ISSUES AND SOLUTIONS TO MORE REALISTICALLY SIMULATE CONVENTIONAL AND COOL ROOFS

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ABSTRACT

Simulation software accounts for the physical properties of cool roofs, in particular, a high short wave solar reflectance (or albedo) and a high long wave emissivity. However, in some instances the observed benefits of cool roofs in practice indicate a level of savings far in excess of what common simulation programs predict. An empirical study to better understand and explain the performance of cool roofs was carried out with the hypothesis that an urban heat island effect occurring at roof and building level was the primary factor leading to the difference between prediction and observation.

Simulation results were then adjusted using additional theory to closely approximate the observed results. Suggestions are made of how common simulation packages can be enhanced to better predict the benefits of cool roofs.

INTRODUCTION

Cool roofs is a loosely used term in the property industry and for the purposes of this paper are classified as those materials having a high three-year aged short wave reflectance (SR>0.55) and a high three-year aged long wave infrared emittance (e>0.75) consistent with the ASHRAE 90.1 definition.

Under clear sky conditions, the effective sky temperature can be quite cold leading to significant long wave radiation heat transfer from a surface to the sky. If this is combined with a high solar reflectance, under some daytime conditions the roof characteristics can lead to a net heat loss to ambient rather than a significant heat gain typical of conventional lower reflectance (higher solar absorptance roofs).

Numerous past studies show that the use of cool materials is one of the most cost effective means to mitigate urban heat island effects (Rosenfeld et al., 1998). The energy savings realised on numerous cool roof installations in temperate and sub-tropical Australia, including supermarkets and airports, have been significant with cooling and air handling energy savings of 40-50% being observed by one cool roof treatment manufacturer. This contrasts with simulation results using IES Virtual Environment and DOE-2.2, which typically only suggests a 15-25% reduction in the author's experience compared to conventional roofs.

After a significant amount of investigation and consideration to understand the prediction gap, a hypothesis was developed that a primary factor was that simulation does not account for local heat island effects and that a temperature bias relative to ambient is likely present at roof level. Heat can be lost from a roof surface by a number of mechanisms. It is the convection to the dominates the heat loss from an insulated roof leading to an above roof temperature that is warmer than ambient. This bias on roof air temperature would lead to:

- An increase in roof surface temperatures as heat loss to ambient is reduced because of elevated above roof temperatures.
- Additional heat gain through the roof to the occupied space below because of higher surface temperatures leading to higher sensible cooling loads.
- Higher above air above the roof that likely roof temperatures affecting condensing temperatures and thus efficiency of air-cooled cooling equipment located at roof level.
- Higher above roof temperatures leading to higher temperature and enthalpy air at outdoor air intakes thus increasing ventilation loads.
- Higher space loads leading to a requirement for lower supply air temperatures, which in a humid climate leads to additional dehumidification.This effect is not fully accounted for in some simulation packages.

These effects no doubt occur in reality, but the question was whether they existed to a degree significant enough to fully explain the gap between historical predictions and observed savings.

Urban heat island research has dealt primarily with city scale effects focussing on urban canyon, rural, and global climate models. Little research has been done on quantifying the urban heat island effect at a roof microclimate level.

One study found that for an average surface albedo increase of 0.01, that the land surface temperature decreased by 0.03°K (Menon et al., 2009). This would suggest that for every 0.1 increase in albedo (10% in Solar Reflectance) that a 0.3°K decrease in surface temperatures would be experienced.

Extrapolating this figure, a 30% increase in solar Reflectance could produce a 1°K drop in ground level temperatures.

Urban scale research into using cool materials for Athens Greece (Synnefa et al., 2008) found that average building surface albedo in Athens was 0.18.

A meso scale climate model of Athens was used to estimate the effect on urban temperatures at ground level if albedo was raised to 0.63 and then 0.85.

Temperature depressions on average of 1.5°K and 2.2°K respectively were determined. The amount of urban surface area considered to be building surfaces was not stated in this paper, but the effect was nevertheless substantial.

