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	%
Jandakot	1.3	3.3	1.6	3.6	0.1	0.3	1.2	2.9	1.2	2.0
Pearce	1.5	3.2	1.8	3.5	0.1	0.3	1.4	2.9	1.5	2.2
Perth Airport	1.4	3.2	1.6	3.5	0.1	0.3	1.3	2.8	1.3	2.0
Perth Metro	1.7	4.3	2.1	4.6	0.1	0.3	1.7	3.8	1.7	2.8
Swanbourne	1.3	4.7	1.8	5.5	0.1	0.3	1.3	4.2	1.5	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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

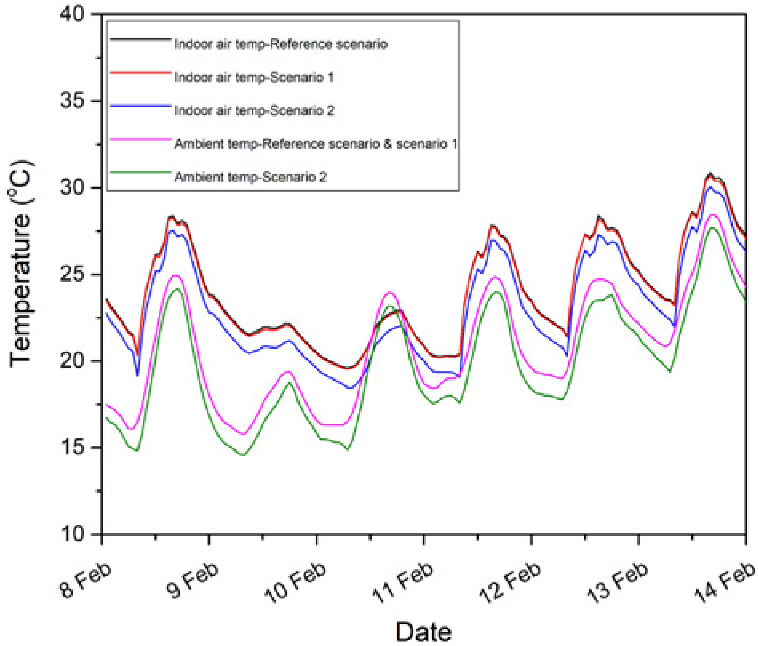

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

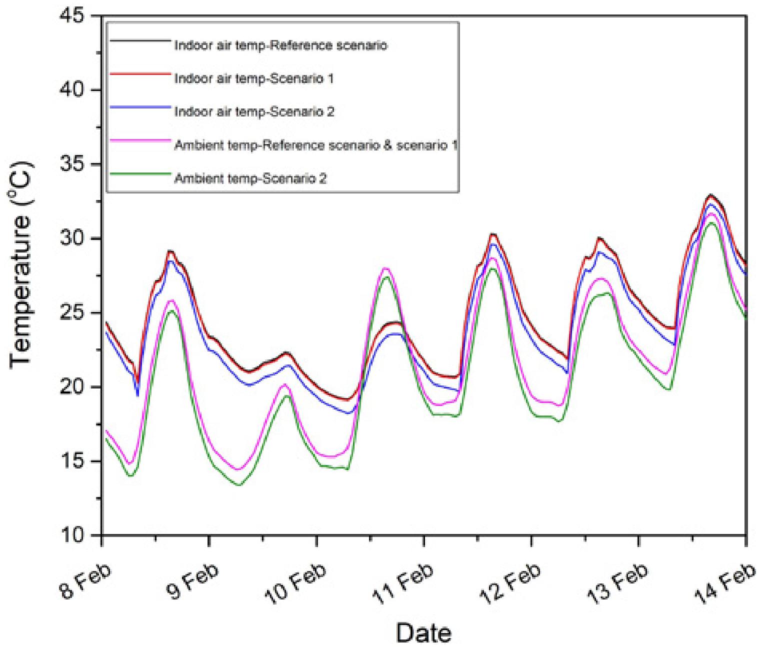

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.6-30.9 °C and 19.2-33.0 °C in Swanbourne and Pearce stations, respectively.

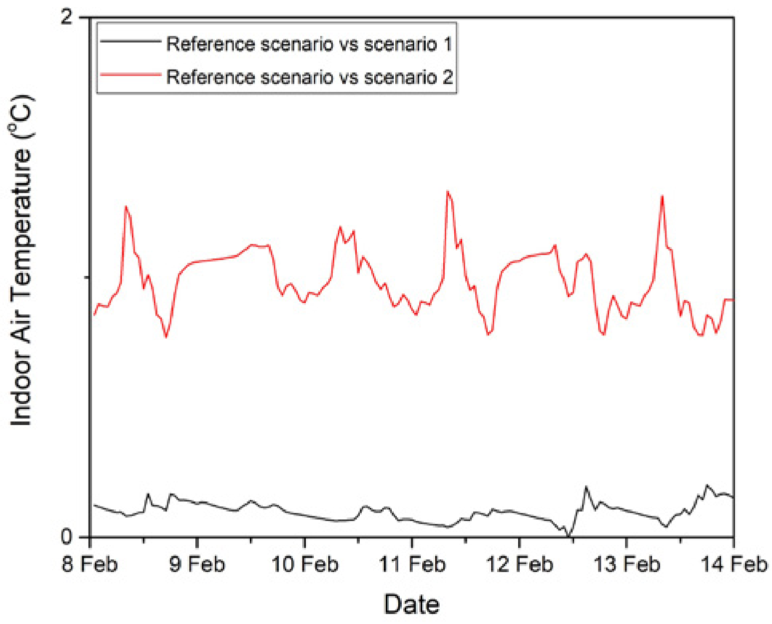

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.2 °C and 0.3 °C in Swanbourne and Pearce stations, respectively.

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

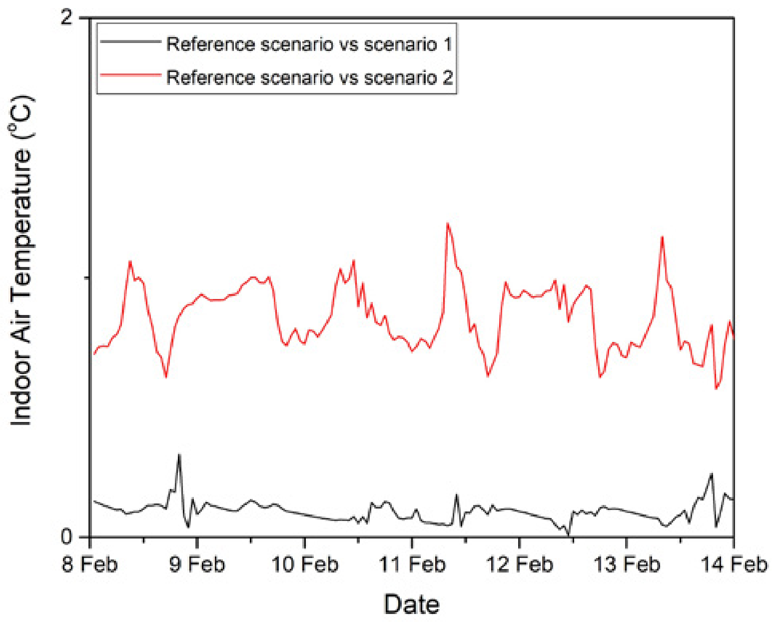

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in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

During a typical winter week, the indoor air temperature is expected to decrease from a range 11.7-22.2 °C in reference scenario to a range 11.6-22.1 °C in scenario 1 in Swanbourne station.

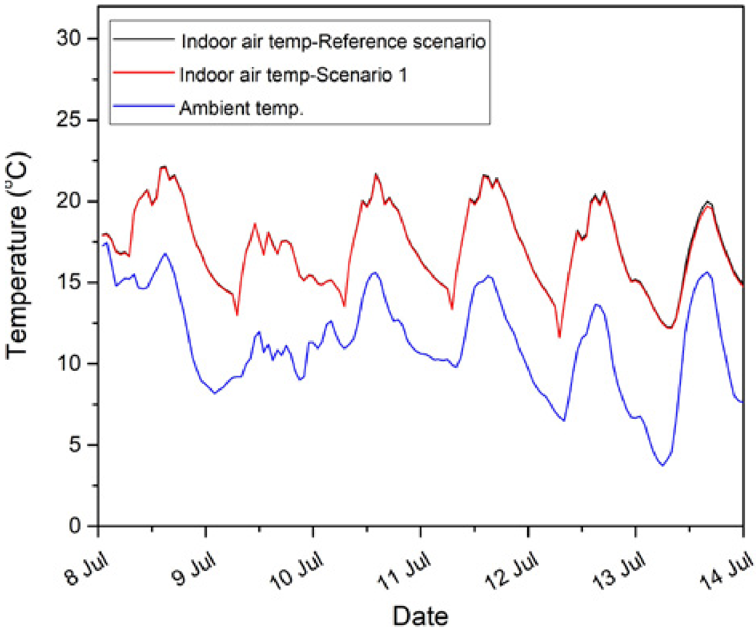

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Swanbourne station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 11.3-21.6 °C in reference scenario to a range11.2-21.5 °C in scenario 1 in Pearce station.

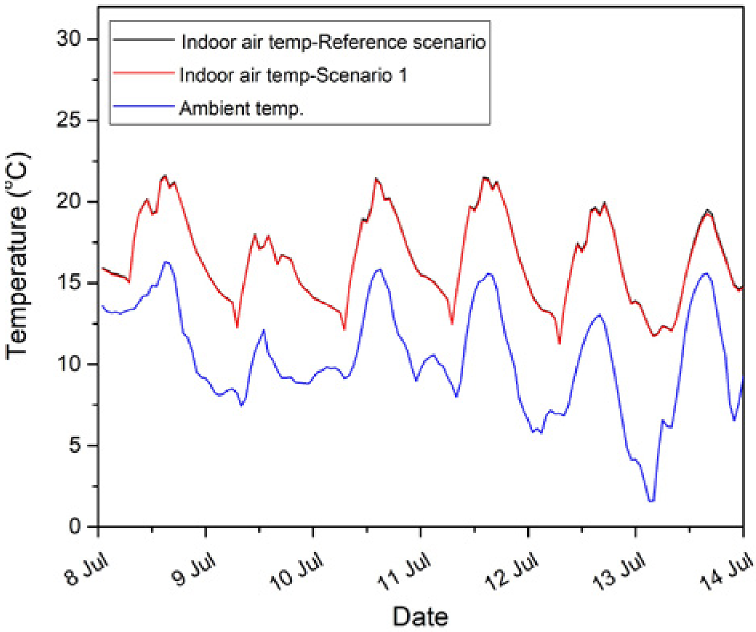

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Pearce station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce stations.

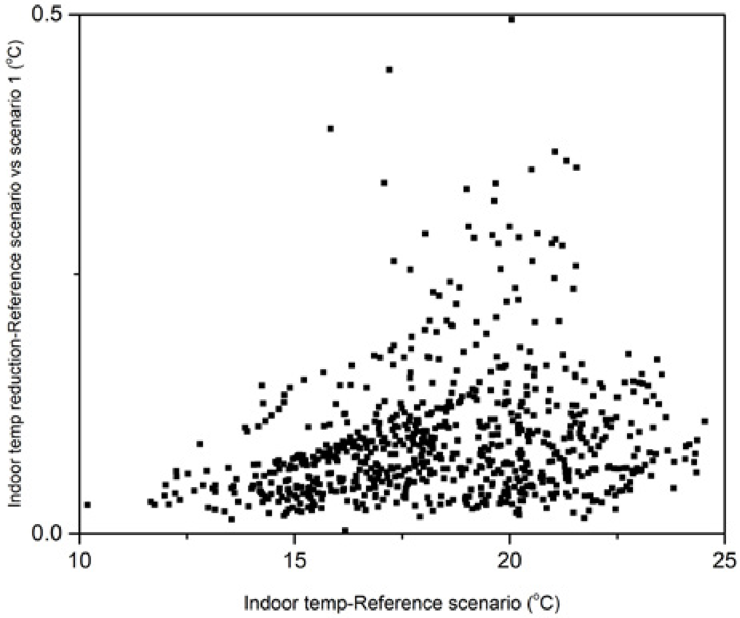

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

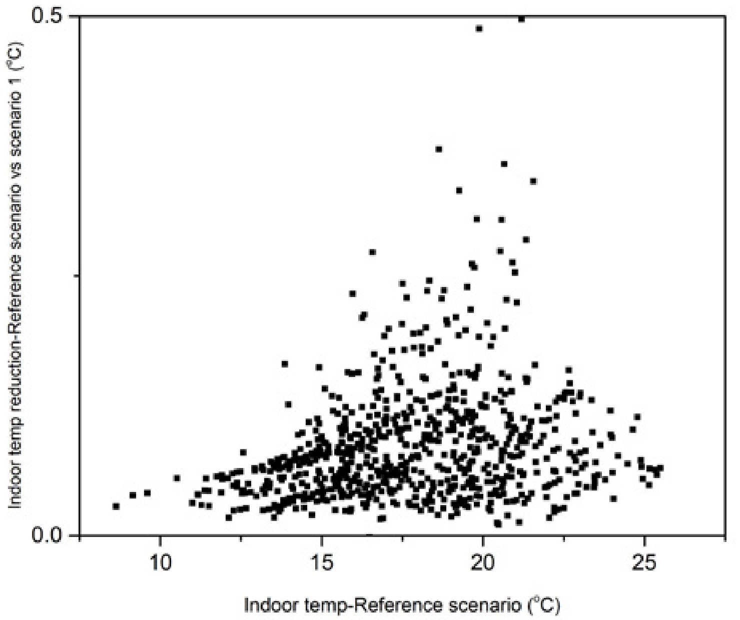

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Perth (i.e. Swanbourne and Pearce) 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 slightly increase from 421 hours in reference scenario to 427 hours; and from 463 to 472 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 142 hours in reference scenario to 147 hours; and from 155 to 161 hours in scenario 1 in Swanbourne and Pearce 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
Swanbourne	142	421	147	427
Pearce	155	463	161	472

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

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 345 hours in reference scenario to 325 and 251 hours under scenario 1 and 2, in Swanbourne station; and from 409 hours in reference scenario to 402 and 347 hours under scenario 1 and 2 in Pearce 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
Swanbourne	345	325	251
Pearce	409	402	347

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 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 Swanbourne and for perth weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 12.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	59,4	90,9
Energy consumption after cool roof (MWh)	57,4	89,0
Energy savings (MWh)	2,0	1,9
Energy savings (%)	3,37%	2,09%
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 in that sense a good example of a new, mid-rise educational building, where the energy conservation potential is modest.

The cool roof refurbishment options

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 for Pearce conditions.

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 3,37% for the Swanbourne and of 2,09% for the Pearce weather conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 19,1% for the low energy price scenario for Swanbourne and 22,3% for the high energy scenario and for Peface 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 Swanbourne and for Pearce 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 Pearce weather conditions.

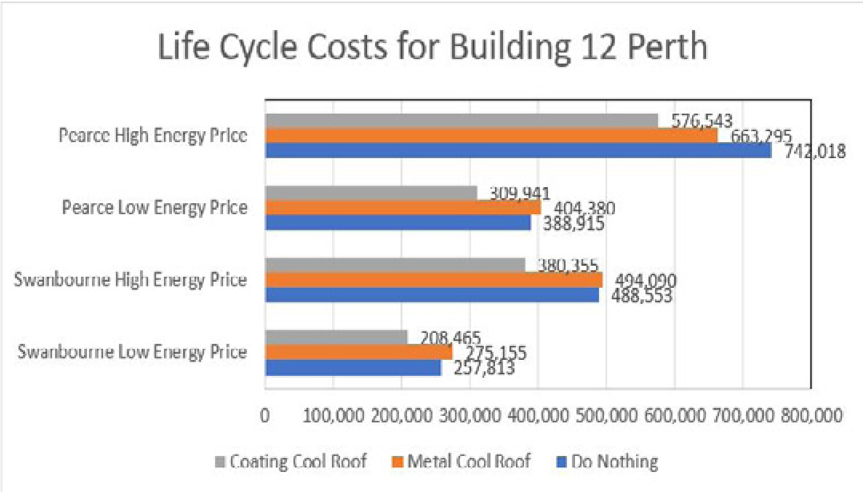

Figure 12. Life Cycle Costs for Building 12 for Swanbourne and Pearce weather stations.

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	-6,73 %	-1,13 %	-3,98 %	10,61 %
Coating Cool Roof	19,14 %	22,15 %	20,31 %	22,30 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing school from 16.0-27.9 kWh/m2 to 15.0-27.0 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.9-1.0 kWh/m^2. This is equivalent to approximately 3.5-6.2 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 5.1-6.5 kWh/m^2. This is equivalent to 18.4-32.7 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.3 kWh/m^2) is significantly lower than the annual cooling load reduction (1.6-2.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.5-4.6 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2-1.7 kWh/m^2 (~2.0-3.4 %) (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 19.6-30.9 °C and 19.2-33.0 °C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.2 and 0.3 °C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.3 and 1.2 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 11.7-22.2 °C in reference scenario to a range between 11.6-22.1 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 11.3-21.6 °C in reference scenario to a range between 11.3-21.5 °C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce 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 421 hours in reference scenario to 427 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slight increase in total number of hours below 19 °C from 463 hours in reference scenario to 472 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to slightly increase from 142 hours in reference scenario to 147 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. Similarly, the calculation in Pearce station shows a slight increase of number of hours below 19 °C from 155 hours to 161 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 345 hours under the reference scenario in Swanbourne station, which slightly decreases to 325 and 251 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also illustrate a significant reduction in number of hours above 26 °C from 409 hours in reference scenario to 402 in reference with cool roof scenario (scenario 1) and 347 hours in cool roof and modified urban temperature scenario (#2), respectively (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 19,1% for the low energy price scenario for Swanbourne and 22,3% for the high energy scenario and for Perace 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 Pearce weather conditions. Building 12 is in that sense a good example of a new, mid-rise educational building, where the energy conservation potential is modest. The coating cool roof is a clearly feasible option leading to significant reductions of life cycle costs, whilst the metal cool roof is feasible for the high energy prices scenario for Pearce conditions.

