BlueScope Steel

BlueScope Microclimate Thermal Study

Microclimate Study

251927-REPv07

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Contents

Appendix E

Monthly Energy Breakdown Data

1 Executive Summary

Standard dynamic thermal modelling of buildings make use of standard empirical models for calculating convection that do not take into account roof size and shape. This implies that these models can miscalculate the heat load on a building, as the simulation may not represent true air flow characteristics, which governs the convective heat transfer coefficient.

A two stage analysis has been conducted for a notional 5,000m^2 shopping centre in Hervey Bay, looking at three different roof types – Bluescope Zincalume® steel, Colorbond® steel in the colour Surfmist® and Colorbond Coolmax®. CFD modelling has been undertaken in order to determine more accurate models for convection coefficient, taking into account wind direction, wind speed and net absorbed radiation. The CFD analysis also predicts the elevated temperatures above the roof that would affect mechanical system performance.

These relationships have been entered into a dynamic thermal model using coding to overwrite the standard simulation parameters. This was performed using the advanced EnergyPlus building simulation control tool, Energy Management System (EMS), and specifically the ERL code language.

The results show that Colorbond Coolmax provides the greatest benefit for reducing energy use and peak demand. Coolmax reduced cooling energy consumption by approximately 6.4% compared to Zincalume, with a peak demand reduction of 4.4%. Colorbond Surfmist demonstrated savings of 5.3% compared with Zincalume with a reduced peak demand of 3.6%. Each of these second order simulation outcomes are considerably greater than what was represented by a first order simulation.

Utilising a simplified cost model, the second order analysis demonstrated savings of approximately $6,558 and $5,436 for Coolmax and Surfmist respectively, when compared against Zincalume. Mechanical capital cost savings of $69,200 for Coolmax and $56,900 for Surfmist were also demonstrated. First order estimates of the operational cost savings and capital cost savings were much smaller than the more accurate second order figures, and were nearly half of the actual savings.

The second order results showed that annual cooling consumption was 0.8% to 4.4% higher than was predicted under the first order analysis. This is because the actual convection over the large roof is lower than assumed in the first order analysis, leading to higher roof surface temperatures and therefore higher heat loads. The high reflectance and high thermal emittance values of Colorbond Coolmax and Colorbond Surfmist mitigate against this by reducing the total absorbed radiation, as well as emitting away more heat as long wave radiation.

Further analysis into the effect of climate showed some specific trends in the thermal behaviour. In all cases, covering Hervey Bay, Ipswich, Western Sydney and Northern Melbourne, reductions in cooling energy and peak cooling load were observed. Cooling energy reductions of 6.4% to 14.4% were observed, and peak cooling reductions of 4.4% to 9.7% were observed for Coolmax over Zincalume. In general, this effect was greater for areas with higher peak and average temperatures, although this can also be influenced by other factors such as low wind speed. Total HVAC equipment savings were higher for buildings in more northern latitudes, in part due to the interaction of cooling and heating. In all cases analysed, there was an operational cost saving and greenhouse gas saving when using a cool roof. Operational cost savings ranged from $2,067 to $6,645 and greenhouse gas emission savings ranged from 18,466 $kgCO_2$ to 29,936 $kgCO_2$ for Coolmax over Zincalume.

The analysis in this report has assumed the use of a high efficiency water-cooled chiller system. If a less efficiency cooling system was used, such as an air-cooled chiller, or DX Air handling units, the overall cooling energy would be higher. Cool roofs would then show larger absolute cooling savings, resulting in improved HVAC savings, operational cost savings and greenhouse gas emissions.

2 Introduction

The roof of a building can potentially be one of the most significant sources of heat load to a building air conditioning system. Cool roofs are one method of mitigating this. Cool roofs have high reflectivity and high thermal emittance. A high reflectance surface reflects most of the direct solar radiation back to the sky, reducing the amount of heat to the building. A high emittance surface allows roof heat to be emitted back to the sky as long-wave radiation, which ensures that less heat enters the building.

Measured results from real buildings seem to indicate that the performance improvement provided by cool roofs is significantly higher than what is predicted from thermal modelling in building simulation software [1]. Dynamic thermal modelling programs of necessity use simplified functions for convection, and these are usually the same for any type of roof, regardless of size or height [2]. This can lead to errors in the calculation of convection at the roof, which could be important in large low buildings, where roof load is more significant. A number of studies have been carried out and indicate that roof microclimate, particularly on large roofs, plays an important part that is not considered by building simulation tools at present [3], [4].

At the roof surface, a number of heat transfer processes will occur. Shortwave radiation from the sun hits the roof and is absorbed and reflected. The roof emits longwave radiation to the surrounding sky. Convection by air movement over the surface of the roof removes heat. Finally, some heat is transferred into the building, where it is typically dealt with by air conditioning (or raises the temperature of the air in the building if there is no air conditioning).

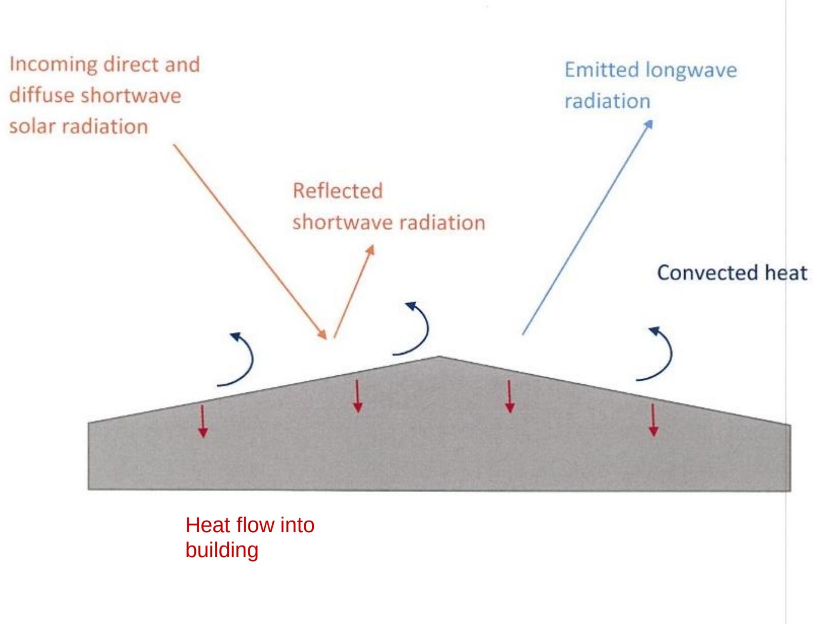

Figure 1: Heat flows at a roof surface

Most of these factors can be correctly accounted for in thermal modelling. However, microclimate effects will change the convection behaviour above the roof. A very large roof may inhibit convection and lead to a hotter surface layer of air, leading to a hotter roof surface and therefore more internal gains. If more detailed models of these convection effects are implemented in the simulation, then the roof surface temperature can be more accurately assessed, and resultant heat balance will be better able to predict internal gains. It is therefore important to understand how the convection behaves with different inputs, and include these effects in the thermal modelling. There will be further impacts as elevated temperatures above the roof will affect the fresh air intake temperature, and the efficiency of any mechanical heat rejection systems that are located there.

Throughout this report, normal building simulation software results will be referred to as first order analysis. The impact of the microclimate on convection, and the consequent changes to roof behaviour and mechanical efficiency will be referred to as second order effects.

3 Approach

This report will look at modelling a simple building. The methodology developed through this can then be applied to more complex buildings.

The building is a 50m x 100m shopping centre. It is 10m high. It has a peaked roof with a 3° slope, with the peak along the long axis of the building. The building will be located in Hervey Bay.

Weather data has been sourced for Bundaberg. This is only 50 km away from Hervey Bay, and both locations are on the coast. The weather will be very similar. The weather file is in the TMY2 format, consisting of an artificial typical year, calculated based on decades of actual weather data. In later comparative analysis, weather for Ipswich, Western Sydney, and Northern Melbourne has been used. This used data from weather stations at Amberley, Richmond, and Tullamarine respectively. Similarly, the data is TMY2 weather file based on 45 years of real weather.

The impact of three different Bluescope steel roof types will be considered – Zincalume, Colorbond Surfmist, and Colorbond Coolmax. Zincalume is a standard corrosion resistant steel roof. Colorbond Surfmist is a pre-painted steel roof with good thermal properties. Colorbond Coolmax is the best thermal performing Bluesecope steel roof. A comparison of their performance will allow their relative benefits and strengths to be identified, and to provide information about improved performance that is not reflected in standard dynamic modelling.

The analysis will be a two stage process. First, Computational Fluid Dynamics (CFD) will be used to simulate a series of test cases, looking at different wind directions, speeds, and net absorbed radiation levels. The objective of Stage 1 is to determine:

- Coefficient of convection as a function of wind speed, wind direction and net absorbed radiation
- Temperature above the roof over a nominal central plant area, as a function of wind speed, wind direction and net absorbed radiation.

These relationships will be used as inputs into the second stage.

In the second stage, these relationships will be included in dynamic building simulation. The software Energy Plus allows for some of the normal parameters to be overwritten by the user with its programming language, ERL. This will allow convection to be calculated with the adjusted convection coefficients that were calculated in the CFD based upon net thermal absorbed radiation. The objective of Stage 2 is to use ERL to input convection coefficient and temperature above the roof into the EnergyPlus simulation. This will have the following impacts:

- Adjusted coefficient of convection will change the amount of convection at the roof, resulting in different roof temperature and different heat loads to the building.

- Temperature above the roof will affect some plant performance. Outside air for air handling units will be adjusted, and cooling tower performance will be affected by local changes in air temperature.

These inputs will be used to determine the building HVAC energy impact based on each roof type. This second order analysis will be compared to the predictions of standard first order analysis.

4 Stage 1 - CFD

4.1 CFD

Computational Fluid Dynamics (CFD) is a numerical technique used to simulate fluid flows, heat and mass transfer, chemical reactions, combustion, multiphase flow, and other phenomena related to the movement of fluid.

CFD analysis has been conducted using ANSYS CFX v16.1. The analysis is a steady state solution.

4.2 Domain

The model domain is the volume of fluid within which the simulation is completed. It is chosen to be large enough to capture all the pertinent fluid dynamics interaction between the model and its surrounds.

The building is located at the centre of a stationary cylindrical domain. This is 200m diameter x 100m height. Around this is a second larger domain that can be rotated to change the wind direction. The overall domain size is 400m wide x 500m long x 100m high. The stationary domain is 50m from the inlet, 100m from the sides and 250m from the outlet. This size will ensure that the boundaries do not influence the results in the area of interest, our building roof. This has been tested by running different models to confirm the size is large enough.

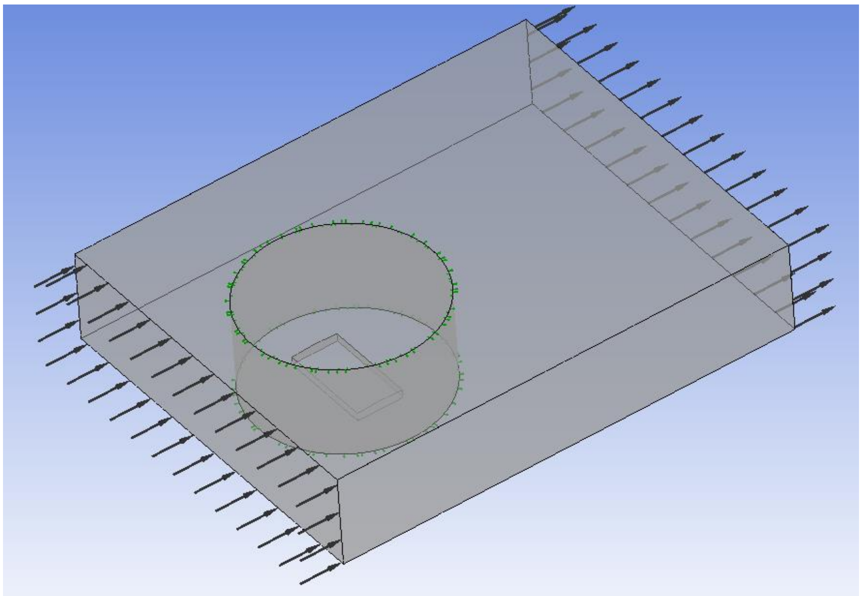

Figure 2: CFD model geometry, including building, cylindrical domain, and rotating rectangular domain

4.3 Mesh

The mesh is approximately 5.6 million cells. It is made up of tetrahedral elements, with prism layers on the ground and building surfaces. It includes a much higher density of cells at the building roof. The mesh can be seen in Figure 1 and Figure 2 below. The mesh sizing has been tested to confirm the sensitivity. For more detail on the mesh, please see Appendix A Section A1.

Figure 3: 2D slice of stationary domain mesh

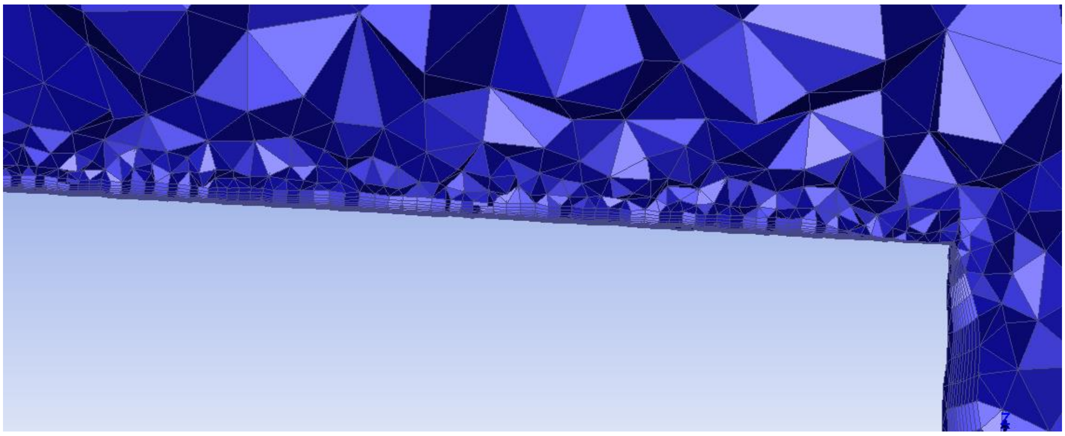

Figure 4: 2D slice of mesh – close-up of building roof

4.4 Verification

In order to confirm that the CFD results were meaningful, a verification study was done. A smaller building was simulated with the same settings. The average convection coefficient *h* over the roof was calculated and checked against standard equations. The CFD results were consistent with these standard equations, which demonstrates that the simulations are providing sensible results. For more detail on the verification study, see Appendix A Section A2.

4.5 Fluid Properties

Shear Stress Transport turbulence modelling was used. This has been shown to be better than the k-epsilon model at calculating convection coefficient [5]. It has also been found to have better accuracy in simulating flow with a large separation region [4], such as the air flow over the roof edge.

The Thermal Energy heat transfer model has been used, as heat flow is vital to calculating convection coefficient.

The fluid is "Air at 25°C", which includes calculations for behaviour outside this range. Although "Air Ideal Gas" would more accurately model buoyancy-driven convection, this produced unstable solutions. A test case found that, for a worst case (high heat flux, low wind speed), the difference in roof-average convection coefficient was only 1%. This was deemed to be an acceptable compromise.

4.6 Boundary Conditions

The behaviour of air at the edges of the model is determined by the boundary conditions.

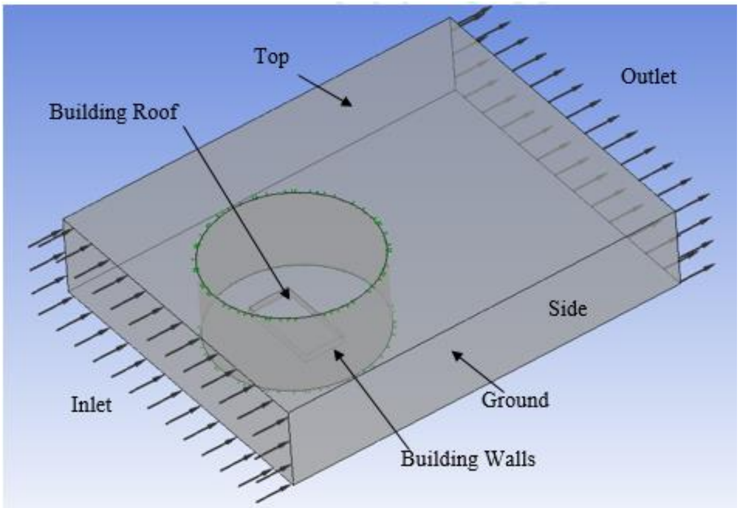

Figure 5: CFD Boundaries

Inlet

The inlet boundary condition will model the incident wind. As this is a suburban shopping centre, it is assumed that there is only low-lying obstructions to wind flow.

The inlet has incoming air at 25°C. The velocity varies with height. As the results will be used as inputs into dynamic energy modelling, the wind profile determined using EnergyPlus was applied to the CFD analysis. The exact values vary depending on details of the weather station and location [6]. In this case, the wind speed, *v*, in the model at any height, *z*, will be:

$$v_{model} = 1.586 v_{weather} \left(\frac{z}{310}\right)^{0.22}$$

Outlet

The outlet has a 0 average static pressure boundary condition.

Sides and top

The sides and top of the domain are modelled as adiabatic free slip walls.

Ground and walls

The ground and building walls are modelled as adiabatic no-slip smooth walls. It is assumed that they are far away enough to have no impact on the roof thermal processes.

Roof

The roof is modelled as a no-slip smooth wall. In order to model heat transfer, a net absorbed radiation level has been modelled. It was not possible to simply set a roof temperature, as this was part of the solution to be captured.