A similar study looked at the role of roof albedo on urban canyon scale heat island models (Oleson et al., 2009) as roofs make up the single largest horizontal component of urban areas, and in this research represent 40% of the model area. It was found that an increase in roof albedo from 0.32 to 0.90 had the effect of lowering average ground level temperatures by 0.4°K (0.6 to 0.7°K during a summer day in urban areas).

While the past research supports that a heat island effect will and does occur, the magnitude of this heat island effect at a building roof level would have to be significant to explain the level of energy savings observed in practice on several supermarkets. As the past research was not focussed on building level heat island effects, additional research was undertaken as part of this current work with the aim of quantifying the heat island bias and the likely impact on predicted energy savings.

METHODOLOGY

There were two main parts to the research and analysis undertaken

- Measurement of above roof heat island effects (temperature bias) in situ with and without a cool roof treatment
- Estimate the impact of the temperature bias on predicted energy savings.

Site selection

While advanced numerical techniques such as three-dimensional computational fluid dynamics (CFD) would enable greater insight into the dynamics of heat dispersion around buildings and more specifically roofs, attempting to measure the heat island temperature bias in situ was chosen for this research due to the desire to measure reality in the event that numerical techniques could not fully represent reality. This decision was justified largely on the basis of conventional simulation's apparent inability to represent above roof heat dynamics fully.

Working with one supplier of a cool roof technology, potential sites were identified and shortlisted. Two Woolworths supermarkets in southeast Queensland were chosen as their design and operation was very similar and two sites were available for study in relative close proximity to each other.

The two supermarkets chosen were from the same supermarket chain, of a similar age, and located in southeast Queensland.

- Control site – Currimundi – Located within 1km of the coast where ambient temperatures are slightly cooler but more humid due to the sea breezes. The exact age of the roof was not known but would have likely have been at least 10 years old when the temperature measurements were taken.
- Cool roof site – Chancellor Park – located slightly inland where ambient temperatures are typically higher. The roof was coated with a cool roof treatment (SkyCool) in 2002.

Related to site selection was the need to have weather stations close by that would allow the local climate to be characterised and any bias between locations to be removed as far as was practical so that the effect of the roof could be observed in isolation. Figure 1 shows the Bureau of Meteorology (BOM) station locations (yellow pins) relative to the two supermarkets (red pins). In 2008 when the measurements were undertaken there were only two weather stations recording temperatures (Nambour and Maroochydore Airport). These two sites did not allow the supermarket locations to be triangulated, but they did allow a comparison between an inland and coastal location for the monitoring period.

Historical data was available for the other locations and is compared to establish the degree of ambient temperature bias that could be expected between sites. Table 1 shows the location details of the sites.

Table 1: Test Site Weather Data Availability

SITE	DETAILS
Chancellor Park Store – Cool Roof Site	26.72°S / 153.05°E Data for 1–20 Feb 2008
Currimundi Store – Conventional Roof Site	26.77°S / 153.12°E Data for 1–20 Feb 2008
Maroochydore Airport BOM	26.60°S / 153.09°E Data for 3–19 Feb 2008 Historical data from mid 1994
Nambour DPI BOM	26.60°S / 153.09°E Data for 3–19 Feb 2008 Historical data up through 2007
Crohamhurst BOM	26.81°S / 152.87°E Historical data up through 1995
Caloundra BOM	26.80°S / 153.15°E Historical data up through 1995

Weather analysis

Although the roof temperatures could be measured with temporary portable weather stations, measuring the unbiased local ambient temperature was much more difficult as biases could be introduced by shade, landscaped surfaces, asphalt surfaces etc. It was decided that using the nearest recording Bureau of Meteorology (BOM) weather stations would be just as accurate as placing a temporary weather station near the measured roofs in inevitably biased locations.