B12

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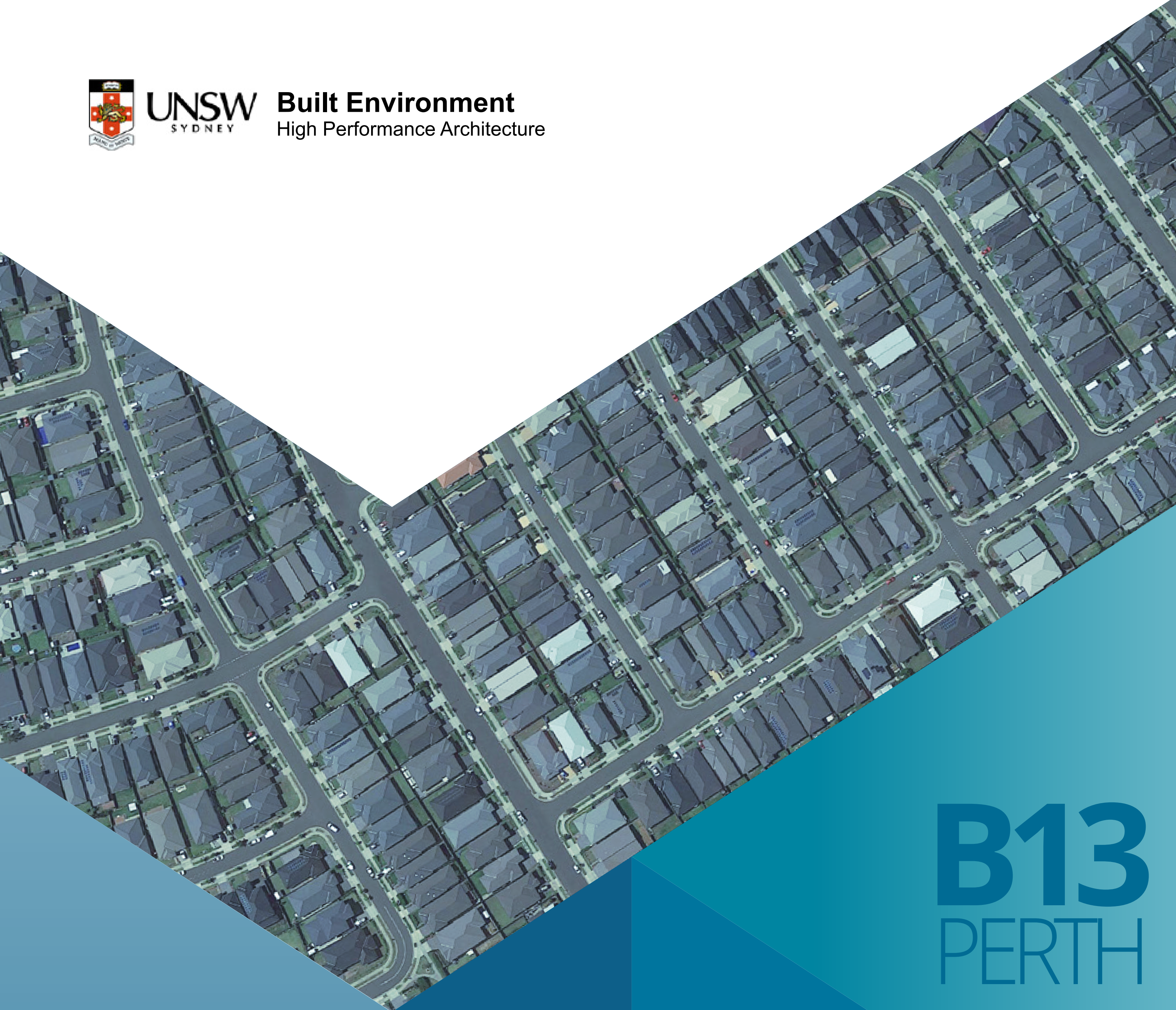

B13
PERTH

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 : $1200 m^2$
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 Perth 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 16.0-25.5 kWh/m² to 11.3-19.4 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)
Jandakot	17.6	19.9	12.4	14.4	10.2	11.1
Pearce	22.7	25.5	16.8	19.4	15.5	16.9
Perth Airport	21.5	24.2	15.8	18.2	13.7	14.6
Perth Metro	18.4	21.1	13.1	15.5	10.7	11.6
Swanbourne	14.1	16.0	9.5	11.3	7.2	7.9

For Scenario 1, the total cooling load saving is around 4.8-6.1 kWh/m² which is equivalent to 24.0-29.8 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 8.2-9.7 kWh/m² which is equivalent to 33.7-50.8 % of total cooling load reduction.

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.

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	%
Jandakot	5.2	29.6	5.5	27.5	7.3	41.7	8.8	44.4
Pearce	5.9	26.1	6.1	24.0	7.2	31.9	8.6	33.7
Perth Airport	5.7	26.7	6.0	24.8	7.9	36.6	9.7	39.9
Perth Metro	5.3	28.8	5.6	26.5	7.7	41.8	9.5	45.0
Swanbourne	4.5	32.2	4.8	29.8	6.9	48.8	8.2	50.8

In the eleven weather stations in Perth, 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.

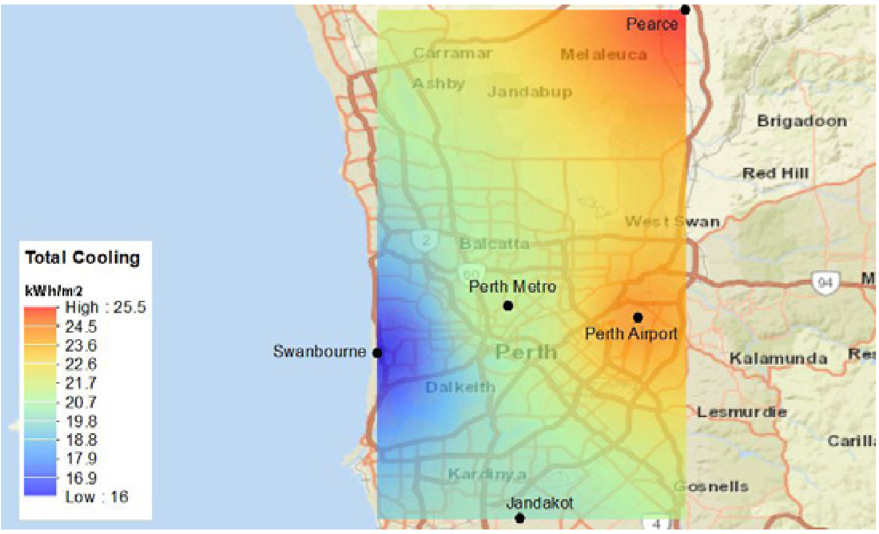

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

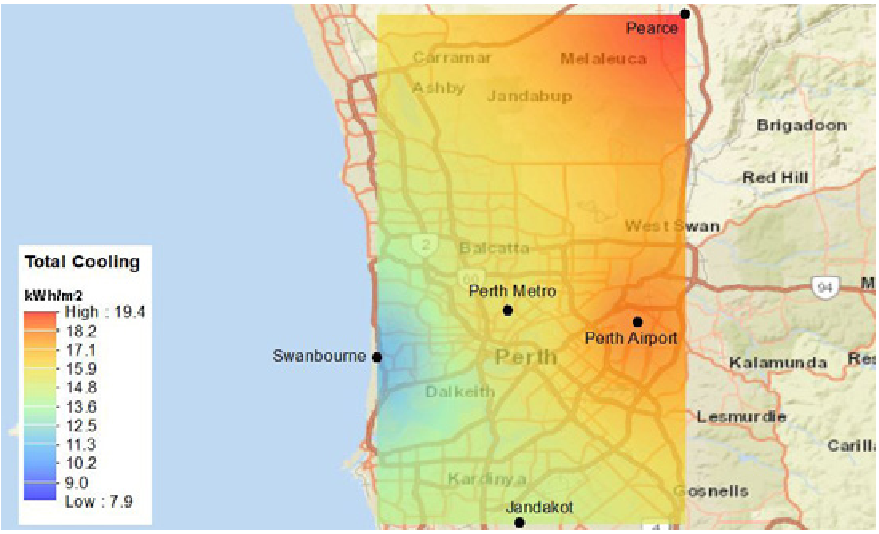

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

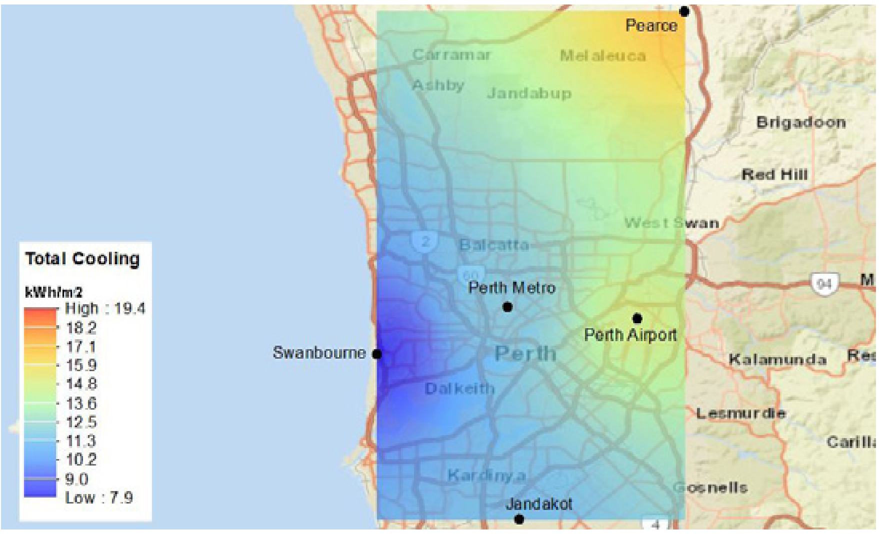

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Perth 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 (0.5-0.6 kWh/m²) is significantly lower than the annual cooling load reduction (7.9-12.2 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
Jandakot	35.7	38.5	2.1	4.6	26.2	28.7	2.5	5.3
Pearce	42.6	46.0	2.0	4.3	31.5	34.4	2.3	5.0
Perth Airport	39.5	42.0	2.0	4.4	29.4	31.6	2.4	5.1
Perth Metro	38.4	42.0	1.8	4.0	26.6	29.8	2.2	4.7
Swanbourne	24.2	27.5	1.3	3.0	16.6	19.5	1.6	3.5

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for 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 24.8-29.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 7.4-11.4 kWh/m² (~21.0-24.9 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Jandakot	9.5	26.5	9.7	25.3	0.4	0.7	9.1	24.0	9.0	21.0
Pearce	11.1	26.2	11.6	25.1	0.4	0.7	10.8	24.1	10.9	21.6
Perth Airport	10.1	25.7	10.4	24.8	0.4	0.7	9.8	23.5	9.8	21.0
Perth Metro	11.7	30.6	12.2	29.0	0.4	0.7	11.3	28.2	11.4	24.9
Swanbourne	7.7	31.7	7.9	28.9	0.3	0.5	7.4	28.9	7.4	24.3

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

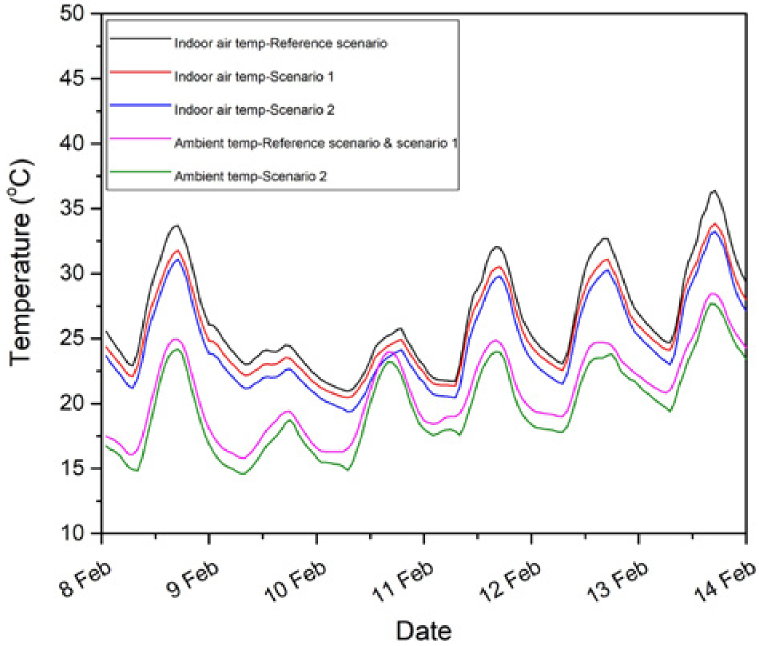

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

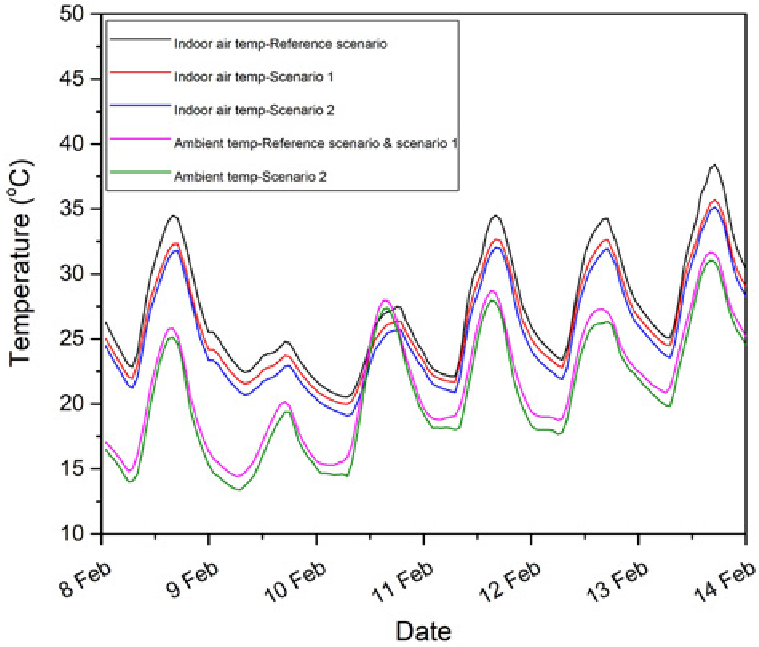

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.0-36.4 °C and 20.5-38.8 °C in Swanbourne and Pearce stations, respectively.

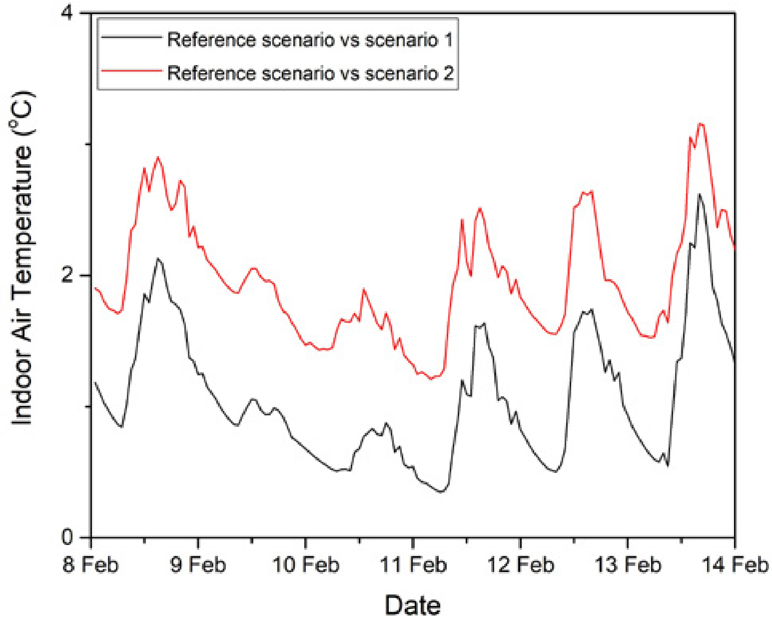

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.6 °C and 2.9 °C in Swanbourne and Pearce stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.5 and 3.7 °C in Swanbourne and Pearce stations, respectively.

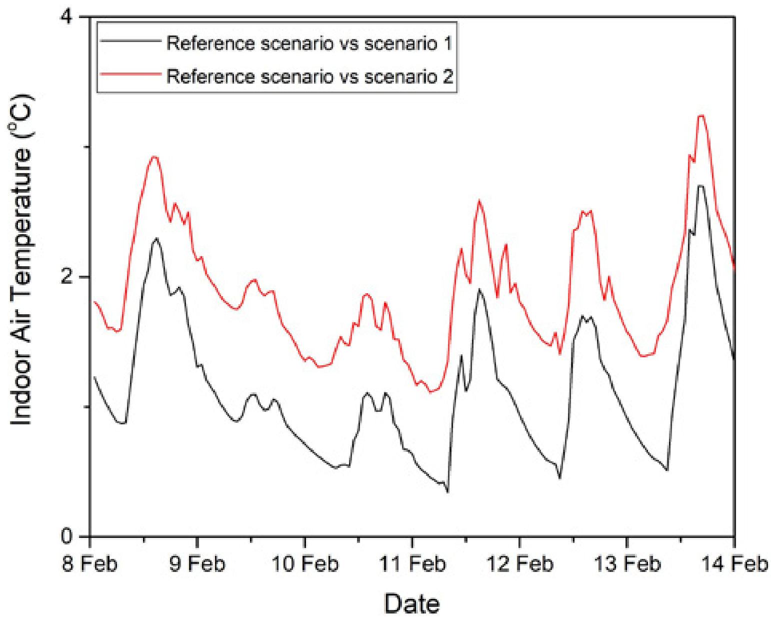

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 12.4-25.9 °C in reference scenario to a range between 12.0-25.0 °C in scenario 1 in Swanbourne station.

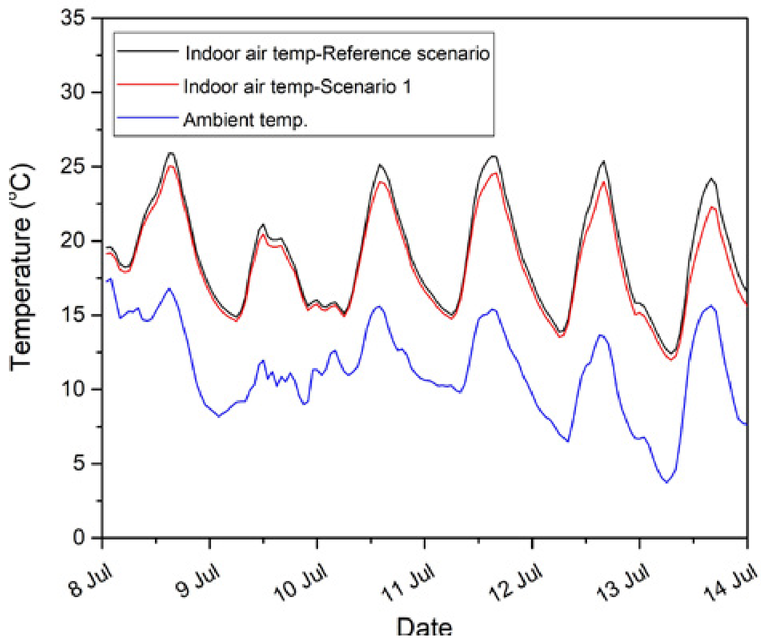

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Swanbourne station* using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

The indoor air temperature is predicted to reduce from a range between 11.9-25.5 °C in reference scenario to a range between 11.4-25.5 °C in scenario 1 in Pearce station.

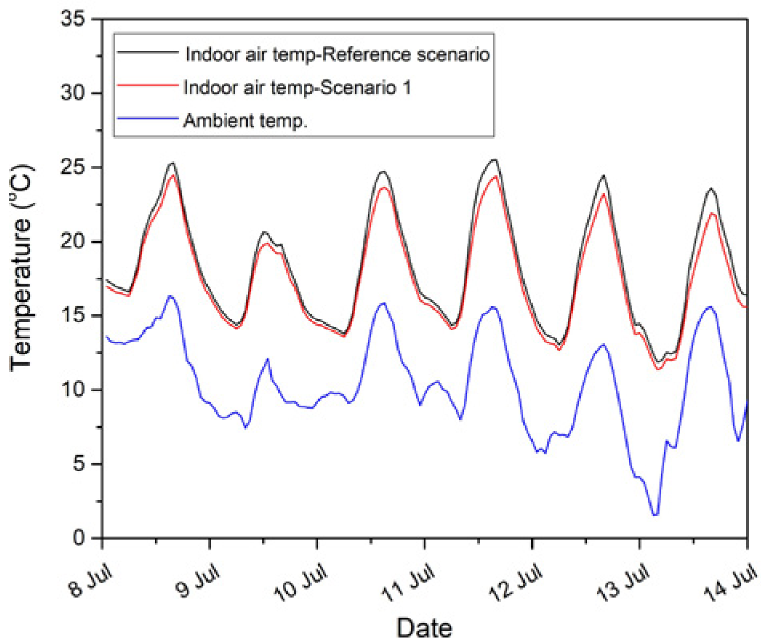

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Pearce station* using 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 0.8 °C in Swanbourne and Pearce stations, respectively.