4.7 Simulations

Wind Distribution

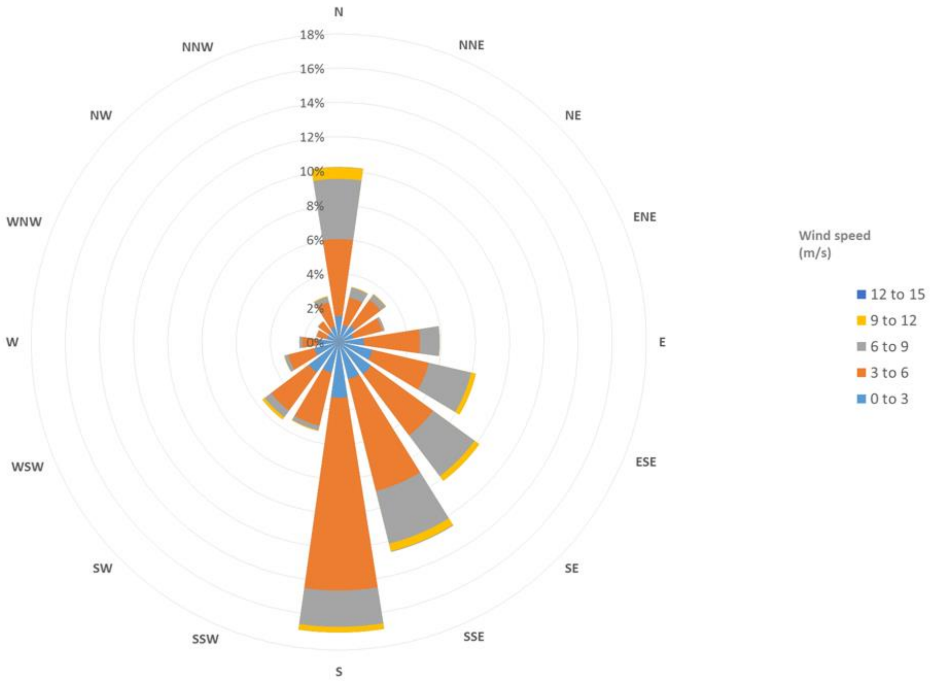

Figure 6: Wind rose for Bundaberg

The wind at Bundaberg mainly occurs at medium speeds around 3-6m/s. It is strongly biased towards the south. Still conditions occur for 4.2% of the year.

Wind cases

Wind has been modelled for 5 different directions – north, north-northwest, northwest, west-northwest and west. Each of the remaining 11 wind directions will be a symmetrical version of one of these cases.

The wind speed has been modelled at six different speeds to determine any important behaviour that needs to be included. In this case, it is the changeover from free convection to forced convection. In free convection, the convection is mainly caused by buoyancy effects. In forced convection, the wind effects dominate over buoyancy. It was found that this occurs between 2m/s and 3m/s, as can be seen in Figure 7 through Figure 9 below. At 0.5m/s, heat plumes are moving up from the roof surface, indicating free convection. At 3m/s, the wind blows the hot air off the roof before any heat plumes can form. In between at 2m/s, the behaviour is partway between these cases, with noticeable vertical plume development and strong wind impacts.

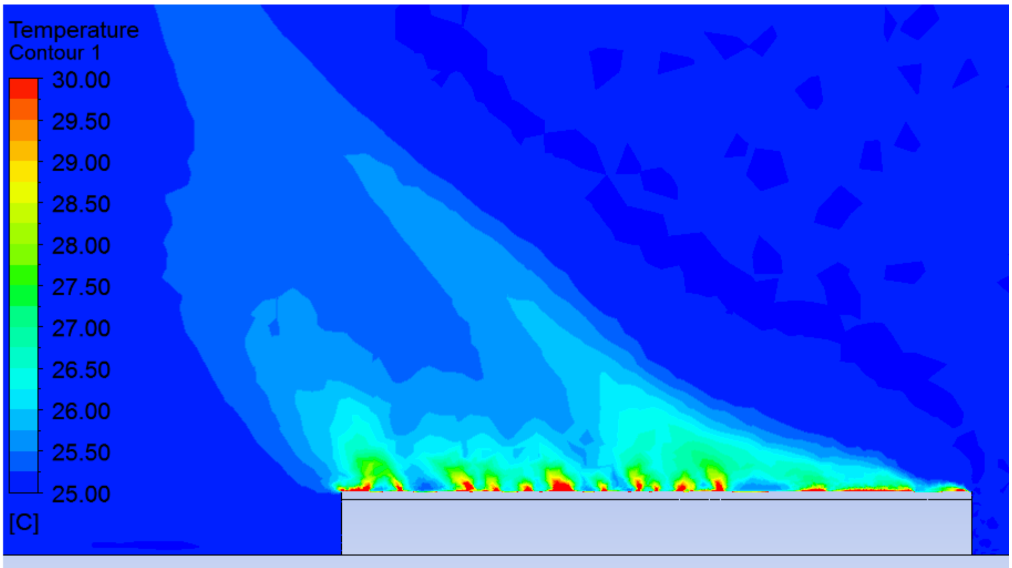

Figure 7: Air temperature for west wind at 0.5m/s – free convection

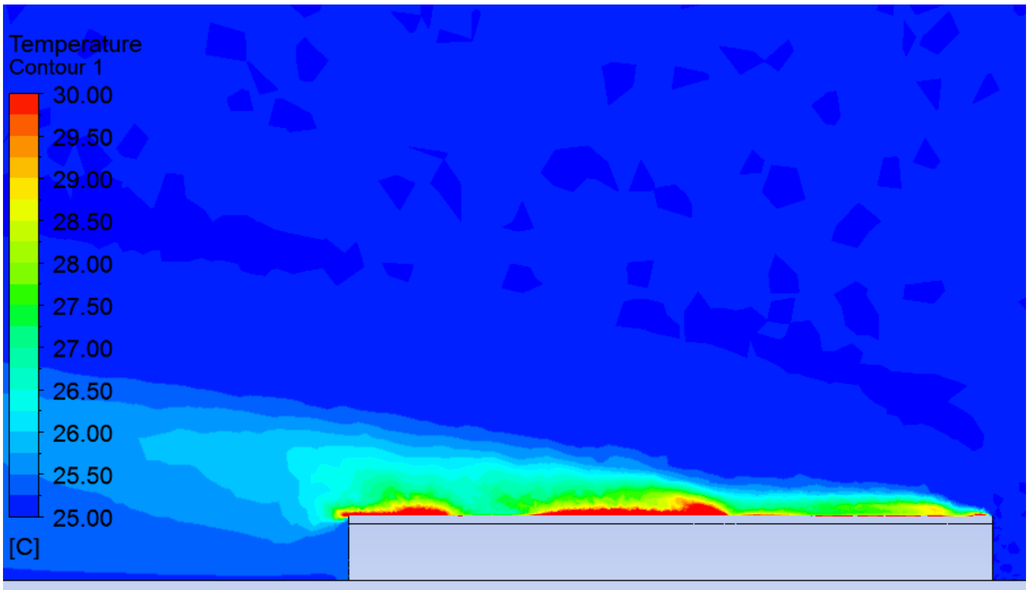

Figure 8: Air temperature for west wind at 2m/s – transition from free to forced convection

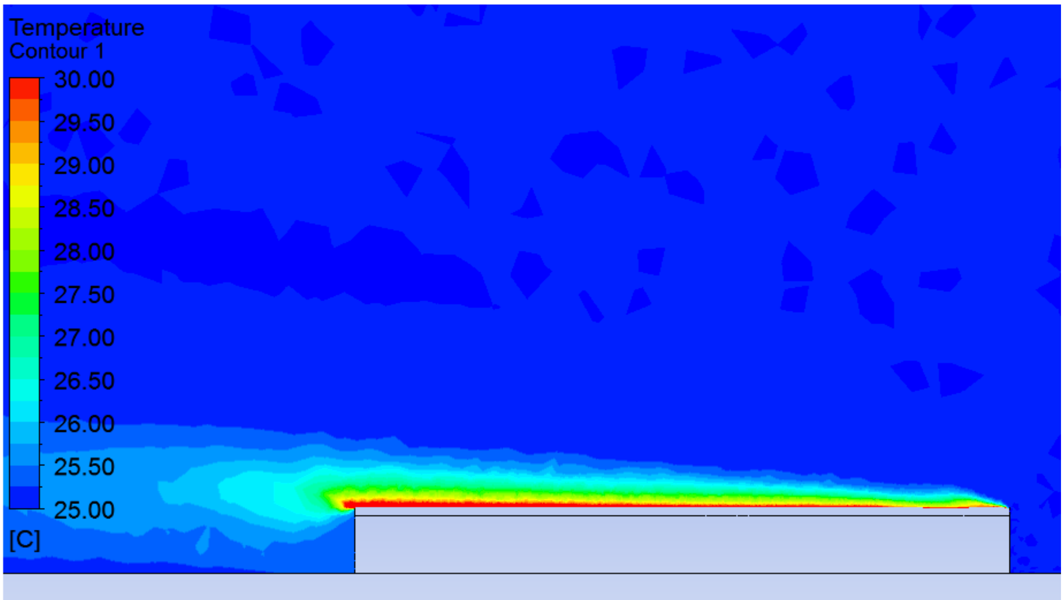

Figure 9: Air temperature for west wind at 3m/s – forced convection

Based on the behaviour identified above, wind speeds were run for each direction at 0.5m/s, 2m/s, 3m/s and 10m/s for each wind direction. This ensured that the different convection behaviour was captured. A still case was not modelled, as CFD has difficulty producing accurate still condition cases, due to the lack of air movement to iteratively adjust to create a solution.

Radiation cases

Two different net absorbed radiation cases were run for a number of key wind cases to determine the impact on convection. When more radiation is absorbed by the roof, it will become hotter, causing greater buoyancy-driven convection. This will have a higher impact at low wind speed, and have minimal impact at high wind speed when wind-driven effects dominate over buoyancy.

The low radiation case was 100 W/m^2 net radiation. The high case was 500 W/m^2, which is the highest absorbed radiation level for any of the roof materials in the dynamic thermal model.

The impact of higher absorbed radiation can be seen in Figure 10 and Figure 11 below. This shows, for a 0.5m/s wind from the west, the difference in convection coefficient over the roof surface for the two radiation cases.

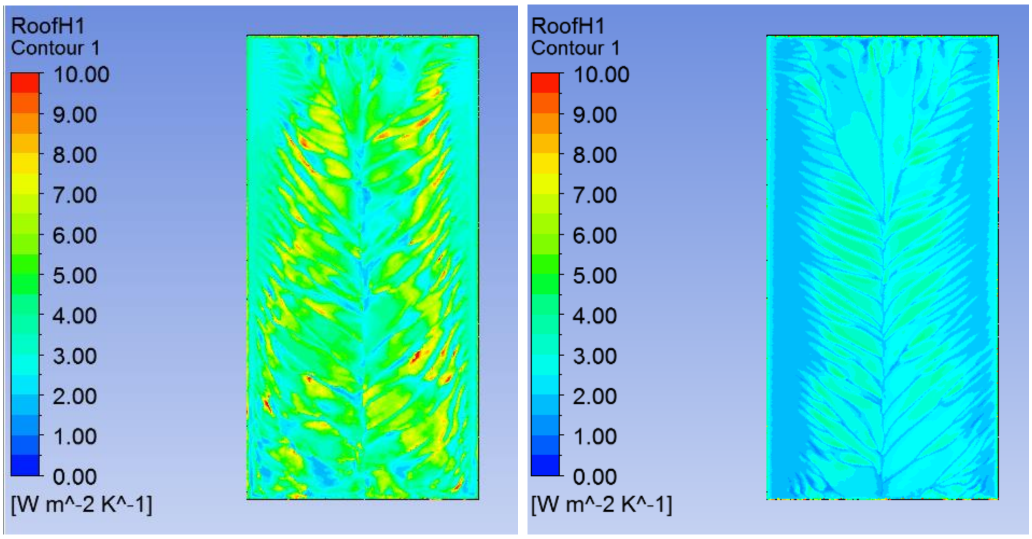

Figure 10: Convection coefficient for 500W/m^2 (left) and 100W/m^2 (right) net absorbed radiation at 0.5m/s west wind

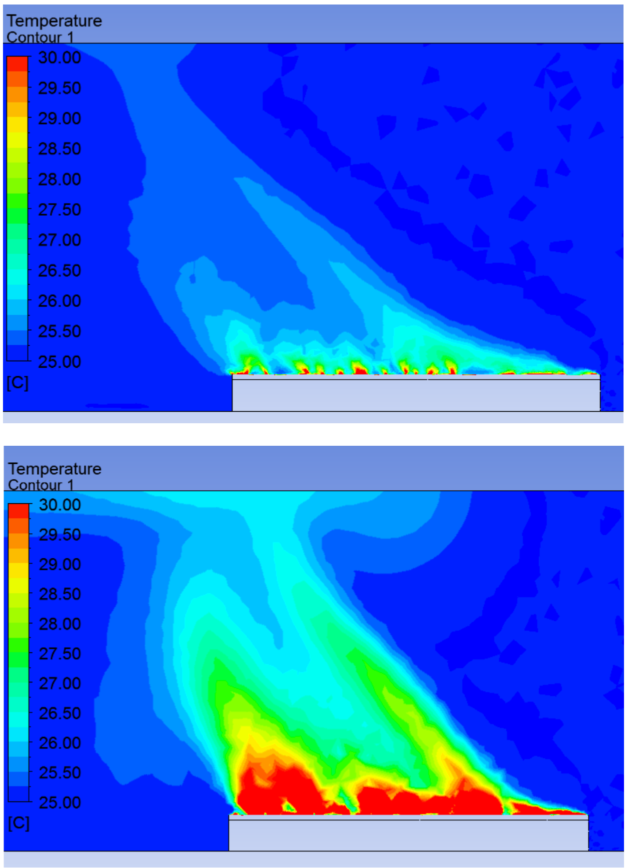

Figure 11: Air temperature showing convection patterns for 100W/m^2 (top) and 500W/m^2 (bottom) net absorbed radiation at 0.5m/s west wind

4.8 Results

Convection coefficient calculation

The convection coefficient has been calculated by dividing the heat flux at the roof surface by the temperature difference between the roof surface and the bulk air temperature (25°C). This will inherently include the effect of any localised elevated temperatures.

Roof grid

The convection coefficient varies across the surface of the roof for each case. Based on common patterns in the results, it is possible to divide the roof into representative sections. The behaviour of each section can be analysed separately and later entered into the dynamic energy building model. An average convection coefficient will be calculated across each roof grid section. This allows localised effects to be included. The sections are shown below in Figure 12. The behaviour of the convection coefficient, *h*, over the roof can be seen in Figure 13 and demonstrates some of these areas – the corner and edges behave differently to the main areas.

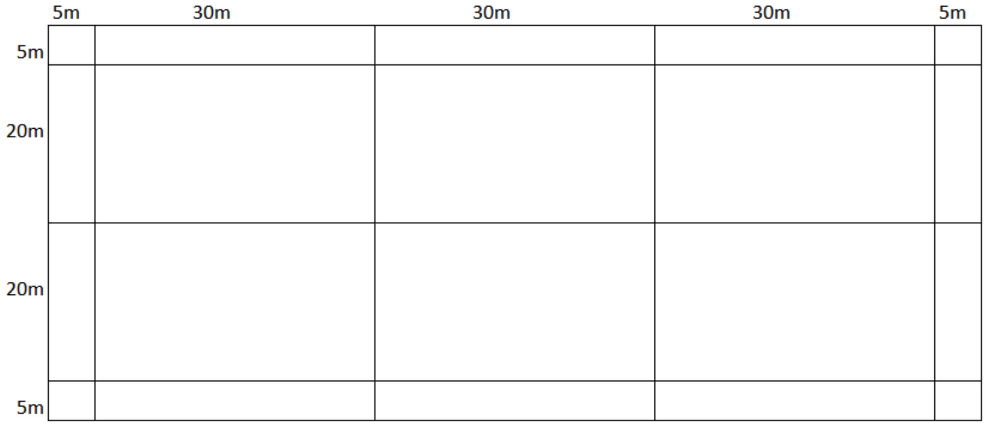

Figure 12: Representative roof sections

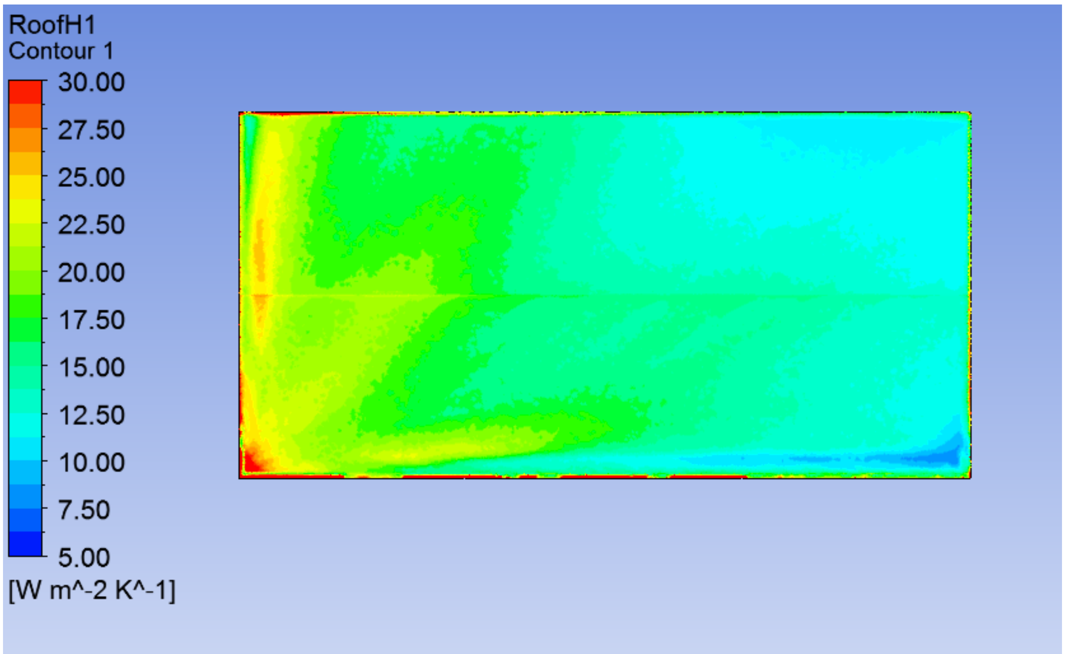

Figure 13: Convection coefficient for southwest wind at 10m/s.

