MAY 2022

COOL ROOFS COST BENEFIT ANALYSIS

Volume 5 – Melbourne: Analysis and Results of the Climatic and Energy Performance of Cool Roofs. Description and Results of Building Case Studies.

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This report is submitted by the University of New South Wales

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Submission date: 22 October 2021.

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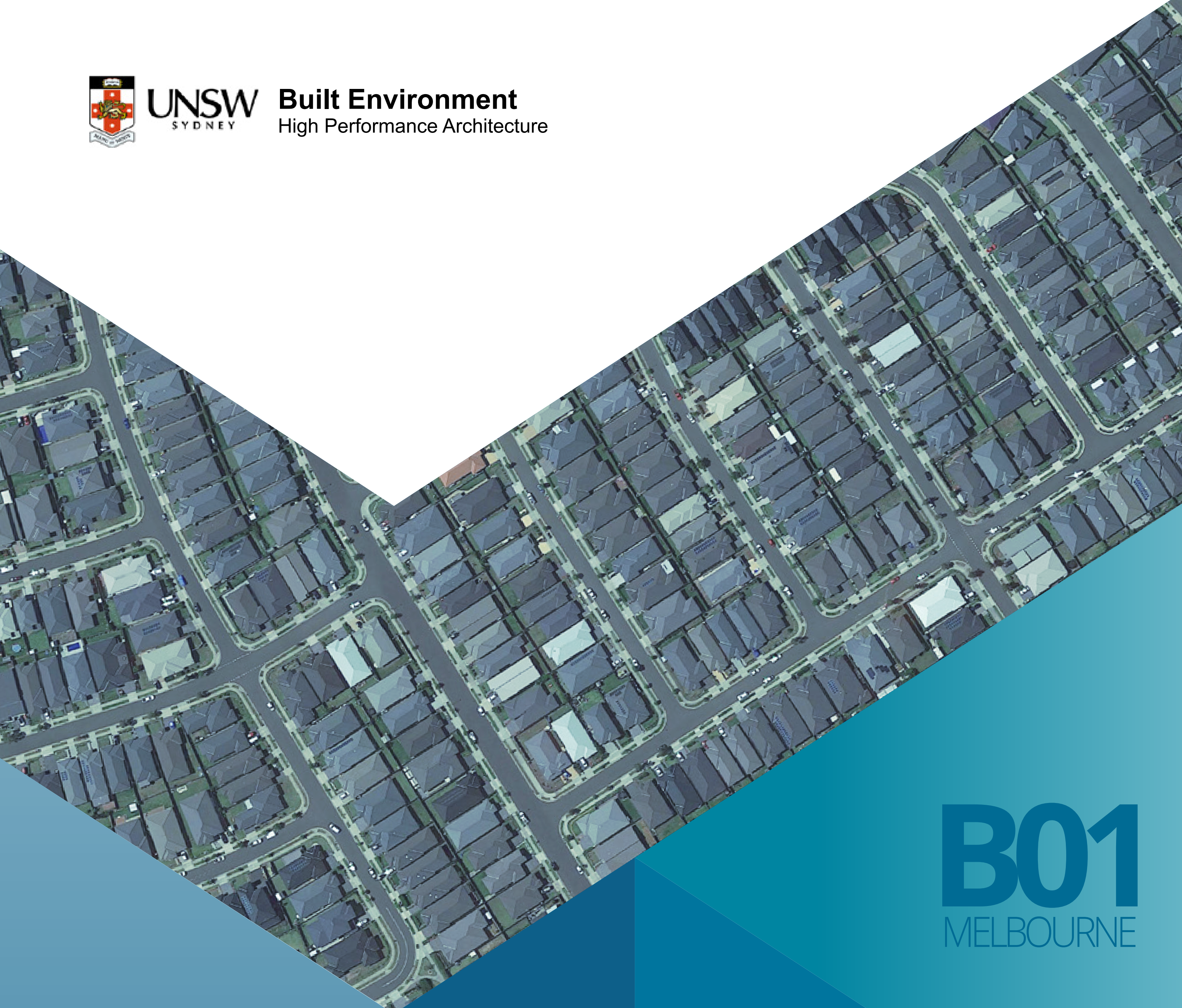

B01
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Low-rise office building without roof insulation
2021

BUILDING 01

LOW-RISE OFFICE BUILDING WITHOUT ROOF INSULATION

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

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

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
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 Melbourne 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 12.6-18.3 kWh/m² to 6.2-8.6 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)
Avalon airport	14.1	14.8	7.2	7.8	5.8	6.0
Coldstream	17.7	18.3	7.8	8.3	6.6	6.7
Essendon	15.6	16.3	7.9	8.4	6.2	6.2
Frankston beach	11.6	12.6	5.5	6.2	4.2	4.3
Melbourne airport	16.1	16.8	8.0	8.6	6.3	6.4
Moorabbin airport	12.3	13.2	5.9	6.7	4.6	4.8
Olympic park	13.8	14.6	6.8	7.5	5.7	5.9

For Scenario 1, the total cooling load saving is around 6.3-10.0 kWh/m² which is equivalent to 47.6-54.9 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 8.3-11.7 kWh/m² which is equivalent to 59.3-65.7 % 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	%
Avalon airport	6.9	49.1	7.1	47.6	8.3	58.6	8.8	59.3
Coldstream	9.9	56.1	10.0	54.9	11.1	62.9	11.7	63.6
Essendon	7.8	49.8	7.9	48.4	9.5	60.6	10.1	61.9
Frankston beach	6.1	52.7	6.3	50.4	7.5	64.1	8.3	65.7
Melbourne airport	8.0	50.0	8.2	48.7	9.8	60.8	10.4	62.1
Moorabbin airport	6.4	51.7	6.5	49.4	7.7	62.4	8.5	64.0
Olympic park	7.0	50.9	7.2	49.0	8.1	58.6	8.7	59.8

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

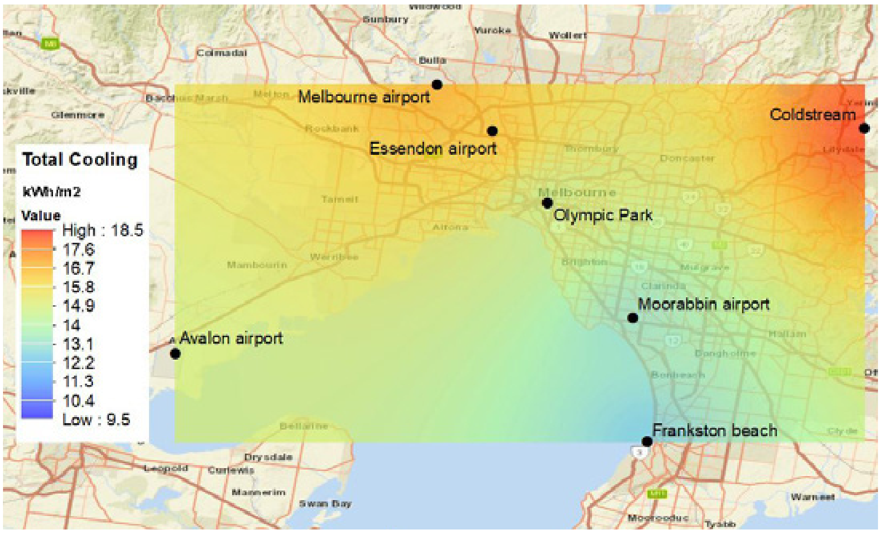

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

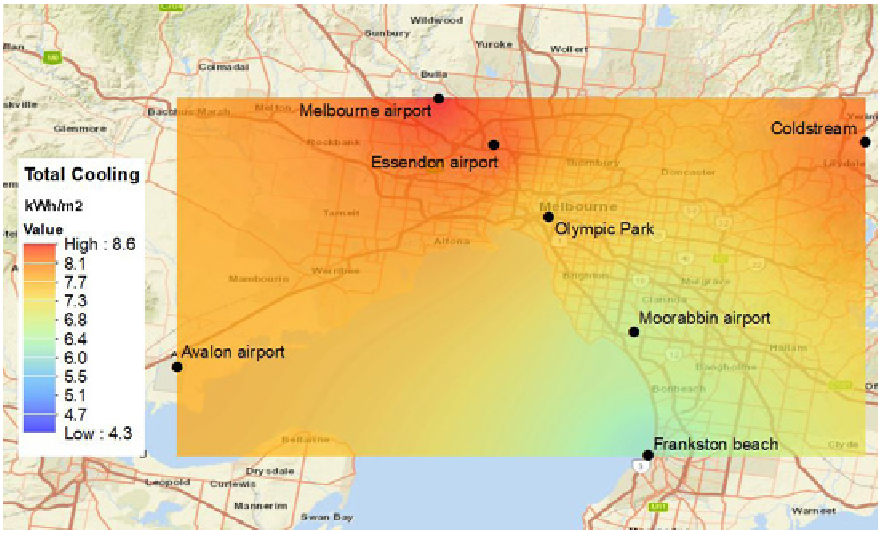

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

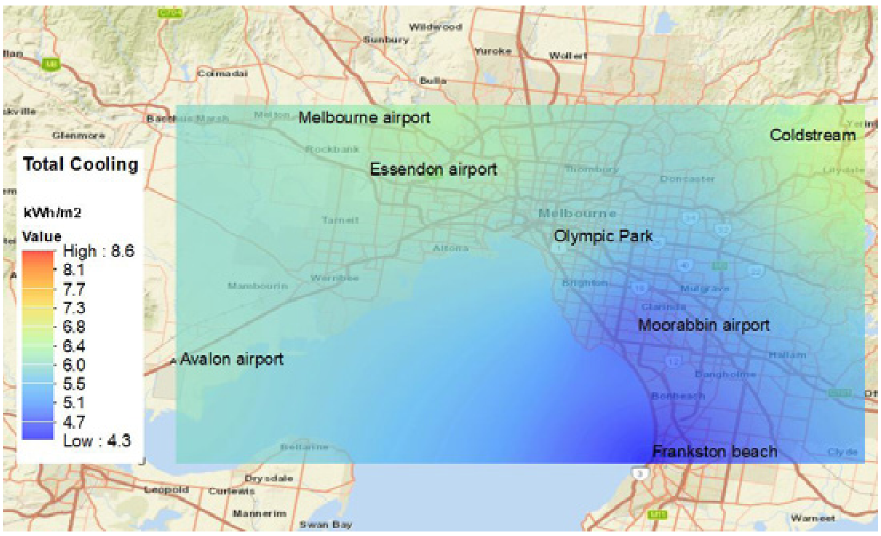

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (3.3-4.7 kWh/m²) is significantly lower than the annual cooling load reduction (8.8-14.4 kWh/m²).

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

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Avalon airport	19.7	21.3	4.5	9.2	11.0	12.3	6.8	12.9
Coldstream	28.7	30.8	4.5	9.6	14.7	16.4	7.3	14.3
Essendon	25.0	26.7	4.4	9.0	14.4	15.7	6.6	12.6
Frankston beach	15.7	17.1	3.8	7.4	7.2	8.3	5.8	11.2
Melbourne airport	24.0	25.4	4.8	9.8	14.1	15.2	7.2	13.7
Moorabbin airport	21.8	23.6	4.0	8.0	12.1	13.5	6.0	11.3
Olympic park	25.1	27.0	3.7	7.2	12.8	14.3	5.7	10.5

The annual cooling load saving by building-scale application of cool roofs is around 40.1-51.4 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.0 and 9.7 kWh/m² (~17.9-27.6 %).

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

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	8.7	44.2	9.1	42.5	2.3	3.6	6.4	26.6	5.5	17.9
Coldstream	14.0	48.8	14.4	46.8	2.8	4.7	11.2	33.7	9.7	24.1
Essendon	10.6	42.5	11.0	41.1	2.2	3.6	8.4	28.6	7.3	20.6
Frankston beach	8.5	54.2	8.8	51.4	2.1	3.7	6.4	33.1	5.0	20.5
Melbourne airport	9.9	41.4	10.2	40.1	2.3	3.8	7.6	26.3	6.3	18.0
Moorabbin airport	9.7	44.5	10.1	42.8	2.0	3.3	7.7	29.8	6.8	21.5
Olympic park	12.3	49.0	12.7	47.1	2.0	3.3	10.3	35.9	9.4	27.6

3

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

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

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

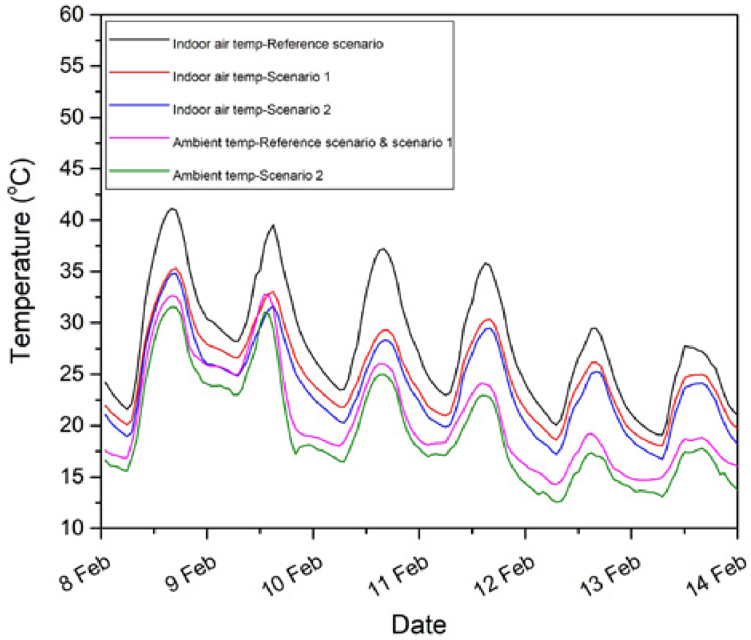

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

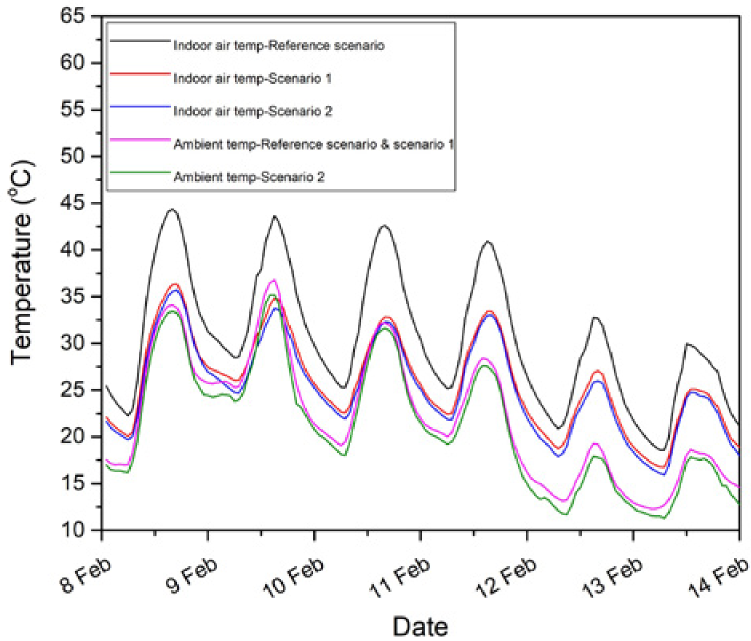

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.0-41.1 °C and 18.5-44.4 °C in Frankston beach and Coldstream stations, respectively.

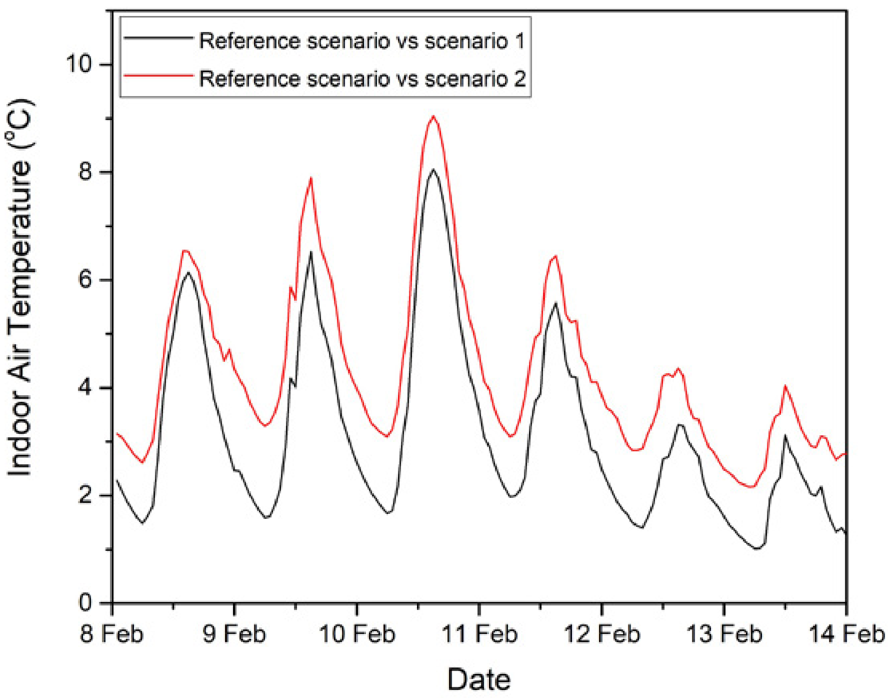

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 8.1 °C and 10.0 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 9.1 °C and 10.4 °C in Frankston beach and Coldstream stations, respectively.

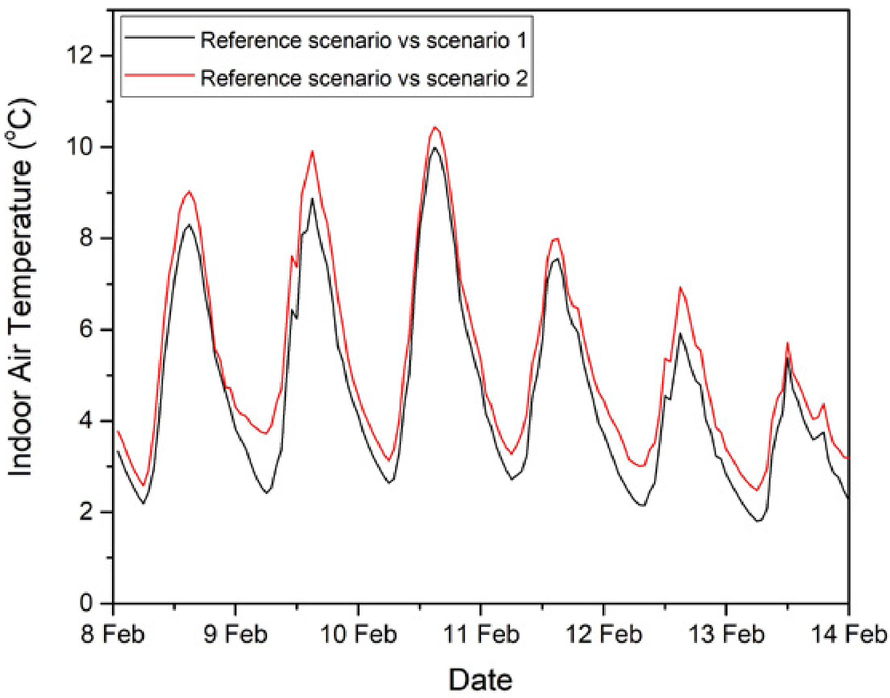

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 11.1-23.0 ºC in reference scenario to a range 10.9-20.9 ºC in scenario 1 in Frankston beach station.

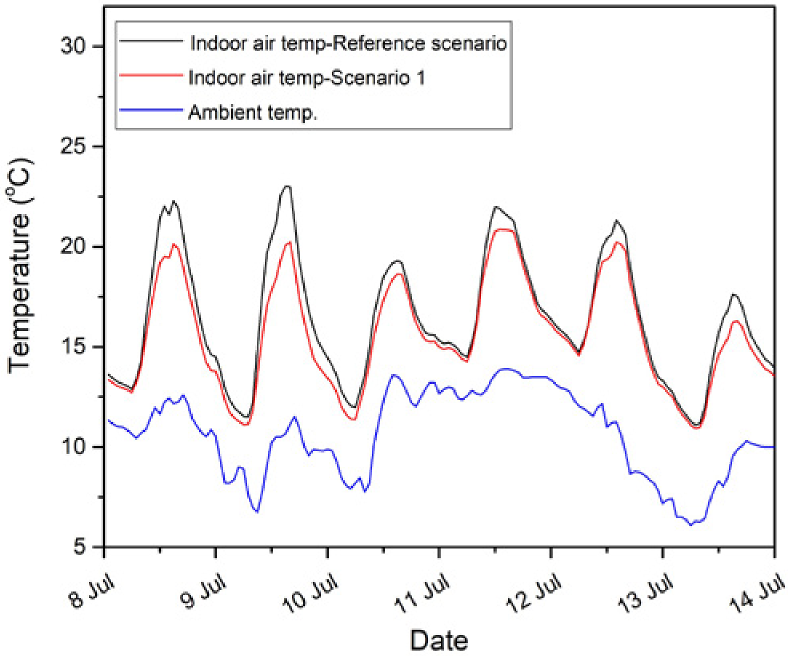

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Frankston beach station* using annual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

The indoor air temperature is predicted to reduce from a range 9.1-24.3 ºC in reference scenario to a range 8.6-21.2 ºC in scenario 1 in Coldstream station.

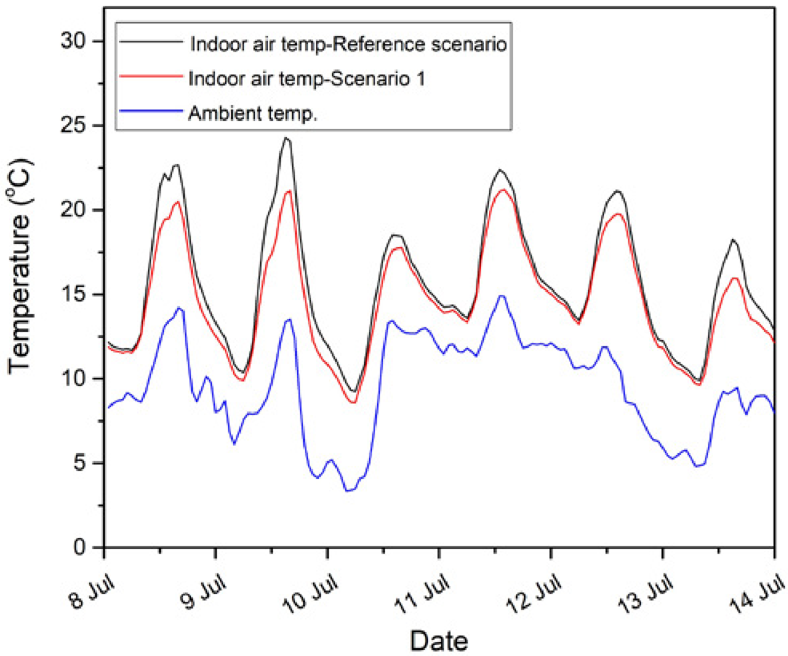

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Coldstream station* using annual 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 1.7 °C and 1.9 °C in Frankston beach and Coldstream stations, respectively.

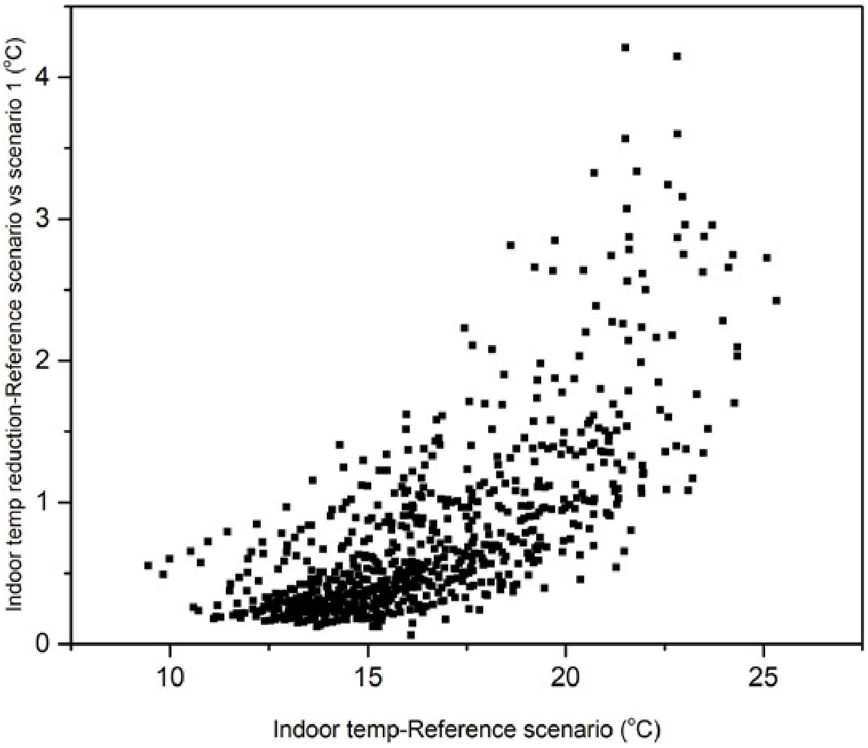

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

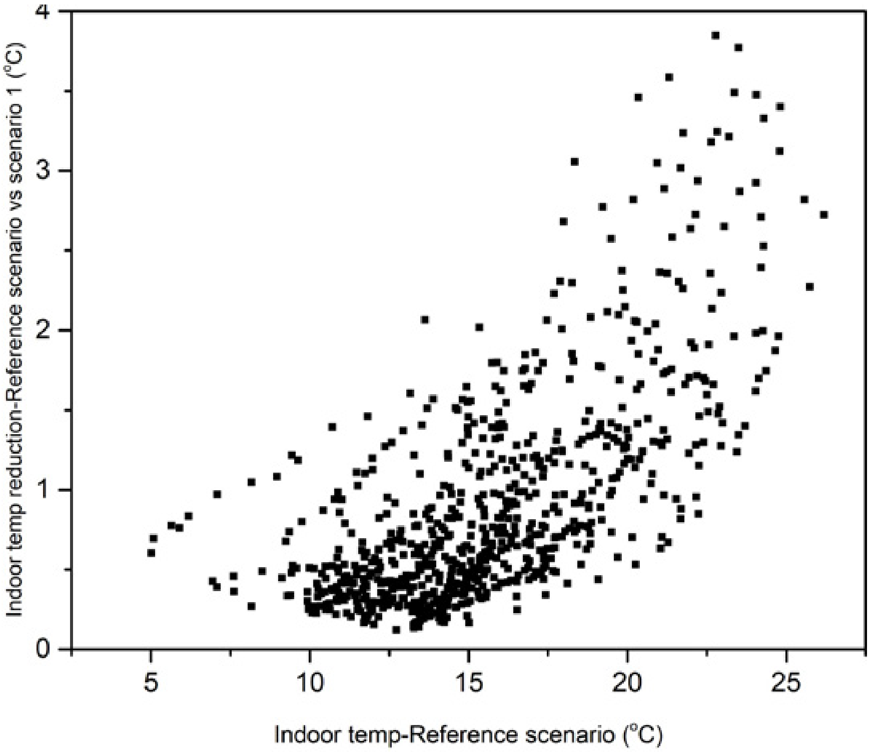

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 580 hours in reference scenario to 645 and hours and from 597 to 656 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during is expected to increase from 217 hours in reference scenario to 276 hours; and from 230 to 285 hours in scenario 1 in Frankston beach and Coldstream 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
Frankston beach	217	580	276	645
Coldstream	230	597	285	656

** 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 334 hours in reference scenario to 193 and 152 hours under scenario 1 and 2 in Frankston beach station; and from 395 hours in reference scenario to 253 and 197 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	334	193	152
Coldstream	395	253	197

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

Table 7. Energy performance features of Building 01.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	23,5	38,8
Energy consumption after cool roof (MWh)	18,7	29,5
Energy savings (MWh)	4,8	9,3
Energy savings (%)	20,43 %	23,97 %
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. Due to low, in absolute terms, value of the savings, the significant initial cost of the metal cool roof reduces its feasibility, hence the coating cool roof is 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 20,43% for the Frankston Beach weather conditions and of 23,97% for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option is the most feasible one, resulting in significant reductions of life cycle costs, that vary between 22,0 and 31,4 %, 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 Frankston Beach and Coldstream weather conditions, respectively.

The metal cool roof is due to its higher initial investment cost only feasible for the Coldstream weather conditions, with reductions of approximately 6%.

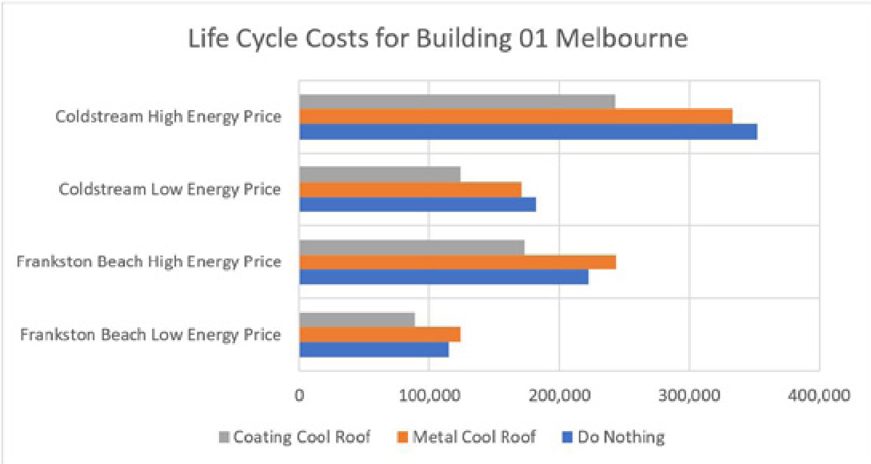

Figure 12. Life Cycle Costs for Building 01 for Frankston Beach and Coldstream stations.

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

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-8,67 %	-9,62 %	6,01 %	5,37 %
Coating Cool Roof	22,55 %	22,03 %	31,43 %	31,08 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 12.6-18.3 kWh/m^2 to 6.2-8.6 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 6.3-10.0 kWh/m^2. This is equivalent to approximately 47.6-54.9 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 & Table 2 and Figure 1 & Figure 2).

• In the eleven weather stations in Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 8.3-11.7 kWh/m^2. This is equivalent to 59.3-65.7% 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 (3.3-4.7 kWh/m^2) is significantly lower than the annual cooling load reduction (8.8-14.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 40.1-51.4%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.0 and 9.7 kWh/m^2 (~17.9-27.6%) (Tables 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 19.0-41.1 °C and 18.5-44.4 °C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 8.1 and 10.0 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 9.1 and 10.4 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream 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 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream station (See Figure 4 and Figure 6).

• During a typical winter week and under free-floating condition, the indoor air temperature is expected to decrease slightly from a range between 11.1 and 23.0 °C in reference scenario to a range between 10.9 and 20.9 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 9.1 and 24.3 °C in reference scenario to a range between 8.6 and 21.2 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 1.7 °C and 1.9 °C in Frankston beach and Coldstream 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 580 hours in reference scenario to 645 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream station also show a increase in total number of hours below 19 °C from 597 hours in reference scenario to 656 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 217 hours in reference scenario to 276 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slightly increase of number of hours below 19 °C from 230 hours to 285 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 334 hours under the reference scenario in Frankston beach station, which significanlty decreases to 193 and 152 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 395 hours in reference scenario to 253 in reference with cool roof scenario (scenario 1) and 197 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 22,0 and 31,4 %, 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 only feasible for the Coldstream weather conditions, with reductions of approximately 6%. 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. Due to low, in absolute terms, value of the savings, the significant initial cost of the metal cool roof reduces its feasibility, hence the coating cool roof is the advisable solution.

B01

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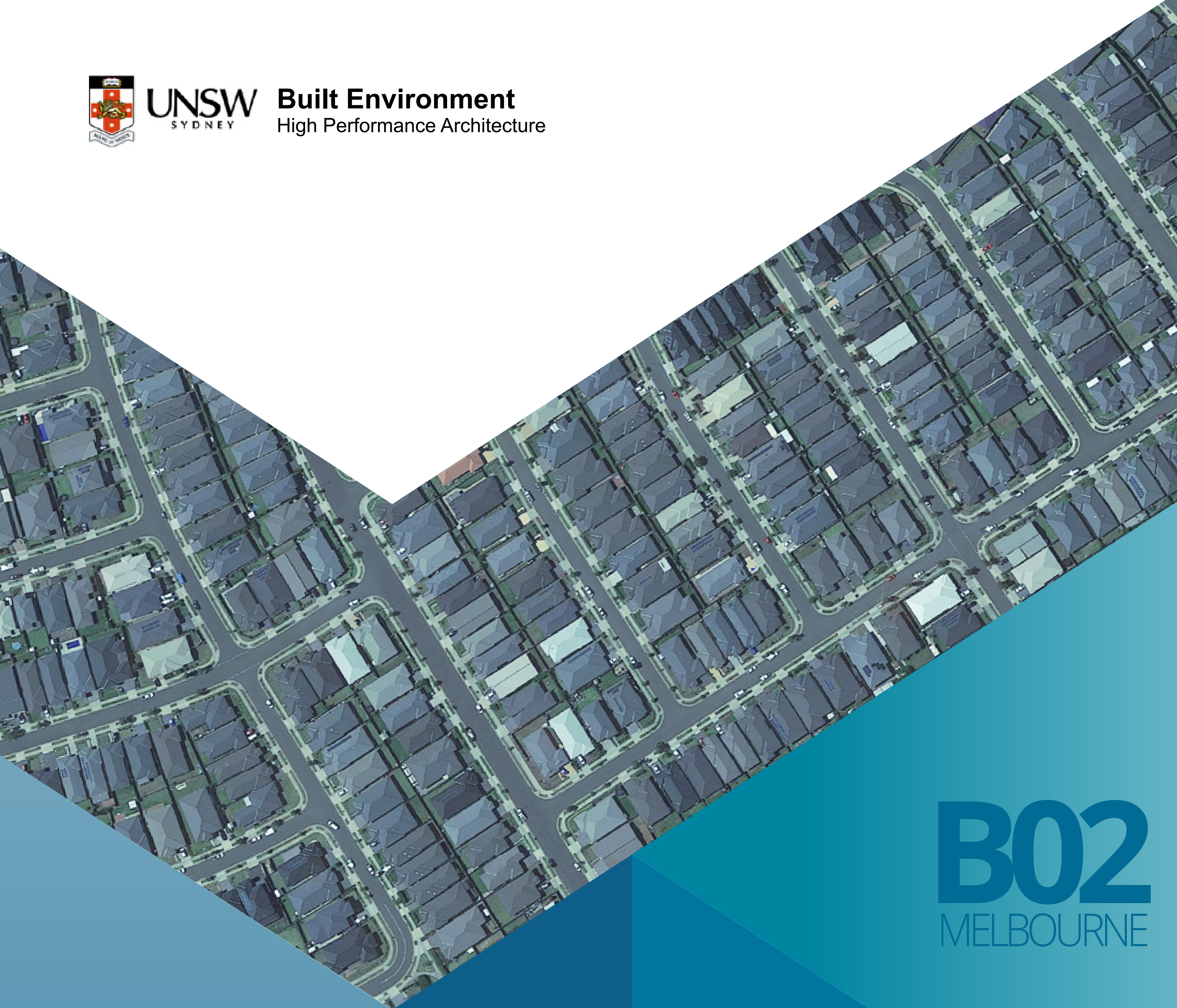

B02
MELBOURNE

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 Melbourne using weather data simulated by WRF.

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of the high-rise office building withour roof insulation from 7.9-10.9 kWh/m² to 6.8-9.3 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)
Avalon airport	9.0	9.6	7.7	8.4	6.3	6.5
Coldstream	10.4	10.9	8.4	8.9	7.0	7.1
Essendon	9.8	10.5	8.4	9.0	6.6	6.6
Frankston beach	7.1	7.9	6.0	6.8	4.5	4.7
Melbourne airport	10.1	10.7	8.6	9.3	6.7	6.8
Moorabbin airport	7.5	8.4	6.4	7.2	5.0	5.1
Olympic park	8.5	9.3	7.2	8.0	6.1	6.3

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

For Scenario 1, the total cooling load saving is around 1.1-2.0 kWh/m² which is equivalent to 13.0-18.1% total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.0-4.0 kWh/m² which is equivalent to 32.0-40.9% 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	%
Avalon airport	1.2	13.7	1.2	13.0	2.6	29.6	3.1	32.2
Coldstream	2.0	18.9	2.0	18.1	3.3	32.0	3.8	34.6
Essendon	1.4	14.2	1.4	13.5	3.3	33.2	3.8	36.5
Frankston beach	1.1	15.5	1.1	14.4	2.6	36.1	3.2	40.9
Melbourne airport	1.4	14.3	1.5	13.7	3.4	33.5	4.0	36.9
Moorabbin airport	1.1	15.0	1.2	13.9	2.6	34.2	3.3	39.0
Olympic park	1.3	14.8	1.3	13.8	2.4	28.0	3.0	32.0

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

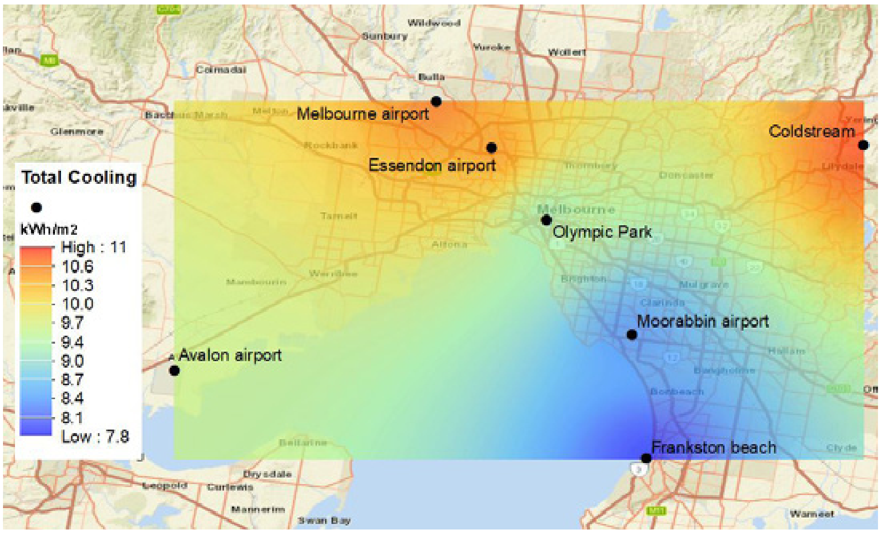

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

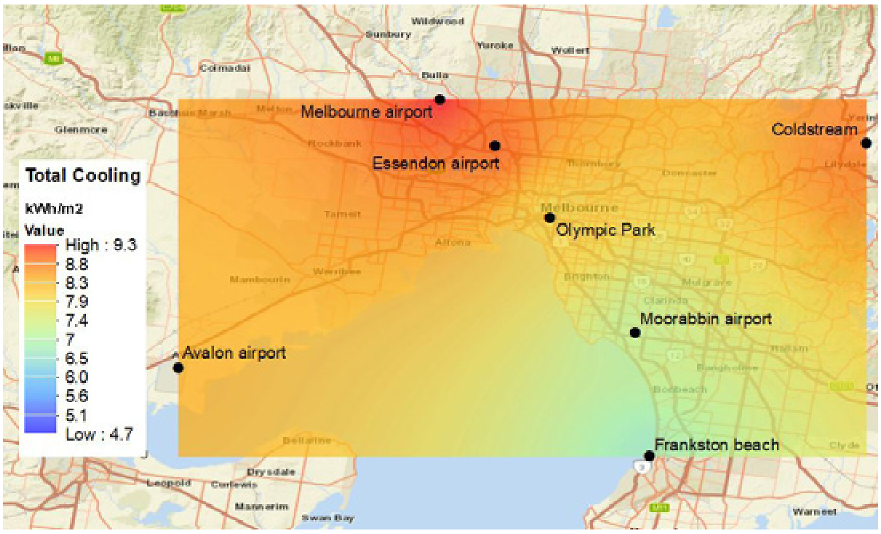

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

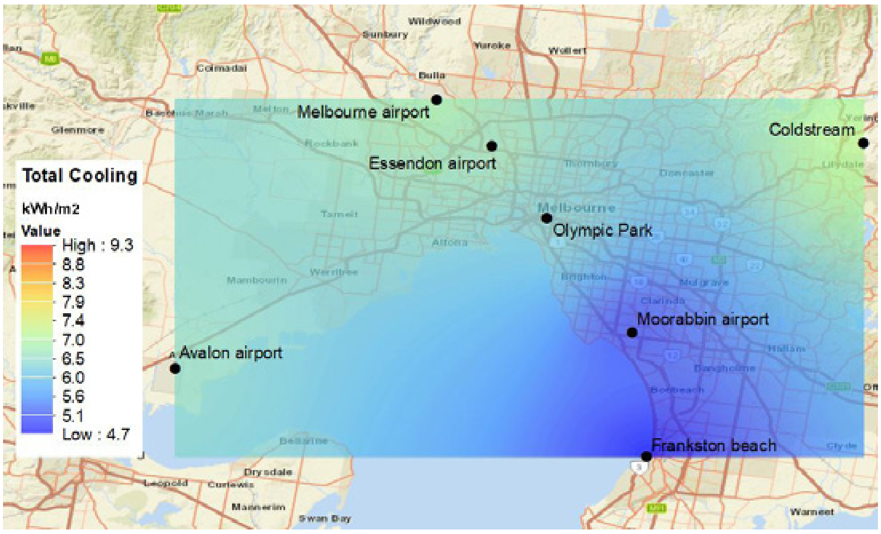

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.6-0.9 kWh/m²) is significantly lower than the annual cooling load reduction (1.5-2.5 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Avalon airport	12.8	14.2	2.7	6.1	11.4	12.7	3.1	6.8
Coldstream	17.4	19.3	3.1	7.2	15.0	16.8	3.6	8.1
Essendon	16.9	18.3	2.4	5.4	15.1	16.5	2.7	6.1
Frankston beach	9.2	10.4	1.5	3.7	7.7	8.9	1.9	4.3
Melbourne airport	16.3	17.6	2.7	6.2	14.7	16.0	3.1	6.8
Moorabbin airport	14.4	15.9	2.0	4.5	12.8	14.3	2.3	5.1
Olympic park	15.7	17.4	1.7	3.9	13.6	15.2	2.0	4.5

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 high-rise office building without roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 9.4-14.9 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8 and 1.6 kWh/m² (~4.1-7.5 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	1.4	10.8	1.5	10.2	0.4	0.6	1.0	6.5	0.8	4.1
Coldstream	2.4	13.8	2.5	12.9	0.5	0.9	1.9	9.3	1.6	6.2
Essendon	1.7	10.3	1.8	9.9	0.4	0.6	1.4	7.1	1.2	5.0
Frankston beach	1.5	16.3	1.5	14.9	0.3	0.7	1.2	10.7	0.9	6.2
Melbourne airport	1.6	9.9	1.7	9.4	0.4	0.7	1.2	6.4	1.0	4.2
Moorabbin airport	1.6	11.0	1.7	10.4	0.3	0.6	1.3	7.7	1.1	5.3
Olympic park	2.1	13.3	2.2	12.5	0.3	0.6	1.8	10.1	1.6	7.5

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. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

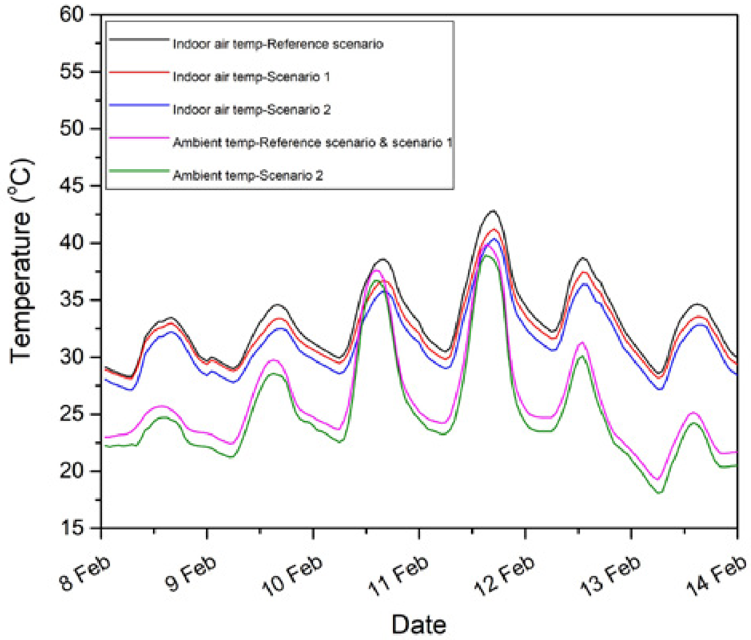

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

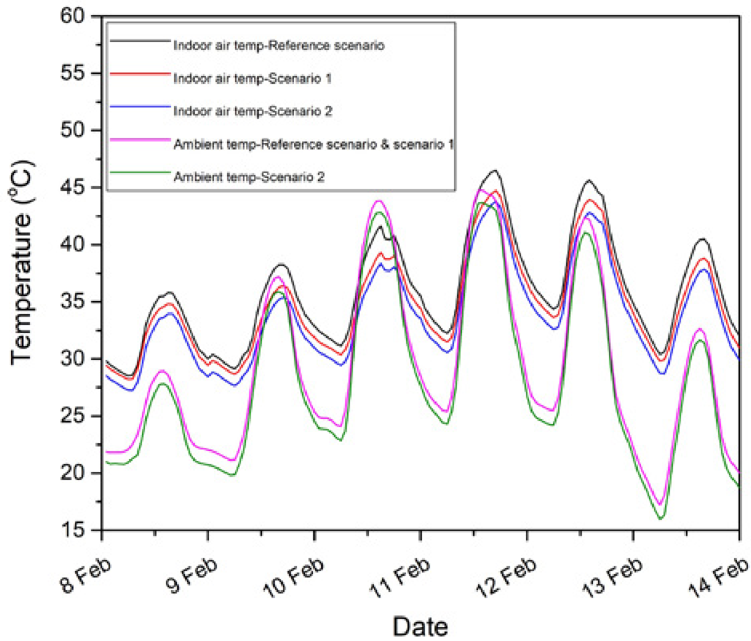

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.5-36.5 °C and 20.9-38.0 °C in Frankston beach and Coldstream stations, respectively.

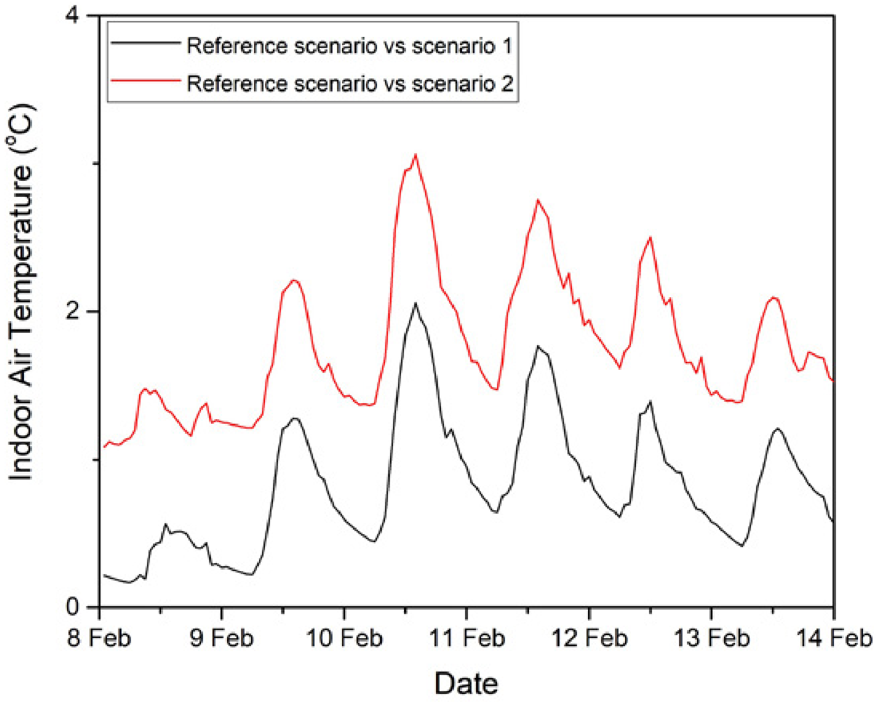

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.4 °C and 2.1 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.6 and 2.8 °C in Frankston beach and Coldstream stations, respectively.

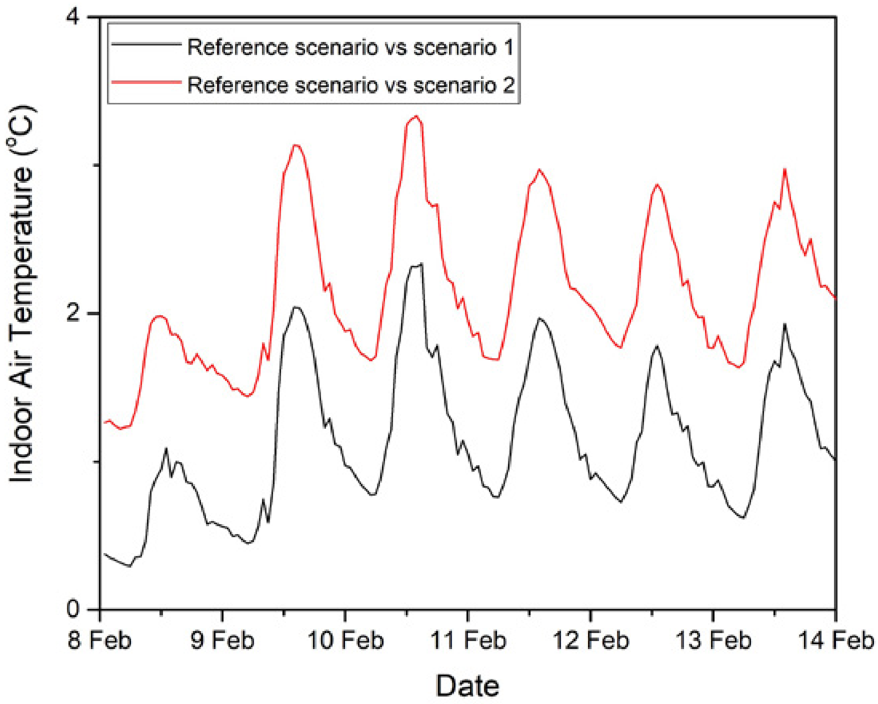

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 14.4 and 22.7 °C in reference scenario to a range between 14.3 and 22.6 °C in scenario 1 in Frankston beach station.

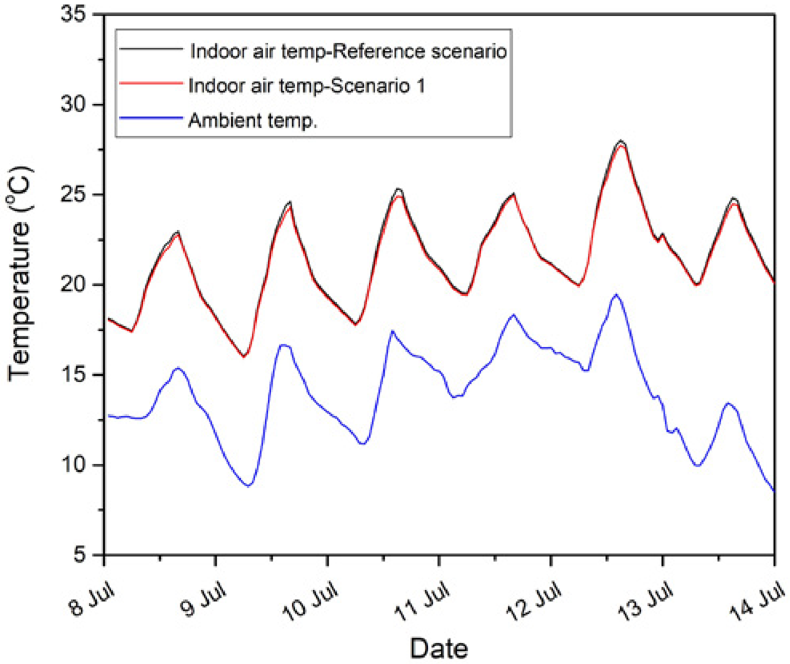

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Frankston beach station* using annual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

The indoor air temperature is predicted to slighly reduce from a range between 13.2 and 23.5 °C in reference scenario to a range between 13.0 and 23.0 °C in scenario 1 in Coldstream station.

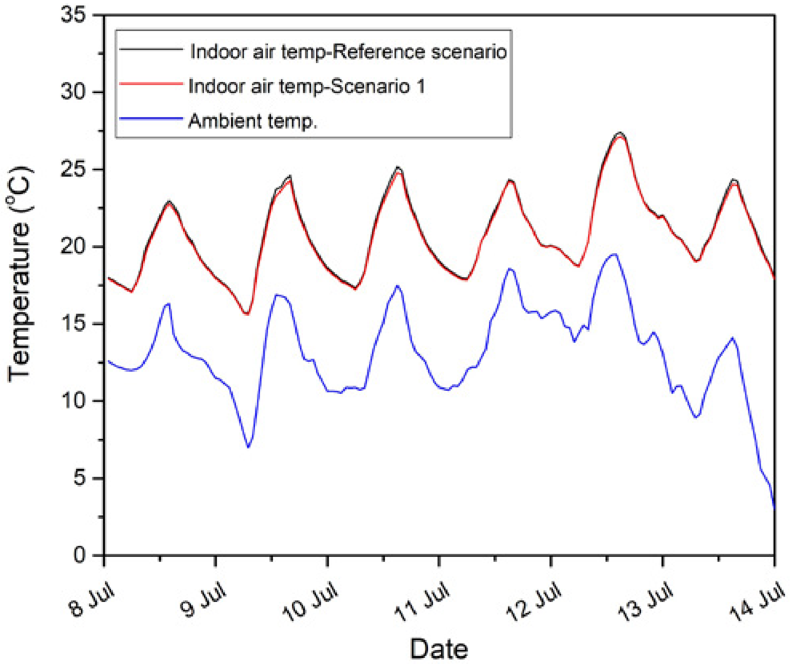

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Coldstream station* using annual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

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

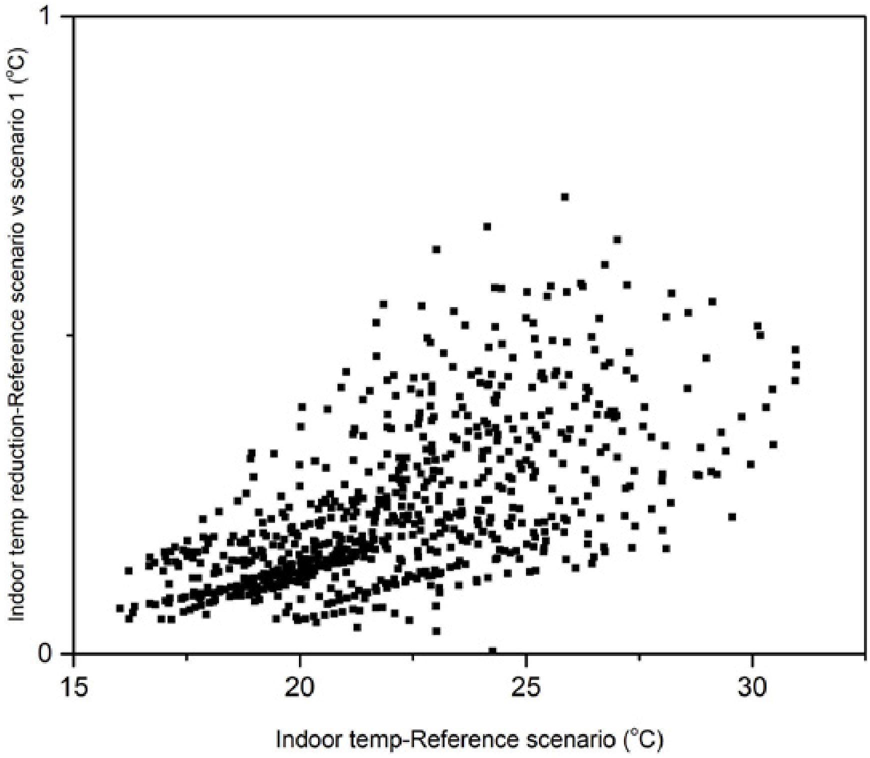

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

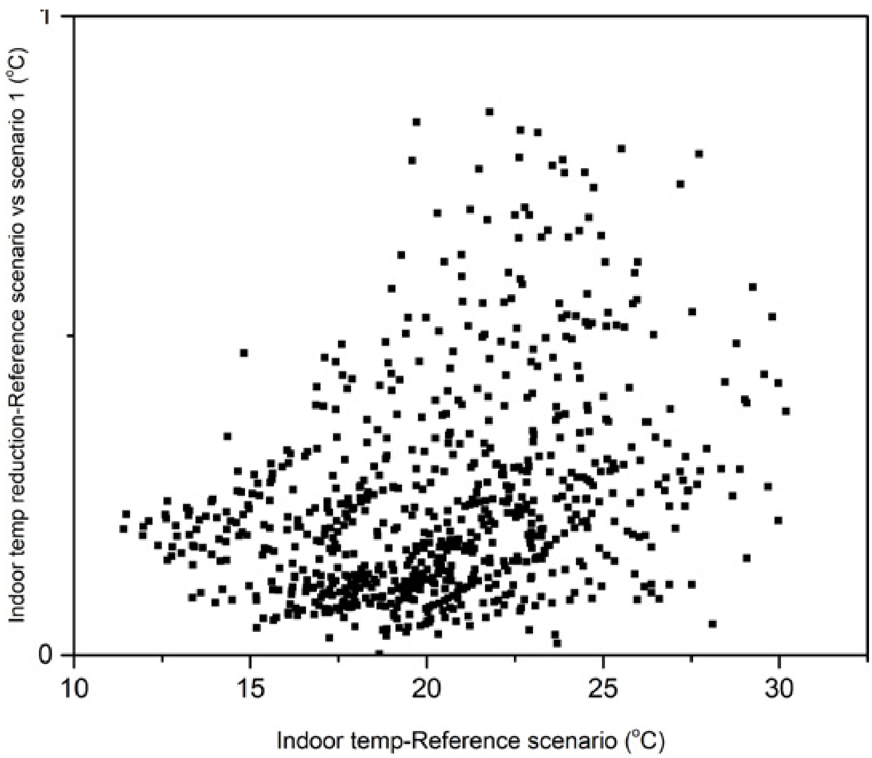

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 430 hours in reference scenario to 439 and hours and from 517 to 531 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 69 hours in reference scenario to 71 hours; and from 185 to 194 hours in scenario 1 in Frankston beach and Coldstream 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
Frankston beach	69	430	71	439
Coldstream	185	517	194	531

** 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 297 hours in reference scenario to 249 and 186 hours under scenario 1 and 2, in Frankston beach station; and from 424 hours in reference scenario to 372 and 310 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	297	249	186
Coldstream	424	372	310

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

Table 7. Energy performance features of Building 02.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	67,7	127,2
Energy consumption after cool roof (MWh)	63,4	119,5
Energy savings (MWh)	4,3	7,7
Energy savings (%)	6,35 %	6,05 %
Area (m^2)	1.200	1.200
Roof costs - Metal roof (AU$/m^2)	38,0	38,0
Roof costs - Coating (AU$/m^2)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m^2)	15,0	15,0

Building 02 is a very good example of a cool roof's contribution to drastically reducing energy requirements and life cycle costs in high-rise office buildings with a poor energy performance of the roof. The impact of the initial cost makes the coating cool roof 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 6,35% for the Frankston Beach weather conditions and of 6,05% for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

. The coating cool roof option is the most feasible one, resulting in significant reductions of life cycle costs, that vary between 22,7 and 26,7 % depending on the weather and energy price scenarios (Table 8).

The metal cool roof is due to its higher initial investment cost only feasible for the high energy prices 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 Frankston Beach and Coldstream weather conditions, respectively.

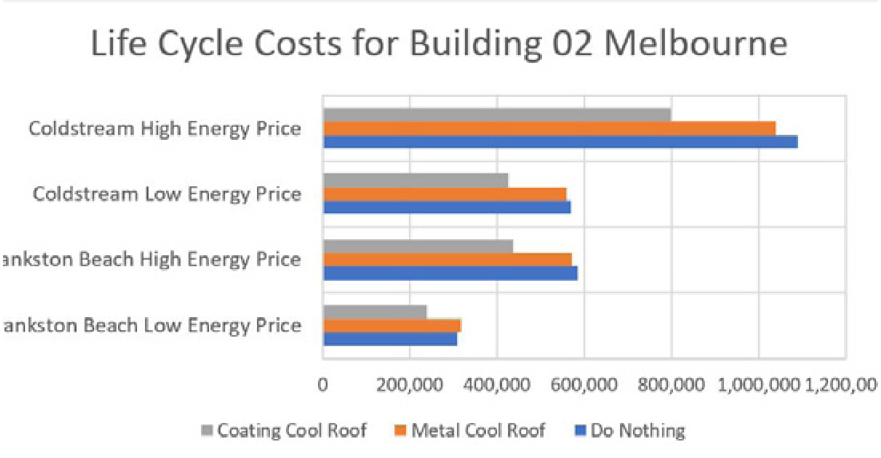

Figure 12. Life Cycle Costs for Building 02 for Frankston Beach and Coldstream stations.

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

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-2,89 %	2,27 %	1,81 %	4,63 %
Coating Cool Roof	22,68 %	25,48 %	25,16 %	26,69 %

7

CONCLUSIONS

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

• In the eleven weather stations in Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 7.9-10.9 kWh/m^2 to 6.8-9.3 kWh/m^2. As computed, the total cooling load saving by building-scale application of cool roofs is around 1.1-2.0 kWh/m^2 for a typical high rise office building without roof insulation. This is equal to 13.0-18.1% 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 Melbourne, 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 3.0-4.0 kWh/m^2. This is equivalent to roughly 32.0-40.9% 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 (0.6-0.9 kWh/m^2) is significantly lower than the annual cooling load reduction (1.5-2.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 9.4-14.9%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8 and 1.6 kWh/m^2 (~4.1-7.5%) (See Table 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 21.5-36.5 °C and 20.9-38.0 °C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.4 and 2.1 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.6 and 2.8 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream 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 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 14.4 and 22.7 ^{o}C in reference scenario to a range between 14.3 and 22.6 ^{o}C in reference with cool roof scenario (scenario 1) in

Frankston beach station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 13.2 and 23.5 °C in reference scenario to a range between 13.0 and 23.0 °C in reference with cool roof scenario (scenario 1) in Coldstream station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.4 °C in Frankston beach and Coldstream 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 430 hours in reference scenario to 439 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight increase in total number of hours below 19 °C from 517 hours in reference scenario to 531 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 69 hours in reference scenario to 71 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slight increase of number of hours below 19 °C from 185 hours to 194 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 297 hours under the reference scenario in Frankston beach station, which decreases to 249 and 185 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 424 hours in reference scenario to 372 in reference with cool roof scenario (scenario 1) and 310 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 22,7 and 26,7 %, 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 only 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 initial cost makes the coating cool roof the advisable solution.

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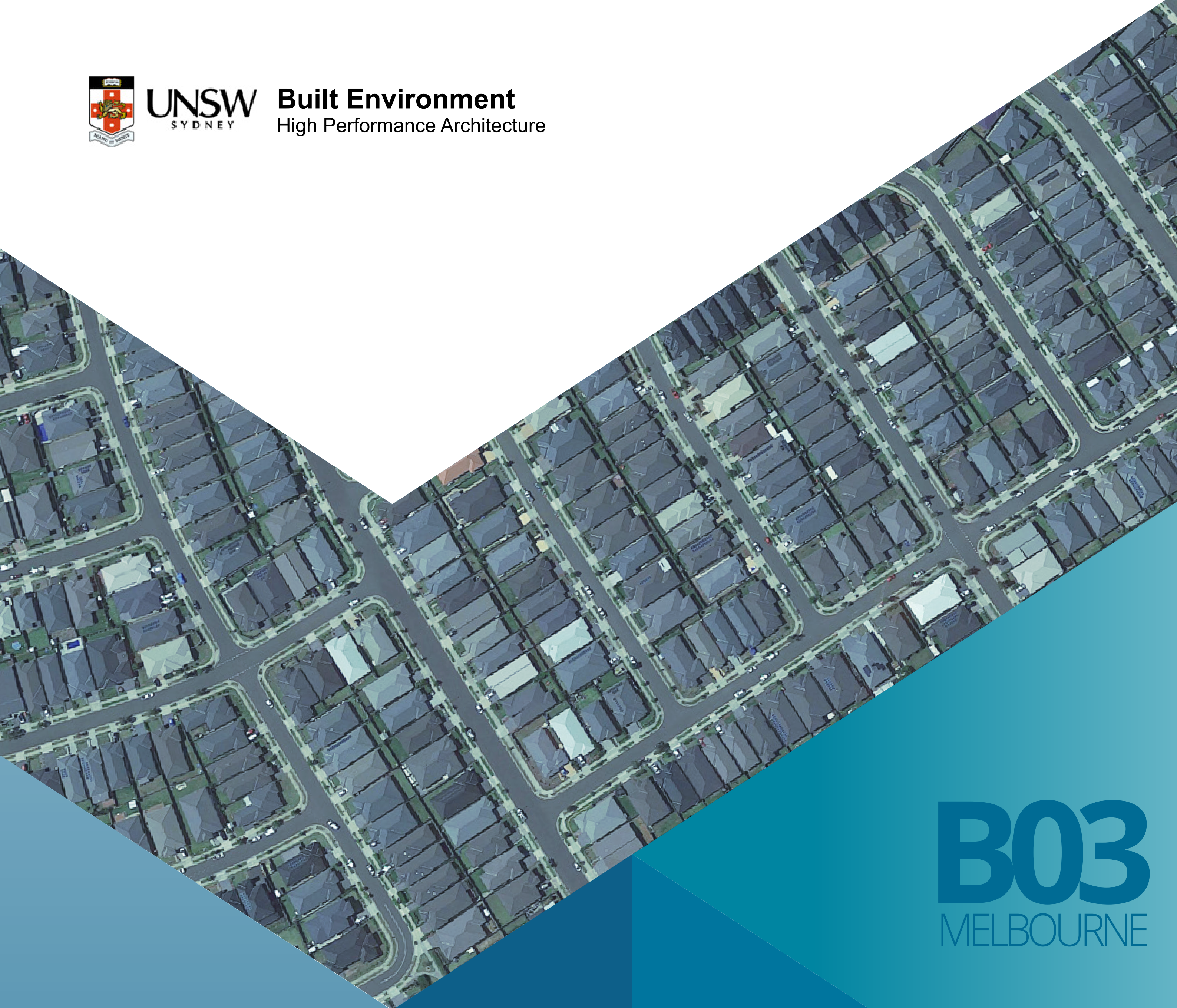

B03
MELBOURNE

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise office building with roof insulation
2021

BUILDING 03

NEW LOW-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : 1200m²
Number of stories : 2

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

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

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

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

1

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

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new low-rise office building with roof insulation from 7.5-10.3 kWh/m² to 6.9-9.5 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	8.5	9.2	7.9	8.5	6.4	6.7
Coldstream	9.4	10.0	8.5	9.1	7.2	7.3
Essendon	9.3	10.0	8.6	9.2	6.7	6.8
Frankston beach	6.7	7.5	6.1	6.9	4.7	4.8
Melbourne airport	9.6	10.3	8.8	9.5	6.9	7.0
Moorabbin airport	7.1	8.0	6.6	7.4	5.1	5.3
Olympic park	8.0	8.8	7.4	8.2	6.3	6.5

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

For Scenario 1, the total cooling load saving is around 0.6-0.9 kWh/m² which is equivalent to 7.1-9.4 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.5-3.3 kWh/m² which is equivalent to 227.0-35.7 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	0.6	7.5	0.7	7.1	2.1	24.6	2.5	27.6
Coldstream	0.9	9.7	0.9	9.4	2.3	23.8	2.7	27.0
Essendon	0.7	7.8	0.7	7.5	2.6	27.9	3.2	31.8
Frankston beach	0.6	8.3	0.6	7.7	2.0	30.0	2.7	35.7
Melbourne airport	0.8	8.0	0.8	7.6	2.7	28.3	3.3	32.1
Moorabbin airport	0.6	8.0	0.6	7.5	2.0	28.2	2.7	33.8
Olympic park	0.6	7.9	0.7	7.5	1.8	22.1	2.4	26.8

In the eleven weather stations in Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to have higher impact on the total cooling load reduction of the new low-rise office building with roof insulation.