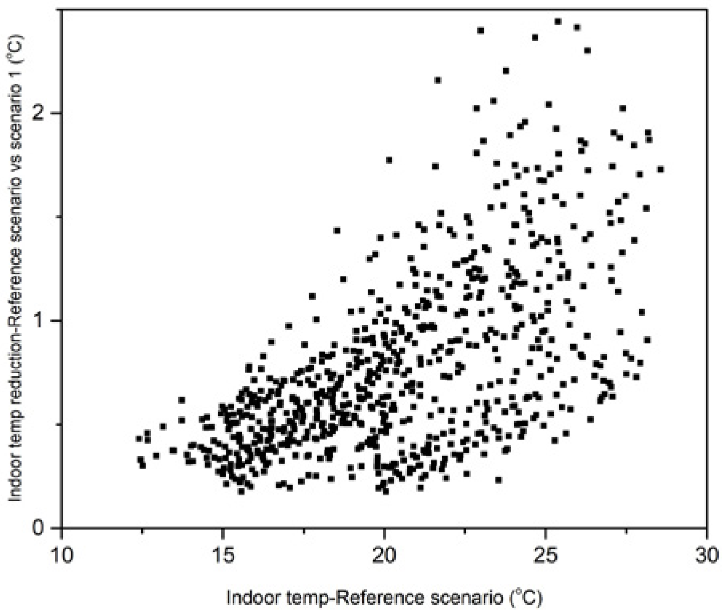

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather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

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

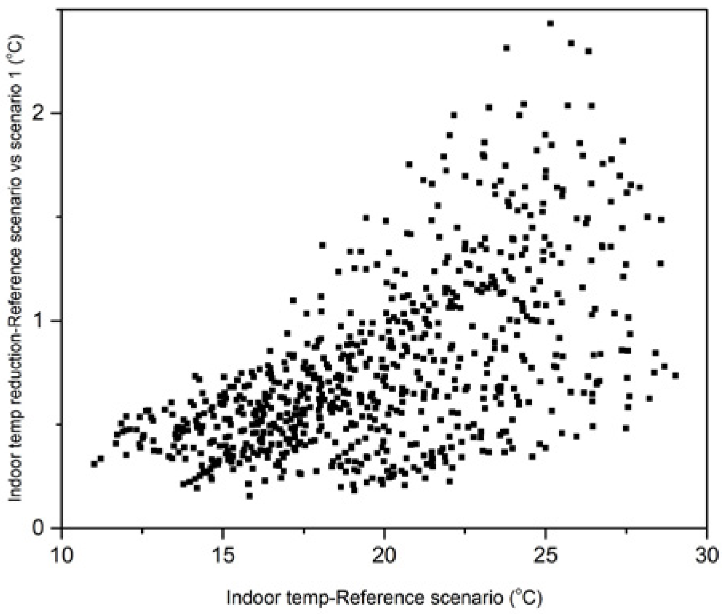

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 273 hours in reference scenario to 323 hours and from 336 to 374 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 83 hours in reference scenario to 98 hours; and from 95 to 112 hours in scenario 1 in Swanbourne and Pearce 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
Swanbourne	83	273	98	323
Pearce	95	336	112	374

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

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 517 hours in reference scenario to 445 and 387 hours under scenario 1 and 2, in Swanbourne station; and from 534 hours in reference scenario to 468 and 429 hours under scenario 1 and 2 in Pearce 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
Swanbourne	517	445	387
Pearce	534	468	429

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

The building and its energy performance

Building 13 is an existing, low-rise building, with a total air-conditioned area of 2.400 m^2 distributed on two levels. The 1.200 m^2 roof is insulated, but since it has a direct impact on half the air-conditioned area, it eventually results in significant energy losses and, consequently, in a respectively significant energy saving potential. The main features of the building's energy performance both for Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 13.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	29,3	48,3
Energy consumption after cool roof (MWh)	22,1	37,8
Energy savings (MWh)	7,2	10,5
Energy savings (%)	24,57%	21,74%
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 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 reductions of life cycle cost, with the coating cool roof being clearly 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 24,57% for the Swanbourne weather conditions and of 21,74% 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.

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 for the high energy prices scenario, whilst it is marginal for the low energy prices scenario and Swanbourne 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 Swanbourne and for Pearce weather conditions respectively.

The application of cool roofs leads to a reduction of life cycle costs of up to 54,83% for the high energy price scenario for Swanbourne conditions

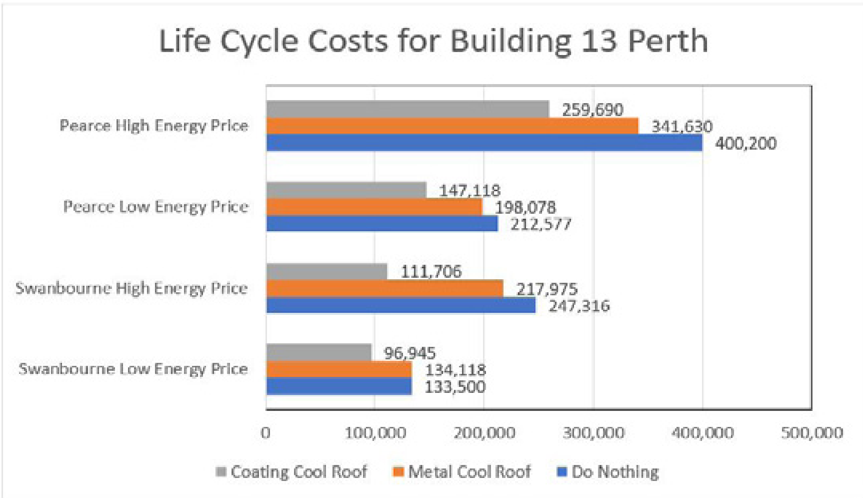

Figure 12. Life Cycle Costs for Building 13 for Swanbourne and Pearce weather stations.

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 %	11,86 %	6,82 %	14,64 %
Coating Cool Roof	27,38 %	54,83 %	30,79 %	35,11 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise office building with roof insulation from 16.0-25.5 kWh/m^2 to 11.3-19.4 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 4.8-6.1 kWh/m^2. This is equivalent to approximately 24.0-29.8 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 8.2-9.7 kWh/m^2. This is equivalent to 33.7-50.8 % 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 (0.5-0.6 kWh/m^2) is significantly lower than the annual cooling load reduction (7.9-12.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 24.8-29.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 7.4-11.4 kWh/m^2 (~21.0-24.9 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 21.0-36.4 ^{o}C and 20.5-38.8 ^{o}C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.6 and 2.9 ^{o}C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.5 and 3.7 ^{o}C by com-bined building-scale and urban-scale application of cool roofs (scenario 2) in Observato-ry and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 12.4-25.9 °C in reference scenario to a range between 12.0-25.0 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 11.9-25.5 °C in reference scenario to a range between 11.4-25.5 °C in reference with cool roof scenario (scenario 1) in Pearce 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 0.8 °C in Swanbourne and Pearce stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when in-door temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase from 273 hours in reference scenario to 323 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slight in-crease in total number of hours below 19 °C from 336 hours in reference scenario to 374 hours in reference with cool roof scenario (scenario 1). The results show less in-crease in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 83 hours in reference scenario to 98 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. Similarly, the calculation in Pearce station shows a slight increase of number of hours below 19 °C from 95 hours to 112 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 517 hours under the reference scenario in Observa-tory station, which significantly decreases to 445 and 387 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also illustrate a significant reduc-tion in number of hours above 26 °C from 534 hours in reference scenario to 468 in ref-erence with cool roof scenario (scenario 1) and 429 hours in cool roof and modified urban temperature 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 for the high energy prices scenario, whilst it is marginal for the low energy prices scenario and Swanbourne conditions. Their application leads to a reduction of life cycle costs of up to 54,83% for the high energy price scenario for Swanbourne conditions, as it can be seen in Table 8. Building 13 is in that sense a good example of an existing, low-rise office building, with a significant energy conservation potential, where both cool roof techniques lead to reductions of life cycle cost, with the coating cool roof being clearly the more feasible investment.

B13

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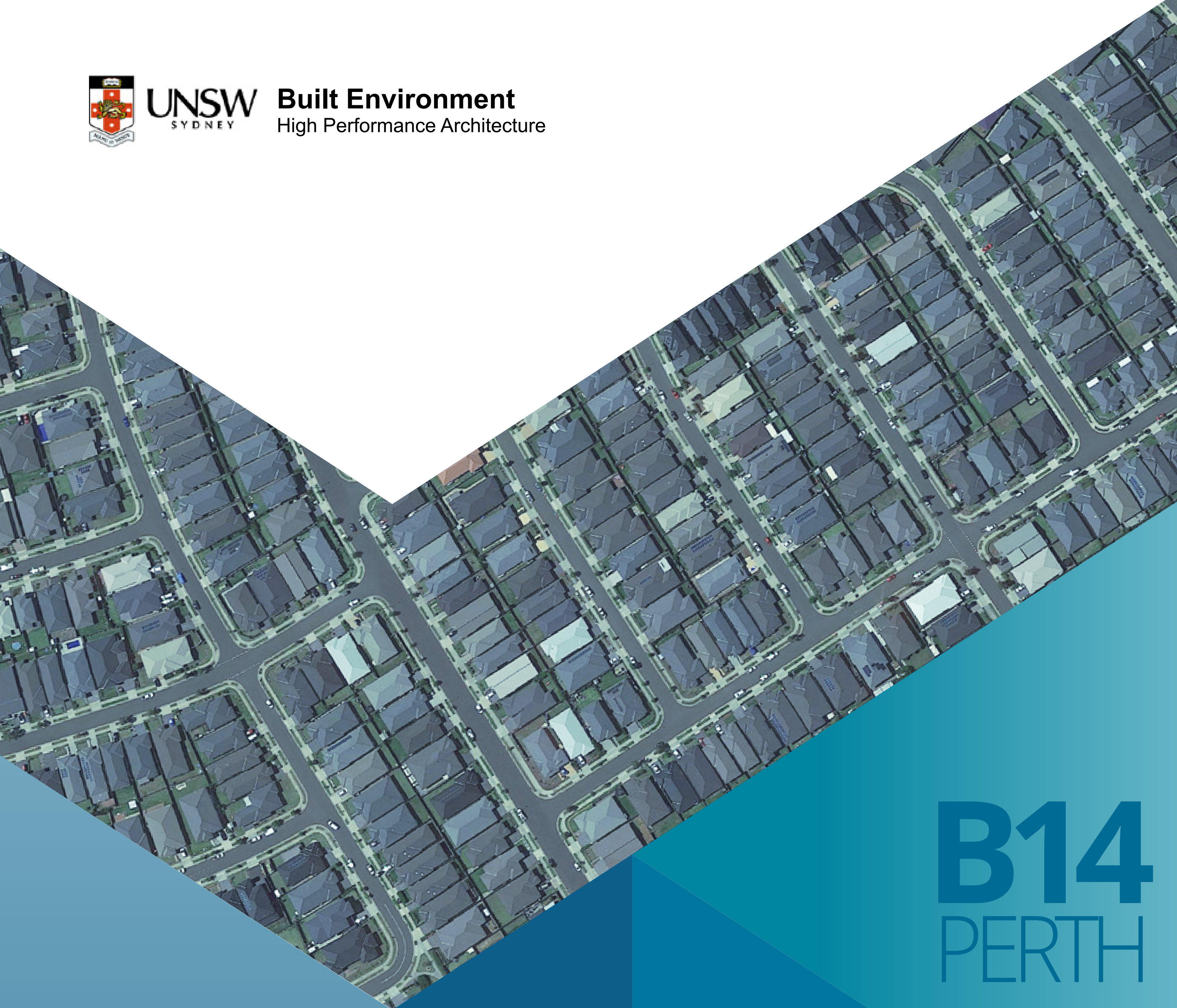

B14
PERTH

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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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 Perth 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 high-rise office building with roof insulation from 12.3-21.0 kWh/m² to 11.5-19.9 kWh/m².

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

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Jandakot	13.5	15.7	12.6	14.7	10.3	11.1
Pearce	18.3	21.0	17.3	19.9	15.8	17.3
Perth Airport	17.2	19.7	16.2	18.7	13.8	14.7
Perth Metro	14.3	16.8	13.4	15.8	10.8	11.7
Swanbourne	10.5	12.3	9.7	11.5	7.2	7.9

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 0.9-1.1 kWh/m² which is equivalent to 5.2-6.9 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.7-5.0 kWh/m² which is equivalent to 17.8-36.2 % 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	%
Jandakot	0.9	6.6	0.9	5.9	3.2	23.7	4.5	28.9
Pearce	1.0	5.6	1.1	5.2	2.5	13.7	3.7	17.8
Perth Airport	1.0	5.9	1.1	5.4	3.4	19.8	5.0	25.4
Perth Metro	0.9	6.4	1.0	5.8	3.5	24.5	5.1	30.4
Swanbourne	0.8	7.6	0.9	6.9	3.3	31.7	4.5	36.2

In the eleven weather stations in Perth, 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.

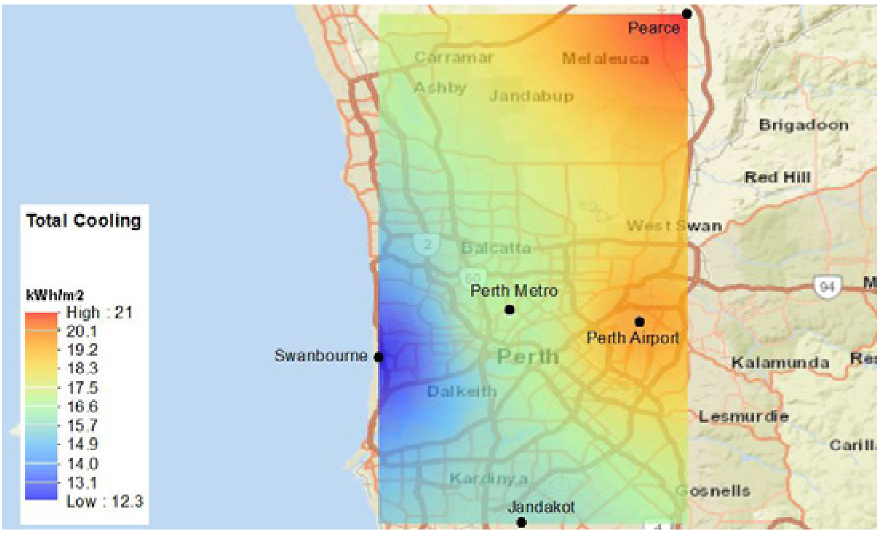

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

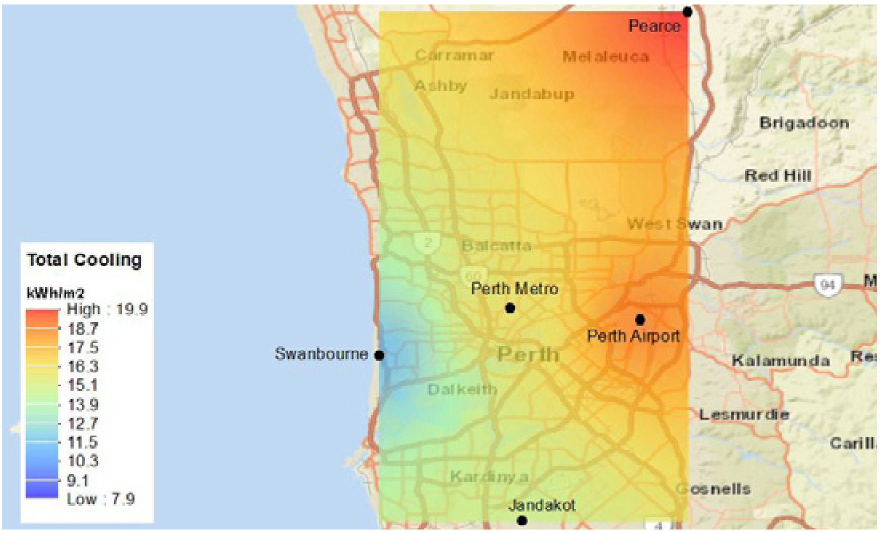

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

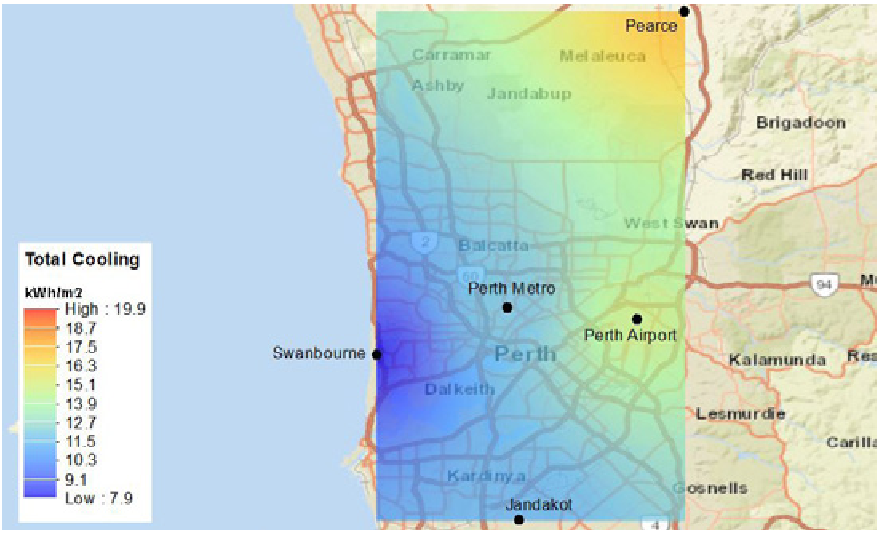

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1 kWh/m²) is lower than the annual cooling load reduction (1.3-2.1 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Jandakot	28.5	31.1	1.0	2.7	26.9	29.5	1.0	2.8
Pearce	34.2	37.4	0.8	2.2	32.4	35.4	0.8	2.4
Perth Airport	31.9	34.3	0.8	2.4	30.2	32.6	0.9	2.5
Perth Metro	29.4	32.8	0.7	2.0	27.4	30.7	0.7	2.1
Swanbourne	18.6	21.7	0.4	1.2	17.3	20.3	0.4	1.3

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 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 5.0-6.4 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2-2.0 kWh/m² (~4.4-5.7 %).