Relationship between wind speed and convection coefficient

For any one roof location, wind direction, and absorbed radiation, it was found that there is a very linear relationship between convection coefficient and wind speed. This can be seen below in Figure 14;

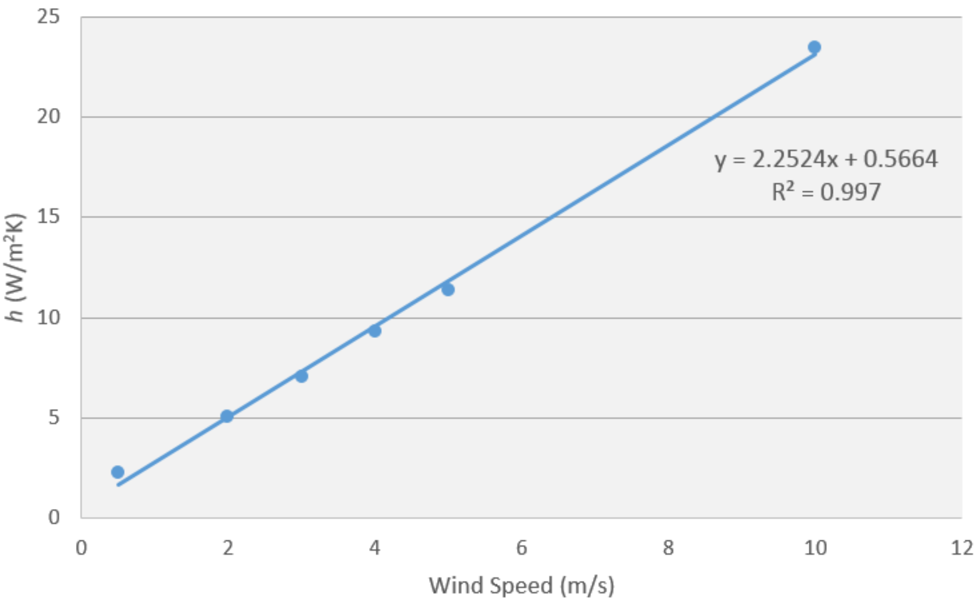

Figure 14: Convection coefficient vs wind speed for NE corner, 100W/m^2 and west wind

A series of relationships has been determined for every combination of roof grid area, wind direction and absorbed radiation. These values are less than would be predicted by standard methods in first order analysis by dynamic thermal modelling. This means that less heat is carried away by convection than would normally be predicted.

Relationship between wind direction and convection coefficient

Different wind angles cause different distributions of air and heat. This is especially noticeable when it interacts with the roof shape.

The differences caused by wind direction are complex. The results have been taken for each different wind direction.

The difference in convection coefficient distribution for two different wind directions is shown below in Figure 15 below. There is higher convection at the edge or corner of the roof where the wind is coming from. Areas of low convection are caused by relatively still areas, caused by air recirculation patterns. An example of this can be seen below in Figure 16;

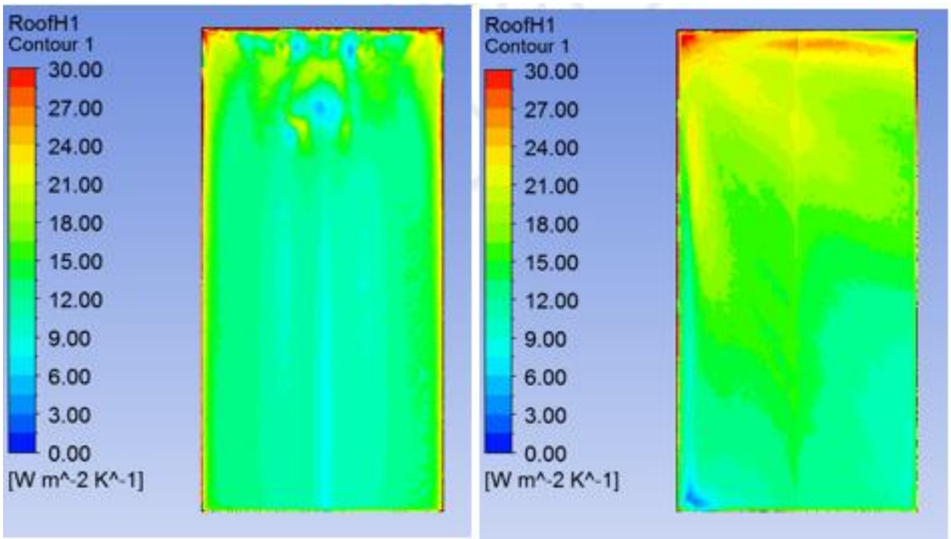

Figure 15: Convection coefficient for 10m/s wind and 500W/m^2. Wind direction is from the east (top) for the left figure, and from northeast (top left) for the right figure.

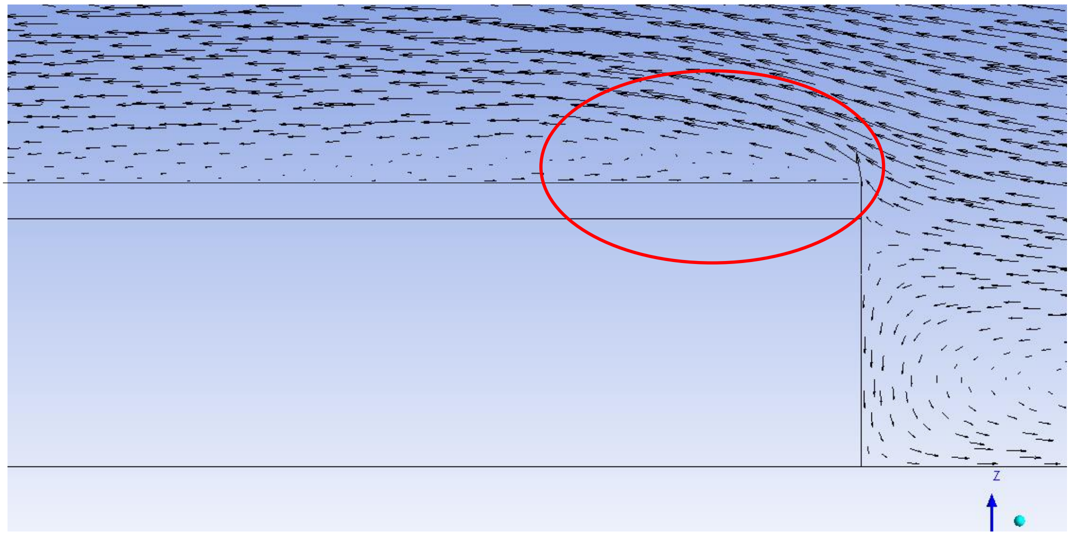

Figure 16: Velocity vectors over roof. Note low speed recirculation zone circled in red.

Temperature above roof for mechanical plant

Mechanical plant on the roof will be affected by local increases in air temperature. For this assessment, it is assumed that plant will be located in the centre of the roof and with intakes at 1.5m above the roof surface.

The area-averaged increase in temperature over the central 30m x 30m area has been taken for each simulation. This will be used to adjust conditions for air conditioning unit fresh air and cooling tower heat rejection.

The roof surface temperature distribution is affected by the convection over the roof. Areas with less convection will get hotter. The air above the roof will be affected by the roof surface temperature and air movement. See Figure 17 and Figure 18 below for examples of roof thermal behaviour. In this case, wind is coming from NNE (top left) or from N (left). The cooler air pushes the rising hot air to the side. Because of the roof shape and turbulence patterns, the different areas have different amounts of air movement and therefore different temperature distribution.

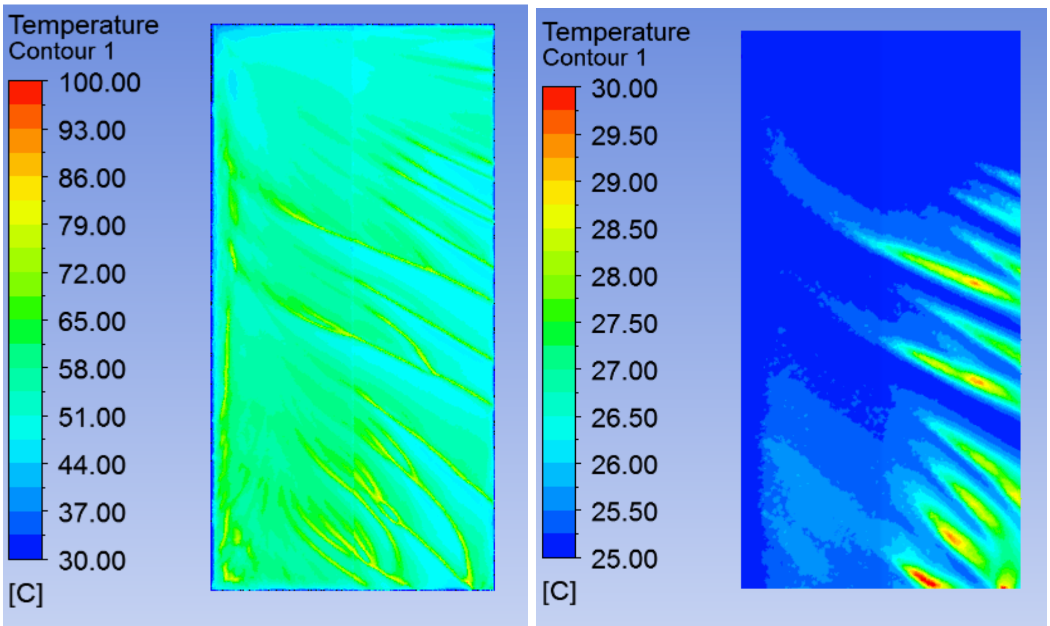

Figure 17: Roof temperature (left) and air temperature 1.5m above the roof (right) for NNE wind at 2m/s with 100W/m^2. Note the different temperature scales.

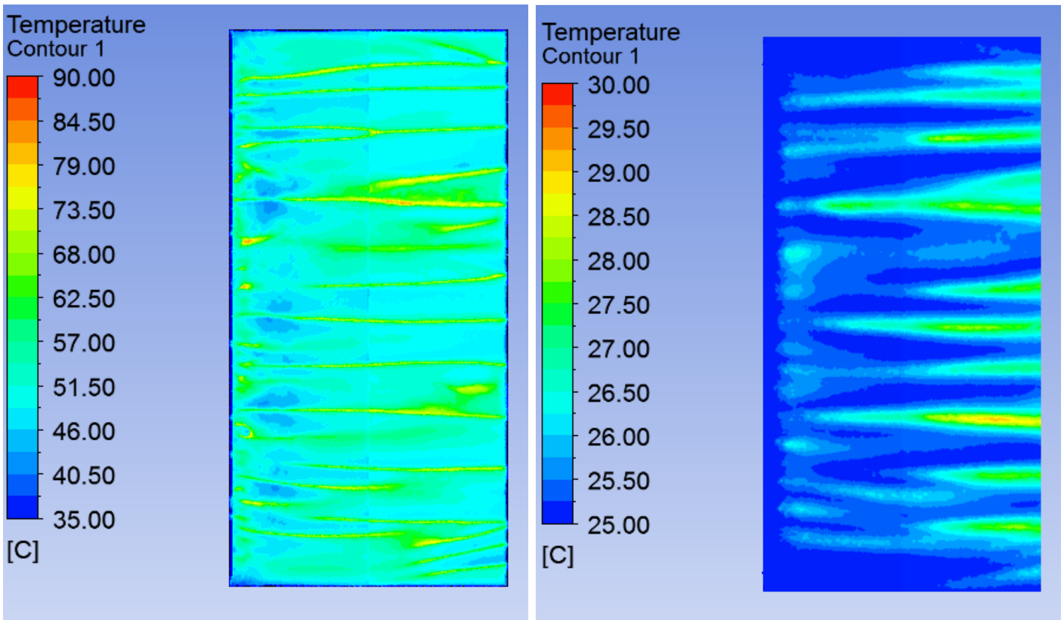

Figure 18: Roof temperature (left) and air temperature 1.5m above the roof (right) for N wind at 2m/s with 100W/m^2. Note the different temperature scales.

5 Stage 2 – Dynamic Thermal Simulation

5.1 Dynamic modelling

Dynamic thermal modelling simulates the behaviour of a building over time. By calculating the changes in properties of spaces over small time steps, a full year of data can be built up. This dynamic modelling is typically not able to capture small scale behaviour such as the effects that have been examined in CFD.

Thermal modelling was performed utilising Simergy, a front end of EnergyPlus. Once the model was constructed, with HVAC assigned, an advanced EnergyPlus simulation control tool called Energy Management System (EMS) was utilised. EMS provides a means to apply unique control configurations, or “actuators” to building energy simulations. For this project, the “actuators” were used to apply unique equations for convection heat transfer coefficients, with the equations developed from CFD post processing.

The EMS “actuators” were also utilised to account for the heat island effect (or temperature bias) above the roof surface, which was connected with the air intake for mechanical equipment such as the air handling units and cooling towers.

5.2 Building construction

The building model was two stories tall with concrete floors and walls, and a metal roof with plasterboard ceilings. Insulation is included in the roof and walls to comply with Section J of the 2016 NCC. For more detailed information, see Appendix B section B1.

Three different metal roof types are considered. These are Zincalume, Colorbond Surfmist and Colorbond Coolmax. The important thermal properties are listed below in Table 1. Note that these properties have been adjusted to include the effect of weathering over time typical for roofs.

Table 1: Roof properties

	Zincalume	Colorbond Surfmist	Colorbond Coolmax
Solar absorptance	0.50	0.37	0.28
Emissivity	0.20	0.85	0.87

Solar absorptance is a measure of how much radiation is absorbed by the material. All radiation not absorbed is reflected away. Low absorptance values mean that less heat is absorbed. Generally light coloured materials have a low absorptance and dark coloured materials have a high absorptance.

Emissivity is a measure of the ability of a surface to reradiate heat away. A high emissivity means that more heat can be dissipated through long wave radiation. If all other properties are equal, a high emissivity roof will be cooler than a low emissivity roof.

5.3 Internal loads

The building internal loads used were as per the JV3 protocol in the 2016 NCC for a retail building. Infiltration rates are 0.5 air changes per hour for perimeter zones and 0 for internal zones. See Appendix B2 for a summary of the internal loads.

5.4 HVAC

The building HVAC system is a Variable Air Volume (VAV) air conditioning system served by a chiller with a cooling tower. Heating is provided by electric duct heaters at each VAV zone.

The chilled water schematic for the HVAC system is shown below in Figure 19 below:

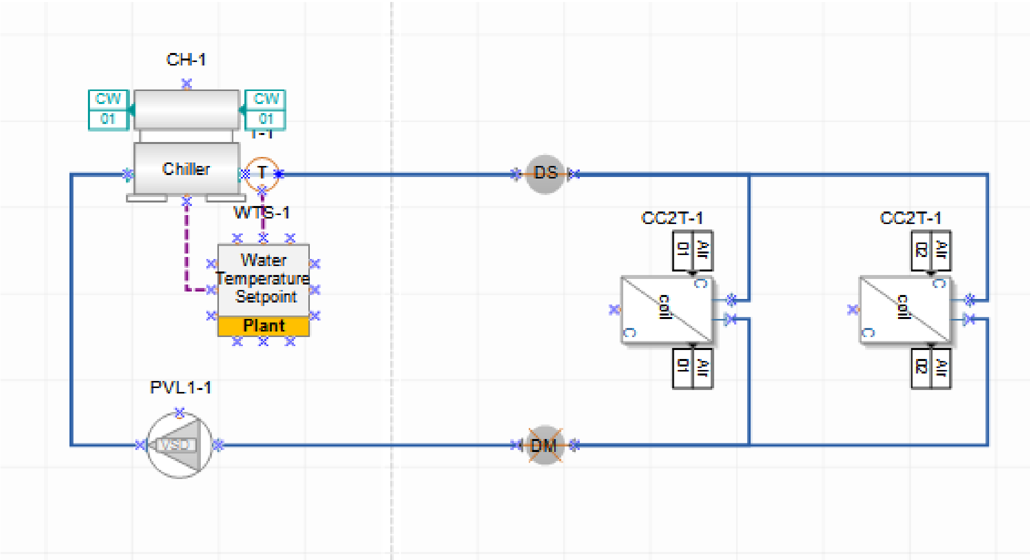

Figure 19: HVAC chilled water schematic

Each floor is served by a separate AHU, and is separated into internal and perimeter thermal zones. The perimeter zones are 5m deep. A schematic showing the AHU setup is shown next in Figure 20. For more detailed information, see Appendix B section B3.

A water-cooled chiller is a very efficient cooling system, with a COP in this case of 6.0 to 7.0. Other cooling systems, such as air-cooled chillers or DX air handling units, have COPs of around 3.0 to 4.5. A building with lower COP cooling systems would have higher cooling energy for the same cooling load. While a water-cooled chiller would be typical for this size building, it should be noted that other mechanical systems would lead to different amounts of cooling and heating energy, which will affect the outcomes.