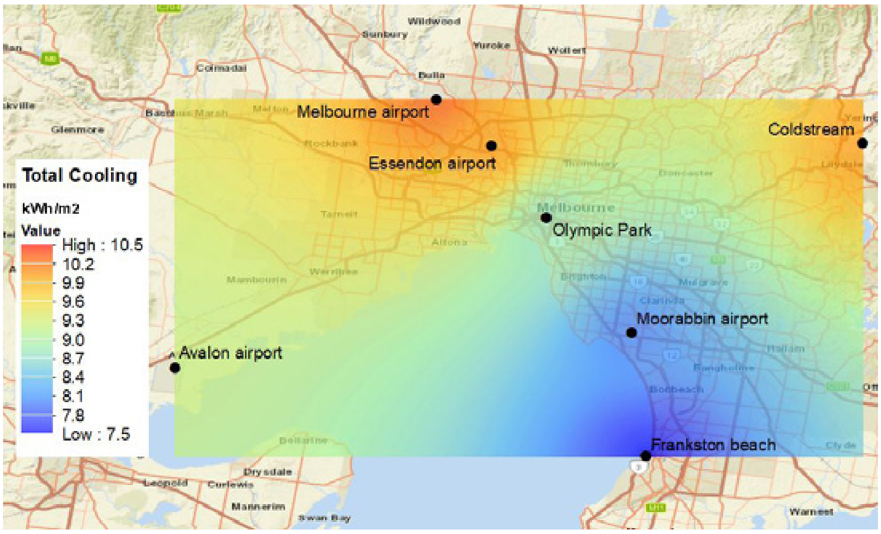

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs has a lower but still noticeable impact on the cooling load reduction of the new low-rise office building with roof insulation.

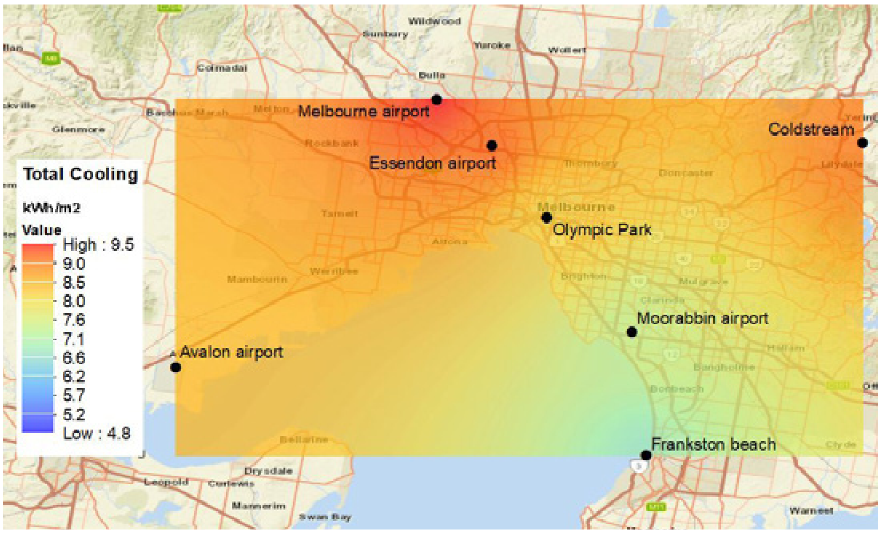

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

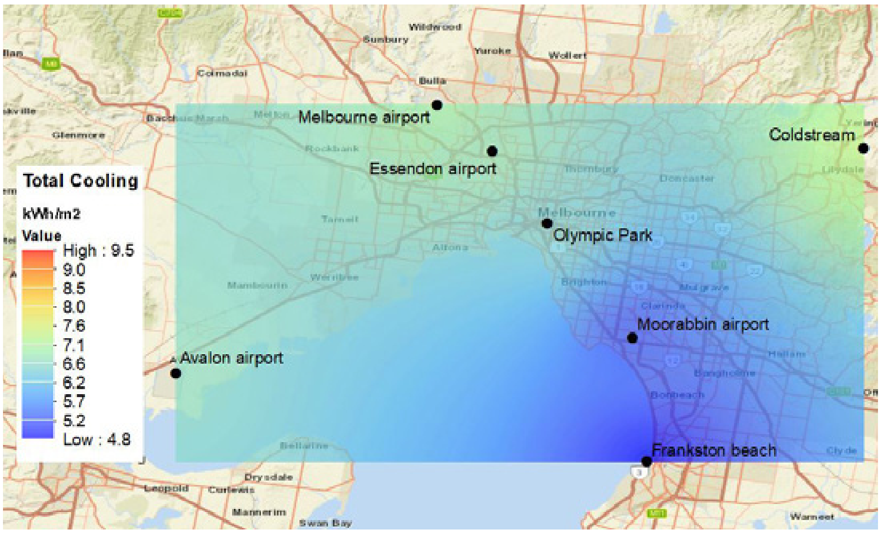

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

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 (0.8-1.3 kWh/m²).

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.

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
Avalon airport	12.7	14.2	2.7	5.9	11.9	13.3	2.9	6.2
Coldstream	16.9	18.7	3.2	7.1	15.6	17.4	3.4	7.5
Essendon	16.6	18.1	2.4	5.2	15.6	17.0	2.5	5.4
Frankston beach	8.7	9.9	1.5	3.4	7.9	9.1	1.6	3.6
Melbourne airport	16.2	17.5	2.7	5.8	15.3	16.5	2.8	6.0
Moorabbin airport	14.2	15.8	2.0	4.4	13.3	14.8	2.1	4.6
Olympic park	15.1	16.8	1.8	3.9	14.0	15.6	1.8	4.1

The annual cooling load saving by building-scale application of cool roofs is around 5.7-8.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6 and 0.9 kWh/m² (~2.9-4.6 %).

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

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	0.8	6.3	0.8	6.0	0.1	0.3	0.7	4.4	0.6	2.9
Coldstream	1.3	7.4	1.3	7.0	0.2	0.4	1.1	5.3	0.9	3.6
Essendon	1.0	6.0	1.0	5.7	0.1	0.2	0.9	4.6	0.8	3.4
Frankston beach	0.8	8.7	0.8	8.0	0.1	0.2	0.7	6.6	0.6	4.5
Melbourne airport	0.9	5.8	1.0	5.6	0.1	0.2	0.8	4.4	0.7	3.1
Moorabbin airport	0.9	6.4	1.0	6.1	0.1	0.2	0.8	5.1	0.8	3.8
Olympic park	1.1	7.3	1.2	7.0	0.1	0.2	1.0	6.0	1.0	4.6

3

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

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

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

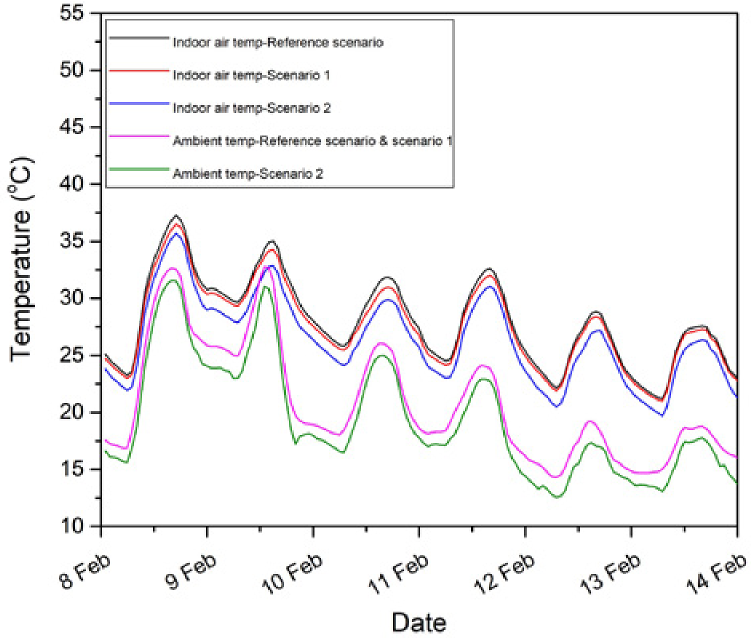

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

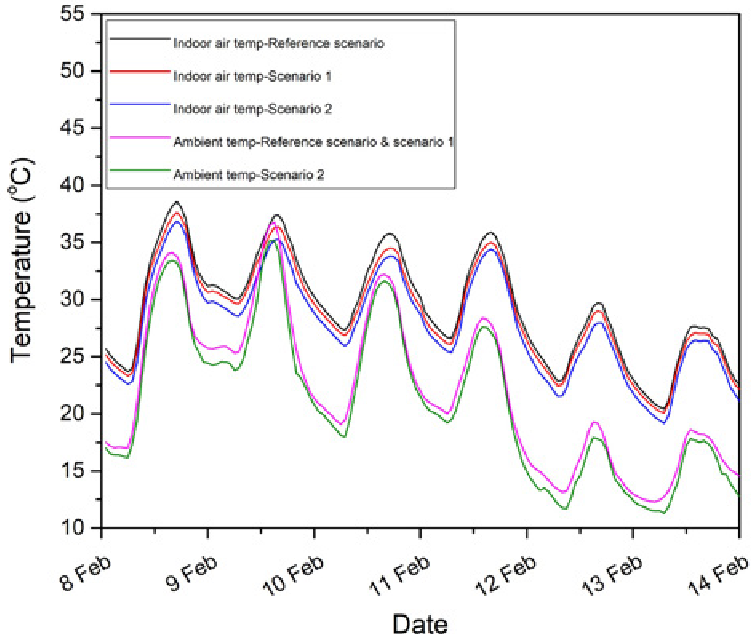

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.2-37.3 °C and 20.4-38.6 °C in Frankston beach and Coldstream stations, respectively.

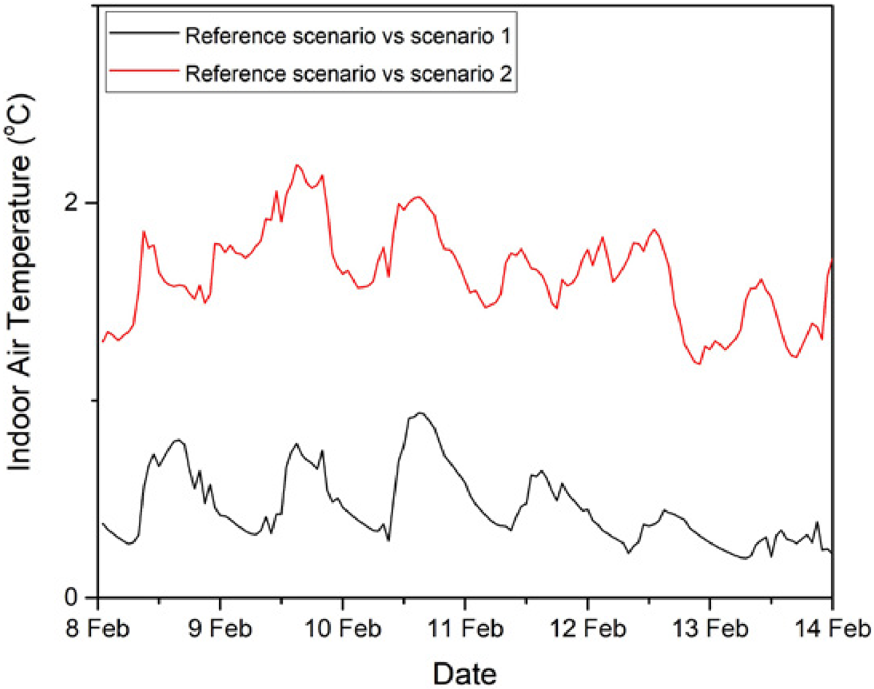

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Frankston beach 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 1.3 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.2 and 2.1 °C in Frankston beach and Coldstream stations, respectively.

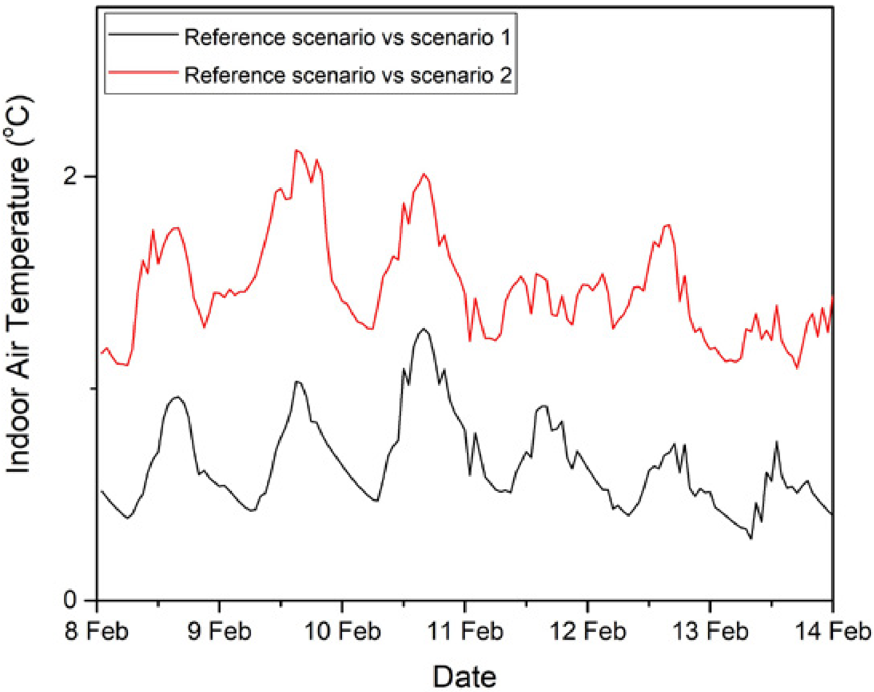

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 14.6 and 24.1 °C in reference scenario to a range between 14.5 and 23.5 °C in scenario 1 in Frankston beach station.

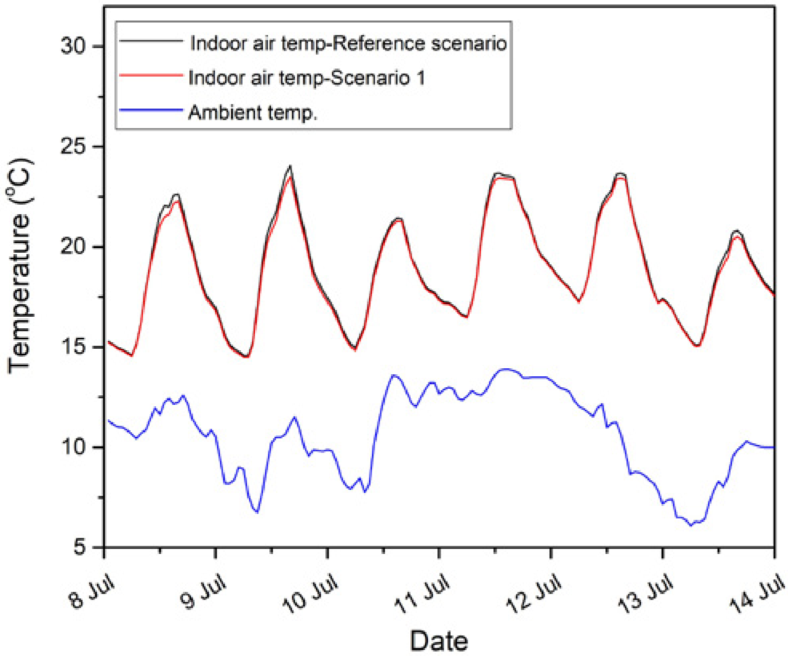

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Frankston beach station* using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

The indoor air temperature is predicted to reduce from a range between 12.2 and 24.9 °C in reference scenario to a range between 12.0 and 24.4 °C in scenario 1 in Coldstream station.

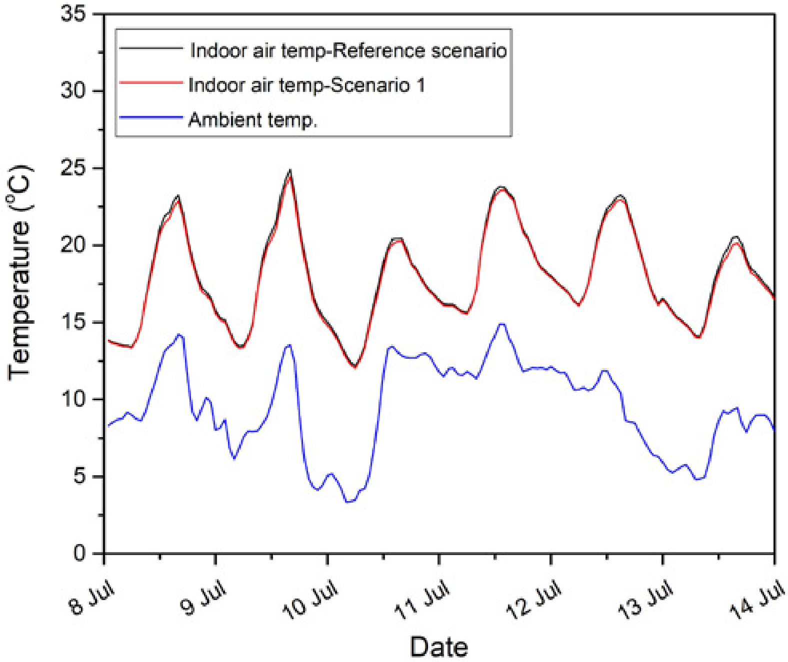

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Coldstream station* using annual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

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

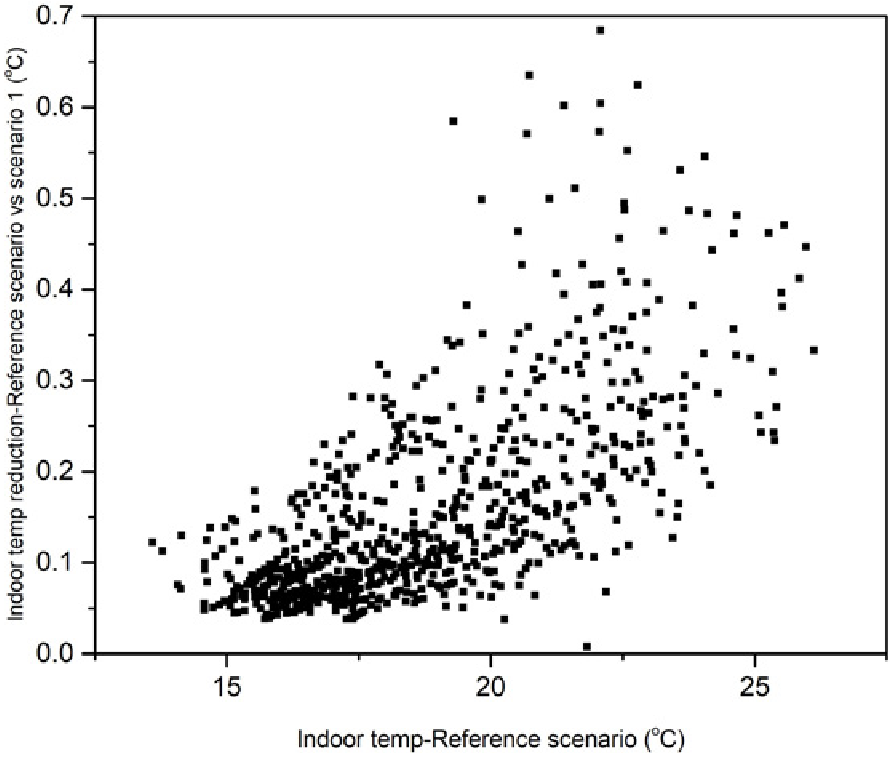

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather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

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

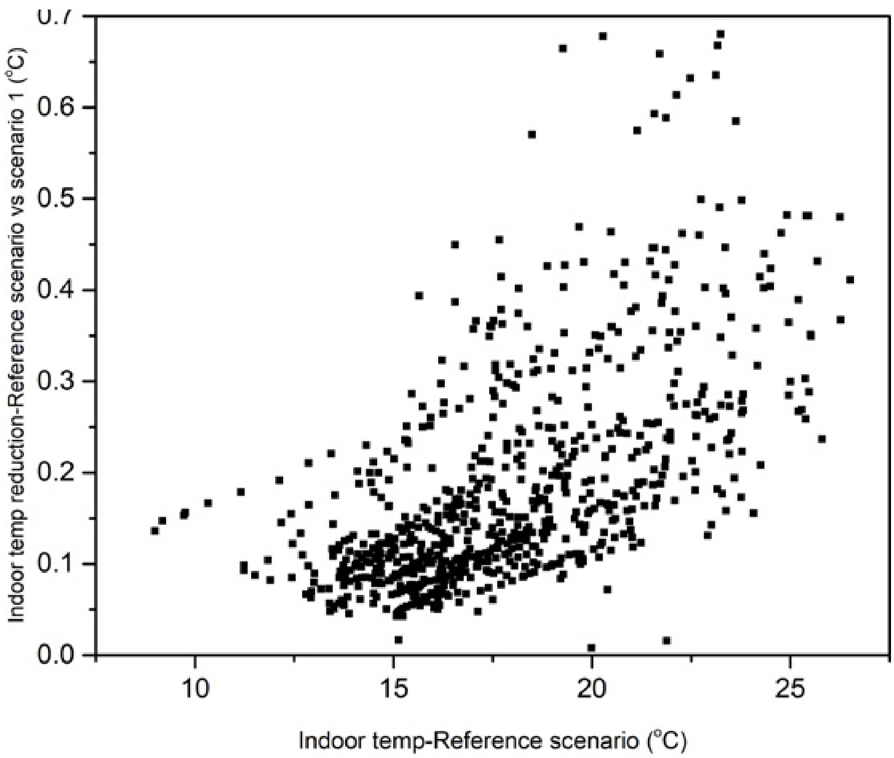

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 ºC) is predicted to increase slightly from 415 hours in reference scenario to 432 hours, and from 492 to 509 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 ºC during is expected to slightly increase from 132 hours in reference scenario to 138 hours; and from 163 to 173 hours in scenario 1 in Frankston beach and Coldstream 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
Frankston beach	132	415	138	432
Coldstream	163	492	173	509

** 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 ºC) is predicted to decrease from 345 hours in reference scenario to 317 and 250 hours under scenario 1 and 2, in Frankston beach station; and from 399 hours in reference scenario to 359 and 305 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	345	317	250
Coldstream	399	359	305

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 only compared to the coating cool roof option (Table 8).

The building and its energy performance

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

Table 7. Energy performance features of Building 03.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	12,8	24,8
Energy consumption after cool roof (MWh)	12,2	23,9
Energy savings (MWh)	0,6	0,9
Energy savings (%)	4,69 %	3,63 %
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 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, especially for high energy prices.

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

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

Both options have the same energy efficiency, resulting in energy savings of 4,69% for the Frankston Beach weather conditions and of 3,63% for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 0,5 % for the low energy price scenario for Frankston and 18,4 % for the high energy scenario and for Coldstream conditions.

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

Feasibility analysis results

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

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

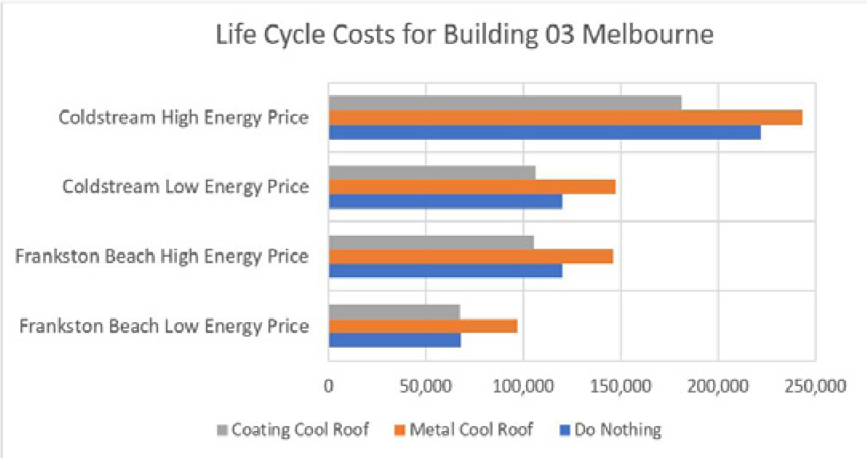

Figure 12. Life Cycle Costs for Building 03 for Frankston Beach and Coldstream stations.

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	-43,05 %	-21,49 %	-22,40 %	-9,73 %
Coating Cool Roof	0,56 %	12,23 %	11,51 %	18,36 %

7

CONCLUSIONS

• In the eleven weather stations in Melbourne, 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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 7.5-10.3 kWh/m^2 to 6.9-9.5 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.6-0.9 kWh/m^2. This is equivalent to approximately 7.1-9.4 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 2.5-3.3 kWh/m^2. This is equivalent to 27.0-35.7 % 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 (0.2-0.4 kWh/m^2) is significantly lower than the annual cooling load reduction (0.8-1.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 5.7-8.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.6 and 0.9 kWh/m^2 (~2.9-4.6 %) (Tables 3 and 4).

• During a typical summer week and under free-floating condition, the indoor air temperature of the reference scenario ranges between 21.2-37.3 °C and 20.4-38.6 °C in Frankston beach and Coldstream 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 1.3 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.2 and 2.1 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream 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 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 14.6 and

24.1 °C in reference scenario to a range between 14.5 and 23.5 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 12.2 and 24.9 °C in reference scenario to a range between 12.0 and 24.4 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 and 0.4 °C in Frankston beach and Coldstream 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 415 hours in reference scenario to 432 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream station also show a increase in total number of hours below 19 °C from 492 hours in reference scenario to 509 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 132 hours in reference scenario to 138 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slightly increase of number of hours below 19 °C from 163 hours to 173 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 Frankston beach station, which decreases to 317 and 250 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 399 hours in reference scenario to 359 in reference with cool roof scenario (scenario 1) and 305 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 the higher cost over the building's life cycle only compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 0,5 % for the low energy price scenario for Frankston and 18,4 % for the high energy scenario and for Coldstream 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, especially for high energy prices.

B03

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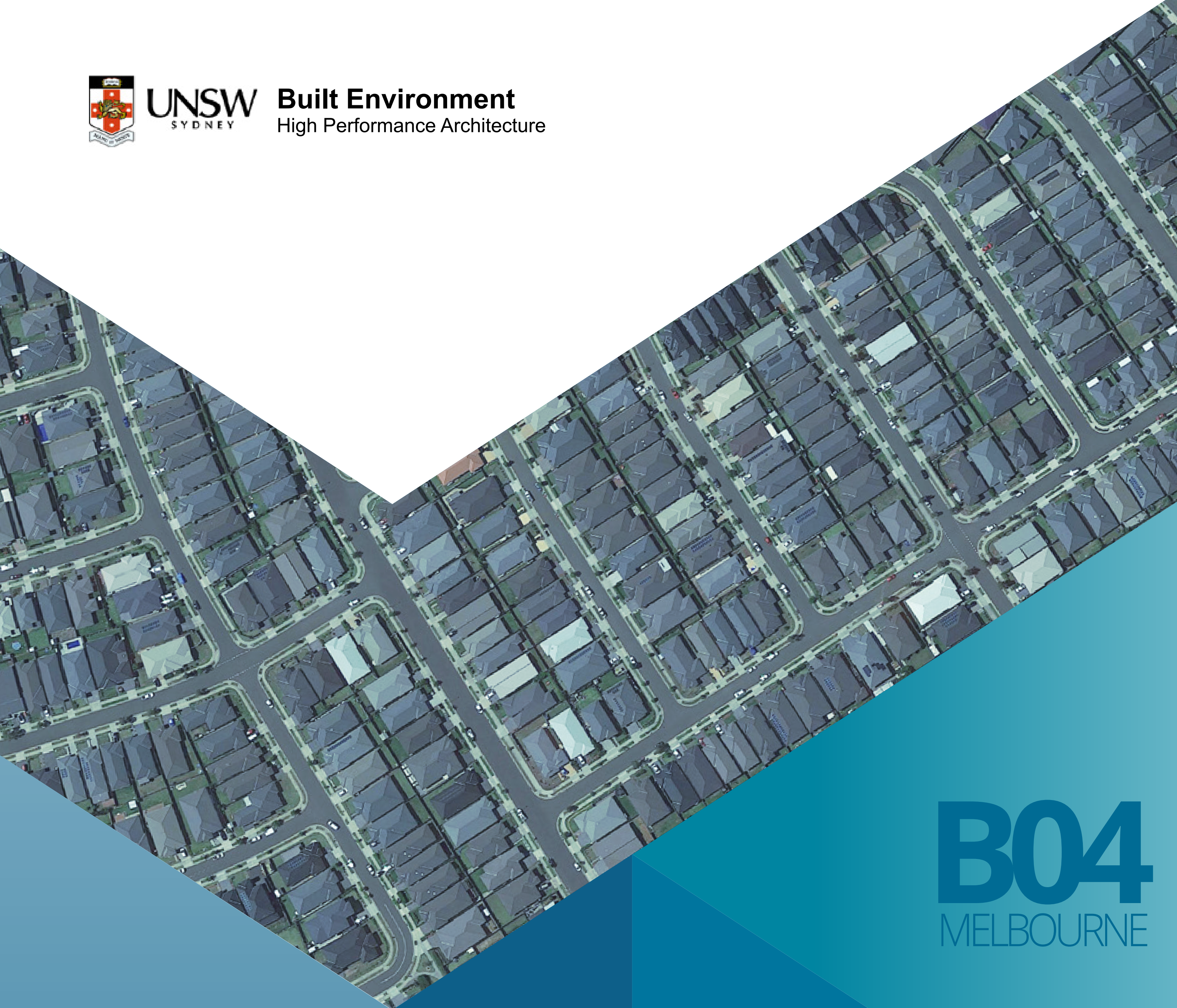

B04
MELBOURNE

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 Melbourne using weather data simulated by WRF.

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new high-rise office building with roof insulation from 7.1-9.7 kWh/m² to 7.0-9.5 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	8.1	8.7	8.0	8.6	6.5	6.7
Coldstream	8.8	9.4	8.6	9.2	7.2	7.3
Essendon	8.8	9.4	8.7	9.3	6.7	6.8
Frankston beach	6.3	7.1	6.2	7.0	4.7	4.8
Melbourne airport	9.0	9.7	8.9	9.5	6.9	7.0
Moorabbin airport	6.7	7.5	6.6	7.4	5.1	5.3
Olympic park	7.6	8.3	7.4	8.2	6.3	6.5

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 0.1-0.2 kWh/m² which is equivalent to 1.3-1.9 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 1.8-2.7 kWh/m² which is equivalent to 21.5-31.8 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	0.1	1.4	0.1	1.3	1.6	19.5	2.0	23.0
Coldstream	0.2	2.0	0.2	1.9	1.6	17.9	2.0	21.5
Essendon	0.1	1.5	0.1	1.4	2.0	23.2	2.6	27.6
Frankston beach	0.1	1.6	0.1	1.5	1.6	25.5	2.3	31.8
Melbourne airport	0.1	1.5	0.1	1.4	2.1	23.6	2.7	27.9
Moorabbin airport	0.1	1.5	0.1	1.4	1.6	23.6	2.3	30.0
Olympic park	0.1	1.5	0.1	1.4	1.3	16.8	1.8	22.1

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

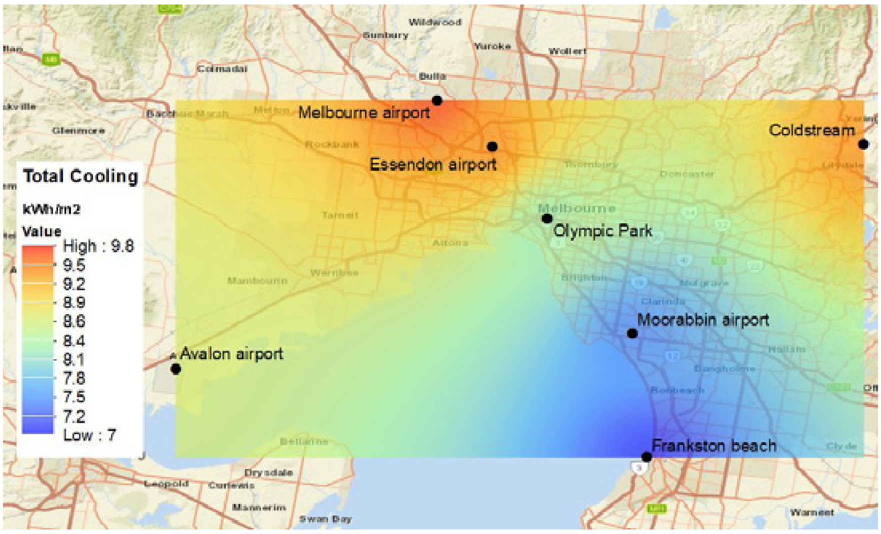

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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

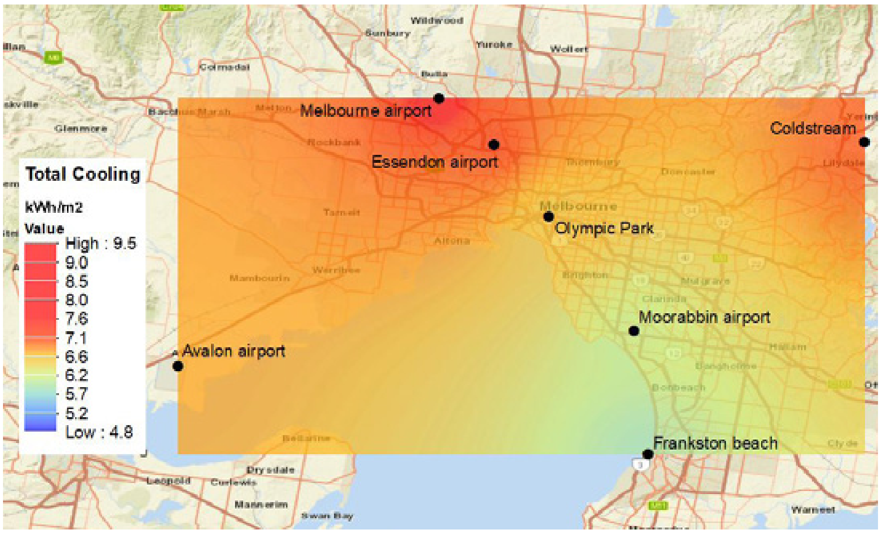

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

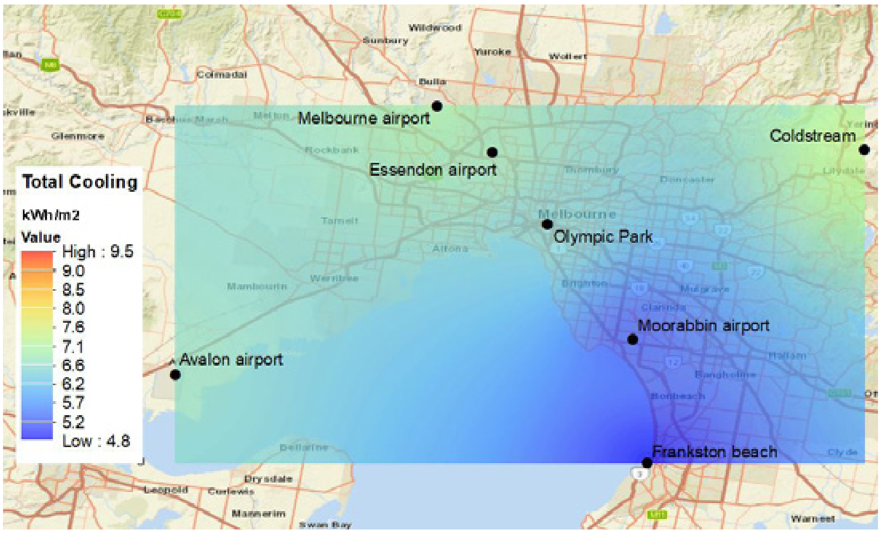

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

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 (0.1-0.2 kWh/m²).

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.

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
Avalon airport	11.9	13.3	2.1	5.1	11.8	13.1	2.1	5.1
Coldstream	15.6	17.5	2.6	6.3	15.4	17.2	2.6	6.4
Essendon	15.7	17.2	1.7	4.3	15.6	17.0	1.8	4.4
Frankston beach	8.1	9.3	1.0	2.7	8.0	9.2	1.0	2.7
Melbourne airport	15.3	16.6	2.0	5.0	15.1	16.4	2.1	5.0
Moorabbin airport	13.3	14.9	1.4	3.5	13.2	14.7	1.4	3.6
Olympic park	14.3	15.8	1.2	3.0	14.1	15.6	1.2	3.1

The annual cooling load saving by building-scale application of cool roofs is around 1.0-1.6 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.1 and 0.2 kWh/m² (~0.5-0.9 %).

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 high-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	0.1	1.1	0.1	1.1	0.0	0.0	0.1	0.8	0.1	0.5
Coldstream	0.2	1.4	0.2	1.3	0.0	0.1	0.2	1.0	0.2	0.7
Essendon	0.2	1.0	0.2	1.0	0.0	0.0	0.1	0.8	0.1	0.6
Frankston beach	0.1	1.7	0.1	1.6	0.0	0.0	0.1	1.4	0.1	0.9
Melbourne airport	0.2	1.0	0.2	1.0	0.0	0.0	0.1	0.8	0.1	0.6
Moorabbin airport	0.2	1.2	0.2	1.1	0.0	0.0	0.1	0.9	0.1	0.6
Olympic park	0.2	1.4	0.2	1.4	0.0	0.0	0.2	1.2	0.2	0.9

3

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

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

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

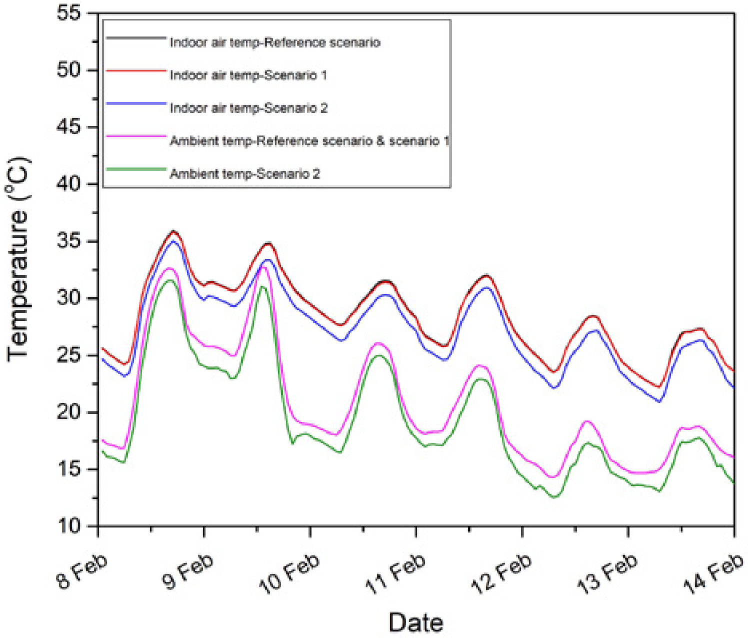

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

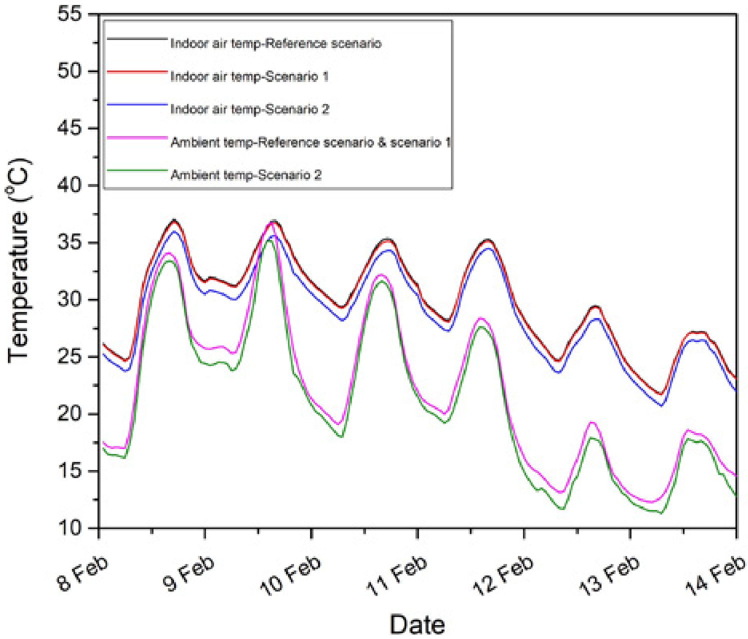

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.0-36.0 °C and 21.3-37.0 °C in Frankston beach and Coldstream stations, respectively.

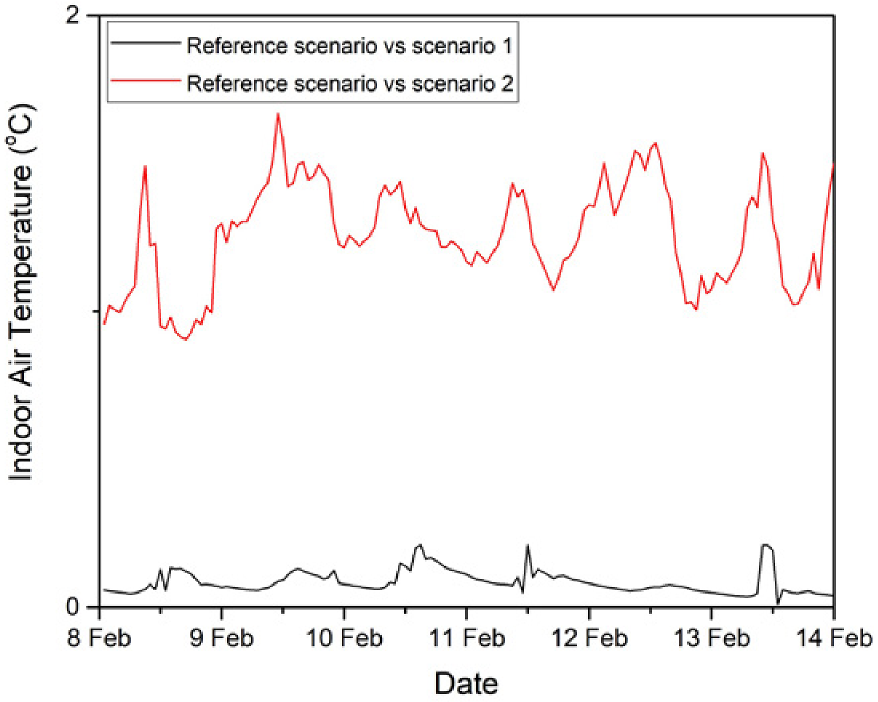

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.2 °C in both Frankston beach and Coldstream stations.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.7 and 1.5 °C in Frankston beach and Coldstream stations, respectively.

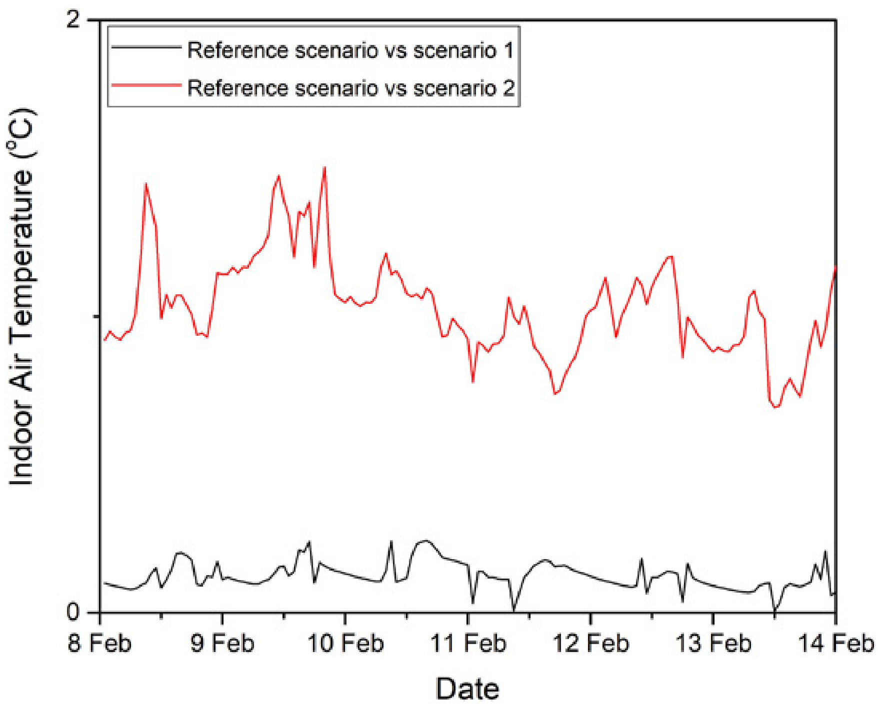

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during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

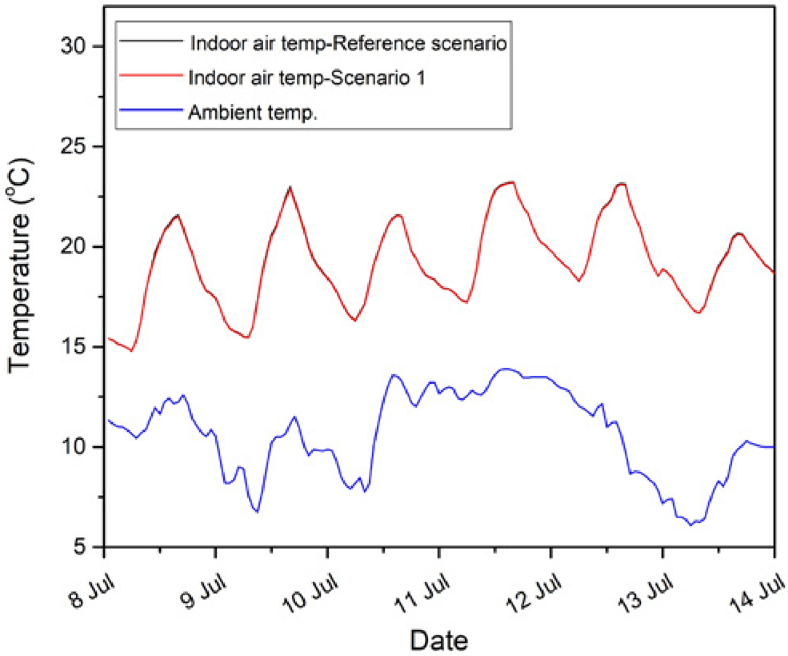

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Frankston beach station* using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

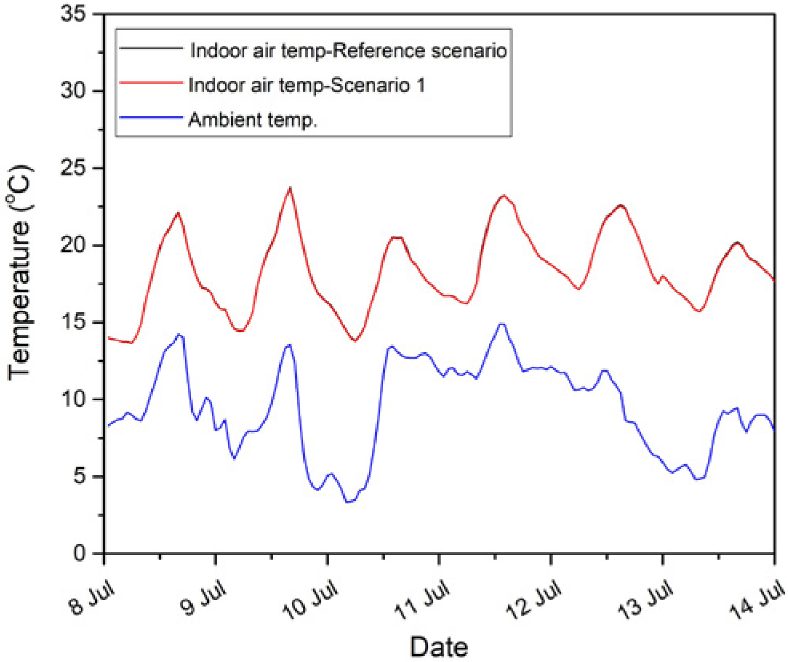

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Coldstream station* using annual 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 and 0.1 °C in Frankston beach and Coldstream stations, respectively.

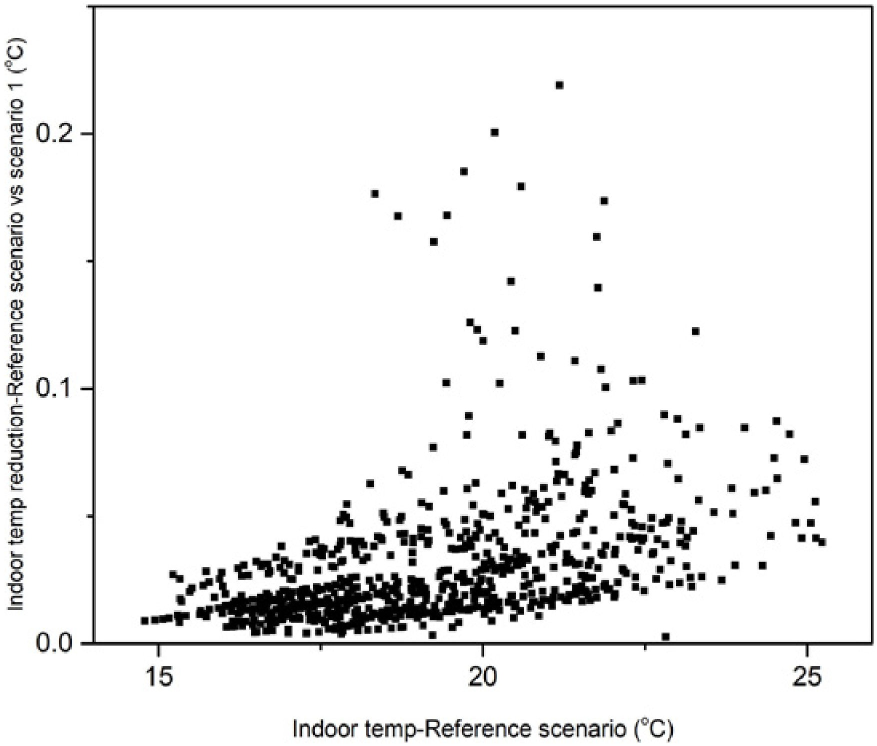

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

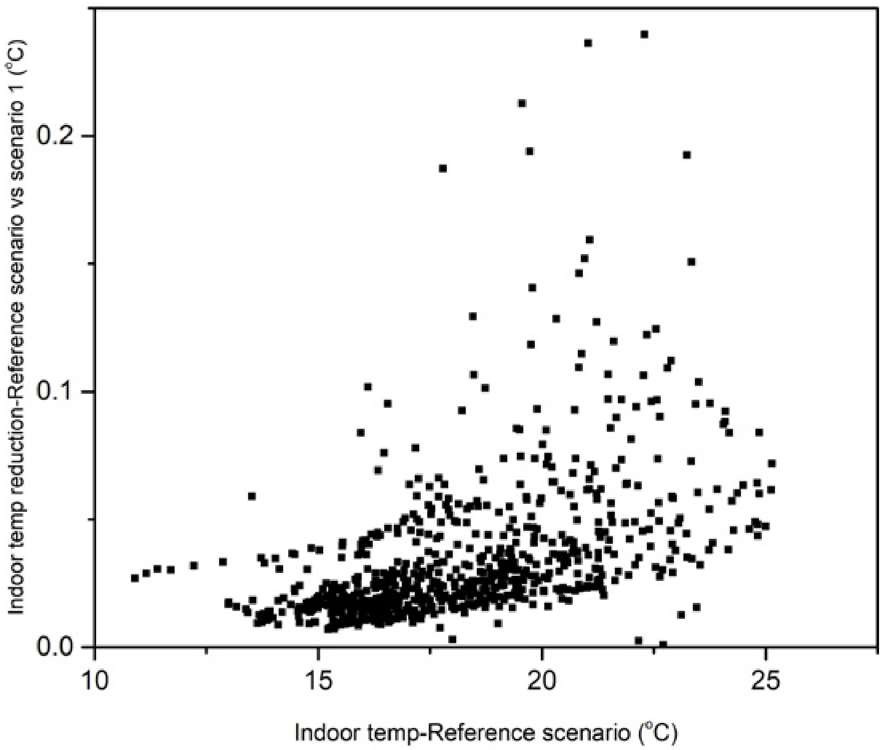

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 353 hours in reference scenario in Frankston beach station while remains the same for Coldstream station.

The number operational hours with air temperature <19 °C during is expected to remain the same for reference scenario and scenario 1 in both Frankston beach and Coldstream 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
Frankston beach	124	353	124	367
Coldstream	164	461	164	461

** 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 382 hours in reference scenario to 375 and 286 hours under scenario 1 and 2, in Frankston beach station; and from 427 hours in reference scenario to 419 and 353 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	382	375	286
Coldstream	427	419	353

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

Table 7. Energy performance features of Building 04.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	57,6	114,2
Energy consumption after cool roof (MWh)	57,1	113,3
Energy savings (MWh)	0,5	0,9
Energy savings (%)	0,87 %	0,79 %
Area (m^2)	1.200	1.200
Roof costs - Metal roof (AU$/$m^2$)	38,0	38,0
Roof costs - Coating (AU$/$m^2$)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/$m^2$)	15,0	15,0

The cool roof refurbishment options

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

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

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

Both options have the same energy efficiency, resulting in energy savings of 0,87% for the Frankston Beach weather conditions and of 0,79% for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option, which leads to a reduction of life cycle costs, that varies between 17,6 % for the low energy price scenario for Frankston and 22,4 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

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

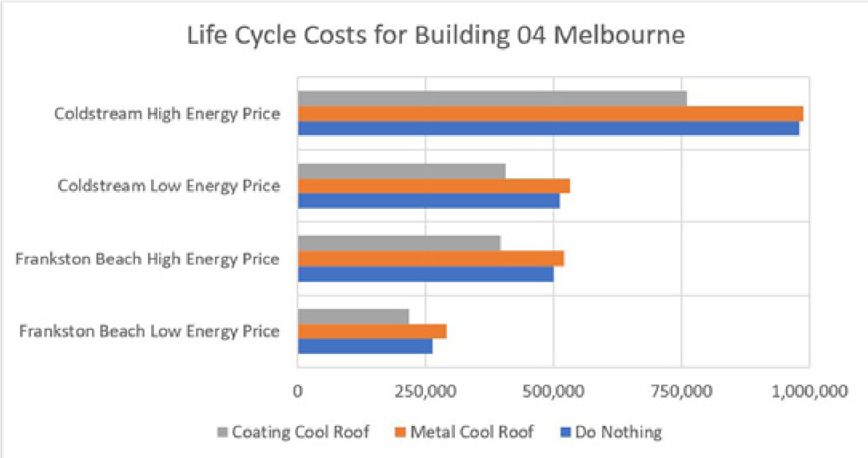

Figure 12. Life Cycle Costs for Building 04 for Frankston Beach and Coldstream stations.

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

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-9,96 %	-4,07 %	-3,99 %	-0,92 %
Coating Cool Roof	17,60 %	20,77 %	20,79 %	22,44 %

7

CONCLUSIONS

• In the eleven weather stations in Melbourne, 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 7.1-9.7 kWh/m^2 to 7.0-9.5 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 0.1-0.2 kWh/m^2 (~1.3-1.9 %) (See Table 1 and 2 and Figures 1 and 2). The combined building-scale and urban-scale application of cool roofs is foreseen to have a significant contribution to cooling load reduction. It is estimated that the cooling load of cool roof with modified urban temperature scenario (scenario 2) is around 1.8-2.7 kWh/m^2 (~21.5-31.8 %) lower than the reference scenario (See Table 1 and 2 and Figures 2 and 3) . Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0-0.1 kWh/m^2) is lower than the annual cooling load reduction (0.1-0.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.0-1.6%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.1 and 0.2 kWh/m^2 (~0.5-0.9 %) (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 22.0-36.0 ^{o}C and 21.3-37.0 ^{o}C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.2 ^{o}C in both Frankston beach and Coldstream stations. The indoor air temperature reduction is foreseen to increase further to 1.7 and 1.5 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 Frankston beach and Coldstream 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 °C and 0.1 °C in Frankston beach and Coldstream 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 353 hours in reference scenario to 367 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations show that the total number of hours below 19 °C remain the same for the reference scenario and scenario 1. Also, the number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to remain the same for both in Frankston beach and Coldstream stations (See Table 5).

• During a typical summer month, the total number of hours with an indoor air temperature (>26 oC) is predicted to decrease from 382 hours in reference scenario to 375 and 286 hours under scenario 1 and 2, in Frankston beach station; and from 427 hours in reference scenario to 419 and 353 hours under scenario 1 and 2 in Coldstream station, 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 only compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 17,6 % for the low energy price scenario for Frankston and 22,4 % for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible. Building 04 is in that sense a very good example of building with very limited energy conservation potential. Still, even in this case, a coating cool roof is a feasible investment over the building's life cycle.

B04

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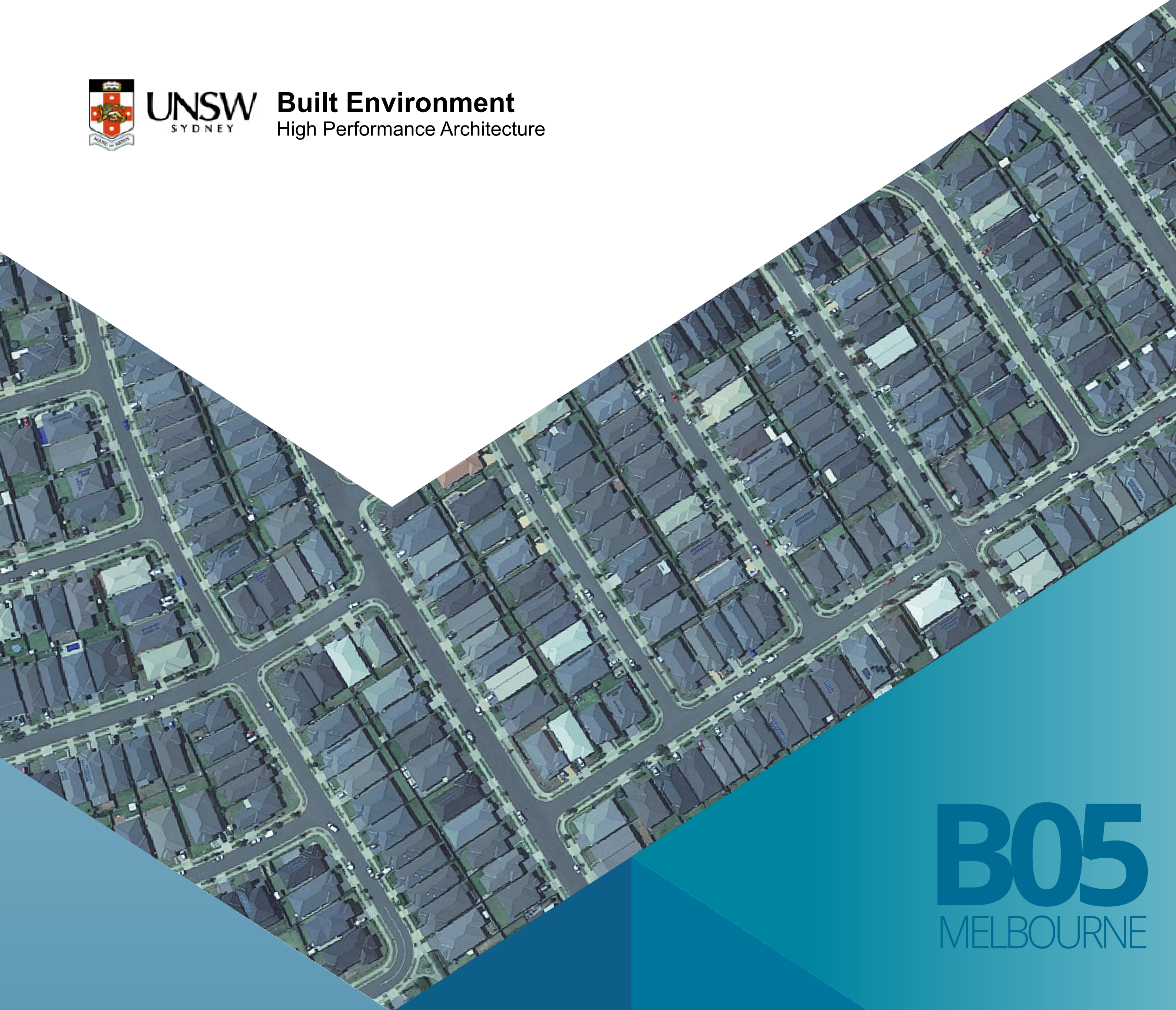

B05
MELBOURNE

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 Melbourne using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new low-rise office building from 41.8-47.7 kWh/m² to 40.3-45.7 kWh/m².

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

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	41.5	44.5	40.1	43.0	36.6	37.6
Coldstream	44.9	47.7	43.0	45.7	38.8	39.8
Essendon	43.5	46.5	42.0	45.0	37.0	37.8
Frankston beach	37.8	41.8	36.3	40.3	31.8	32.9
Melbourne airport	44.2	47.1	42.7	45.6	37.6	38.4
Moorabbin airport	38.7	42.8	37.3	41.3	32.6	33.7
Olympic park	41.0	44.5	39.5	43.0	36.1	37.3

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

For Scenario 1, the total cooling load saving is around 1.4-2.0 kWh/m² which is equivalent to 3.2-4.2 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.9-9.1 kWh/m² which is equivalent to 15.5-21.4 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	1.4	3.4	1.4	3.2	4.9	11.8	6.9	15.5
Coldstream	2.0	4.4	2.0	4.2	6.1	13.6	7.8	16.5
Essendon	1.5	3.5	1.5	3.3	6.5	14.9	8.7	18.8
Frankston beach	1.5	3.9	1.5	3.7	6.0	16.0	8.9	21.4
Melbourne airport	1.5	3.5	1.6	3.3	6.6	14.9	8.8	18.6
Moorabbin airport	1.5	3.8	1.5	3.6	6.1	15.8	9.1	21.2
Olympic park	1.5	3.6	1.5	3.4	4.9	12.0	7.3	16.3

In the eleven weather stations in Melbourne, 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.