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	%
Jandakot	1.5	5.4	1.6	5.2	0.1	0.1	1.5	5.0	1.5	4.4
Pearce	1.9	5.4	2.0	5.2	0.1	0.1	1.8	5.1	1.8	4.6
Perth Airport	1.7	5.2	1.7	5.0	0.1	0.1	1.6	4.9	1.6	4.4
Perth Metro	2.0	6.9	2.1	6.4	0.1	0.1	2.0	6.5	2.0	5.7
Swanbourne	1.3	6.9	1.3	6.1	0.0	0.1	1.2	6.5	1.2	5.4

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

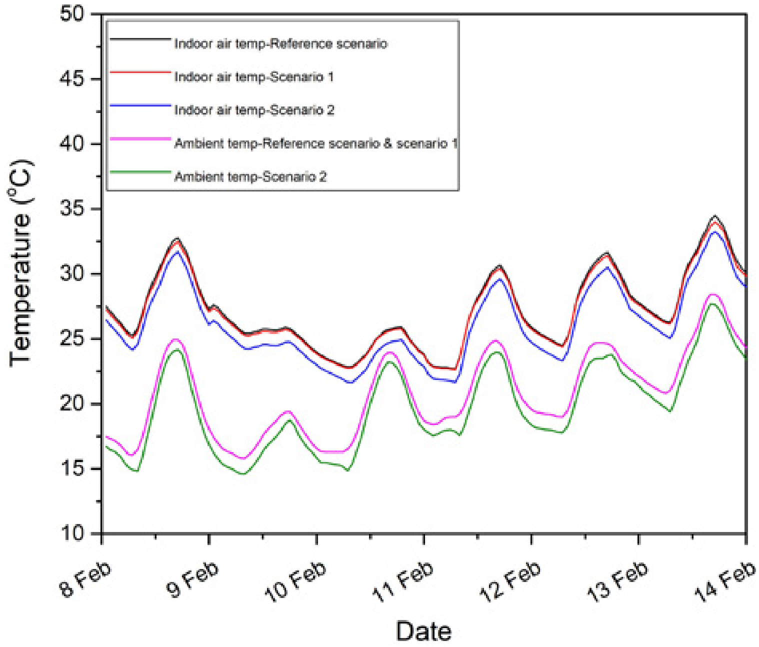

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

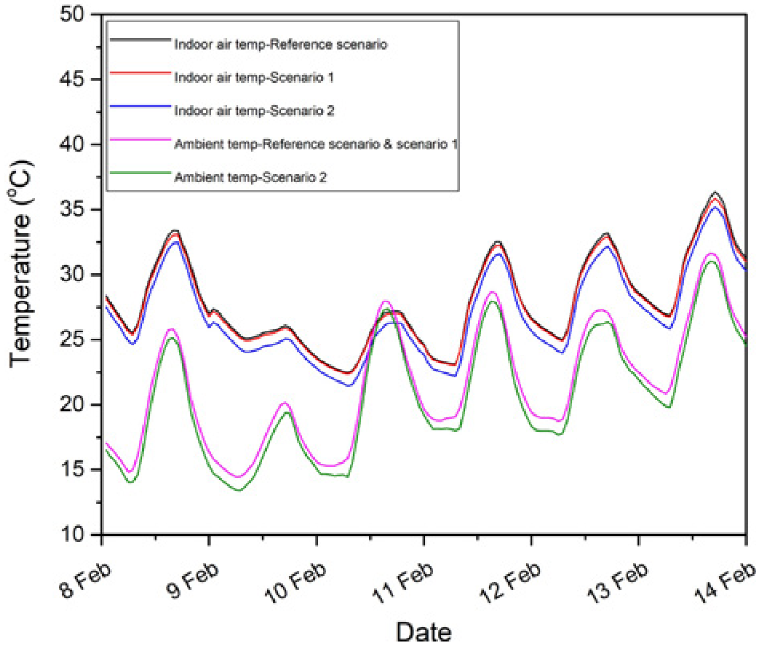

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.7-34.5 °C and 22.5-36.9 °C in Swanbourne and Pearce stations, respectively.

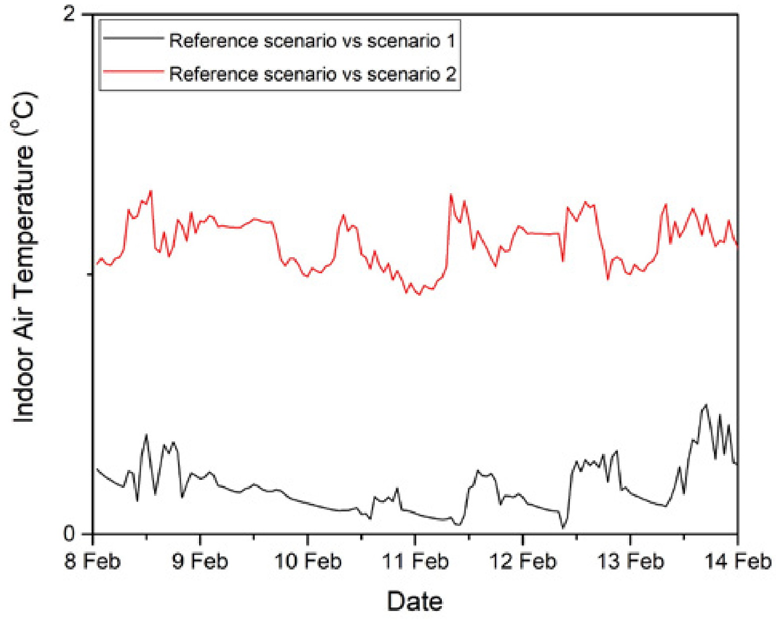

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions during a typical summer week in *Swanbourne 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 0.5 °C in Swanbourne and Pearce stations, respectively.

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

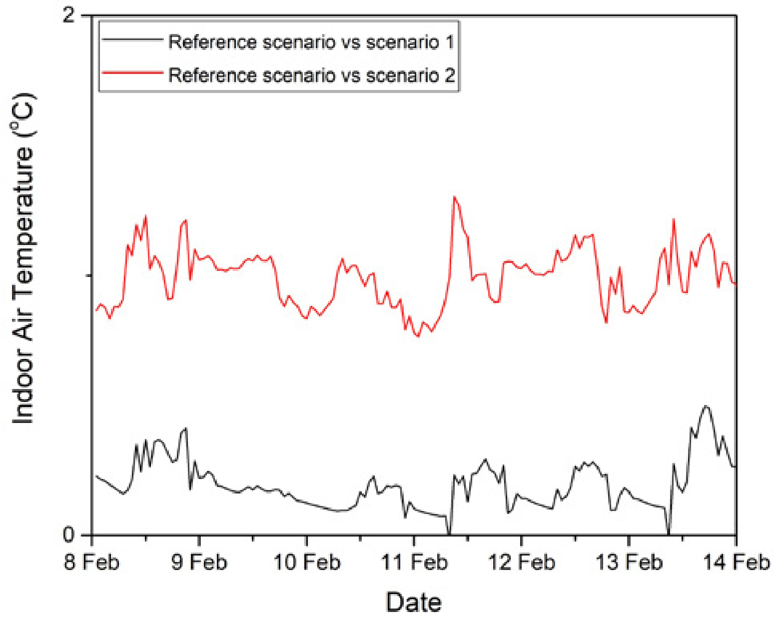

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 16.0-25.6 °C in reference scenario to a range between 16.0-25.4 °C in scenario 1 in Swanbourne station.

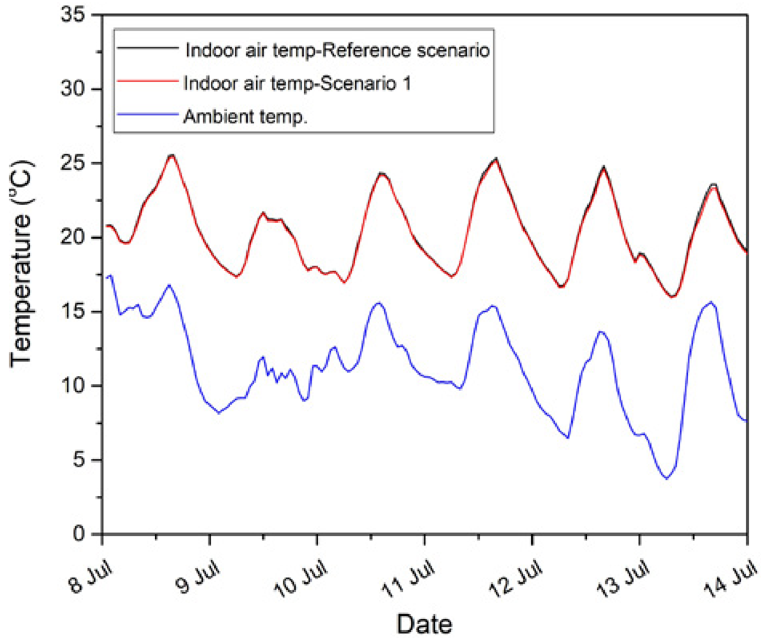

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Swanbourne station* using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

The indoor air temperature is predicted to reduce from a range between 15.6-25.1 °C in reference scenario to a range between 15.5-24.9 °C in scenario 1 in Pearce station.

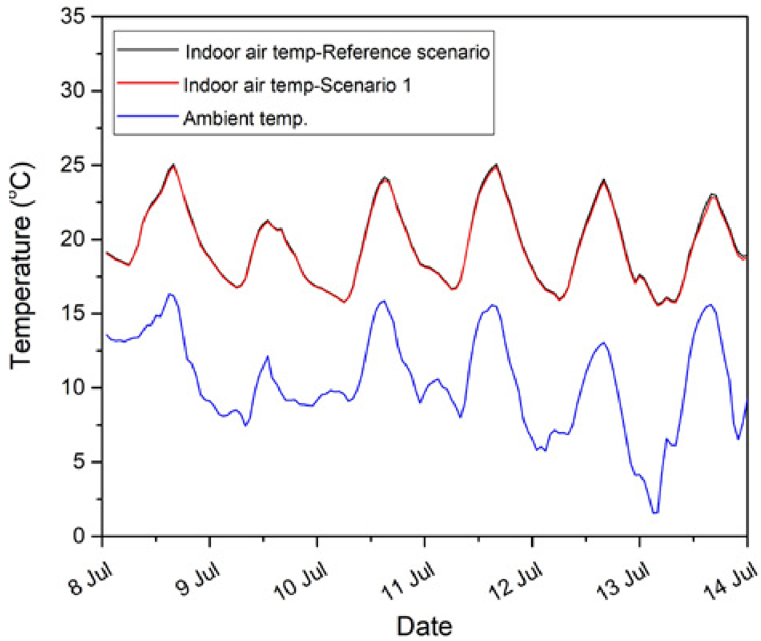

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Pearce station* using annual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

> *For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce stations.*

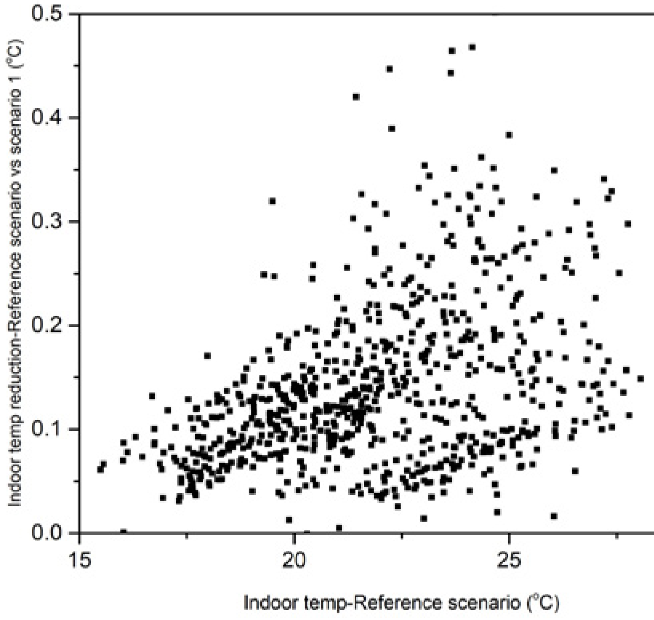

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather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

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

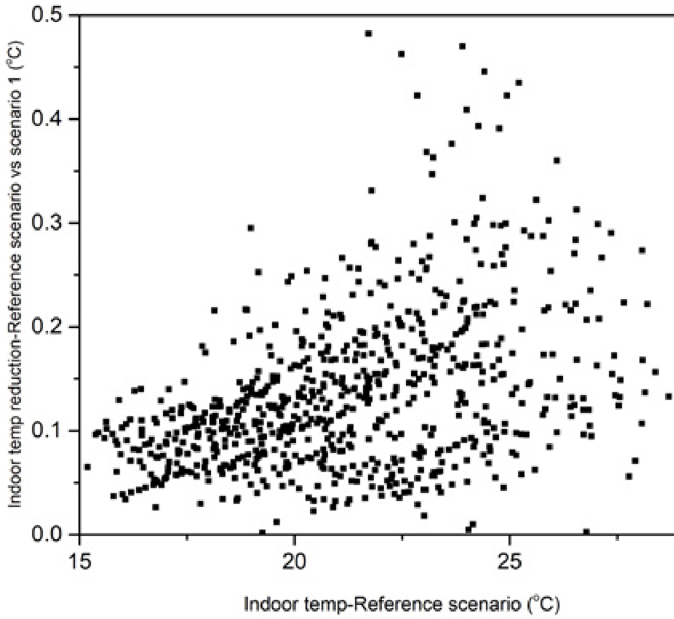

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 121 hours in reference scenario to 131 and hours and from 187 to 194 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 40 hours in reference scenario to 44 hours; and from 58 to 59 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Swanbourne	40	121	44	131
Pearce	58	187	59	194

** 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 decrease from 592 hours in reference scenario to 587 and 534 hours under scenario 1 and 2, in Swanbourne station; and from 604 hours in reference scenario to 596 and 567 hours under scenario 1 and 2 in Pearce station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	592	587	534
Pearce	604	596	567

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the fact that it is a high-rise office building with roof insulation, the 'Do Nothing' approach has 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 Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 14.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	109,9	190,1
Energy consumption after cool roof (MWh)	103,7	181,4
Energy savings (MWh)	6,2	8,7
Energy savings (%)	5,64%	4,58%
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 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 cool roof refurbishment options

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

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

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

Both options have the same energy efficiency, resulting in energy savings of 5,64% for the Swanbourne weather conditions and of 4,58% for the Pearce 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, that varies between 0,2% for the metal cool roof, the low energy price scenario and for Swanbourne and 25,3% for coating cool roof, the high energy scenario and for Pearce 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 Swanbourne and for Pearce 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 Pearce weather conditions.

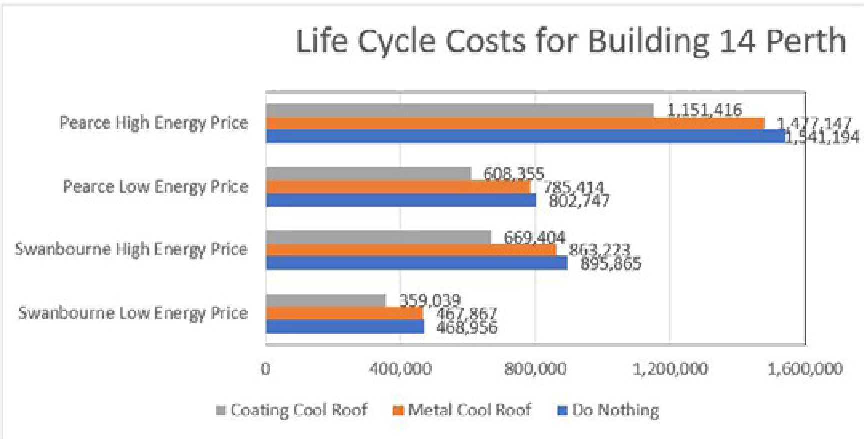

Figure 12. Life Cycle Costs for Building 14 for Swanbourne and Pearce weather stations.

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	0,23 %	3,64 %	2,16 %	4,16 %
Coating Cool Roof	23,44 %	25,28 %	24,22 %	25,29 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building from 12.3-21.0 kWh/m^2 to 11.5-19.9 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.9-1.1 kWh/m^2. This is equivalent to approximately 5.2-6.9 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.7-5.0 kWh/m^2. This is equivalent to 17.8-36.2 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (1.3-2.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 5.0-6.4 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2-2.0 kWh/m^2 (~4.4-5.7 %) (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 22.7-34.5 ^{o}C and 22.5-36.9 ^{o}C in Swanbourne and Pearce 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 0.5 ^{o}C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.4 and 1.4 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 16.0-25.6 ^{o}C in reference scenario to a range between 16.0-25.4 ^{o}C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 15.6-25.1 °C in reference scenario to a range between 15.5-24.9°C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce 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 121 hours in reference scenario to 131 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slight increase in total number of hours below 19 °C from 187 hours in reference scenario to 194 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 40 hours in reference scenario to 44 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. Similarly, the calculation in Pearce station shows a slight increase of number of hours below 19 °C from 58 hours to 59 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 592 hours under the reference scenario in Observa-tory station, which significantly decreases to 587 and 534 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station also illustrate a significant reduc-tion in number of hours above 26 °C from 604 hours in reference scenario to 596 in ref-erence with cool roof scenario (scenario 1) and 567 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the fact that it is a high-rise office building with roof insulation, the 'Do Nothing' approach has 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 0,2% for the metal cool roof, the low energy price scenario and for Swanbourne and 25,3% for coating cool roof, the high energy scenario and for Pearce conditions. 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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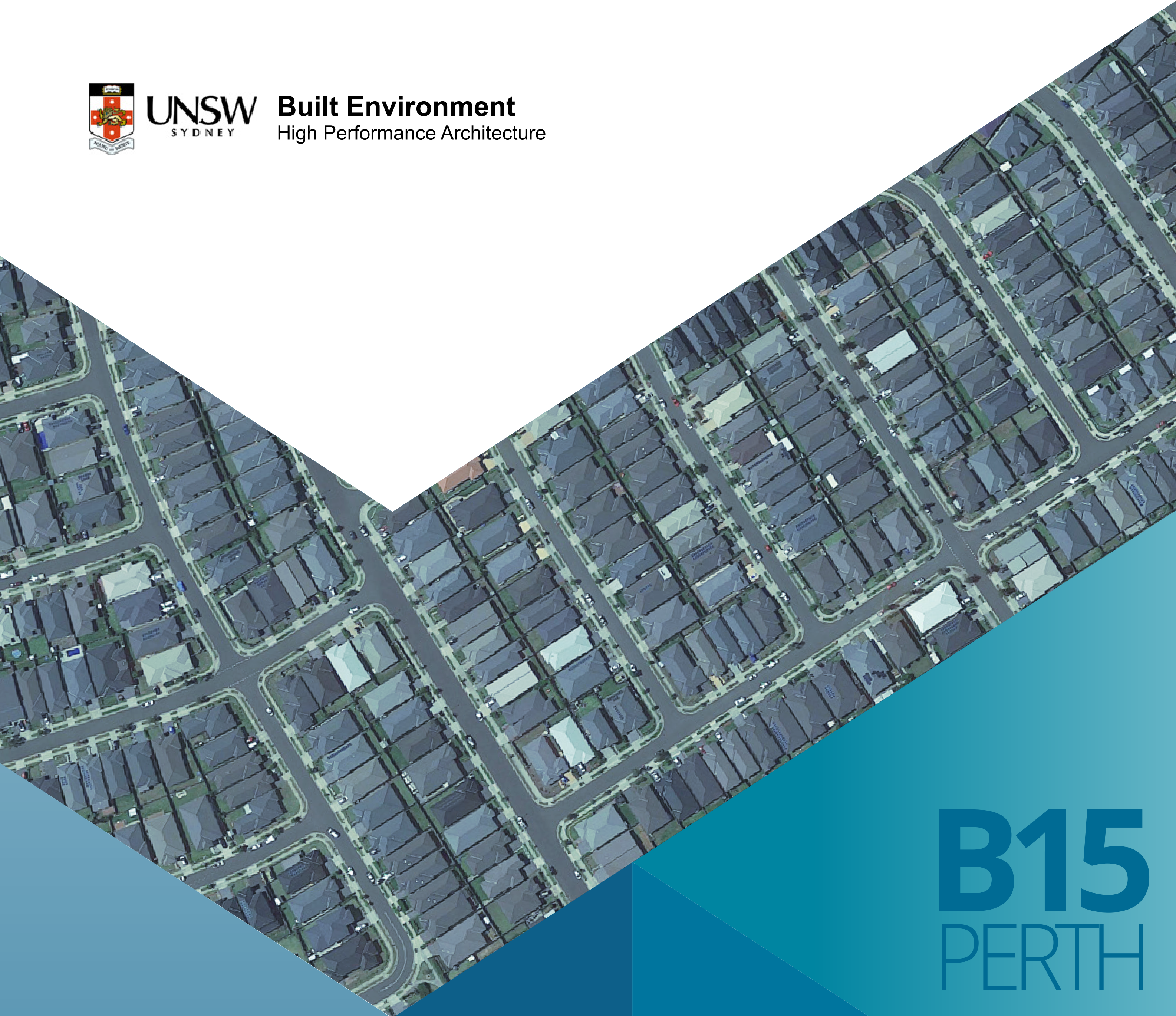

B15 PERTH

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 Perth using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise shopping mall centre from 62.1-73.6 kWh/m² to 54.1-65.4 kWh/m².