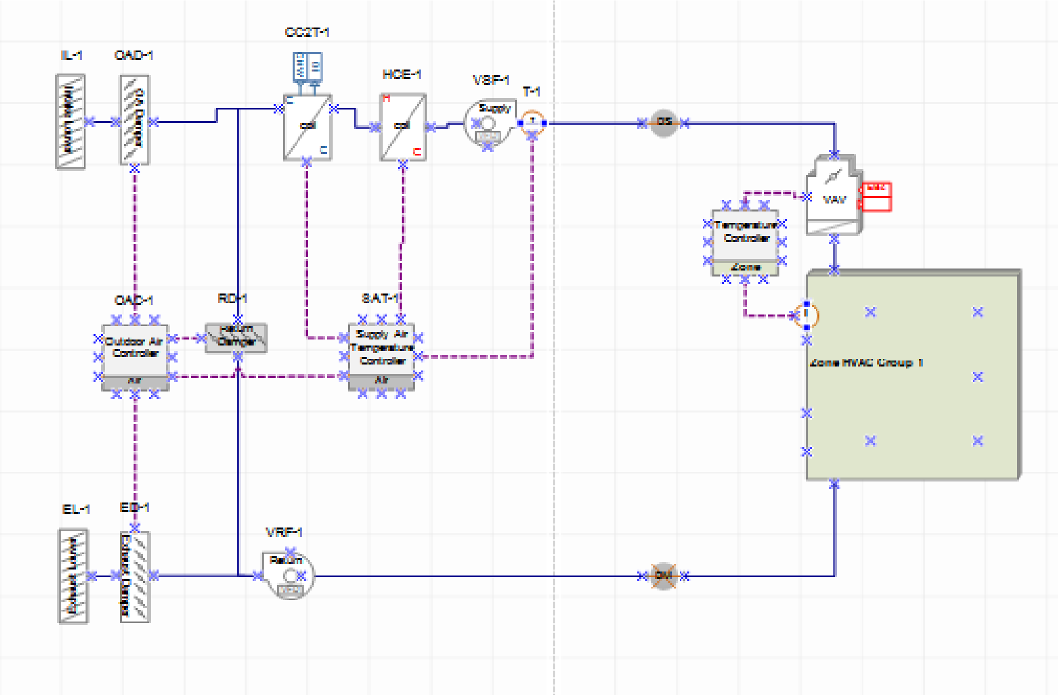

Figure 20: HVAC Air handling unit schematic

The rooftop surface was separated into zones to match the areas of interest identified during the CFD analysis, as shown in Figure 12 in Section 4.8. These zones within the thermal model are shown in Figure 21, below:

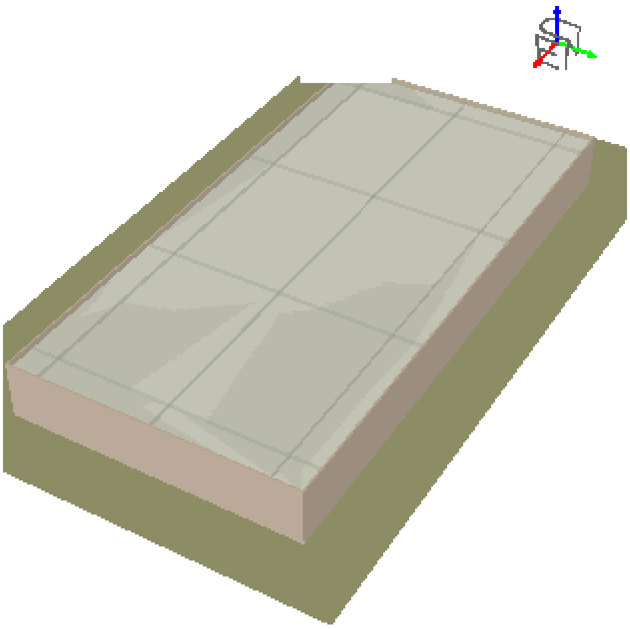

Figure 21: Individual roof space zones used for the dynamic thermal simulations

5.5 First order analysis

The results of the first order analysis are summarised in the Table 2 below:

Table 2: First order simulation results

	Zincalume	Colorbond Surfmist	Colorbond Coolmax
Annual system cooling energy (kWh_e)	336,250	327,994	326,144
Cooling system savings (relative to Zincalume)	0%	2.5%	3.0%
Peak chiller demand (kW_{th})	1,629	1,604	1,597
Peak chiller demand (kW_e)	280	273	272
Peak load thermal load reduction (relative to Zincalume)	0%	1.6%	2.0%
Total HVAC energy (kWh_e)	737,561	727,566	725,356
HVAC energy savings (relative to Zincalume)	0	1.4%	1.7%
Annual operational cost savings (relative to Zincalume) *	$0	$2,499	$3,051
Capital cost savings (relative to Zincalume)**	$0	$23,700	$30,100
Greenhouse gas savings (relative to Zincalume) ($kgCO_2$)***	0	9,295	11,351

*Note that the cost savings are a high level estimate based on a median annual electricity fee of $0.25 per kWh.

**Capital cost savings based on $929/$kW_{th}$ [7], assuming plant can be installed with lower capacity alternatives, as well as small reductions in pipe and duct size.

***Greenhouse gas emissions are calculated based on Scope 3 emissions for electricity of 0.93 $kgCO_2$/kWh for QLD.

The Zincalume roof had the highest annual cooling energy consumption and largest cooling load. Colorbond Surfmist provided moderate cooling energy savings (2.5% below Zincalume). Colorbond Coolmax demonstrated the best savings, with a 3.0% reduction in annual cooling energy against Zincalume.

The peak chiller demand was highest for the Zincalume roof. Colorbond Coolmax had a 2.0% lower peak demand, while Colorbond Surfmist provided a 1.6% lower peak demand.

The two Colorbond roofs will result in lower operational costs due to electricity savings. This is estimated to be approximately $2,499pa for Surfmist and $3,051pa for Coolmax. In addition to this, the reduction in peak demand can result in smaller plant sizing and smaller ducts and pipes, therefore providing capital cost savings on the mechanical plant. Although estimates can vary, a figure of $929/kW$_{th}$ [7] has been used and is believed to be conservative. This is estimated to be approximately $23,700 for Surfmist and $30,100 for Coolmax.

Figure 22 shows a typical chiller cooling demand profile for each of the three simulations. The chiller load of the Zincalume roof type is noticeably higher throughout the day.

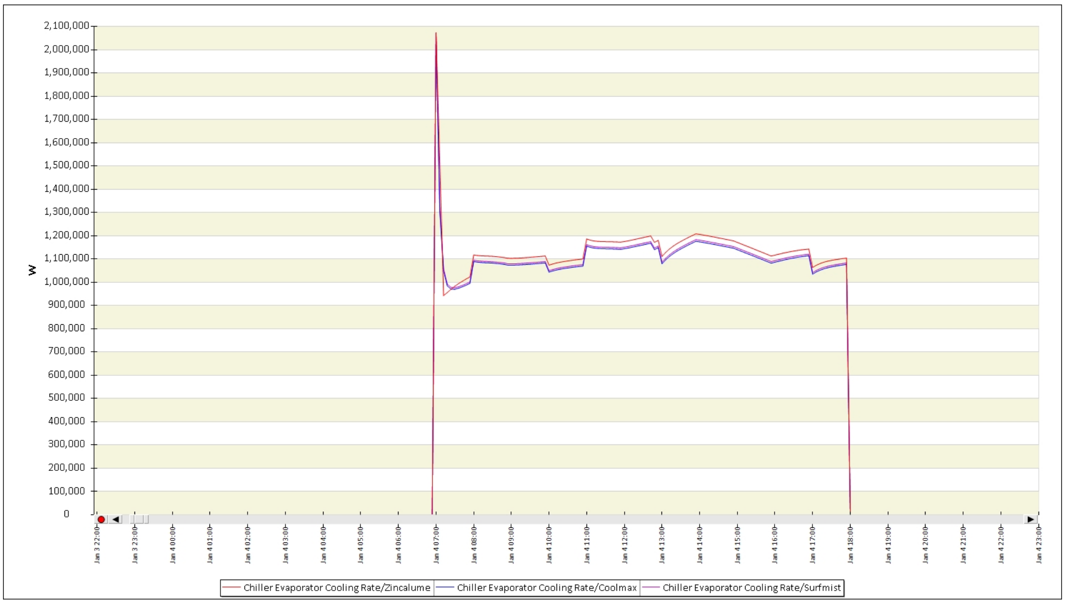

Figure 22: Typical summer day chiller load for three building types

The surface temperature of the roof is shown for a typical 3 day summer period in Figure 23 below. There is a clear distinction in temperature between the three roof types, with Zincalume reaching much higher surface temperatures than the two Colorbond roof types. Coolmax demonstrates the lowest surface temperature profile.

For a comparison of the first order results with other, similar studies, please see Appendix C Section C1.

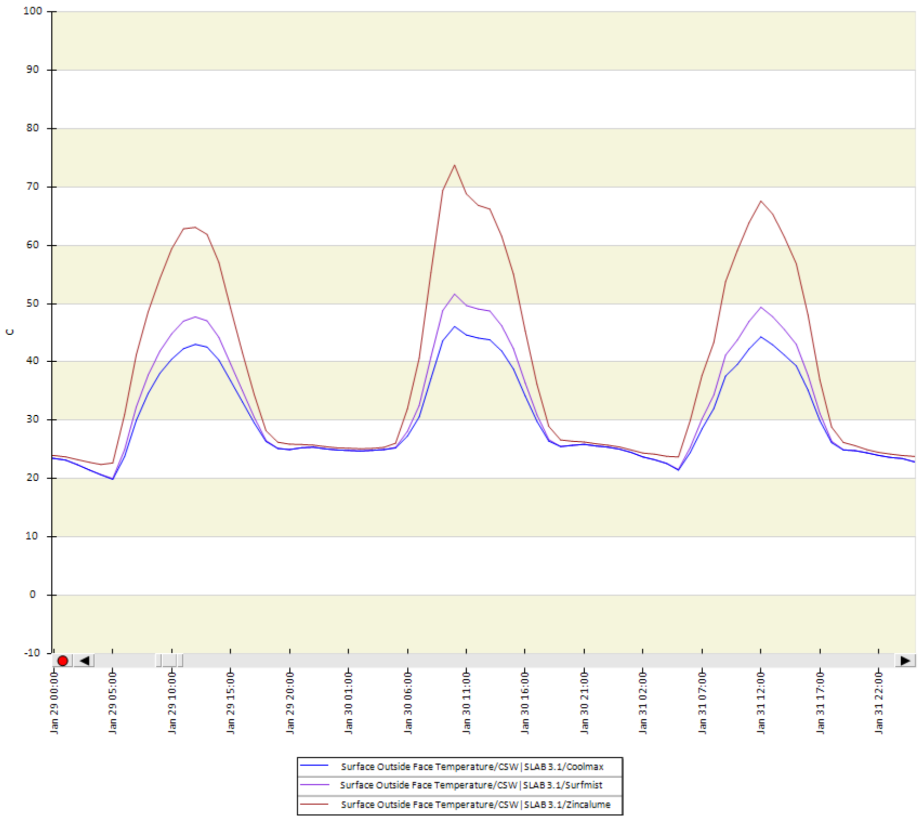

Figure 23: Roof surface temperature over 3 day summer period

5.6 Second order analysis

The second order analysis includes the following differences against the first order analysis:

- Roof convection coefficient is calculated based on the relationships determined from the Stage 1 CFD simulation.
- AHU outside air conditions are calculated based on the increased air temperature relationship determined from the Stage 1 CFD simulation.
- Cooling tower performance is calculated based on the increased air temperature relationship determined from the Stage 1 CFD simulation.

For the second order simulations, all other building parameters were kept unchanged. This included building constructions (only roof changed between the three buildings), internal loads, profiles, schedules and plant equipment sizes.

The results of the second order analysis are summarised in the Table 3 below:

Table 3: Second order simulation results

	Zincalume	Colorbond Surfmist	Colorbond Coolmax
Annual system cooling energy (kWh_e)	350,947	332,325	328,603
Cooling system savings (relative to Zincalume)	0%	5.3%	6.4%
Annual total consumption difference relative to 1st order of same roof type	4.4%	1.3%	0.8%
Peak chiller demand (kW_{th})	1,689	1,628	1,614
Peak chiller demand (kW_e)	294	279	276
Peak thermal load reduction relative to Zincalume	0%	3.6%	4.4%
Total HVAC energy (kWh_e)	755,144	733,400	728,911
HVAC energy savings (relative to Zincalume)	0	2.9%	3.5%
Annual operational cost savings (relative to Zincalume) *	$0	$5,436	$6,558
Capital cost savings (relative to Zincalume)**	$0	$56,900	$69,200
Greenhouse gas savings (relative to Zincalume) ($kgCO_2$)***	0	20,222	24,397

*Note that the cost savings are a high level estimate based on a median annual electricity fee of $0.25 per kWh.

**Capital cost savings based on $929/kW [7], assuming plant can be installed with lower capacity alternatives, as well as small reductions in pipe and duct size.

***Greenhouse gas emissions are calculated based on Scope 3 emissions for electricity of 0.93 $kgCO_2/kWh$ for QLD.

The second order results show that the cooling system energy use is higher than was initially predicted, with a 0.8% to 4.4% increase in annual cooling energy. The reduced convection, along with increased air temperatures entering the air handling units and cooling towers had led to higher loads.

Colorbond Coolmax and Colorbond Surfmist roofs save much more energy than was predicted under the first order analysis, with savings of 5.3% and 6.4% respectively. This is a bigger improvement than the 2.5% and 3.0% savings predicted in the first order analysis. This is because the second order analysis shows there is less convection removing heat from the roof surface than the standard first order analysis would predict, leading to higher roof temperatures. In this environment, a high reflectance is important to reduce the total heat reaching the roof, and a high emittance is important as it allows more heat from the hot roof to be emitted as long wave radiation away from the building. The Colorbond Coolmax and Colorbond Surfmist roof types have high reflectance and emittance values.

The Colorbond Coolmax and Colorbond Surfmist roofs show a greater peak demand reduction under the second order analysis. The peak demand is reduced by 4.4% and 3.6% for Colorbond Coolmax and Colorbond Surfmist respectively, compared to only 2.0% and 1.6% in the first order analysis.

Annual operational cost savings and estimated mechanical capital cost savings are both substantially higher when second order effects are included. The annual energy savings, at $5,436 for Surfmist and $6,558 for Coolmax, are 118% to 115% greater than the first order estimates. The capital cost savings of $56,900 for Surfmist and $69,200 for Coolmax are 140% and 130% greater than the first order estimates.

Table 4 below provides the annual cooling thermal load for all six simulations.

Table 4: Annual cooling consumption for each simulation

Coolmax 1st order cooling consumption (MWh_r)	**Surfmist 1st order cooling consumption (MWh_r)**	**Zincalume 1st order cooling consumption (MWh_r)**	**Coolmax 2nd order cooling consumption (MWh_r)**	**Surfmist 2nd order cooling consumption (MWh_r)**	**Zincalume 2nd order cooling consumption (MWh_r)**
1,915.1	1,927.1	1,976.7	1,928.1	1,952.3	2,073.7

The roof surface temperatures for the three roof materials are shown for a typical 3 day summer period in Figure 24 below.

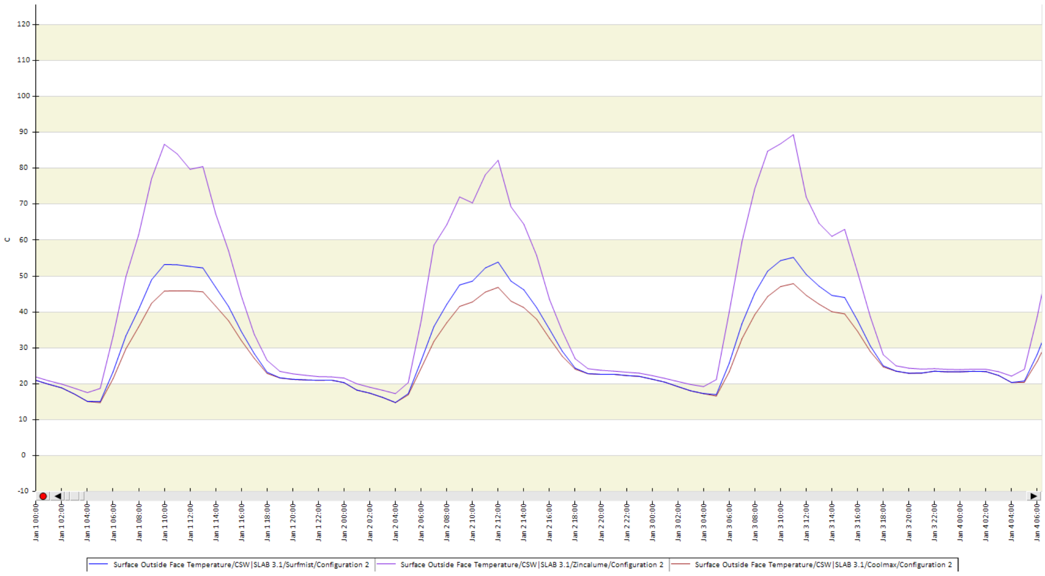

Figure 24: Roof surface temperature over 3 day summer period (second order)

As with the first order results, the Zincalume roof is much hotter than the two Colorbond roofs. The difference between the first order and second order surface temperatures for Zincalume and Colorbond Coolmax is shown in Figure 25 and Figure 26 below:

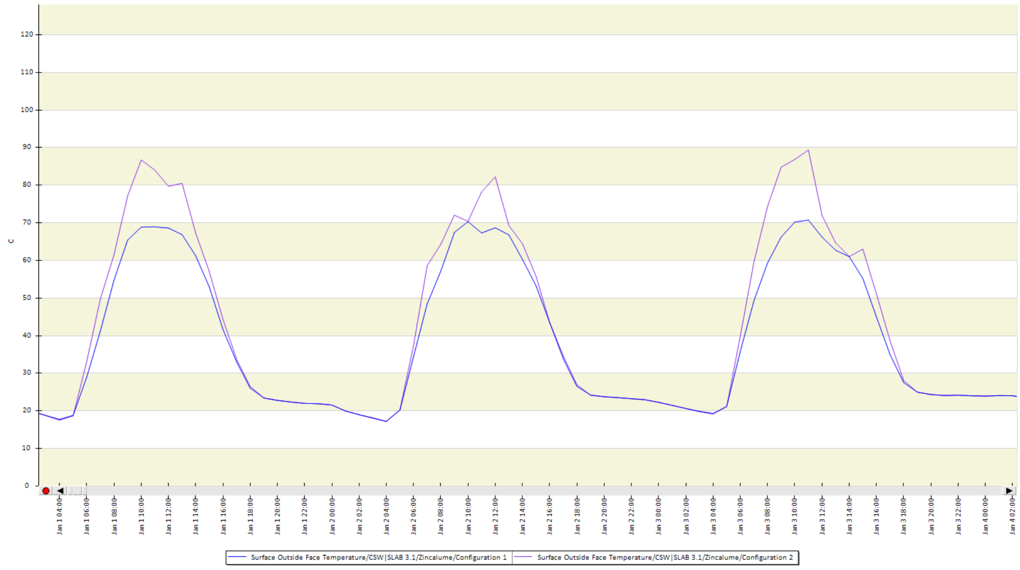

Figure 25: Zincalume roof surface temperature for first and second order

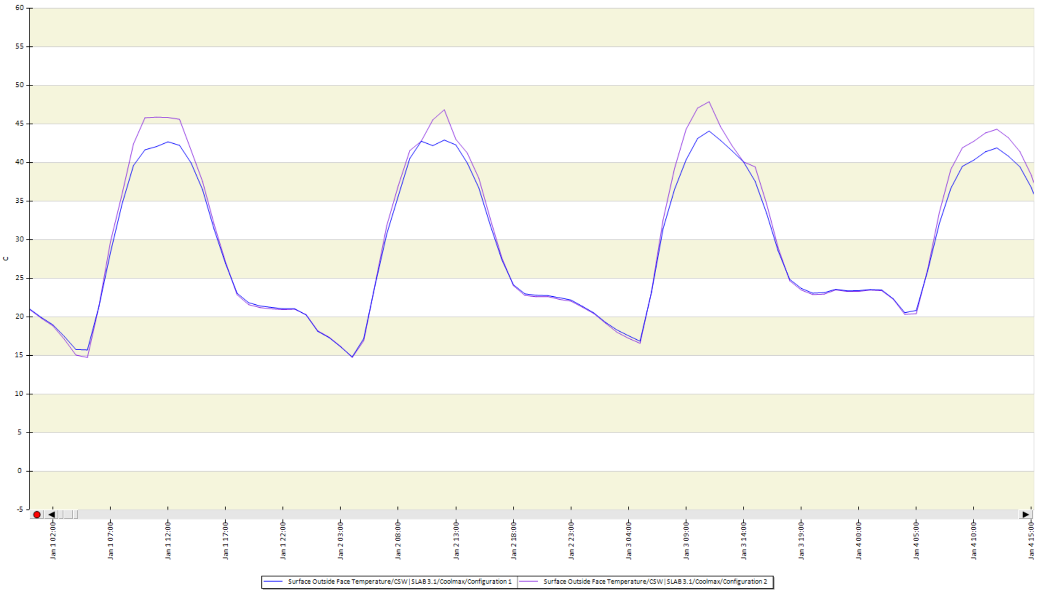

Figure 26: Coolmax roof surface temperature for first and second order

It can be seen that although the roof is hotter in all cases, once second order effects are considered, the Zincalume roof is affected much more.