As BOM weather stations have been rationalised over the years, the number of stations reporting parameters beyond rainfall has diminished. For the test period of 1–20 February 2008 the

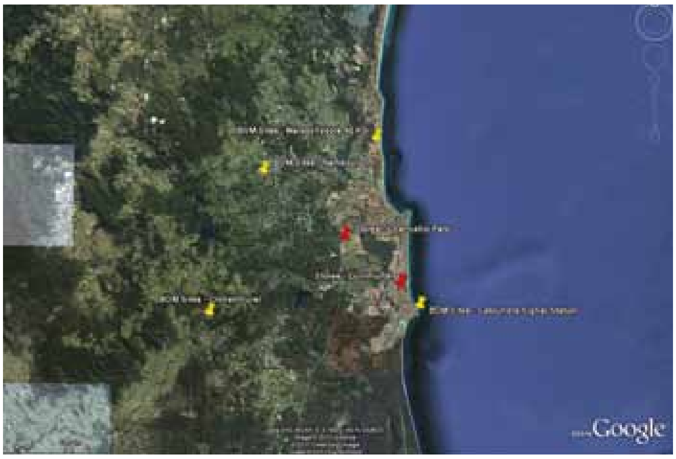

Figure 1: Test site locations.

closest two weather stations reporting ambient temperature were Maroochydore and Nambour. As these sites are both north and between 14 and 25km from the two test stores, there is a risk that they were not representative of the local climate.

For this reason, historical weather data for additional weather stations were also assessed to understand the variations in the area on a given day.

Roof temperature measurements

Two identical weather stations (WeatherMaster 2000 units) were rented for a five-week period in late January 2008 and installed on the two roofs.

Locations were chosen on the roof that provided a shielded dry bulb temperature measurement approximately 0.7 m above roof level and in a location that was near the centre of the roof but away from any obvious biasing of condenser or exhaust discharges.

Data logging problems were experienced initially leaving a valid data period of 3 weeks in February 2008.

Upon completion of the field tests, the two weather stations were tested for a 90-minute period at the renting company's test facilities to check for any temperature bias between the two sets of measurements. The weather station used on the Chancellor Park cool roof site was found to have a systematic bias of +1.54°C relative to the weather station used on the control site at Currimundi.

Simulation

A simple DOE-2.2 model was created that focussed on providing a baseline of fan and space cooling energy that was representative of the supermarkets under consideration. Given the limitations of simulation in representing roof microclimates the base case simulation is effectively the cool roof scenario where there is no bias in air temperatures above the roof. Key assumptions for this base case simulation included:

- 3,300 m^2 store with 2,630 m2 of conditioned area
- The closest available weather file for energy simulation purposes was the Brisbane Airport 1986 Test Reference Year (TRY)
- Un-aged cool roof properties confirmed by the supplier including a solar reflectance of 90% and long wave emissivity of 0.95
- Metal deck roof with an effective roof insulation thickness of 38mm allowing for thermal bridging.
- Uninsulated block work or plasterboard lined precast assumed with minimal glazing
- 0.25 air-changes per hour of infiltration for the store volume at 7.5m/s (lower at lower wind speeds)
- 15 W/m^2 of light and power assumed during trading hours
- Systems designed to 6.5 m^2/person and 7.5 L/s/person, but typical daytime occupancy level is assumed to be 75% of design
- Store conditioned hours assumed to be 6am to midnight 7 days a week.
- Constant volume air handling systems sized to 4 L/s/m^2 for the store.
- Air-cooled direct expansion (AC DX) systems for space cooling assumed to have a coefficient of performance (COP) of 2.8 (allowing for some ageing) at 35°C ambient, and systems for refrigerated casework a COP of 2.0 at 35°C
- In line with DOE-2.2 part load equipment curves, the AC DX space cooling efficiency is assumed to improve by 2.4%/°C reduction in ambient temperature, and for the refrigerated casework systems 3.0%/°C
- In line with DOE-2.2 part load equipment curves, the AC DX efficiency is assumed to decrease by 0.25% / % decrease in PLR
- No economy cycles assumed given humid climate and supermarket application
- Space cooling modulates (valve) between 0% at 23°C and 100% at 24°C space temperature.

While some of these assumptions are ultimately uncertain, they are reasonable assumptions.