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

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/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)
Jandakot	55.2	64.0	47.6	56.2	43.6	47.8
Pearce	64.7	73.6	56.7	65.4	53.6	58.7
Perth Airport	62.0	70.6	54.2	62.5	49.5	53.3
Perth Metro	56.6	66.2	49.0	58.3	44.6	49.0
Swanbourne	50.7	62.1	43.3	54.1	39.2	44.7

For Scenario 1, the total cooling load saving is around 7.9-8.2 kWh/m² which is equivalent to 11.1-12.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 14.9-17.4 kWh/m² which is equivalent to 20.2-28.0 % total cooling load reduction.

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

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Jandakot	7.5	13.6	7.9	12.3	11.5	20.9	16.2	25.4
Pearce	7.9	12.3	8.2	11.1	11.0	17.1	14.9	20.2
Perth Airport	7.9	12.7	8.1	11.5	12.5	20.1	17.3	24.6
Perth Metro	7.5	13.3	7.9	11.9	12.0	21.3	17.2	26.0
Swanbourne	7.5	14.7	7.9	12.8	11.5	22.7	17.4	28.0

In the eleven weather stations in Perth, 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.

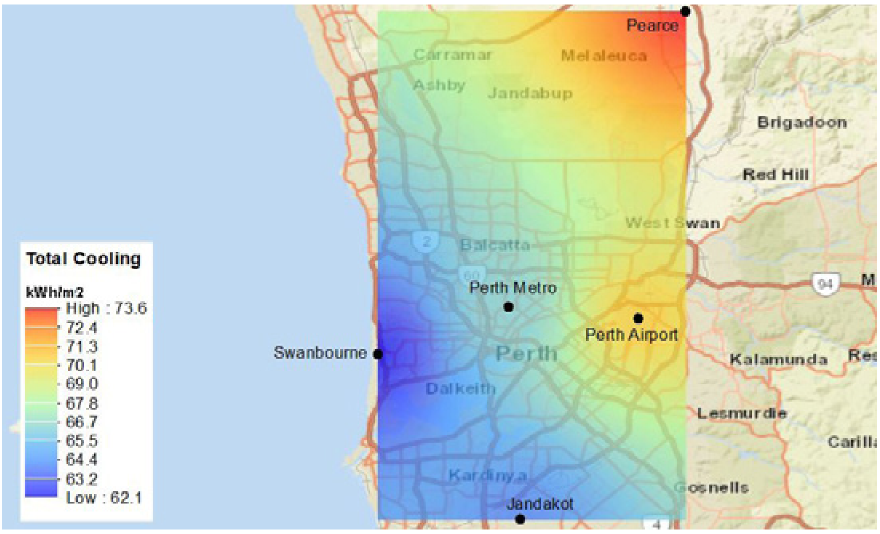

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

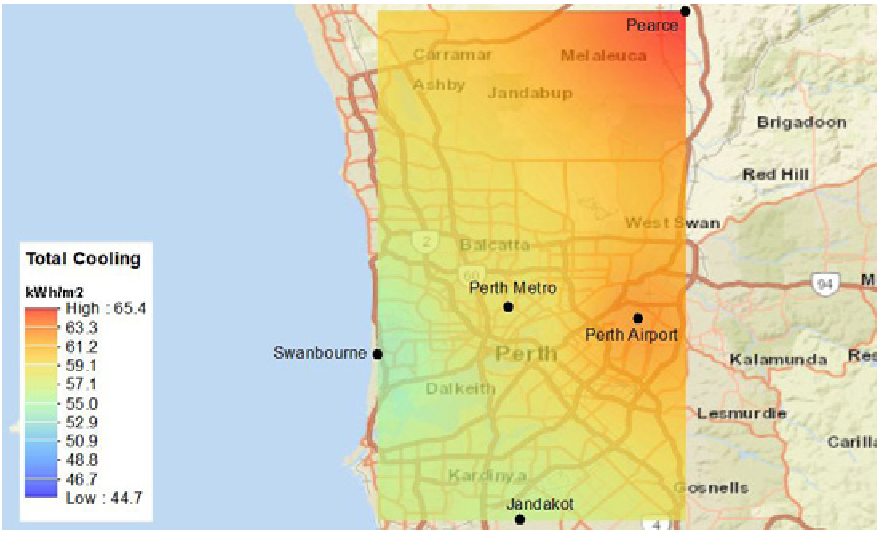

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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 Perth 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 (0.2-0.4 kWh/m²) is significantly lower than the annual cooling load reduction (23.5-31.1 kWh/m²).

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.

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
Jandakot	164.7	177.4	2.2	6.8	141.6	153.9	2.4	7.1
Pearce	179.5	195.4	1.9	5.7	154.4	169.6	2.0	6.1
Perth Airport	173.6	185.2	2.0	6.1	150.0	161.2	2.1	6.4
Perth Metro	181.0	198.2	1.8	5.4	150.6	167.1	1.9	5.8
Swanbourne	156.0	180.3	1.2	3.4	130.5	153.8	1.3	3.7

The annual cooling load saving by building-scale application of cool roofs is around 13.0-15.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 23.1-30.7 kWh/m² (~12.4-15.1 %).

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 low-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Jandakot	23.1	14.0	23.5	13.3	0.1	0.4	23.0	13.8	23.1	12.6
Pearce	25.1	14.0	25.8	13.2	0.1	0.4	25.0	13.8	25.4	12.6
Perth Airport	23.7	13.6	24.1	13.0	0.1	0.3	23.6	13.4	23.7	12.4
Perth Metro	30.4	16.8	31.1	15.7	0.1	0.4	30.2	16.6	30.7	15.1
Swanbourne	25.5	16.4	26.5	14.7	0.1	0.2	25.5	16.2	26.2	14.3

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

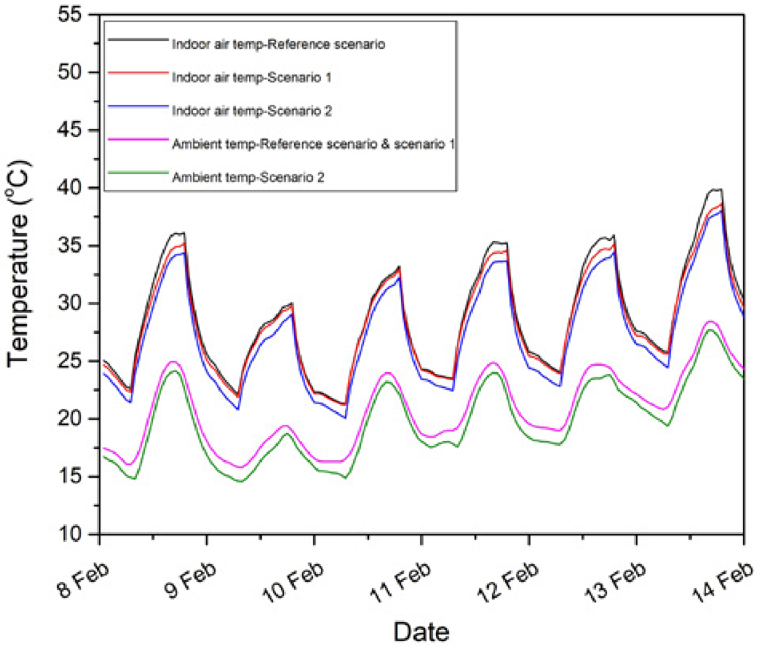

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

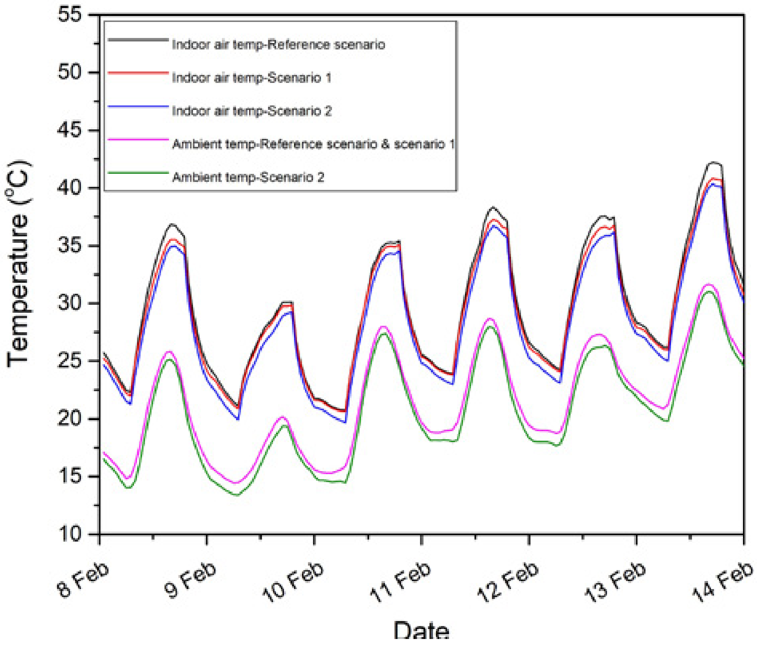

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.3-39.9 °C and 20.8-42.2 °C in Swanbourne and Pearce stations, respectively.

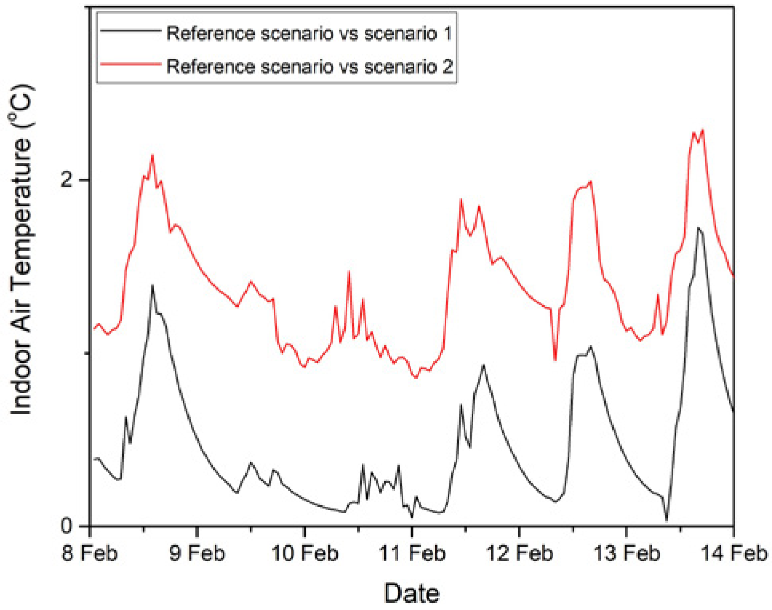

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free-floating conditions during a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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.8 °C and 1.8 °C in Swanbourne and Pearce stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.7 °C and 2.6 °C in Swanbourne and Pearce stations, respectively.

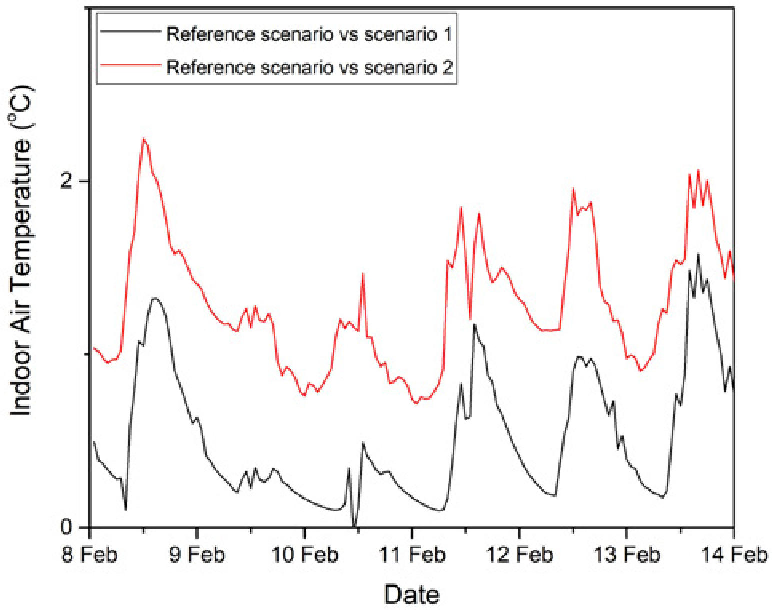

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) an existing new low-rise shopping mall centre under free-floating conditions during a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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 11.0-30.0 °C in reference scenario to a range 10.9-29.3 °C in scenario 1 in Swanbourne station.

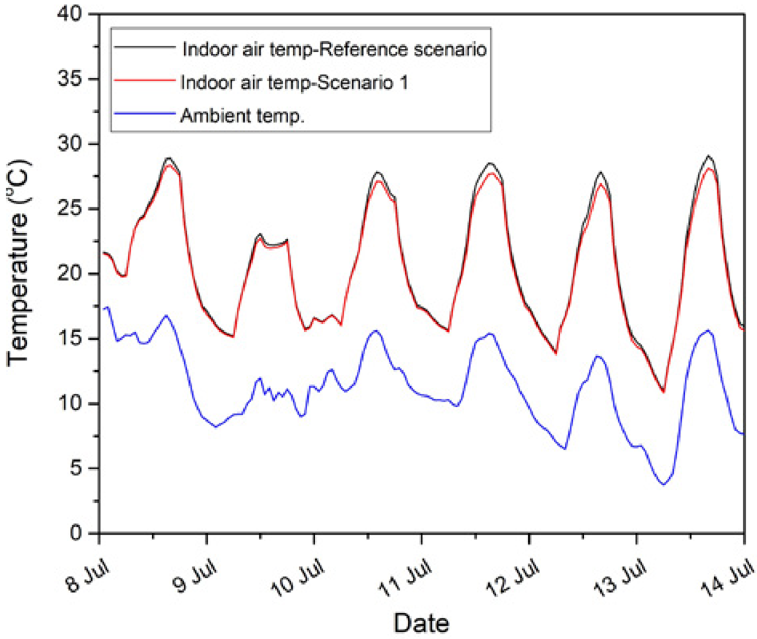

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Swanbourne station* using annual measured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

The indoor air temperature is predicted to reduce from a range 9.8-29.4 °C in reference scenario to a range 9.7-28.9 °C in scenario 1 in Pearce station.

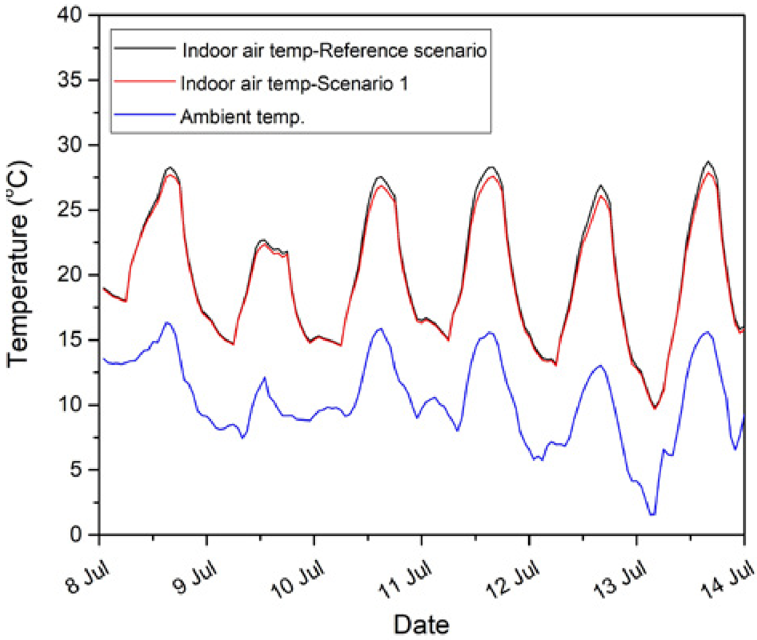

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Pearce station* using annual measured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

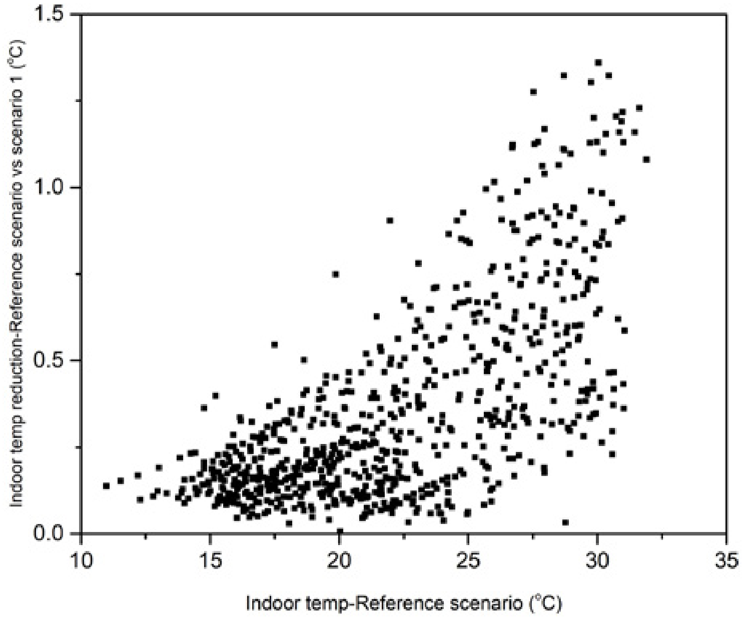

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

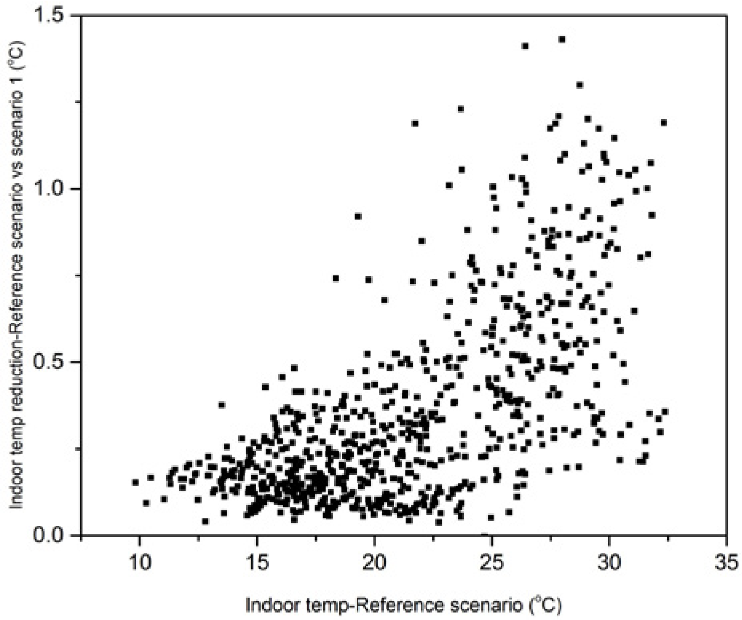

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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
Swanbourne	43	223	46	232
Pearce	50	272	54	282

** 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 223 hours in reference scenario to 232 hours, and from 272 to 282 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 43 hours in reference scenario compared to 46 hours in scenario 1 in Swanbourne; and from 50 to 54 hours in Pearce station.

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

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	557	539	501
Pearce	558	545	511

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 557 hours in reference scenario to 539 and 501 hours under scenario 1 and 2 in Swanbourne station; while decreases from 558 hours to 545 for scenario 1 and to 511 for scenario 2 in Pearce station.

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques.

The building and its energy performance

Building 15 is an existing, low-rise commercial building, with a total air-conditioned area of 2.200 m^2 distributed on two levels. The 1.100 m^2 roof is insulated, but given its impact on half of the building's air-conditioned space, there are important energy losses and, consequently, an important energy saving potential. The main features of the building's energy performance both for Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 15.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	161,7	177,0
Energy consumption after cool roof (MWh)	138,6	154,6
Energy savings (MWh)	23,1	22,4
Energy savings (%)	14,29%	12,66%
Area (m^2)	1.100	1.100
Roof costs - Metal roof (AU$/$m^2$)	38,0	38,0
Roof costs - Coating (AU$/$m^2$)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/$m^2$)	15,0	15,0

Building 15 is 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.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in significant energy savings for both locations, namely 14,29% for Swanbourne and 12,66% for the Pearce 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 significant reduction of life cycle costs over the building's life cycle, that varies between 10,2% for the metal roof, the low energy price scenario and for Pearce conditions and 33,5% for the cool coating, the high energy scenario and for Swanbourne 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 Swanbourne and for Pearce weather conditions respectively.