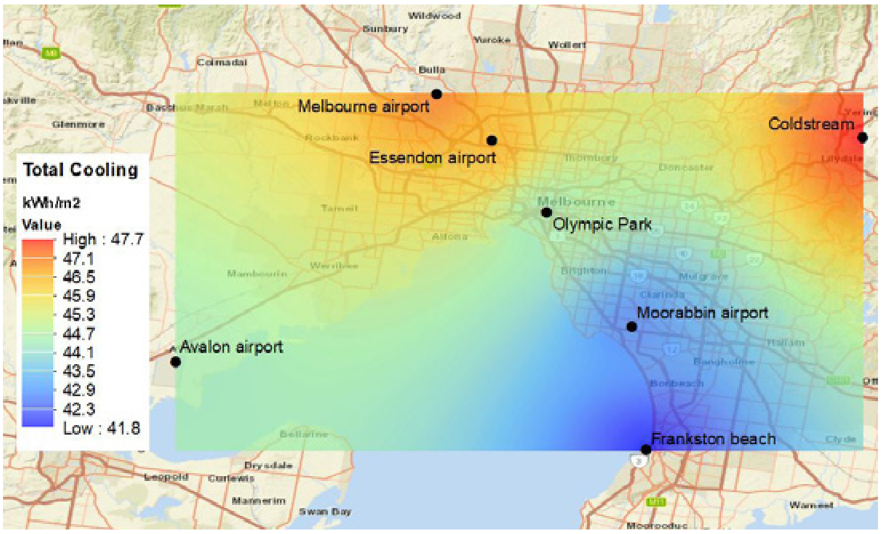

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

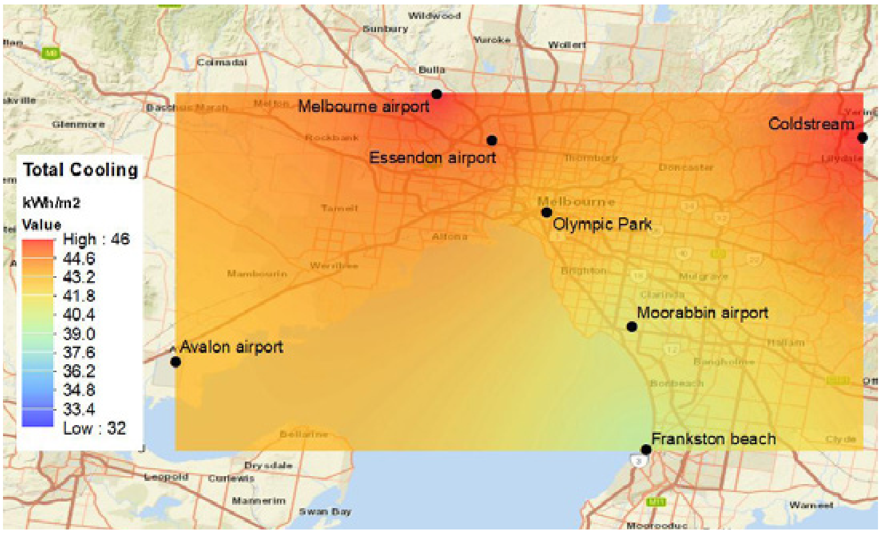

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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 Melbourne 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 (0.1-0.3 kWh/m²) is significantly lower than the annual cooling load reduction (3.7-4.7 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
Avalon airport	99.5	112.4	2.9	7.9	95.9	108.6	2.9	8.1
Coldstream	107.0	118.6	3.7	10.3	102.4	113.9	3.8	10.6
Essendon	107.1	117.8	2.3	6.3	103.4	114.0	2.3	6.4
Frankston beach	87.4	101.2	1.3	3.2	83.0	96.7	1.3	3.3
Melbourne airport	102.3	110.5	2.6	7.2	98.7	106.8	2.6	7.4
Moorabbin airport	104.1	116.5	1.9	5.2	100.2	112.5	2.0	5.3
Olympic park	113.8	126.3	1.7	4.4	108.9	121.3	1.7	4.5

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

The annual cooling load saving by building-scale application of cool roofs is around 3.3-4.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.5 and 4.9 kWh/m² (~2.9-4.2 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	3.6	3.7	3.8	3.4	0.0	0.2	3.6	3.5	3.6	3.0
Coldstream	4.6	4.3	4.7	4.0	0.1	0.3	4.5	4.1	4.5	3.5
Essendon	3.7	3.5	3.8	3.3	0.0	0.1	3.7	3.4	3.7	3.0
Frankston beach	4.4	5.0	4.5	4.5	0.0	0.1	4.3	4.9	4.4	4.2
Melbourne airport	3.6	3.5	3.7	3.3	0.1	0.2	3.5	3.4	3.5	2.9
Moorabbin airport	3.9	3.7	4.0	3.4	0.0	0.1	3.8	3.6	3.8	3.1
Olympic park	4.9	4.3	5.0	4.0	0.0	0.1	4.8	4.2	4.9	3.7

3

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

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

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

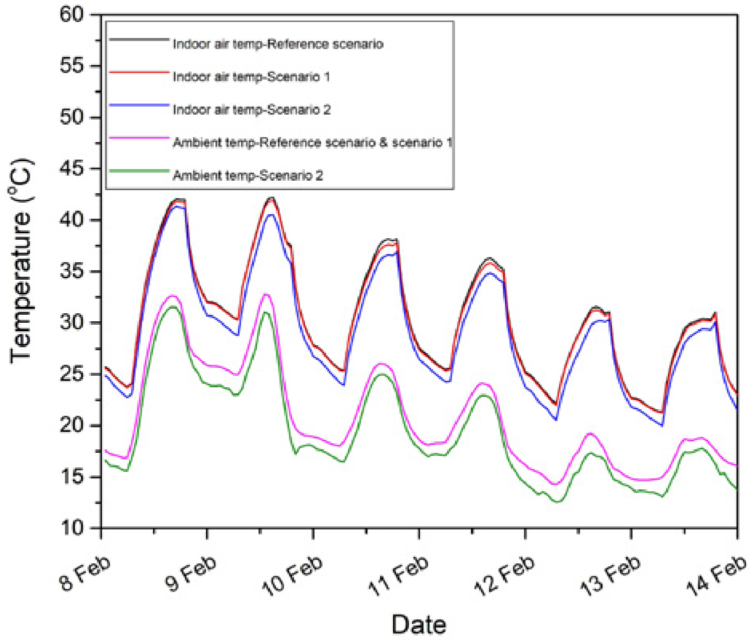

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new low-rise shopping mall centre under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

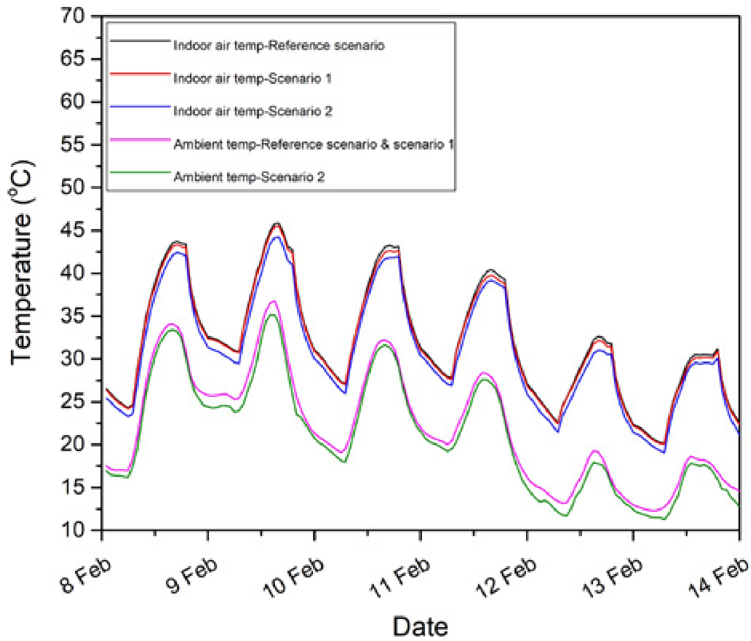

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.3-42.2 °C and 20.2-45.9 °C in Frankston beach and Coldstream stations, respectively.

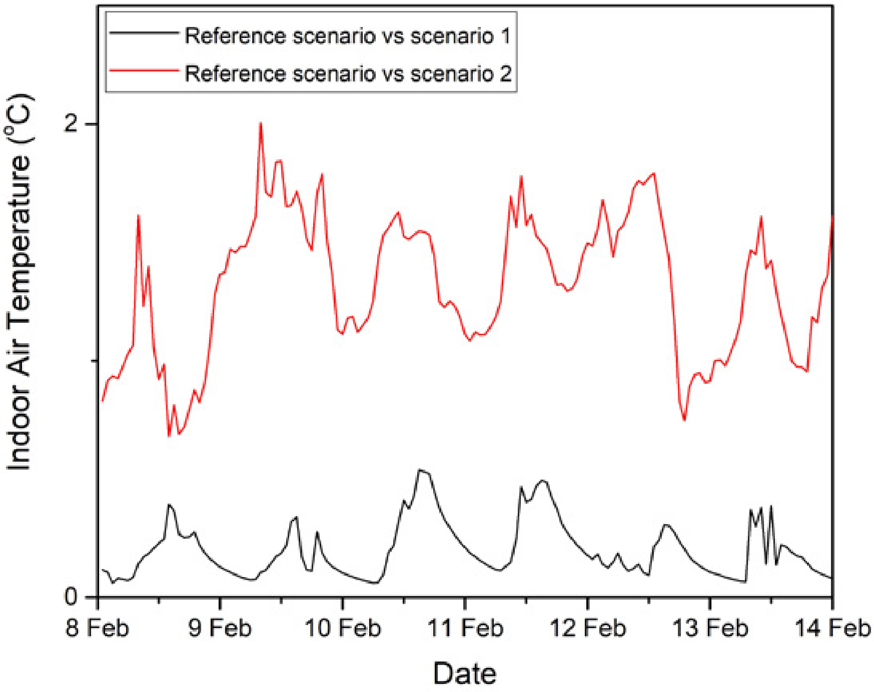

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Frankston beach 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 0.7 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.0 °C in Frankston beach and Coldstream stations.

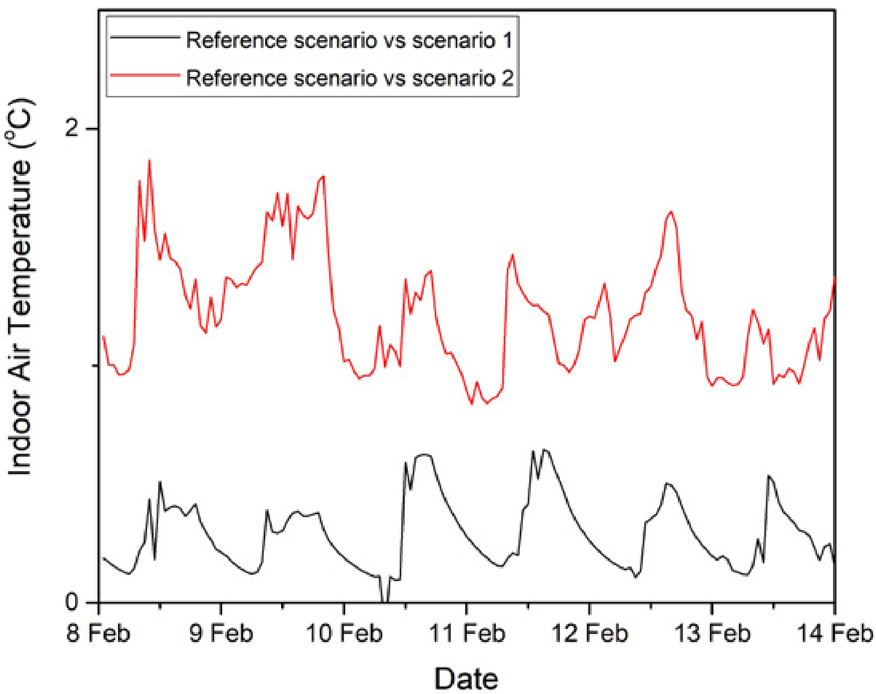

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 13.4-27.0 °C in reference scenario to a range 13.3-26.7 °C in scenario 1 in Frankston beach station.

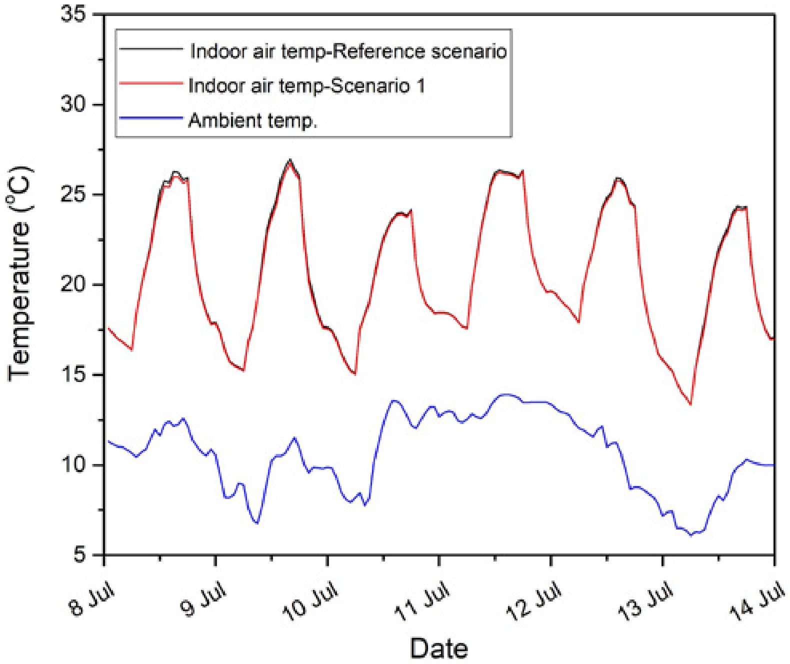

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Frankston beach station* using annual measured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

The indoor air temperature is predicted to reduce from a range 11.8-28.2 °C in reference scenario to a range 11.7-28.0 °C in scenario 1 in Coldstream station.

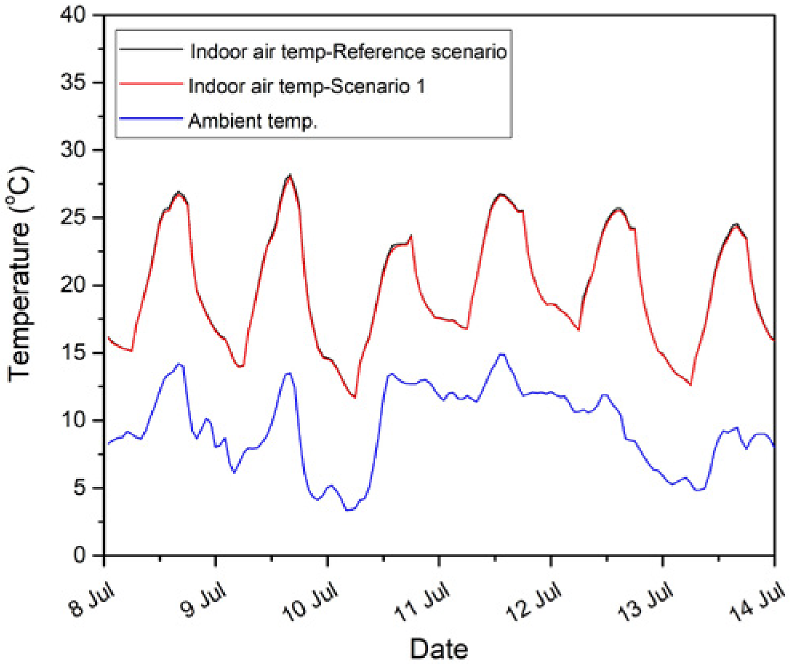

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Coldstream station* using annual measured weather 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 and 0.3°C in Frankston beach and Coldstream stations, respectively.

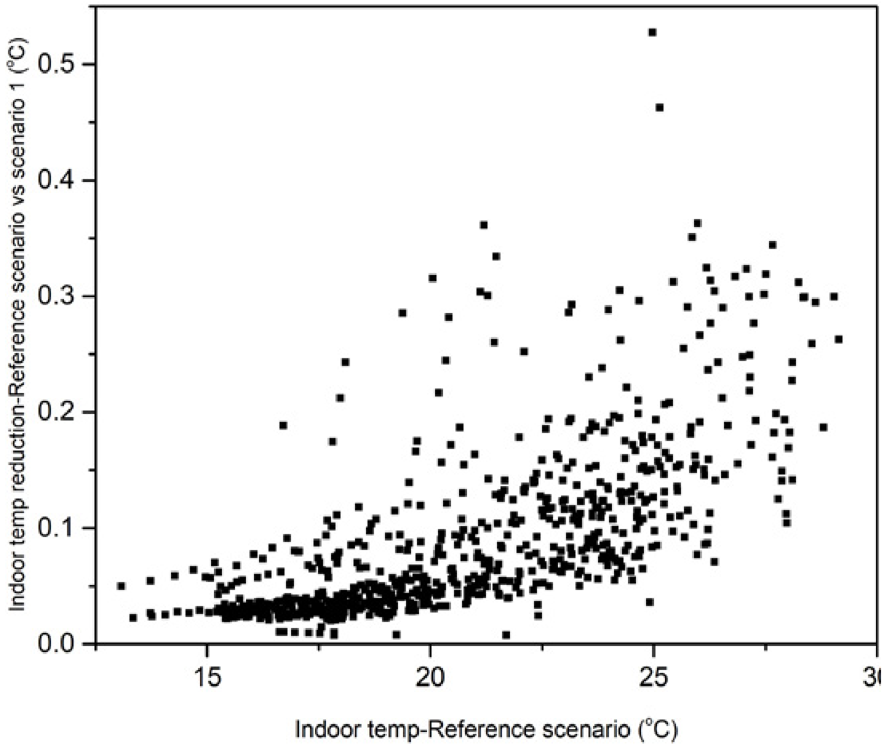

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

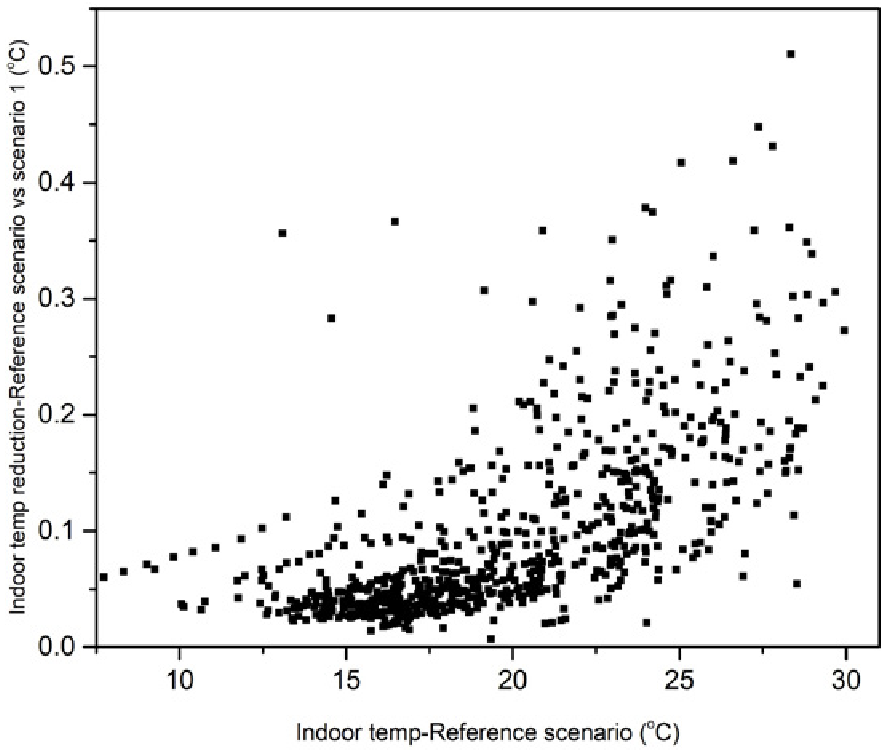

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 283 hours in reference scenario to 287 hours, and from 355 to 361 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 32 hours in reference scenario to 34 hours; and from 65 to 68 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Frankston beach	32	283	34	287
Coldstream	65	355	68	361

** 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 430 hours in reference scenario to 418 and 382 hours under scenario 1 and 2 in Frankston beach station; and from 455 hours in reference scenario to 444 and 408 hours under scenario 1 and 2 in Coldstream station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Frankston beach	430	418	382
Coldstream	455	444	408

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. (Table 8).

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

Table 7. Energy performance features of Building 05.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	91,9	113,4
Energy consumption after cool roof (MWh)	88,0	109,6
Energy savings (MWh)	3,9	3,8
Energy savings (%)	4,24 %	3,35 %
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 big 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 4,24 % for the Frankston Beach weather conditions and of 3,35 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 22,9 % for the low energy price scenario for Frankston and 24,6 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

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

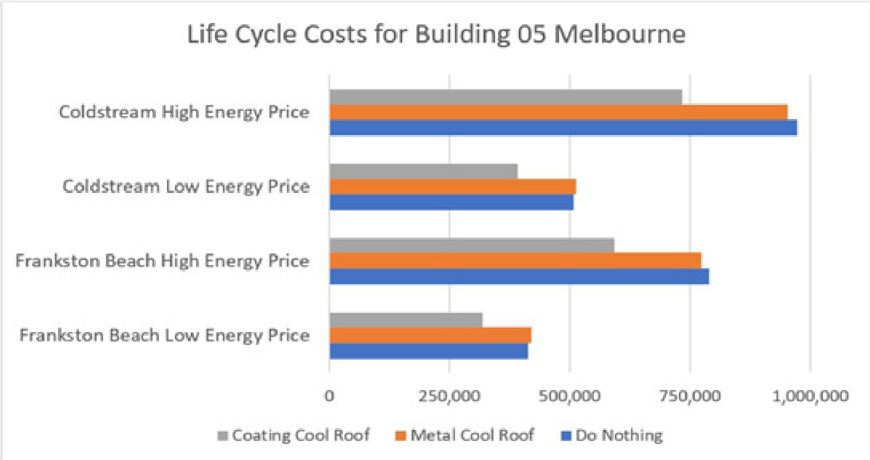

Figure 12. Life Cycle Costs for Building 05 for Frankston Beach and Coldstream stations.

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	-1,49 %	2,03 %	-1,00 %	1,87 %
Coating Cool Roof	22,95 %	24,86 %	23,01 %	24,56 %

7

CONCLUSIONS

• In the eleven weather stations in Melbourne, 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 Melbourne, the total cooling load of a typical low-rise shopping mall centre under the reference scenario is approximately 41.8 and 47.7 kWh/m^2, which reduces to a range between 40.3 and 45.7 kWh/m^2 under Reference with cool roof scenario (scenario 1). As computed, the total cooling load saving by building-scale application of cool roofs is around 1.4-2.0kWh/m^2 (~ 3.2-4.2 %) (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Melbourne, the total cooling load of low-rise shopping mall centre is estimated to be around 6.9-9.1 kWh/m^2 lower under cool roof with modified urban temperature scenario (scenario 2) compared to the reference scenario. This is equivalent to 15.5-21.4 % total cooling load saving by combined building-scale and urban-scale application of cool roof.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1-0.3 kWh/m^2) is significantly lower than the annual cooling load reduction (3.7-4.7 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.3-4.0%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.5 and 4.9 kWh/m^2 (~2.9-4.2 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 21.3-42.2 °C and 20.2-45.9 °C in Frankston beach and Coldstream 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 0.7 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.0 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 13.4 and 27.0 °C in reference scenario to a range between 13.3 and 26.7 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 11.8 and 28.2 °C in reference scenario to a range between 11.7 and 28.0 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 0.2 °C and 0.3 °C in Frankston beach and Coldstream 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 283 hours in reference scenario to 287 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight increase in total number of hours below 19 °C from 355 hours in reference scenario to 361 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 32 hours in reference scenario to 34 hours; and from 65 to 68 hours in scenario 1 in Frankston beach and Coldstream 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 430 hours under the reference scenario in Frankston beach station, which decreases to 418 and 382 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a reduction in number of hours above 26 °C from 455 hours in reference scenario to 444 in reference with cool roof scenario (scenario 1) and 408 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 the higher cost over the building's life cycle compared to the coating cool roof option. The latter leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 22,9 % for the low energy price scenario for Frankston and 24,6 % for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible, or only marginally so. Building 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 big impact of the roof on the building's cooling loads.

B05

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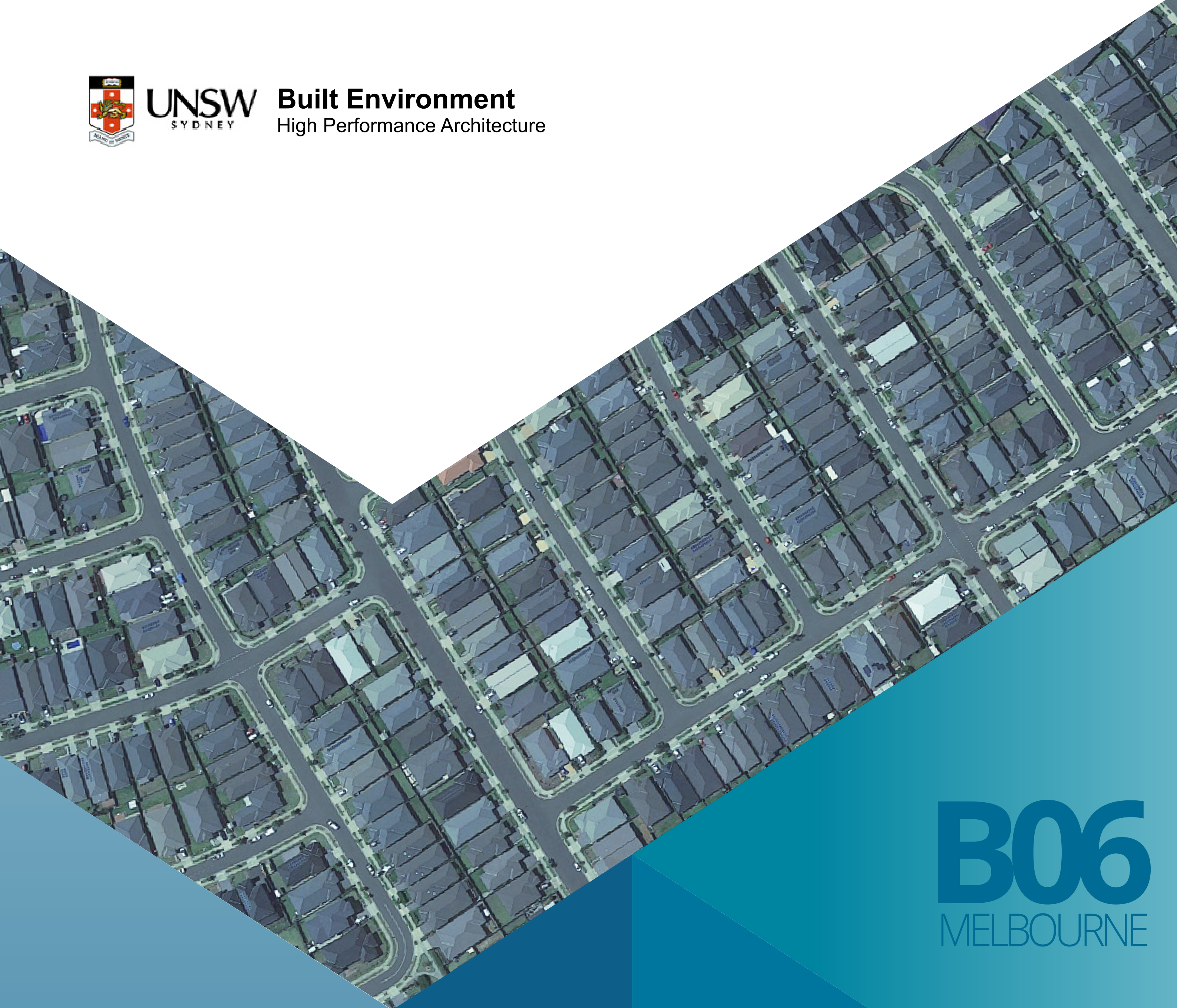

B06
MELBOURNE

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.

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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 Melbourne 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 40.2-45.9 kWh/m² to 39.5-45.0 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	39.9	42.9	39.2	42.2	35.7	36.7
Coldstream	43.2	45.9	42.3	45.0	38.0	39.0
Essendon	41.9	44.9	41.2	44.1	36.1	36.9
Frankston beach	36.2	40.2	35.5	39.5	30.9	32.0
Melbourne airport	42.5	45.4	41.8	44.7	36.7	37.4
Moorabbin airport	37.1	41.2	36.4	40.4	31.7	32.8
Olympic park	39.4	42.9	38.7	42.2	35.2	36.4

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 0.7-1.0 kWh/m² which is equivalent to 1.6-2.1 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.2-8.2 kWh/m² which is equivalent to 14.4-20.4 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	0.7	1.7	0.7	1.6	4.2	10.5	6.2	14.4
Coldstream	1.0	2.2	1.0	2.1	5.2	12.1	6.9	15.1
Essendon	0.7	1.7	0.7	1.6	5.8	13.8	8.0	17.8
Frankston beach	0.7	1.9	0.7	1.8	5.3	14.7	8.2	20.4
Melbourne airport	0.7	1.7	0.7	1.6	5.8	13.7	8.0	17.6
Moorabbin airport	0.7	1.9	0.7	1.7	5.4	14.6	8.4	20.3
Olympic park	0.7	1.8	0.7	1.7	4.2	10.6	6.5	15.1

In the eleven weather stations in Melbourne, 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.

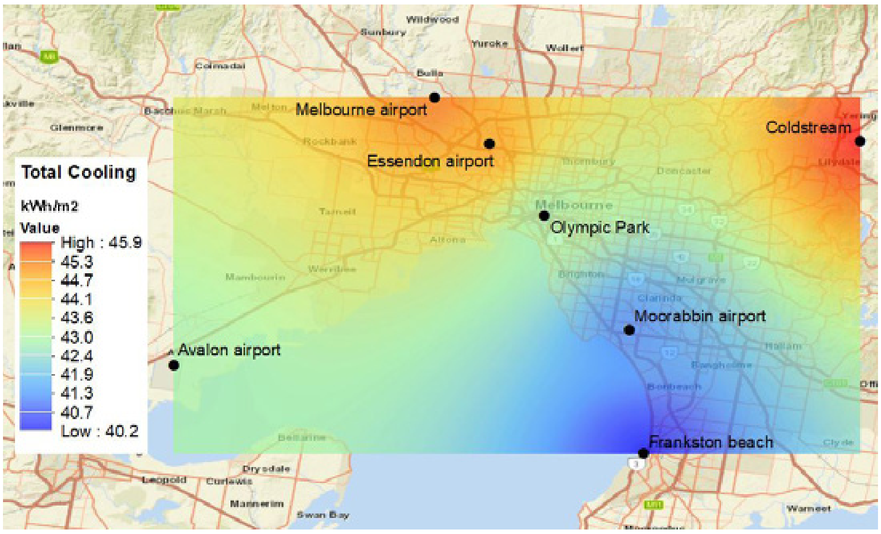

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

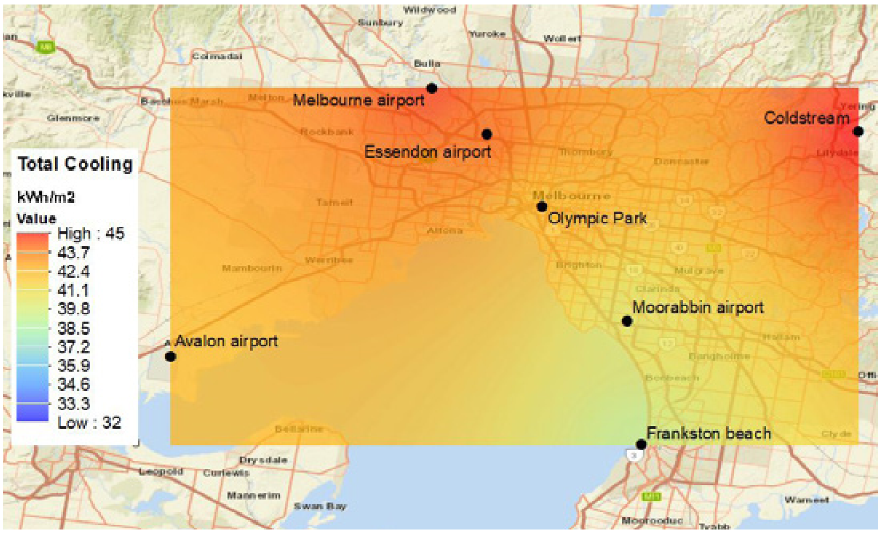

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

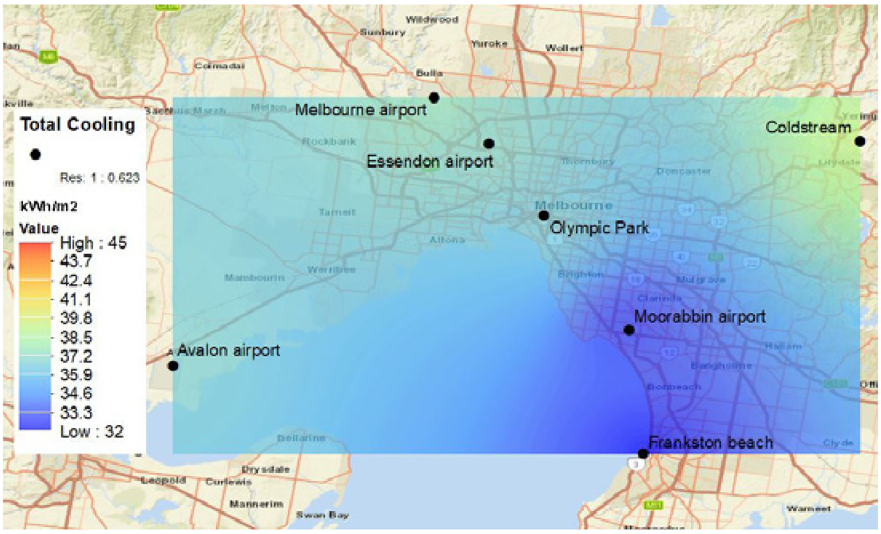

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (1.6-2.3 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
Avalon airport	93.1	105.8	2.4	7.4	91.4	104.1	2.4	7.5
Coldstream	100.0	111.5	3.2	9.8	97.8	109.3	3.3	9.9
Essendon	101.1	111.7	1.9	5.8	99.3	109.9	1.9	5.8
Frankston beach	81.9	95.6	1.0	2.7	79.9	93.5	1.0	2.8
Melbourne airport	96.1	104.3	2.2	6.8	94.5	102.6	2.2	6.9
Moorabbin airport	98.0	110.3	1.6	4.7	96.2	108.5	1.6	4.7
Olympic park	107.2	119.7	1.3	3.8	105.0	117.4	1.3	3.9

The annual cooling load saving by building-scale application of cool roofs is around 1.6-2.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.6-2.1 kWh/m² (~1.4-2.1%).

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 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	%
Avalon airport	1.6	1.8	1.7	1.6	0.0	0.1	1.6	1.7	1.6	1.4
Coldstream	2.1	2.1	2.2	2.0	0.0	0.1	2.1	2.0	2.1	1.7
Essendon	1.7	1.7	1.8	1.6	0.0	0.1	1.7	1.7	1.7	1.4
Frankston beach	2.0	2.5	2.1	2.2	0.0	0.0	2.0	2.4	2.0	2.1
Melbourne airport	1.6	1.7	1.6	1.6	0.0	0.1	1.6	1.6	1.6	1.4
Moorabbin airport	1.8	1.8	1.8	1.6	0.0	0.1	1.7	1.8	1.8	1.5
Olympic park	2.3	2.1	2.3	1.9	0.0	0.1	2.2	2.1	2.3	1.8

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

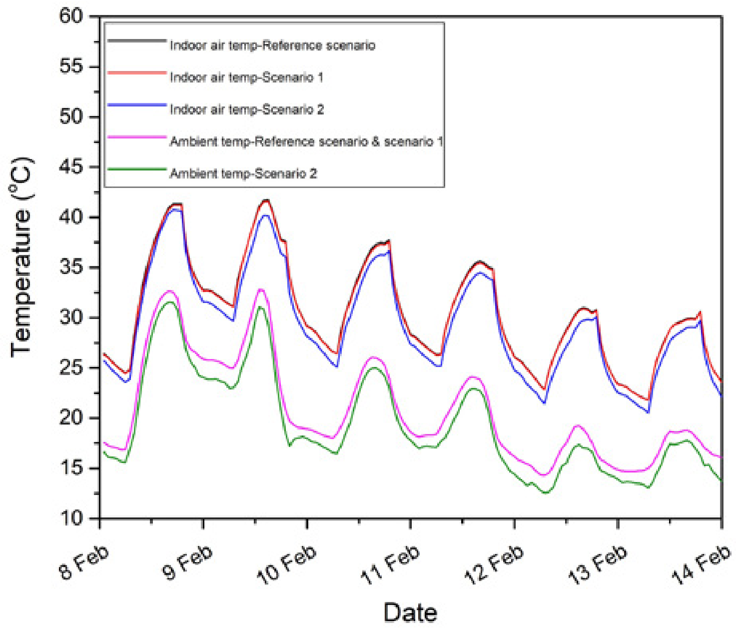

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new mid-rise shopping mall centre under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

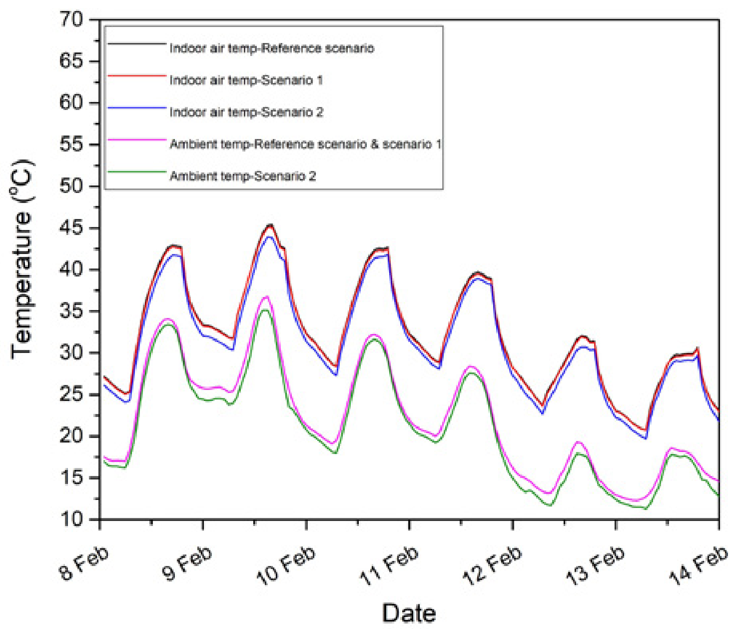

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.8-41.8 °C and 20.8-45.4 °C in Frankston beach and Coldstream stations, respectively.

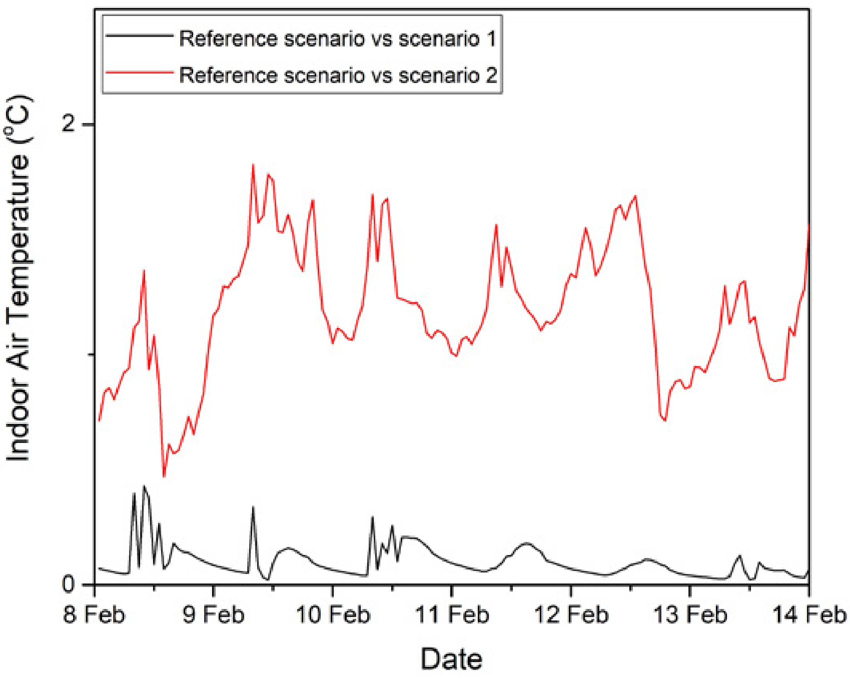

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical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

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

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

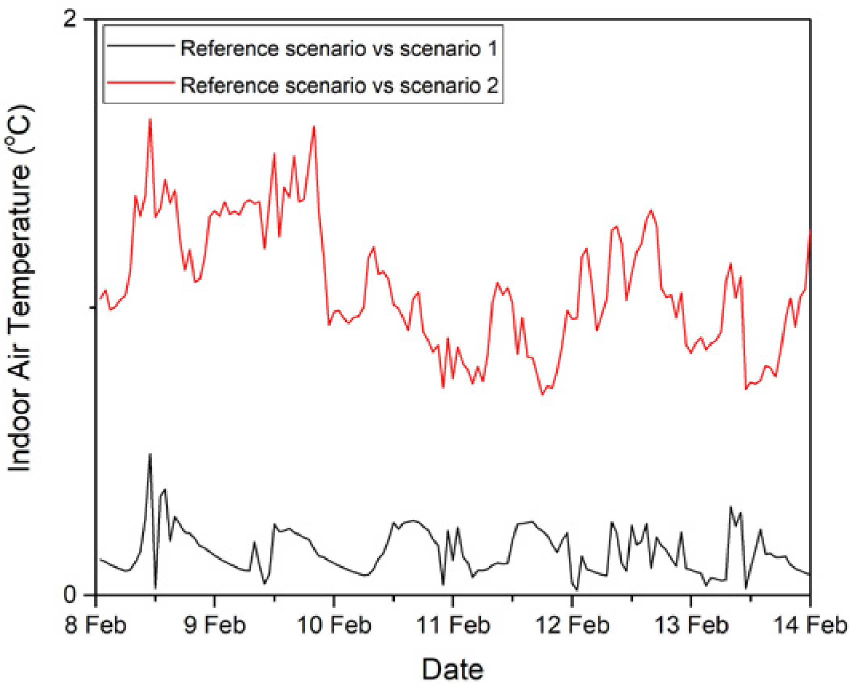

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to slightly reduce from a range 14.1-26.4 °C in reference scenario to a range 14.1-26.2 °C in scenario 1 in Frankston beach station.

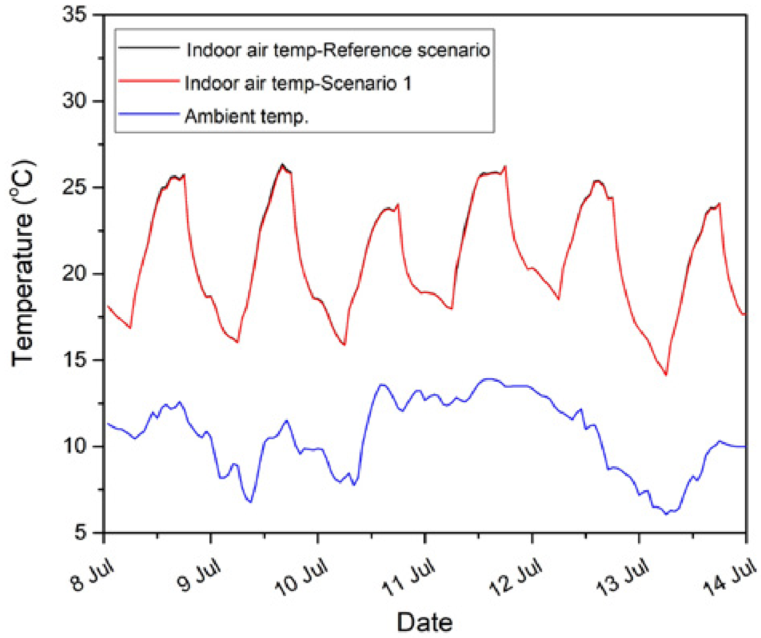

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Frankston beach station* using annual measured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

The indoor air temperature is predicted to slightly reduce from a range 12.7-27.6 °C in reference scenario to a range 10.7-12.7-27.4 °C in scenario 1 in Coldstream station.

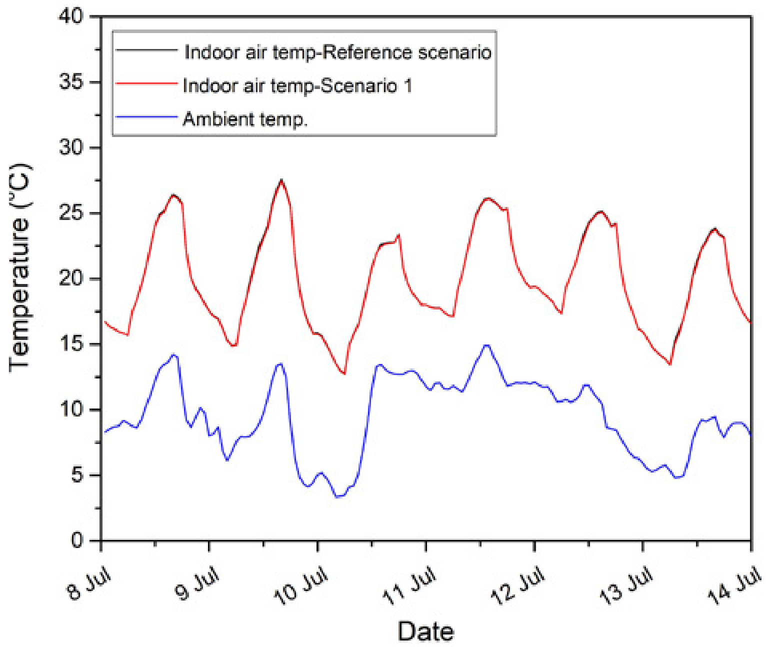

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Coldstream station* using annual measured weather 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 and 0.2 °C in Frankston beach and Coldstream stations, respectively.

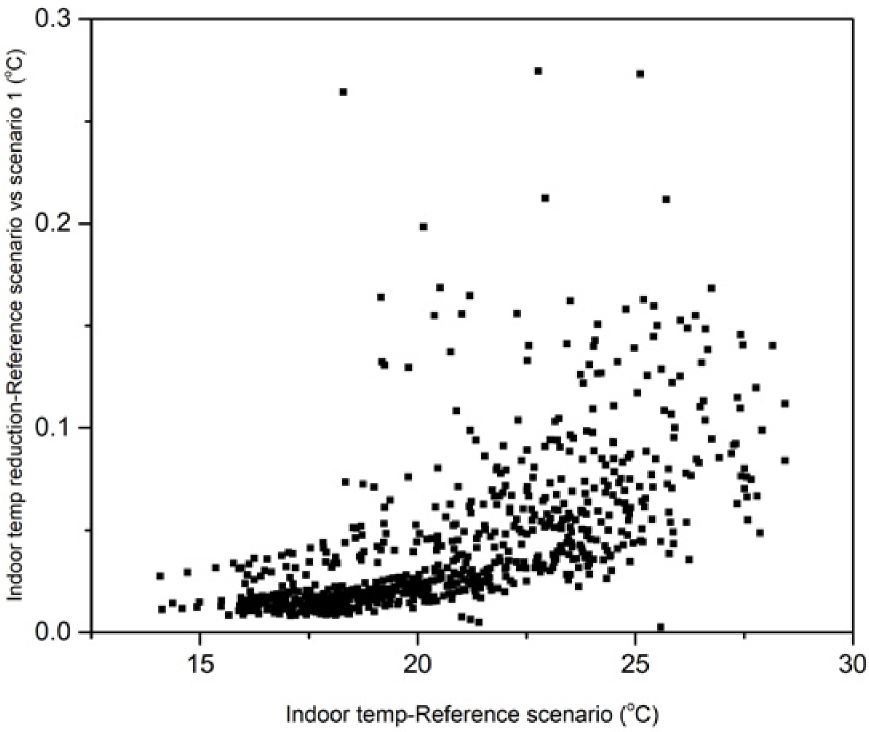

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

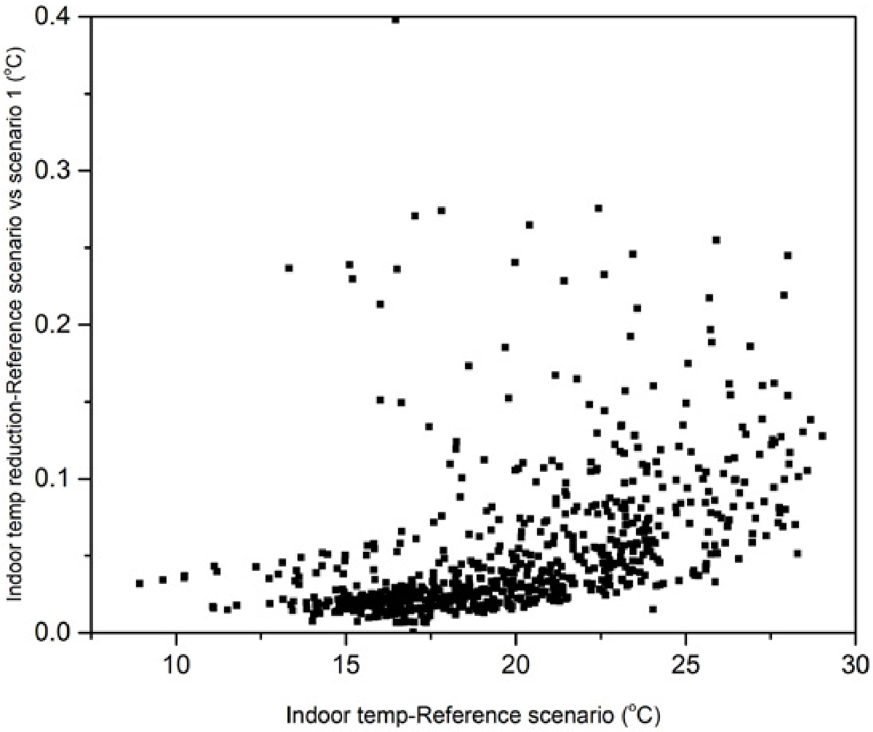

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 ºC) is predicted to slightly increase from 244 hours in reference scenario to 247 hours, and from 331 to 334 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 ºC during is expected to slightly increase from 26 hours in reference scenario to 27 hours; and from 63 to 64 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Frankston beach	26	244	27	247
Coldstream	63	331	64	334

** 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 ºC) is predicted to decrease from 455 hours in reference scenario to 451 and 398 hours under scenario 1 and 2 in Frankston beach station; and from 479 hours in reference scenario to 473 and 425 hours under scenario 1 and 2 in Coldstream station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Frankston beach	455	451	398
Coldstream	479	473	425

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

Table 7. Energy performance features of Building 06.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	173,0	213,5
Energy consumption after cool roof (MWh)	169,5	209,8
Energy savings (MWh)	3,5	3,7
Energy savings (%)	2,02%	1,73%
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.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 2,02 % for the Frankston Beach weather conditions and of 1,73 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,1 % for the low energy price scenario for Frankston and 24,1 % for the high energy scenario for the same conditions(Table 8).

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

Feasibility analysis results

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

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

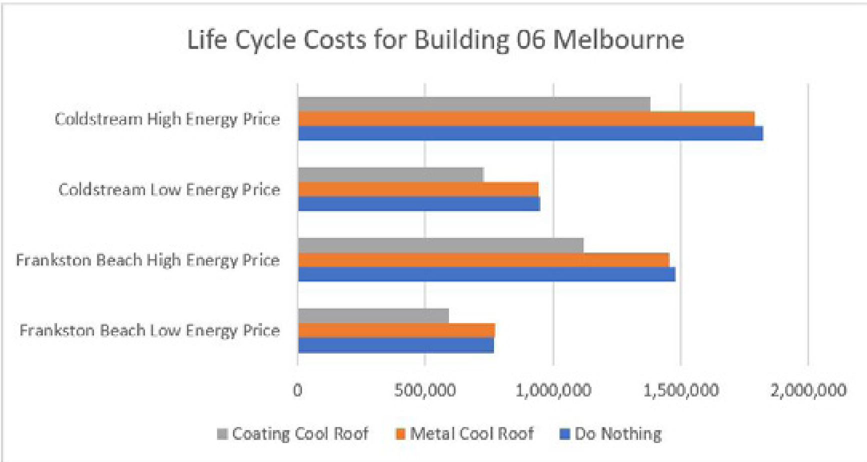

Figure 12. Life Cycle Costs for Building 06 for Frankston Beach and Coldstream stations.

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	-0,26 %	1,63 %	0,19 %	1,73 %
Coating Cool Roof	23,09 %	24,11 %	23,27 %	24,09 %

7

CONCLUSIONS

- In the eleven weather stations in Melbourne, 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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of the mid-rise shopping mall centre from 40.2-45.9 kWh/m^2 to 39.5-45.0 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.7-1.0 kWh/m^2. This is equivalent to approximately 1.6-2.1 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 6.2-8.2 kWh/m^2. This is equivalent to 14.4-20.4 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

- The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (1.6-2.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.6-2.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.6 and 2.1 kWh/m^2 (~1.4-2.1%) (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 21.8-41.8 °C and 20.8-45.4 °C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.4 and 0.5 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations (See Figures 4-7).

- During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 14.1-26.4 °C in reference scenario to a range between 14.1-26.2 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce between 12.7 and 27.6 °C in reference scenario to a range between 12.7 and 27.4 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 and 0.2 °C in Frankston beach and Coldstream 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 244 hours in reference scenario to 247 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight increase in total number of hours below 19 °C from 331 hours in reference scenario to 334 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 26 hours in reference scenario to 27 hours; and from 63 to 64 hours in scenario 1 in Frankston beach and Coldstream 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 455 hours under the reference scenario in Frankston beach station, which decreases to 451 and 398 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a reduction in number of hours above 26 °C from 479 hours in reference scenario to 473 in reference with cool roof scenario (scenario 1) and 425 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 the higher cost over the building's life cycle compared to the coating cool roof option. The latter leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,1 % for the low energy price scenario for Frankston and 24,1 % for the high energy scenario for the same conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost not feasible, or only marginally so. Building 06 is in that sense an interesting example of a new, insulated, mid-rise commercial building where, despite its rather limited energy conservation potential, the coating cool roof is a feasible investment, over the building's life cycle, due to the large impact of the roof on the building's cooling loads.

B06

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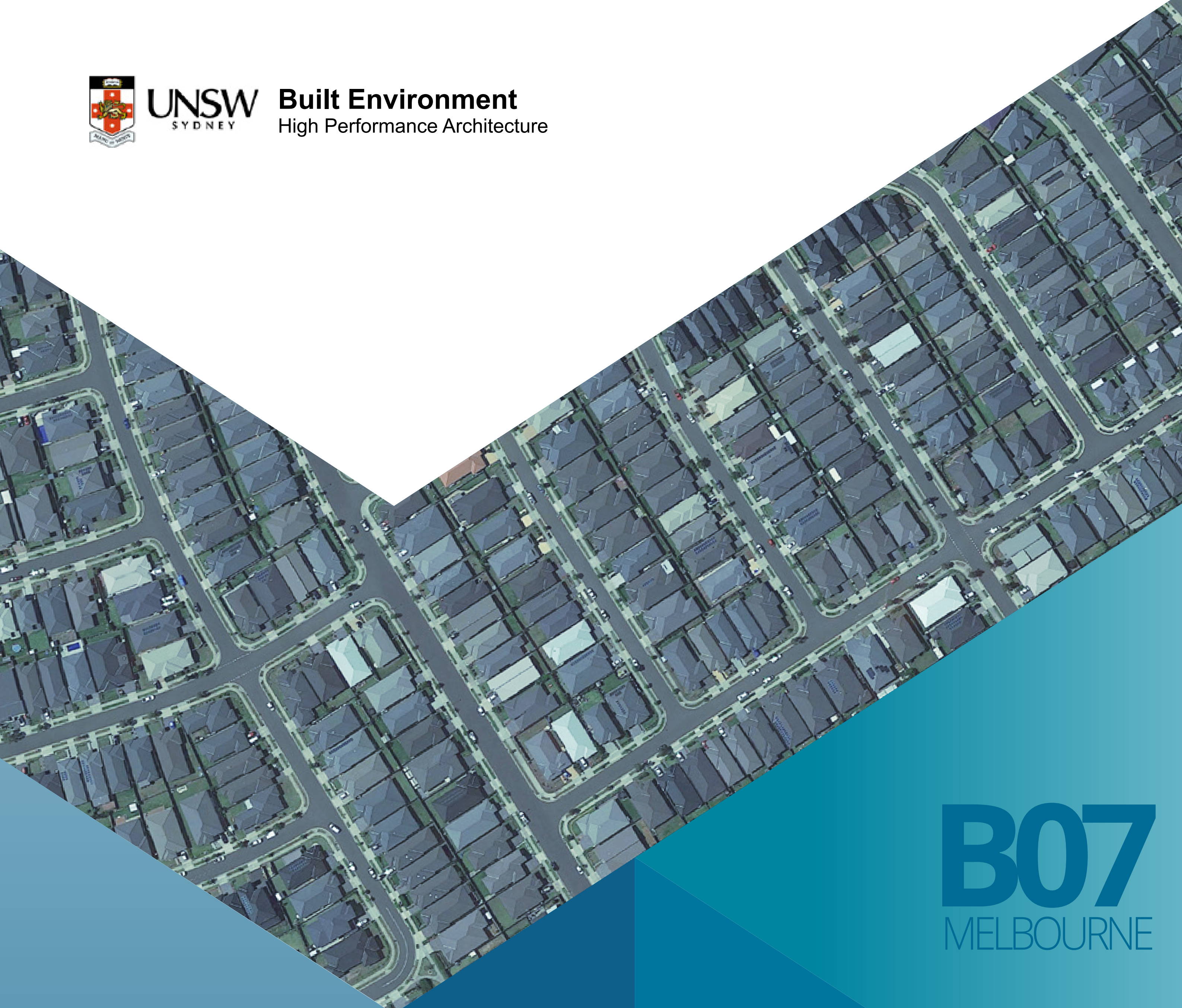

B07
MELBOURNE

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise shopping mall centre
2021

BUILDING 07

NEW 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 Melbourne using weather data simulated by WRF.

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise shopping mall centre from 39.6-45.3 kWh/m² to 39.1-44.7 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	39.3	42.3	38.9	41.8	35.4	36.4
Coldstream	42.6	45.3	42.0	44.7	37.7	38.7
Essendon	41.3	44.2	40.8	43.8	35.8	36.5
Frankston beach	35.6	39.6	35.2	39.1	30.6	31.7
Melbourne airport	41.9	44.8	41.4	44.3	36.3	37.1
Moorabbin airport	36.5	40.5	36.1	40.1	31.4	32.4
Olympic park	38.8	42.3	38.3	41.8	34.9	36.1

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 0.5-0.6 kWh/m² which is equivalent to 1.0-1.4 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 5.9-8.1 kWh/m² which is equivalent to 14.0-20.0 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	0.4	1.1	0.4	1.0	3.9	10.0	5.9	14.0
Coldstream	0.6	1.5	0.6	1.4	4.9	11.6	6.7	14.7
Essendon	0.5	1.1	0.5	1.1	5.5	13.4	7.7	17.5
Frankston beach	0.5	1.3	0.5	1.2	5.0	14.2	7.9	20.0
Melbourne airport	0.5	1.1	0.5	1.1	5.6	13.3	7.7	17.3
Moorabbin airport	0.4	1.2	0.5	1.1	5.2	14.1	8.1	19.9
Olympic park	0.5	1.2	0.5	1.1	3.9	10.0	6.2	14.7

In the eleven weather stations in Melbourne, 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.

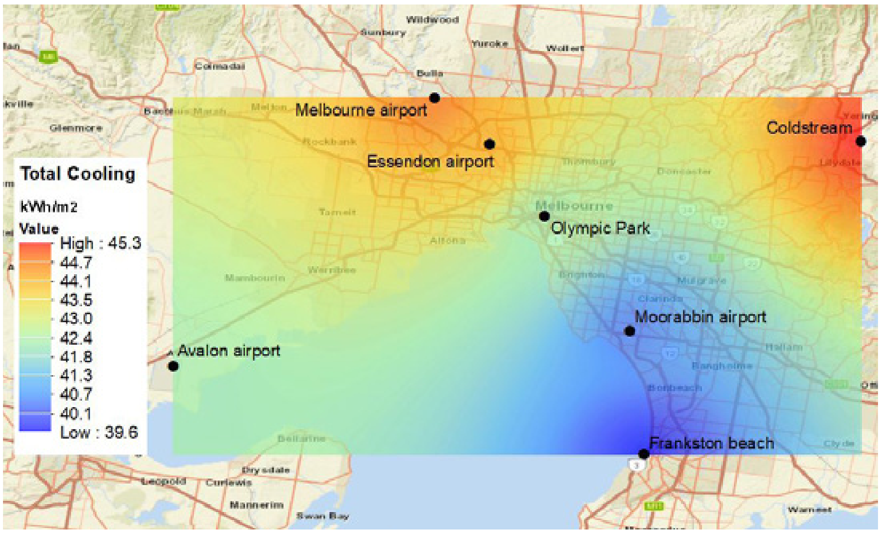

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

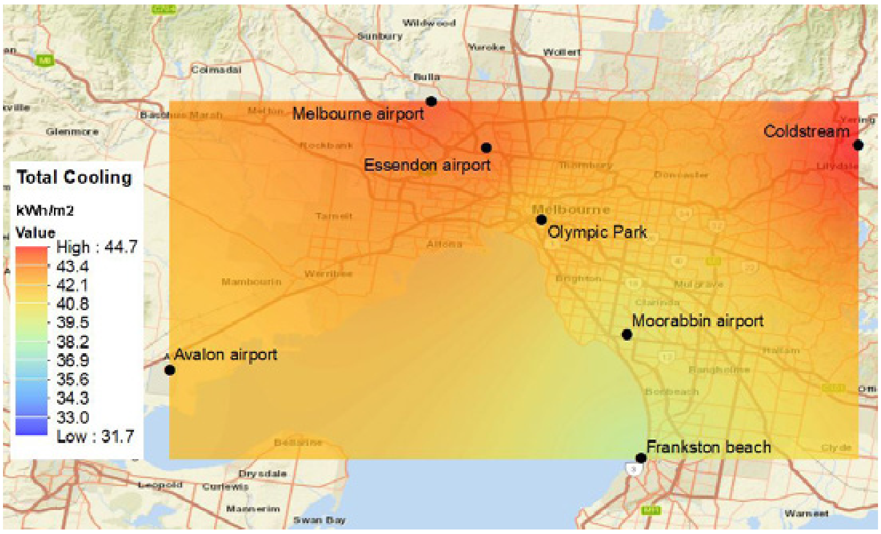

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

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 Melbourne using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (1.0-1.5 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Avalon airport	90.7	103.4	2.3	7.3	89.7	102.3	2.3	7.4
Coldstream	97.5	108.9	3.1	9.7	96.1	107.5	3.1	9.7
Essendon	98.8	109.3	1.8	5.7	97.7	108.2	1.8	5.7
Frankston beach	79.8	93.4	0.9	2.6	78.5	92.1	0.9	2.6
Melbourne airport	93.9	102.0	2.1	6.7	92.9	101.0	2.1	6.8
Moorabbin airport	95.7	108.0	1.5	4.6	94.6	106.8	1.5	4.6
Olympic park	104.8	117.2	1.2	3.7	103.4	115.7	1.2	3.7

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 1.0-1.4 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.0 and 1.4 kWh/m² (~0.9-1.3 %).

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	%
Avalon airport	1.1	1.2	1.1	1.1	0.0	0.1	1.0	1.1	1.0	0.9
Coldstream	1.4	1.4	1.4	1.3	0.0	0.1	1.4	1.4	1.3	1.1
Essendon	1.1	1.1	1.1	1.0	0.0	0.1	1.1	1.1	1.1	0.9
Frankston beach	1.3	1.6	1.3	1.4	0.0	0.0	1.3	1.6	1.3	1.3
Melbourne airport	1.0	1.1	1.0	1.0	0.0	0.1	1.0	1.0	1.0	0.9
Moorabbin airport	1.1	1.2	1.2	1.1	0.0	0.0	1.1	1.1	1.1	1.0
Olympic park	1.4	1.4	1.5	1.3	0.0	0.0	1.4	1.4	1.4	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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

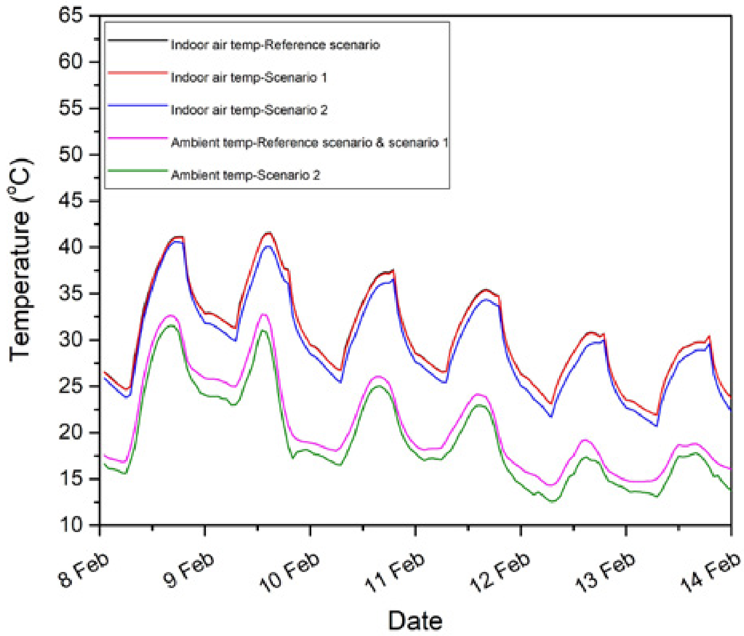

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

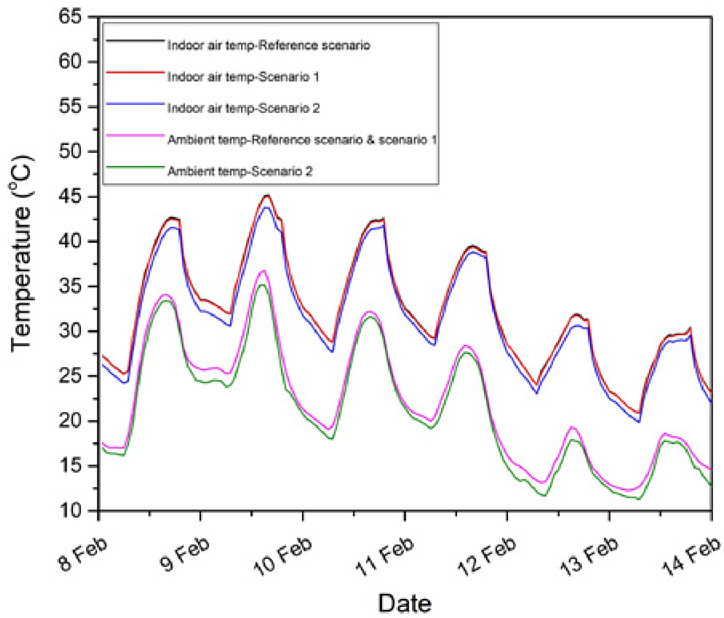

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 22.0-41.6 °C and 20.9-45.2 °C in Frankston beach and Coldstream stations, respectively.