For a comparison of the results with other, similar studies, please see Appendix C Section C1.

5.7 Climate comparison

Additional analysis has been conducted to compare the performance of the different roof products in different locations throughout Australia. Simulations have been run for Ipswich, West Sydney, and Northern Melbourne. Although only specific locations were tested, some general trends can be developed and used to predict behaviour in other regions.

TMY2 weather files were used for each of the locations – these are representative of a typical year, and based on 45 years of data. Climate data for each simulated weather file are shown in Table 5.

Table 5: Climate data for each location

	Hervey Bay	Ipswich	Western Sydney	Northern Melbourne
Max temperature (°C)	34.4	39.1	42.8	40.3
Min temperature (°C)	4.5	-1.9	-4.6	-2.0
Ave temperature (°C)	21.2	19.6	16.8	14.1
Max radiation (W/m^2)	1094	1107	1085	1083
Ave radiation (W/m^2)	226	209	193	175
Max wind speed (m/s)	12.3	12.4	14.9	18.1
Ave wind speed (m/s)	4.2	2.4	2.6	4.8

For each test location, the building fabric was adjusted to meet the BCA Section J requirements for each different climate (see Appendix B section B1). In Western Sydney and Northern Melbourne, the HVAC system included a condensing gas boiler connected to a central heating coil, in addition to the electric reheat coils (see Appendix B section B3). The HVAC system was resized for each location.

The results for each location and roof type are presented in Table 6 through Table 8 over the next few pages. For Colorbond Coolmax and Surfmist, this also includes savings and differences compared to the Zincalume case. Further to this, monthly HVAC energy use breakdowns for each location are shown in Appendix E.

Table 6: Zincalume results across climates

	Hervey Bay	Ipswich	Western Sydney	Northern Melbourne
1st order Cooling energy (kWh_e)	336,250	249,806	160,456	69,603
2nd order Cooling energy (kWh_e)	350,947	268,400	174,339	76,392
1st order peak chiller thermal load (kW_{th})	1,629	1,313	1,320	1,012
2nd order peak chiller thermal load (kW_{th})	1,689	1,386	1,407	1,040
1st order peak chiller electrical load (kW_e)	280	221	240	167
2nd order peak chiller electrical load (kW_e)	294	236	263	172
Total 2nd order HVAC electricity (kWh)	755,144	694,723	490,008	290,201
Total 2nd order HVAC gas (MJ)	0	0	1,123,312	2,111,731
2nd order annual cooling load (kWh_{th})	2,073,700	1,605,200	993,500	424,400
2nd order annual heating load (kWh_{th})	0	82,000	302,600	564,200

Table 7: Colorbond Surfmist results across climates

	Hervey Bay	Ipswich	Western Sydney	Northern Melbourne
1st order Cooling energy (kWh_e)	327,994	241,414	151,756	65,736
2nd order Cooling energy (kWh_e)	332,325	243,519	153,525	67,100
1st order peak chiller thermal load (kW_{th})	1,604	1,290	1,272	997
2nd order peak chiller thermal load (kW_{th})	1,628	1,298	1,290	1,001
1st order peak chiller electrical load (kW_e)	273	216	227	164
2nd order peak chiller electrical load (kW_e)	279	217	232	165
Total 2nd order HVAC electricity (kWh)	733,400	673,596	461,404	276,933
Total 2nd order HVAC gas (MJ)	0	0	1,251,871	2,259,191
2nd order annual cooling load (kWh_{th})	1,952,300	1,446,100	867,000	370,200
2nd order annual heating load (kWh_{th})	0	93,300	337,200	603,800
2nd order cooling savings (kWh)	18,622	24,881	20,814	9,292
2nd order cooling savings (%)	5.3%	9.3%	11.9%	12.2%
Annual operational savings*	$5,436	$5,282	$5,723	$1,679
Capital cost savings**	$56,900	$81,800	$108,900	$40,000
GHG Savings (kg CO_2)***	20,222	19,648	26,032	15,526

*Note that the cost savings are a high level estimate based on a median annual electricity fee of $0.25 per kWh, and gas costs of $0.04 per kWh.

**Capital cost savings based on $929/kW_r$ [7], assuming plant can be installed with lower capacity alternatives, as well as small reductions in pipe and duct size.

***Greenhouse gas emissions are calculated based on Scope 3 emissions as follows: Electricity 0.93 $kgCO_2/kWh$ in QLD, 0.99 $kgCO_2/kWh$ in NSW, and 1.34 $kgCO_2/kWh$ in VIC. Gas 0.064 $kgCO_2/kWh$ in NSW, and 0.055 $kgCO_2/kWh$ in VIC.

Table 8: Colorbond Coolmax results across climates

	Hervey Bay	Ipswich	Western Sydney	Northern Melbourne
1st order Cooling energy (kWh_e)	326,144	239,750	208,161	64,942
2nd order Cooling energy (kWh_e)	328,603	240,147	150,511	65,383
1st order peak chiller thermal load (kW_{th})	1,597	1,285	1,262	993
2nd order peak chiller thermal load (kW_{th})	1,614	1,290	1,271	995
1st order peak chiller electrical load (kW_e)	272	215	224	163
2nd order peak chiller electrical load (kW_e)	276	216	226	164
Total 2nd order HVAC electricity (kWh)	733,400	673,596	461,404	276,933
Total 2nd order HVAC gas (MJ)	0	0	1,251,871	2,259,191
2nd order annual cooling load (kWh_{th})	1,952,300	1,446,100	867,000	370,200
2nd order annual heating load (kWh_{th})	0	93,300	337,200	603,800
2nd order cooling savings (kWh)	22,344	28,253	23,828	11,009
2nd order cooling savings (%)	6.4%	10.5%	13.7%	14.4%
Annual operational savings*	$6,558	$6,124	$6,645	$2,067
Capital cost savings**	$69,200	$89,100	$126,500	$42,400
GHG Savings (kg CO_2)***	24,397	22,781	29,936	18,466

*Note that the cost savings are a high level estimate based on a median annual electricity fee of $0.25 per kWh, and gas costs of $0.04 per kWh.

**Capital cost savings based on $929/kW_r$ [7], assuming plant can be installed with lower capacity alternatives, as well as small reductions in pipe and duct size.

***Greenhouse gas emissions are calculated based on Scope 3 emissions as follows: Electricity 0.93 $kgCO_2/kWh$ in QLD, 0.99 $kgCO_2/kWh$ in NSW, and 1.34 $kgCO_2/kWh$ in VIC. Gas 0.064 $kgCO_2/kWh$ in NSW, and 0.055 $kgCO_2/kWh$ in VIC.

The simulation results showed that in all climates, cool roofs provided savings in cooling energy. Coolmax energy savings were between 6.4% and 14.4% (5.3% to 12.2% for Surfmist). Higher percentage savings were seen in Sydney and

Melbourne, although this was partly because their overall cooling energy was lower. When looking at absolute savings, the energy savings are generally higher the further north the location is. The exception to this is Hervey Bay, where the absolute cooling energy savings were not as high as for Ipswich or Sydney. Although Hervey Bay has higher average temperatures and radiation, it has lower peak temperatures. This is because Ipswich and Western Sydney are both inland locations, and will have higher maximum and minimum temperatures than coastal locations at the same latitude.

The peak cooling load for all climates was reduced by using Coolmax or Surfmist. Absolute peak reduction varied between 46 kW_r and 136 kW_r which represented a 4.4% to 9.7% reduction. The second order effects were responsible for 70% or more of this effect. In general, the locations further inland had better improvements in peak load. The inland locations had lower average wind speeds and higher peak temperatures. When low wind speed occurred at the same time as high temperatures, peak loads were substantially higher for Zincalume. There is also a trend for more northern locations to have higher reductions in peak load using cool roofs.

In all locations studied, the cooling savings are found to be larger than the heating gains in terms of thermal load. The thermal load savings were highest in Ipswich. They reduced for coastal locations and for further south locations (similar to the effect found for cooling energy above).

The study has assumed that cooling is done by a high efficiency chiller system with a COP around 6-7, and heating is done by a gas boiler with a 95% efficiency. The thermal loads for cooling and heating for each climate are shown in Figure 27 below. HVAC energy breakdown between climates is shown in Figure 28.

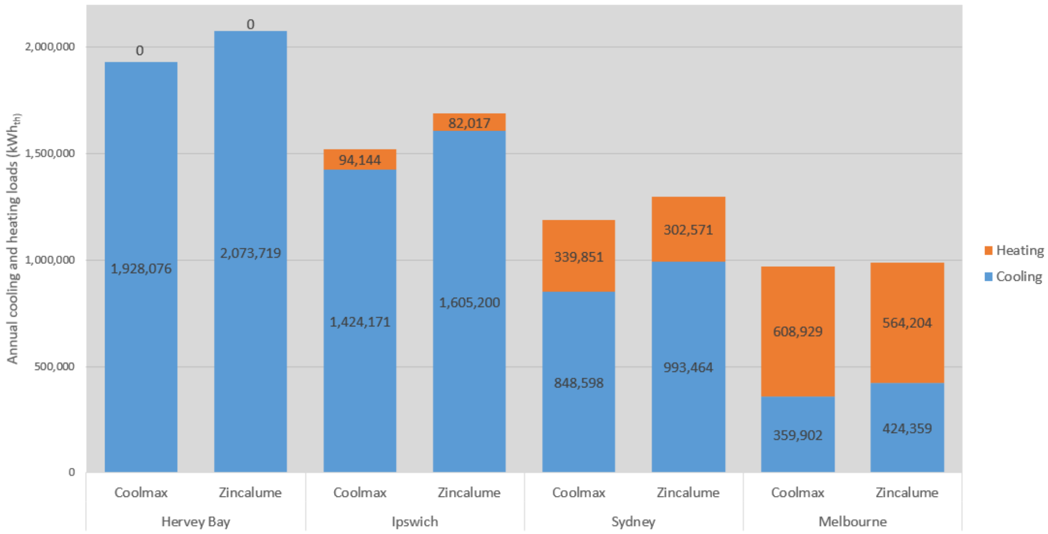

Figure 27: Thermal cooling and heating loads comparison between climates

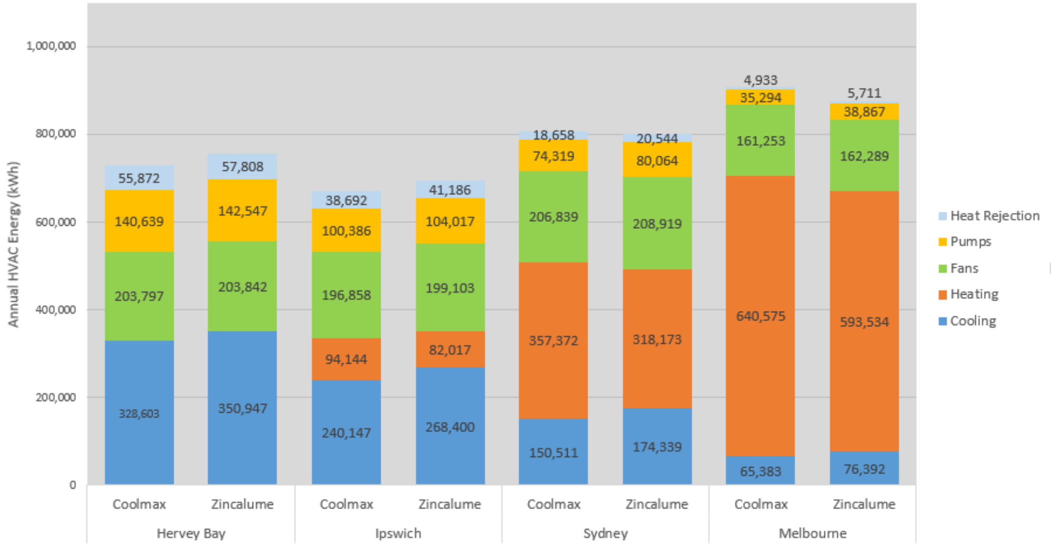

Figure 28: HVAC energy comparison between climates

As a result of the high efficiency chiller reducing the cooling electrical consumption and the lower efficiency of gas heating, some locations had a higher energy usage with a cool roof. Despite this it was still beneficial to use Coolmax or Surfmist. Because gas is cheaper than electricity and has a lower carbon intensity, the operational costs and greenhouse gas emissions were both reduced with the introduction of the cool roof. Operational savings varied from $2,067 in Melbourne to $6,645 in Hervey Bay. The savings for Hervey Bay, Ipswich, and Western Sydney were all similar in magnitude ($6,558, $6,124 and $6,645 respectively), due to the larger cooling impact in these cities. Coolmax and Surfmist provided greater savings in cooling dominated climates, and were less effective (although still beneficial) in the more heating dominated climate of Melbourne.

The impact of the second order impacts on roof surface temperature and mechanical plant intake air temperature was similar across the different climates. The difference between first and second order results, or bias, is demonstrated in the figures below. Figure 29 and Figure 30 show the maximum and average roof surface temperature bias, and Figure 31 and Figure 32 show the maximum and average mechanical plant intake air temperature bias. The roof temperature bias is calculated 24 hrs/day over the whole year, while the plant intake air bias is calculated over plant operational hours only. Note that the maximum biases are not typical, and do not necessarily occur during the hottest time. The Coolmax roof has a substantially lower peak and average roof temperature than the Zincalume, with similar impacts on the mechanical plant air intake temperature. This is a large impact that is ignored in first order simulations.

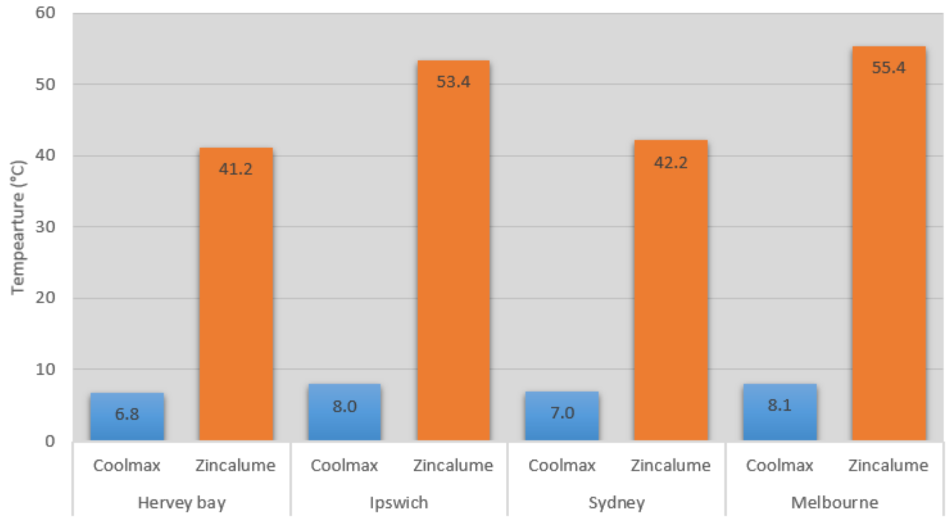

Figure 29: Maximum roof surface temperature bias

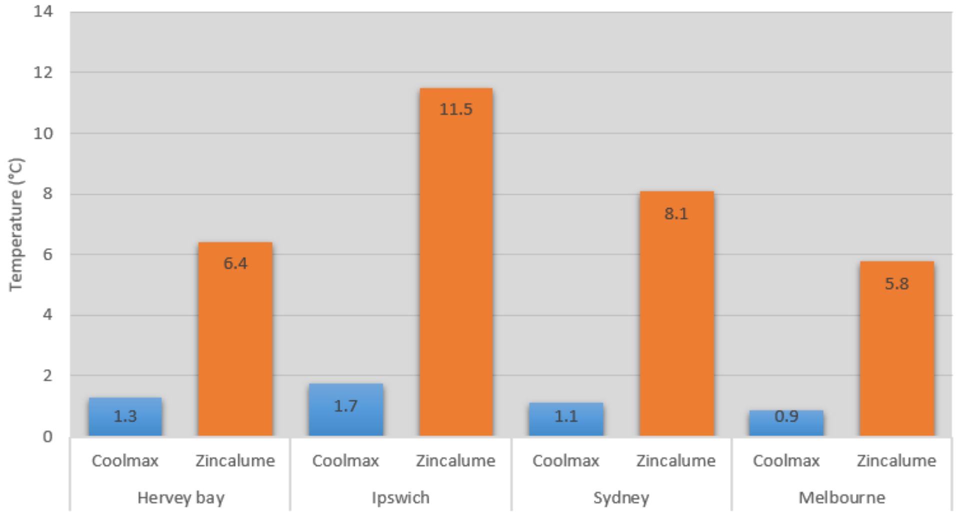

Figure 30: Average roof surface temperature bias over 24 hours

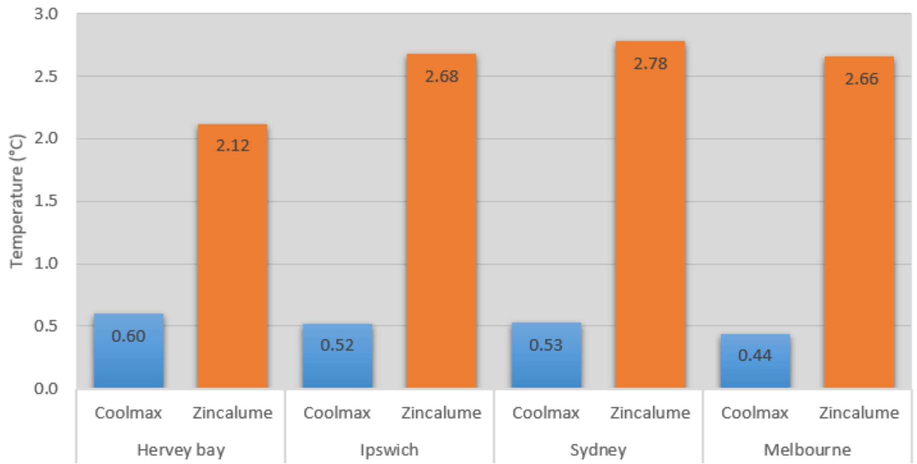

Figure 31: Maximum plant intake air temperature bias

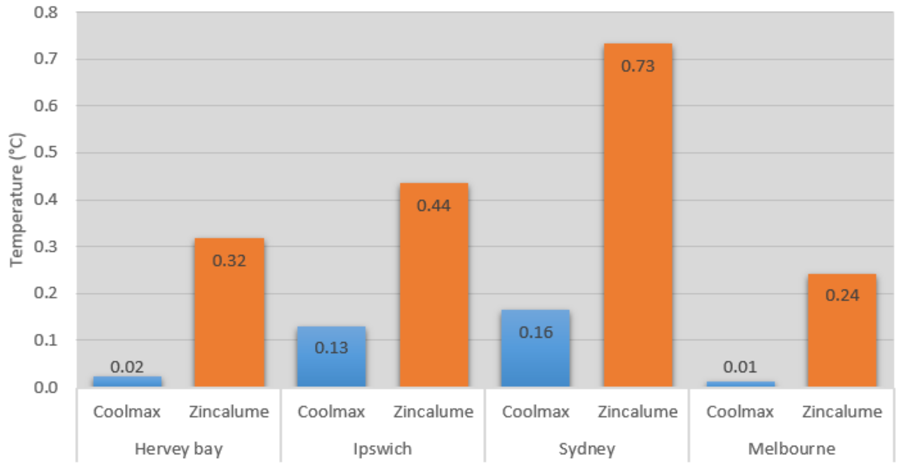

Figure 32: Average plant intake air temperature bias over operational hours

Although this study has only looked at four specific locations, the implications can easily be applied throughout Australia. In particular, when considering peak and average temperatures and radiation levels for capital cities throughout Australia:

- The performance in Adelaide is expected to be similar to the Western Sydney results.
- Brisbane results will be very similar to Ipswich (although without the inland location impacts of larger peaks and lower wind speeds).
- Perth will behave roughly halfway between the results in Western Sydney and Ipswich/Hervey Bay.
- Hobart will have similar results to Northern Melbourne, although with more heating and less cooling affecting the overall performance.
- Darwin will show stronger effects than the northernmost simulated climate, Hervey Bay, due to the higher peak and average temperatures and solar radiation.