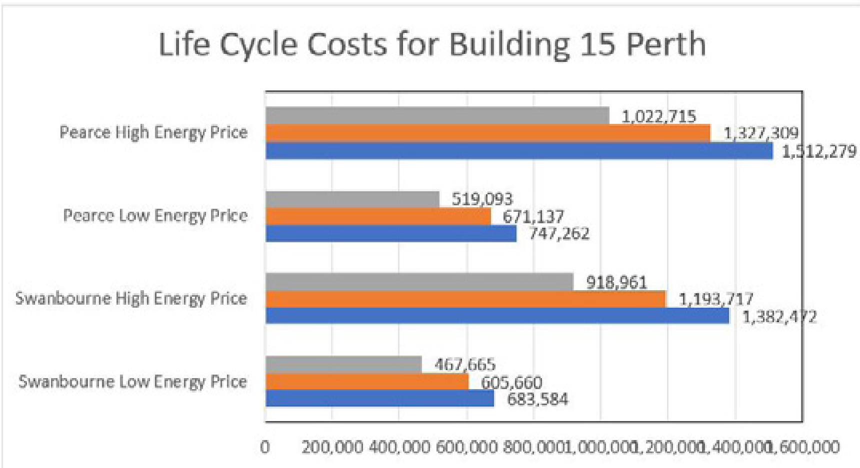

Figure 12. Life Cycle Costs for Building 15 for Swanbourne and Pearce weather stations.

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	11,40 %	13,65 %	10,19 %	12,23 %
Coating Cool Roof	31,59 %	33,53 %	30,53 %	32,37 %

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 Perth, 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 62.1-73.6 kWh/m^2 to 54.1-65.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 7.9-8.2 kWh/m^2. This is equivalent to approximately 11.1-12.8 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 14.9-17.4 kWh/m^2. This is equivalent to 20.2-28.0 % 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 (0.2-0.4 kWh/m^2) is significantly lower than the annual cooling load reduction (23.5-31.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 13.0-15.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 23.1-30.7 kWh/m^2 (~12.4-15.1 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 21.3-39.9 ^{o}C and 20.8-42.2 ^{o}C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.8 and 1.8 ^{o}C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.7 and 2.6 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 11.0-30.0 °C in reference scenario to a range between 10.9-29.3 °C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 9.8-29.4 °C in reference scenario to a range between 9.7-28.9 °C in reference with cool roof scenario (scenario 1) in Pearce 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 in Swanbourne and Pearce 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 223 hours in reference scenario to 232 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slight increase in total number of hours below 19 °C from 272 hours in reference scenario to 282 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 43 hours in reference scenario to 46 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. Similarly, the calculation in Pearce station shows a slight increase of number of hours below 19 °C from 50 hours to 54 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 557 hours under the reference scenario in Swanbourne station, which decreases to 539 and 501 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Pearce station show that the number of hours above 26 °C decreases from 558 to 545 and 511 hours for scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques, which lead to a significant reduction of life cycle costs over the building's life cycle, that varies between 10,2% for the metal roof, the low energy price scenario and for Pearce conditions and 33,5% for the cool coating, the high energy scenario and for Swanbourne 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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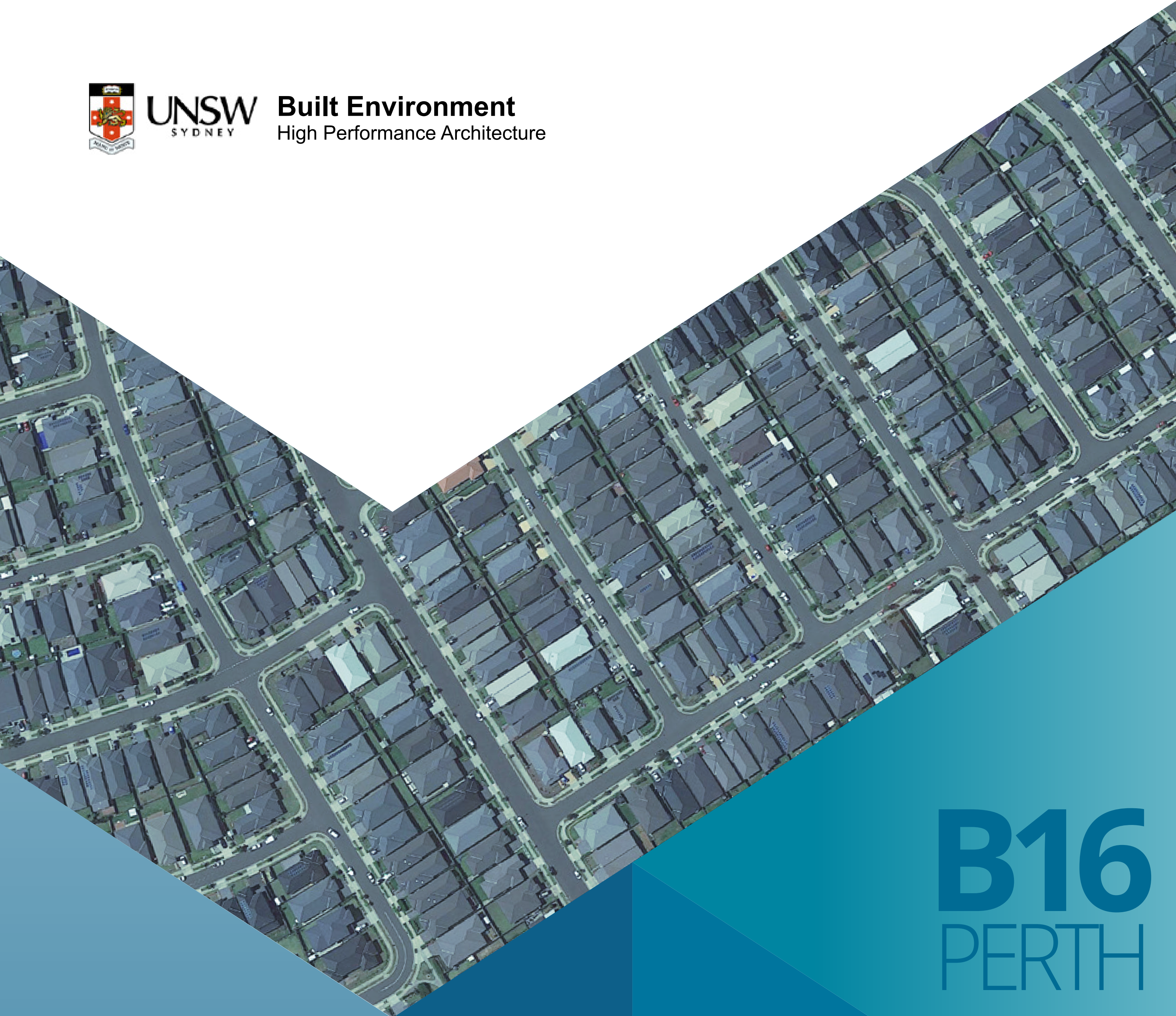

B16
PERTH

COOL ROOFS
COST BENEFIT ANALYSIS

Existing high-rise shopping mall centre
2021

BUILDING 16

EXISTING HIGH-RISE SHOPPING MALL CENTRE

Floor area : 1100m^2
Number of stories : 6

Image source: Mall of America, Minneapolis

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

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

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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 Perth using weather data simulated by WRF.

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.

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 57.2-68.2 kWh/m^2 to 54.9-65.7 kWh/m^2.

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)
Jandakot	50.2	59.0	48.0	56.7	43.9	48.1
Pearce	59.4	68.2	57.0	65.7	53.8	59.0
Perth Airport	56.8	65.3	54.5	62.9	49.7	53.5
Perth Metro	51.6	61.1	49.4	58.8	44.8	49.3
Swanbourne	46.0	57.2	43.8	54.9	39.6	45.2

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 2.3-2.4 kWh/m^2 which is equivalent to 3.6-4.1 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 9.3-12.0 kWh/m^2 which is equivalent to 13.5-21.0 % 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	%
Jandakot	2.2	4.4	2.3	3.9	6.4	12.7	10.9	18.5
Pearce	2.4	4.0	2.4	3.6	5.5	9.3	9.2	13.5
Perth Airport	2.3	4.1	2.4	3.7	7.1	12.5	11.8	18.1
Perth Metro	2.2	4.3	2.3	3.8	6.8	13.3	11.8	19.3
Swanbourne	2.2	4.8	2.3	4.1	6.4	13.9	12.0	21.0

In the eleven weather stations in Perth, 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.

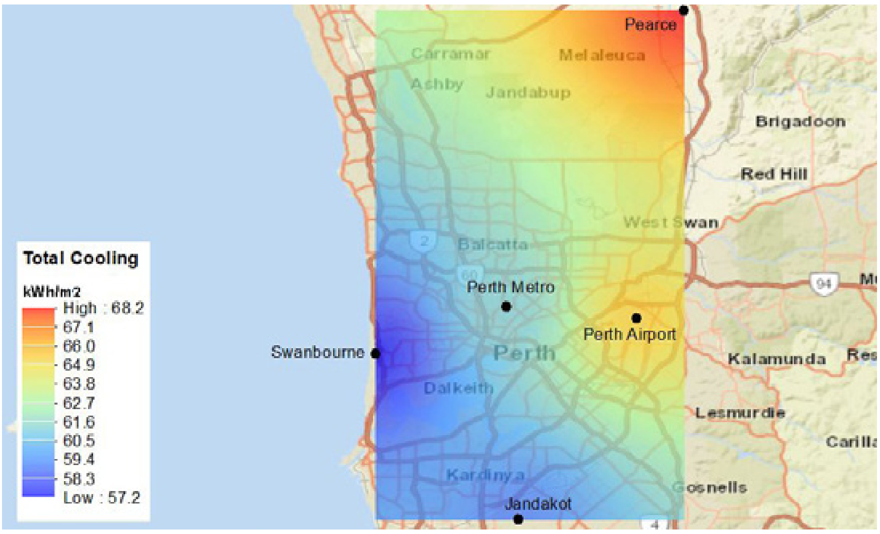

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

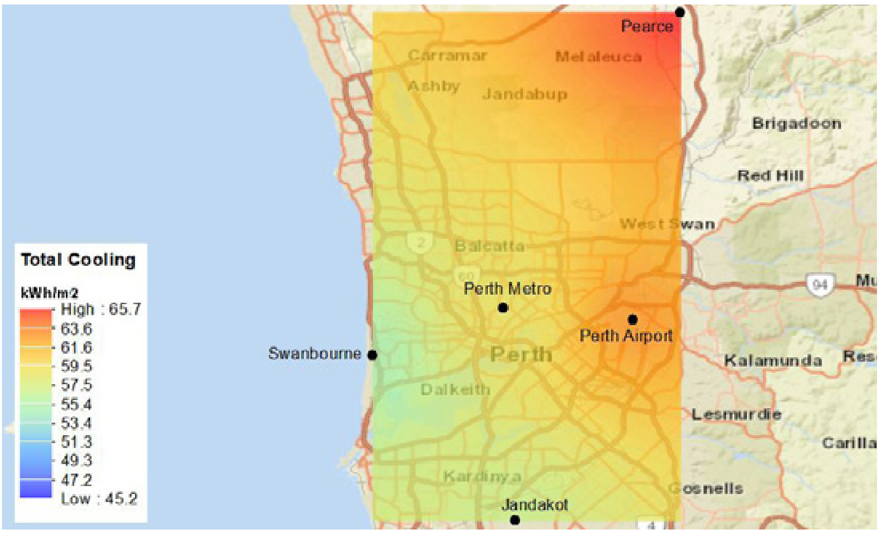

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

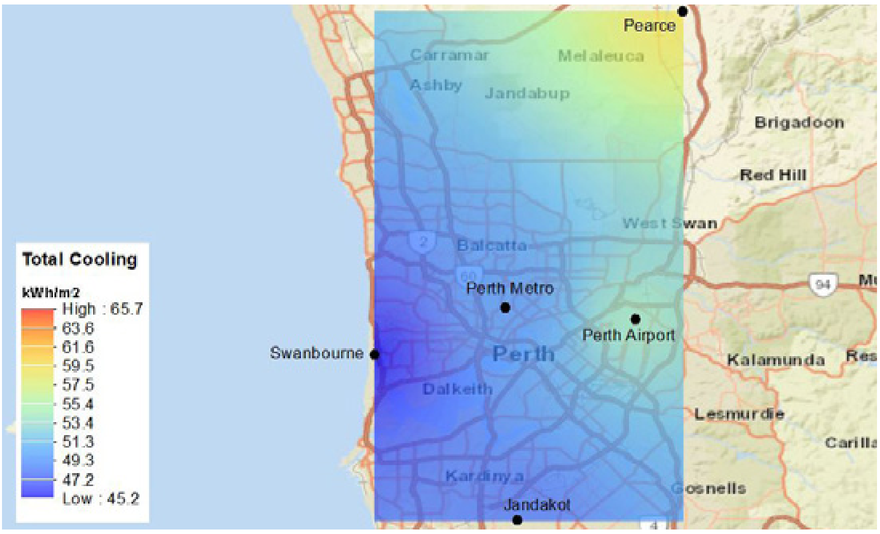

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1 kWh/m²) is significantly lower than the annual cooling load reduction (6.6-9.0 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Jandakot	149.5	162.2	1.5	5.0	143.1	155.6	1.6	5.1
Pearce	163.0	178.8	1.2	3.9	155.8	171.4	1.3	4.0
Perth Airport	158.3	169.9	1.3	4.3	151.7	163.1	1.3	4.4
Perth Metro	161.8	178.8	1.1	3.6	152.9	169.8	1.1	3.7
Swanbourne	141.1	165.3	0.7	2.0	133.9	157.8	0.7	2.1

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

The annual cooling load saving by building-scale application of cool roofs is around 4.0-5.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.5-8.9 kWh/m² (~3.8-4.9 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Jandakot	6.5	4.3	6.6	4.1	0.0	0.1	6.4	4.2	6.5	3.9
Pearce	7.1	4.4	7.3	4.1	0.0	0.1	7.1	4.3	7.2	3.9
Perth Airport	6.7	4.2	6.8	4.0	0.0	0.1	6.6	4.2	6.7	3.8
Perth Metro	8.8	5.5	9.0	5.0	0.0	0.1	8.8	5.4	8.9	4.9
Swanbourne	7.2	5.1	7.5	4.5	0.0	0.1	7.2	5.1	7.4	4.4

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

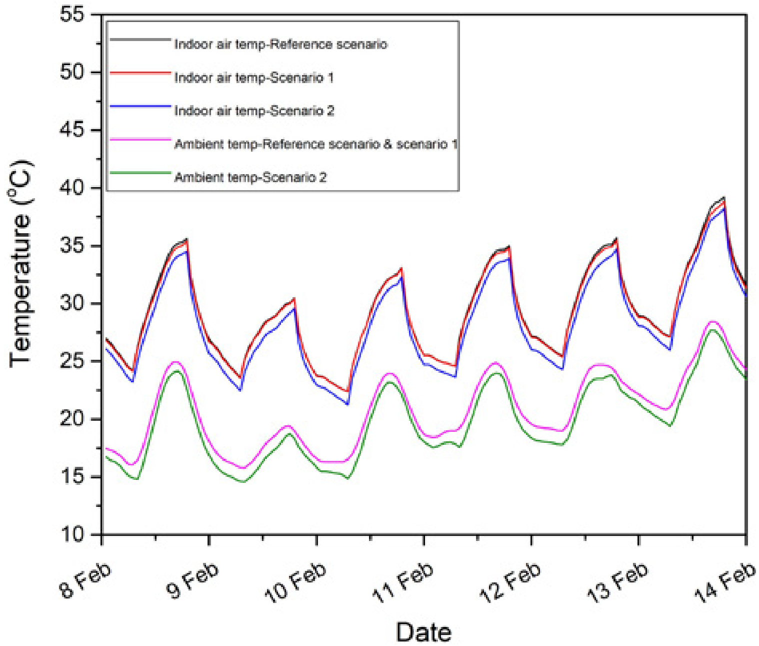

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

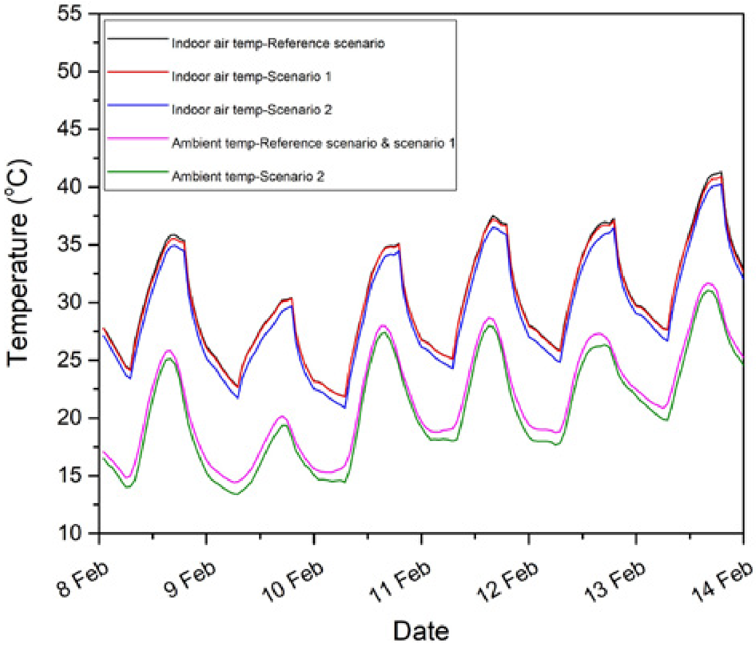

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.4-39.2 °C and 21.9-41.3 °C in Swanbourne and Pearce stations, respectively.

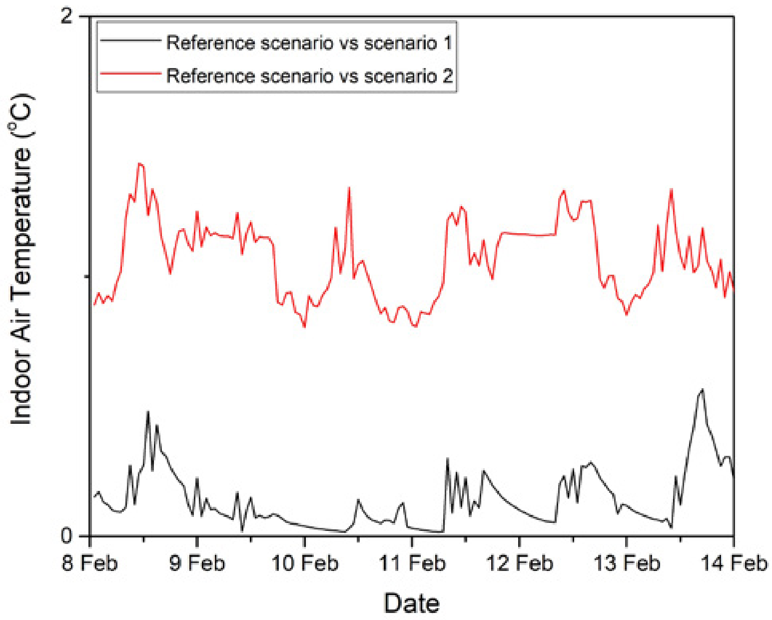

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free-floating conditions during a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

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

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.4 °C and 1.3 °C in Swanbourne and Pearce stations, respectively.