Importantly the analysis focuses on a relative comparison so that any systematic biases associated with common assumptions are constant between the simulation scenarios and as a result cancel each other out to a degree.

Several scenario simulations were run for different roof absorptance, long wave emissivity and effective insulation value. Simulated total cooling loads were then exported to a spreadsheet for further calculations.

The conventional roof was assumed to have an aged solar reflectance of 30%, but ultimately the results are somewhat insensitive to this assumption as the heat island bias is set independent of this assumption.

The cool roof supplier found that a sample tested six to seven years after an initial test had only lost 1.5% in its solar reflectance suggesting these products may be less prone to degradation. Performance degradation due to ageing is important to understand the full benefit of cool roofs, but is beyond this study.

From each of these scenarios a negative cooling allowance (60kWr in the daytime and 24kWr outside trading hours) was deducted to account for the passive cooling the refrigerated casework provides to the conditioned space.

Within the spreadsheet the roof heat island effects were then applied in the following manner:

- An additional sensible ventilation load was calculated assuming a constant temperature bias and ventilation airflow rate during conditioning hours.

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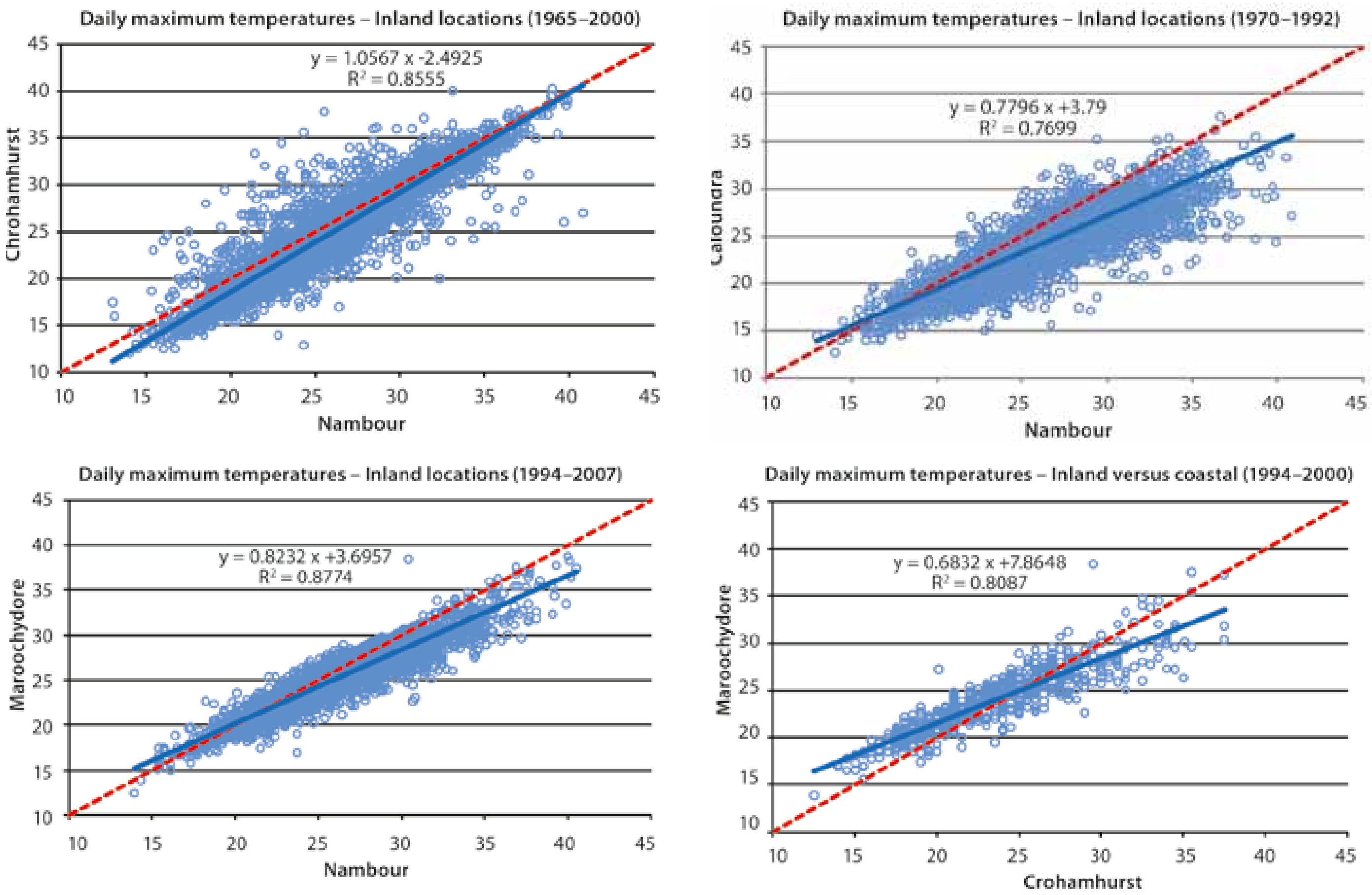