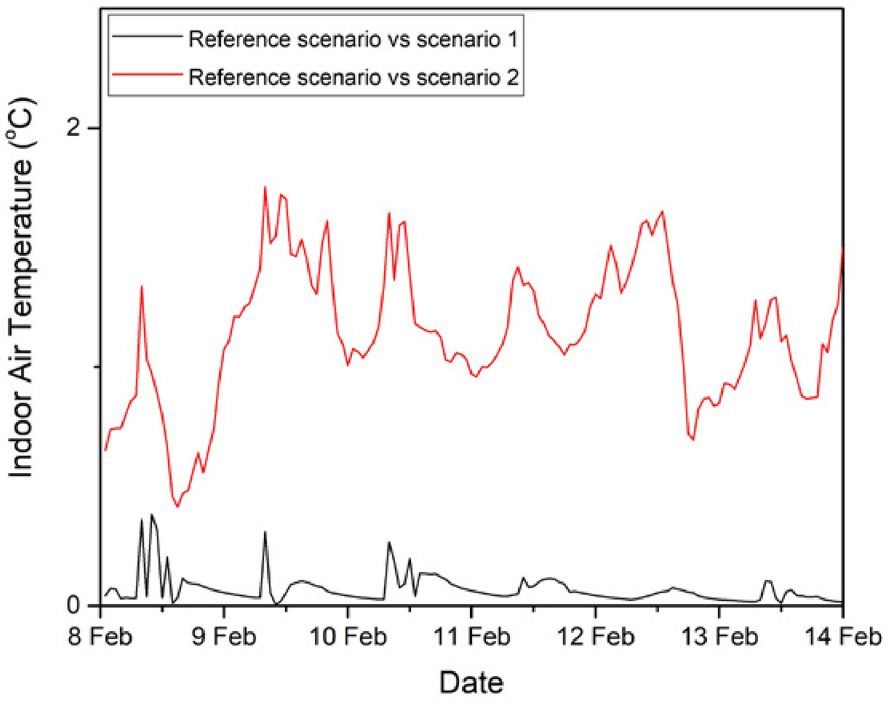

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free-floating conditions during a typical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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.4 °C in Frankston beach and Coldstream stations.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.8 °C and 1.7 °C in Frankston beach and Coldstream stations, respectively.

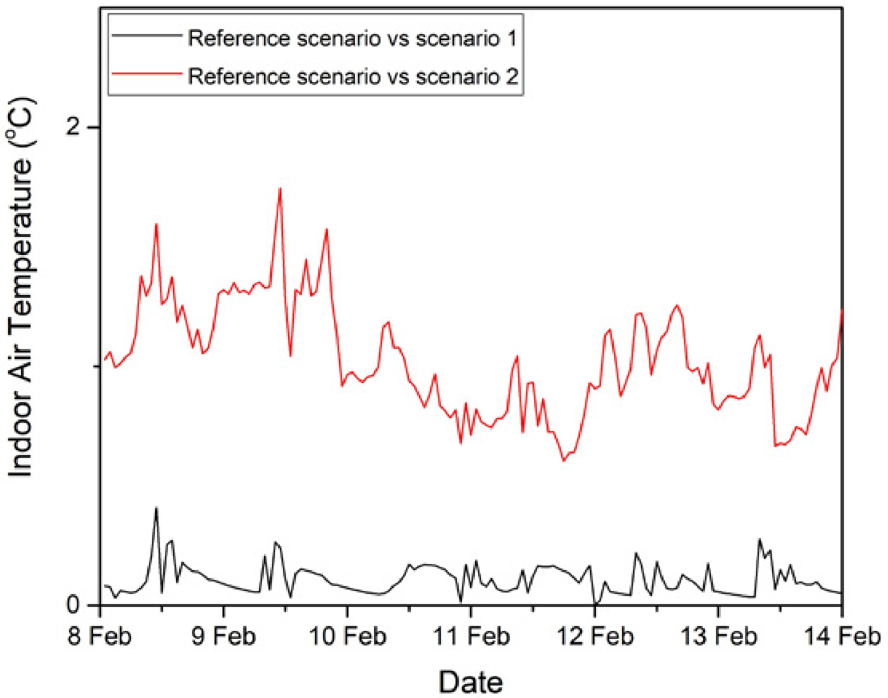

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new highrise shopping mall centre under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 14.3-26.2 °C in reference scenario to a range 14.3-26.1 °C in scenario 1 in Frankston beach station.

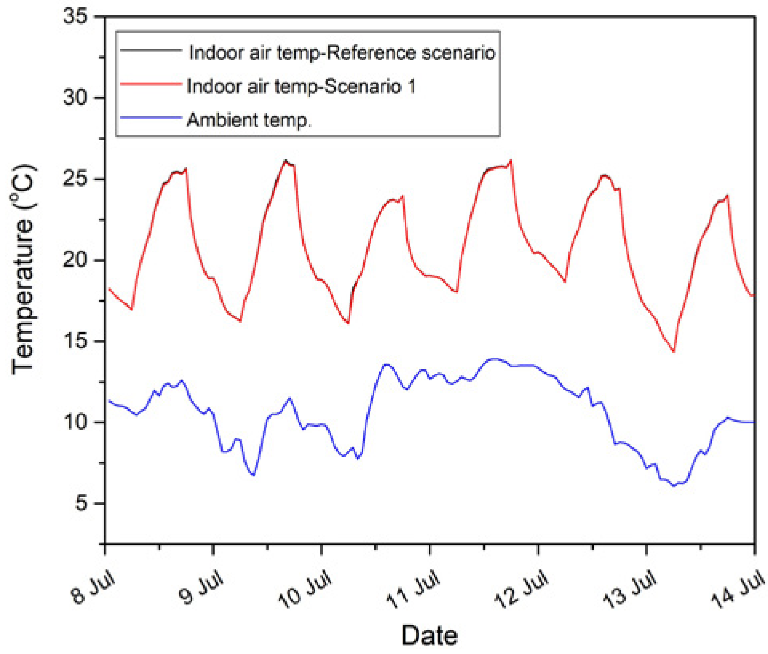

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Frankston beach station* using annual measured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

The indoor air temperature is predicted to reduce from a range 13.0-27.4 °C in reference scenario to a range 12.9-27.3 °C in scenario 1 in Coldstream station.

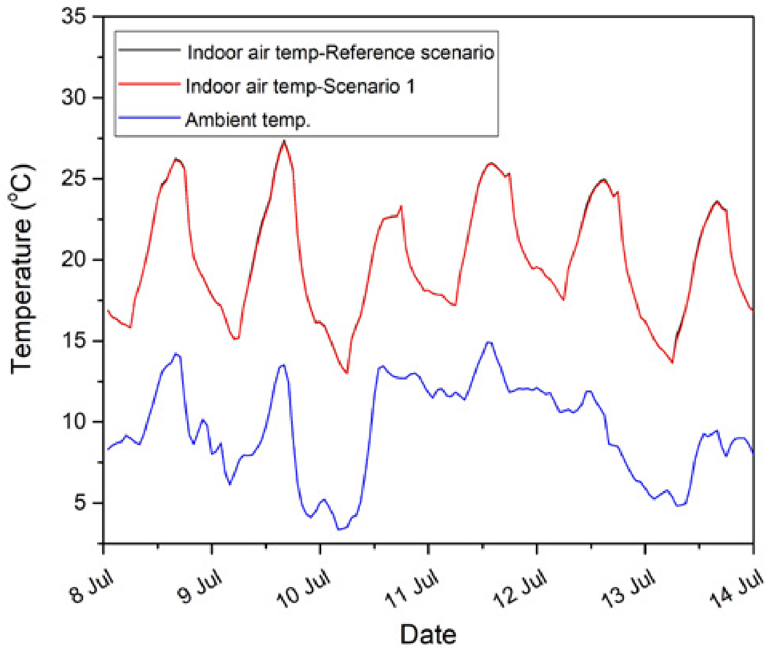

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Coldstream station* using annual measured 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 and 0.1 °C in Frankston beach and Coldstream stations, respectively.*

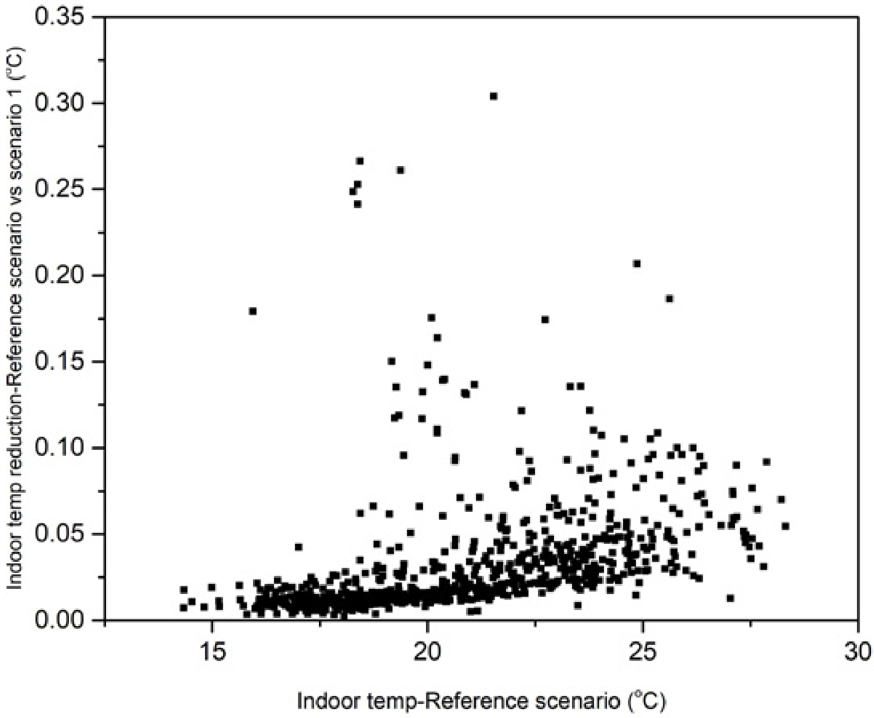

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

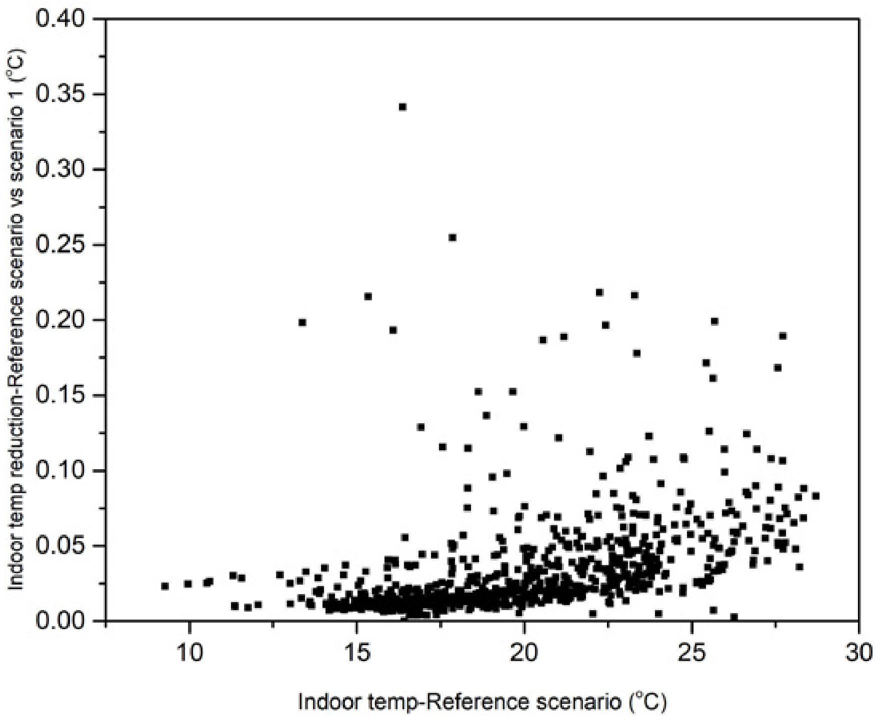

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 with 236 and 325 hours for both scenarios in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during remain the same in reference scenario compared to scenario 1 in Frankston beach and Coldstream 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
Frankston beach	26	236	26	236
Coldstream	63	325	64	326

** 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 460 hours in reference scenario to 404 hours under scenario 2 in Frankston beach station; and from 482 hours in reference scenario to 431 hours under scenario 2 in Coldstream 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
Frankston beach	460	459	404
Coldstream	482	482	431

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

Given the building's existing 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 07 is a new, high-rise commercial building, with a total air-conditioned area of 6.600 m^2 distributed on six levels. The 1.100 m^2 roof is insulated, resulting in low energy losses and, consequently, in a very limited energy saving potential, given also the small impact of the roof on the overall building's energy demand. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 07.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	253,4	313,1
Energy consumption after cool roof (MWh)	250,0	309,4
Energy savings (MWh)	3,4	3,7
Energy savings (%)	1,34%	1,18%
Area (m^2)	1.100	1.100
Roof costs - Metal roof (AU$/m^2)	38,0	38,0
Roof costs - Coating (AU$/m^2)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m^2)	15,0	15,0

Building 07 is a good example of a new, insulated, high-rise commercial building where, despite its rather limited energy conservation potential, the coating cool roof is a feasible investment, over the building's life cycle, due to the large impact of the roof on the building's cooling loads.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 1,34 % for the Frankston Beach weather conditions and of 1,18 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,2 % for the low energy price scenario for Frankston and 24,0 % for the high energy scenario for Coldstream conditions (Table 8).

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

Feasibility analysis results

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

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

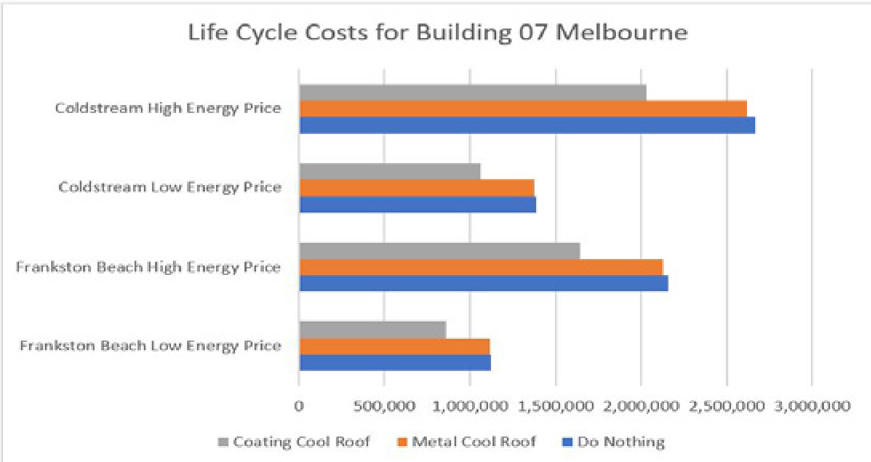

Figure 12. Life Cycle Costs for Building 07 for Frankston Beach and Coldstream stations.

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	0,30 %	1,60 %	0,65 %	1,71 %
Coating Cool Roof	23,23 %	23,93 %	23,38 %	23,95 %

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 Melbourne, 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 39.6-45.3 kWh/m^2 to 39.1-44.7 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5-0.6 kWh/m^2. This is equivalent to approximately 1.0-1.4 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 5.9-8.1 kWh/m^2. This is equivalent to 14.0-20.0 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (1.0-1.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.0-1.4 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.0 and 1.4 kWh/m^2 (~0.9-1.3 %) (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 22.0-41.6 ^oC and 20.9-45.2 ^oC in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.4 ^oC in Frankston beach and Coldstream stations. The indoor air temperature reduction is foreseen to increase further to 1.8 and 1.7 ^oC by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 14.3 and 26.2 ^oC in reference scenario to a range between 14.3 and 26.1 ^oC in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 13.0 and 27.4 °C in reference scenario to a range between 12.9 and 27.3 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 and 0.1 °C in Frankston beach and Coldstream 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 almost remain the same with 236 hours for both scenarios in Frankston beach station. The estimations for Coldstream stations also show the same number of hours below 19 °C with 325 for both scenarios. The results show no significant increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7am-6 pm) also remain the same between reference scenario and cool roof scenario (scenario 1) with 26 hours in Frankston beach station and 63 hours in Coldstream 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 460 hours under the reference scenario in Frankston beach station, which remains almost the same for the cool roof scenario (scenario 1: 459 hours) and decreases to 404 hours for the cool roof and modified urban temperature scenario (scenario 2). The simulations in Coldstream station also illustrate a similar reduction in number of hours above 26 °C from 482 hours in reference scenario to 431 hours in cool roof and modified urban temperature scenario (scenario 2) (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 the coating cool roof option. The latter leads to a significant reduction of life cycle costs over the building's life cycle, that varies between 23,2 % for the low energy price scenario for Frankston and 24,0 % for the high energy scenario for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost only marginally feasible. Building 07 is in that sense a good 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.

B07

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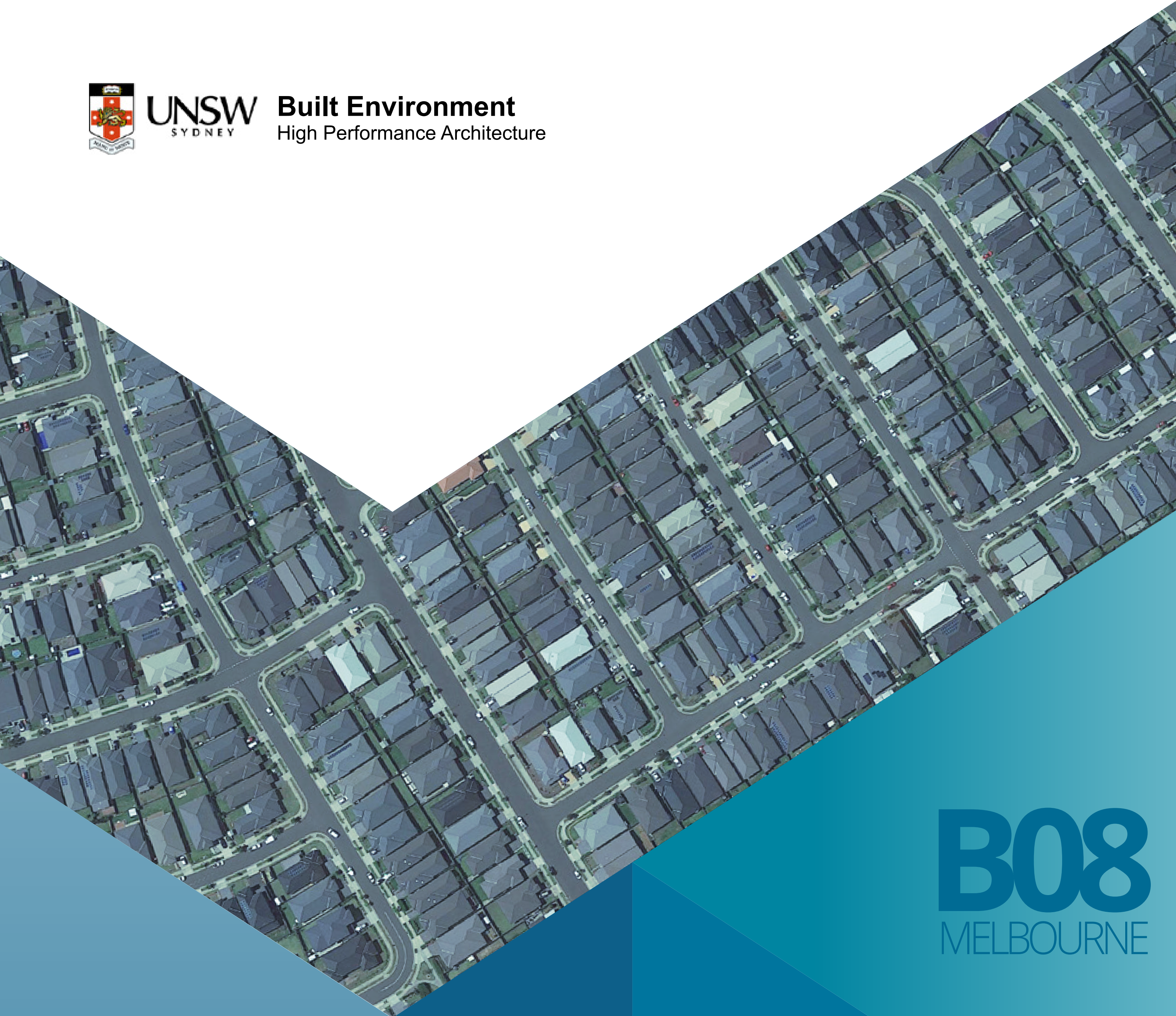

B08
MELBOURNE

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 Melbourne using weather data simulated by WRF.

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment building from 3.4-6.1 kWh/m² to 2.8-5.1 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	3.8	4.4	3.3	3.8	2.5	2.6
Coldstream	5.4	6.1	4.5	5.1	3.4	3.6
Essendon	4.6	5.3	4.0	4.6	2.8	2.9
Frankston beach	2.8	3.4	2.3	2.8	1.5	1.5
Melbourne airport	4.9	5.6	4.2	4.8	3.0	3.1
Moorabbin airport	3.1	3.7	2.5	3.0	1.7	1.8
Olympic park	3.8	4.4	3.2	3.8	2.4	2.6

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

For Scenario 1, the total cooling load saving is around 0.6-1.0 kWh/m² which is equivalent to 13.3-18.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 1.8-2.5 kWh/m² which is equivalent to 40.3-54.0 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	0.6	14.9	0.6	14.2	1.4	35.2	1.8	40.3
Coldstream	0.9	17.0	1.0	16.2	2.0	37.0	2.5	40.8
Essendon	0.7	14.3	0.7	13.6	1.9	40.4	2.4	45.6
Frankston beach	0.5	18.9	0.6	18.3	1.3	47.9	1.8	54.0
Melbourne airport	0.7	14.0	0.7	13.3	2.0	39.7	2.5	44.9
Moorabbin airport	0.5	17.8	0.6	17.2	1.4	46.0	1.9	52.3
Olympic park	0.6	15.9	0.7	15.1	1.4	36.2	1.9	42.0

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

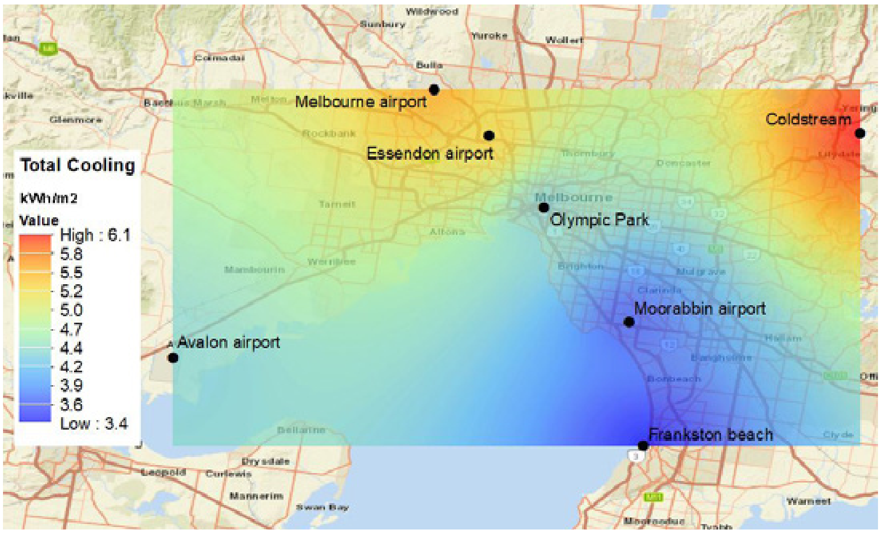

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

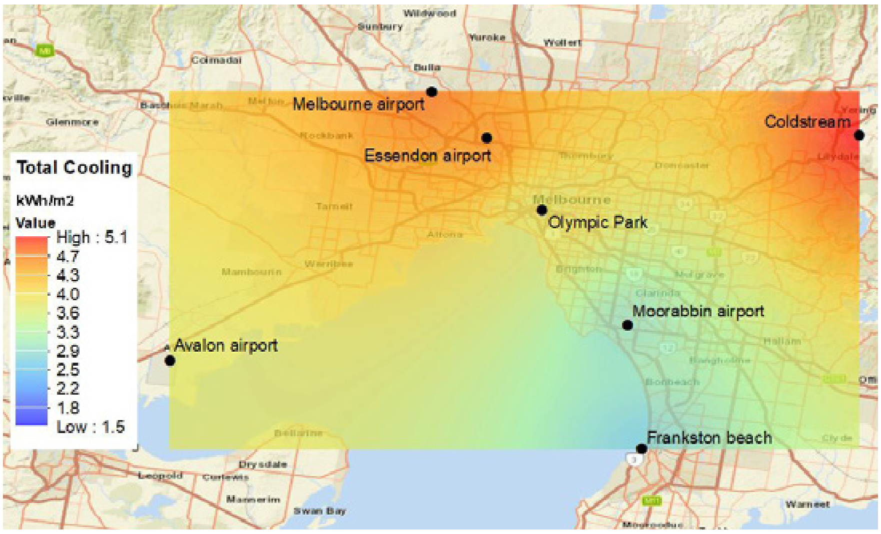

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

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

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Melbourne 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 (1.1-1.5 kWh/m²) is similar to the annual cooling load reduction (0.9-1.3 kWh/m²).

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.

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
Avalon airport	5.3	6.3	27.7	41.2	4.6	5.6	28.6	42.3
Coldstream	8.1	9.8	28.8	43.7	7.0	8.6	30.0	45.2
Essendon	7.6	8.9	26.0	38.6	6.8	7.9	26.8	39.7
Frankston beach	4.7	6.0	22.2	33.5	3.9	5.0	23.2	34.8
Melbourne airport	6.9	7.9	28.7	42.4	6.2	7.1	29.6	43.5
Moorabbin airport	6.6	8.1	23.5	35.1	5.8	7.1	24.3	36.2
Olympic park	8.0	9.8	20.3	30.7	6.9	8.5	21.2	31.9

The annual cooling load saving by building-scale application of cool roofs is around 10.8-13.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.3 and 0.1 kWh/m² (~ -0.7 to 0.2 %).

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

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	0.6	11.7	0.8	12.1	0.9	1.1	-0.3	-0.8	-0.3	-0.7
Coldstream	1.0	12.9	1.2	12.3	1.2	1.5	-0.1	-0.3	-0.3	-0.5
Essendon	0.8	10.9	1.0	11.0	0.8	1.1	0.0	-0.1	-0.1	-0.2
Frankston beach	0.8	16.9	1.0	16.7	1.0	1.3	-0.2	-0.7	-0.3	-0.9
Melbourne airport	0.7	10.8	0.9	10.8	0.9	1.1	-0.1	-0.4	-0.2	-0.5
Moorabbin airport	0.8	11.5	0.9	11.5	0.8	1.1	-0.1	-0.3	-0.2	-0.4
Olympic park	1.1	13.3	1.3	13.2	0.9	1.2	0.1	0.5	0.1	0.2

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

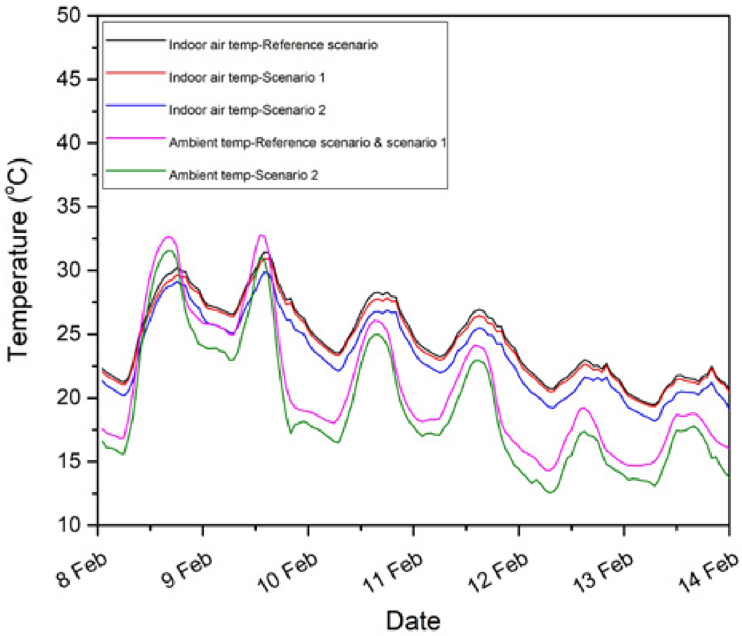

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

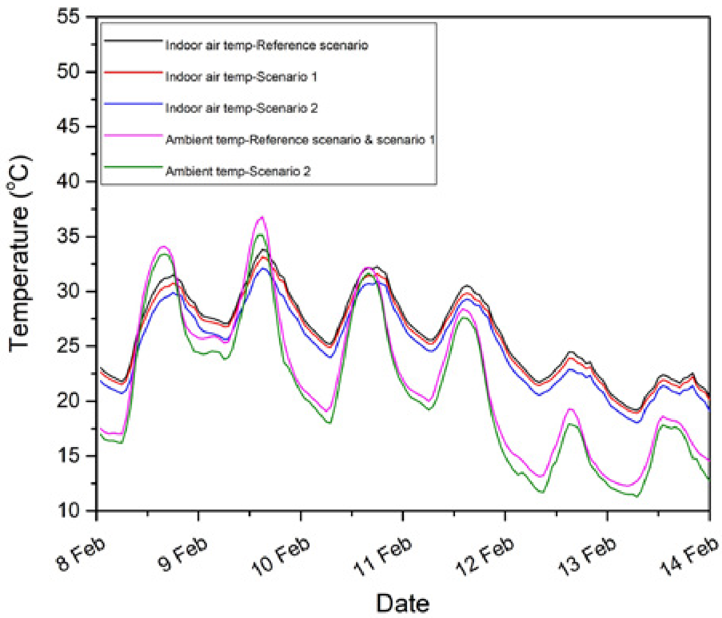

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.3-31.4 °C and 18.9-33.8 °C in Frankston beach and Coldstream stations, respectively.

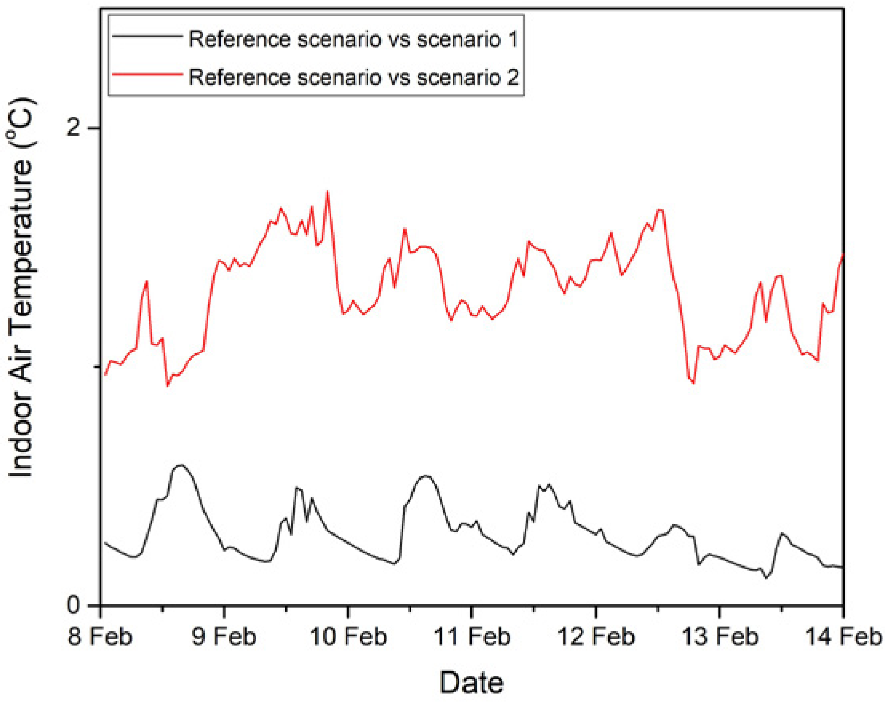

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical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

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

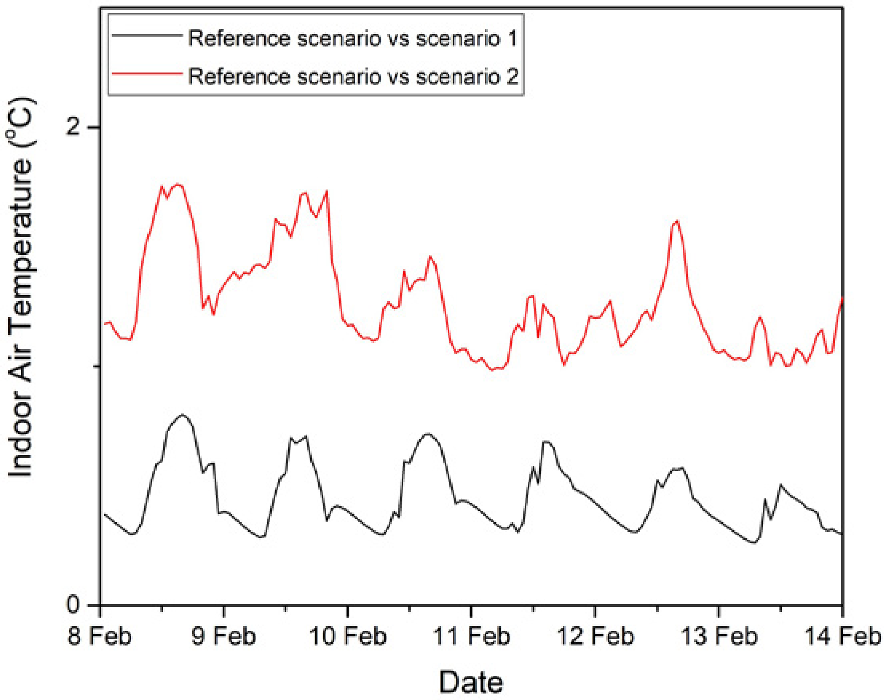

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.3-18.2 °C in reference scenario to a range 12.3-18.0 °C in scenario 1 in Frankston beach station.

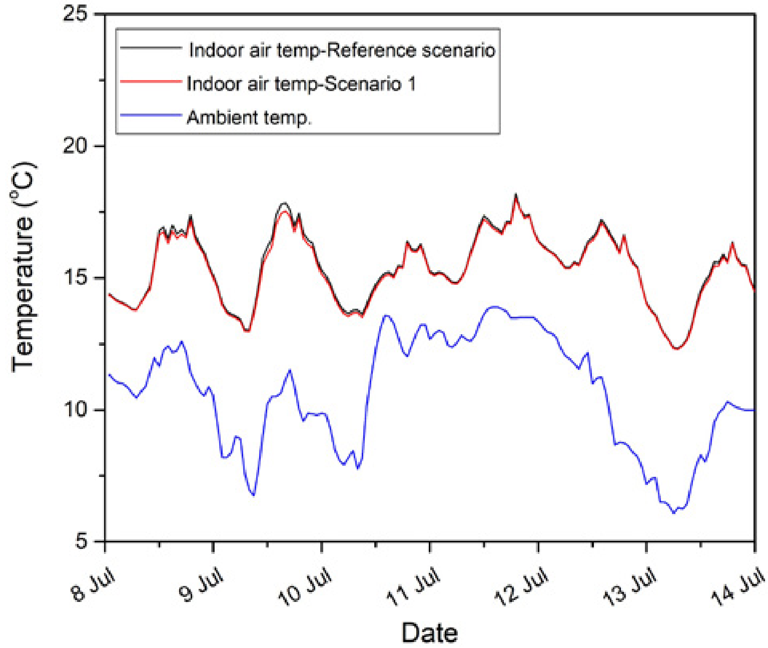

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Frankston beach station* using annual measured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

The indoor air temperature is predicted to reduce from a range 11.2-18.5 °C in reference scenario to a range 11.1-18.2 °C in scenario 1 in Coldstream station.

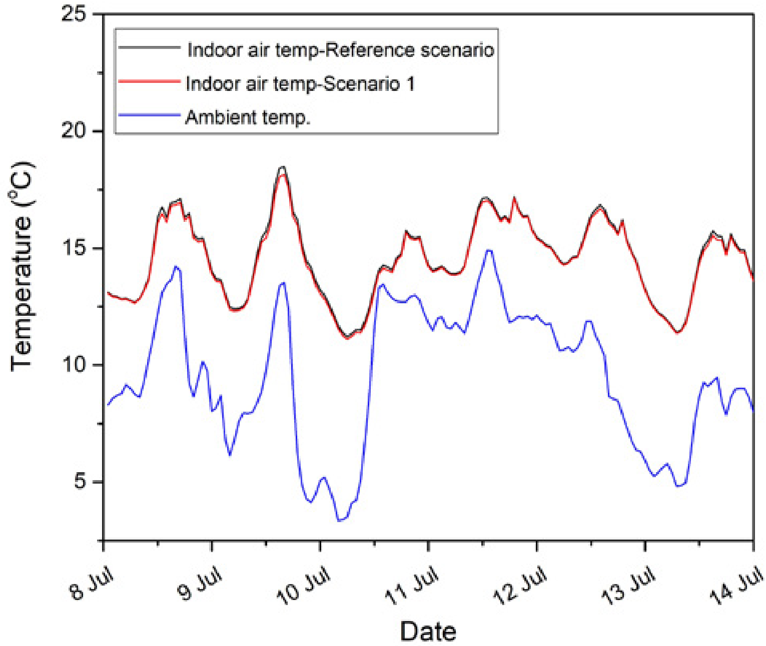

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Coldstream station* using annual measured weather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

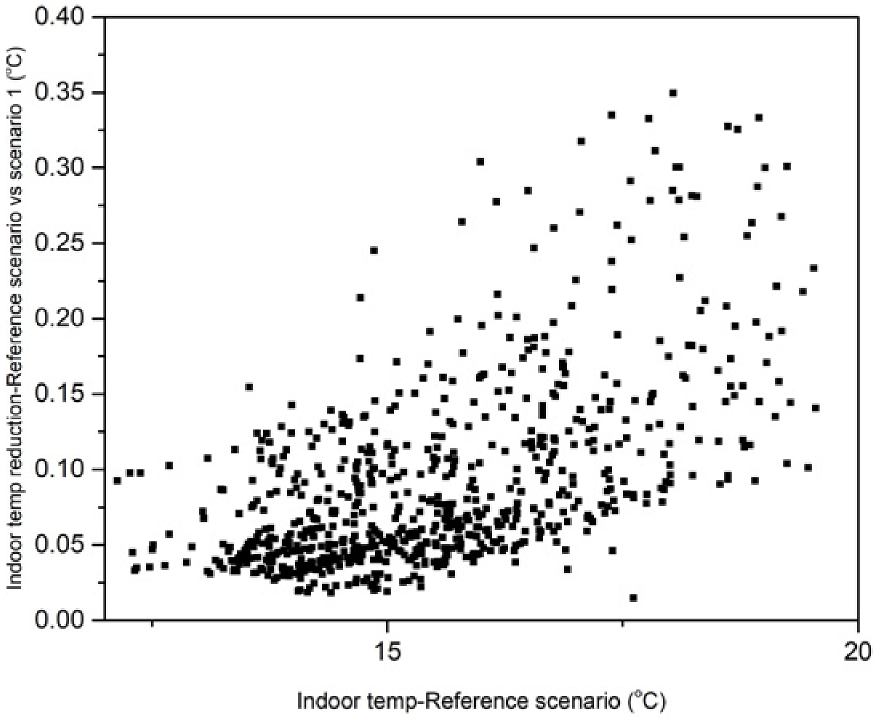

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

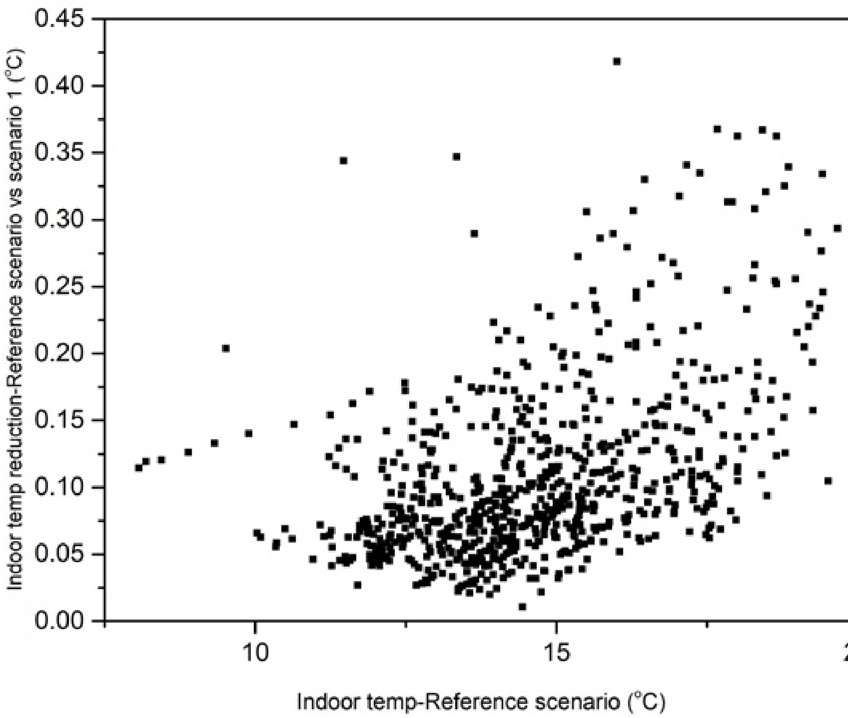

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 729 hours in reference scenario to 737 and hours and from 731 to 735 hours in scenario 1 in Frankston beach and Coldstream 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
Frankston beach	729	737
Coldstream	731	735

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 135 hours in reference scenario to 114 and 64 hours under scenario 1 and 2 in Frankston beach station; and from 212 hours in reference scenario to 191 and 138 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	135	114	64
Coldstream	212	191	138

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 m² distributed on three levels. The 624 m² roof is insulated, resulting in a fairly unique situation: When applying cool roof techniques, the overall energy savings are, albeit to a very small degree, negative, since there is an increase in heating requirements, that is in absolute terms higher than the reduction in cooling loads. However, due to the different efficiencies of the HVAC equipment for heating and cooling and due to the need to perform a mid-life refurbishment of the existing roof after 15 years, the overall economic outcome is positive for the lower cost cool coating roof. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 08.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	29,6	40,1
Energy consumption after cool roof (MWh)	29,8	40,3
Energy savings (MWh)	-0,2	-0,2
Energy savings (%)	-0,68 %	-0,50 %
Area (m²)	624	624
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 08 is a very interesting example of a new, low-rise residential building, where the energy conservation potential is in practice indifferent. However, given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a meaningful investment.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in an energy requirements' increase of 0,68% for the Frankston Beach weather conditions and of 0,50% for the Coldstream conditions. Given the margin of error of simulations, in practice one can deduce that the energy requirements remain practically unaltered. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that vary between 16,4 % for the low energy price scenario for Frankston and 20,6 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

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

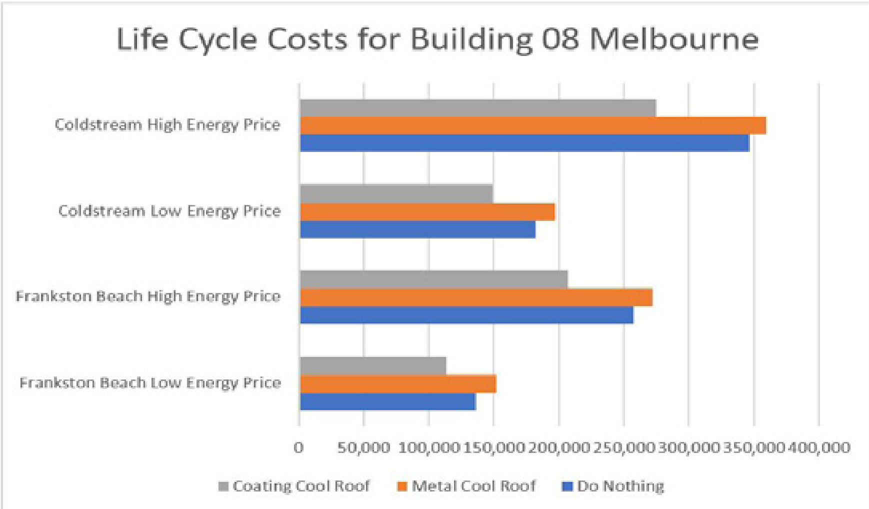

Figure 12. Life Cycle Costs for Building 08 for Frankston Beach and Coldstream stations.

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	-11,58 %	-5,66 %	-8,23 %	-3,77 %
Coating Cool Roof	16,37 %	19,55 %	18,21 %	20,60 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment from 3.4-6.1 kWh/m^2 to 2.8-5.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.6-1.0 kWh/m^2. This is equivalent to approximately 13.3-18.3 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 1.8-2.5 kWh/m^2. This is equivalent to 40.3-54.0 % 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 (1.1-1.5 kWh/m^2) is similar to 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 10.8-13.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.3 and 0.1 kWh/m^2 (~ -0.7 to 0.2 %) (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 19.3-31.4 ^{o}C and 18.9-33.8 ^{o}C in Frankston beach and Coldstream 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 0.8 ^{o}C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.7 and 1.9 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 12.3-18.2 ^{o}C in reference scenario to a range between 12.3-18.0 ^{o}C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.2-18.5 °C in reference scenario to a range between 11.1-18.2 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 Frankston beach and Coldstream 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 729 hours in reference scenario to 737 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slightly increase in total number of hours below 19 °C from 731 hours in reference scenario to 735 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 135 hours under the reference scenario in Frankston beach station, which decreases to 114 and 64 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 212 hours in reference scenario to 191 in reference with cool roof scenario (scenario 1) and 138 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 16,4% for the low energy price scenario for Frankston and 20,6% for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the indifferent energy savings, clearly not feasible. Building 08 is in that sense a very interesting example of a new, low-rise residential building, where the energy conservation potential is in practice indifferent. However, given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a meaningful investment.

B08

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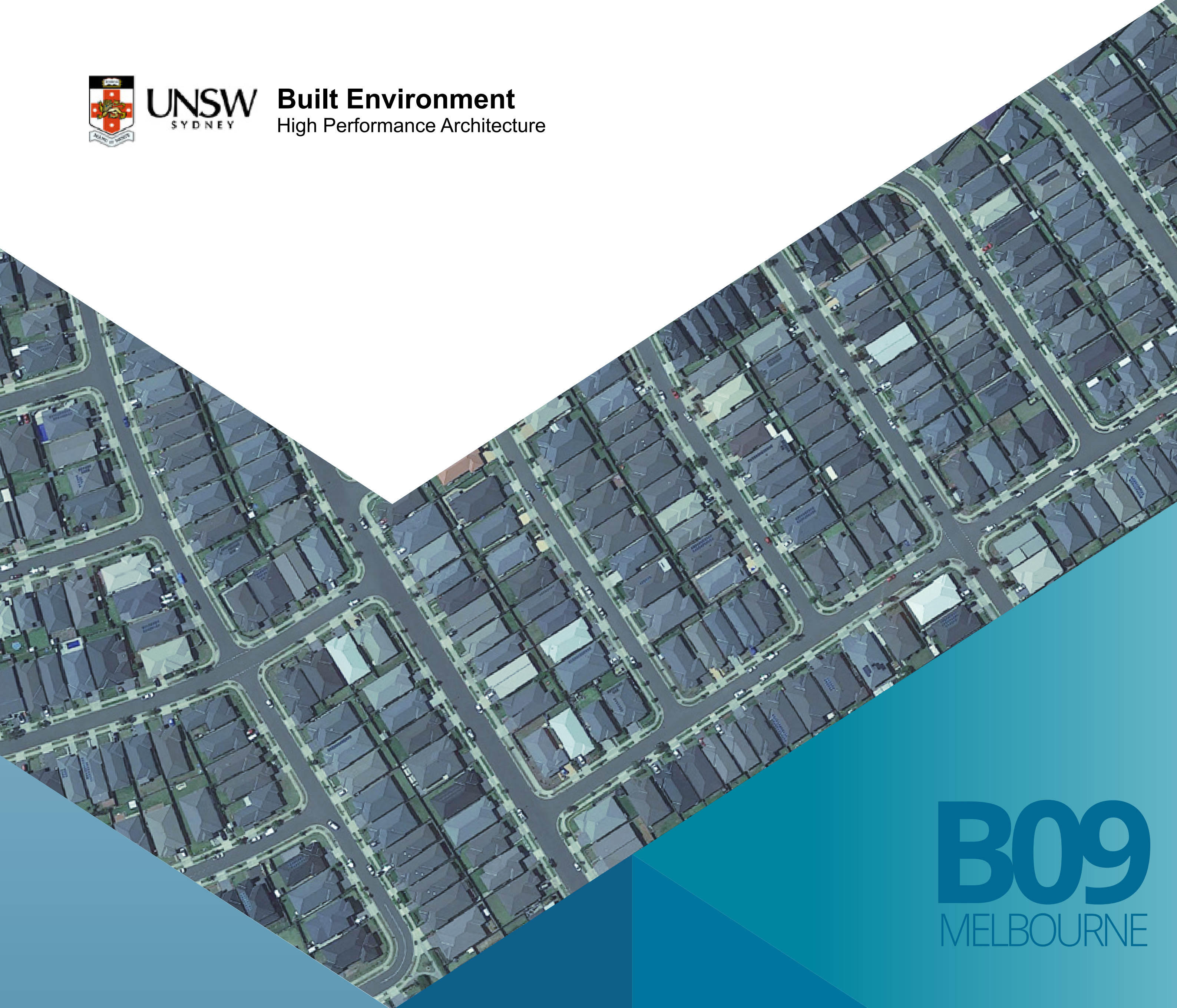

B09
MELBOURNE

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 Melbourne 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 apparment building from 3.1-5.7 kWh/m² to 2.7-5.1 kWh/m².

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

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)
Avalon airport	3.6	4.1	3.2	3.7	2.4	2.6
Coldstream	5.0	5.7	4.5	5.1	3.3	3.5
Essendon	4.3	4.9	3.9	4.5	2.7	2.8
Frankston beach	2.5	3.1	2.2	2.7	1.5	1.5
Melbourne airport	4.6	5.2	4.2	4.8	2.9	3.0
Moorabbin airport	2.8	3.4	2.5	3.0	1.6	1.7
Olympic park	3.5	4.1	3.1	3.7	2.4	2.5

For Scenario 1, the total cooling load saving is around 0.4-0.6 kWh/m² which is equivalent to 8.3-11.7 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 1.5-2.2 kWh/m² which is equivalent to 36.9-49.5 % total cooling load reduction.

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

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Avalon airport	0.3	9.4	0.4	8.9	1.1	31.2	1.5	36.9
Coldstream	0.5	11.0	0.6	10.4	1.7	33.3	2.1	37.6
Essendon	0.4	9.0	0.4	8.5	1.6	37.2	2.1	43.0
Frankston beach	0.3	12.2	0.4	11.7	1.1	42.4	1.5	49.5
Melbourne airport	0.4	8.7	0.4	8.3	1.7	36.6	2.2	42.4
Moorabbin airport	0.3	11.4	0.4	10.9	1.2	42.2	1.7	49.3
Olympic park	0.3	10.1	0.4	9.5	1.1	31.9	1.6	38.5

In the eleven weather stations in Melbourne, 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.

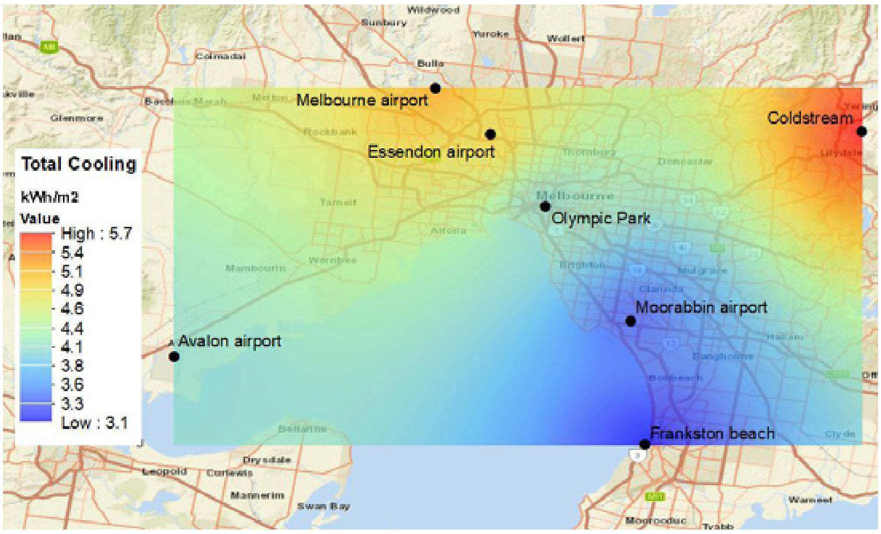

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

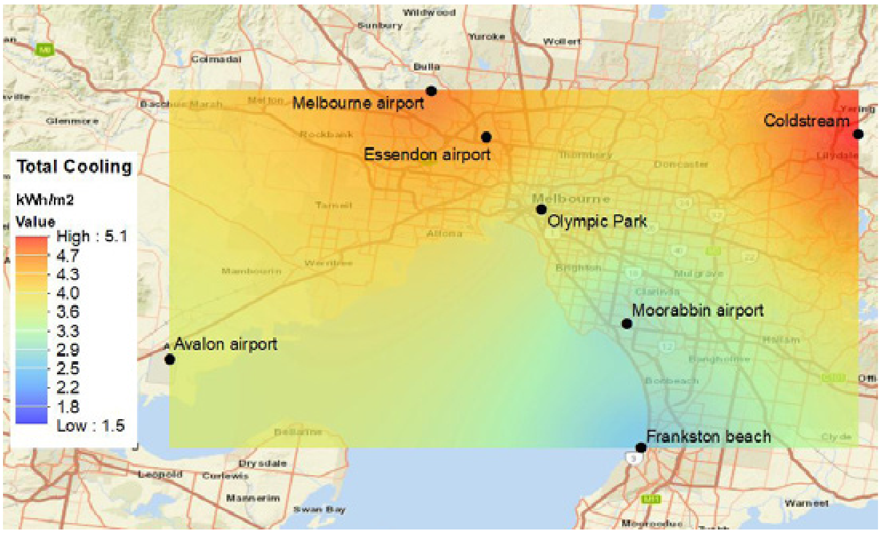

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

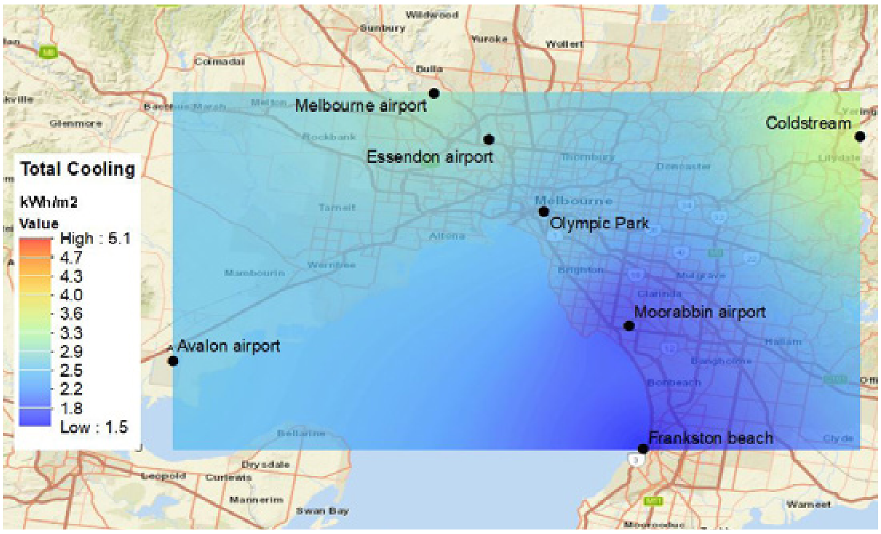

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Melbourne 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 (0.6-0.9 kWh/m²) is slightly lower than the annual cooling load reduction (0.6-1.2 kWh/m²).

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

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Avalon airport	4.9	5.9	26.9	40.4	4.4	5.3	27.4	41.0
Coldstream	7.5	9.1	27.9	42.7	6.7	8.3	28.6	43.6
Essendon	7.1	8.3	25.2	37.8	6.5	7.6	25.7	38.4
Frankston beach	4.3	5.5	21.4	32.7	3.8	4.9	21.9	33.4
Melbourne airport	6.9	7.9	28.0	41.7	5.9	6.8	28.5	42.3
Moorabbin airport	6.1	7.6	22.6	34.2	5.6	6.9	23.1	34.9
Olympic park	7.5	9.2	19.4	29.8	6.7	8.4	20.0	30.4

The annual cooling load saving by building-scale application of cool roofs is around 8.3-11.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.1 and 0.5 kWh/m² (~ -0.1 to 1.1 %).

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

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	0.5	9.6	0.6	9.8	0.5	0.6	0.0	-0.1	-0.1	-0.1
Coldstream	0.8	10.1	0.9	9.3	0.7	0.9	0.1	0.2	0.0	0.0
Essendon	0.6	8.5	0.7	8.3	0.5	0.6	0.1	0.4	0.1	0.2
Frankston beach	0.5	12.2	0.7	11.7	0.6	0.8	0.0	-0.1	-0.1	-0.3
Melbourne airport	1.0	14.9	1.2	14.5	0.5	0.6	0.5	1.6	0.5	1.1
Moorabbin airport	0.5	8.8	0.7	8.6	0.5	0.6	0.1	0.2	0.0	0.1
Olympic park	0.7	9.6	0.9	9.3	0.5	0.7	0.2	0.7	0.2	0.4

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

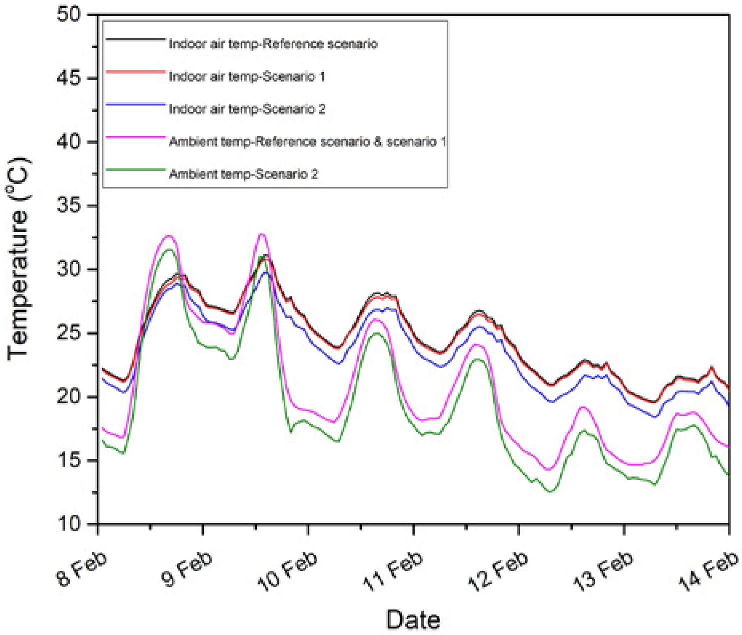

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

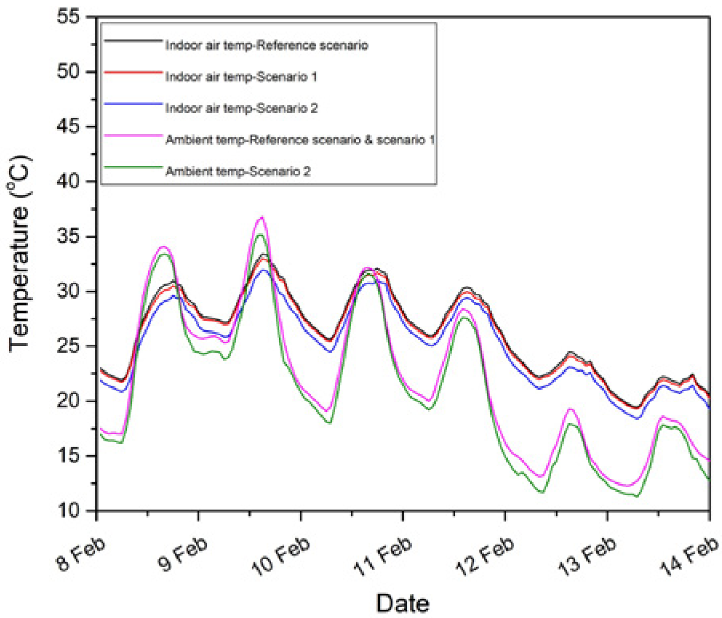

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.4-31.1 °C and 19.0-33.4 °C in Frankston beach and Coldstream stations, respectively.

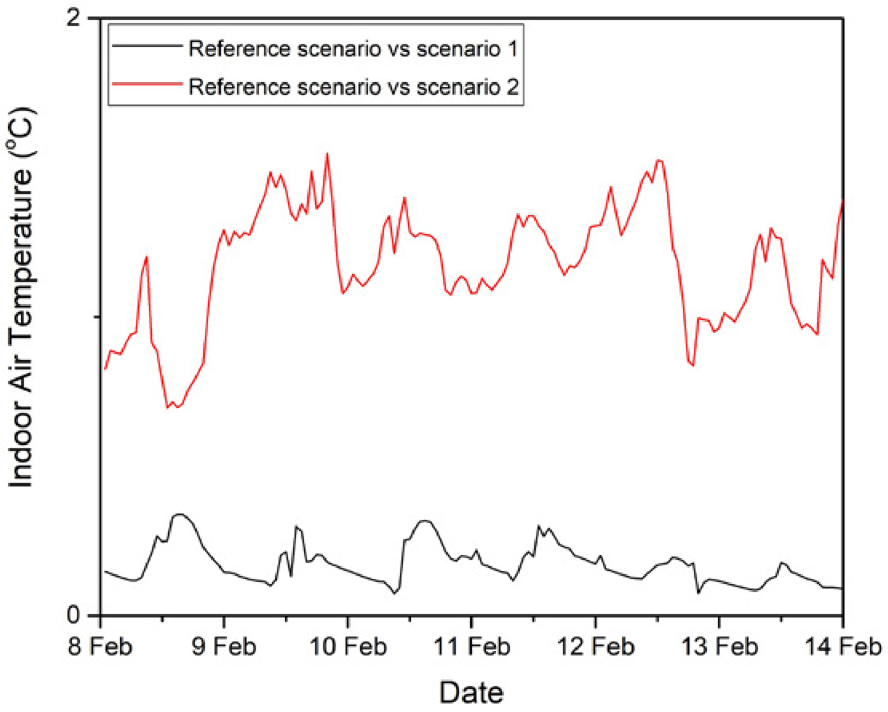

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical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

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.5 °C and 1.6 °C in Frankston beach and Coldstream stations, respectively.

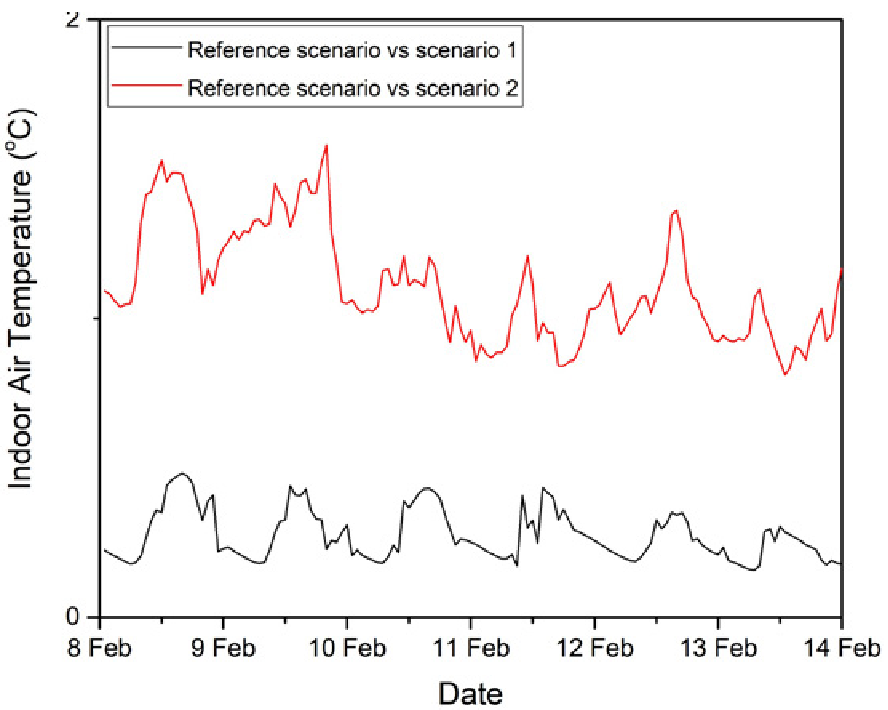

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 12.6-18.2 ºC in reference scenario to a range 12.5-18.0 ºC in scenario 1 in Frankston beach station.