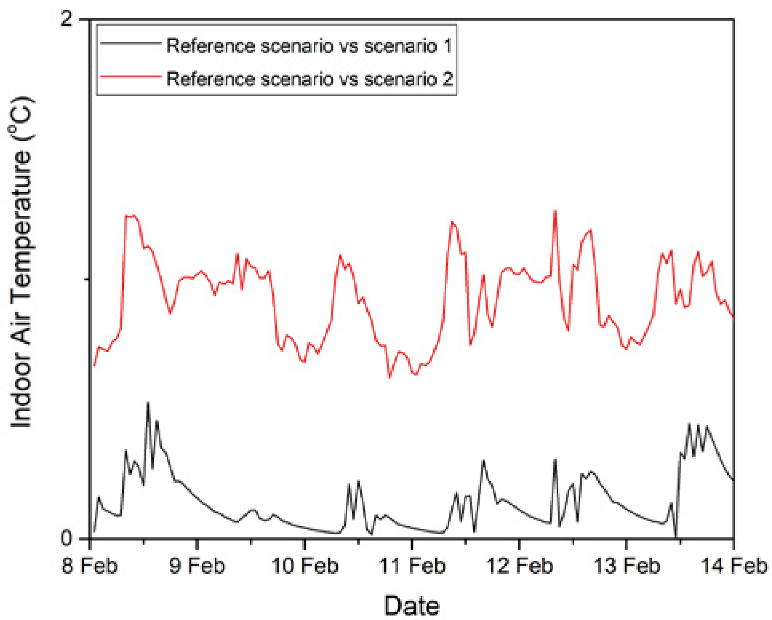

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing highrise shopping mall centre under free-floating conditions during a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

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 13.0-29.4 °C in reference scenario to a range 12.9-29.3 °C in scenario 1 in Swanbourne station.

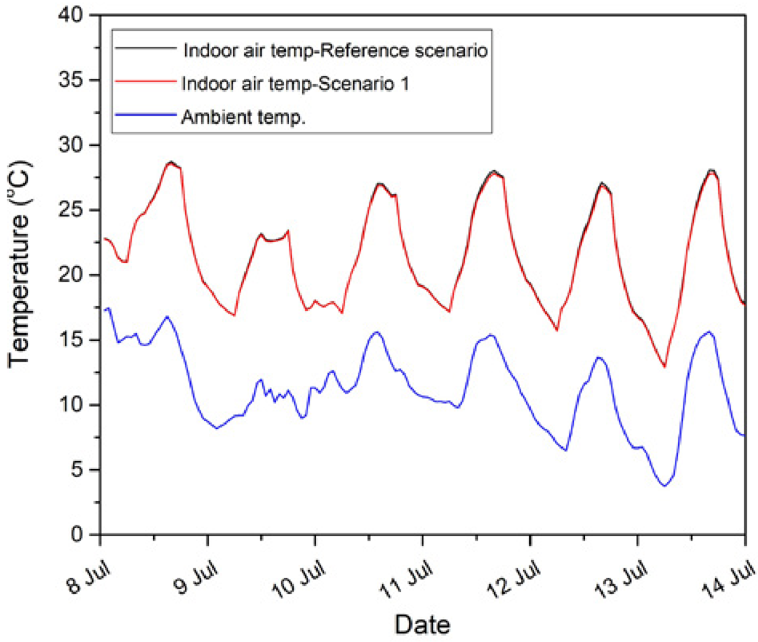

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Swanbourne station* using annual measured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

The indoor air temperature is predicted to reduce from a range 12.1-29.1 °C in reference scenario to a range 12.1-29.0 °C in scenario 1 in Pearce station.

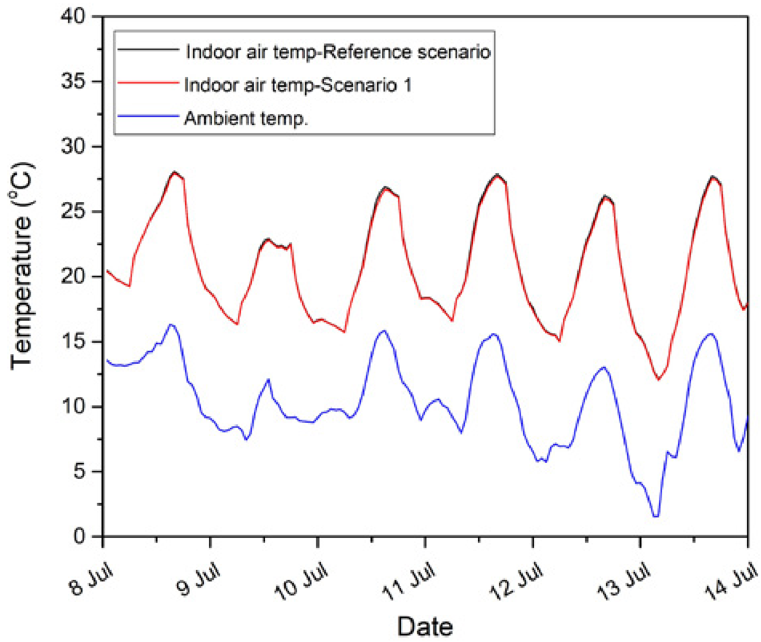

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Pearce station* using annual measured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

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce stations.

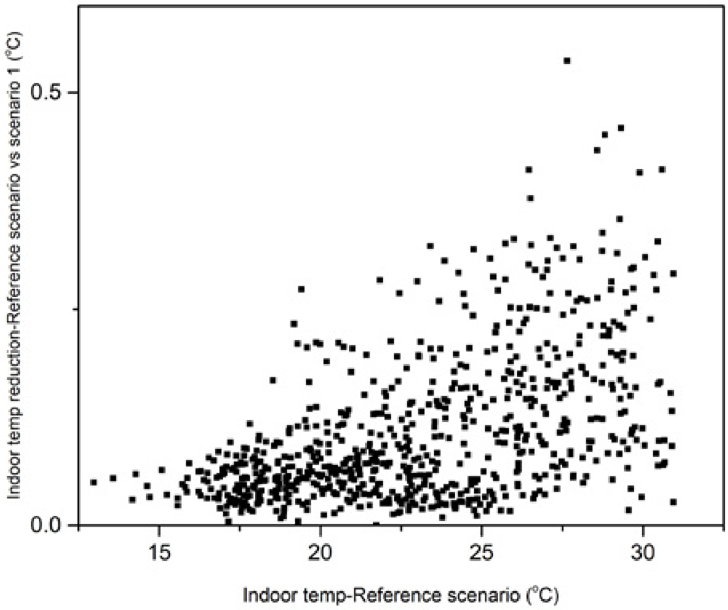

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

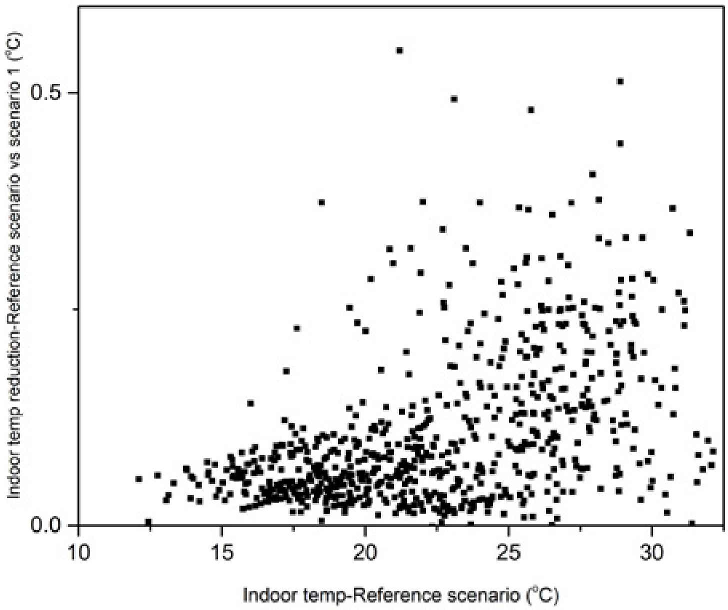

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 144 in the reference scenario to 153 hours in Scenario 1 in Swanbourne; and from 196 to 199 hours in Pearce stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 28 hours in reference scenario compared to 29 hours in scenario 1 in Pearce 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
Swanbourne	28	144	29	153
Pearce	39	196	39	199

** 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 618 hours in reference scenario to 612 hours under scenario 2 in Swanbourne station; while decreases from 615 hours to 615 for scenario 1 and to 588 for scenario 2 in Pearce station.

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

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	618	612	577
Pearce	615	615	588

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques

The building and its energy performance

Building 16 is an existing, high-rise commercial building, with a total air-conditioned area of 6.600 m^2 distributed on six levels. The 1.100 m^2 roof is not insulated, resulting in energy losses which have a direct impact on the building's last floor only and, consequently, lead to a modest energy saving potential. The main features of the building's energy performance both for Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 16.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	441,7	482,3
Energy consumption after cool roof (MWh)	422,1	463,1
Energy savings (MWh)	19,6	19,2
Energy savings (%)	4,44%	3,98%
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 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 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, modest energy savings for both locations, namely of 4,44% for Swanbourne and of 3,98% for the Pearce 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 25,4% for the low energy price scenario, the metal cool roof and the Swanbourne conditions and 25,3% for the high energy scenario, the coating cool roof and 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 Swanbourne and for Pearce weather conditions respectively.

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.

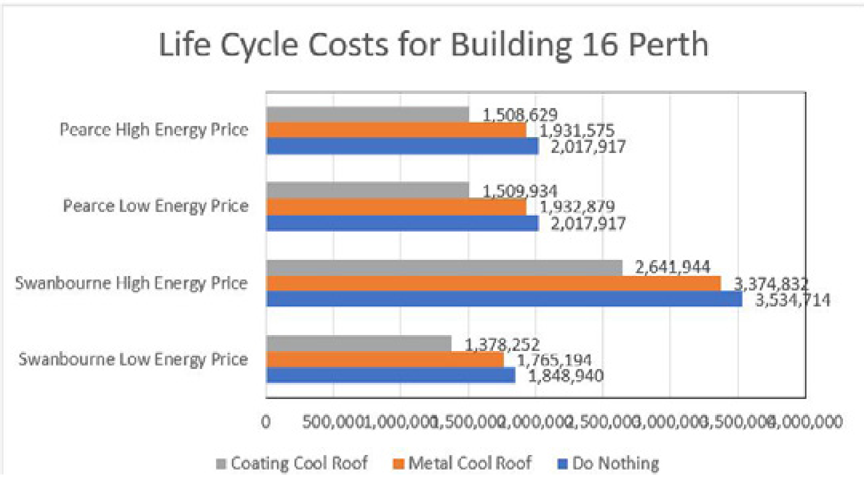

Figure 12. Life Cycle Costs for Building 16 for Swanbourne and Pearce weather stations.

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	4,53 %	4,52 %	4,21 %	4,28 %
Coating Cool Roof	25,46 %	25,26 %	25,17 %	25,24 %

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 Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 57.2-68.2 kWh/m^2 to 54.9-65.7 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 2.3-2.4 kWh/m^2. This is equivalent to approximately 3.6-4.1 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 9.3-12.0 kWh/m^2. This is equivalent to 13.5-21.0 % 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 (0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (6.6-9.0 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.0-5.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.5-8.9 kWh/m2 (~3.8-4.9 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 22.4-39.2 ^{o}C and 21.9-41.3 ^{o}C in Swanbourne and Pearce stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.6 and 0.6 ^{o}C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.4 and 1.3 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce 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 13.0-29.4 ^{o}C in reference scenario to a range between 12.9-29.3 ^{o}C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 12.1-29.1 °C in reference scenario to a range between 12.1-29.0 °C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C in Swanbourne and Pearce 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 144 hours in reference scenario to 153 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slight increase in total number of hours below 19 °C from 196 hours in reference scenario to 199 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 28 hours in reference scenario to 29 hours in reference with cool roof scenario (scenario 1) in Pearce 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 618 hours under the reference scenario in Swanbourne station, which decreases to 612 hours under the modified urban temperature scenario (scenario 2). The simulations in Pearce station show that the number of hours above 26 °C decreases from 615 to 615 and 588 hours for scenario 1 and 2, respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's typology, the 'Do Nothing' approach has the highest cost over the building's life cycle compared to both cool roof techniques. These lead to a reduction of life cycle costs over the building's life cycle, that varies for the coating cool roof between 25,4% for the low energy price scenario, the metal cool roof and the Swanbourne conditions and 25,3% for the high energy scenario, the coating cool roof and both locations, 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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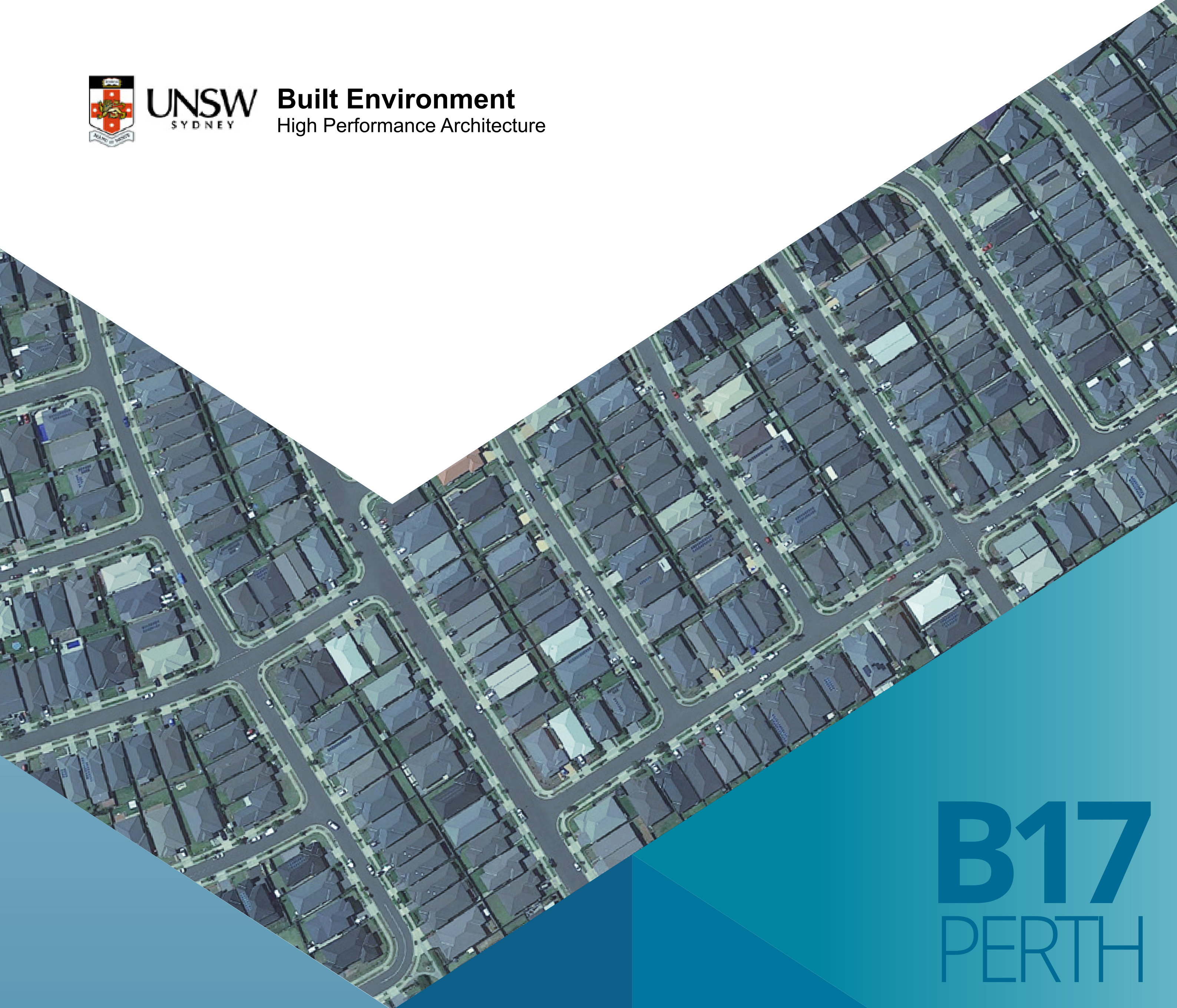

B17
PERTH

COOL ROOFS
COST BENEFIT ANALYSIS

New standalone house
2021

BUILDING 17

NEW STANDALONE HOUSE

Floor area : 242m^2
Number of stories : 1

Image source: https://www.newhomesguide.com.au/builders/long-island-homes/homes/new-homes/moonbi-240

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

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

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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 Perth 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 8.7-13.2 kWh/m² to 5.3-9.6 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/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)
Jandakot	8.3	9.9	5.4	6.6	4.2	4.6
Pearce	11.3	13.2	8.0	9.6	7.0	7.8
Perth Airport	10.5	12.2	7.3	8.7	5.9	6.3
Perth Metro	8.7	10.5	5.7	7.1	4.4	4.9
Swanbourne	6.7	8.7	4.0	5.3	3.0	3.4

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 3.4-3.6 kWh/m² which is equivalent to 27.2-39.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 5.2-5.9 kWh/m² which is equivalent to 40.8-60.3 % 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	%
Jandakot	2.9	35.3	3.4	33.8	4.1	49.0	5.3	53.1
Pearce	3.3	29.0	3.6	27.2	4.2	37.6	5.4	40.8
Perth Airport	3.2	30.3	3.5	28.7	4.6	43.9	5.9	48.1
Perth Metro	3.0	34.1	3.4	32.4	4.2	48.9	5.6	53.2
Swanbourne	2.7	40.7	3.4	39.0	3.7	55.6	5.2	60.3

In the eleven weather stations in Perth, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new standalone house during the summer season.

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

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

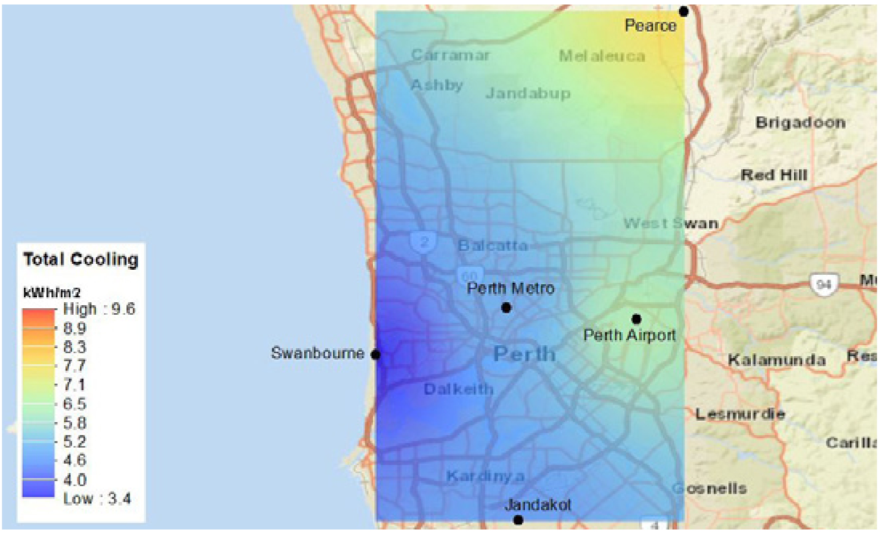

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Perth 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 (1.3-1.7 kWh/m²) is lower than the annual cooling load reduction (5.9-7.8 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
Jandakot	17.0	19.2	15.8	19.3	11.5	13.2	17.1	20.9
Pearce	20.8	23.5	14.7	18.0	14.3	16.6	16.0	19.6
Perth Airport	19.6	21.8	14.7	18.0	13.6	15.4	15.9	19.4
Perth Metro	19.4	22.5	13.5	16.6	12.3	14.7	15.0	18.2
Swanbourne	12.5	15.8	10.2	12.7	7.3	9.5	11.4	14.0

The annual cooling load saving by building-scale application of cool roofs is around 29.2-39.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.4-6.2 kWh/m² (~11.4-17.2 %).