Figure 2: Historical Weather Data

- An additional roof heat loads were calculated assuming a constant temperature bias and roof insulation value during conditioning hours.
- The estimated direct expansion system efficiency was estimated hourly given the same temperature bias assumed for the adjusted loads.

Revised simulation results were then tabulated showing a progression from an idealised cool roof scenario through to a modified conventional roof scenario. The progression enabled an understanding to be gained of the portion of the estimated savings that were due to effects represented within simulation versus those that are not currently represented within simulation.

RESULTS AND DISCUSSION

Measured energy use

The cool roof supplier had obtained 18 months (January 2003 to June 2004) of measured mechanical system energy use (excluding refrigeration for refrigerated casework) for the two supermarkets in Southeast Queensland:

- Chancellor Park which had a cool roof treatment applied in 2002
- Currimundi which has a conventional metal deck roof.

These results were obtained prior to this research being undertaken and while for a single case study they are representative of similar results observed by the cool roof supplier. The results were accepted at face value as accurate and representative of the savings attributable to the cool roof treatment. The measured annual electricity use for the two stores showed a 47% reduction – 166 kWh/m2 pa down to 84 kWh/m2 pa for the mechanical systems.

Historical weather data

Historical weather data for the four weather stations of interest was limited to daily minimum and maximum temperatures. To assess the degree to which regional variations in temperature exist in the daytime, coincident daily maximum temperatures have been plotted to compare the different locations in Figure 2. From this data we can observe:

- There is no overlap in coastal weather station measurements to allow any analysis of coastal variations.
- The two inland locations compare well, particularly during the cooling season where differences for coincident daily maximums are on average less than 1.1°C at 25°C and less than 0.5°C at 35°C.
- The inland daily maximum temperatures are consistently higher than coincident coastal temperatures during the cooling season which is what we would expect as we move inland. This bias varies and increases on hotter days. For example on average when daytime maximum temperature is 35°C in Nambour it is 2.5°C cooler in Maroochydore and 4°C on average cooler in Caloundra.
- With the average temperatures measured during the February 2008 between 20 to 30°C we would expect the inland locations similar or slightly warmer on the cooler days and upwards of 2.5°C warmer inland on hotter days.

Recognising the limitations of the data available and methods used, the Nambour weather data available for 2008 was assumed to be representative of the ambient climate around Chancellor Park where the cool roof treatment site was located. Furthermore the Maroochydore weather data was assumed to be representative of the Currimundi control site's ambient climate.

Heat island measurements

Over the monitoring period of February 1-19, 2008, the Nambour weather site was found to have a consistent warm bias relative to Maroochydore as shown in Figure 3.

It is important to note that the three-week measurement period was coincident with some unusually cool and wet weather. As the benefits of cool roof treatments are expected to be greatest under clear and dry skies, the results obtained here are believed to understate the benefits of the cool roof treatment.

Temperature corrections

The temperatures measured above the supermarket roofs were corrected for the ambient bias observed at the BOM weather stations and for the systematic bias between the temporary weather station temperature sensors.