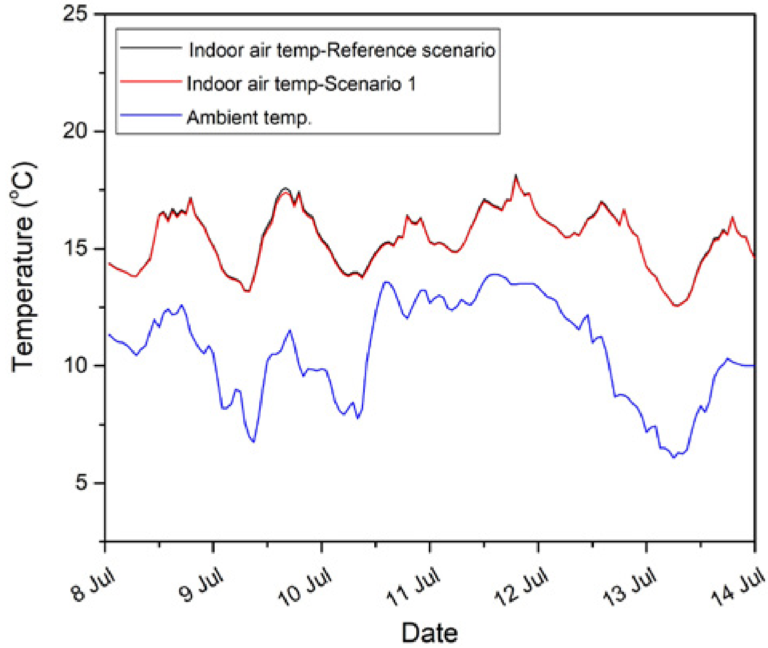

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Frankston beach station* using annual measured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

The indoor air temperature is predicted to reduce from a range 11.5-18.2 ºC in reference scenario to a range 11.4-18.0 ºC in scenario 1 in Coldstream station.

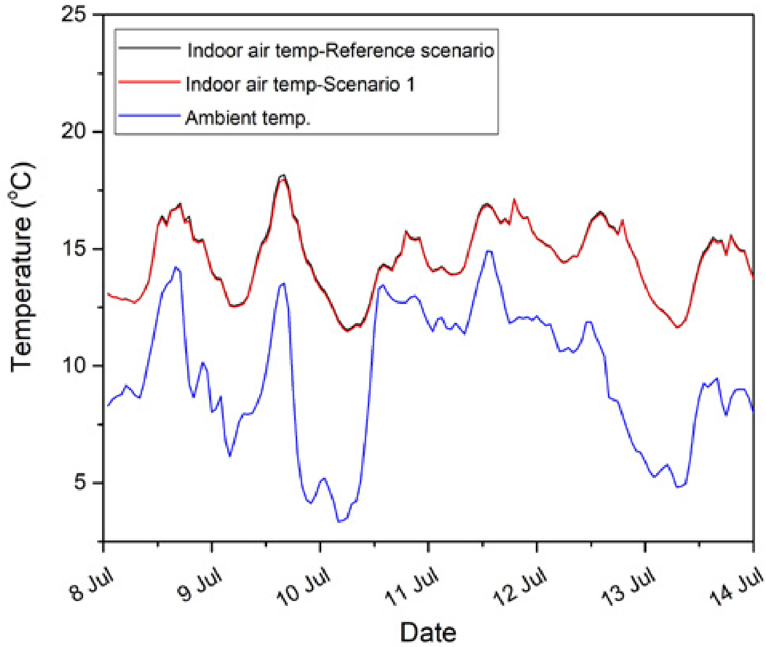

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Coldstream station* using annual measured weather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

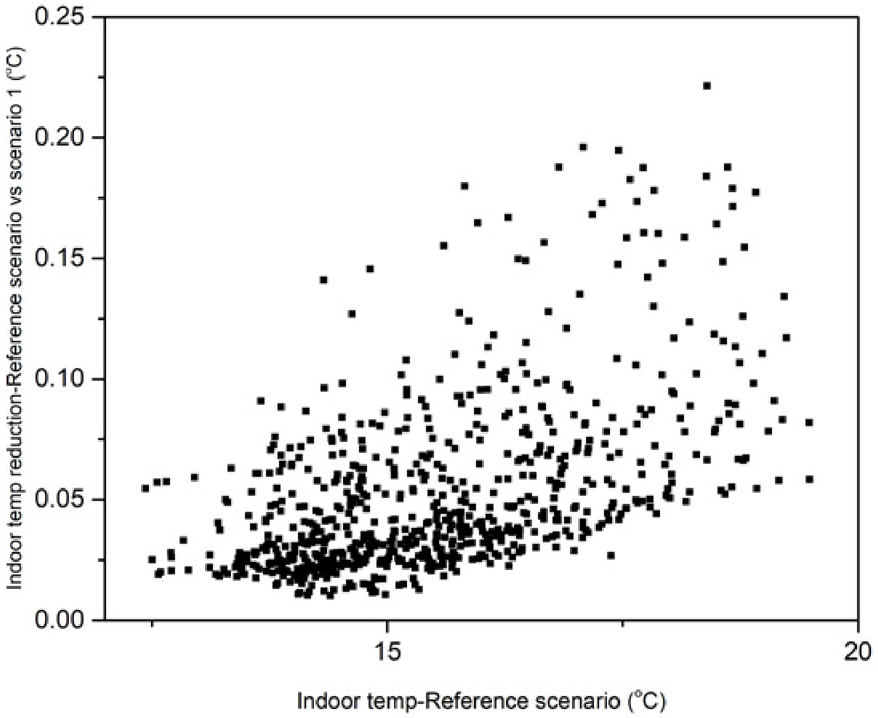

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

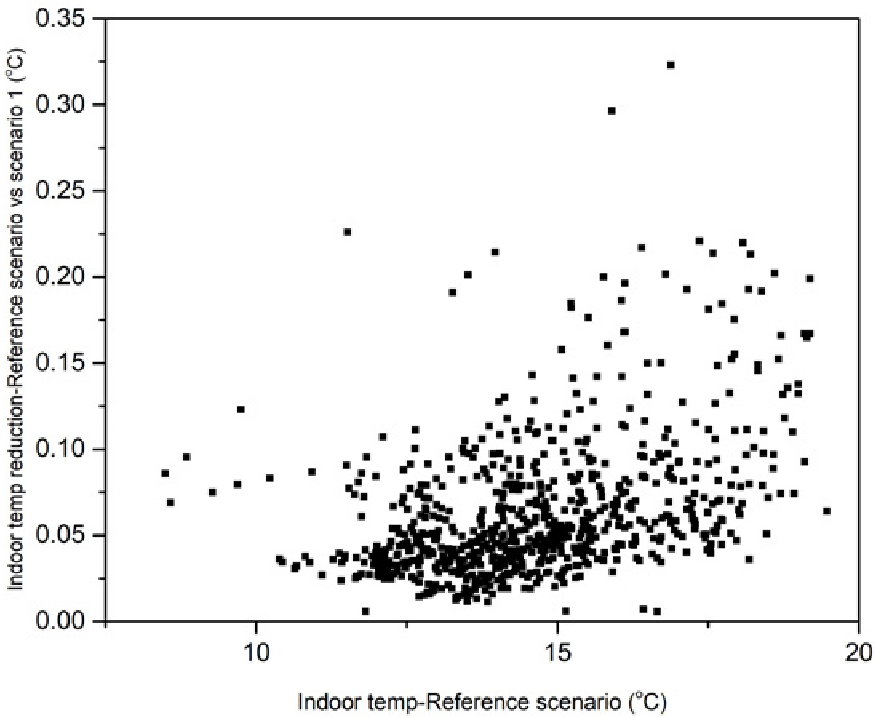

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 for the reference scenario and scenario 1 in Frankston beach station with 736-737; and to slightly increase from 738 hours to 741 hours in Coldstream 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
Frankston beach	736	737
Coldstream	738	741

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 125 hours in reference scenario to 108 and 64 hours under scenario 1 and 2 in Frankston beach station; and from 210 hours in reference scenario to 197 and 133 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	125	108	64
Coldstream	210	197	133

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 a quite unique situation: When applying cool roof techniques, the overall energy savings are, albeit to a very small degree, negative, since there is an increase in heating requirements, that is in absolute terms higher than the reduction in cooling loads. However, due to the different efficiencies of the HVAC equipment for heating and cooling and due to the need to perform a mid-life refurbishment of the existing roof after 15 years, the overall economic outcome is positive for the lower cost cool coating roof. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 09.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	47,7	64,6
Energy consumption after cool roof (MWh)	47,8	64,8
Energy savings (MWh)	-0,1	-0,2
Energy savings (%)	-0,21 %	-0,31 %
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 a very interesting example of a mid-rise residential building, where the energy conservation potential is in practice indifferent. However, given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a meaningful investment.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in an energy requirements' increase of 0,21 % for the Frankston Beach weather conditions and of 0,31 % for the Coldstream conditions. Given the margin of error of simulations, in practice one can deduce that the energy requirements remain practically unaltered. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that vary between 19,2 % for the low energy price scenario for Frankston and 21,7 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

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

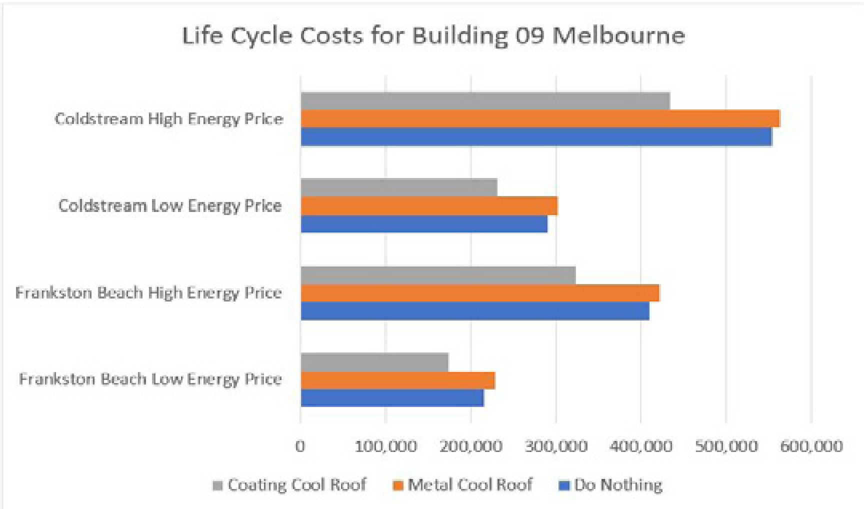

Figure 12. Life Cycle Costs for Building 09 for Frankston Beach and Coldstream stations.

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	-6,49 %	-2,71 %	-4,56 %	-1,74 %
Coating Cool Roof	19,21 %	21,24 %	20,23 %	21,74 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise apartment from 3.1-5.7 kWh/m^2 to 2.7-5.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.4-0.6 kWh/m^2. This is equivalent to approximately 8.3-11.7 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 1.5-2.2 kWh/m^2 . This is equivalent to 36.9-49.5 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.6-0.9 kWh/m^2) is slightly lower than the annual cooling load reduction (0.6-1.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 8.3-11.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.1 and 0.5 kWh/m^2 (~ -0.1 to 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 19.4-31.1 ^{o}C and 19.0-33.4 ^{o}C in Frankston beach and Coldstream 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 0.5 ^{o}C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.5 and 1.6 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 112.6-18.2 ^{o}C in reference scenario to a range between 12.5-18.0 ^{o}C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.5-18.2 °C in reference scenario to a range between 11.4-18.0 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 for Frankston beach and Coldstream 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 remain the same for both the reference scenario and reference with cool roof scenario (scenario 1) with 736-737 in Frankston beach station. The estimations for Coldstream stations also show a slightly increase in total number of hours below 19 °C from 738 hours in reference scenario to 741 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 125 hours under the reference scenario in Frankston beach station, which decreases to 108 and 64 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 210 hours in reference scenario to 197 in reference with cool roof scenario (scenario 1) and 133 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 19,2 % for the low energy price scenario for Frankston and 21,7 % for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the indifferent energy savings, clearly not feasible. Building 09 is in that sense a very interesting example of a mid-rise residential building, where the energy conservation potential is in practice indifferent. However, given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a meaningful investment.

B09

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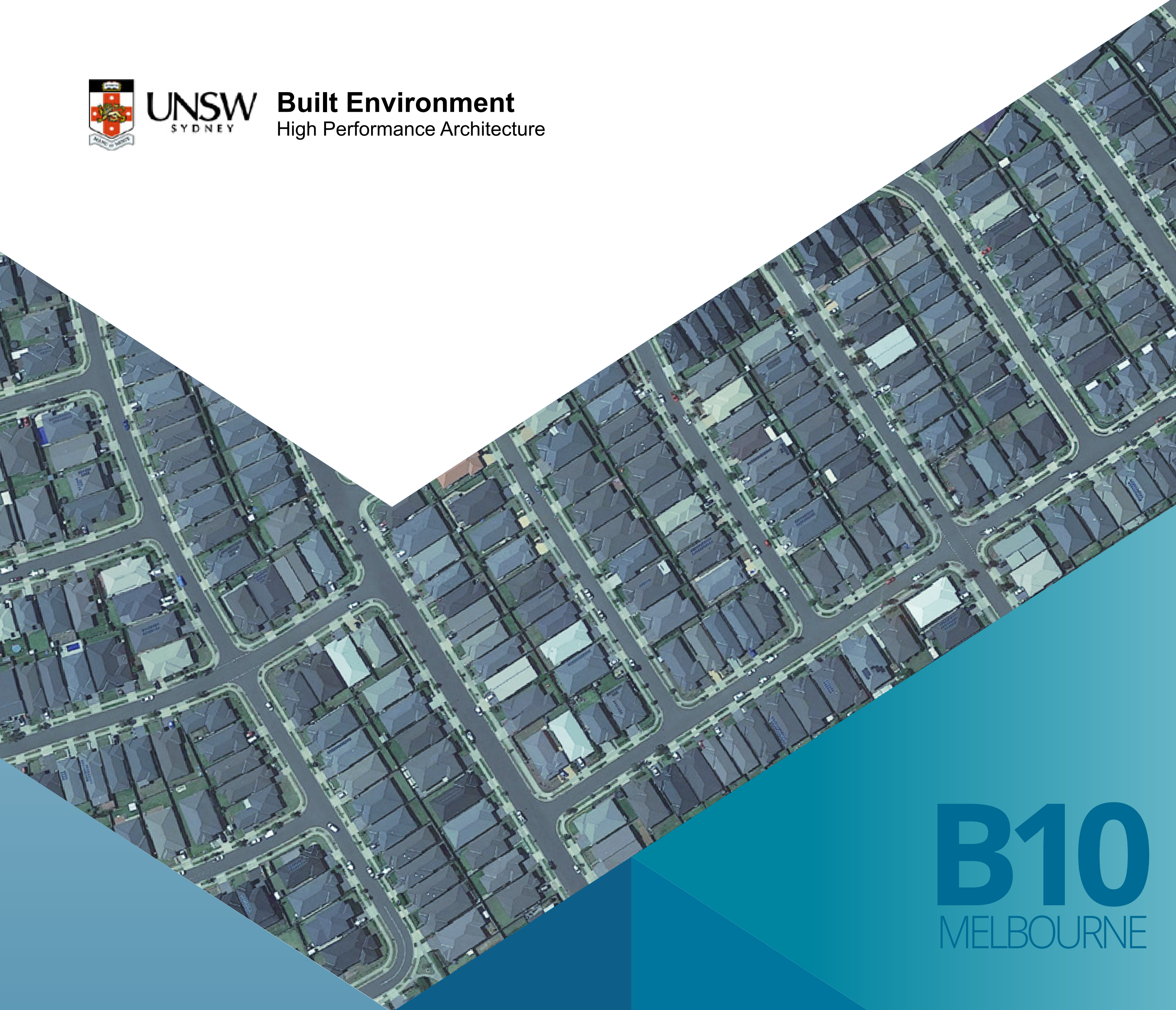

B10
MELBOURNE

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

1

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment building from 2.9-5.4 kWh/m² to 2.7-5.1 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/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)
Avalon airport	3.4	3.9	3.2	3.7	2.4	2.5
Coldstream	4.8	5.4	4.4	5.1	3.3	3.5
Essendon	4.1	4.7	3.9	4.5	2.6	2.8
Frankston beach	2.3	2.9	2.2	2.7	1.4	1.5
Melbourne airport	4.4	5.0	4.1	4.7	2.8	3.0
Moorabbin airport	2.6	3.2	2.4	2.9	1.6	1.7
Olympic park	3.3	3.9	3.1	3.6	2.3	2.5

For Scenario 1, the total cooling load saving is around 0.2-0.4 kWh/m² which is equivalent to 5.2-7.4 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 1.4-2.0 kWh/m² which is equivalent to 34.8-47.3 % total cooling load reduction.

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.

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	%
Avalon airport	0.2	5.8	0.2	5.5	1.0	28.6	1.4	34.8
Coldstream	0.3	7.1	0.4	6.7	1.5	31.0	1.9	35.6
Essendon	0.2	5.6	0.3	5.3	1.4	35.2	1.9	41.4
Frankston beach	0.2	7.7	0.2	7.4	0.9	39.6	1.4	47.3
Melbourne airport	0.2	5.5	0.3	5.2	1.5	34.7	2.0	40.8
Moorabbin airport	0.2	7.2	0.2	6.9	1.0	39.7	1.5	47.3
Olympic park	0.2	6.3	0.2	5.9	0.9	29.1	1.4	36.2

In the eleven weather stations in Melbourne, 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.

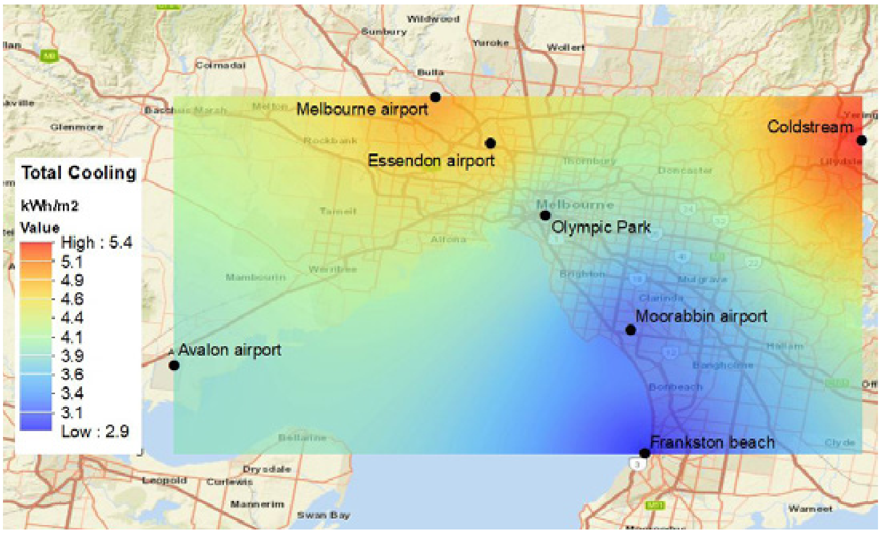

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

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

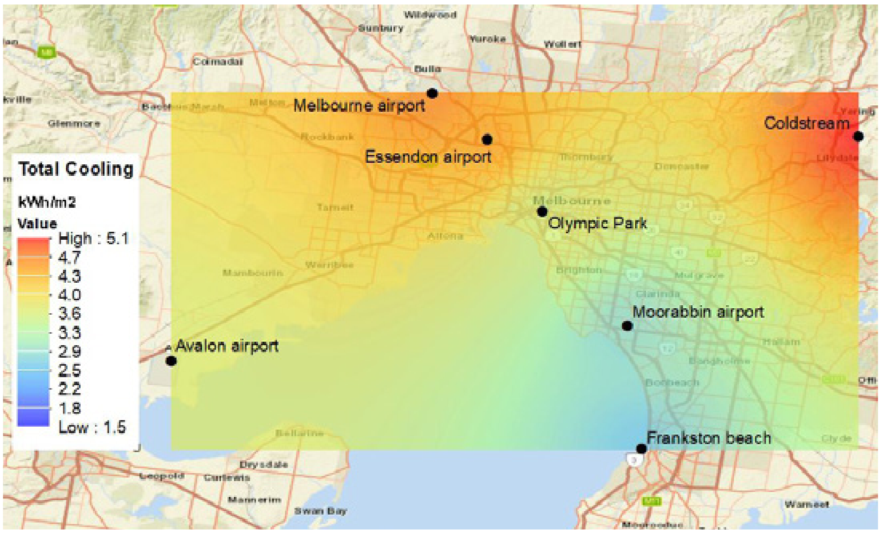

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

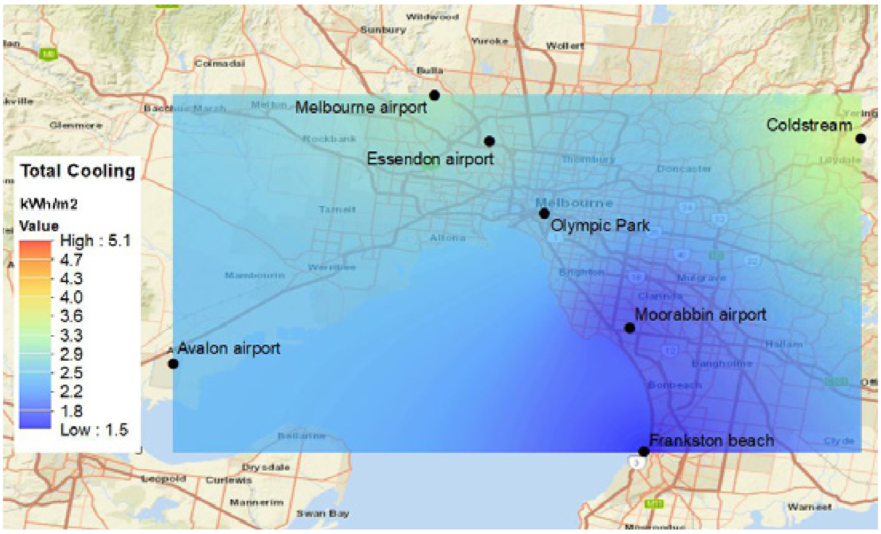

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Melbourne 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 (0.4-0.5 kWh/m²) is slightly lower than the annual cooling load reduction (0.2-0.6 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Avalon airport	4.6	5.5	26.7	40.2	4.4	5.3	27.1	40.6
Coldstream	7.1	8.7	27.6	42.4	6.7	8.3	28.0	42.9
Essendon	6.8	8.0	25.0	37.6	6.5	7.6	25.3	38.0
Frankston beach	4.0	5.2	21.1	32.5	3.8	4.9	21.5	33.0
Melbourne airport	6.5	7.4	27.8	41.5	5.9	6.8	28.1	41.9
Moorabbin airport	5.8	7.2	22.4	34.0	5.6	6.9	22.7	34.4
Olympic park	7.1	8.8	19.1	29.5	6.7	8.4	19.5	29.9

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 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 4.1-8.6 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.3 and 0.8 kWh/m² (~ -0.1-05 %).

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	%
Avalon airport	0.2	4.3	0.2	4.4	0.3	0.4	-0.1	-0.3	-0.1	-0.3
Coldstream	0.4	5.0	0.4	4.7	0.4	0.5	-0.1	-0.2	-0.1	-0.2
Essendon	0.3	4.0	0.3	4.1	0.3	0.4	0.0	-0.1	0.0	-0.1
Frankston beach	0.3	6.7	0.3	6.5	0.3	0.5	-0.1	-0.3	-0.1	-0.3
Melbourne airport	0.6	8.8	0.6	8.6	0.3	0.4	0.3	0.8	0.3	0.5
Moorabbin airport	0.2	4.2	0.3	4.2	0.3	0.4	0.0	-0.2	-0.1	-0.2
Olympic park	0.4	5.0	0.4	5.0	0.3	0.4	0.0	0.1	0.0	0.1

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

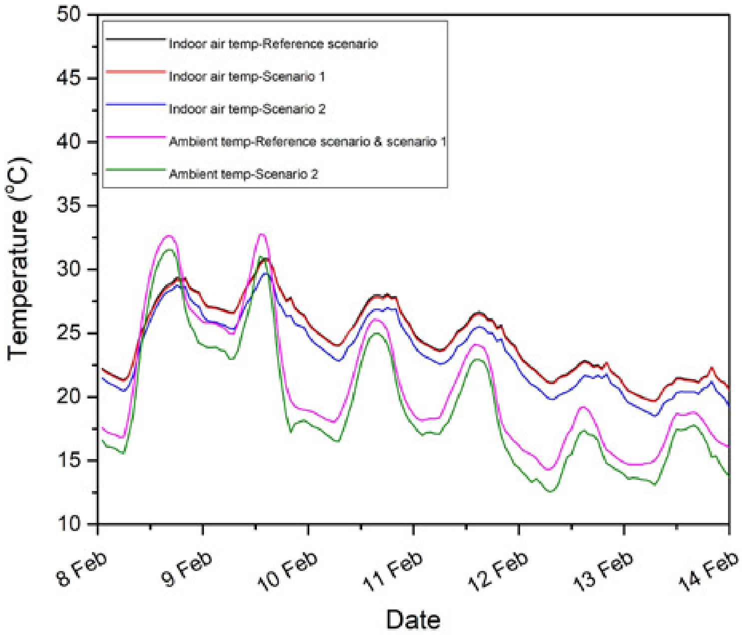

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

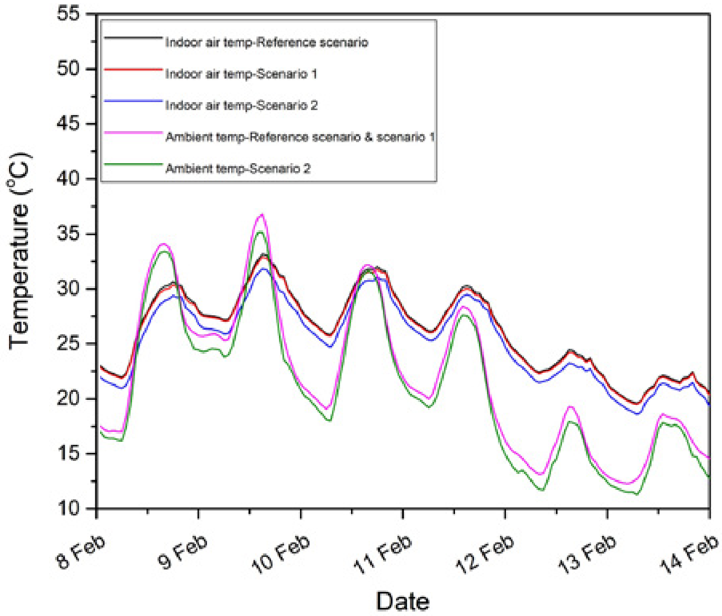

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.4-30.9 °C and 19.0-33.1 °C in Frankston beach and Coldstream stations, respectively.

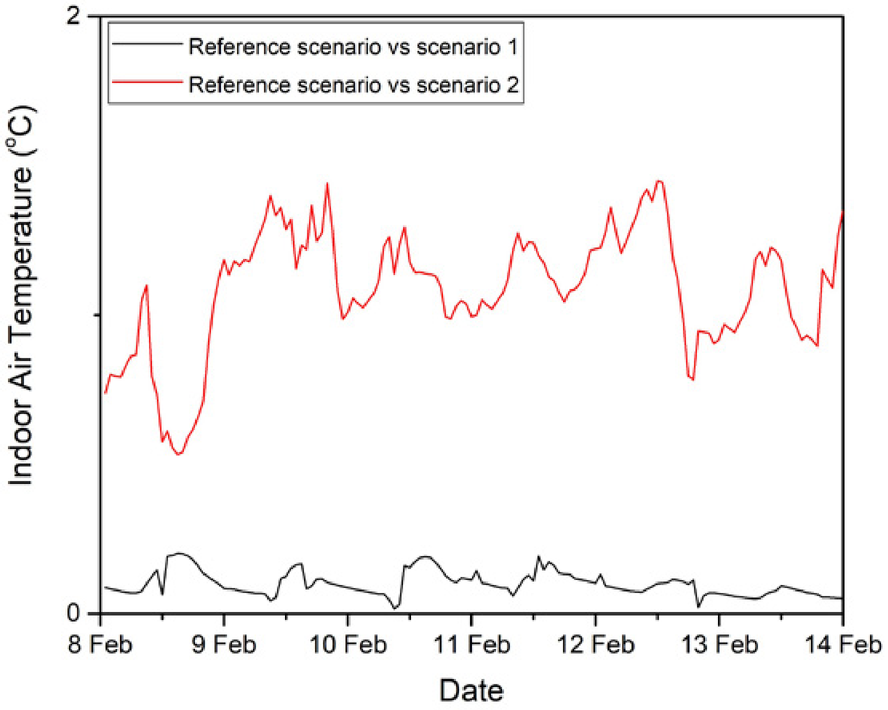

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical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

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

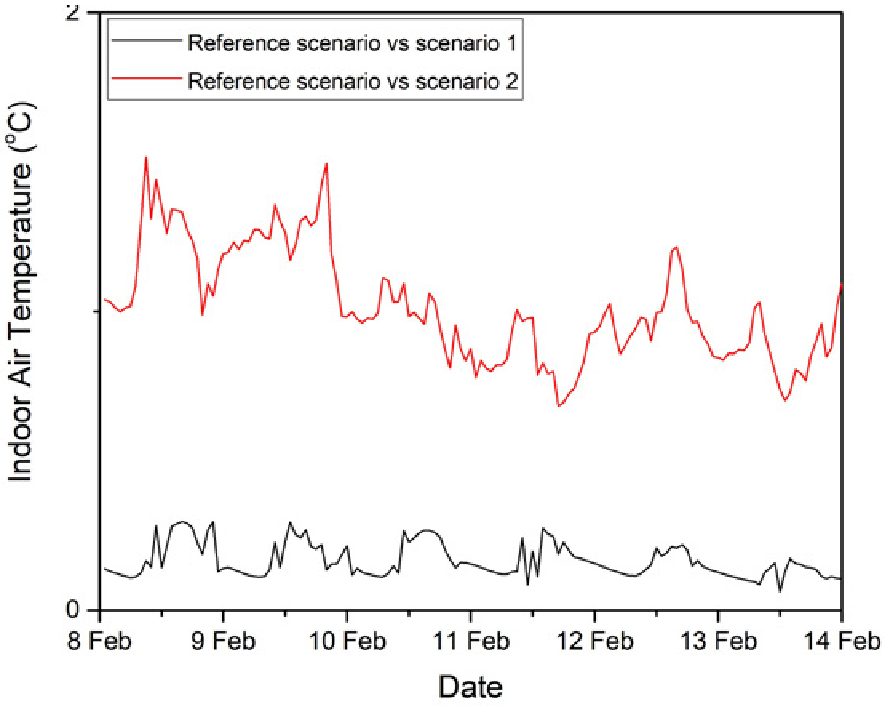

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.7-18.1 °C in reference scenario to a range 12.7-18.0 °C in scenario 1 in Frankston beach station.

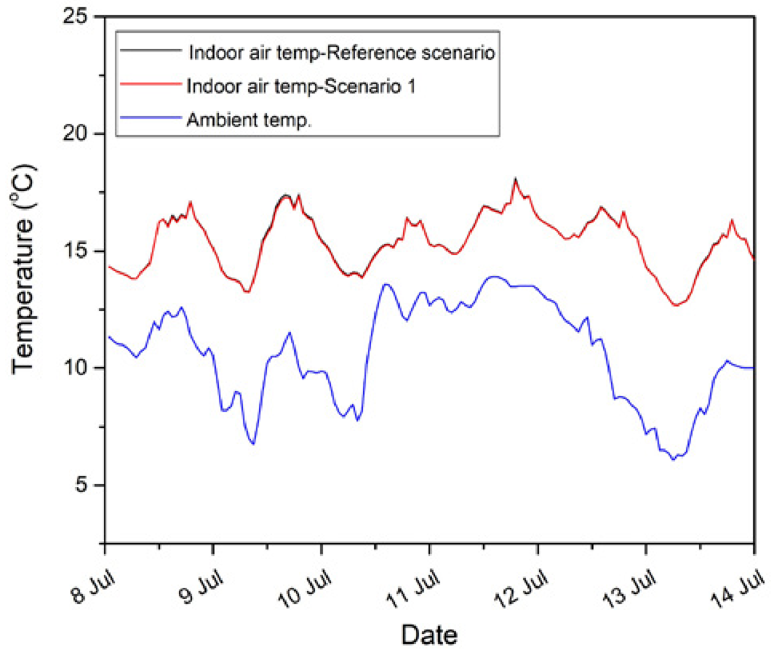

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Frankston beach station* using annual measured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

The indoor air temperature is predicted to reduce from a range 11.6-18.0 °C in reference scenario to a range 11.5-17.9 °C in scenario 1 in Coldstream station.

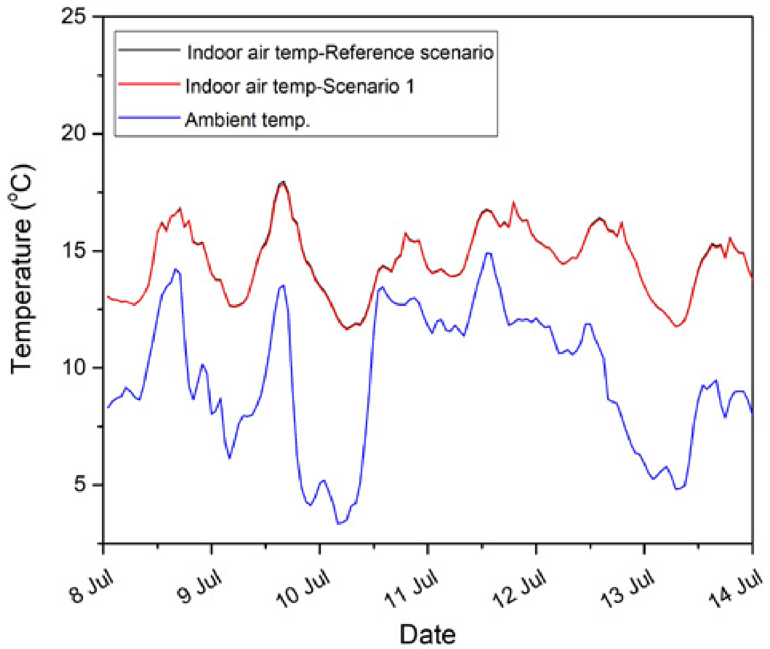

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Coldstream station* using annual measured weather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

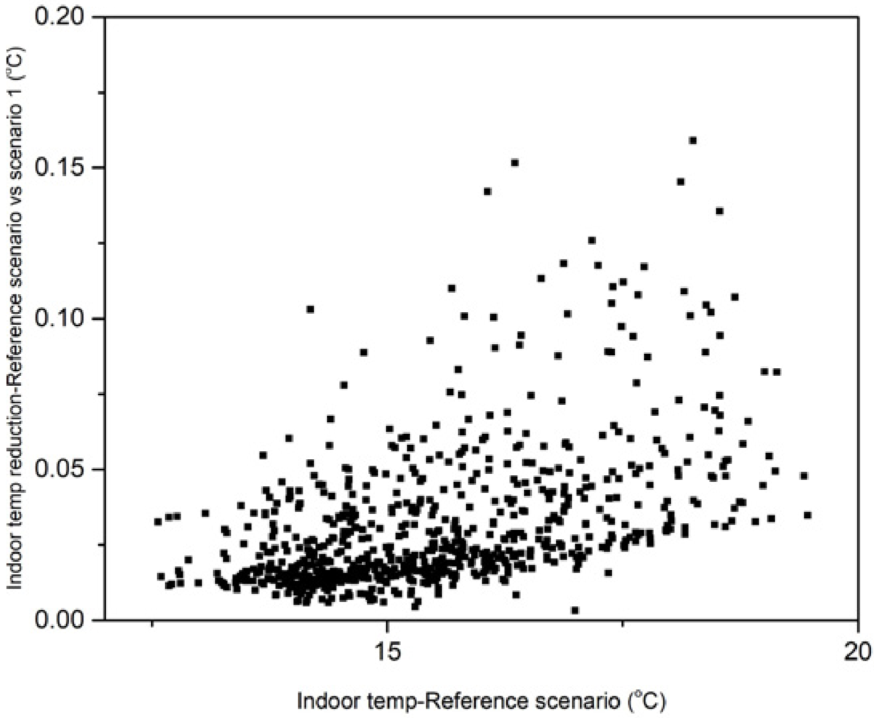

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

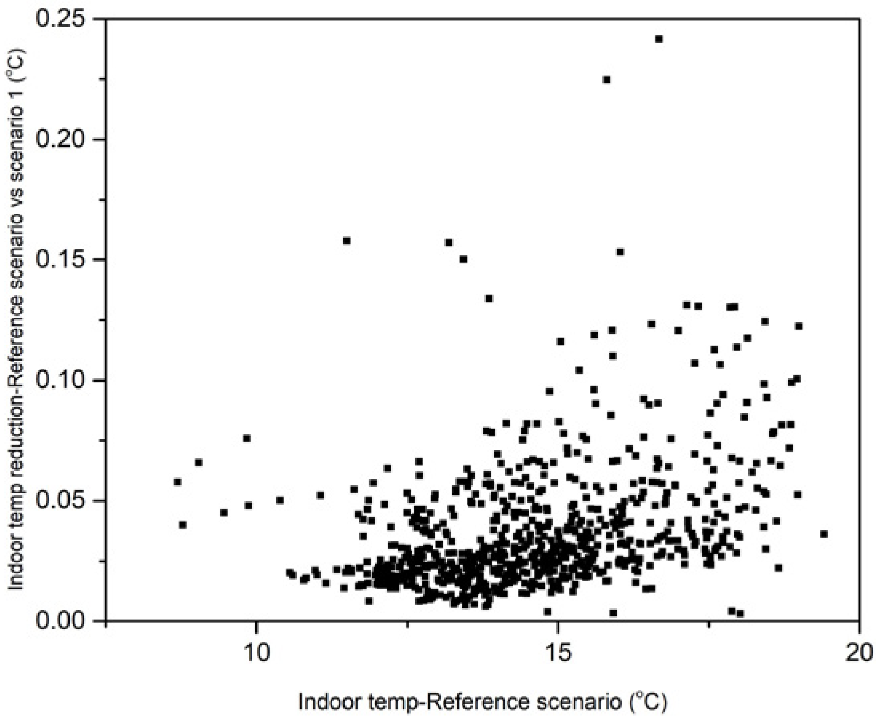

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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
Frankston beach	737	738
Coldstream	743	743

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 737 hours in reference scenario to 738 hours, and remains the same (743 hours) in scenario 1 in Frankston beach and Coldstream stations, respectively.

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

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Frankston beach	114	106	63
Coldstream	205	198	132

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to decrease from 114 hours in reference scenario to 106 and 63 hours under scenario 1 and 2 in Frankston beach station; and from 205 hours in reference scenario to 198 and 132 hours under scenario 1 and 2 in Coldstream station, respectively.

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 what is probably the most unsuitable condition for applying cool roof techniques: the roof is insulated, its impact on the whole building is limited, hence the overall energy savings are, albeit to a very small degree, negative, since there is an increase in heating requirements, that is in absolute terms higher than the reduction in cooling loads. However, due to the different efficiencies of the HVAC equipment for heating and cooling and due to the need to perform a mid-life refurbishment of the existing roof after 15 years, the overall economic outcome is positive for the lower cost cool coating roof. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 10.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	75,3	102,0
Energy consumption after cool roof (MWh)	75,7	102,2
Energy savings (MWh)	-0,4	-0,2
Energy savings (%)	-0,53 %	-0,20 %
Area (m^2)	624	624
Roof costs - Metal roof (AU$/$m^2$)	38,0	38,0
Roof costs - Coating (AU$/$m^2$)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/$m^2$)	15,0	15,0

Building 10 is a highly interesting example of a new, high-rise residential building, where the energy conservation potential is in practice indifferent. However, given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a very meaningful investment.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in an energy requirements' increase of 0,53% for the Frankston Beach weather conditions and of 0,20% for the Coldstream conditions. Given the margin of error of simulations, in practice one can deduce that the energy requirements remain practically unaltered. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

> *The coating cool roof option leads to a reduction of life cycle costs, that varies between 20,5% for the low energy price scenario for Frankston and 22,4 % for the high energy scenario and for Coldstream conditions (Table 8).*

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

Feasibility analysis results

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

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

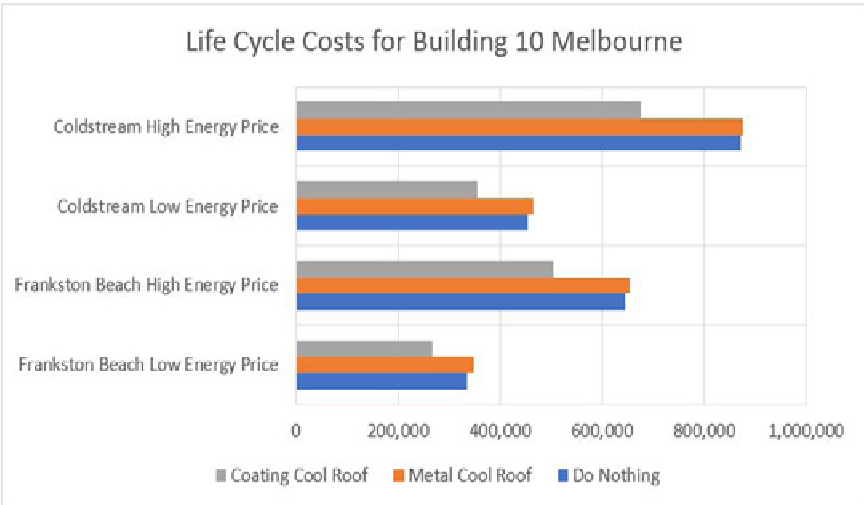

Figure 12. Life Cycle Costs for Building 10 for Frankston Beach and Coldstream stations.

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

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-3,95 %	-1,52 %	-2,31 %	-0,50 %
Coating Cool Roof	20,50 %	21,80 %	21,46 %	22,43 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 2.9-5.4 kWh/m^2 to 2.7-5.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.2-0.4 kWh/m^2. This is equivalent to approximately 5.2-7.4 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 1.4-2.0 kWh/m^2. This is equivalent to 34.8-47.3 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.4-0.5 kWh/m^2) is slightly lower than the annual cooling load reduction (0.2-0.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.1-8.6 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -0.3 and 0.8 kWh/m^2 (~ -0.1-05 %) (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 19.4-30.9 ^oC and 19.0-33.1 ^oC in Frankston beach and Coldstream 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 ^oC in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.5 and 1.5 ^oC by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 12.7-18.1 ^oC in reference scenario to a range between 12.7-18.0 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8). Similarly, the indoor air temperature is predicted to slightly reduce from a range between 11.6-18.0 °C in reference scenario to a range between 11.5-17.9 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 for Frankston beach and Coldstream 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 737 hours in reference scenario to 738 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations show that the total number of hours below 19 °C (743 hours) remain the same for the reference scenario and the 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 114 hours under the reference scenario in Frankston beach station, which decreases to 106 and 63 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 205 hours in reference scenario to 198 in reference with cool roof scenario (scenario 1) and 132 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 20,5% for the low energy price scenario for Frankston and 22,4% for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the indifferent energy savings, not feasible. Building 10 is in that sense a highly interesting example of a new, high-rise residential building, where the energy conservation potential is in practice indifferent. However, given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a very meaningful investment.

B10

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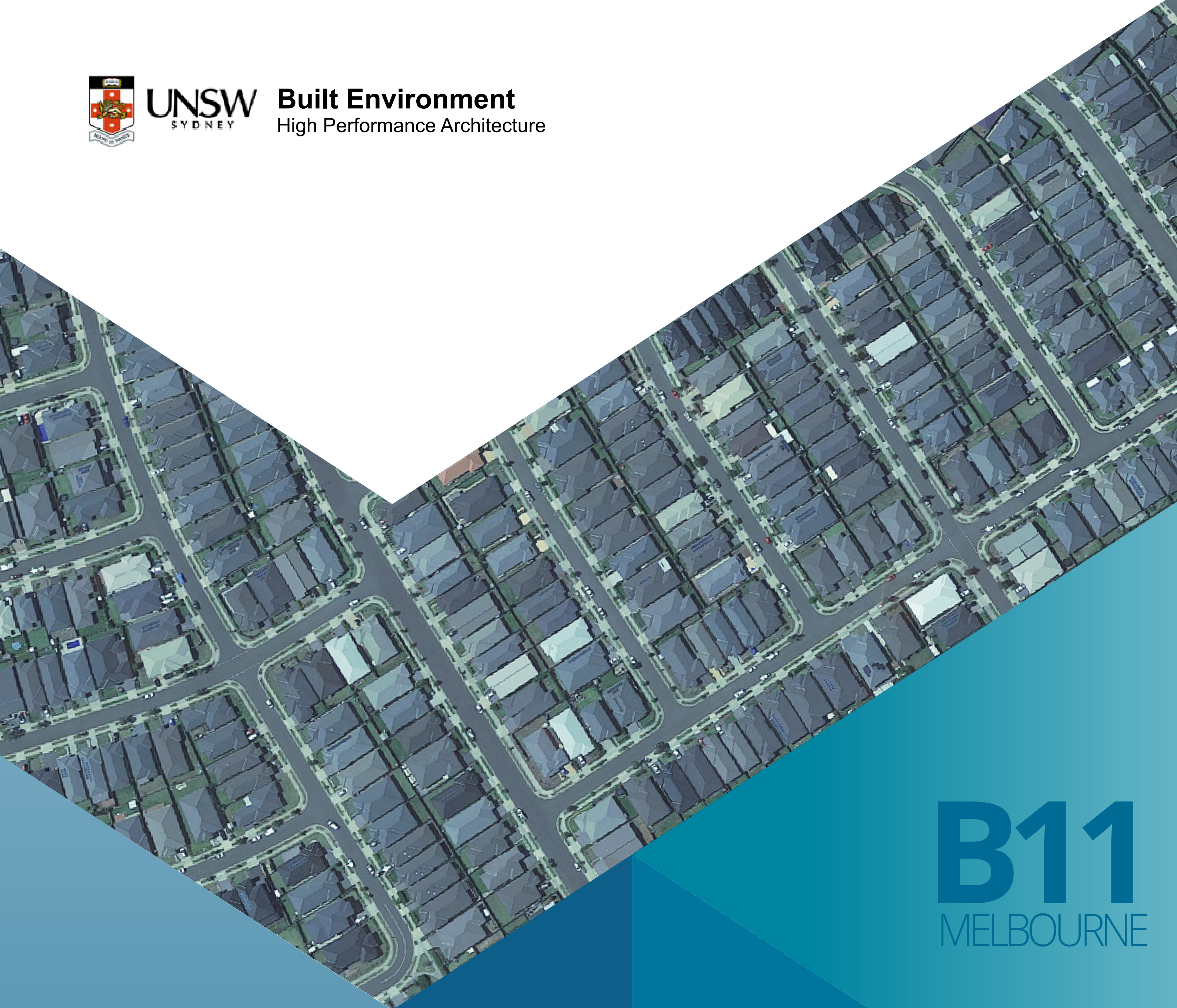

B11
MELBOURNE

COOL ROOFS COST BENEFIT **ANALYSIS STUDY**

Existing standalone house
2021

BUILDING 11

EXISTING STANDALONE HOUSE

Floor area : 242m²
Number of stories : 1

Image source: https://www.newhomesguide.com.au/builders/long-island-homes/homes/new-homes/moonbi-240

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

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 Melbourne 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 6.6-10.0 kWh/m² to 2.4-3.1 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	6.9	7.5	3.0	2.6	2.4	2.4
Coldstream	9.4	10.0	3.8	2.5	3.1	3.2
Essendon	8.0	8.6	3.6	2.5	2.7	2.7
Frankston beach	5.9	6.6	2.1	3.2	1.4	1.5
Melbourne airport	8.3	8.9	3.8	2.4	2.8	2.9
Moorabbin airport	6.2	6.9	2.3	3.1	1.6	1.7
Olympic park	7.0	7.7	2.9	2.8	2.3	2.4

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

For Scenario 1, the total cooling load saving is around 3.4-7.5 kWh/m² which is equivalent to 51.9-75.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 5.1-6.8 kWh/m² which is equivalent to 67.4-77.4 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	4.0	57.1	4.9	65.2	4.6	66.1	5.1	67.4
Coldstream	5.6	59.2	7.5	75.3	6.4	67.4	6.8	68.2
Essendon	4.4	55.1	6.1	71.4	5.4	66.8	5.9	68.3
Frankston beach	3.9	65.2	3.4	51.9	4.5	75.9	5.1	77.4
Melbourne airport	4.5	54.4	6.5	73.4	5.5	66.1	6.0	67.6
Moorabbin airport	3.9	62.8	3.8	55.3	4.6	73.6	5.2	75.3
Olympic park	4.1	58.9	4.9	63.9	4.7	67.5	5.3	68.9

In the eleven weather stations in Melbourne, 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.

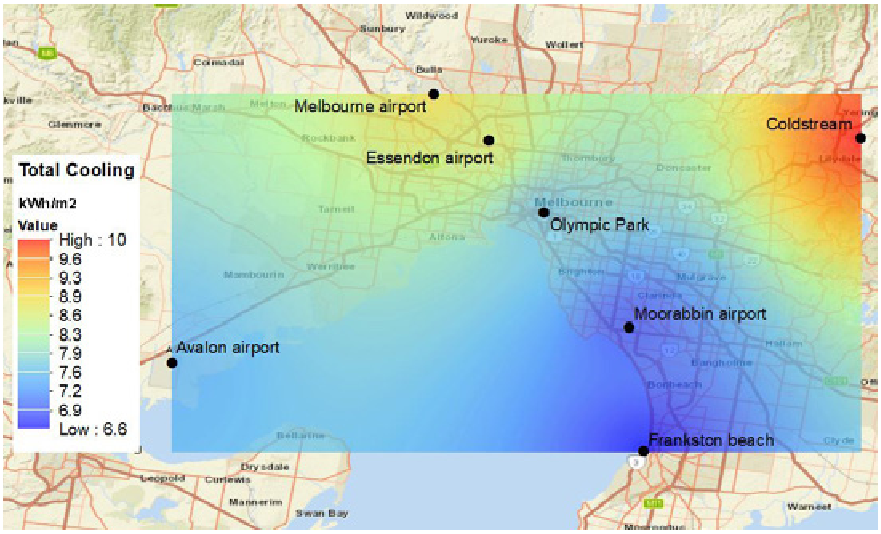

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

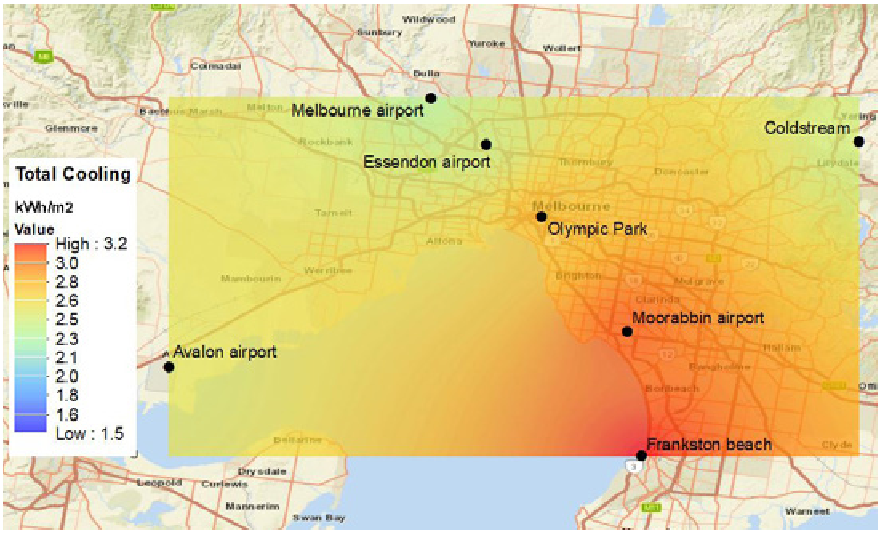

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

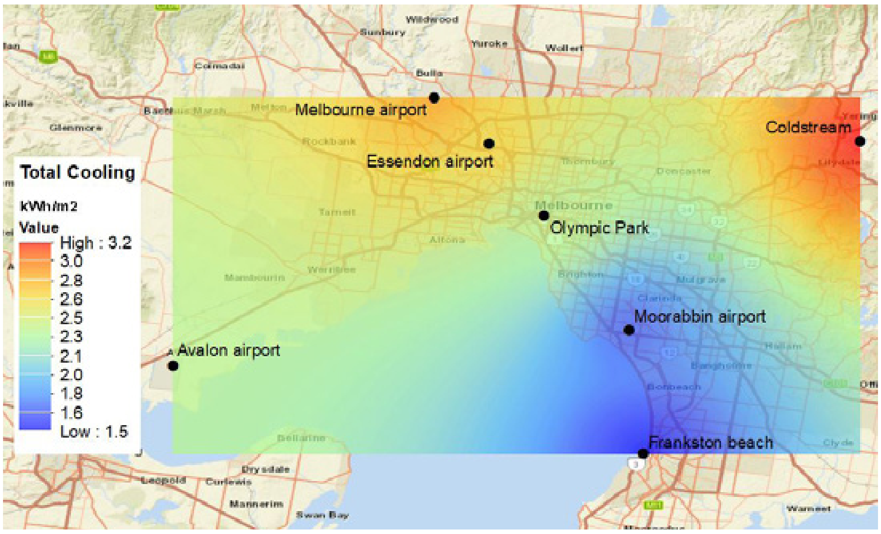

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

b Reference scenario and scenario 1; estimated for eleven weather stations in Melbourne 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 (6.8-7.9 kWh/m²) is relatively similar to the annual cooling load reduction (5.6-8.3 kWh/m²).

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

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)		Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Avalon airport	9.1	10.6	33.1	39.5	4.2	4.9	39.7	46.7
Coldstream	14.0	15.8	34.6	41.5	6.5	7.6	42.5	50.0
Essendon	11.8	13.1	31.8	37.9	5.8	6.6	38.2	44.8
Frankston beach	8.6	10.4	29.6	35.1	3.0	3.8	36.6	43.0
Melbourne airport	11.0	12.1	33.8	40.3	5.5	6.2	40.4	47.5
Moorabbin airport	10.4	12.2	30.3	36.0	5.0	6.0	36.5	42.8
Olympic park	13.0	15.0	28.0	33.2	5.6	6.7	34.5	40.3

The annual cooling load saving by building-scale application of cool roofs is around 48.8-63.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -1.6 and 1.2 kWh/m² (~ -3.1-2.5 %).

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 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/m^2	%	kWh/m^2	%	kWh/m^2		kWh/m^2	%	kWh/m^2	%
Avalon airport	4.9	54.1	5.6	53.2	6.6	7.2	-1.7	-4.0	-1.6	-3.1
Coldstream	7.6	54.0	8.2	51.9	7.8	8.5	-0.3	-0.5	-0.3	-0.5
Essendon	5.9	50.4	6.5	49.4	6.4	7.0	-0.5	-1.0	-0.5	-0.9
Frankston beach	5.5	64.7	6.6	63.5	7.0	7.9	-1.5	-3.9	-1.3	-2.8
Melbourne airport	5.5	49.9	5.9	48.8	6.6	7.2	-1.1	-2.4	-1.3	-2.5
Moorabbin airport	5.4	52.3	6.2	50.9	6.2	6.8	-0.8	-1.9	-0.6	-1.3
Olympic park	7.4	56.9	8.3	55.4	6.5	7.1	1.0	2.3	1.2	2.5

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

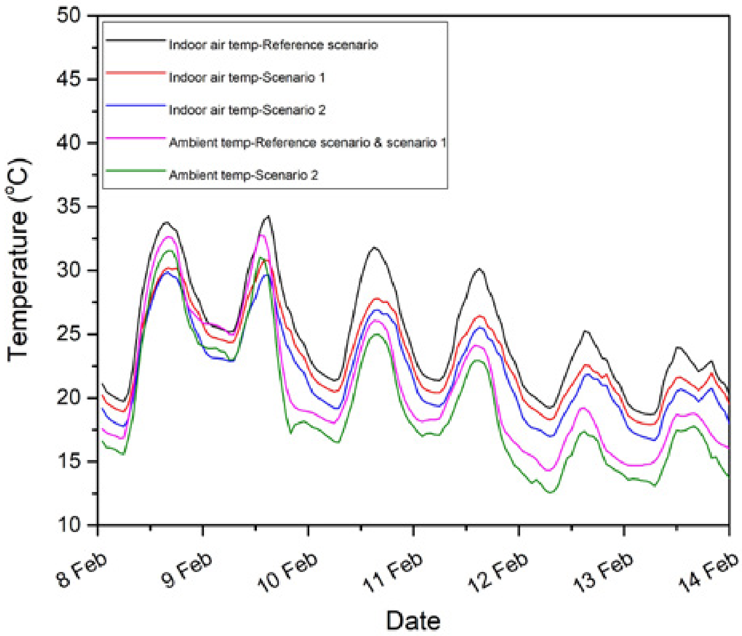

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

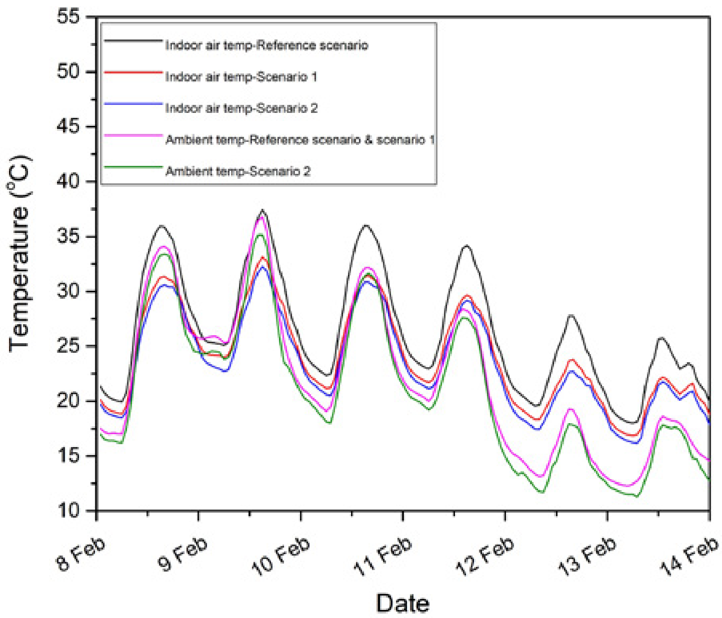

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 18.5-34.3 °C and 18.0- 37.4 °C in Frankston beach and Coldstream stations, respectively.

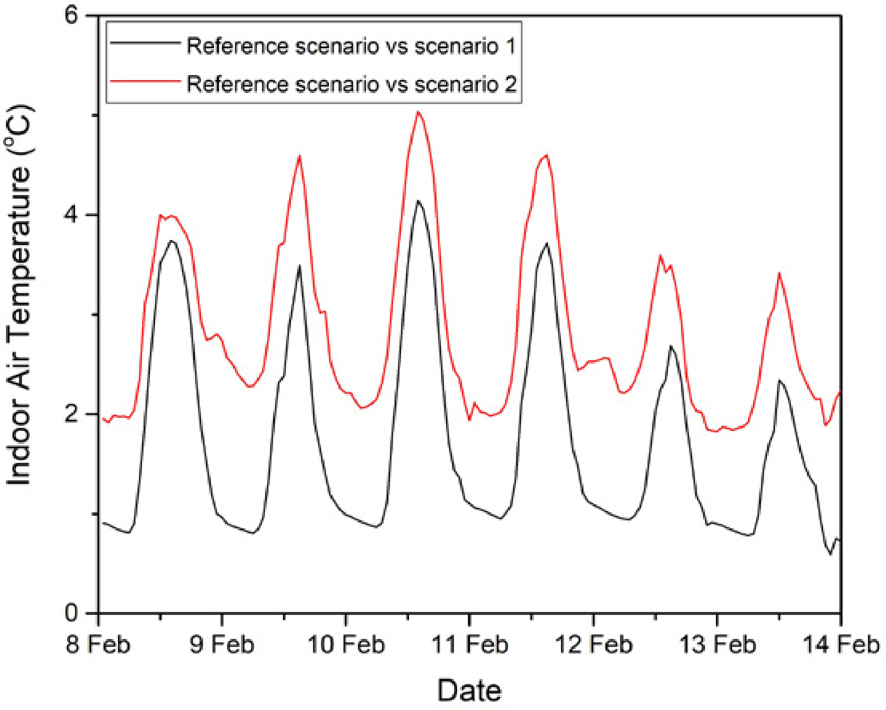

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 4.2 °C and 4.7 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 5.0 °C and 5.6 °C in Frankston beach and Coldstream stations, respectively.

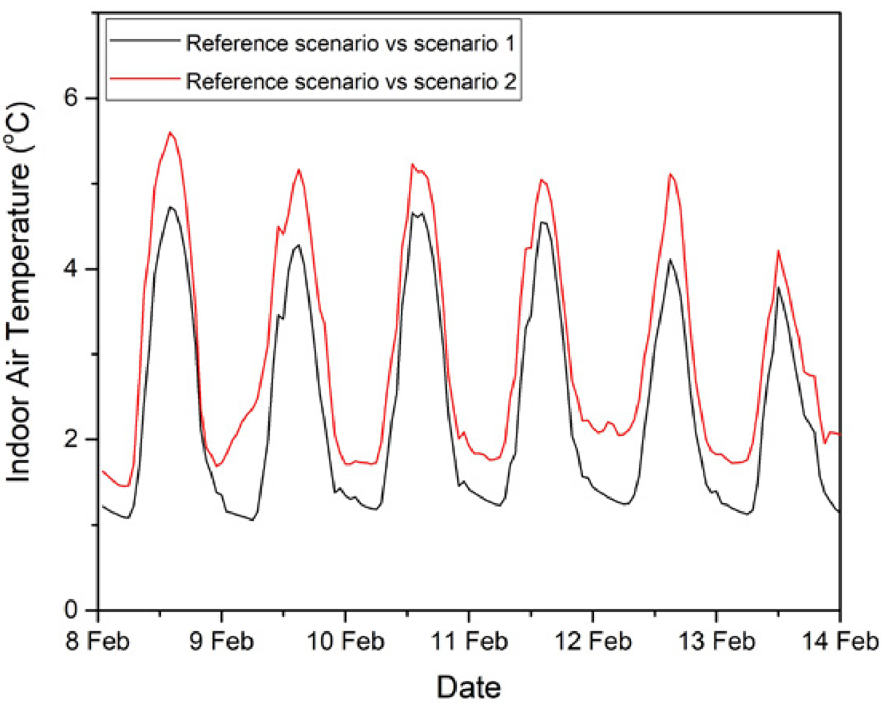

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer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

During a typical winter week, the indoor air temperature is expected to decrease from a range 10.5-19.4 °C in reference scenario to a range 10.4-17.5 °C in scenario 1 in Frankston beach station.

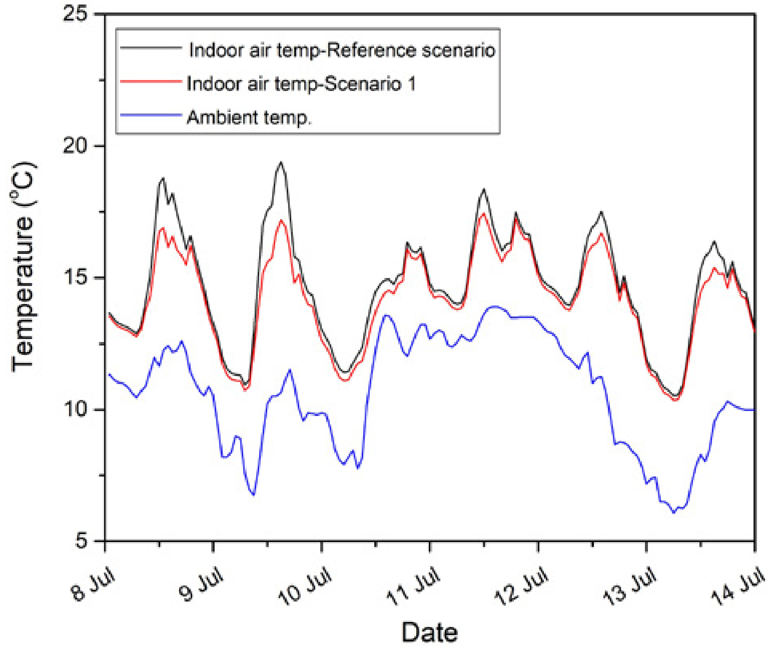

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Frankston beach station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 8.7-20.1 °C in reference scenario to a range 8.4-17.9 °C in scenario 1 in Coldstream station.

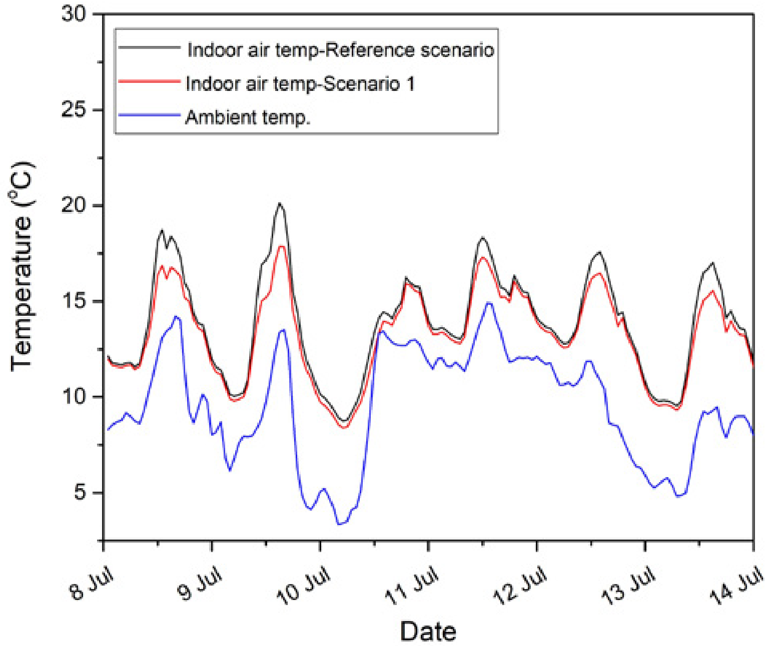

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Coldstream station* using annual measured weather 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 and 1.4 °C in Frankston beach and Coldstream stations, respectively.