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	%
Jandakot	5.6	32.6	5.9	30.9	1.3	1.5	4.2	12.8	4.4	11.4
Pearce	6.4	31.0	6.9	29.4	1.4	1.6	5.1	14.3	5.3	12.8
Perth Airport	6.0	30.8	6.4	29.2	1.3	1.4	4.8	13.9	4.9	12.4
Perth Metro	7.2	36.9	7.8	34.7	1.4	1.7	5.7	17.3	6.2	15.7
Swanbourne	5.2	41.5	6.2	39.5	1.2	1.3	4.0	17.7	4.9	17.2

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 Perth (i.e. Swanbourne and Pearce) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 15.8-28.4 °C in reference scenario to a range 14.6-27.7 °C in scenario 2 in Swanbourne station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-2.3 °C compared to the reference scenario in Swanbourne station.

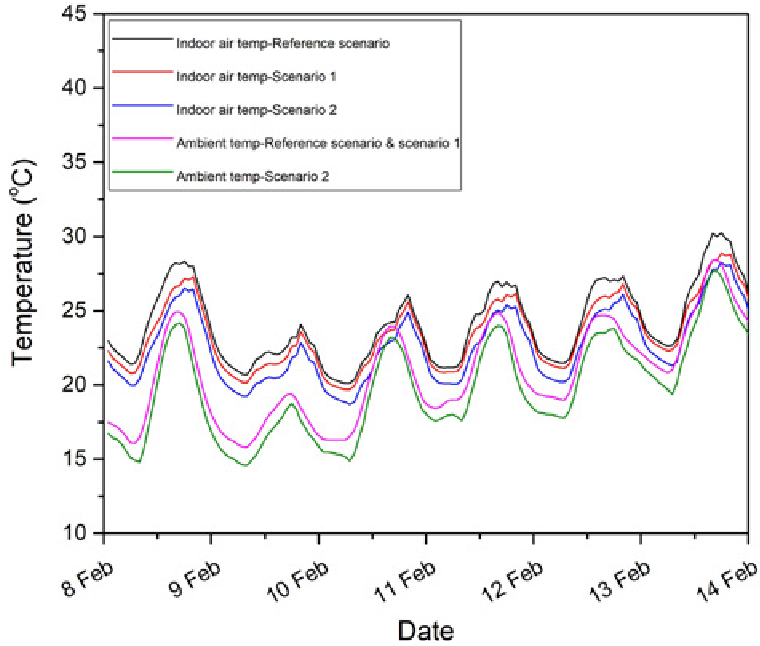

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer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

For scenario 2, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in Pearce station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-1.6 °C compared to the reference scenario in Pearce station.

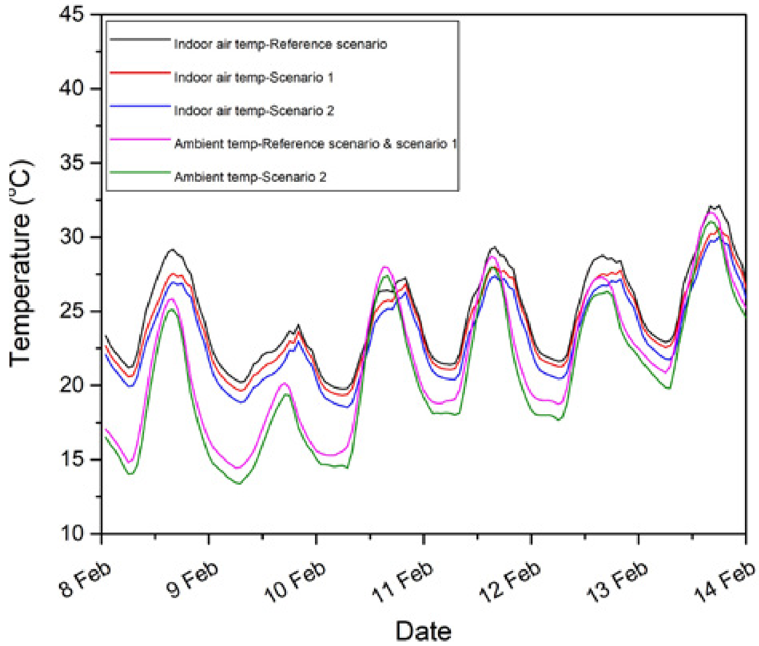

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 20.1-30.3 °C and 19.8-32.2 °C in Swanbourne and Pearce stations, respectively.

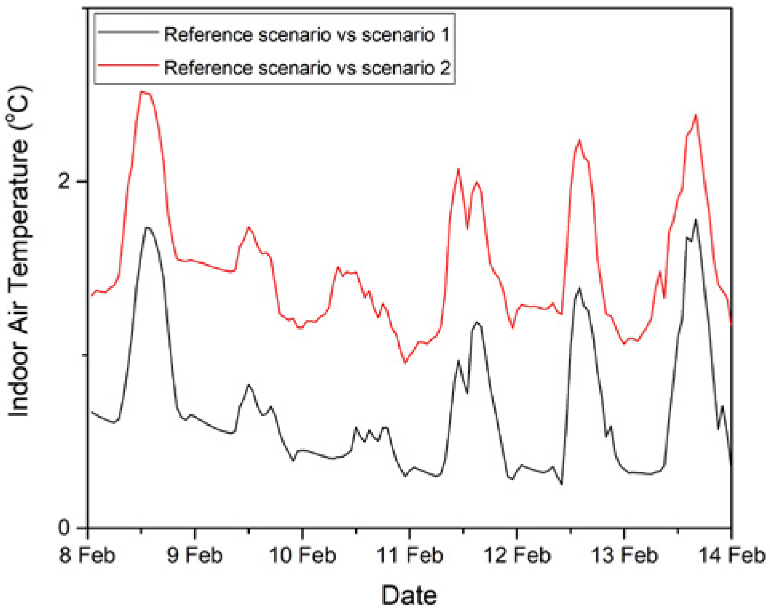

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week in *Swanbourne 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 2.0 °C in Swanbourne and Pearce stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.8 °C and 2.7 °C in Swanbourne and Pearce stations, respectively.

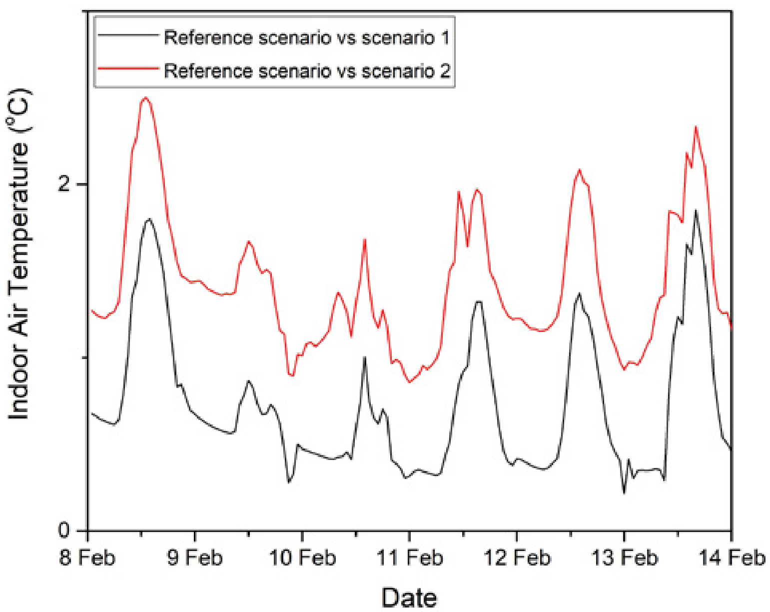

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week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

During a typical winter week, the indoor air temperature is expected to decrease from a range 10.8-22.5 °C in reference scenario to a range 10.6-21.6 °C in scenario 1 in Swanbourne station.

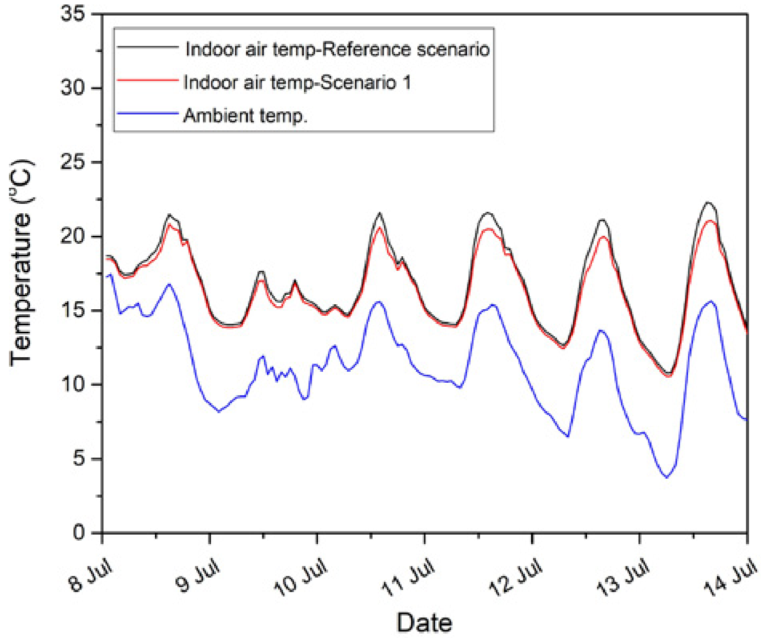

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Swanbourne station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 9.5-21.9 °C in reference scenario to a range C in scenario 1 in Pearce station.

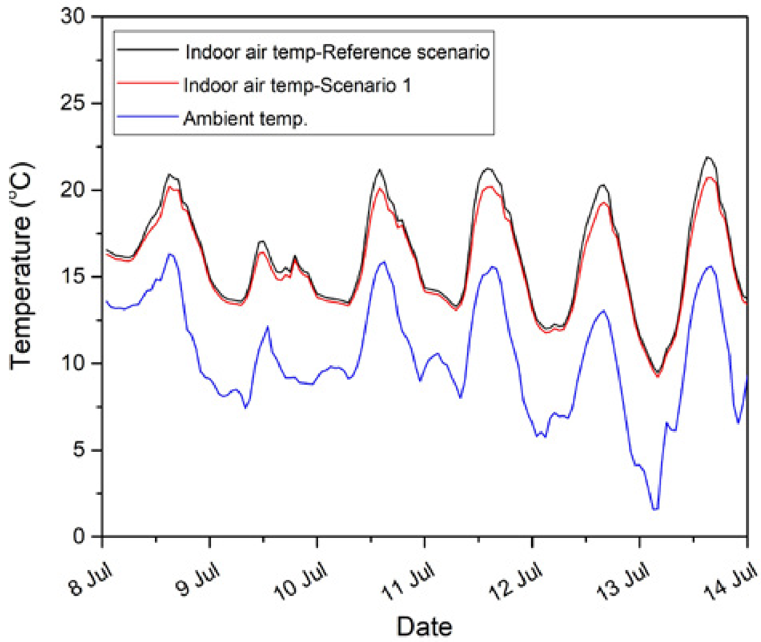

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Pearce station* using annual measured weather data.

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

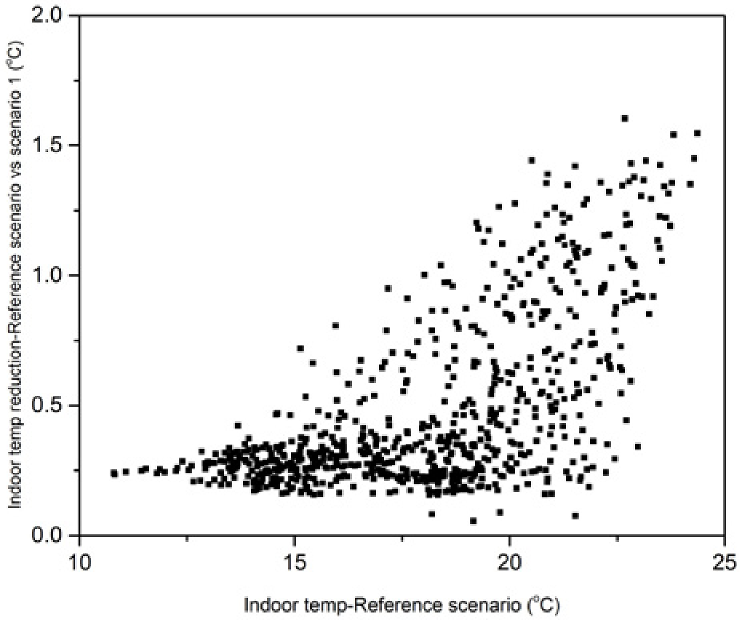

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Swanbourne station* using annual measured weather data.

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

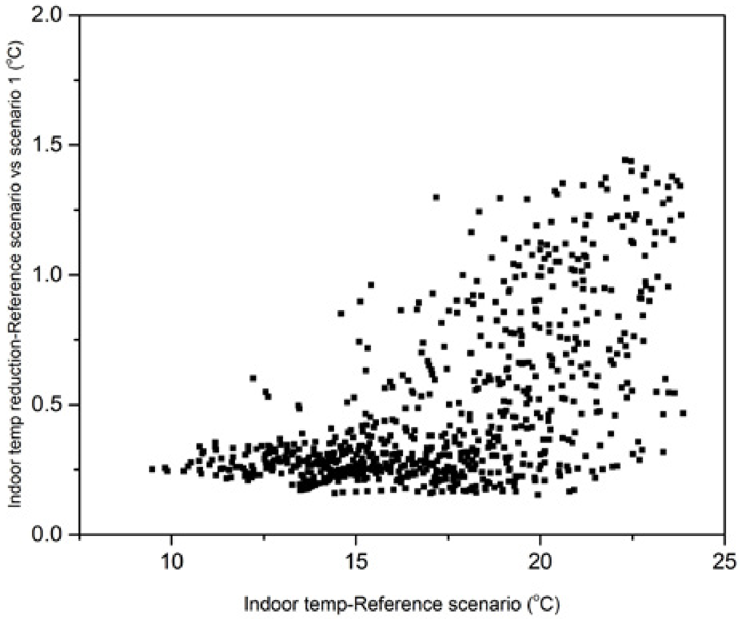

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Pearce station* using annual measured weather data.

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 Perth (i.e. Swanbourne and Pearce) 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 446 hours in reference scenario to 487 hours; and from 486 to 535 hours in scenario 1 in Swanbourne and Pearce stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Swanbourne	446	487
Pearce	486	535

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

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease significantly from 330 hours in reference scenario to 256 and 192 hours under scenario 1 and 2 in Swanbourne station; and from 376 hours in reference scenario to 327 and 288 hours under scenario 1 and 2 in Pearce station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Swanbourne	330	256	192
Pearce	376	327	288

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 17 is an existing, stand-alone residential building, with a total air-conditioned area of 242 m^2 distributed on one level. The 242 m^2 roof is insulated, but given the fact that it affects the entire building are, the energy conservation potential is significant. The main features of the building's energy performance both for Swanbourne and for Pearce weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 17.

Energy performance features	Swanbourne	Pearce
Energy consumption prior cool roof (MWh)	2,8	4,0
Energy consumption after cool roof (MWh)	2,3	3,5
Energy savings (MWh)	0,5	0,5
Energy savings (%)	17,86%	12,50%
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 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.

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 17,86% for the Swanbourne weather conditions and of 12,50% for the Pearce 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 9,2% for the low energy price scenario for Swanbourne and 21,8% for the high energy scenario and for Pearce 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 Swanbourne and for Pearce weather conditions respectively.

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 is, not feasible, for both scenarios and locations.

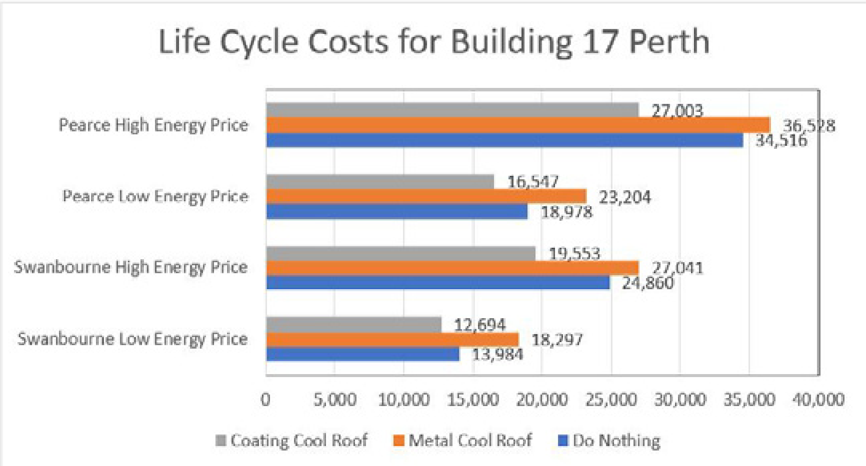

Figure 12. Life Cycle Costs for Building 17 for Swanbourne and Pearce weather stations.

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

Reduction of Life Cycle Costs	**Observatory**		**Richmond**	
	Low Energy Price	**High Energy Price**	**Low Energy Price**	**High Energy Price**
Metal Cool Roof	-30,85 %	-8,77 %	-22,27 %	-5,83 %
Coating Cool Roof	9,22 %	21,35 %	12,81 %	21,77 %

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CONCLUSIONS

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

• In the eleven weather stations in Perth, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 8.7-13.2 kWh/m^2 to 5.3-9.6 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 3.4-3.6 kWh/m^2. This is equivalent to approximately 27.2-39.0 % 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 Perth, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 5.2-5.9 kWh/m^2. This is equivalent to 40.8-60.3 % 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 (1.3-1.7 kWh/m^2) is lower than the annual cooling load reduction (5.9-7.8 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 29.2-39.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.4-6.2 kWh/m^2 (~11.4-17.2 %) (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 20.1-30.3 ^{o}C and 19.8-32.2 ^{o}C in Swanbourne and Pearce 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 2.0 ^{o}C in Swanbourne and Pearce stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.8 and 2.7 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Swanbourne and Pearce stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 15.8-28.4 °C in reference scenario to a range between 14.6-27.7 °C in cool roof and modified urban temperature scenario (scenario 2) in Swanbourne station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-2.3 °C. Similarly, the ambient temperature is predicted to decrease from 15.5-31.7 °C in reference scenario to 13.4-31.1 °C in cool roof and modified urban temperature scenario (scenario 2) in Pearce station. The estimated ambient temperature reduction is 0.4-1.6 °C in Pearce station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease from a range between 10.8-22.5 ^{o}C in reference scenario to a range between 10.6-21.6 ^{o}C in reference with cool roof scenario (scenario 1) in Swanbourne station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 9.5-21.9 ^{o}C in reference scenario to a range between 9.2-21.2 ^{o}C in reference with cool roof scenario (scenario 1) in Pearce station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.5 ^{o}C for both Swanbourne and Pearce stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase from 446 hours in reference scenario to 487 hours in reference with cool roof scenario (scenario 1) in Swanbourne station. The estimations for Pearce stations also show a slightly increase in total number of hours below 19 ^{o}C from 486 hours in reference scenario to 535 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 330 hours under the reference scenario in Swanbourne station, which slightly decreases to 256 and 192 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Pearce station also illustrate a significant reduction in number of hours above 26 ^{o}C from 376 hours in reference scenario to 327 in reference with cool roof scenario (scenario 1) and 288 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 9,2% for the low energy price scenario for Swanbourne and 21,8% for the high energy scenario and for Pearce conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the limited in absolute terms energy savings, not feasible, for both scenarios and locations. Building 17 is in that sense an interesting example of a new, stand-alone residential building, with a single ground floor and an insulated roof, where the energy conservation potential is important. The application of a coating cool technology emerges as a meaningful and appealing investment. On the other hand, given the low in absolute terms value of energy expenditures and the high initial investment cost of the metal cool roof, the latter is not feasible.

B17

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