The ambient bias correction was calculated as the difference between Nambour and Maroochydore BOM weather station measurements that were coincident with the roof air temperature measurements for February 2008. There were some gaps in the bureau measurements which were filled by using the best-fit line to coincident maximum daily temperatures from Figure 3 to estimate the bias.

This location bias estimate was deducted from the Currimundi conventional roof measurements.

The historical comparison of Nambour to Caloundra (near Currimundi) versus that of Nambour to Maroochydore suggests that Caloundra and thus Currimundi are on average measurably cooler on hot summer days than Maroochydore. If this is in fact is the case as the data suggests then the microclimate adjustments applied in this paper would lead to an understatement of the heat island effect and thus energy savings associated with the particular cool roof treatment under study.

The systematic temperature sensor bias from the temporary weather stations of +1.54°C was added to the Currimundi measurements.

The resulting adjusted daytime (7am-6pm) hourly temperature measurements are shown in Figure 4.

As hypothesised, the temperatures above the roofs are higher for a conventional aged metal deck roof compared to the cool roof. The three weeks of measured data were relatively cool, cloudy and wet yet a significant 2 to 5°C bias is typically observed (3.33°C on average for all samples). Even with the climate correction removed, the average bias remains at 3.33°C. In this

Table 2: Sumary of simulation results showing progressive impact of assumptions

	Air Conditioning	Roof Properties			Annual Energy Use			
		Effective Insulation Thickness	Solar Absorptance	Longwave Emmissivity	Microclimate kWWh/m2 pa	Bias (3.3°C) % of gap	Microclimate kWWh/m² pa	Bias (5.0°C) % of gap
8	Cool Roof	20	10%	0.95	64	–	64	–
1	Conventional Roof –Design Assumptions	38	50%	0.88	71	18%	71	13%
2	Conventional Roof –Higher Solar Absorptance (aged)	38	70%	0.88	74	7%	74	5%
3	Conventional Roof –Reduced effective insulation thickness	20	70%	0.88	76	5%	76	4%
4	Microclimate – Increased roof load	20	70%	0.88	87	29%	93	31%
5	Microclimate – Increased ventilation load	20	70%	0.88	95	22%	106	24%
6	Microclimate – Poorer DX efficiency (AC Systems only)	20	70%	0.88	103	19%	119	24%

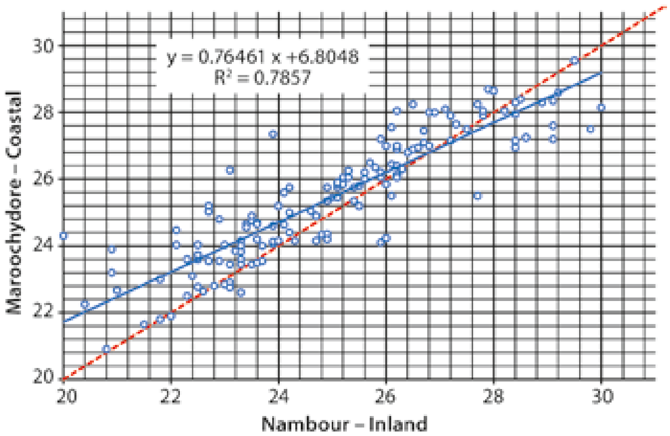

Figure 3: February 3–19, 2008
Daytime hourly weather station measurements.

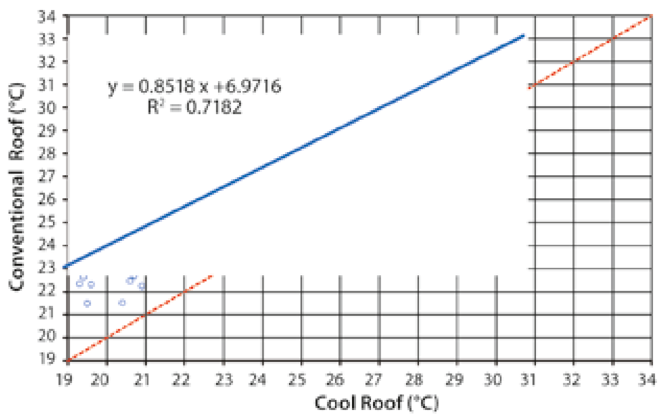

Figure 4: Adjusted hourly Daytime above Roof
Dry Bulb Temperatures.

case the relationship at cooler and higher temperatures changes, but the average remains the same.