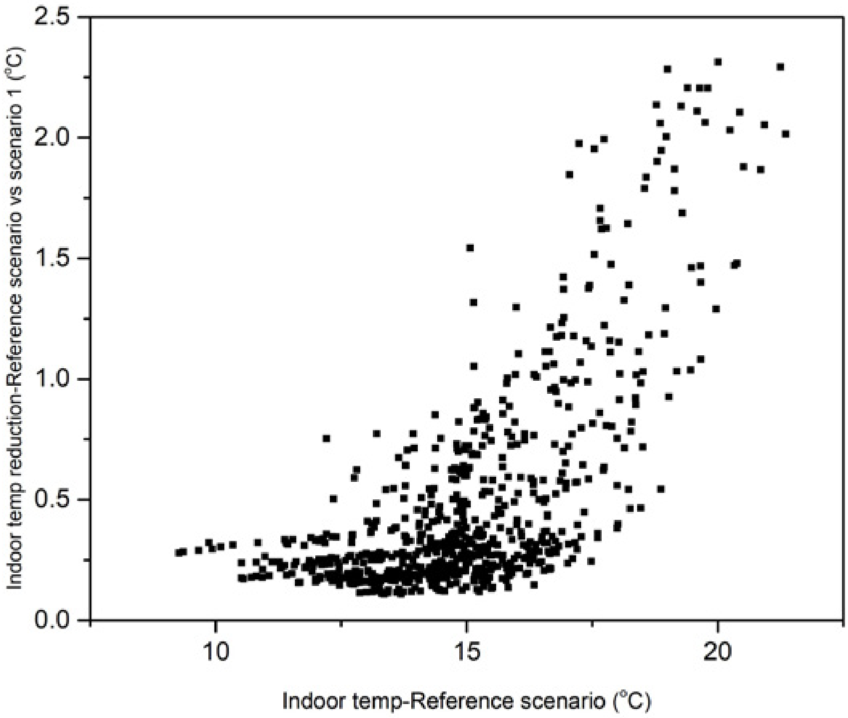

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

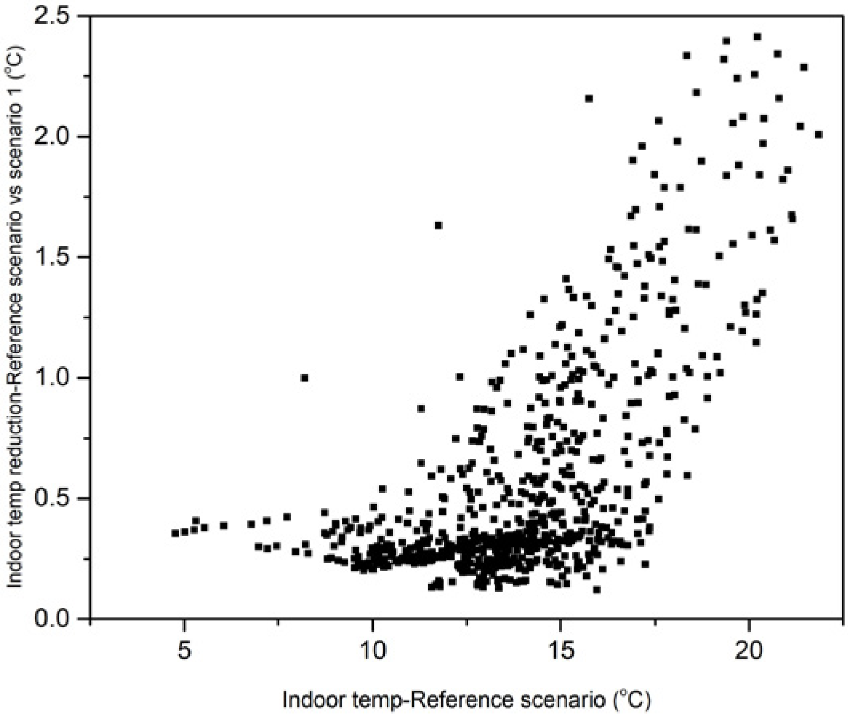

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 considerably increase from 717 hours in reference scenario to 743 hours; and from 708 to 735 hours in scenario 1 in Frankston beach and Coldstream 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
Frankston beach	717	743
Coldstream	708	735

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 192 hours in reference scenario to 96 and 62 hours under scenario 1 and 2 in Frankston beach station; and from 250 hours in reference scenario to 151 and 121 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	192	96	62
Coldstream	250	151	121

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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

The building and its energy performance

Building 11 is an existing, stand-alone residential building, with a total air-conditioned area of 242 m^2 distributed on one level. The 242 m^2 roof is insulated, resulting in a very limited energy conservation potential, despite the roof's impact on the building's energy balance. The overall energy savings are, albeit to a very small degree, negative, since there is an increase in heating requirements, that is in absolute terms higher than the reduction in cooling loads. However, due to the different efficiencies of the HVAC equipment for heating and cooling and due to the need to perform a mid-life refurbishment of the existing roof after 15 years, the overall economic outcome is positive for the lower cost cool coating roof. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 11.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	4,4	5,5
Energy consumption after cool roof (MWh)	4,5	5,6
Energy savings (MWh)	-0,1	-0,1
Energy savings (%)	-2,27 %	-1,82 %
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 an interesting example of a new, stand-alone residential building, with a single floor and an insulated roof, where the energy conservation potential is at best indifferent. However, given the higher cost of cooling than heating and the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a meaningful investment.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in an energy requirements' increase of 2,27 % for the Frankston Beach weather conditions and of 1,82 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a moderate reduction of life cycle costs, that varies between 5,6 % for the low energy price scenario for Frankston and 15,0 % for the high energy scenario and for Coldstream conditions (Table 8).

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

Feasibility analysis results

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

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

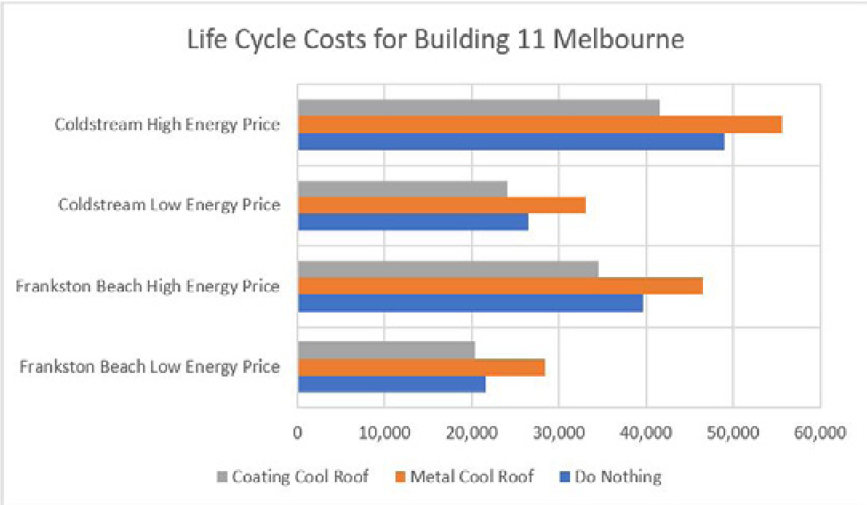

Figure 12. Life Cycle Costs for Building 11 for Frankston Beach and Coldstream stations.

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

Reduction of Life Cycle Costs	Observatory		Richmond	
	Low Energy Price	High Energy Price	Low Energy Price	High Energy Price
Metal Cool Roof	-31,04 %	-17,21 %	-25,08 %	-13,62 %
Coating Cool Roof	5,58 %	12,98 %	8,87 %	15,01 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 6.6-10.0 kWh/m^2 to 2.4-3.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 3.4-7.5 kWh/m^2. This is equivalent to approximately 51.9-75.3 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 5.1-6.8 kWh/m^2. This is equivalent to 67.4-77.4 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (6.8-7.9 kWh/m2) is relatively similar to the annual cooling load reduction (5.6-8.3 kWh/m2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 48.8-63.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between -1.6 and 1.2 kWh/m^2 (~ -3.1-2.5 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 18.5-34.3 °C and 18.0- 37.4 °C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 4.2 and 4.7 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 5.0 and 5.6 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 10.5-19.4 °C in reference scenario to a range between 10.4-17.5 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 8.7-20.1 °C in reference scenario to a range between 8.4-17.9 °C in reference with cool roof scenario (scenario 1) in Coldstream station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.2 and 1.4 °C for Frankston beach and Coldstream 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 considerably increase from 717 hours in reference scenario to 743 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slightly increase in total number of hours below 19 °C from 708 hours in reference scenario to 735 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 192 hours under the reference scenario in Frankston beach station, which significantly decreases to 96 and 62 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 250 hours in reference scenario to 151in reference with cool roof scenario (scenario 1) and 121 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 moderate reduction of life cycle costs, that varies between 5,6% for the low energy price scenario for Frankston and 15,0% for the high energy scenario and for Coldstream conditions, as it can be seen in Table8 . The metal cool roof is, due to its higher initial investment cost and the indifferent energy savings, not feasible. 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 at best indifferent. However, given the higher cost of cooling than heating and the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a meaningful investment.

B11

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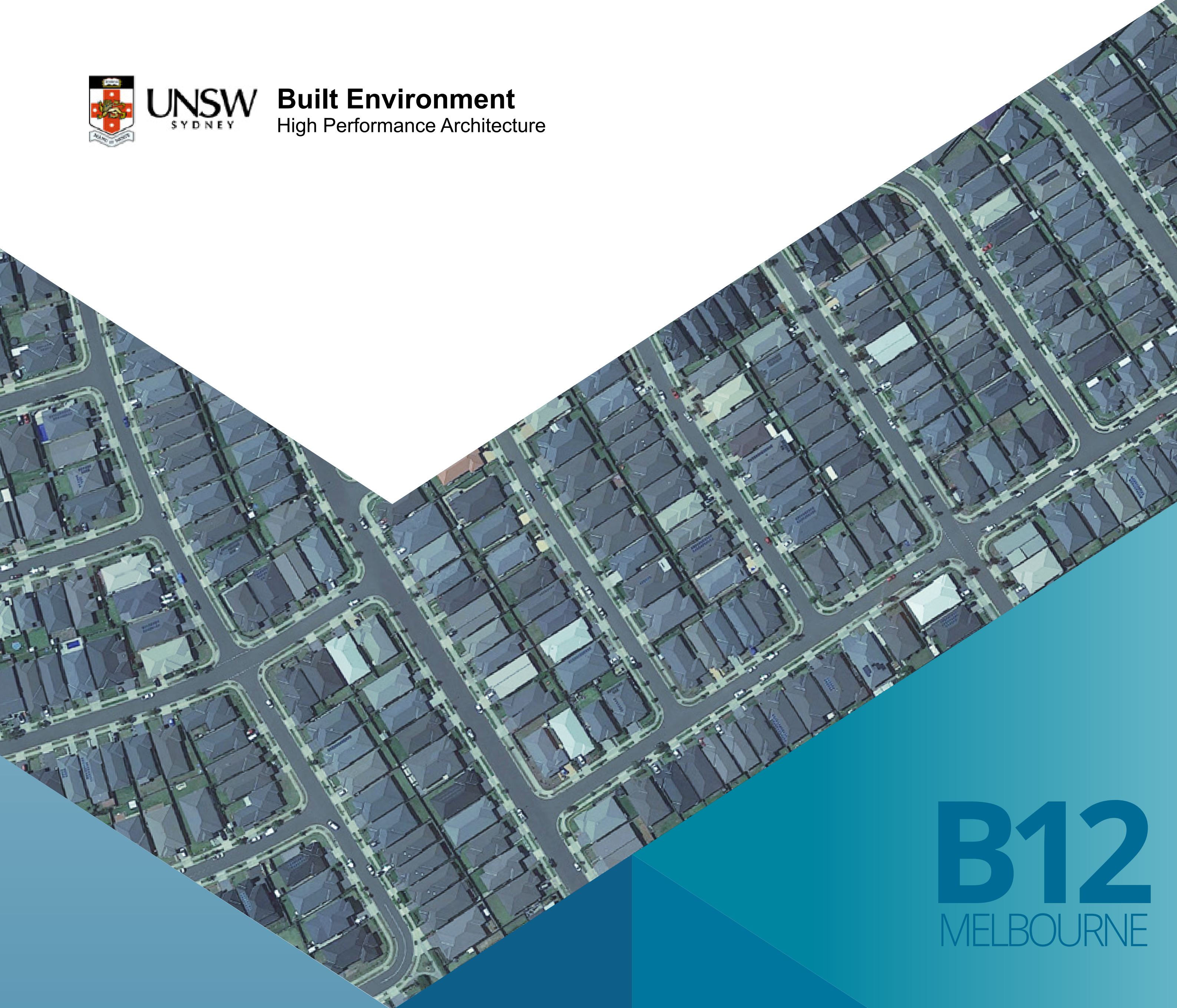

B12
MELBOURNE

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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Figure 12. Life Cycle Costs for Building 12 for *Frankston Beach* and *Coldstream stations* 12

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 Melbourne using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing school from 9.3-13.7 kWh/m² to 8.8-13.1 kWh/m².

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.

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)
Avalon airport	11.8	12.1	11.3	11.6	9.2	9.3
Coldstream	13.0	13.4	12.3	12.6	10.3	10.3
Essendon	13.0	13.3	12.4	12.8	9.5	9.5
Frankston beach	8.9	9.3	8.4	8.8	6.2	6.3
Melbourne airport	13.3	13.7	12.8	13.1	9.8	9.8
Moorabbin airport	9.7	10.1	9.2	9.6	6.9	6.9
Olympic park	11.2	11.6	10.7	11.1	8.7	8.7

For Scenario 1, the total cooling load saving is around 0.5-0.7 kWh/m² which is equivalent to 4.1-5.6 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.9-3.9 kWh/m² which is equivalent to 22.6-32.4 % total cooling load reduction.

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.

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	%
Avalon airport	0.5	3.9	0.5	4.1	2.5	21.5	2.9	23.6
Coldstream	0.7	5.1	0.7	5.6	2.7	20.6	3.0	22.6
Essendon	0.5	3.9	0.6	4.2	3.4	26.4	3.8	28.5
Frankston beach	0.4	5.0	0.5	5.5	2.6	29.7	3.0	32.4
Melbourne airport	0.5	3.9	0.6	4.2	3.5	26.2	3.9	28.2
Moorabbin airport	0.4	4.6	0.5	5.1	2.8	28.7	3.2	31.6
Olympic park	0.5	4.2	0.5	4.7	2.5	22.5	2.9	25.0

In the eleven weather stations in Melbourne, 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.

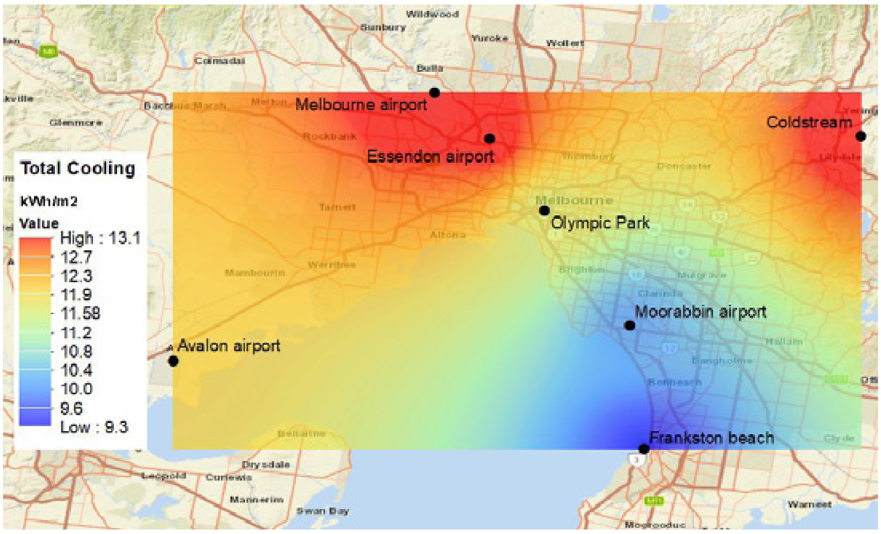

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for aan existing school with weather data simulated by WRF for COP=1 for heating and cooling.

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

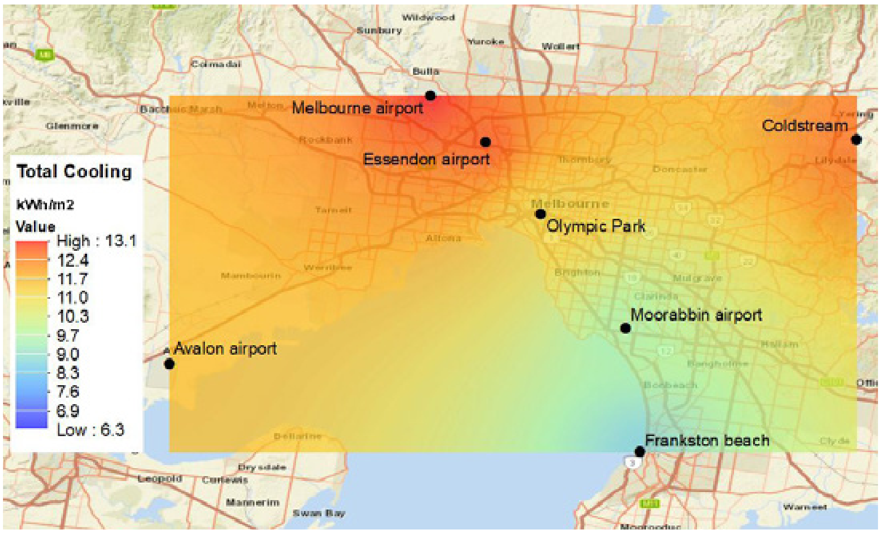

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

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 Melbourne 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 (0.5-0.8 kWh/m²) is slower than the annual cooling load reduction (0.8-1.1 kWh/m²).

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

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Avalon airport	18.6	19.4	5.2	31.0	17.9	18.6	5.3	31.5
Coldstream	23.0	24.1	6.1	36.4	22.1	23.0	6.2	37.2
Essendon	22.8	23.6	4.7	29.3	22.0	22.7	4.8	29.8
Frankston beach	11.7	12.5	3.6	25.7	11.0	11.6	3.7	26.4
Melbourne airport	22.0	22.6	5.1	32.2	21.3	21.8	5.2	32.8
Moorabbin airport	19.7	20.6	4.2	25.8	19.0	19.7	4.3	26.3
Olympic park	21.3	22.5	3.8	23.6	20.3	21.3	3.9	24.1

The annual cooling load saving by building-scale application of cool roofs is around 3.4-7.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.2-0.6 kWh/m² (~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 school using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	0.7	3.6	0.8	4.0	0.1	0.5	0.6	2.5	0.2	0.5
Coldstream	0.9	4.1	1.1	4.7	0.1	0.8	0.8	2.7	0.4	0.6
Essendon	0.8	3.3	0.9	3.6	0.1	0.5	0.7	2.5	0.3	0.6
Frankston beach	0.7	5.9	0.9	7.0	0.1	0.7	0.6	4.0	0.2	0.5
Melbourne airport	0.7	3.2	0.8	3.4	0.1	0.5	0.6	2.2	0.2	0.4
Moorabbin airport	0.7	3.6	0.9	4.2	0.1	0.5	0.6	2.6	0.4	0.8
Olympic park	0.9	4.3	1.1	5.0	0.1	0.5	0.8	3.4	0.6	1.3

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

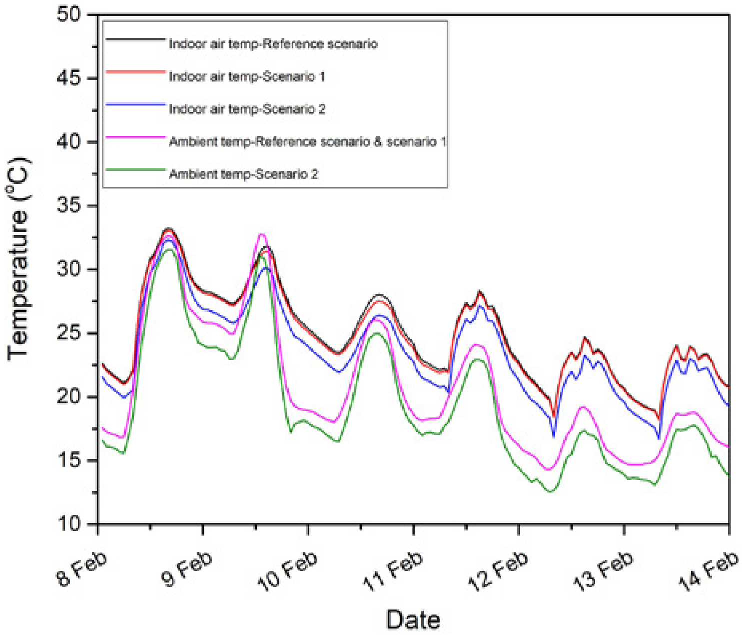

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

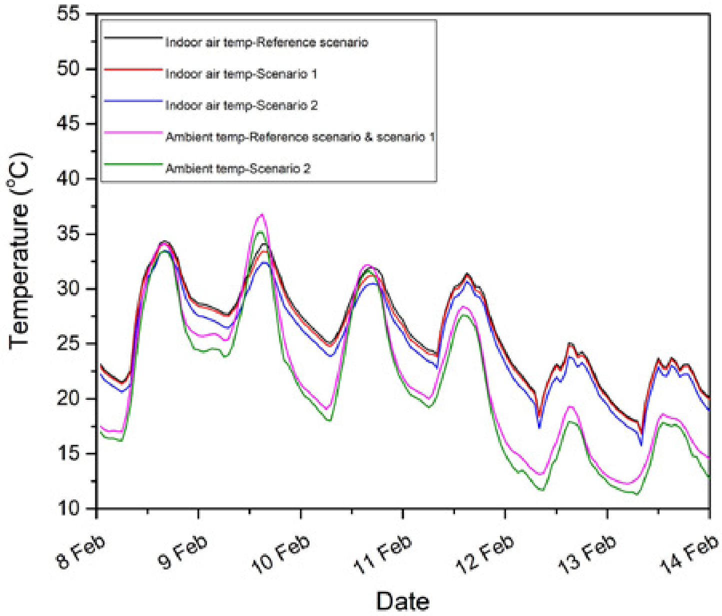

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 18.2-33.2 °C and 16.9-34.4 °C in Frankston beach and Coldstream stations, respectively.

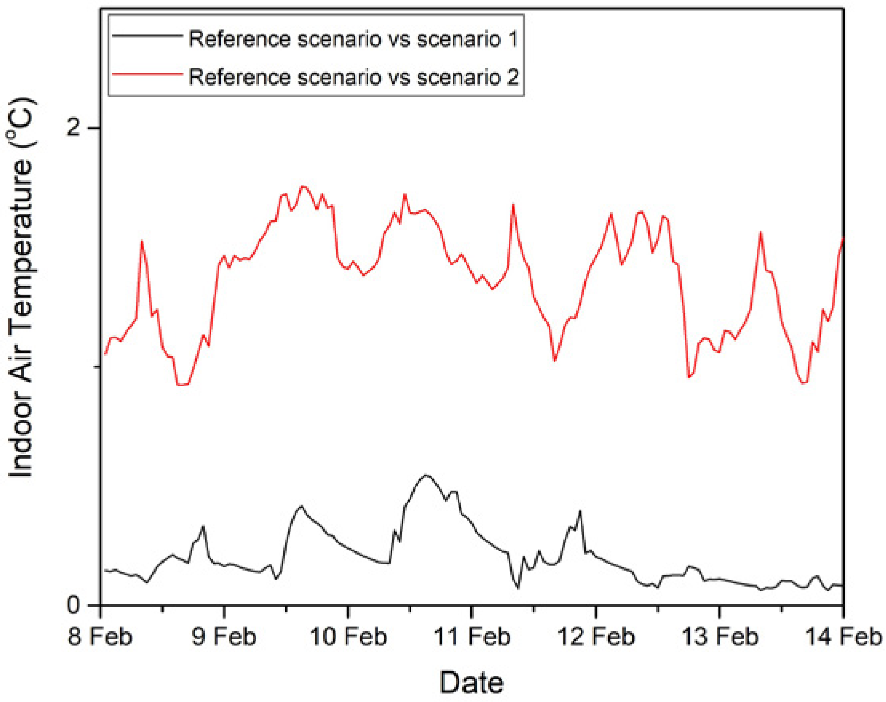

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in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

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.8 °C and 1.7 °C in Frankston beach and Coldstream stations, respectively.

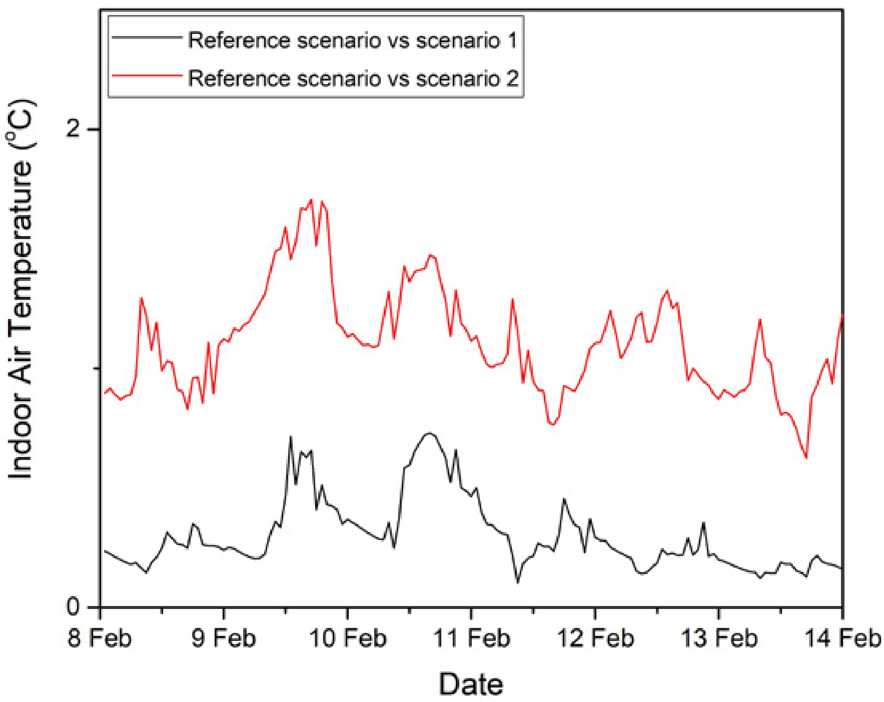

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in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

During a typical winter week, the indoor air temperature is expected to decrease from a range 11.3-20.2 °C in reference scenario to a range 11.2-20.2 °C in scenario 1 in Frankston beach station.

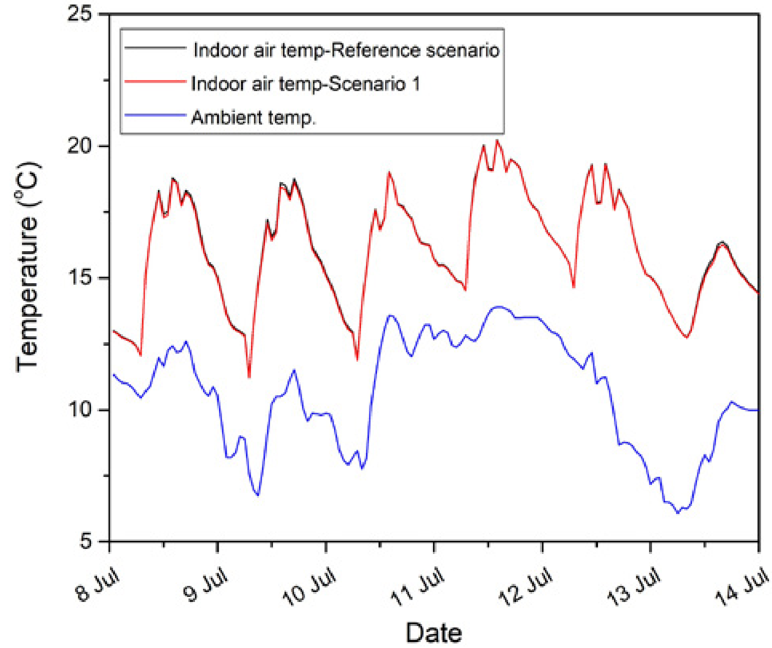

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Frankston beach station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 8.8-20.7 °C in reference scenario to a range 8.7-20.6 °C in scenario 1 in Coldstream station.

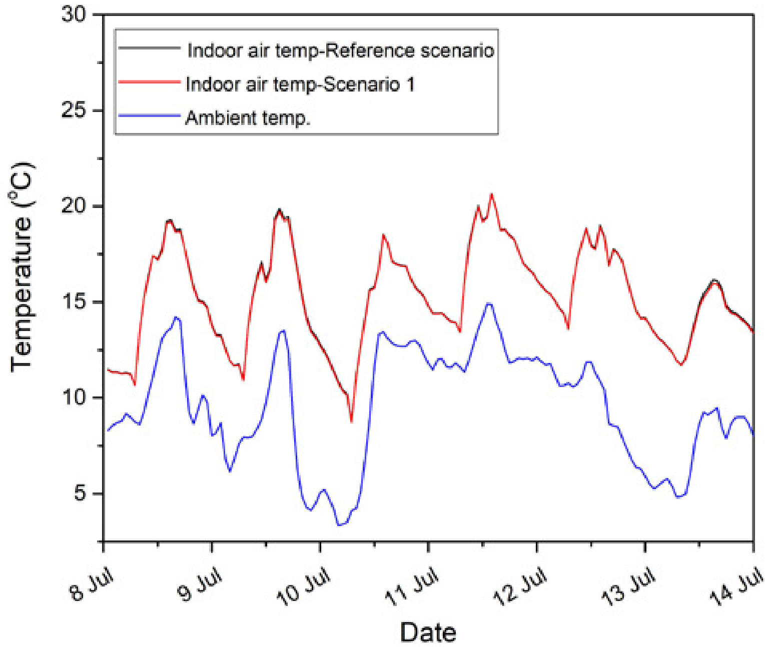

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Coldstream station* using annual measured weather data.

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 Frankston beach and Coldstream stations.

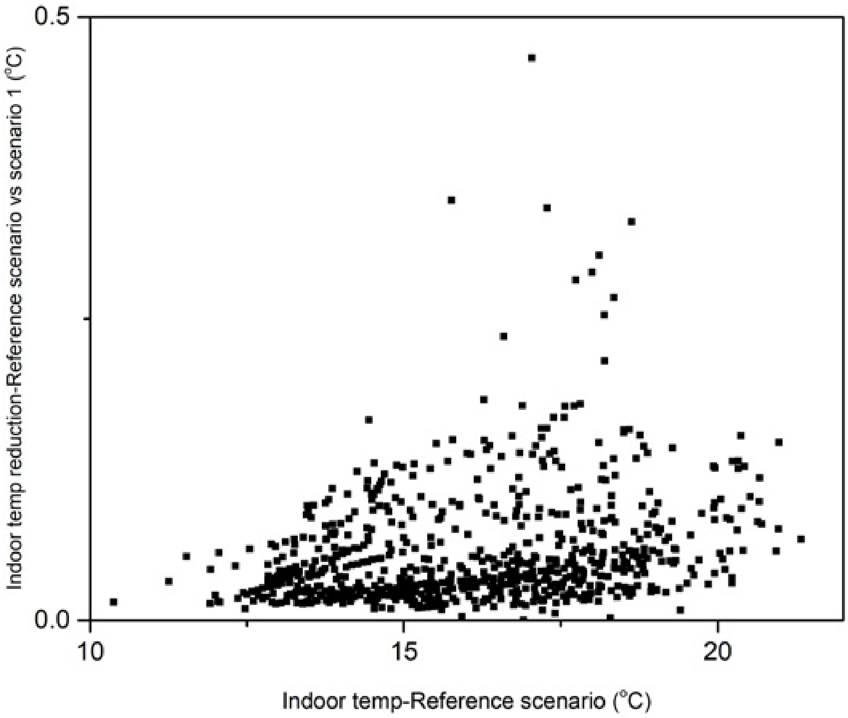

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

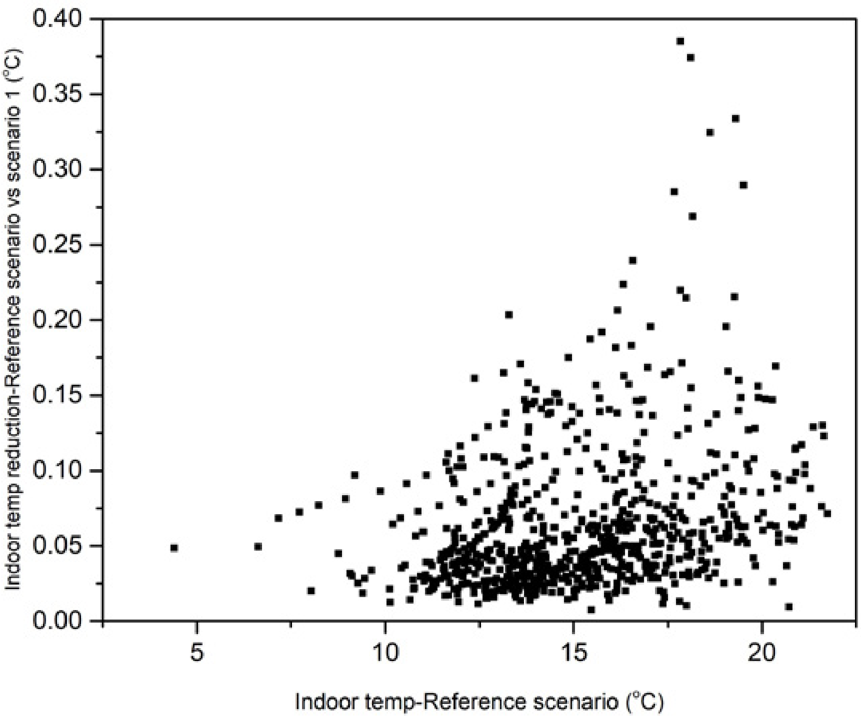

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 684 hours in reference scenario to 688 hours; and from 664 to 672 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 206 hours in reference scenario to 210 hours; and from 186 to 190 hours in scenario 1 in Frankston beach and Coldstream 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
Frankston beach	206	684	210	688
Coldstream	186	664	190	672

** 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 159 hours in reference scenario to 154 and 120 hours under scenario 1 and 2, in Frankston beach station; and from 226 hours in reference scenario to 211 and 173 hours under scenario 1 and 2 in Coldstream 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
Frankston beach	159	154	120
Coldstream	226	211	173

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 a rather unfavourable situation for applying cool roof techniques: the overall energy savings are very small indeed. However, due to the expected need to perform a mid-life refurbishment of the existing roof after 15 years, the overall economic outcome is positive for the lower cost cool coating roof. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 12.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	50,4	79,9
Energy consumption after cool roof (MWh)	50,2	79,5
Energy savings (MWh)	0,2	0,4
Energy savings (%)	0,40%	0,50%
Area (m²)	1.100	1.100
Roof costs - Metal roof (AU$/m²)	38,0	38,0
Roof costs - Coating (AU$/m²)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m²)	15,0	15,0

Building 12 is a good example of a new, mid-rise educational building, where the energy conservation potential is very limited. However, even so and given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a very meaningful investment.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in an energy requirements' increase of 0,40 % for the Frankston Beach weather conditions and of 0,50 % for the Coldstream conditions. Given the margin of error of simulations, in practice one can deduce that the energy requirements remain practically unaltered. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 16,9 % for the low energy price scenario for Frankston and 21,7% for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

The metal cool roof is, due to its higher initial investment cost and the indifferent energy savings, only for the high energy prices scenario and for Coldstream weather conditions feasible.

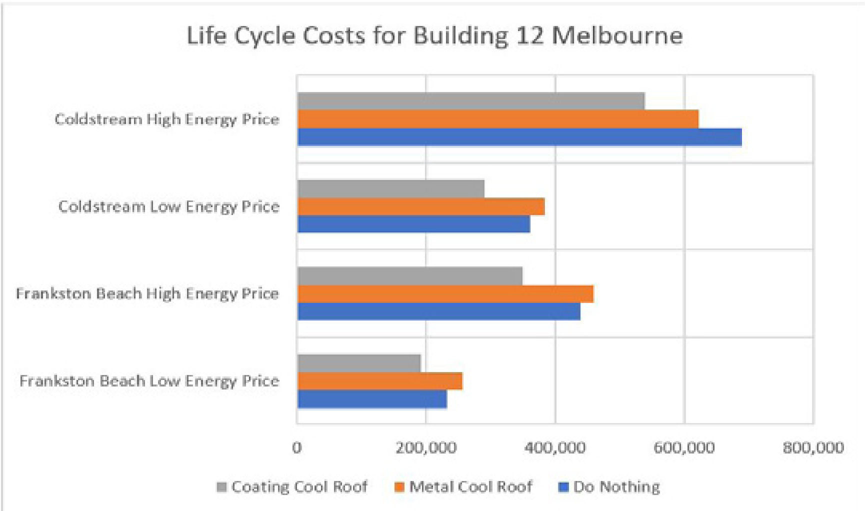

Figure 12. Life Cycle Costs for Building 12 for Frankston Beach and Coldstream stations.

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	-10,98 %	-4,84 %	-6,21 %	9,54 %
Coating Cool Roof	16,94 %	20,24 %	19,53 %	21,67 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing school from 9.3-13.7 kWh/m2 to 8.8-13.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5-0.7 kWh/m^2. This is equivalent to approximately 4.1-5.6 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 2.9-3.9 kWh/m^2. This is equivalent to 2.6-32.4 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.5-0.8 kWh/m^2) is significantly lower than the annual cooling load reduction (0.8-1.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.4-7.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.2-0.6 kWh/m^2 (~0.4-1.3 %) (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 18.2-33.2 °C and 16.9-34.4 °C in Frankston beach and Coldstream 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 Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 and 1.7 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 11.3-20.2 °C in reference scenario to a range between 11.2-20.2 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 8.8-20.7 °C in reference scenario to a range between 8.7-20.6°C in reference with cool roof scenario (scenario 1) in Coldstream 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 Frankston beach and Coldstream 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 684 hours in reference scenario to 688 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight increase in total number of hours below 19 °C from 664 hours in reference scenario to 672 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 206 hours in reference scenario to 210 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slight increase of number of hours below 19 °C from 186 hours to 190 hours during the operational hours.

• 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 159 hours under the reference scenario in Frankston beach station, which slightly decreases to 154 and 120 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 226 hours in reference scenario to 211 in reference with cool roof scenario (scenario 1) and 173 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the building's roof insulation, the 'Do Nothing' approach has a higher cost over the building's life cycle compared to the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 16,9% for the low energy price scenario for Frankston and 21,7% for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the indifferent energy savings, only for the high energy prices scenario and for Coldstream weather conditions feasible. Building 12 is i a good example of a new, mid-rise educational building, where the energy conservation potential is very limited. However, even so and given the need to refurbish after a period the existing roof, the application of a coating cool technology emerges as a very meaningful investment.

B12

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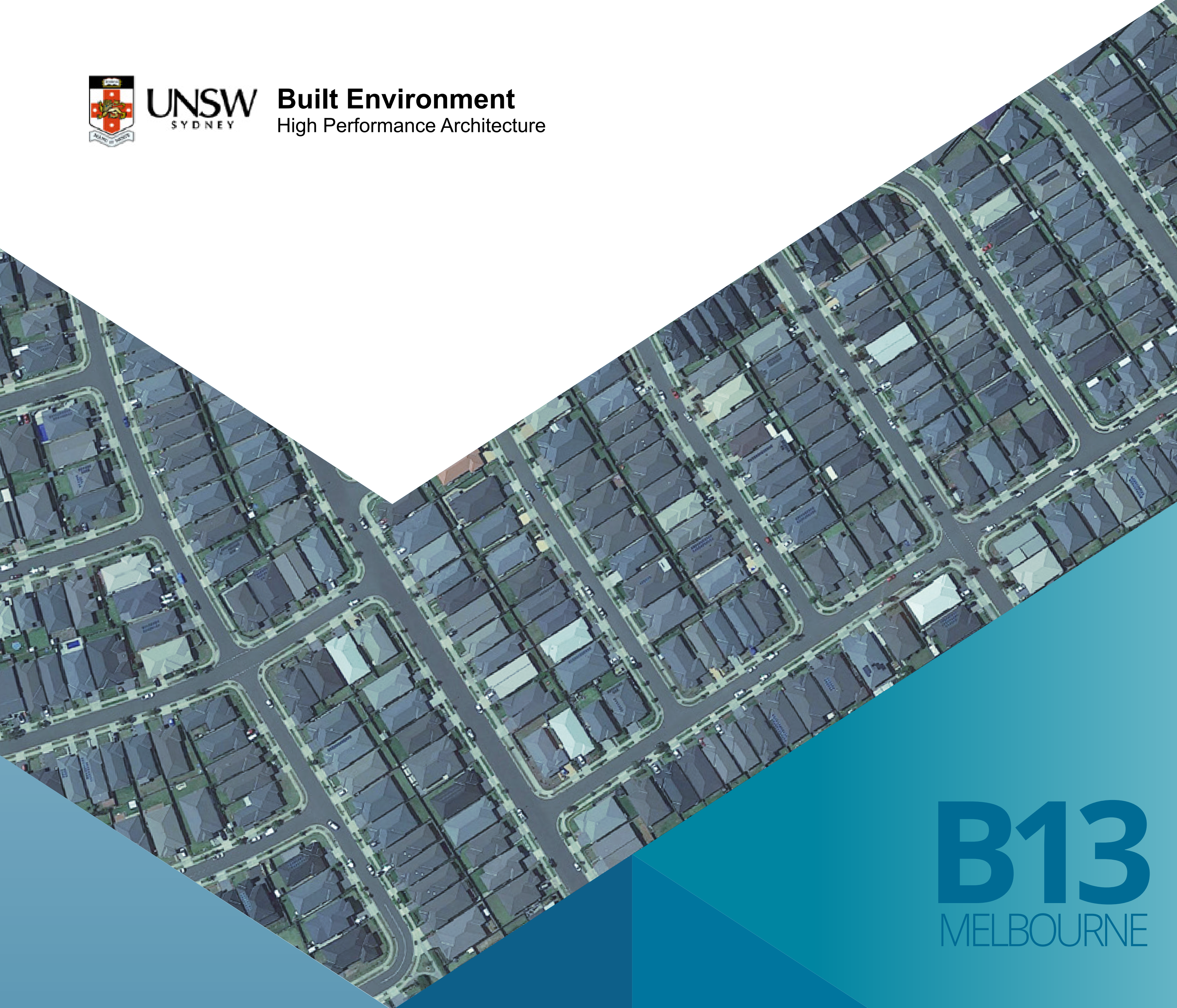

B13
MELBOURNE

COOL ROOFS
COST BENEFIT ANALYSIS

Existing low-rise office building with roof insulation
2021

BUILDING 13

EXISTING LOW-RISE OFFICE BUILDING WITH ROOF INSULATION

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

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

Note: building characteristics change with climate zones

Reference scenario

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

Scenario 1: Reference with cool roof scenario

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

Scenario 2 : Cool roof with modified urban temperature scenario

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

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
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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 Melbourne 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 9.4-13.3 kWh/m² to 6.5-8.9 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)
Avalon airport	10.7	11.4	7.4	8.0	6.0	6.2
Coldstream	12.7	13.3	8.0	8.5	6.8	6.9
Essendon	11.8	12.5	8.1	8.7	6.3	6.4
Frankston beach	8.5	9.4	5.7	6.5	4.3	4.5
Melbourne airport	12.1	12.8	8.3	8.9	6.5	6.5
Moorabbin airport	9.1	10.0	6.2	6.9	4.8	4.9
Olympic park	10.2	11.1	7.0	7.7	5.9	6.1

For Scenario 1, the total cooling load saving is around 2.9-4.8 kWh/m² which is equivalent to 29.4-36.0 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.9-6.4 kWh/m² which is equivalent to 45.2-52.4 % 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	%
Avalon airport	3.3	30.5	3.3	29.4	4.7	43.6	5.1	45.2
Coldstream	4.7	37.0	4.8	36.0	5.9	46.7	6.4	48.4
Essendon	3.7	31.3	3.8	30.2	5.4	46.3	6.0	48.6
Frankston beach	2.8	32.9	2.9	31.1	4.2	49.2	4.9	52.4
Melbourne airport	3.8	31.5	3.9	30.4	5.6	46.5	6.3	48.8
Moorabbin airport	2.9	32.1	3.0	30.4	4.3	47.3	5.0	50.6
Olympic park	3.3	31.9	3.4	30.4	4.4	42.6	5.0	45.2

In the eleven weather stations in Melbourne, 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.

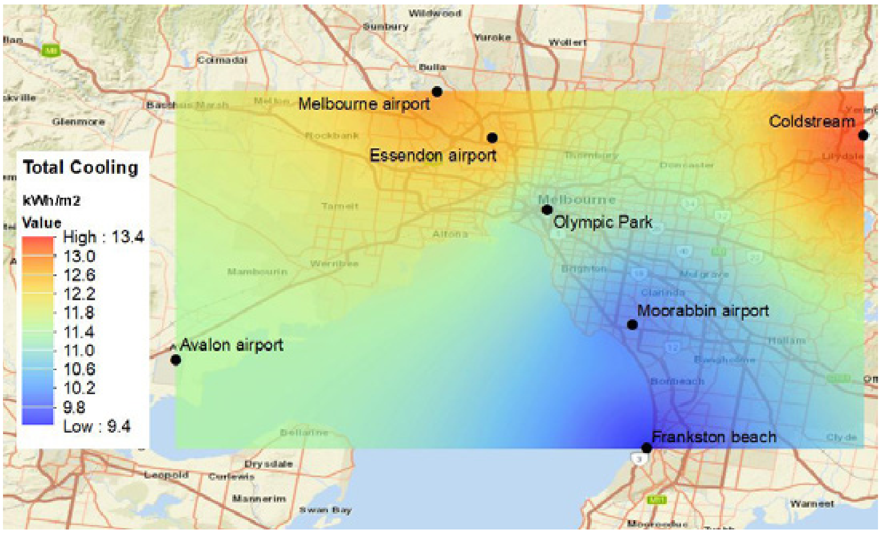

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

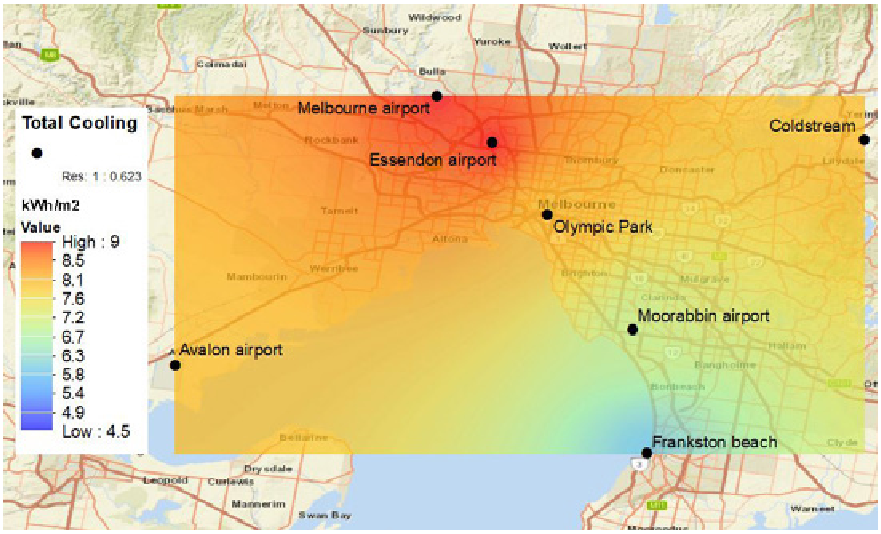

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

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.

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Melbourne 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 (1.0-1.7 kWh/m²) is significantly lower than the annual cooling load reduction (4.1-6.6 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
Avalon airport	15.2	16.8	3.4	7.4	11.3	12.6	4.0	8.6
Coldstream	21.2	23.3	3.8	8.4	14.9	16.6	4.7	10.2
Essendon	19.7	21.3	3.2	6.9	14.7	16.1	3.7	8.0
Frankston beach	11.3	12.6	2.4	5.2	7.4	8.6	2.9	6.3
Melbourne airport	19.1	20.4	3.5	7.6	14.4	15.7	4.1	8.8
Moorabbin airport	16.9	18.6	2.8	6.0	12.4	13.9	3.3	7.0
Olympic park	18.8	20.5	2.6	5.5	13.2	14.7	3.1	6.6

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

The annual cooling load saving by building-scale application of cool roofs is around 23.4-32.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.9-4.9 kWh/m² (~12.4-18.2 %).

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	%
Avalon airport	4.0	26.1	4.2	24.9	0.6	1.2	3.4	18.1	3.0	12.4
Coldstream	6.4	30.0	6.6	28.5	0.9	1.7	5.5	21.9	4.9	15.4
Essendon	4.9	25.1	5.1	24.1	0.6	1.2	4.4	19.1	4.0	14.1
Frankston beach	3.9	34.4	4.1	32.2	0.5	1.2	3.4	24.5	2.9	16.4
Melbourne airport	4.6	24.3	4.8	23.4	0.6	1.2	4.0	17.8	3.5	12.6
Moorabbin airport	4.5	26.6	4.7	25.4	0.5	1.0	4.0	20.2	3.7	15.0
Olympic park	5.6	30.0	5.8	28.4	0.6	1.1	5.1	23.8	4.7	18.2

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

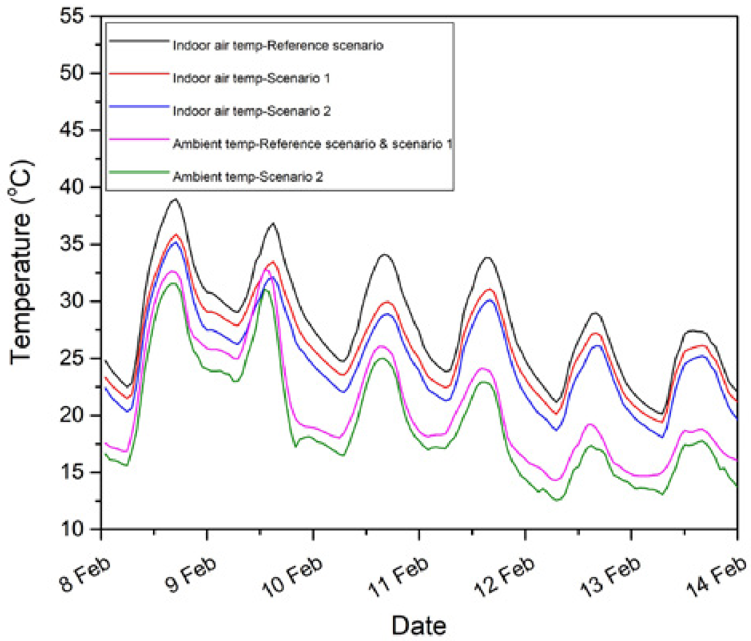

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

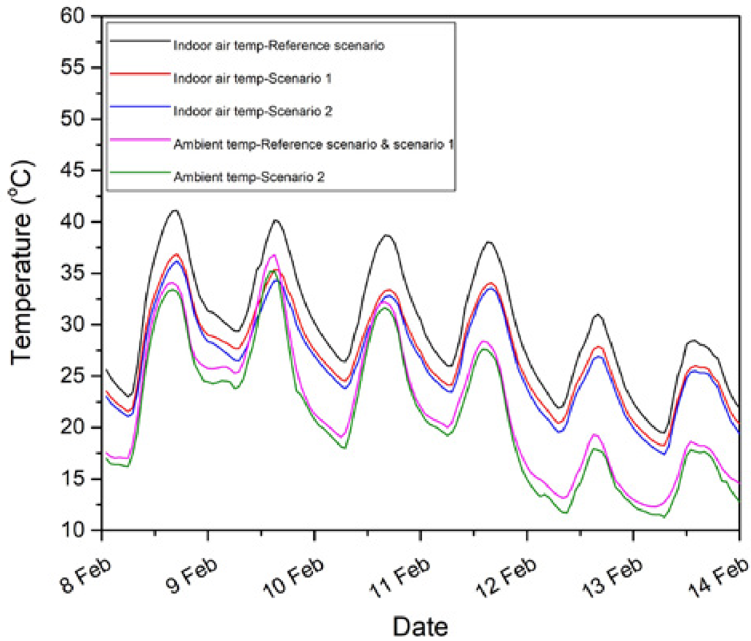

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 20.1-39.0 °C and 19.5-41.0 °C in Frankston beach and Coldstream stations, respectively.

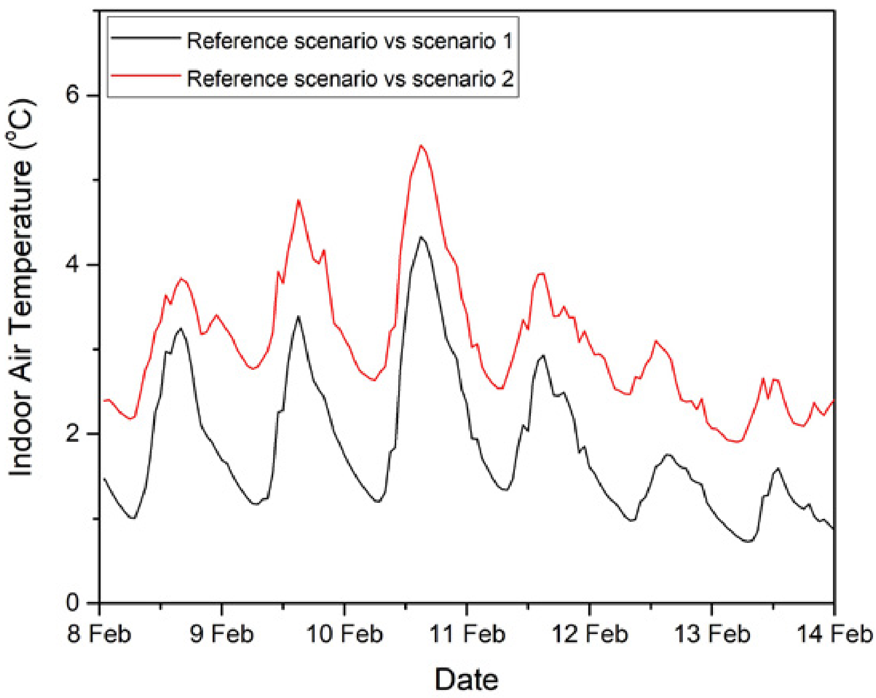

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 4.3 °C and 5.4 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 5.4 and 6.0 °C in Frankston beach and Coldstream stations, respectively.

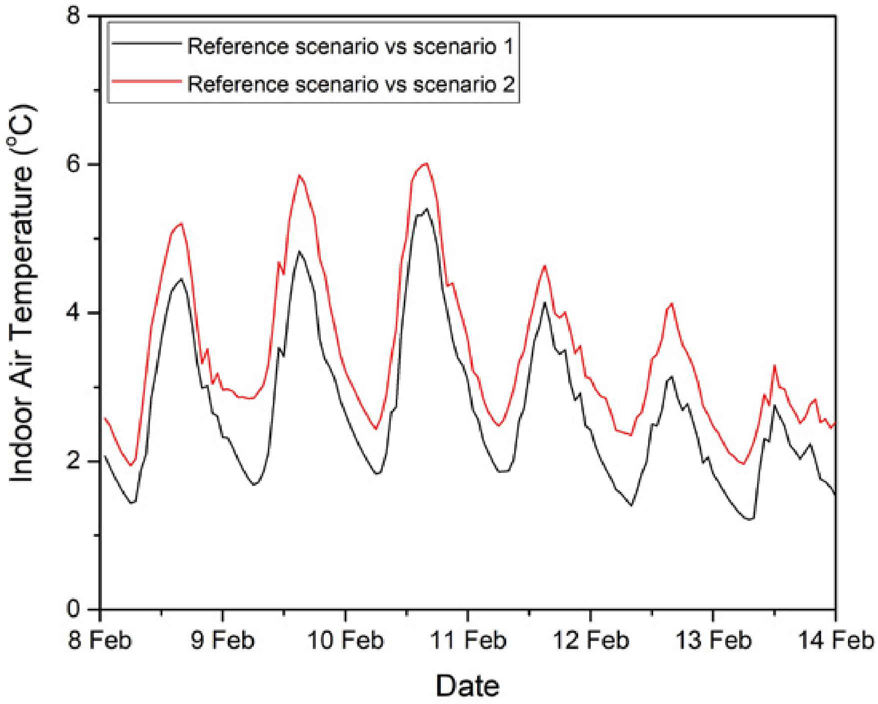

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 13.0 and 23.4 °C in reference scenario to a range between 12.7 and 22.2 °C in scenario 1 in Frankston beach station.

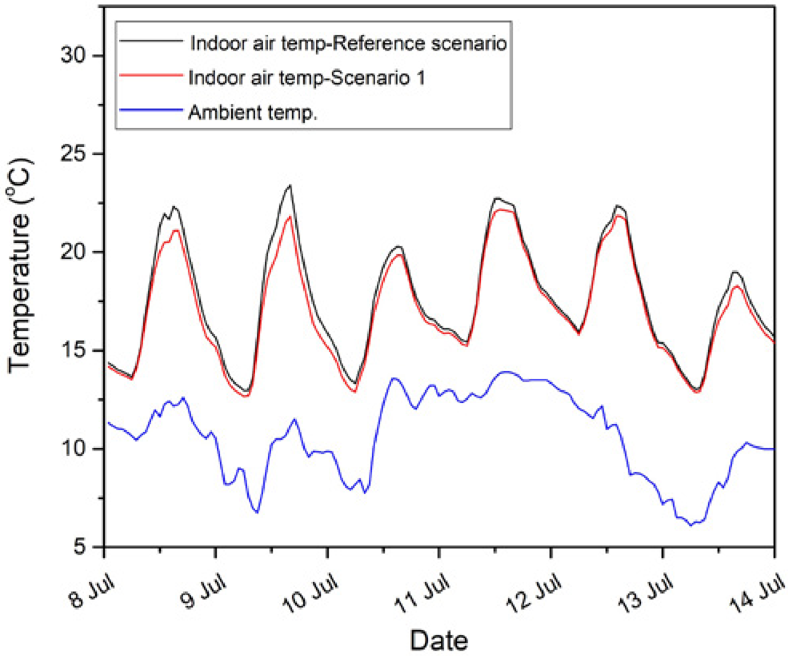

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Frankston beach station*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

The indoor air temperature is predicted to reduce from a range between 10.5 and 24.3 °C in reference scenario to a range between 10.0 and 22.8 °C in scenario 1 in Coldstream station.

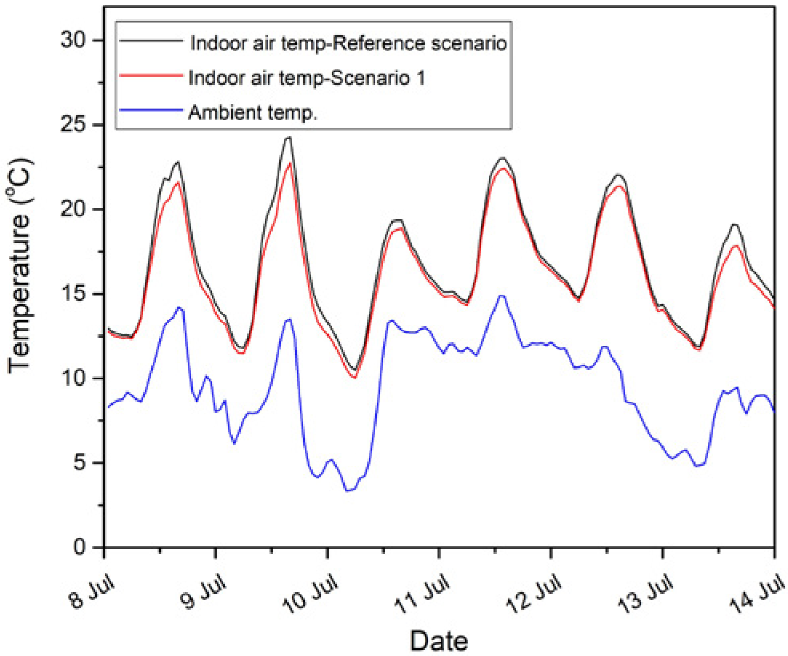

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Coldstream station* using 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 0.9 °C and 1.1 °C in Frankston beach and Coldstream stations, respectively.

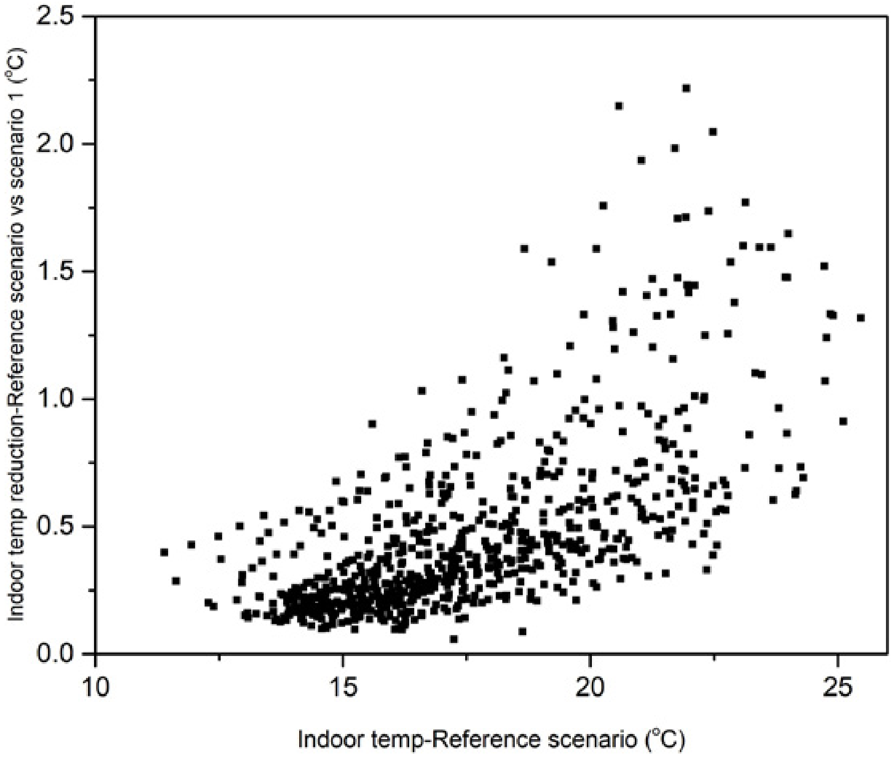

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather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

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

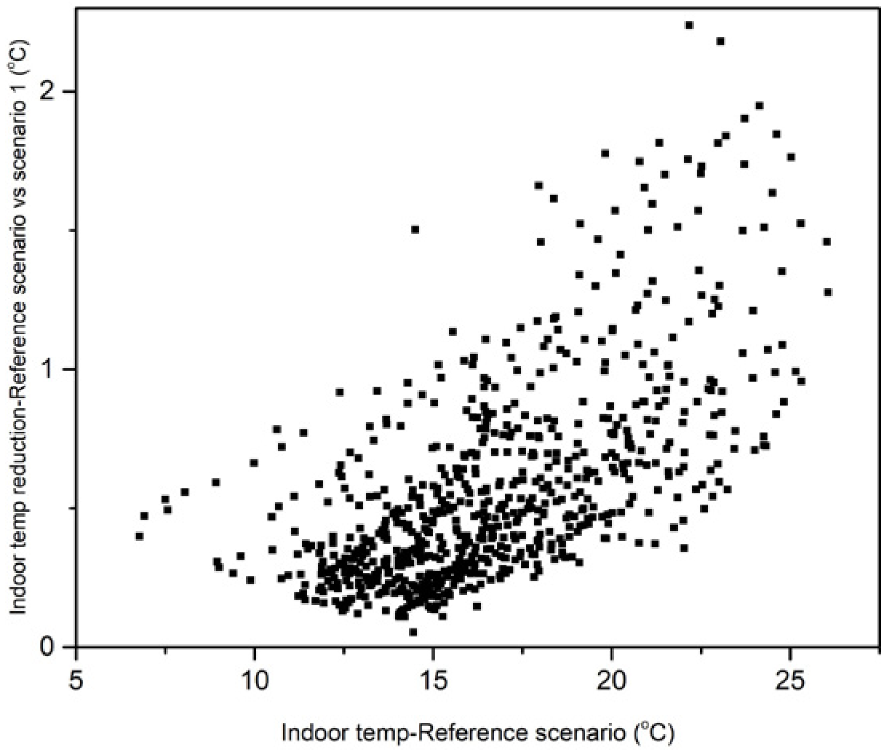

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather 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 Melbourne (i.e. Frankston beach and Coldstream) 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
Frankston beach	179	520	200	556
Coldstream	200	558	229	595

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

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 520 hours in reference scenario to 556 and hours and from 558 to 595 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 179 hours in reference scenario to 200 hours; and from 200 to 229 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

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

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Frankston beach	340	236	185
Coldstream	393	276	240

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 340 hours in reference scenario to 236 and 185 hours under scenario 1 and 2, in Frankston beach station; and from 393 hours in reference scenario to 276 and 240 hours under scenario 1 and 2 in Coldstream station, respectively.