5.8 Further Considerations

Green Star

There are two areas in the Green Star Design and As Built Tool that can reward buildings with cool roofs such as Bluescope Colorbond Coolmax and Colorbond Surfmist.

Heat Island Effect

The Heat Island Effect in the Ecology category is awarded to projects where at least 75% of the total project site area comprises building or landscaping elements that reduce the impact of the heat island effect. One way of demonstrating compliance for this is to select a roof material that has a three year SRI greater than 64 for a roof pitch of less than 15°, or greater than 34 for a roof pitch of more than 15°. Where a three-year figure is not available, the roof material must have an initial SRI greater than 82 for a roof pitch of less than 15°, or greater than 39 for a roof pitch of more than 15°.

Colorbond Coolmax has an initial SRI of 95. Colorbond Surfmist has an initial SRI of 82 and a 5 year SRI of 79. Both of these products will inherently comply, and can assist a project achieving this Green star point. A number of other Colorbond products are also compliant, as seen in Table 9.

Table 9: Colorbond roof product SRI data

Roof	Initial SRI	3-year SRI	Green Star Compliant
Coolmax / Whitehaven	95	Data not available	Yes
Classic Cream	82	79*	Yes
Surfmist	82	79*	Yes
Galactic	80	Data not available	Only if roof pitch > 15° **
Cosmic	73	Data not available	Only if roof pitch > 15° **
Paperbark	68	68	Yes
Evening Haze	66	66	Yes
Shale Grey	66	65*	Yes
Dune	61	61*	Only if roof pitch > 15°
Rhea	58	Data not available	Only if roof pitch > 15°
Cove	51	Data not available	Only if roof pitch > 15°
Windspray	46	45*	Only if roof pitch > 15°
Pale Eucalypt	43	43	Only if roof pitch > 15°
Astro	41	Data not available	Only if roof pitch > 15°

*3 year data not available, so conservatively the 5 year SRI figure is used instead.

**This product would very likely comply in all circumstances if 3 year (or more) SRI data was available.

We recommend that the 3-year SRI values are published online, so that they can be found by design consultants that are looking at using light coloured roofs for Green Star projects. This will increase the range of products that comply and attract project teams seeking Green Star.

Greenhouse Gas Emissions

The Greenhouse Gas Emissions credit in the Energy category rewards projects with verifiably low levels of operational greenhouse gas production. There are five different pathways that can be used to demonstrate this and be awarded these credits

15A Prescriptive Pathway

Points are gained by improving on BCA Deemed-to-Satisfy values, including 1 point for increasing roof, wall, floor and ceiling insulation levels above BCA Deemed-to-Satisfy levels by 15%.

In Climate Zones 1, 2 and 3, the required insulation level is dependent on the roof solar absorptance value, and so it would be easier to achieve one point by using cool roofs such as Colorbond Coolmax or Surfmist. There are reduced levels for solar absorptace values below 0.6 and 0.4. There is currently no opportunity to demonstrate second order effects, as this pathway is intended to be simple and quick to calculate.

15B NatHERS / 15C BASIX

These two pathways use the NatHERS software to calculate greenhouse gas emissions. Roof colour is part of this, although only as a light / medium / dark colour input. Cool roofs such as Colorbond Coolmax and Surfmsit would count as light roofs and achieve the maximum benefit. There is currently no opportunity to demonstrate second order effects, as this pathway uses specific software with simplified calculations for roof loads. Additionally, this pathway is only for residential buildings, which typically have relatively small roof areas and so would not show significant second order effects.

15D NABERS Energy Commitment Agreement / 15E Modelled Performance

These two pathways use energy modelling to demonstrate the greenhouse gas emissions for the building. There is much greater flexibility in these calculations than in the other pathways.

Standard first order calculations will show benefits in most Australian climates. Second order calculations could be used, which would allow the benefits of Cool Roofs to be demonstrated and allow for more energy points to be achieved. In particular, the Modelled Performance Pathway compares energy use against a reference building, which means more energy points can be gained due to the worse performance of the reference building with a non-cool roof. The GBCA allows for calculation methods to be used as long as there is robust proof and evidence to support it, and it is anticipated that there would not be any problem in using second order analysis.

Second order impacts on AHU locations

The CFD results demonstrated localised elevated air temperatures above the roof, which varied depending on wind speed and direction. This can cause a significant increase in HVAC energy if mechanical plant is located on the roof and has outside air intakes (such as package AHUs, outside air fans, or cooling towers).

This analysis assumed that mechanical plant was located in the centre of the roof. The average temperature rise observed varied between 0.1°C and 4.6°C depending on the conditions (note that this was the average temperature rise over a 900m^2 area, and so higher temperature rises will exist over smaller areas).

The centre of the roof would generally be the worst case to locate mechanical plant. Although the hottest area above the roof varied depending on the wind speed and direction, the centre had the highest temperatures on average. This is because wind from any direction tends to push hot air from just above the roof towards the centre (and beyond). No matter which direction the wind is coming from, there is likely to be hotter air over the middle.

If there is a strongly predominant wind direction, the side of the roof opposite to this wind direction would also be a poor location for the mechanical plant. Hot air from the roof would be mainly blown towards this edge of the roof. This effect is shown in Figure 33.

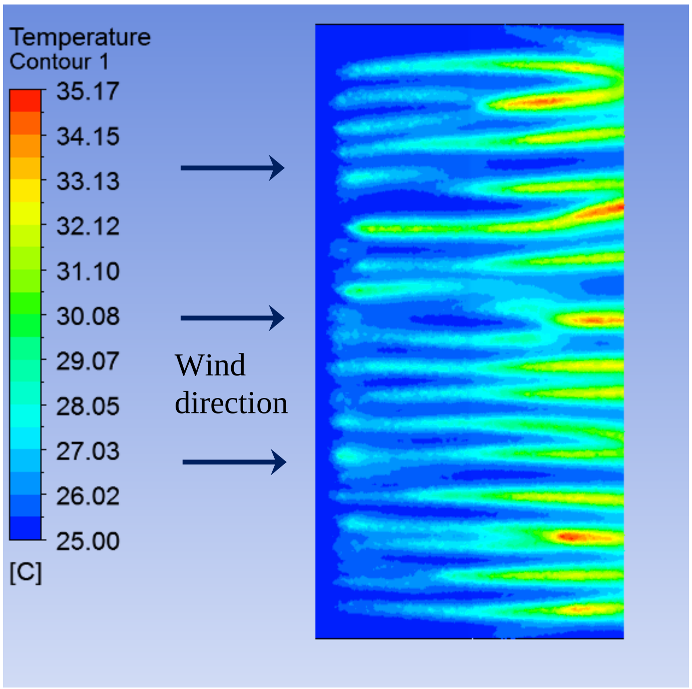

Figure 33: Air temperature 1.5m above roof with 3m/s wind from the north (left) and 500W/m^2 net absorbed solar load

Note that this may not be the case for other roof configurations. In particular, a roof with a parapet around all sides will likely reduce this effect. Further, the still air behind the parapets may become the more consistently hot area in this case, as still conditions tended to produce higher temperature rises. In general, any sheltered area is likely to have higher local air temperatures.

This elevated air temperature applies both to cool roofs and standard roofs. The magnitude of the effect will be higher for standard roofs.

Insulation reduction

The Building Code of Australia (BCA) allows for the required roof insulation level to be reduced in some climates based on the roof solar absorptance. For Climate Zones 1, 2 and 3, reductions in insulation of R0.5 and R1.0 are applicable if the roof solar absorptance is less than 0.6 or 0.4.

In the case of the roof materials investigated in this study, Zincalume is in the middle category, and Surfmist and Coolmax are in the lightest category. Accordingly, a roof in the appropriate Climate Zone with Coolmax is allowed to have R0.5 less insulation than a roof with Zincalume. In the main analysis of this study, the same insulation levels were used to keep the results consistent and ensure that they demonstrated the effects of the roof material only.

Hervey Bay and Ipswich are in Climate Zone 2, while Western Sydney and Northern Melbourne are in Climate Zone 6. The BCA does not allow reductions in roof insulation based on roof solar absorptance in Climate Zone 6, and these two locations, while still having lower total heating and cooling thermal loads, did have an overall increase in HVAC energy with the use of the lighter roofs (there were overall operating cost and greenhouse gas emissions savings however).

The equivalent effect of Coolmax, compared to additional insulation, has been investigated for Ipswich. A number of simulations were run to determine the level of insulation a Coolmax roof would need to be equivalent to a Zincalume code-compliant roof.

The BCA compliant Zincalume roof had a total insulation level of R3.45 (in order for the entire roof structure to be R3.7 overall). A Coolmax roof with only R0.3 insulation consumed the same amount of energy, once second order effects were taken into account. This is a reduction of R3.15 insulation in the roof.

It is important to note that this was for a large roof, and a small roof would not have the same level of second order impacts. The exact climate conditions are also important, as there is typically a complex relationship between heating, cooling, and the overnight cooldown behaviour of a building. However, the results show that a cool roof such as Coolmax provides similar impacts to higher levels of insulation. In a building where there is difficulty in achieving the required roof insulation level, a JV3 simulation approach could be taken to demonstrate that the cool roof will can provide similar results to a standard roof with more insulation.

6 Conclusion

The Colorbond Coolmax roof demonstrated the greatest thermal performance of the three roof types. The second order analysis showed that, relative to Zincalume, it provided 6.4% savings in annual cooling energy, as well as a 4.4% reduction in peak demand. This is due to its high reflectance and high thermal emittance.

Second order results, which incorporated the adjusted convection coefficients and temperatures above the roof, showed that a first order analysis underestimated total cooling energy use by 0.8% to 4.4%.

This results in the 1st order analysis underestimating the true energy savings provided by Colorbond Coolmax and Colorbond Surfmist. Second order analysis shows that these roofing materials reduced the cooling energy consumption of the building by 6.4% and 5.3%, rather than the 3.0% and 2.5% predicted by first order analysis.

Looking at operational cost savings for mechanical plant, it was found that the first order simulation underestimated operational energy savings. The predicted operational savings were 2.3 and 2.4 times the first order simulation savings for Coolmax and Zincalume respectively.

The analysis in this report is based on a high efficiency water-cooled chiller system. If a less efficiency cooling system was used, such as an air-cooled chiller, or DX Air handling units, the overall cooling energy would be higher. Cool roofs would then show larger absolute cooling savings, resulting in improved HVAC savings, operational cost savings and greenhouse gas emissions.

The CFD simulation was for a simple building and did not include parapets or roof obstructions from plant or other equipment. These would create extra areas with low air movement, and therefore less convection. It is expected that the high performance Colorbond Coolmax and Surfmist roofs would show an even higher energy savings against Zincalume when these effects are included.

In the CFD model, the AHUs were assumed to be located at the centre of the roof. The centre was often one of the hotter areas. Roof plant would be better placed closer to the roof edge if possible. If the wind predominantly comes from one direction, it would be recommended not to place the plant on the opposite side of the roof.

Further analysis into the effect of climate showed some specific trends in the thermal behaviour. In all cases, reductions in cooling energy and peak cooling load were observed. In general, this was greater for areas with higher peak and average temperatures, although this can be influenced by other factors such as low wind speed. Total HVAC equipment savings were higher the further north the building was, in part due to the interaction of cooling and heating. When there is a significant heating requirement, the cooling saving from a cool roof erodes as a result of an increased need for heating, however in all cases analysed, there was still an operational cost saving and greenhouse gas saving when using a cool roof.

The outcomes of this project demonstrate that standard building energy simulations for large surfaced rooftops underrepresent heat island effects by miscalculating the coefficients of convective heat transfer. The heat island was observed through the CFD simulations, and by incorporation of results into the thermal model, a major increase in annual system energy was calculated.

There are a number of implications for the use of cool roofs as the global climate becomes warmer. Average temperatures are expected to become warmer, and extreme heat events are expected to become more frequent and with higher intensity. This study found that cool roofs were more effective in warmer climates, due to the increased time spent in cooling mode and less time in heating mode. As the temperatures increase, it is likely that cooler climates will gradually become warmer and require more time in cooling mode. It is therefore likely that the findings of this study will understate the benefits of cool roofs in future years in the cooler climates of Sydney and Melbourne.

During heat waves and extreme heat events, air conditioning systems can end up exceeding their design capacity as they struggle to cope with higher temperatures than they were designed for. This will lead to warmer spaces that are less comfortable than they were designed for. Additionally, in some cases there will be power losses if the grid cannot cope with the high electricity demand, which can lead to rapidly overheated spaces. Both of these scenarios would be particularly important in residential situations, such as houses, aged care facilities or apartment buildings, as well as for warehouses storing temperature-sensitive stock. This study has showed that cool roofs have a much lower surface temperature than standard roofs, and are much better at reflecting and reradiating heat away. This leads to lower amounts of heat entering the room, meaning that overloaded air-conditioning systems will perform better, and during blackouts spaces will take longer to overheat.

The urban heat island effect is a well-known consequence of modern city design. Large areas of hard and/or dark surfaces, such as concrete, dark roofs, and roads, absorb and then reradiate heat, leading to localised areas of higher temperatures. This often means that some city areas are several degrees warmer than the surrounding area. Cool roofs are one way to mitigate the impacts of urban heat island effect – they reflect and radiate most heat away, rather than absorbing it.

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Trademarks

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Appendix A

CFD Details

A1 Mesh Sensitivity

For the SST turbulence model, it is recommended that y+ is around 1 to 5, to ensure boundary layer effects are modelled. Y+ is a measure of the mesh refinement, with lower values indicating higher refinement. Different levels of mesh refinement were tested to ensure that the results were not affected by insufficient mesh density.

The average convection coefficient is plotted against different $1/y+_{max}$ values in Figure 34 below. Results for the final mesh show y+ values with an average of around 2 and a maximum of 4.

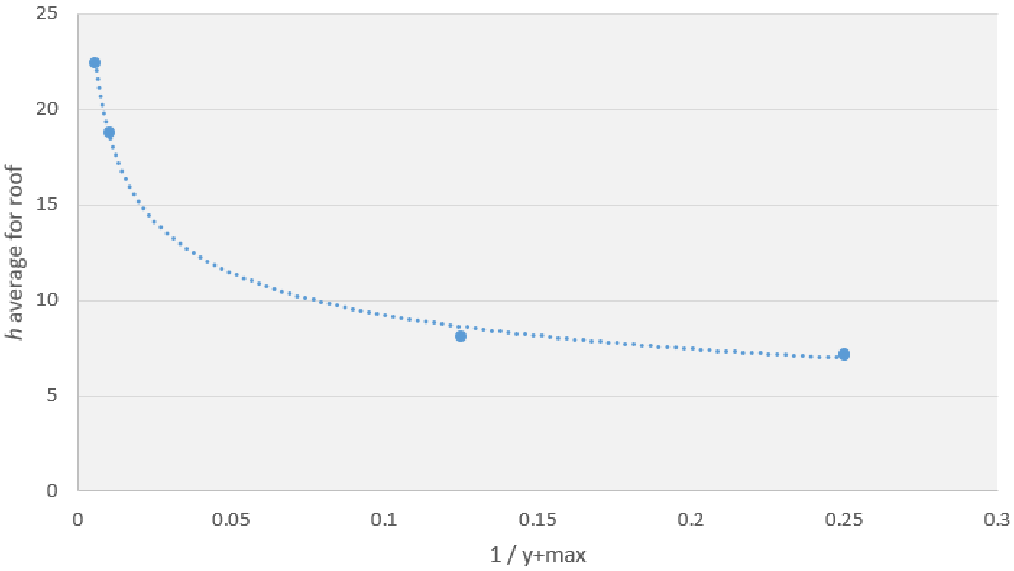

Figure 34: Mesh optimisation – average convection coefficient vs $1/y+_{max}$

It can be seen that further refinement (value to the right) will only have a minor impact on the convection coefficient. Further mesh refinement beyond the levels shown here was too computationally complex to be run.

A2 Verification Study

In order to prove that the CFD results were meaningful, a verification study was run. The hypothesis is that the large roof size will result in lower convection coefficients than standard models in dynamic thermal simulations would predict. The verification study was for a much smaller building (10m x 5m x 10m). Three different wind speeds were simulated for $100 W/m^2$ absorbed radiation, and the average convection coefficient across the roof was calculated and compared to two standard equations.