Given the abnormally cool and wet weather during the measurement period, we believe the 3.33°C average heat island bias for a conventional metal deck roof is slightly conservative. For a more typical weather year we believe the average heat island bias could be higher and for this reason two heat island bias scenarios were simulated, 3.33°C and 5.0°C.

Estimated energy savings

Following the methodology described, Table 2 summarises the results for the two temperature bias scenarios. Overall the theory would suggest that 39 kWh/m2 pa (at 3.33°C bias) to 56 kWh/m2 pa (at 5.0°C bias) can be explained. This compares to the observed savings of 82 kWh/m2 pa between two comparable supermarkets – one conventional and one with a cool roof treatment. While the savings are different in absolute terms they are similar in percentage terms – 38% to 46% simulated savings versus 47% observed for the same mechanical system end uses.

Conventional simulation engines that do not account for roof heat island effects only predict 20 to 30% of the modified simulation estimated savings. The additional energy use attributable to the heat island effect is broken down into a:

- 29–31% increase due to added roof heat load
- 22–24% increase due to added ventilation loads
- 19–24% increase due to reduced air-cooled DX cooling efficiency.

The shortfall in estimated versus observed savings could be due to a variety of factors including:

- Limitations in the heat island measurements taken.
- Differences in trading patterns between stores leading to a difference in sensible and latent space cooling loads.

Table 3: Indicative Heat Island Bias Calculations

	Scenario				
	1	2	3	4	5
Air Density (kg/m³) =	1.124	1.124	1.124	1.124	1.124
Specific Heat capacity of Air (kJ/kg°K) =	1.006	1.006	1.006	1.006	1.006
Boundary Layer Thickness (m) =	3.0	5.0	5.0	5.0	5.0
Width / Depth of Surface (m) =	30.0	30.0	30.0	30.0	30.0
Ambient Drybulb Temperature T_a (°C) =	25.0	25.0	25.0	25.0	25.0
Roof Surface Temperature, T_{roof} (°C) =	60.0	60.0	60.0	60.0	50.0
Ambient Wind Velocity (m/s) =	0.5	0.5	3.0	5.0	5.0
Estimated Temperature Pick Up (°K) =	4.33	2.66	1.05	0.91	0.65

- Marine grade environment near coastal store leading to corrosion of heat exchange surfaces and poorer DX efficiency at the coastal site (untreated roof).
- The summer of 2004 was very hot in Southeast Queensland and would lead to additional load beyond that simulated with the chosen weather file.
- The heat rejected from the air-cooled DX equipment would also be biasing the air temperatures above the roof. Short circuiting of discharge airflow likely leads to poorer cooling efficiencies.
- Some of the discharge air from the condensers may also be biasing the ventilation air intake temperatures.

- Differences in infiltration and moisture migration through the roof joints that may arise where conventional roofs are subject to increased thermo-cycling and thus degradation of joints – cool roofs are more dimensionally stable.

All of these factors would be influencing the measured savings and thus quite likely explain the gap between the modified simulated savings and the observed savings.

Potential simulation solutions

While there are potential work arounds within simulation software to modify the weather file parameters for certain aspects of the simulation, to have these work arounds approximate the dynamics of reality (wind, solar, variable heat transfer coefficients etc) is impractical and will inevitably lead to inaccuracies.

This research does not define how the simulation of roof microclimates should be addressed to provide a generalised heat island representation. This work would be the subject of further study by the industry which would potentially be best carried out using three-dimensional computational fluid dynamics (CFD).