6

ECONOMIC FEASIBILITY OF COOL ROOFS: EVALUATION OF REFURBISHMENT

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 the coating cool roof option.

The building and its energy performance

Building 13 is an existing, low-rise building, with a total air-conditioned area of 2.400 m² distributed on two levels. The 1.200 m² roof is insulated, but since it has a direct impact on half the air-conditioned area, it eventually results in moderate energy losses and, consequently, in a respective energy saving potential. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 13.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	17,1	30,4
Energy consumption after cool roof (MWh)	14,3	25,7
Energy savings (MWh)	2,8	4,7
Energy savings (%)	16,37 %	15,46 %
Area (m²)	1.200	1.200
Roof costs - Metal roof (AU$/m²)	38,0	38,0
Roof costs - Coating (AU$/m²)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m²)	15,0	15,0

Building 13 is a good example of an existing, low-rise office building, with a moderate energy conservation potential, where the coating cool roof is clearly a feasible investment under all conditions and the metal cool roof is feasible for high energy prices and for hotter weather conditions.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 16,37 % for the Frankston Beach weather conditions and of 15,46 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that vary between 14,3 % for the low energy price scenario for Frankston and 28,6 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

The metal cool roof is due to its higher initial investment cost only feasible for the high energy prices and the Coldstream conditions.

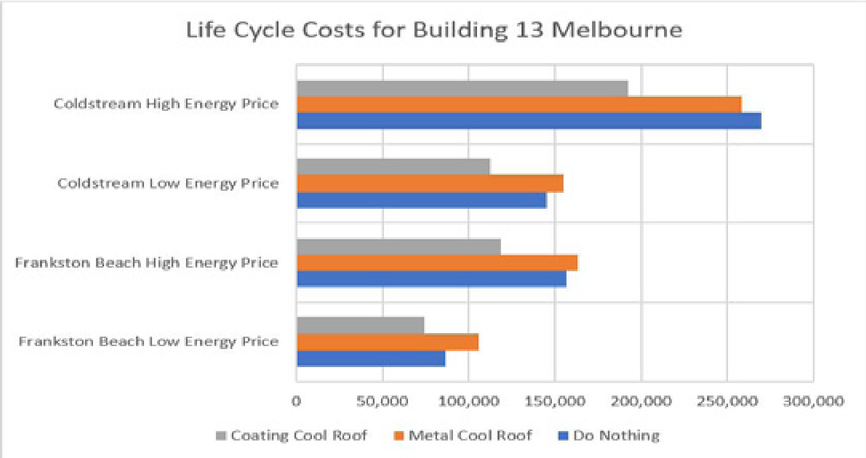

Figure 12. Life Cycle Costs for Building 13 for Frankston Beach and Coldstream stations.

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	-22,16 %	-4,19 %	-6,82 %	4,24 %
Coating Cool Roof	14,29 %	24,18 %	22,54 %	28,62 %

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 Melbourne, 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 9.4-13.3 kWh/m^2 to 6.5-8.9 kWh/m^2 . As computed, the two sum-mer months total cooling load saving by building-scale application of cool roofs is around 2.9-4.8 kWh/m^2. This is equivalent to approximately 29.4-36.0 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 4.9-6.4 kWh/m^2. This is equivalent to 45.2-52.4 % 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 (1.0-1.7 kWh/m^2) is significantly lower than the annual cooling load reduction (4.1-6.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 23.4-32.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.9-4.9 kWh/m^2 (~12.4-18.2%) (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 20.1-39.0 ^{o}C and 19.5-41.0 ^{o}C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 4.3 and 5.4 ^{o}C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 5.4 and 6.0 ^{o}C by com-bined building-scale and urban-scale application of cool roofs (scenario 2) in Observato-ry and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 and 23.4 ^{o}C in reference scenario to a range between 12.7 and 22.2 ^{o}C in reference with cool roof scenario (scenario 1) in

Frankston beach station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 10.5 and 24.3 °C in reference scenario to a range between 10.0 and 22.8 °C in reference with cool roof scenario (scenario 1) in Coldstream 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 0.9 °C and 1.1 °C in Frankston beach and Coldstream 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 520 hours in reference scenario to 556 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight in-crease in total number of hours below 19 °C from 558 hours in reference scenario to 595 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 179 hours in reference scenario to 200 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slight increase of number of hours below 19 °C from 200 hours to 229 hours during the operational hours (Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 340 hours under the reference scenario in Observa-tory station, which significantly decreases to 236 and 185 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduc-tion in number of hours above 26 °C from 393 hours in reference scenario to 276 in ref-erence with cool roof scenario (scenario 1) and 240 hours in cool roof and modified ur-ban temperature scenario (scenario 2), respectively (See Table 6).

• As it can be deduced from the feasibility analysis, given the fact that it is a low-rise building with roof insulation, the 'Do Nothing' approach has the higher costs over the building's life cycle, compared to the coating cool roof option, which leads to a reduction of life cycle costs, that vary between 14,3% for the low energy price scenario for Frankston and 28,6% for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost only feasible for the high energy prices and the Coldstream conditions. Building 13 is in that sense a good example of an existing, low-rise office building, with a moderate energy conservation potential, where the coating cool roof is clearly a feasible investment under all conditions and the metal cool roof is feasible for high energy prices and for hotter weather conditions.

B13

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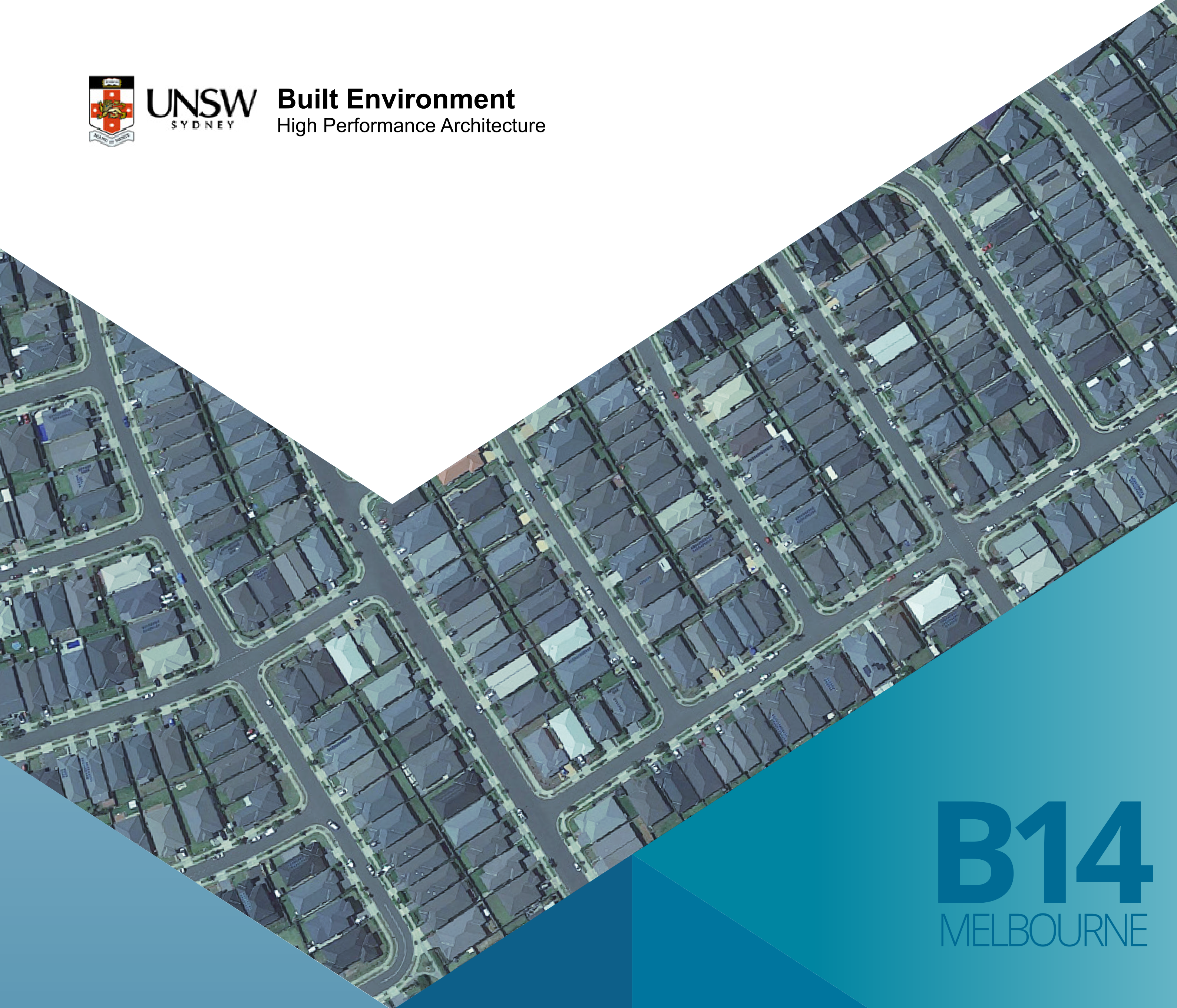

B14
MELBOURNE

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

1

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

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building with roof insulation from 7.4-10.1 kWh/m² to 6.9-9.4 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	8.4	9.1	7.8	8.5	6.4	6.6
Coldstream	9.4	10.0	8.5	9.0	7.1	7.2
Essendon	9.2	9.8	8.5	9.1	6.6	6.7
Frankston beach	6.6	7.4	6.0	6.9	4.6	4.7
Melbourne airport	9.4	10.1	8.7	9.4	6.8	6.9
Moorabbin airport	7.0	7.9	6.5	7.3	5.0	5.2
Olympic park	7.9	8.7	7.3	8.1	6.2	6.4

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 0.5-0.9 kWh/m² which is equivalent to 6.5-9.4 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 2.3-3.2 kWh/m² which is equivalent to 26.5-35.9 % 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	%
Avalon airport	0.6	6.8	0.6	6.5	2.0	24.0	2.5	27.1
Coldstream	0.9	9.8	0.9	9.4	2.3	24.4	2.7	27.6
Essendon	0.7	7.2	0.7	6.9	2.5	27.7	3.1	31.6
Frankston beach	0.5	7.7	0.5	7.2	2.0	30.3	2.7	35.9
Melbourne airport	0.7	7.3	0.7	7.0	2.6	28.1	3.2	32.0
Moorabbin airport	0.5	7.5	0.5	7.0	2.0	28.4	2.7	34.1
Olympic park	0.6	7.4	0.6	6.9	1.7	21.8	2.3	26.5

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

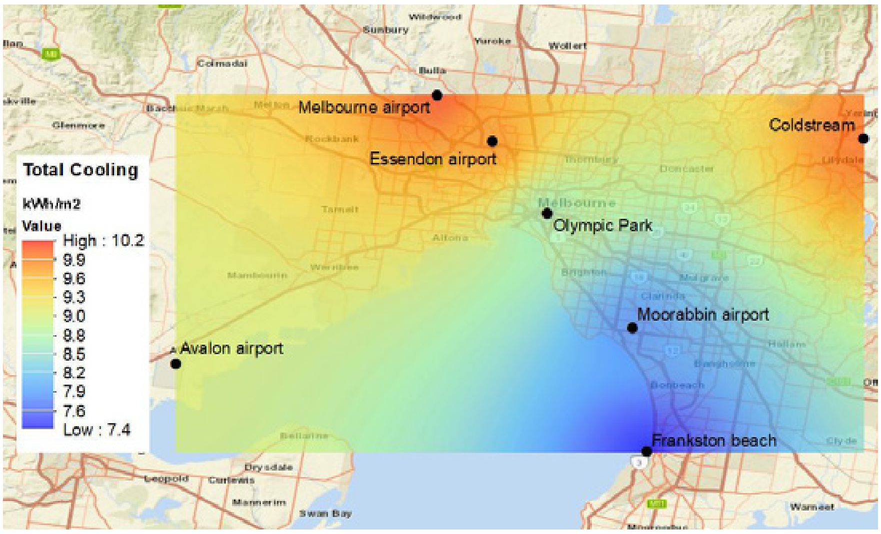

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

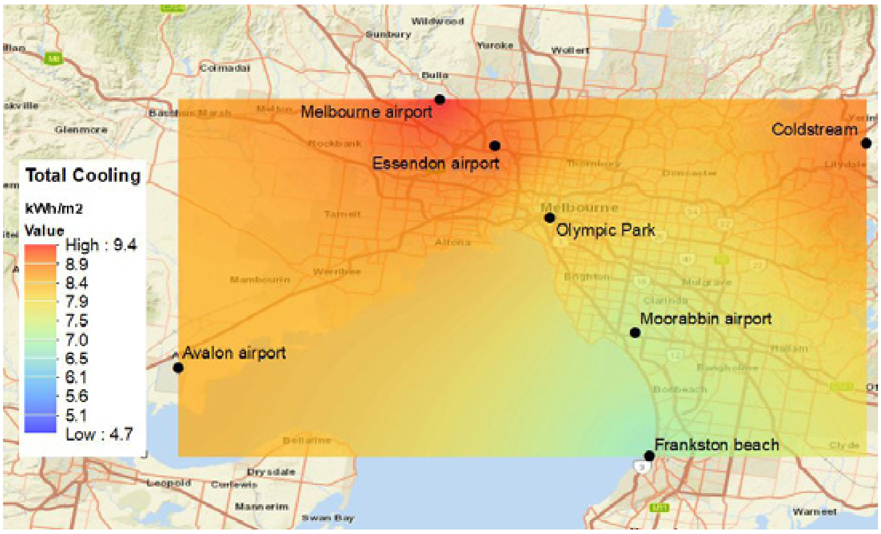

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

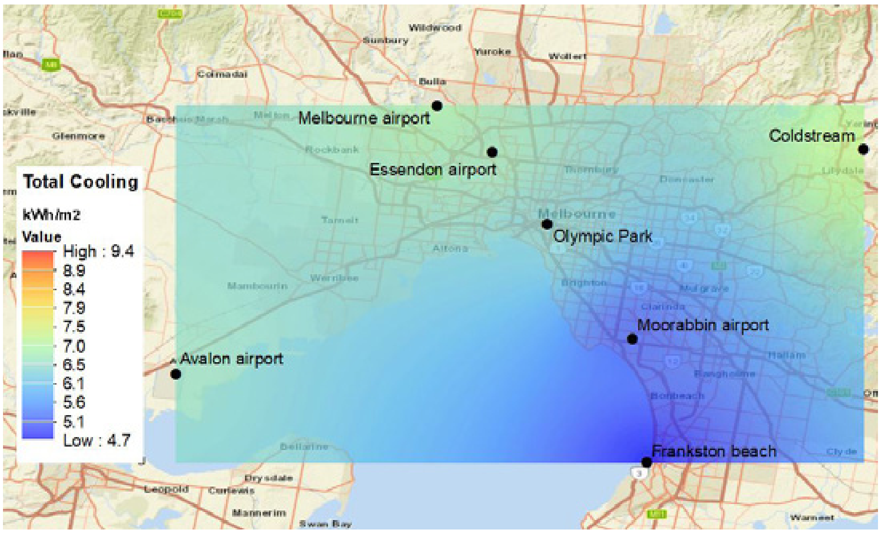

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Melbourne 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 (0.2-0.3 kWh/m²) is significantly lower than the annual cooling load reduction (0.7-1.2 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
Avalon airport	12.2	13.6	2.3	5.5	11.6	12.9	2.4	5.7
Coldstream	16.3	18.1	2.7	6.7	15.2	17.0	2.9	7.0
Essendon	16.1	17.6	1.9	4.7	15.3	16.7	2.0	4.9
Frankston beach	8.5	9.7	1.2	3.1	7.8	9.0	1.3	3.3
Melbourne airport	15.7	16.9	2.2	5.4	14.9	16.1	2.3	5.6
Moorabbin airport	13.7	15.2	1.6	3.9	12.9	14.5	1.7	4.1
Olympic park	14.8	16.4	1.3	3.4	13.8	15.4	1.4	3.6

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

The annual cooling load saving by building-scale application of cool roofs is around 4.7-7.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.5-0.8 kWh/m² (~2.5-4.1 %).

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	%
Avalon airport	0.7	5.4	0.7	5.1	0.1	0.2	0.5	3.8	0.5	2.5
Coldstream	1.1	6.8	1.2	6.4	0.2	0.3	0.9	4.9	0.8	3.3
Essendon	0.8	5.1	0.9	4.9	0.1	0.2	0.7	4.0	0.6	2.9
Frankston beach	0.7	8.2	0.7	7.5	0.1	0.2	0.6	6.4	0.5	4.1
Melbourne airport	0.8	4.9	0.8	4.7	0.1	0.2	0.7	3.7	0.6	2.6
Moorabbin airport	0.8	5.5	0.8	5.2	0.1	0.2	0.7	4.4	0.6	3.2
Olympic park	1.0	6.5	1.0	6.2	0.1	0.2	0.9	5.4	0.8	4.1

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

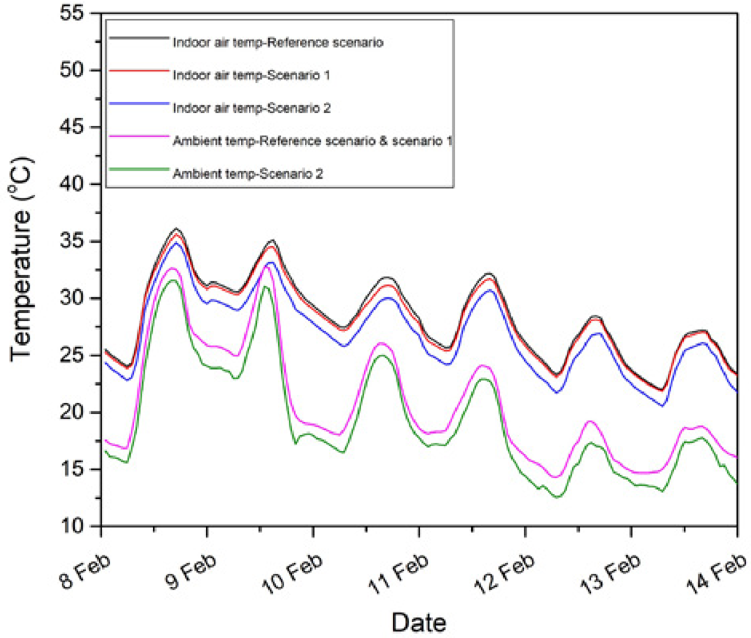

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

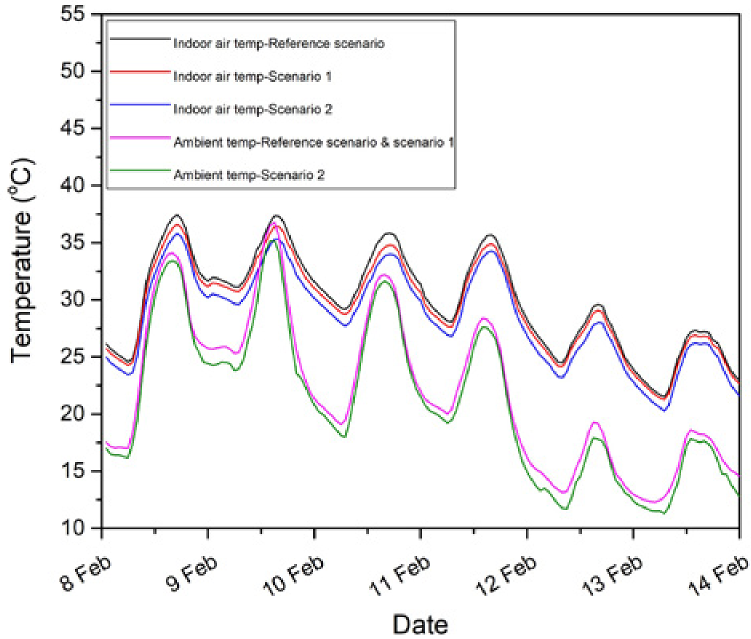

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.8-36.2 °C and 21.1-37.5 °C in Frankston beach and Coldstream stations, respectively.

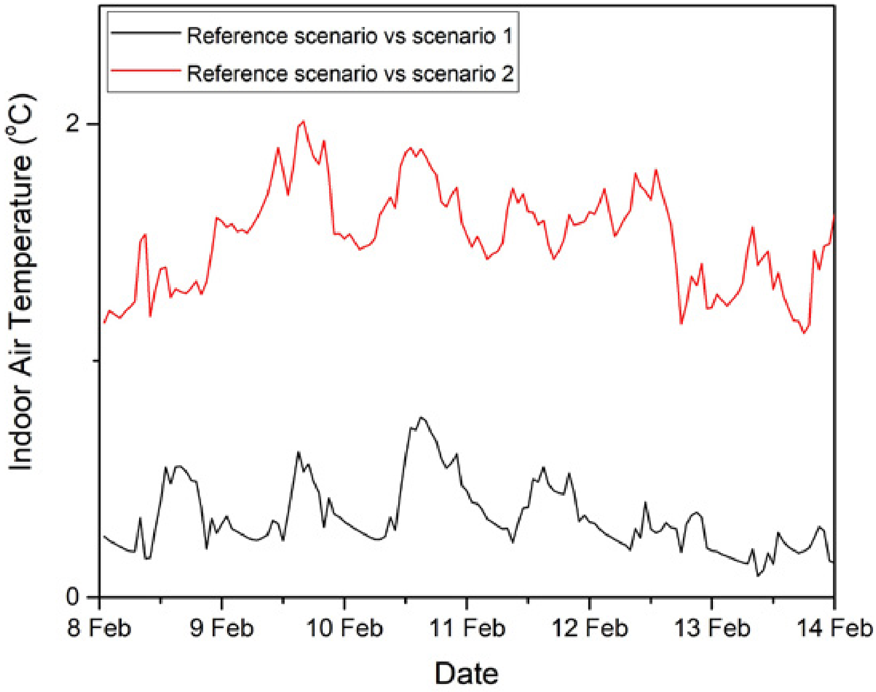

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.8 °C and 1.2 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.0 and 2.1 °C in Frankston beach and Coldstream stations, respectively.

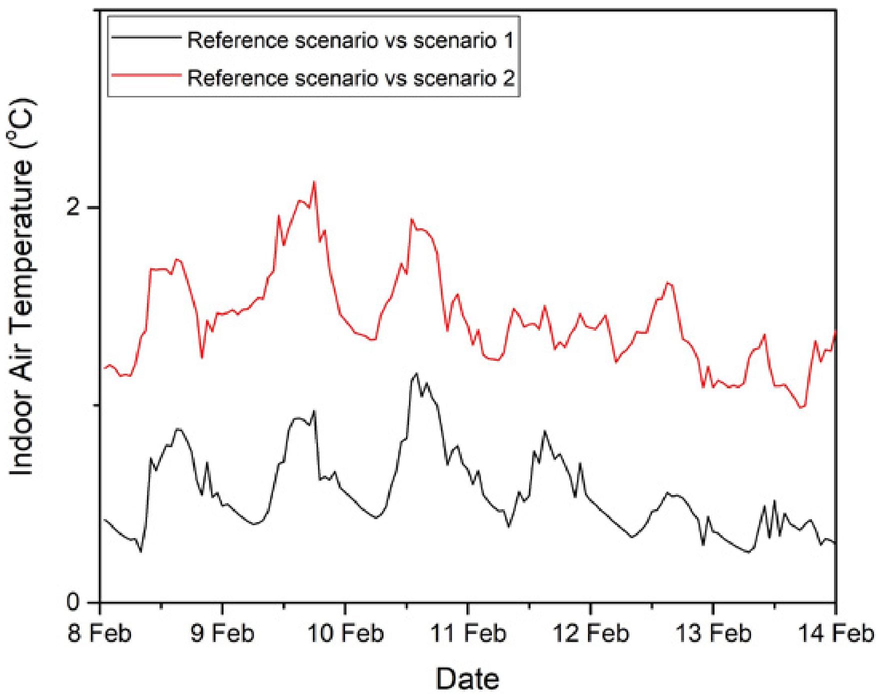

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions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

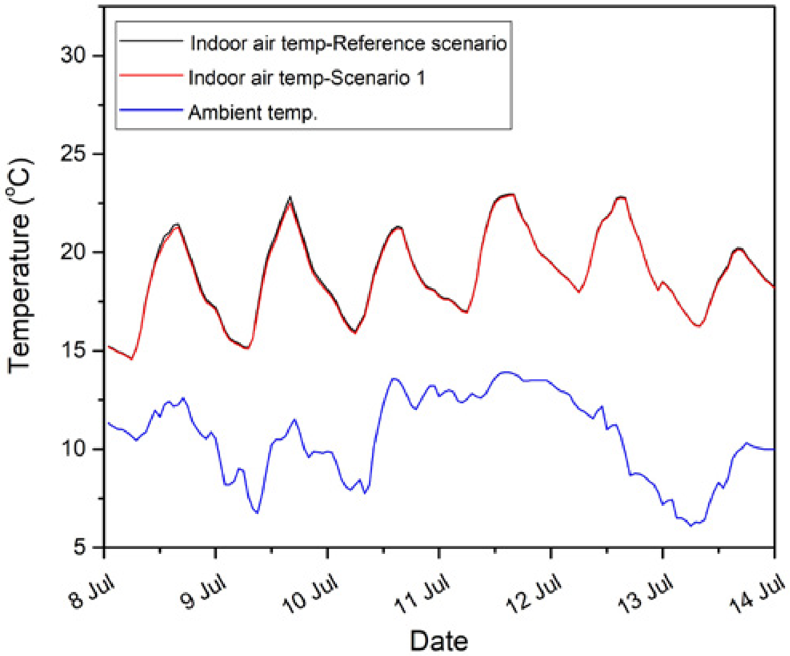

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Frankston beach station*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

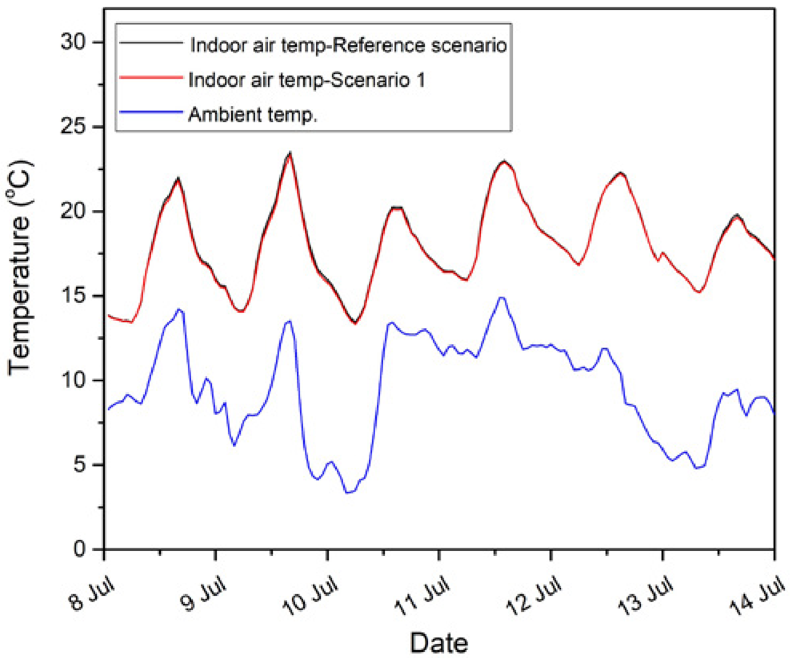

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Coldstream station* using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

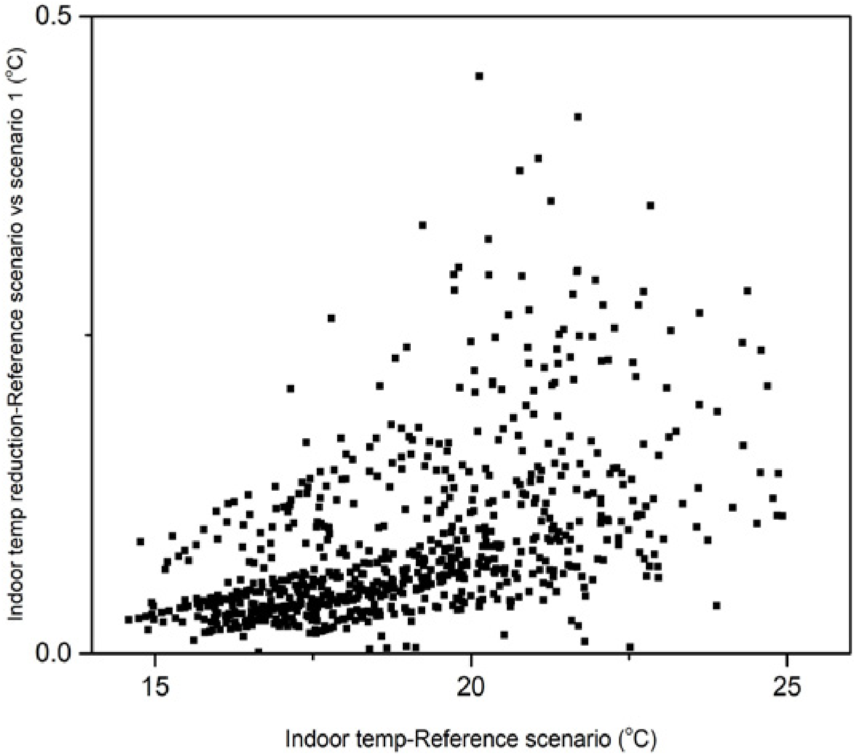

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather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

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

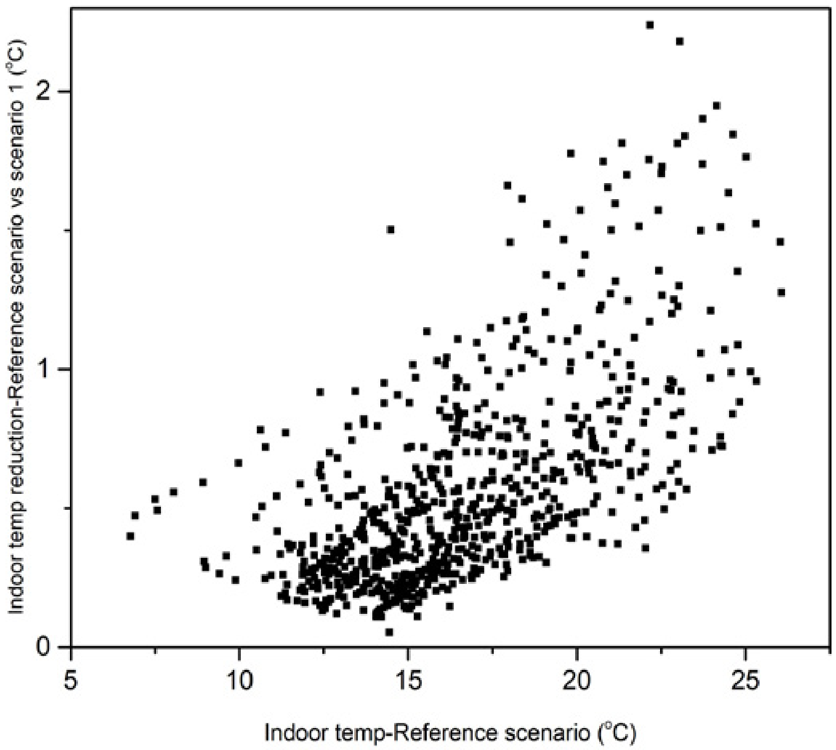

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather 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 Melbourne (i.e. Frankston beach and Coldstream) 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
Frankston beach	137	398	140	405
Coldstream	175	488	179	501

** 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 398 hours in reference scenario to 405 and hours and from 488 to 501 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 137 hours in reference scenario to 140 hours; and from 175 to 179 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

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

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Frankston beach	375	341	262
Coldstream	424	395	332

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 375 hours in reference scenario to 341 and 262 hours under scenario 1 and 2, in Frankston beach station; and from 424 hours in reference scenario to 395 and 332 hours under scenario 1 and 2 in Coldstream station, respectively.

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 the coating cool roof option.

The building and its energy performance

Building 14 is an existing, high-rise office building, with a total air-conditioned area of 12.000 m² distributed on ten levels. The 1.200 m² roof is insulated and, since it has a direct impact only on the last floor, it eventually results in limited energy losses and, consequently, in a respectively limited energy saving potential. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 14.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	61,4	119,0
Energy consumption after cool roof (MWh)	59,0	115,2
Energy savings (MWh)	2,4	3,8
Energy savings (%)	3,91 %	3,19 %
Area (m²)	1.200	1.200
Roof costs - Metal roof (AU$/m²)	38,0	38,0
Roof costs - Coating (AU$/m²)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m²)	15,0	15,0

Building 14 is a good example of an existing, insulated, high-rise office building, with a limited energy conservation potential, where the coating cool roof is clearly a feasible investment under all conditions and the metal cool roof is feasible only for high energy prices and for hotter weather conditions.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 3,91 % for the Frankston Beach weather conditions and of 3,19 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 20,3 % for the low energy price scenario for Frankston and 24,4 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

The metal cool roof is due to its higher initial investment cost only feasible for the high energy prices and the Coldstream conditions.

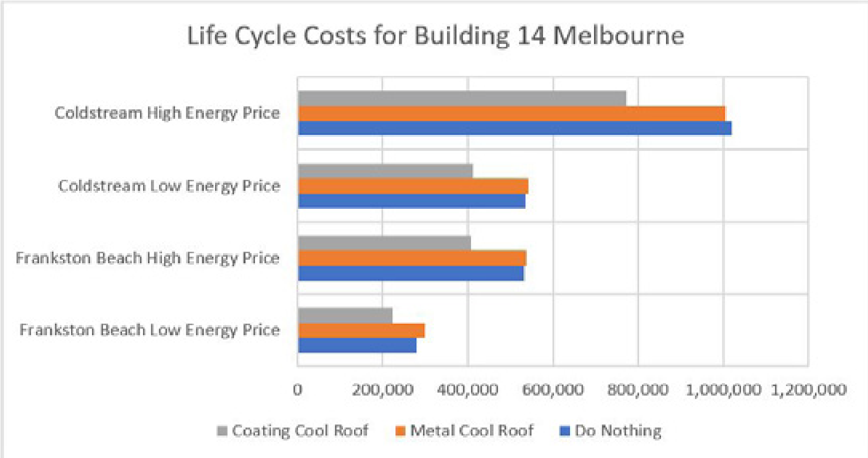

Figure 12. Life Cycle Costs for Building 14 for Frankston Beach and Coldstream stations.

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	-6,30 %	-0,70 %	-1,38 %	1,59 %
Coating Cool Roof	20,27 %	23,30 %	22,76 %	24,37 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building from 7.4-10.1 kWh/m^2 to 6.9-9.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5-0.9 kWh/m^2. This is equivalent to approximately 6.5-9.4 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 2.3-3.2 kWh/m^2. This is equivalent to 26.5-35.9 % 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 (0.2-0.3 kWh/m^2) is significantly lower than the annual cooling load reduction (0.7-1.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.7-7.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.5-0.8kWh/m^2 (~2.5-4.1 %) (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 21.8-36.2 °C and 21.1-37.5 °C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.8 and 1.2 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.0 and 2.1 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 Frankston beach and Coldstream stations, respectively (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C in Frankston beach and Coldstream 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 398 hours in reference scenario to 405 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight increase in total number of hours below 19 °C from 488 hours in reference scenario to 501 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 137 hours in reference scenario to 140 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slight increase of number of hours below 19 °C from 175 hours to 179 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 375 hours under the reference scenario in Frankston beach station, which decreases to 341 and 262 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 424 hours in reference scenario to 395 in reference with cool roof scenario (scenario 1) and 332 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 the coating cool roof option, which leads to a reduction of life cycle costs, that varies between 20,3% for the low energy price scenario for Frankston and 24,4% for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is due to its higher initial investment cost only feasible for the high energy prices and the Coldstream 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 investment under all conditions and the metal cool roof is feasible only for high energy prices and for hotter weather conditions.

B14

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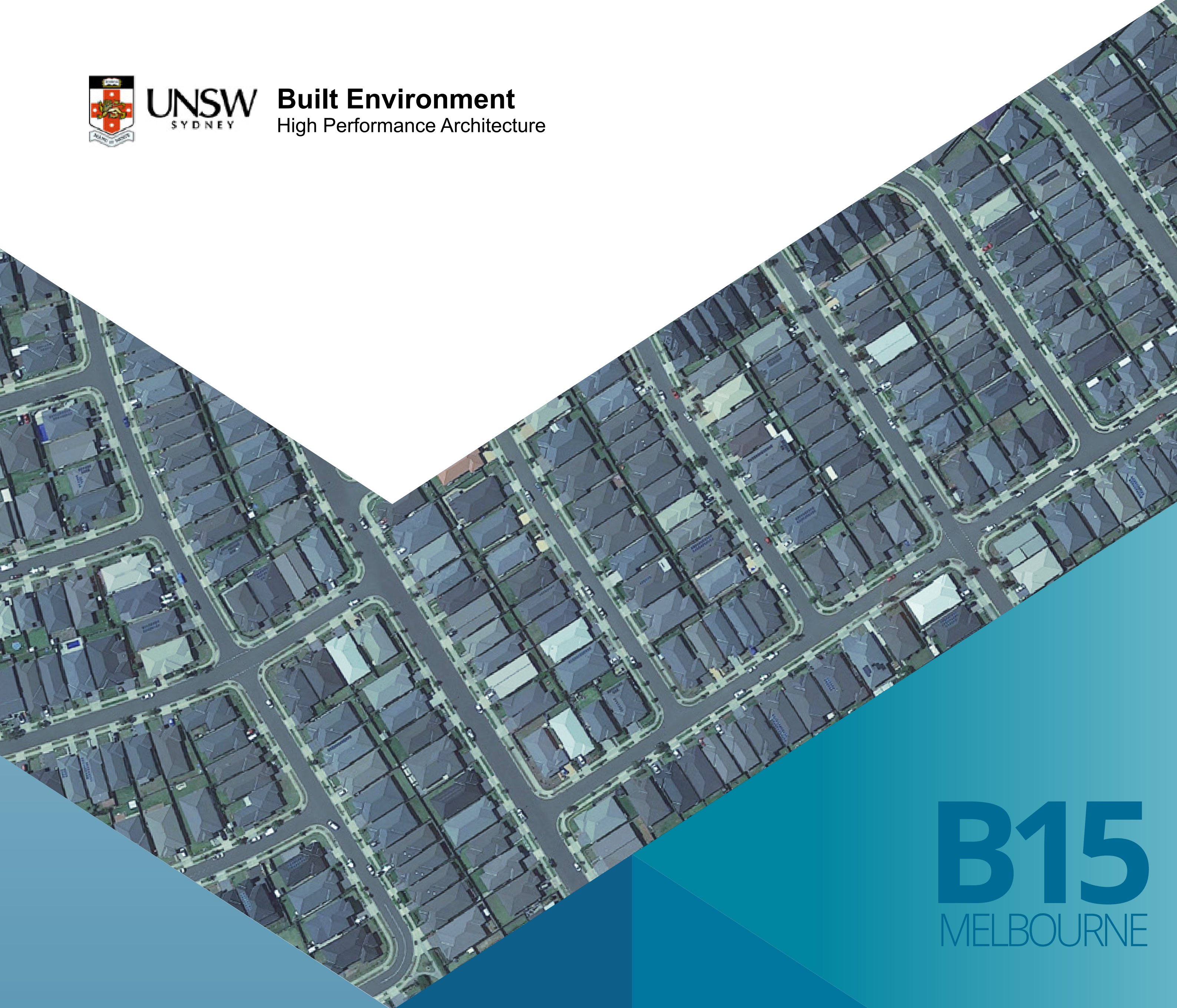

B15
MELBOURNE

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 Melbourne using weather data simulated by WRF.

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

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise shopping mall centre from 44.7-52.9 kWh/m² to 37.3-43.0 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Avalon airport	44.2	47.1	37.3	40.2	34.0	35.0
Coldstream	50.1	52.9	40.4	43.0	36.3	37.3
Essendon	46.8	49.7	39.4	42.3	34.6	35.3
Frankston beach	40.6	44.7	33.5	37.3	29.1	30.2
Melbourne airport	47.5	50.4	40.0	42.9	35.2	35.9
Moorabbin airport	41.6	45.6	34.5	38.3	30.0	31.1
Olympic park	44.0	47.5	36.8	40.2	33.5	34.6

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

For Scenario 1, the total cooling load saving is around 6.9-9.8 kWh/m² which is equivalent to 14.7-18.6 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 12.2-15.6 kWh/m² which is equivalent to 25.8-32.4 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Avalon airport	6.8	15.4	6.9	14.7	10.1	23.0	12.2	25.8
Coldstream	9.7	19.4	9.8	18.6	13.8	27.5	15.6	29.4
Essendon	7.4	15.7	7.5	15.0	12.2	26.0	14.4	29.0
Frankston beach	7.2	17.7	7.4	16.5	11.5	28.3	14.5	32.4
Melbourne airport	7.5	15.7	7.6	15.1	12.3	25.9	14.5	28.8
Moorabbin airport	7.1	17.1	7.3	16.0	11.6	27.8	14.6	31.9
Olympic park	7.2	16.3	7.3	15.4	10.5	23.8	12.9	27.1

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

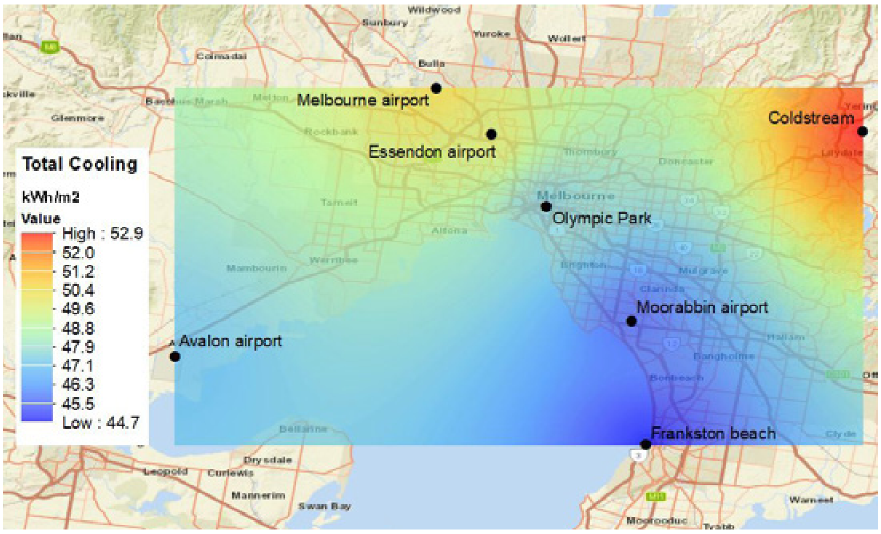

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

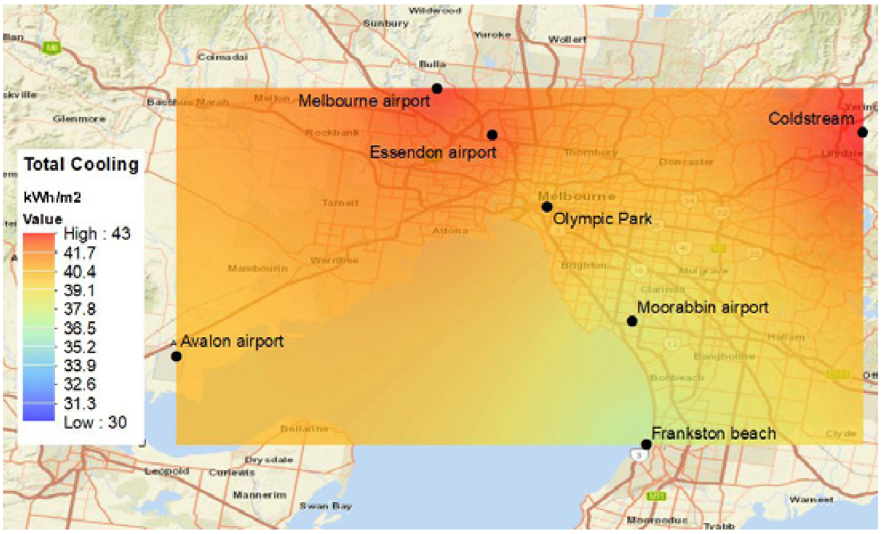

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

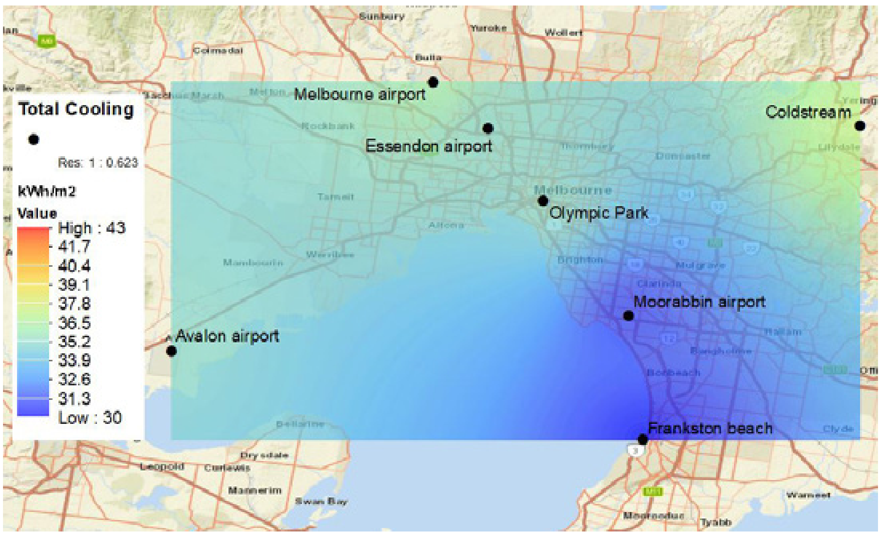

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.4-0.9 kWh/m²) is significantly lower than the annual cooling load reduction (15.5-22.1 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
Avalon airport	99.0	111.6	3.1	9.7	83.5	95.5	3.3	10.3
Coldstream	111.3	122.8	3.8	11.9	90.8	101.7	4.1	12.8
Essendon	107.0	117.3	2.6	8.2	90.7	100.7	2.8	8.7
Frankston beach	89.3	102.9	1.6	4.7	70.2	83.1	1.7	5.1
Melbourne airport	102.1	110.1	2.9	9.3	86.9	94.6	3.1	9.9
Moorabbin airport	103.2	115.4	2.3	6.9	86.8	98.6	2.4	7.3
Olympic park	116.0	128.4	2.0	6.0	94.5	106.3	2.1	6.5

The annual cooling load saving by building-scale application of cool roofs is around 14.1-19.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 15.0-21.6 kWh/m² (~12.5-18.0 %).

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 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	%
Avalon airport	15.4	15.6	16.0	14.4	0.2	0.6	15.3	14.9	15.5	12.7
Coldstream	20.5	18.4	21.0	17.1	0.3	0.9	20.2	17.6	20.1	14.9
Essendon	16.2	15.2	16.6	14.2	0.2	0.5	16.1	14.7	16.1	12.9
Frankston beach	19.1	21.4	19.8	19.2	0.1	0.4	18.9	20.8	19.4	18.0
Melbourne airport	15.2	14.9	15.5	14.1	0.2	0.5	15.1	14.3	15.0	12.5
Moorabbin airport	16.4	15.9	16.8	14.6	0.1	0.4	16.2	15.4	16.4	13.4
Olympic park	21.6	18.6	22.1	17.2	0.1	0.4	21.4	18.1	21.6	16.1

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

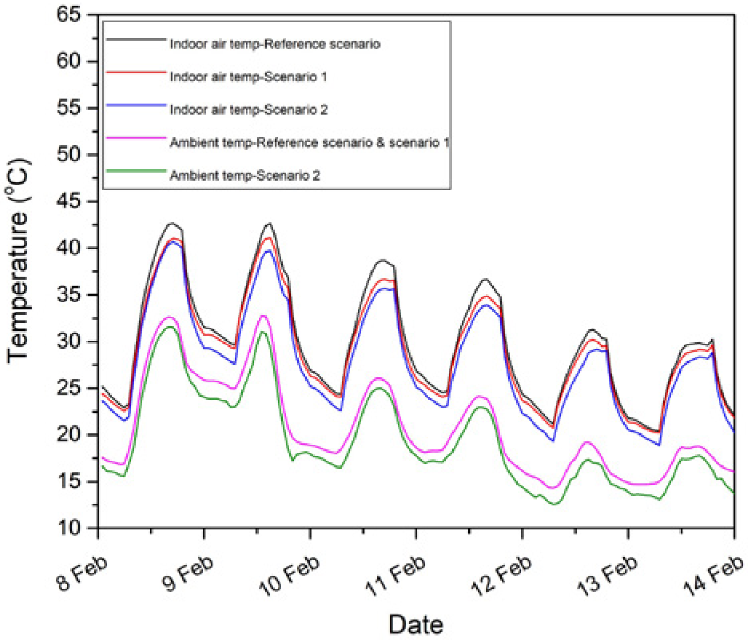

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

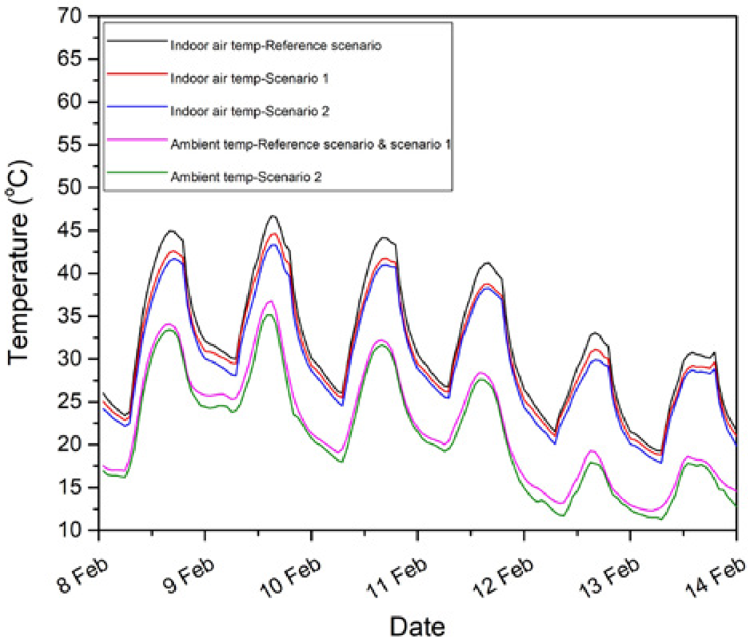

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 20.4-42.7 °C and 19.3-46.7 °C in Frankston beach and Coldstream stations, respectively.

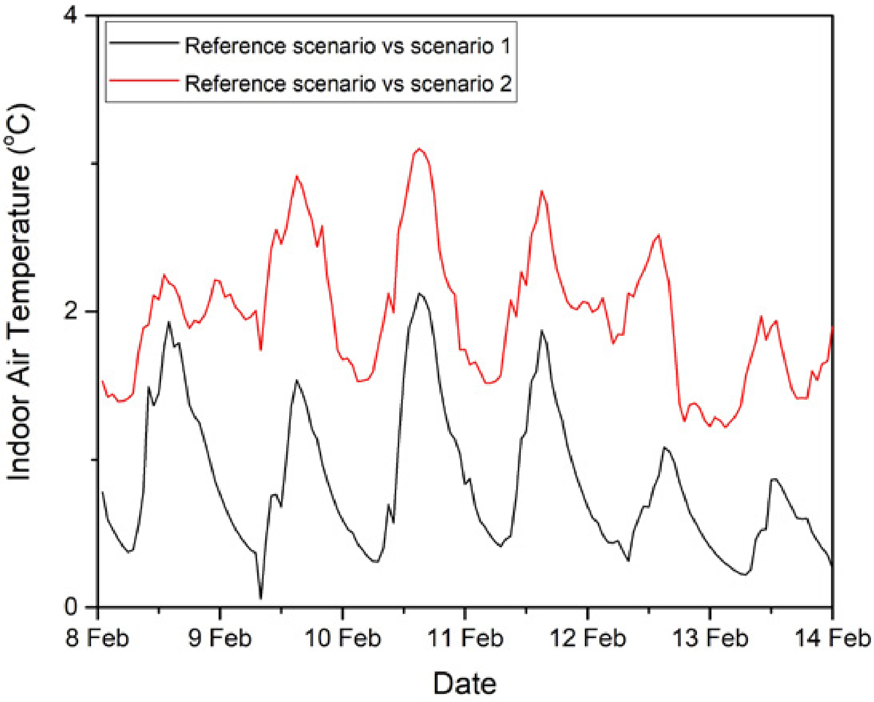

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free-floating conditions during a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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.1 °C and 2.7 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.1 °C and 3.7 °C in Frankston beach and Coldstream stations, respectively.

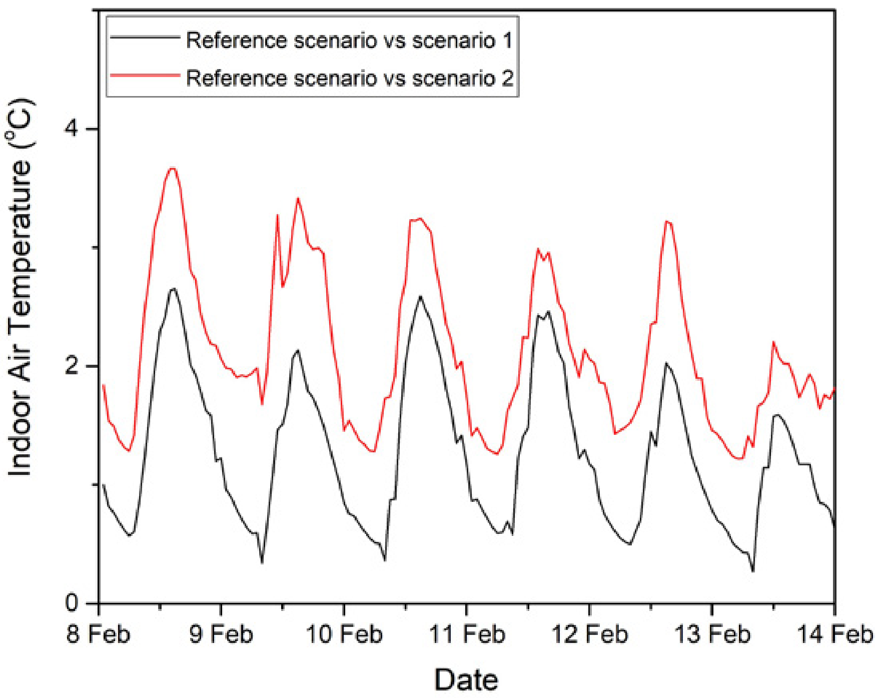

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) an existing new low-rise shopping mall centre under free-floating conditions during a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

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 12.2-26.3 °C in reference scenario to a range 12.2-25.2 °C in scenario 1 in Frankston beach station.

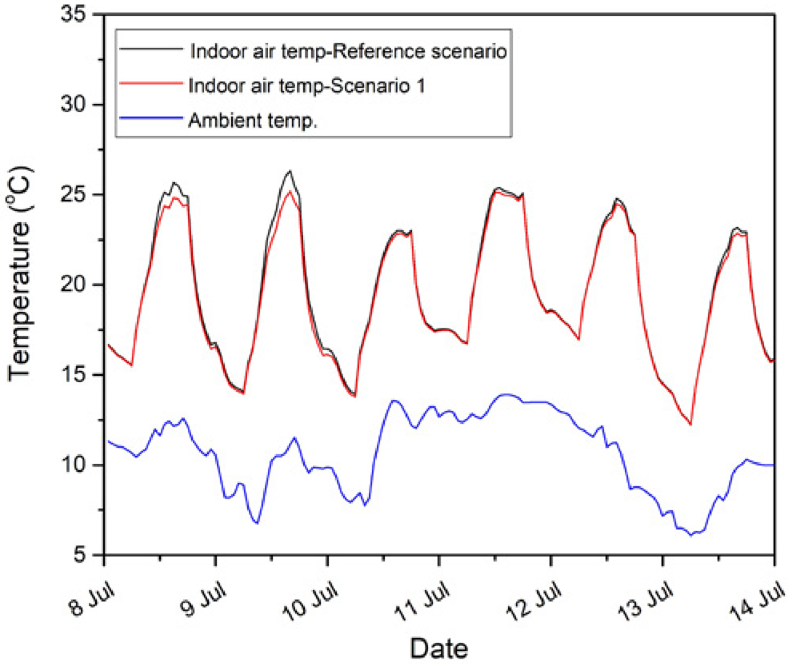

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Frankston beach station* using annual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

The indoor air temperature is predicted to reduce from a range 10.6-27.6 °C in reference scenario to a range 10.4-26.6 °C in scenario 1 in Coldstream station.

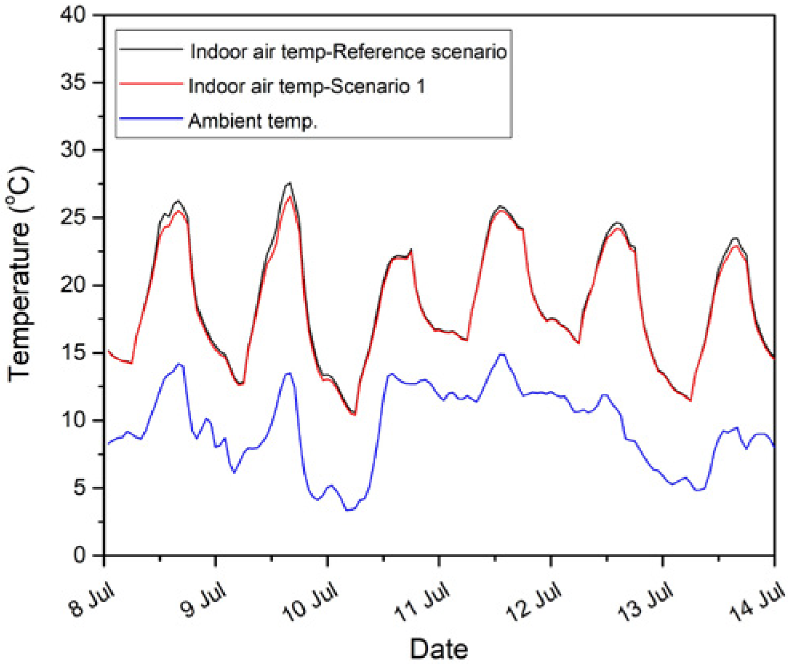

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Coldstream station* using annual measured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

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

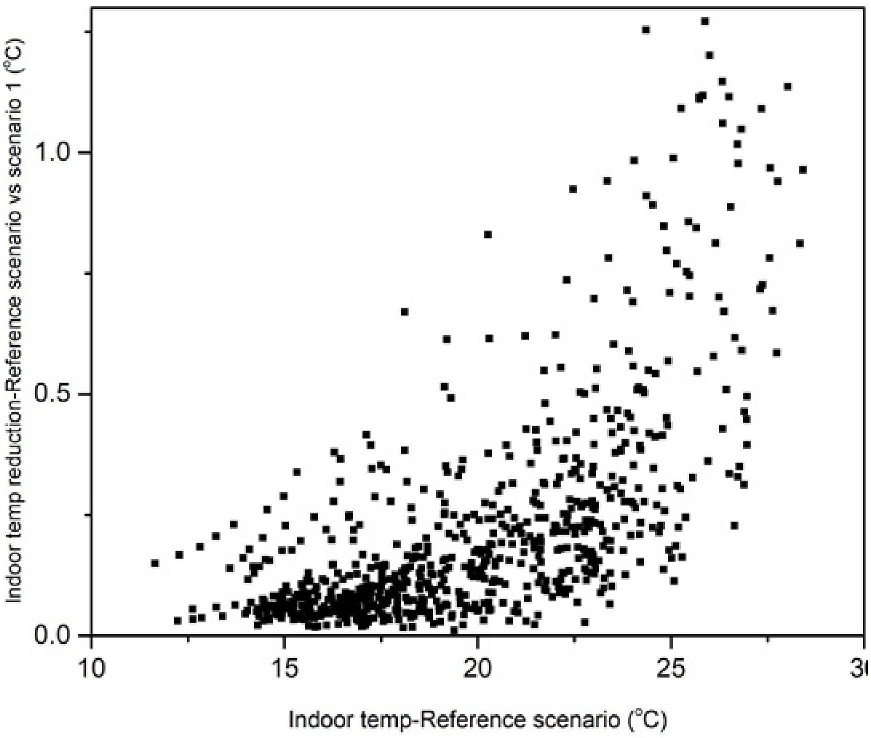

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

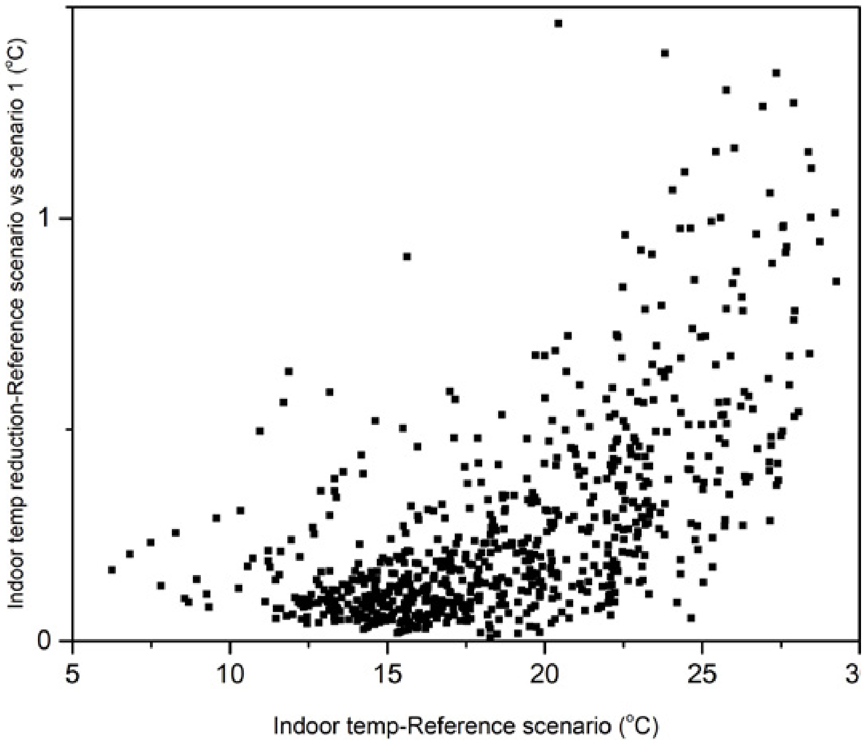

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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
Frankston beach	48	350	54	364
Coldstream	84	407	86	412

** 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 350 hours in reference scenario to 364 hours, and from 407 to 412 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 48 hours in reference scenario compared to 54 hours in scenario 1 in Frankston beach; and from 84 to 86 hours in Coldstream 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
Frankston beach	401	378	333
Coldstream	436	401	364

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 401 hours in reference scenario to 378 and 333 hours under scenario 1 and 2 in Frankston beach station; and from 436 hours in reference scenario to 6401 and 364 hours under scenario 1 and 2 in Coldstream station, respectively.

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 the coating cool roof option.

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 moderate to significant energy losses and, consequently, an important energy saving potential. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 15.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	94,7	118,5
Energy consumption after cool roof (MWh)	77,6	100,8
Energy savings (MWh)	17,1	17,7
Energy savings (%)	18,06 %	14,94 %
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 14 is a good example of an existing, insulated, high-rise office building, with a limited energy conservation potential, where the coating cool roof is clearly a feasible investment under all conditions and the metal cool roof is feasible only for high energy prices and for hotter weather conditions.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 18,06 % for the Frankston Beach weather conditions and of 14,94 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a reduction of life cycle costs, that varies between 20,3 % for the low energy price scenario for Frankston and 24,4 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

The metal cool roof is due to its higher initial investment cost only feasible for the high energy prices and the Coldstream conditions.

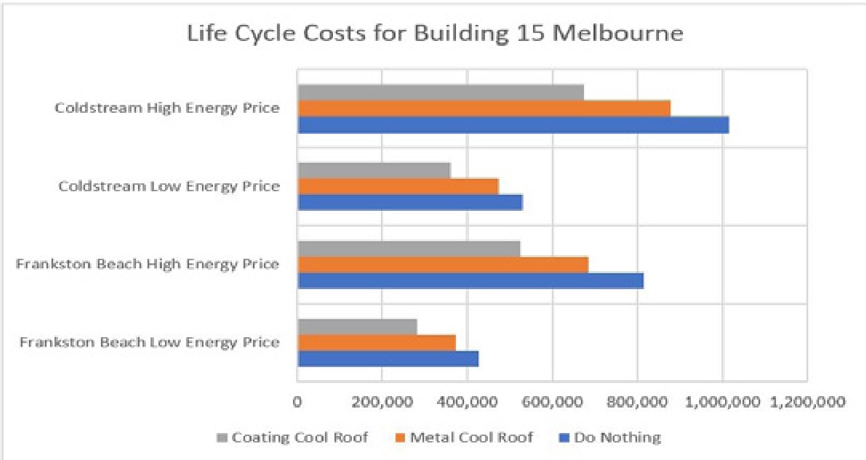

Figure 12. Life Cycle Costs for Building 15 for Frankston Beach and Coldstream stations.