Two different equations for convection coefficient were checked:

$$h = 2.8 + 3v_{wind} \quad (1)$$

$$h = 5.6 + 4v_{wind} \text{ for } v_{wind} < 4.88\ m/s$$

$$= 7.2{v_{wind}}^{0.78} \text{ for } v_{wind} > 4.88\ m/s \quad (2)$$

The results of the verification study is shown against the equations in Figure 35 below. The CFD results are in between the two standard equation results. This demonstrates that the CFD methodology provides meaningful outputs for calculating convection coefficient. Differences between convection coefficient in the main study and standard equations will be due to the differences caused by the large roof.

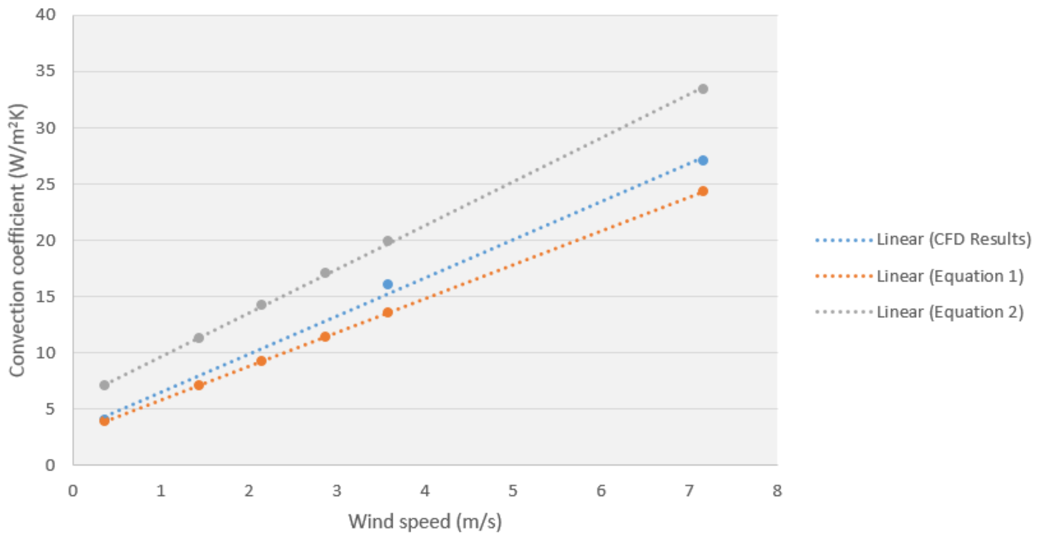

Figure 35: Verification study – Convection coefficient vs wind speed

Appendix B

Dynamic Simulation Details

B1 Construction types

The thermal model was constructed in line with materials types that would comprise a typical retail shopping centre. These parameters are shown in the following table:

Item	Value
Roof	3 roof materials – Bluescope Coolmax, Bluescope Colorbond Surfmist, and Zincalume. Surface absorptance values as per product values. Section J compliant insulation – to meet overall R-value of 3.7 for Hervey Bay and Ipswich, and 3.2 for Western Sydney and Northern Melbourne. 10mm plasterboard ceiling.
Walls	190mm concrete insulation walls. Section J compliant insulation – to meet overall R-value of 2.8 for Hervey Bay and Ipswich, and 2.3 for Western Sydney and Northern Melbourne. 13mm internal plasterboard lining.
Floor	200mm concrete slab on ground. 3mm vinyl tiles above. Constant ground temperature below
Glazing	None

B2 Internal Loads

The internal loads of the building were typically in line with the JV3 protocol of the BCA. The equipment load is higher, at 15 W/m^2 rather than 5 W/m^2, in order to provide a more realistic load. The infiltration rates are lower, again to provide more realistic loads.

Item	Value
Lighting	22 W/m^2, varying throughout the day as per Section J JV3 profile
Equipment	15 W/m^2, varying throughout the day as per Section J JV3 profile.
People	3 m^2/person, varying throughout the day as per Section J JV3 profile. 75 W/person sensible, 55 W/person latent
Outside air	10 L/s/person.
Infiltration	0.5 air changes per hour for perimeter zones and roof void.

B3 HVAC

The HVAC network was constructed to represent a similar system type that would be designed for within retail shopping centres. These parameters are shown in the following table:

Item	Value
Cooling set point	23°C
Heating set point	21°C
Zoning	5m deep perimeter zones with a central core space
System type	VAV system for zone air-conditioning. One AHU per floor AHUs served by a single chiller Chilled water system served by a single two-speed cooling tower. Heating by electric duct heaters.
Capacity and airflows	Autosized by the modelling program for the highest load case. All models use the same sizing values for chiller size, cooling and heating coil size, and fan size.
Efficiencies	Chiller – COP of 6.0, varies with capacity. Pumps – chilled water and condenser water pumps have a motor efficiency of 90%. The chilled water pumps are variable speed and the condenser water pumps are constant speed. Fan – supply and return air fans for each AHU have motor efficiency of 90% and fan efficiency of 70%, with a 650 Pa static pressure at design load. Cooling tower – 2 speed fan with 70% condenser pump efficiency and 90% motor efficiency. Boiler – 95% efficient (Western Sydney and Northern Melbourne only)

Appendix C

Comparison to Not So Cool Roofs Study

C1 Results comparison

Graham Carter and Buyung Kosasih wrote the study *Not So Cool Roofs* [3]. This study also looked at the impact of cool roofs on building energy, and examined the first order and second order effects. The study had a similar overall methodology, with some key differences as follows:

- The CFD simulations were only run for one wind direction, rather than sixteen.
- The energy model was for a larger, somewhat different building using the Green Star Retail protocol (although in both cases it is a shopping centre located in Hervey Bay).
- The second order effects were applied using a series of calculations applied via spreadsheet to the hourly results of the energy model, rather than adjusting the energy model to account for them directly. This was due to the limitations of the software package used.
- Different weather data used in both projects – this study used Bundaberg, whereas Carter and Kosasih used interpolation techniques to generate weather weather data for Hervey Bay between two different locations.

The results of this study show similar trends to those found in *Not So Cool Roofs*. It would be expected that would be some differences due to the variances in methodology, however, the similarity in trends shows that both studies have identified the same issues. These are presented in more detail below in Table 10 through Table 13.

Table 10: Additional peak thermal load, in W_{th}/m^2

	Zincalume	Colorbond Surfmist	Colorbond Coolmax
Carter & Kosasih	23.5	14.7	11.1
Arup	12.0	4.8	3.6

Table 11: Cooling energy savings over Zincalume

	Zincalume	Colorbond Surfmist	Colorbond Coolmax
Carter & Kosasih – 1st order results	0%	3.7%	4.6%
Arup – 1st order results	0%	2.5%	3.0%
Carter & Kosasih – 2nd order results	0%	7.2%	9.4%
Arup – 2nd order results	0%	5.3%	6.4%

Table 12: First order savings as a fraction of second order savings

	Colorbound Coolmax
Carter & Kosasih	25% - 50%*
Arup	35% - 45%**

*Depending on climate and plant location

**Range based on all 4 climates analysed

Table 13: Roof surface temperature bias, °C

	Zincalume, Peak	Coolmax, Peak	Zincalume, Average	Coolmax, Average
Carter & Kosasih	21.1	9.9	5.2	1.6
Arup*	41.2	6.8	6.4	1.3

*Arup figures are for a specific central section of the roof, rather than the whole roof, although should be representative of the overall trend over the entire roof.

This study has shown effects that are similar to the results in the *Not So Cool Roofs* study. They show similar behaviour of both first order and second order effects for the three different roof types.

Appendix D

Guide for Calculating Second Order Results

D1 Instructions for Second Order Calculations

In order to correctly calculate the second order effects, it is necessary to carry out a CFD study to confirm the relationships that will be applied to the dynamic energy simulation.

Most CFD simulation packages should be able to provide all of the required outputs. However, many dynamic building simulation software packages do not allow the required changes to convection co-efficient. Energy Plus does allow for this (as well as various front-end programs such as Design Builder and Simergy that use the Energy Plus engine).

CFD and dynamic building energy software are specialised software, and should be used by people with a background in using the software. This guide is not intended to replace training in these programs.

D2 CFD

It is necessary to model the building under different wind and radiation conditions in order to produce realistic results.

The CFD model will include a number of different cases so that any situation in the dynamic model can be calculated using interpolation. In particular, this should include different wind speeds and direction, and different solar radiation.

Building 3D model

Build a 3D model of the building. It will be important to use simplified geometry in order to reduce computational time to reasonable levels. It is beneficial if the building has some symmetry to reduce the number of simulations, although this will not always be possible.

Build a rectangular prism domain for the air surrounding the building. Ensure that there is sufficient space in all directions from the building to ensure that the boundary conditions do not affect the airflow near the building. This can be tested by running simple test cases.

One face will be the inlet. The opposite face will be the outlet. The bottom surface will be the ground. The top and sides will be open air.

Create rotating domain

If possible in your CFD software, create a separate cylindrical domain centred around the building. The cylinder with the building is the stationary domain, the surrounding rectangular prism is the rotating domain. It will be rotated as required to simulate the wind coming from different angles.

Meshing

Mesh sizing is very important. It is strongly recommended to perform a mesh sensitivity study – run the model with different mesh sizes to confirm that the results will not change significantly with further mesh refinement. This can be done graphing the calculated average roof convection coefficient value* against the inverse of the maximum y+ value for the roof.

Finer mesh is required over the roof surface, and at the building walls.

*See the note in the Results section on correctly viewing convection coefficient.

Boundary Conditions

Inlet

The wind profile in the CFD model should match how the dynamic modelling program treats the wind profile.

In the case of Energy Plus, the velocity varies with height according to the following formula:

$$v_z = v_{met} \left(\frac{\delta_{met}}{z_{met}}\right)^{\alpha_{met}} \left(\frac{z}{\delta}\right)^{\alpha}$$

Where:

z = height

α = wind speed profile exponent at site

δ = wind speed profile boundary layer thickness at site

v_z = wind speed at altitude z

v_{met} = wind speed measured at weather station

α_{met} = wind speed profile exponent at weather station

δ_{met} = wind speed profile boundary layer thickness at weather station

Values for α and δ vary depending on the terrain at the site, according to the following table:

Terrain Description	Exponent	Boundary Layer Thickness (m)
Flat, open country	0.14	270
Rough, wooded country	0.22	370
Towns and cities	0.33	460
Ocean	0.1	210
Urban, industrial, forest	0.22	370

By default, Energy Plus uses the values for Flat Open Country and a z_{met} of 10m for the weather file values unless overridden by the user.

In the case of a building in flat open country, with standard weather file values, this simplifies to:

$$v_z = 1.586 v_{met} \left(\frac{z}{310}\right)^{0.22}$$

This equation, or similar for any case, can be used in the CFD model to simulate the wind profile for any reported wind speed v_{met}.

When choosing the wind speeds to model, include:

- The minimum recorded wind speed
- The maximum recorded wind speed (or something close to it)
- A number of wind speeds in between – at least 1 and preferably 2 or more. There are more changes in behaviour at lower speeds, in particular the changeover from free to forced convection, and so it is important to include when choosing the wind speed cases.

When choosing the wind directions to model, consider whether any directions can be covered through symmetry of another case. Modelling at least 8 wind directions (directly or indirectly) will include cases with wind perpendicular to the building surface and at an angle to it.

Outlet

The outlet should be modelled to allow air to flow out of the model without affecting the overall flow (such as 0 static pressure). The outlet generally must be much further away from the building than the inlet. Ensure that the results show no change to the air stream pattern as it approaches the outlet.

Building roof

The building roof should be modelled as a no slip wall with a heat flux applied due to the net absorbed radiation. It is recommended to model exactly 2 different cases (this makes later analysis easier – more complex calculations will be required to allow for 3 or more radiation cases).

The highest radiation case should be a little higher than the highest net absorbed radiation that is expected in the model. This can be determined by checking first order dynamic modelling results for the building, for roof absorbed solar radiation and net long wave radiation. In Energy Plus, these two variables are called “Surface Outside Face Solar Radiation Heat Gain Rate per Area” and “Surface Outside Face Net Thermal Radiation Heat Gain Rate per Area”. Adding these two together (the long wave radiation is typically negative) will give the net absorbed radiation for the roof.

The lowest radiation case should be a low figure, such as 100 W/m^2 or 0 W/m^2.

Ground and walls

The ground plane and the walls of the building should be modelled as adiabatic non-slip walls.

<u>Sides and top</u>

The sides and top should not impact the flow of the air (and should be far away enough from the building to avoid constraining the solution).

One way to do this is to model them as free slip adiabatic walls.

Domain Conditions

Both the stationary and rotating domains should have the same domain settings. The fluid properties should be set to Air at 25°C (Air Ideal Gas would be more accurate, although may be harder to get the model to solve. Comparisons showed negligible differences in the results). The air should be buoyant ($-9.81m/s^2$ in the z direction).

Heat transfer should be set to Thermal Energy.

Turbulence should be set to the Shear Stress Transport (SST) – this is much better at modelling heat transfer coefficient than the k-epsilon model model.

Verification checks

As with all CFD, some verifications should be conducted to make sure that yoru results are sensible.

It is suggested that a very simple, small building of the same height is built. By running a few different wind speeds (one direction should be sufficient), it can be confirmed that the convection coefficient results are similar to standard formulas.

Mesh sensitivity should be checked by comparing convection coefficient for different mesh sizes ($1/y+_{max}$). SST results will not be meaningful unless the y+ values are low (around 1 to 5).

Results

Once the CFD simulations have been run and verified, the key information to extract from the results are:

- Determine important roof areas – which areas generally act differently from other parts of the roof? Although making more roof segments will be more accurate, it will also lead to more work in processing the results, and so careful consideration is needed.
- Calculate average convection coefficient for each roof area for each wind speed, wind direction, and radiation case.
- Calculate the average air temperature rise for the roof area where the mechanical plant will be located, at the height appropriate for the mechanical

plant air intake and/or cooling tower intake. Do this for each wind speed, wind direction, and radiation case.

It is very important to note that in some CFD programs, by default convection coefficient is measured using the temperature difference between the surface and the first row of cells. This will provide very inaccurate results, as we are interested in the convection between the roof and the ambient air. In order to correctly measure convection coefficient, a new variable can be defined ConvectionCoefficient = Wall Heat Flux / (Temperature-298°K)

This particular formula works when the model ambient temperature is 25°C (298°K), and can be corrected if a different ambient temperature has been used.

Determining relationships

There will be a different relationship between convection coefficient and velocity for each wind direction, each roof segment and each of the 2 radiation cases.

For each combination of wind direction, roof segment, and radiation case, graph the average roof segment convection coefficient against velocity. It should be possible to calculate a linear relationship between convection coefficient and velocity, with a high R^2 value. Determine the relationship for each case (this can be automated in Microsoft Excel using the LINEST and INDEX functions (or could be calculated in another programs).

For each combination of wind direction and radiation case, graph the air temperature rise against velocity. This relationship may be log related, follow a different function or may follow no direct relationship. In the final case, it can be represented as a series of linear relationships depending on the range.

For both convection coefficient and temperature rise, the value can be calculated for any radiation value by linear interpolation for values between the upper and lower radiation values.

Note that, where the building is symmetrical, some wind direction results will be mirrored versions of the results of other wind directions. This allows for less CFD cases to be run.

D3 Dynamic Energy Modelling

The dynamic energy model uses the relationships determined from the CFD to alter the roof convection coefficients and the air temperature used for roof-based mechanical plant. In the event that there is no roof-based plant, the temperature corrections are not necessary. This guide provides some information specific to Energy Plus, however, similar steps would be taken in any other software that has the capacity to vary convection coefficients and plant air intake temperature.

Model geometry

Create the building model as normal. It is important that the roof space is split into the same segments that have been determined to act differently in the CFD analysis. They must be separate thermal zones or it will not be possible to apply different properties to them, for example altered convection heat transfer coefficients along the rooftop surface.

EnergyPlus/EMS Programming

Utilising EnergyPlus, and more specifically the Energy Management System (EMS) feature of EnergyPlus, customised simulation controls and routines can be created. This includes a wide range of building simulation variables that can be altered, based upon some function or statement. These functions or statements are written in as code within EnergyPlus, following the ERL language protocols.

Sensors

Within EMS, a library of sensors exist. These sensors are the same as the RDD outputs that EnergyPlus provides. Through the EMS code, these sensors may be linked to specific variables that the user wishes to be custom controlled, and used to execute some function. These variables that can be custom controlled within EMS are known as “actuators”. For more information on sensors, refer to the EnergyPlus application guide for EMS.

Actuators

The EMS actuators are the conduits by which EnergyPlus controls simulations. The actuators essentially override parameters of a typical simulation. For example, a supply air temperature actuator exists in EMS, which can be used to override normal supply air temperature, such as by sensing outdoor air temperature and executing some function to output the new supply air temperature.

For this project, EMS actuators were used to adjust the coefficients of convective heat transfer for the external surface of the roof. Equations for the coefficient were developed through CFD, based upon total absorbed radiation of the rooftop surface. Sensors had to be used to compute what the absorbed radiation was on the rooftop for each time step (as described in D2 Boundary Conditions – Building Roof).

Other sensors that were required were wind direction and wind speed. Wind direction was used to determine which equations of convection to apply, based on CFD results. The wind speed was used directly to calculate what the coefficient of convection was for that timestep.

For more information creating and using actuators, refer to the EnergyPlus application guide for EMS.

ERL Script example

An example ERL code is shown below:

```
IF (WindDirection >= 258.75) && (WindDirection <= 281.25) && Rad_8 <=100,
   SET H_corner = 1.686*WindSpeed+0.673,
   ELSEIF (WindDirection >= 258.75) && (WindDirection <= 281.25) && Rad_8 >100,
   SET H_corner = (1.686*WindSpeed+0.673)+((Rad_8-100)*((SedgeE_W)-(1.686*WindSpeed+0.673))/400),
```

The previous code is a small extract from the model. Essentially, a value for H (coefficient of convection) is being determined at each timestep, based upon wind direction and total absorbed radiation. These are all connected through an AND statement.

Apply to mechanical plant behaviour

Any air intakes located on the roof will be bringing in air that has been heated by the roof. This can include the outside air intake for air handling units or other ventilation fans, as well as the air intake for cooling towers. In both cases, the dry bulb temperature will be increased by the amount determined in the CFD relationships. The wet bulb temperature will also be increased, although this can be calculated automatically.

For outside air intake, it is important that the air supply seen by the plant will have dry bulb temperature and wet bulb temperature increased.

For cooling towers, it will only be necessary to change the wet bulb temperature.