As a minimum allowing a constant temperature bias to be added to condenser air intakes and ventilation air intakes could be easily achieved.

A more representative method may be to estimate this bias as a function of wind speed and incident solar radiation. Within IES' Virtual Environment this could be achieved using a formula profile; however, the level of bias would need to be assumed rather than simulated.

To calculate the heat island bias without having to predetermine the magnitude of the bias ultimately will require further research using CFD, but could then potentially use an empirical relationship that accounts for the following parameters:

- Convective heat transfer coefficient (W/m2 °K) as a function of wind speed. As an example IES's VE (IES 2007) assumes: $h = 5.6 + 4v$ where $v<4.88$ m/s (Eq1) $h = 7.2 (v^{0.78})$ where $v>4.88$ m/s (Eq2)
- A characteristic dimension of the roof which could be either set by the user or determined from roof geometry. Allowing for the variations in wind direction this could possibly be taken as the radius of a circle that has equal surface area to the roof.
- Boundary layer thickness over which the heat is immediately dissipated within – the thicker the dispersion layer is the lower the temperature rise.
- Roof surface temperature as calculated in an unbiased situation.
- Heat rejection loads from air-cooled condensers would be an extension to this if additional research showed that the discharge of condensing units fails to disperse the heat away from the roof microclimate. This would be a particular problem with smaller horizontal discharge split system condensing units.
- Rain would be a further enhancement and area of research as the moisture on a warm roof would be evaporated thus having a cooling effect on the roof with all else equal.

Making some reasonable assumptions to align with the supermarkets studied, Table 3 shows that the above methodology does produce a degree of heat island bias that is consistent with observations. The temperature bias is calculated using a single dimension finite difference model with steady state conditions. For simplicity no additional heat was assumed to be transferred through the roof to below.

These results would suggest that simulation developers could adopt these principles with some calibration from CFD or other empirical studies.

The simplified finite difference model suggests the heat island bias will be very sensitive to wind speed as well as how quickly the heat disperses in the vertical direction (boundary layer thickness).

The level of heat island bias observed and estimated we believe is also consistent with the referenced heat island studies as these studies are looking at temperature effects across an urban scale and with a thicker zone of heat dispersion. It is reasonable to assume there will be a gradient from the roof surface to the broader urban model and thus a concentrated heat island effect at roof level than predicted at an urban level.

CONCLUSION

Many if not all simulation packages currently do not take into account the localised heat island created above roof surfaces as a result of hot roof surfaces warming the local air. This local heat island effect can significantly affect the predicted and actual energy use of buildings, particularly where cooling and ventilation equipment is located at roof level.

As simulation programs do not take into account the warming of the roof microclimate they represent cool roofs accurately. However, with more conventional or high solar absorptance the heat island effect and level of cooling energy use will be understated. For this reason the energy savings associated with cool roofs is typically under-predicted by simulation, in some instances significantly.

Location corrected measurements at two supermarkets suggest that the heat island effect over a cooler three-week summer period may be 3.3°C, possibly higher under more typical summer conditions. There are uncertainty and limitations in these measurements, but for reasons discussed, we believe this measured bias is a conservative estimate of the actual bias on average.

Modified simulation results accounting for the heat island effect suggest that conventional simulation only accounts for 25-35% of the potential energy savings for these supermarkets. The additional 65% – 75% savings estimated for the heat island effects leads to a total level of savings broadly in line with measured savings thus suggesting these effects explain why simulation underestimates the savings associated with cool roofs.

Addressing the heat island issues in simulation will ensure appropriate adoption of cool roof technologies, which have widespread application for conditioned building types such as airport terminals, warehouses, shopping centres, factories, supermarkets, and bulky goods stores. This is critical where the mechanical plant is air-cooled and roof mounted as the heat island effects on cooling efficiency and ventilation loads are potentially significant.

With further work, a geometry and wind dependent heat island model should be achievable by simulation developers to ensure conventional roofs are fairly represented within energy simulation. This development is necessary to ensure cool roof technologies are appropriately adopted on projects.

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