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	12,19 %	15,78 %	10,61 %	13,47 %
Coating Cool Roof	33,57 %	35,55 %	32,01 %	33,58 %

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 Melbourne, 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 44.7-52.9 kWh/m^2 to 37.3-43.0 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 6.9-9.8 kWh/m^2. This is equivalent to approximately 14.7-18.6 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 12.2-15.6 kWh/m^2. This is equivalent to 25.8-32.4 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.4-0.9 kWh/m^2) is significantly lower than the annual cooling load reduction (15.5-22.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 14.1-19.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 15.0-21.6 kWh/m^2 (~12.5-18.0 %) (Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 20.4-42.7 ^{o}C and 19.3-46.7 ^{o}C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.1 and 2.7 ^{o}C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.1and 3.7 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 12.2-26.3 ^{o}C in reference scenario to a range between 12.2-25.2 ^{o}C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 10.6-27.6 ^{o}C in reference scenario to a range between 10.4-26.6^{o}C in reference with cool roof scenario (scenario 1) in Coldstream station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.6 ^{o}C and 0.7 ^{o}C in Frankston beach and Coldstream 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 350 hours in reference scenario to 354 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight increase in total number of hours below 19 ^{o}C from 407 hours in reference scenario to 412 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 ^{o}C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 ^{o}C during operational hours of the building (i.e. 7 am-6 pm) is expected to increase from 48 hours in reference scenario to 54 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slight increase of number of hours below 19 ^{o}C from 84 hours to 86 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 401 hours under the reference scenario in Frankston beach station, which decreases to 378 and 333 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 ^{o}C from 436hours in reference scenario to 401in reference with cool roof scenario (scenario 1) and 364 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 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 10,6 % for the metal roof, the low energy price scenario and for Coldstream conditions and 35,5 % for the cool coating, the high energy scenario and for Frankston Beach 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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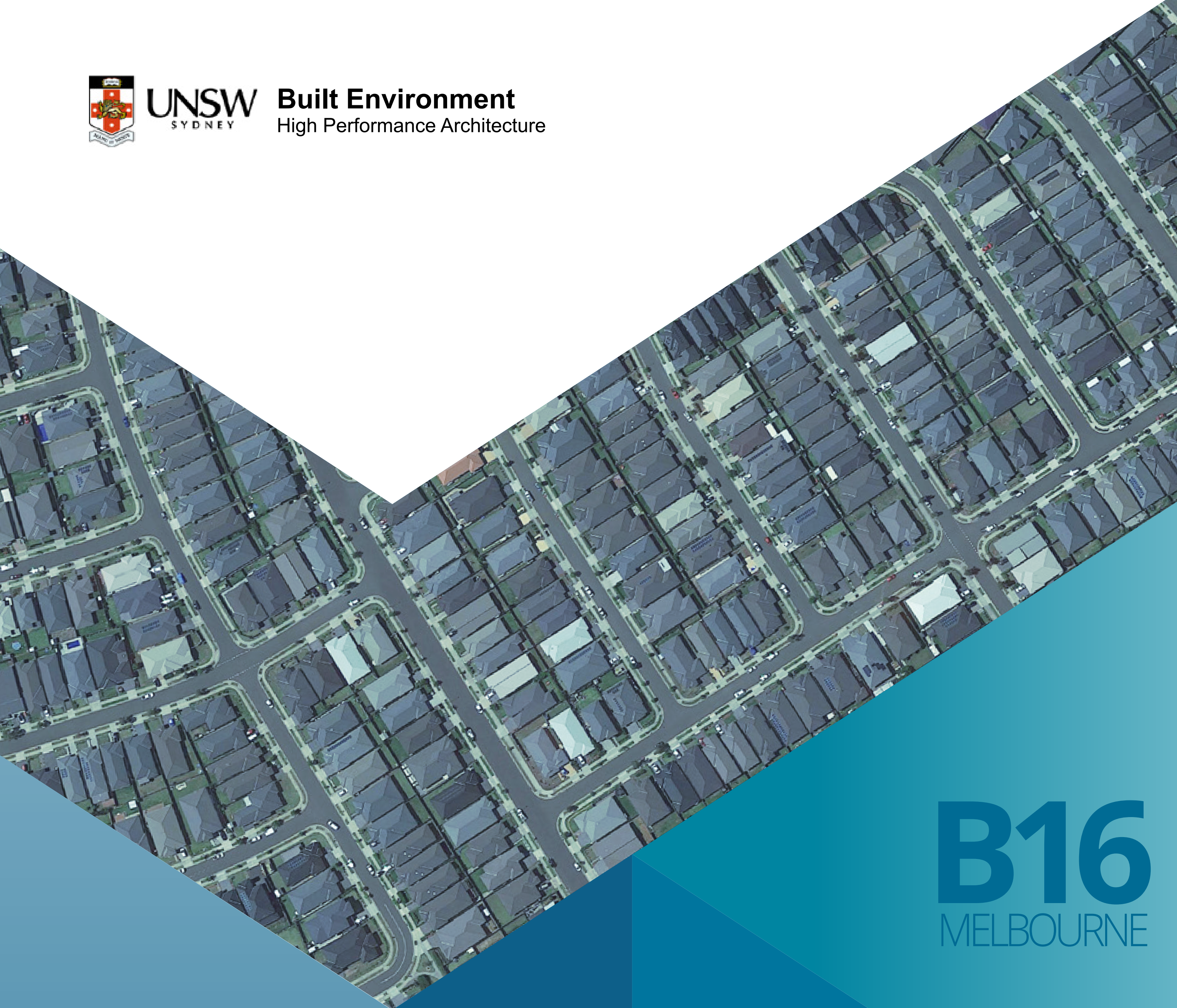

B16
MELBOURNE

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 Melbourne using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing high-rise shopping mall centre from 40.2-46.8 kWh/m² to 38.0-43.7 kWh/m².

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

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/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)
Avalon airport	39.9	42.9	37.9	40.8	34.4	35.4
Coldstream	44.1	46.8	41.0	43.7	36.7	37.7
Essendon	42.0	45.0	39.8	42.7	34.8	35.6
Frankston beach	36.2	40.2	34.1	38.0	29.6	30.7
Melbourne airport	42.7	45.6	40.5	43.3	35.4	36.2
Moorabbin airport	37.1	41.1	35.0	39.0	30.4	31.5
Olympic park	39.4	43.0	37.3	40.8	33.9	35.1

For Scenario 1, the total cooling load saving is around 2.1-3.2 kWh/m² which is equivalent to 4.8-6.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.5-9.7 kWh/m² which is equivalent to 17.4-23.7 % total cooling load reduction.

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

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Avalon airport	2.0	5.1	2.1	4.8	5.5	13.7	7.5	17.4
Coldstream	3.1	7.1	3.2	6.8	7.4	16.8	9.1	19.5
Essendon	2.2	5.2	2.2	5.0	7.2	17.1	9.4	20.9
Frankston beach	2.2	5.9	2.2	5.5	6.7	18.4	9.6	23.7
Melbourne airport	2.3	5.3	2.3	5.0	7.3	17.1	9.5	20.7
Moorabbin airport	2.1	5.7	2.2	5.3	6.8	18.2	9.7	23.6
Olympic park	2.1	5.4	2.2	5.1	5.5	14.0	7.9	18.3

In the eleven weather stations in Melbourne, 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.

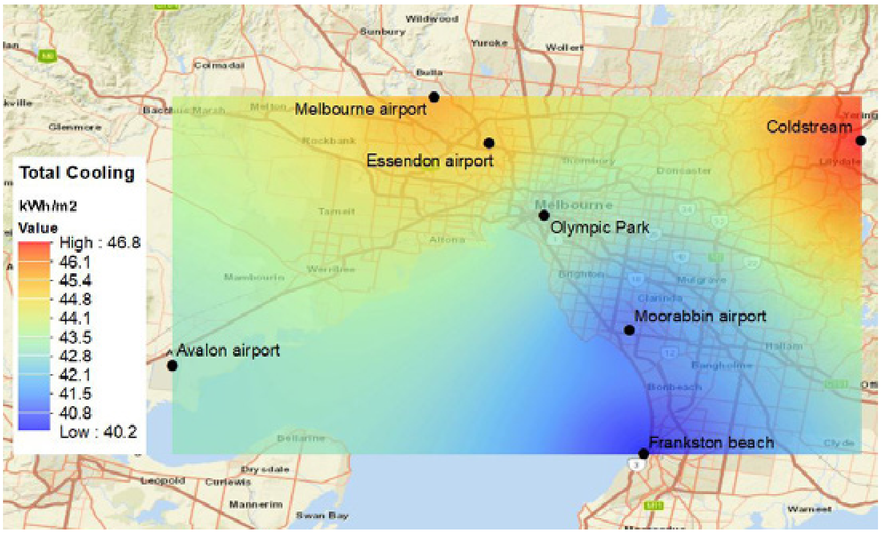

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

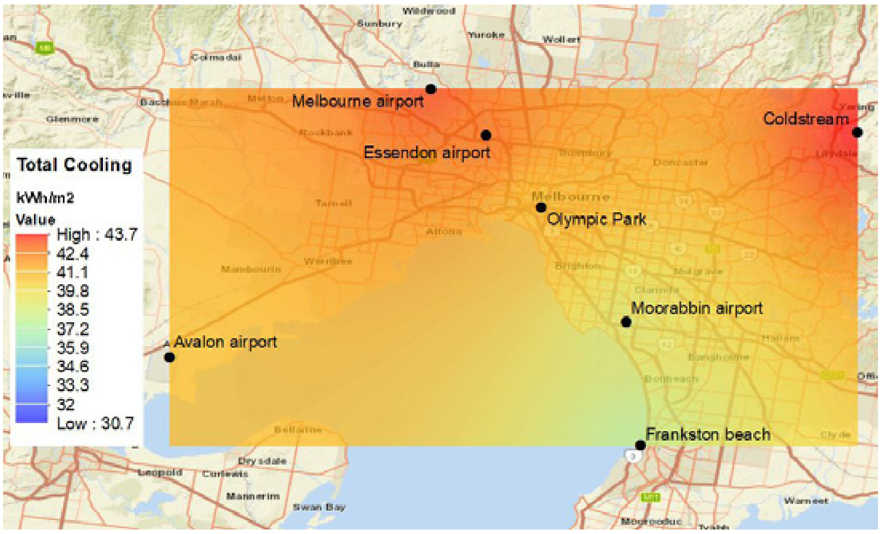

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

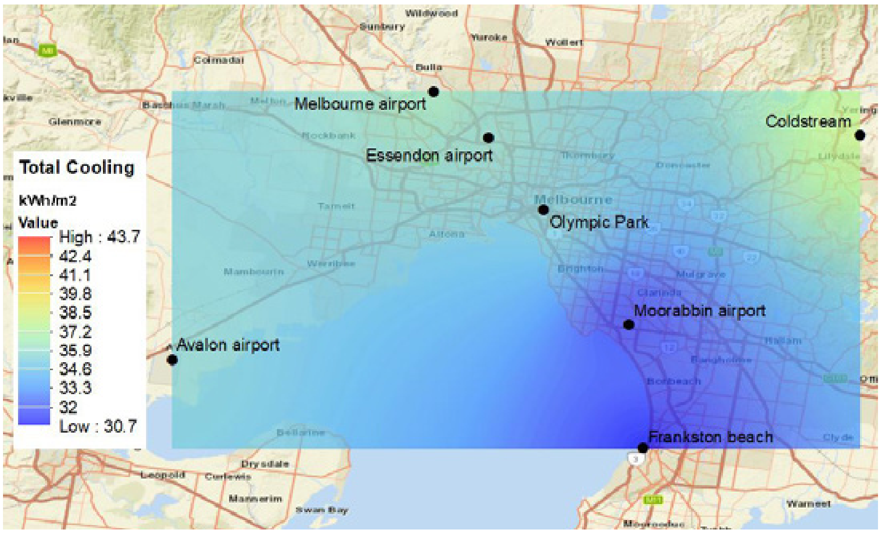

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1-0.3 kWh/m²) is significantly lower than the annual cooling load reduction (4.3-6.1 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
Avalon airport	89.7	102.2	2.4	7.9	85.4	97.8	2.4	8.1
Coldstream	98.0	109.4	3.1	10.2	92.1	103.3	3.2	10.5
Essendon	97.8	108.3	1.9	6.3	93.3	103.6	1.9	6.5
Frankston beach	79.6	93.1	1.0	3.1	74.0	87.3	1.0	3.3
Melbourne airport	93.0	101.0	2.2	7.4	88.7	96.7	2.2	7.6
Moorabbin airport	94.4	106.6	1.6	5.1	89.9	102.0	1.6	5.2
Olympic park	104.5	116.8	1.3	4.2	98.3	110.5	1.3	4.4

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 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 4.3-6.2 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.2-6.2 kWh/m² (~3.9-5.9 %).

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	%
Avalon airport	4.3	4.8	4.4	4.3	0.1	0.2	4.2	4.6	4.3	3.9
Coldstream	6.0	6.1	6.1	5.6	0.1	0.3	5.9	5.8	5.8	4.9
Essendon	4.5	4.6	4.7	4.3	0.0	0.2	4.5	4.5	4.5	3.9
Frankston beach	5.5	7.0	5.8	6.2	0.0	0.1	5.5	6.8	5.7	5.9
Melbourne airport	4.2	4.6	4.3	4.3	0.0	0.2	4.2	4.4	4.2	3.8
Moorabbin airport	4.5	4.8	4.7	4.4	0.0	0.1	4.5	4.7	4.5	4.1
Olympic park	6.2	5.9	6.4	5.4	0.0	0.1	6.2	5.8	6.2	5.1

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

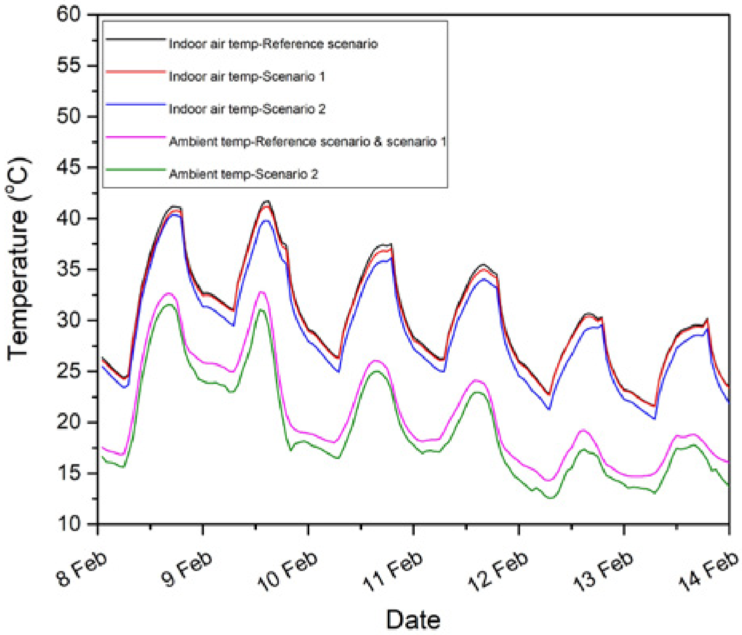

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

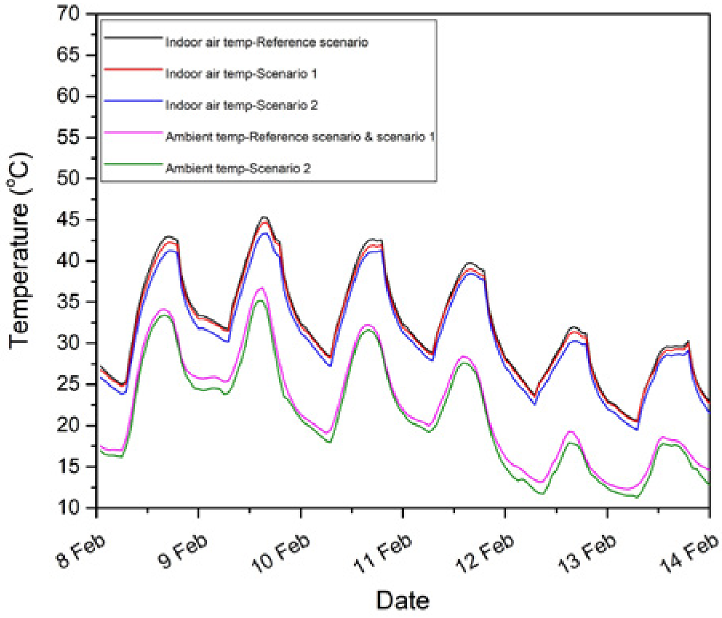

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 21.6-41.7 °C and 20.6-45.45 °C in Frankston beach and Coldstream stations, respectively.

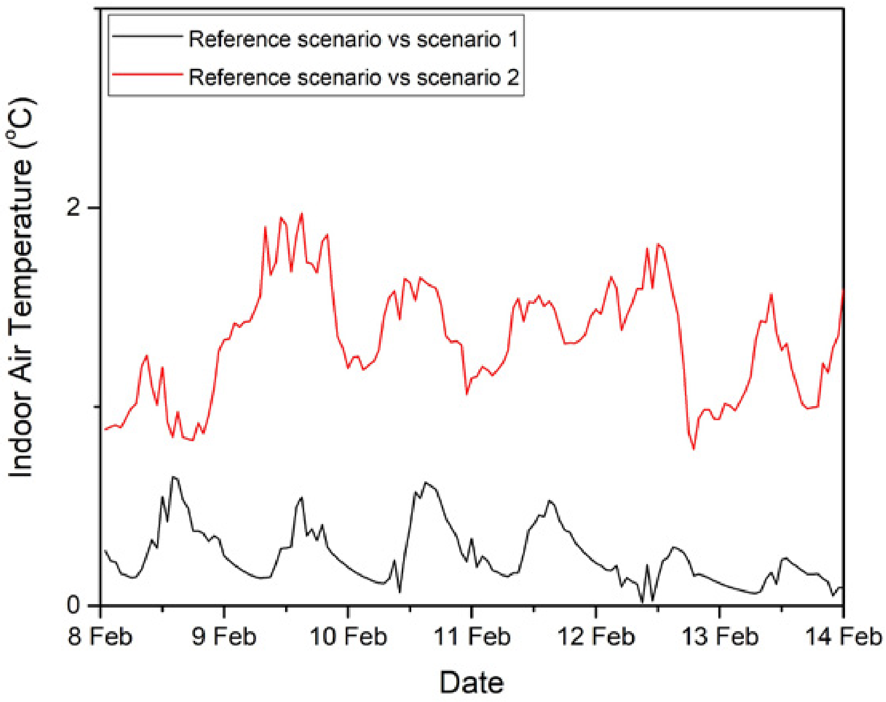

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free-floating conditions during a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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.7 °C and 0.9 °C in Frankston beach and Coldstream stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.0 °C and 2.1 °C in Frankston beach and Coldstream stations, respectively.

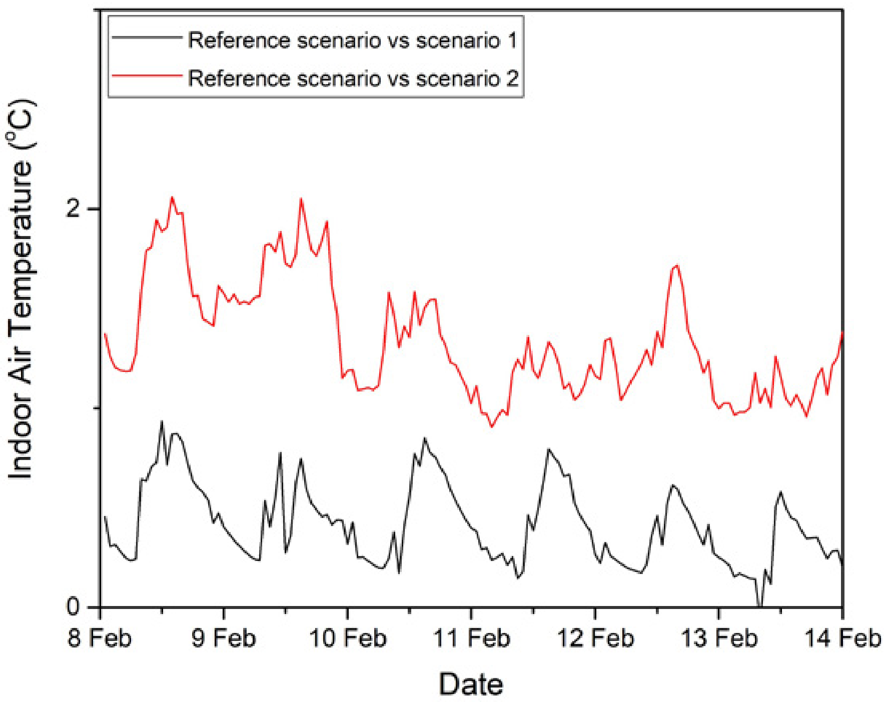

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing highrise shopping mall centre under free-floating conditions during a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

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 13.9-25.9 °C in reference scenario to a range 13.9-25.7 °C in scenario 1 in Frankston beach station.

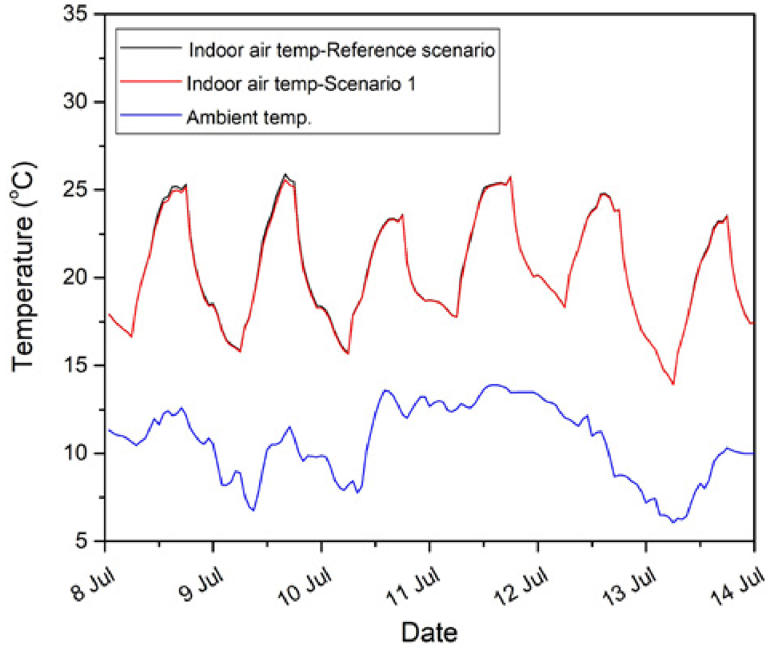

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Frankston beach station* using annual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

The indoor air temperature is predicted to reduce from a range 12.6-27.0 °C in reference scenario to a range 12.5-26.8 °C in scenario 1 in Coldstream station.

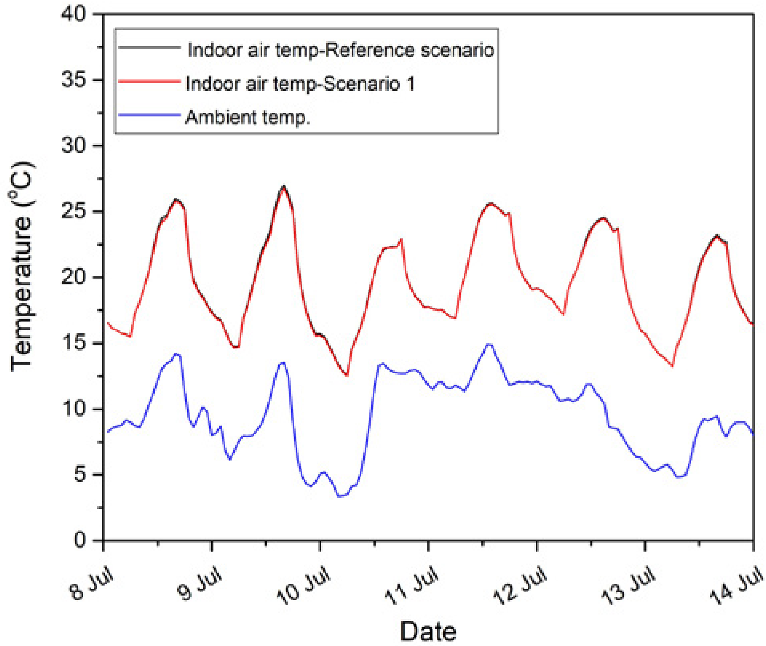

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Coldstream station* using annual measured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

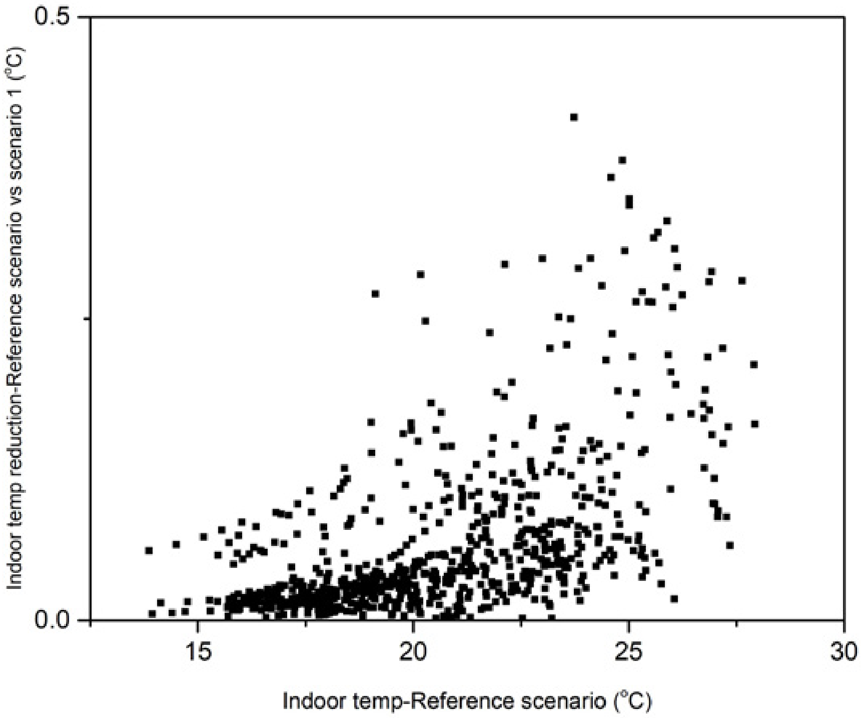

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

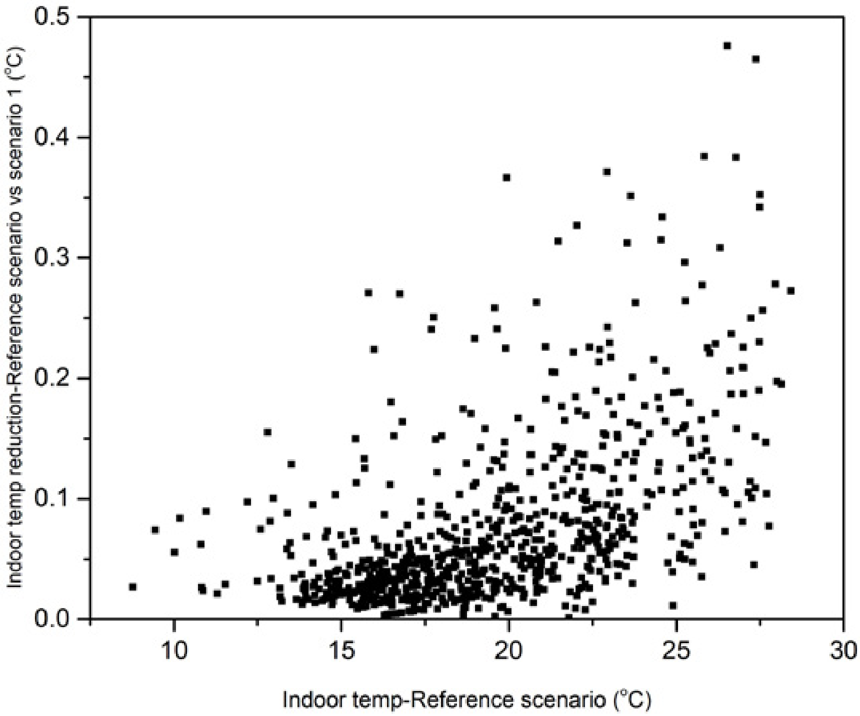

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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 Melbourne (i.e. Frankston beach and Coldstream) 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 269 in the reference scenario to 275 hours in Scenario 1 in Frankston beach; and from 349 to 354 hours in Coldstream stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 36 hours in reference scenario compared to 38 hours in scenario 1 in Frankston beach; and from 71 to 72 hours in Coldstream 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
Frankston beach	36	269	38	275
Coldstream	71	349	72	354

** 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 448 hours in reference scenario to 440 and 383 hours under scenario 1 and 2 in Frankston beach station; and from 474 hours in reference scenario to 465 and 416 hours under scenario 2 in Coldstream 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
Frankston beach	448	440	383
Coldstream	474	465	416

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 m² distributed on six levels. The 1.100 m² roof is not insulated, resulting in energy losses which have a direct impact on the building's last floor and, consequently lead to a moderate energy saving potential. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 16.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	254,0	315,7
Energy consumption after cool roof (MWh)	239,2	300,4
Energy savings (MWh)	14,8	15,3
Energy savings (%)	5,83%	4,85%
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 16 is a good example of an existing, insulated, high-rise commercial building where, despite the rather moderate energy conservation potential, the coating cool roof is a highly feasible investment over the building's life cycle. Due to its typology and operational patterns, the impact of the different weather conditions is negligible.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in energy savings of 5,83 % for the Frankston Beach weather conditions and of 4,85 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads lead to a significant reduction of life cycle costs over the building's life cycle, that varies between 26,2% for the low energy price scenario for Coldstream and 26,8% for the high energy scenario for Frankston Beach conditions (Table 8).

Feasibility analysis results

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

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

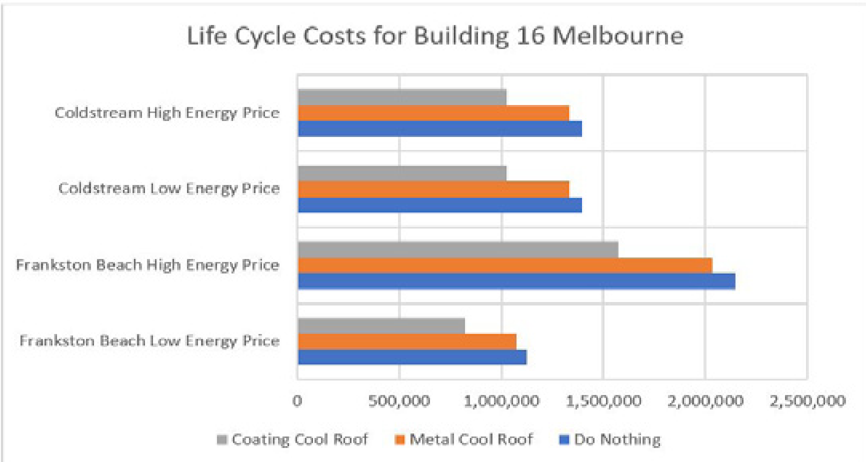

Figure 12. Life Cycle Costs for Building 16 for Frankston Beach and Coldstream stations.

The metal cool roof also shows a positive feasibility, but due to its higher initial investment cost it is less appealing than the coating cool roof.

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	4,75 %	5,31 %	4,31 %	4,38 %
Coating Cool Roof	26,70 %	26,83 %	26,23 %	26,31 %

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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 40.2-46.8 kWh/m^2 to 38.0-43.7 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 2.1-3.2 kWh/m^2. This is equivalent to approximately 4.8-6.8 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 7.5-9.7 kWh/m^2. This is equivalent to 17.4-23.7 % 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 (0.1-0.3 kWh/m^2) is significantly lower than the annual cooling load reduction (4.3-6.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.3-6.2 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.2-6.2 kWh/m2 (~3.9-5.9 %) (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 21.6-41.7 ^{o}C and 20.6-45.45 ^{o}C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.7 and 0.9 ^{o}C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.0 and 2.1 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream 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 13.9-25.9 ^{o}C in reference scenario to a range between 13.9-25.7 ^{o}C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 12.6-27.0 ^{o}C in reference scenario to a range between 12.5-26.8 ^{o}C in reference with cool roof scenario (scenario 1) in Coldstream 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 Frankston beach and Coldstream stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 269 hours in reference scenario to 275 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slight increase in total number of hours below 19 ^{o}C from 349 hours in reference scenario to 354 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 ^{o}C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 ^{o}C during operational hours of the building (i.e. 7 am-6 pm) is expected to increase from 36 hours in reference scenario to 38 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. Similarly, the calculation in Coldstream station shows a slight increase of number of hours below 19 ^{o}C from 71 hours to 72 hours during the operational hours (See Table 5).

• During a typical summer month 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 448 hours under the reference scenario in Frankston beach station, which slightly decreases to 440 and 383 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 ^{o}C from 474 hours in reference scenario to 465 in reference with cool roof scenario (scenario 1) and 416 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 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 significant reduction of life cycle costs over the building's life cycle, that varies for the coating cool roof between 26,2% for the low energy price scenario for Coldstream and 26,8% for the high energy scenario for Frankston Beach conditions, as it can be seen in Table 8. The metal cool roof also shows a positive feasibility, but due to its higher initial investment cost it is less appealing than the coating cool roof. 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. 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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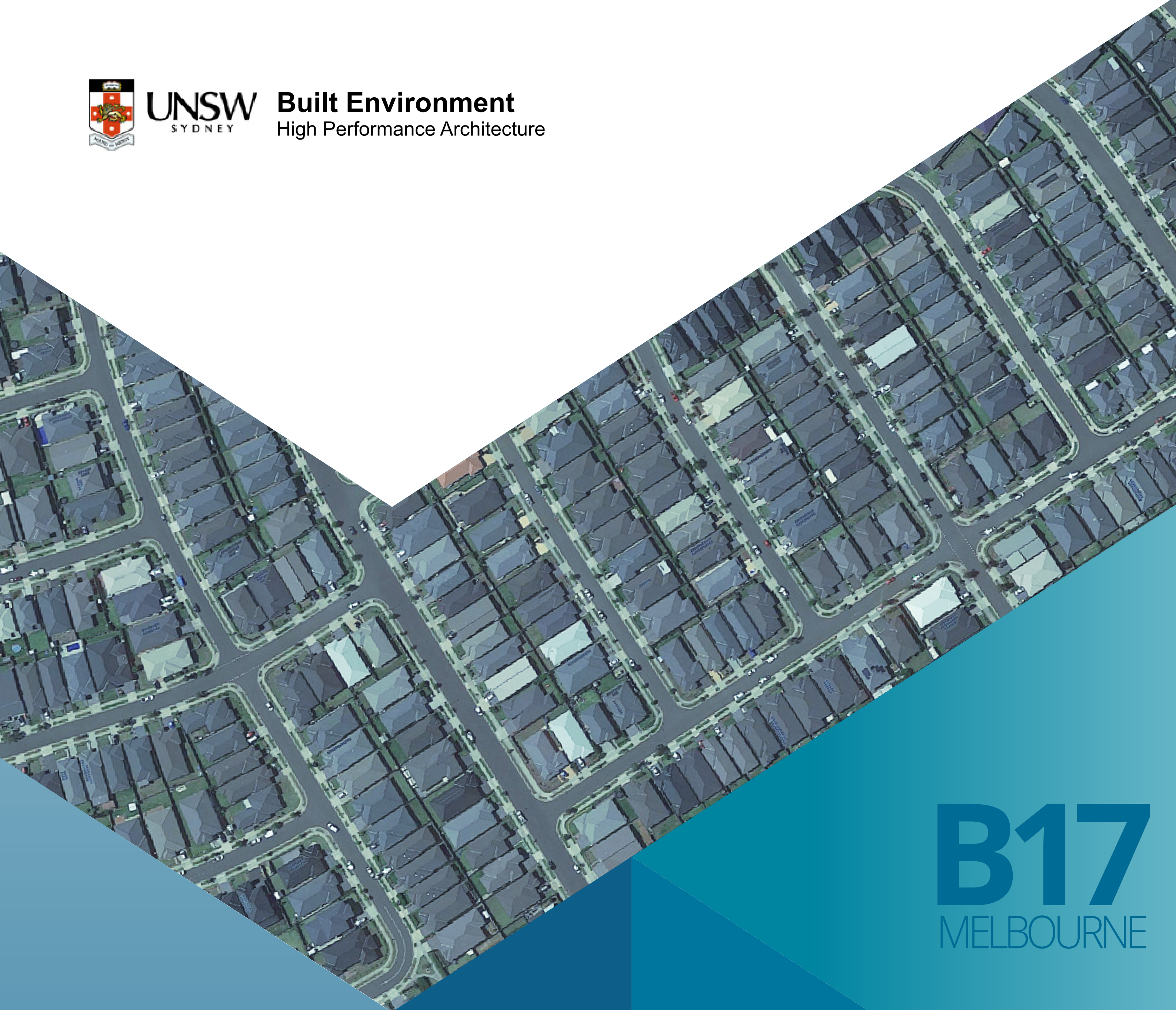

B17
MELBOURNE

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

1

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

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 4.6 -7.1 kWh/m² to 2.4-4.1 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/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)
Avalon airport	5.0	5.5	2.9	3.3	2.2	2.3
Coldstream	6.5	7.1	3.7	4.1	2.9	3.0
Essendon	5.8	6.3	3.5	3.9	2.5	2.5
Frankston beach	4.0	4.6	2.0	2.4	1.3	1.4
Melbourne airport	6.0	6.6	3.7	4.1	2.6	2.7
Moorabbin airport	4.2	4.9	2.3	2.7	1.5	1.6
Olympic park	4.9	5.6	2.8	3.3	2.1	2.2

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

For Scenario 1, the total cooling load saving is around 2.1-3.0 kWh/m² which is equivalent to 37.5-46.9 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.2-4.1 kWh/m² which is equivalent to 57.1-69.9 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Avalon airport	2.1	41.4	2.2	39.9	2.8	55.6	3.2	57.9
Coldstream	2.9	43.7	3.0	42.3	3.6	55.3	4.1	57.1
Essendon	2.3	39.4	2.4	38.0	3.3	57.2	3.8	59.9
Frankston beach	1.9	48.8	2.1	46.9	2.7	67.0	3.2	69.9
Melbourne airport	2.3	38.9	2.5	37.5	3.4	56.2	3.9	58.9
Moorabbin airport	2.0	46.5	2.2	44.7	2.7	64.7	3.3	67.7
Olympic park	2.1	43.0	2.3	41.3	2.8	57.0	3.3	59.7

In the eleven weather stations in Melbourne, 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.

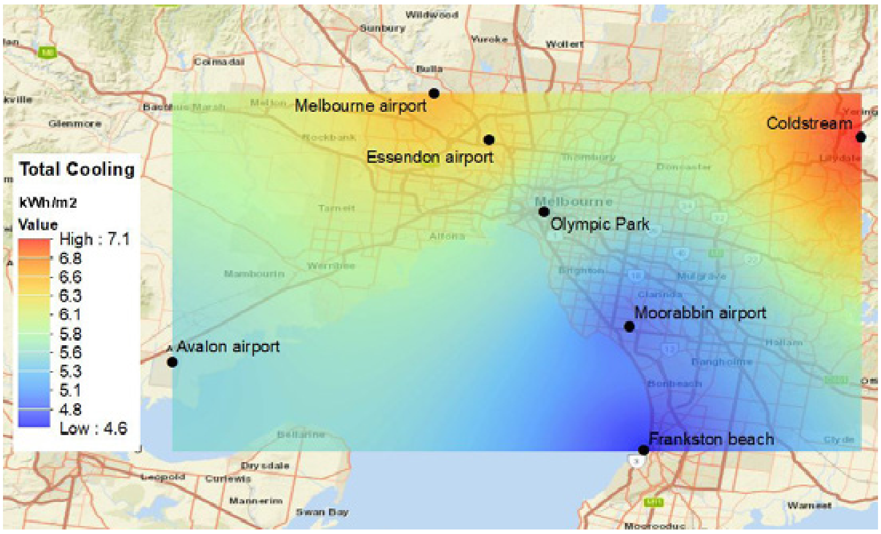

Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

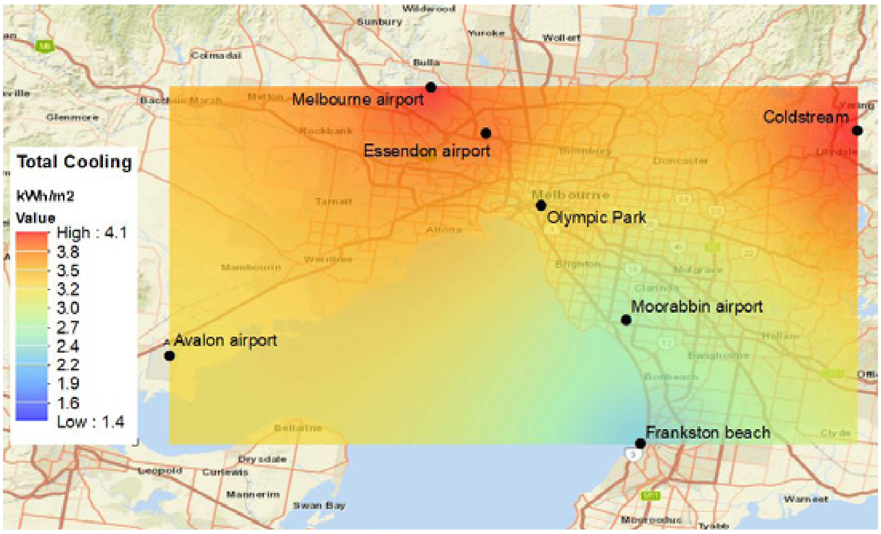

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

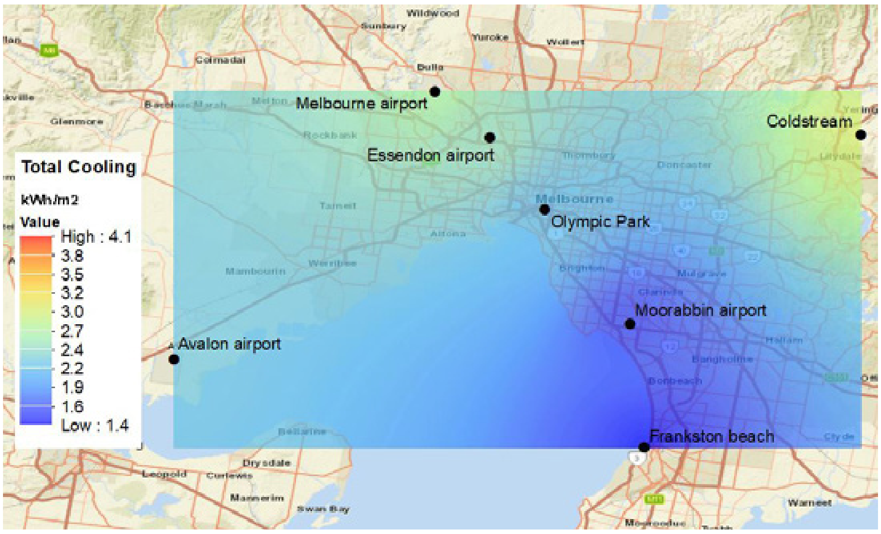

Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

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

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

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

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (1.9-2.9 kWh/m²) is significantly lower than the annual cooling load reduction (2.9-4.2 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
Avalon airport	6.4	7.6	24.4	29.6	4.0	4.8	26.1	31.7
Coldstream	9.7	11.3	28.1	34.1	6.0	7.2	30.6	37.0
Essendon	8.7	9.9	22.1	27.0	5.7	6.5	23.9	29.0
Frankston beach	5.5	7.0	18.0	22.0	2.9	3.7	19.8	24.2
Melbourne airport	8.0	9.0	24.2	29.5	5.3	6.0	26.0	31.5
Moorabbin airport	7.5	9.1	20.2	24.6	4.8	5.9	21.8	26.5
Olympic park	9.1	10.8	18.3	22.3	5.4	6.6	20.1	24.4

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 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 33.4-46.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8-2.1 kWh/m² (~2.2-6.5 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Avalon airport	2.4	37.6	2.9	37.4	1.8	2.0	0.6	2.1	0.8	2.2
Coldstream	3.6	37.6	4.1	36.0	2.5	2.9	1.1	3.0	1.2	2.7
Essendon	3.0	34.4	3.3	33.9	1.7	2.0	1.3	4.1	1.4	3.7
Frankston beach	2.6	47.0	3.3	46.7	1.9	2.2	0.7	3.1	1.1	3.7
Melbourne airport	2.7	34.0	3.0	33.4	1.8	2.0	1.0	3.0	1.0	2.6
Moorabbin airport	2.7	36.1	3.2	35.5	1.6	1.9	1.1	3.9	1.3	4.0
Olympic park	3.6	40.0	4.2	39.1	1.8	2.1	1.8	6.6	2.1	6.5

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 Melbourne (i.e. Frankston beach and Coldstream) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 13.3-32.8 °C in reference scenario to a range 11.4-31.6 °C in scenario 2 in Frankston beach station.

For Scenario 2, the estimated ambient temperature reduction is 0.9-2.5 °C compared to the reference scenario in Frankston beach station.

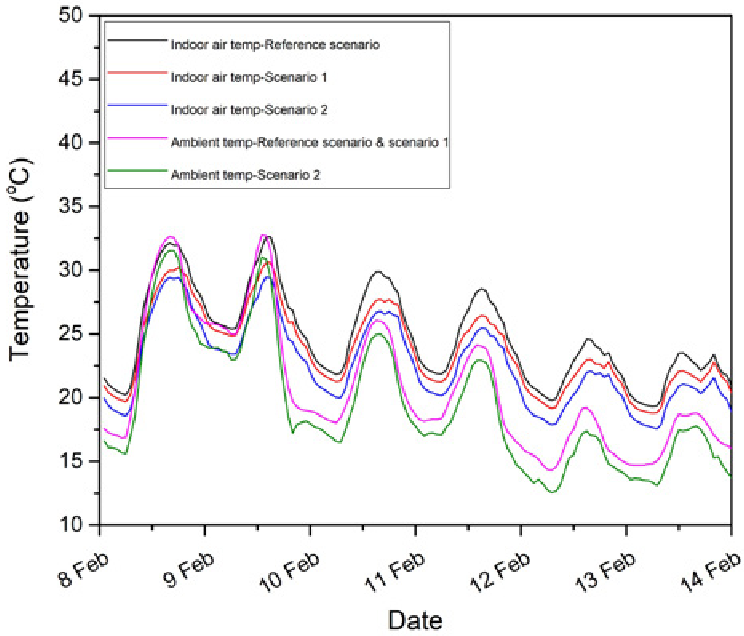

Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer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

For scenario 2, the ambient temperature is predicted to decrease from 12.3-36.8°C in reference scenario to 11.3-35.2°C in Coldstream station.

For Scenario 2, the estimated ambient temperature reduction is 0.4-2.0 °C compared to the reference scenario in Coldstream station.

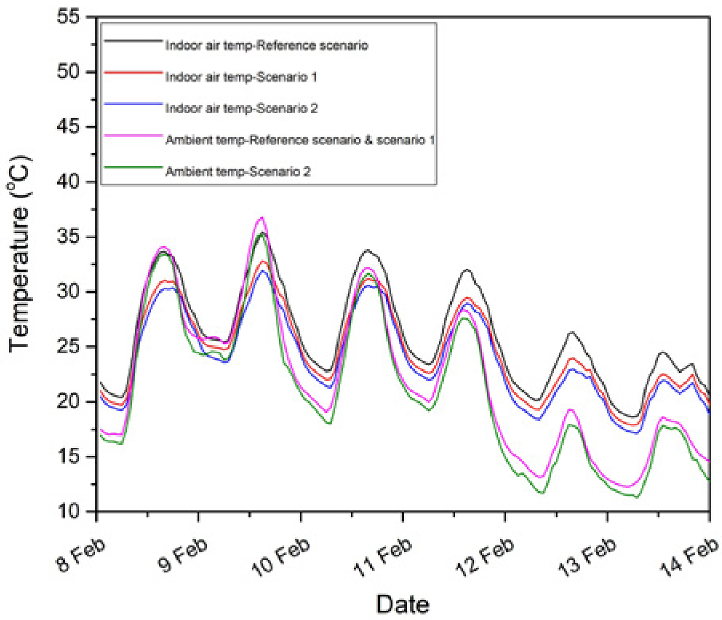

Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer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

During a typical summer week, the indoor air temperature of the reference scenario ranges between 19.1-32.6 °C and 18.6-35.4 °C in Frankston beach and Coldstream stations, respectively.

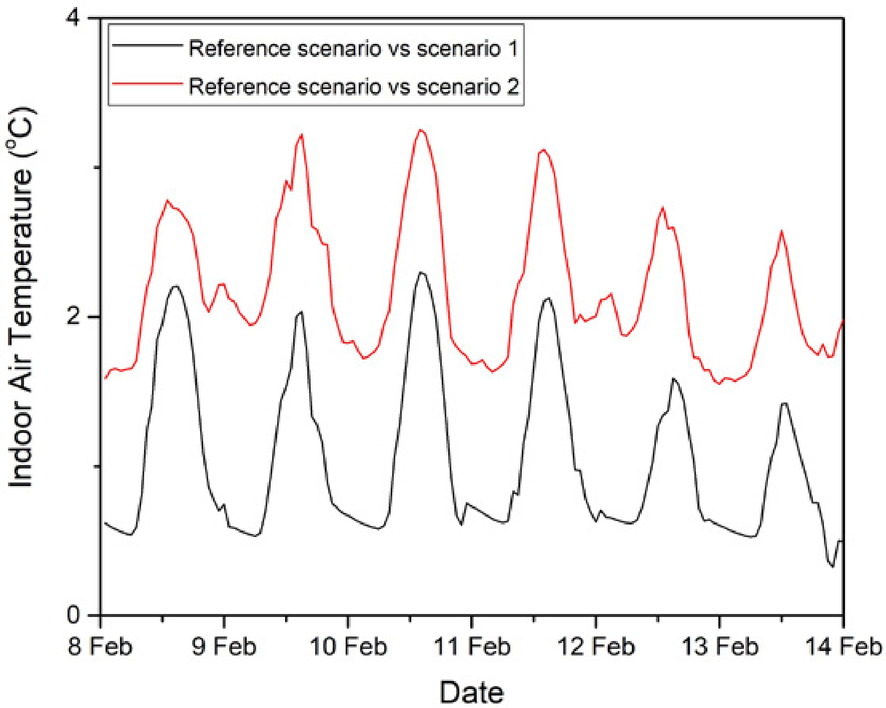

Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week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

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.3 °C and 2.8 °C in Frankston beach and Coldstream stations, respectively.

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

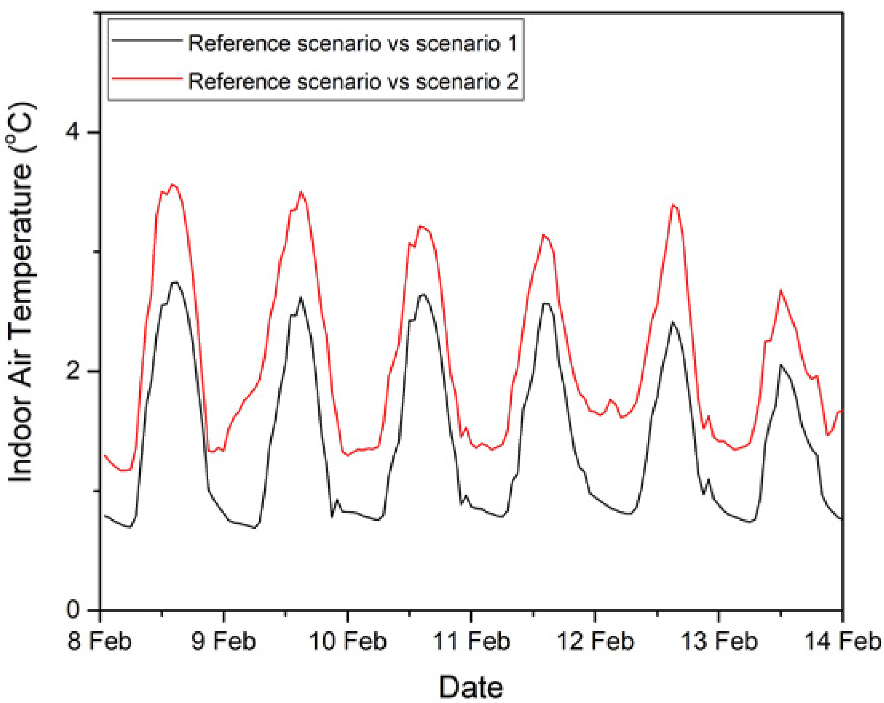

Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week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

During a typical winter week, the indoor air temperature is expected to decrease from a range 11.6-19.4 °C in reference scenario to a range 11.5-18.5 °C in scenario 1 in Frankston beach station.

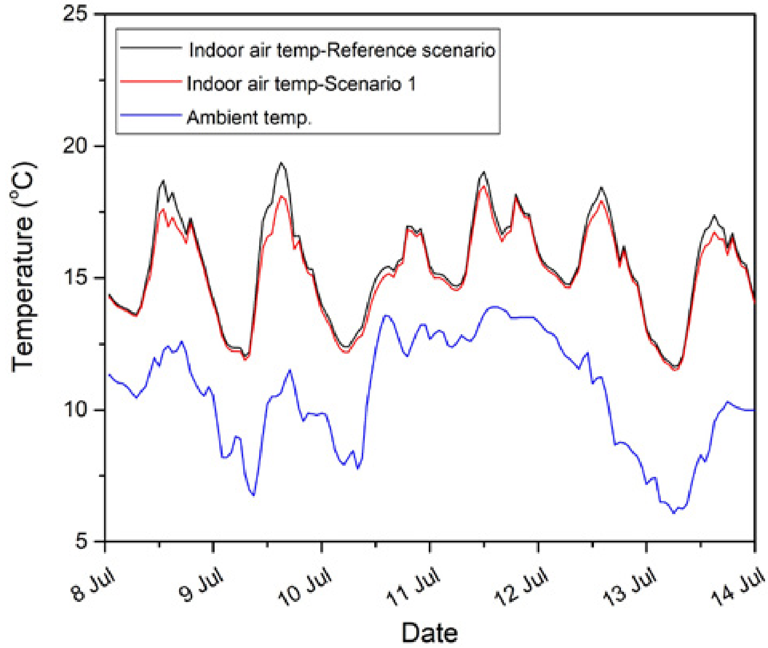

Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Frankston beach station* using annual measured weather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

The indoor air temperature is predicted to reduce from a range 9.8-20.0 °C in reference scenario to a range 9.6-18.7 °C in scenario 1 in Coldstream station.

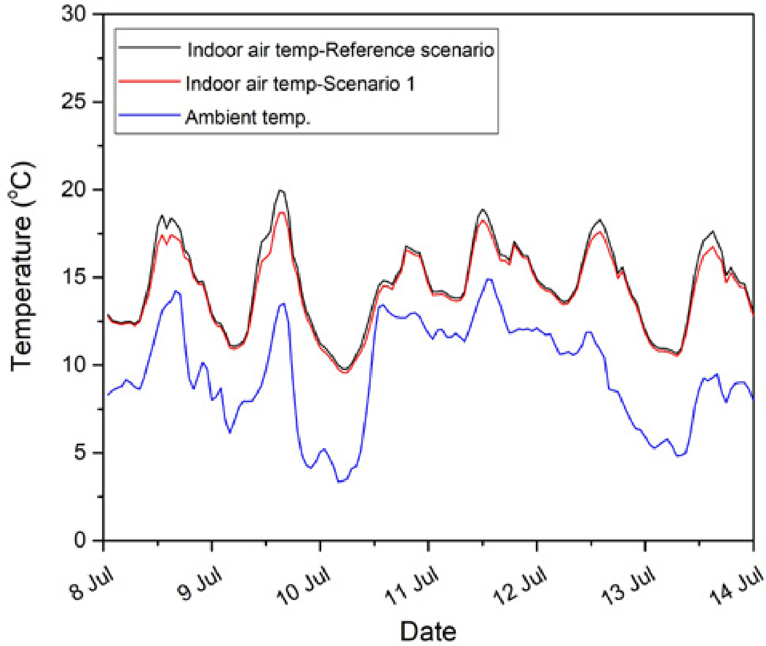

Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Coldstream station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.7 and 0.8 °C in Frankston beach and Coldstream stations, respectively.

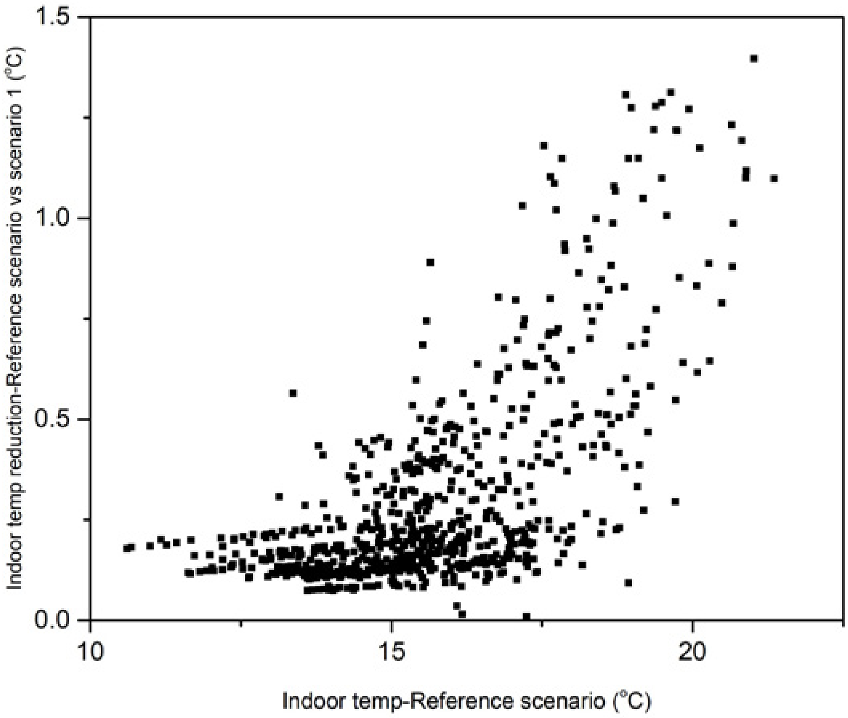

Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Frankston beach station* using annual measured weather data.

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

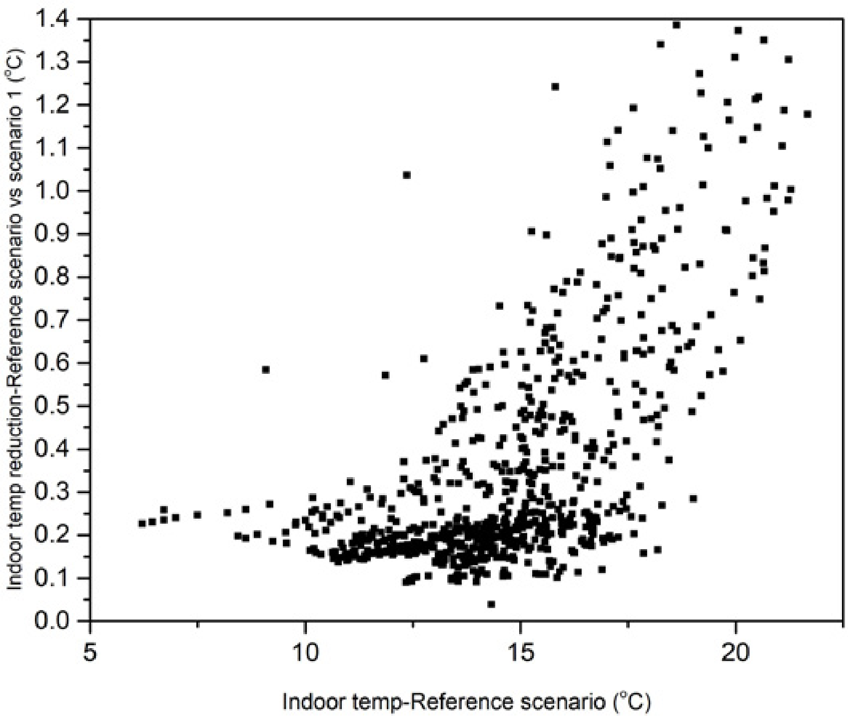

Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Coldstream station* using annual measured weather data.

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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 Melbourne (i.e. Frankston beach and Coldstream) 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 704 hours in reference scenario to 728hours; and from 702 to 720 hours in scenario 1 in Frankston beach and Coldstream stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Frankston beach	704	728
Coldstream	702	720

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

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 171 hours in reference scenario to 107 and 64 hours under scenario 1 and 2 in Frankston beach station; and from 230 hours in reference scenario to 161 and 129 hours under scenario 1 and 2 in Coldstream station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Frankston beach	171	107	64
Coldstream	230	161	129

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 m² distributed on one level. The 242 m² roof is insulated, resulting in a very limited energy conservation potential, despite the roof's impact on the building's energy balance. The main features of the building's energy performance both for Frankston Beach and for Coldstream weather conditions, are presented in Table 7.

Table 7. Energy performance features of Building 17.

Energy performance features	Frankston Beach	Coldstream
Energy consumption prior cool roof (MWh)	2,8	4,4
Energy consumption after cool roof (MWh)	2,7	4,3
Energy savings (MWh)	0,1	0,1
Energy savings (%)	3,57 %	2,27 %
Area (m²)	242	242
Roof costs - Metal roof (AU$/m²)	38,0	38,0
Roof costs - Coating (AU$/m²)	22,75	22,75
Life expectancy - Metal roof (years)	28,5	28,5
Life expectancy - Coating (years)	22,5	22,5
HVACs COP	2,5	2,5
Existing roof's renovation costs (AU$/m²)	15,0	15,0

Building 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 limited. Still, the application of a coating cool technology emerges as a meaningful investment, especially for the high energy prices scenario.

The cool roof refurbishment options

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

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

Both options have the same energy efficiency, resulting in an energy requirements' reduction of 3,57 % for the Frankston Beach weather conditions and of 2,27 % for the Coldstream conditions. The metal roof option has higher investment costs, but also a greater life expectancy, namely of 28,5 vs. 22,5 years, as presented in Table 7.

The coating cool roof option leads to a moderate reduction of life cycle costs, that varies between 1,6 % for the low energy price scenario for Frankston and 16,3 % for the high energy scenario and for Coldstream conditions (Table 8).

Feasibility analysis results

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

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

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

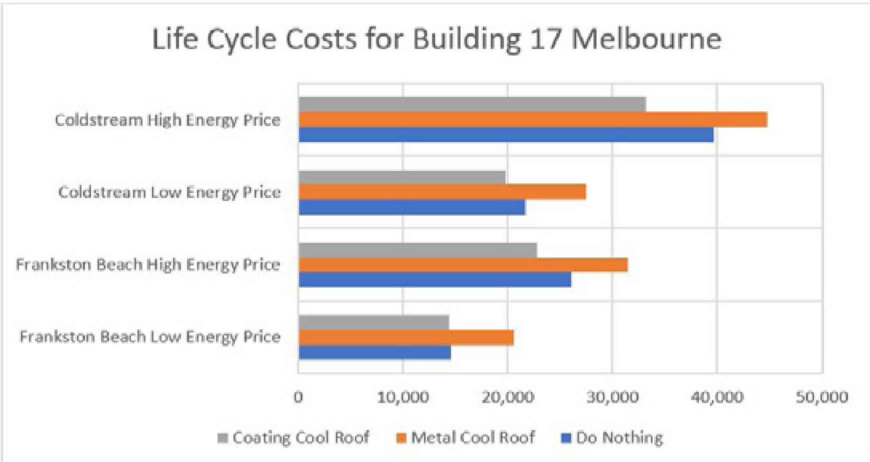

Figure 12. Life Cycle Costs for Building 17 for Frankston Beach and Coldstream stations.

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	-40,74 %	-20,53 %	-26,98 %	-12,94 %
Coating Cool Roof	1,59 %	12,51 %	8,74 %	16,32 %

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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 Melbourne, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 4.6 -7.1 kWh/m^2 to 2.4-4.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 2.1-3.0 kWh/m^2. This is equivalent to approximately 37.5-46.9 % 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 Melbourne, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 3.2-4.1 kWh/m^2. This is equivalent to 57.1-69.9 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (1.9-2.9 kWh/m^2) is lower than the annual cooling load reduction (2.9-4.2 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 33.4-46.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.8-2.1 kWh/m^2 (~2.2-6.5 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 19.1-32.6 °C and 18.6-35.4 °C in Frankston beach and Coldstream stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.3 and 2.8 °C in Frankston beach and Coldstream stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.3 and 3.7 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Frankston beach and Coldstream stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 13.3 and 32.8 °C in reference scenario to a range between 11.4 and 31.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Frankston beach station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.9-2.5 °C. Similarly, the ambient temperature is predicted to decrease from 12.3-36.8 °C in reference scenario to 11.3-35.2 °C in cool roof and modified urban temperature scenario (scenario 2) in Coldstream station. The estimated ambient temperature reduction is 0.4-2.0 °C in Coldstream station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease from a range between 11.6-19.4 °C in reference scenario to a range between 11.5-18.5 °C in reference with cool roof scenario (scenario 1) in Frankston beach station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 9.8-20.0 °C in reference scenario to a range between 9.6-18.7 °C in reference with cool roof scenario (scenario 1) in Coldstream station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.7 °C and 0.8 °C for both Frankston beach and Coldstream 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 704 hours in reference scenario to 728 hours in reference with cool roof scenario (scenario 1) in Frankston beach station. The estimations for Coldstream stations also show a slightly increase in total number of hours below 19 °C from 702 hours in reference scenario to 720 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 171 hours under the reference scenario in Frankston beach station, which significantly decreases to 107 and 64 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively.

The simulations in Coldstream station also illustrate a significant reduction in number of hours above 26 °C from 230 hours in reference scenario to 161 in reference with cool roof scenario (scenario 1) and 129 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 moderate reduction of life cycle costs, that varies between 1,6% for the low energy price scenario for Frankston and 16,3% for the high energy scenario and for Coldstream conditions, as it can be seen in Table 8. The metal cool roof is, due to its higher initial investment cost and the limited energy savings, not feasible. 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 limited. Still, the application of a coating cool technology emerges as a meaningful investment, especially for the high energy prices scenario.

B17

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