Within EMS, a psychrometric function exists that allows you to adjust air properties based upon two or some other air properties. For example if you developed a code and an actuator that adjusted outdoor dry bulb temperature, the psychrometric function could be used to adjust the wet bulb temperature also, based upon that varied dry bulb temperature.

For this project, the wet bulb temperature increase for mechanical plant equipment is calculated from the adjusted dry bulb temperature and humidity ratio sensor, by the following function:

- New Wet Bulb Temp = @TwbFnTdbWPb (New Dry Bulb Temp, Humidity ratio OA, Barometric pressure OA)

Note that to execute the above function within the EMS code, sensors would also need to be created to read the humidity ratio and barometric pressure at each time step.

For more information on the built in functions that can be used in EMS/ERL, refer to the EnergyPlus application guide for EMS.

Appendix E

Monthly Energy Breakdown Data

E1 Hervey Bay – Zincalume and Coolmax

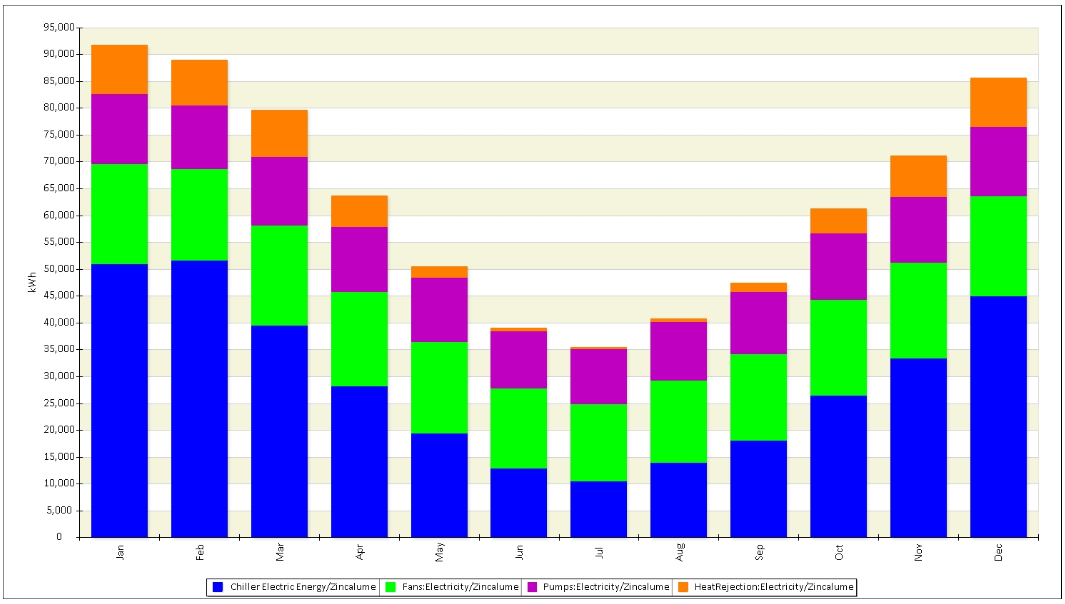

Figure 36: Monthly HVAC system energy breakdown for Zincalume, in Hervey Bay

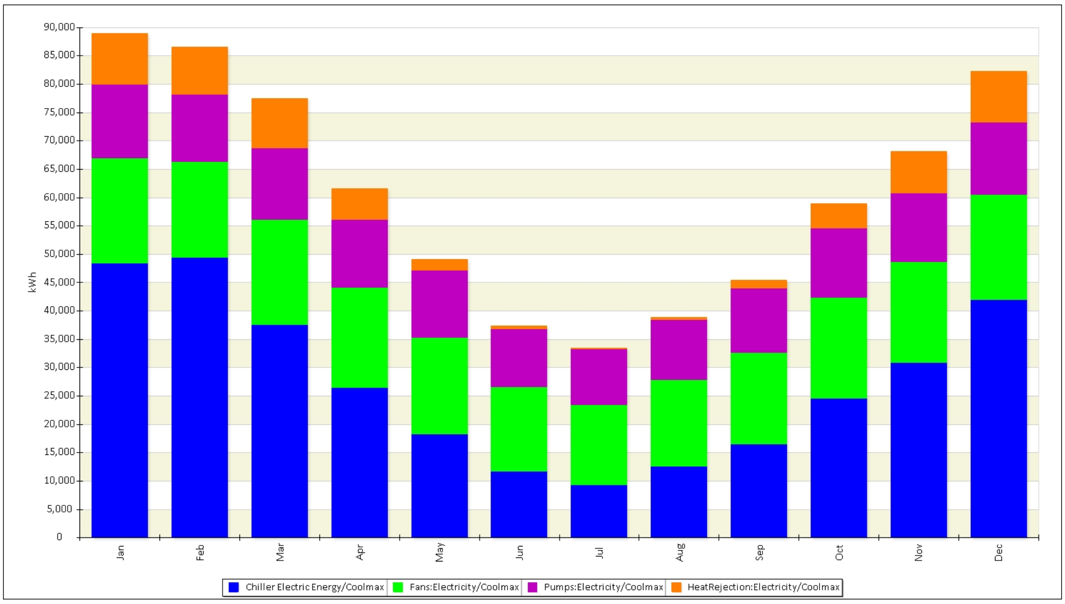

Figure 37: Monthly HVAC system energy breakdown for Coolmax, in Hervey Bay

E2 Ipswich – Zincalume and Coolmax

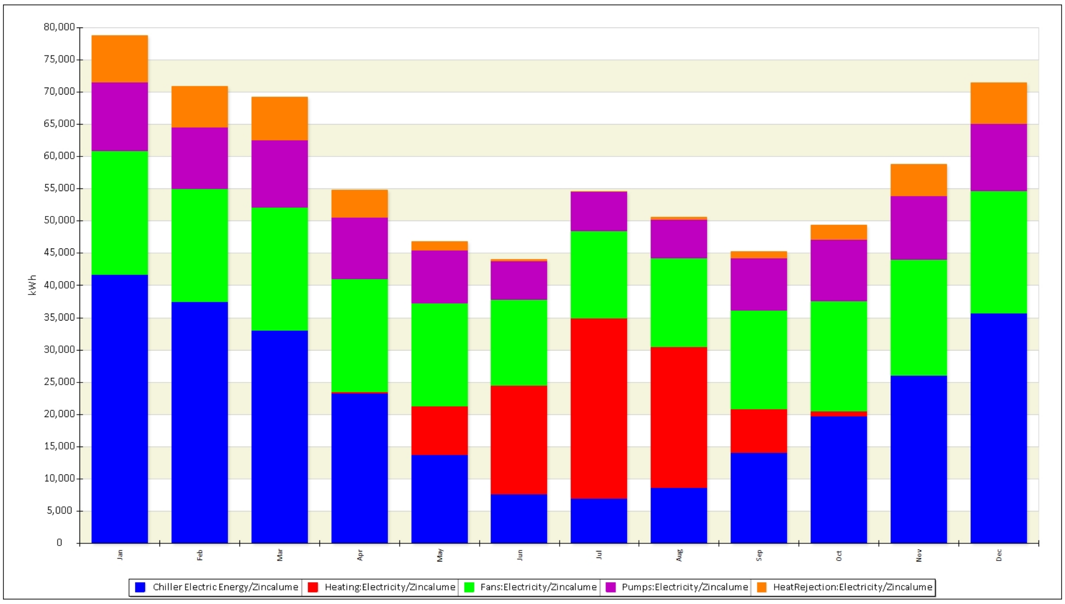

Figure 38: Monthly HVAC system energy breakdown for Zincalume, in Ipswich

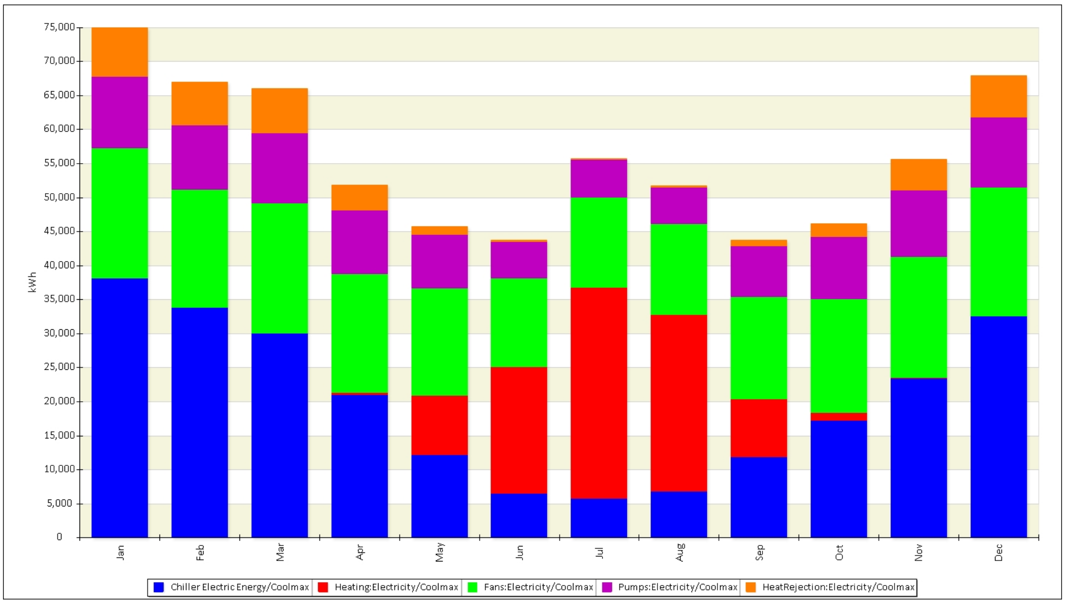

Figure 39: Monthly HVAC system energy breakdown for Coolmax, in Ipswich

E3 Western Sydney – Zincalume and Coolmax

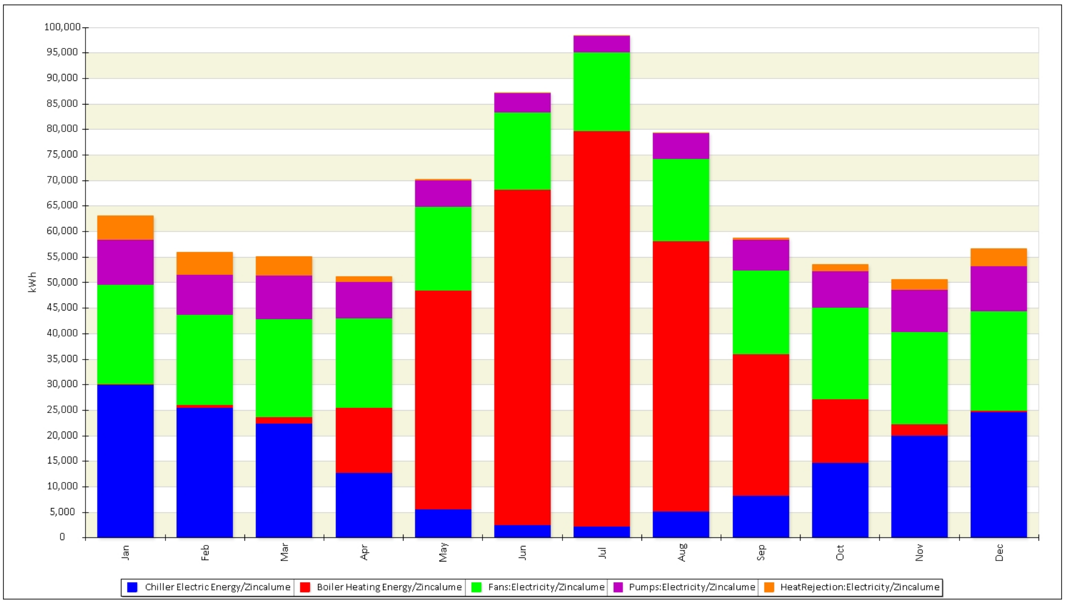

Figure 40: Monthly HVAC system energy breakdown for Zincalume, in Western Sydney

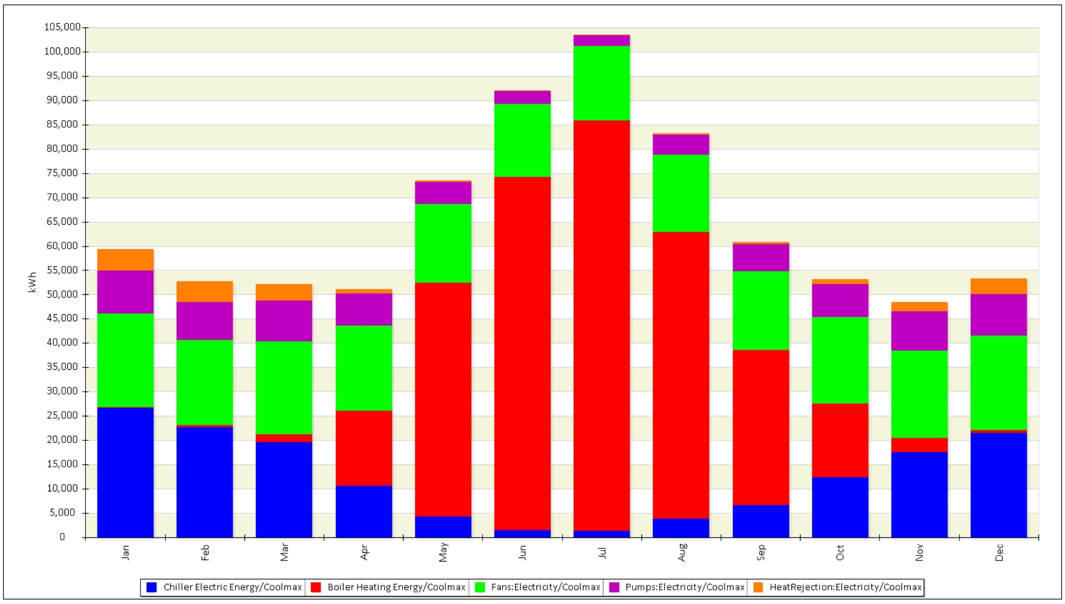

Figure 41: Monthly HVAC system energy breakdown for Coolmax, in Western Sydney

E4 Northern Melbourne – Zincalume and Coolmax

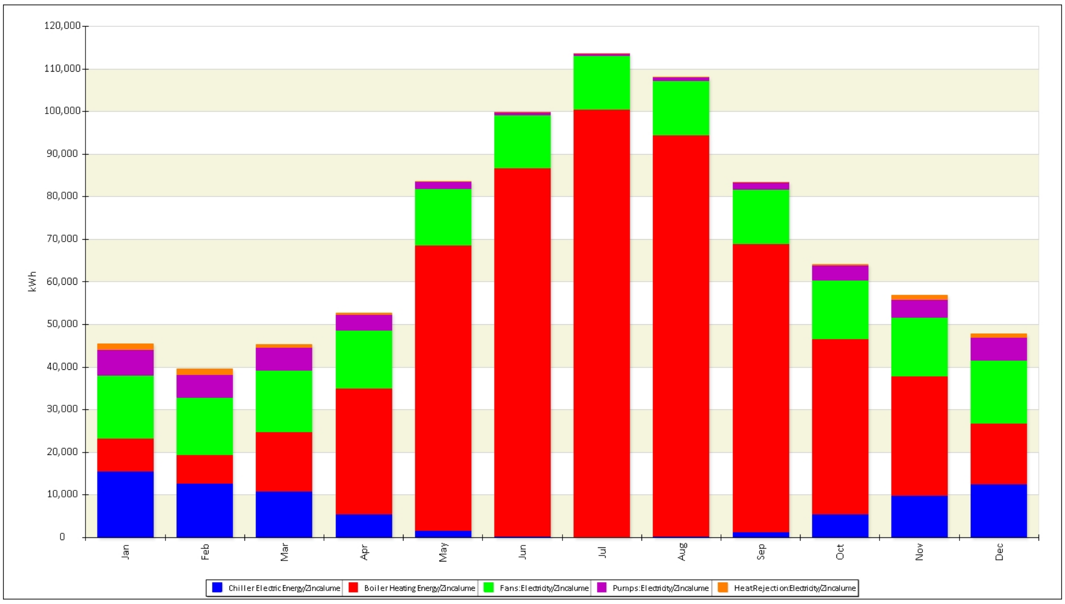

Figure 42: Monthly HVAC system energy breakdown for Zincalume, in Northern Melbourne

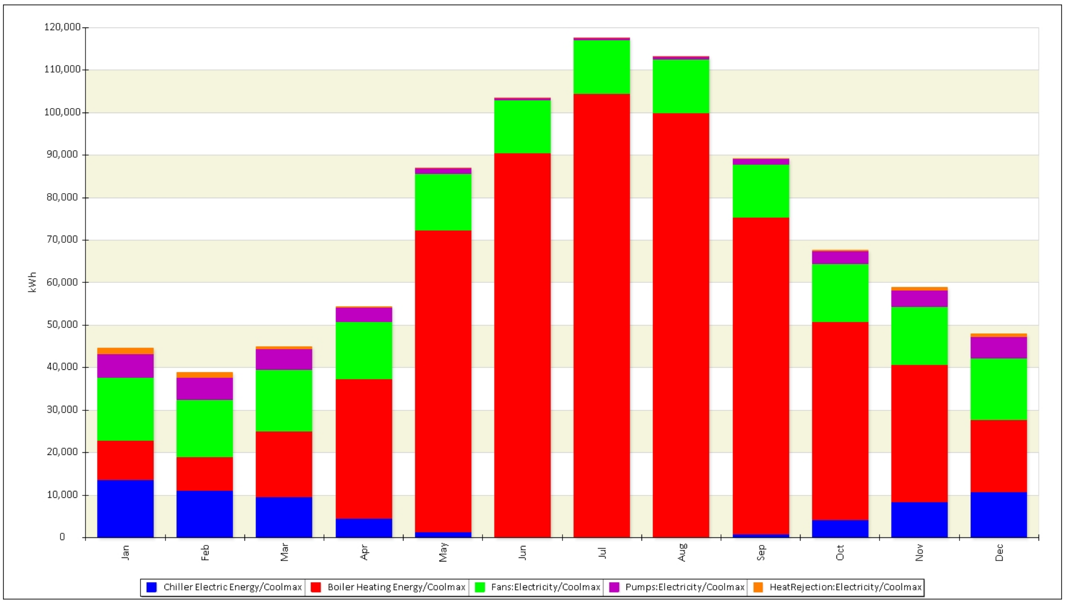

Figure 43: Monthly HVAC system energy breakdown for Coolmax, in Northern Melbourne