RP1037u1: Above-Roof Temperature Impacts on Heating Penalties of Large Cool Roofs in Australian Climates

Interim Report 2

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Disclaimer

Peer Review Statement

The CRCLCL recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The authors confirm that this document has been reviewed and approved by the project's program leader and steering committee. The program leader provided constructive feedback, which has been addressed.

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Acronyms

HVAC	Heating, ventilation and air-conditioning
PV	Photovoltaic
BPS	Building performance simulation
RMS	Root-mean squared
RMSE	Root-mean squared error
CFD	Computational fluid dynamics
UDF	User-defined function
NCC219	Australian national construction code 2019
COP	Coefficient of performance
IWEC	International Weather for Energy Calculation
EMS	Energy management system

Executive Summary

This is the second interim report for project RP1037u1. It contains key research outcomes produced since the first interim report was published, including three primary activities:

1. Implementation of the newly developed roof condensation model in dynamic building performance simulations (BPS).
2. A parametric BPS study, investigating the performance of cool and 'non-cool' bare metal-coated steel roofs on a case-study building, as well as the influence of the roof condensation model and revised above-roof temperature model on those simulations.
3. Cost-benefit analysis and greenhouse gas emissions abatement estimates of a cool roof product, based on results from the BPS study.

The roof condensation model was successfully implemented in the BPS software EnergyPlus, using the energy management system (EMS) feature. Preliminary simulations were run to quantify the sensitivity of results to the timestep length and check whether the thermal capacitance of accumulated dew needed to be taken into account to produce accurate results. A timestep of 2 min was found to be appropriate, and the thermal capacitance of dew did not influence results significantly.

The parametric BPS study included seven Australian climate zones, three roof types (one bare metal-coated steel roof, one light-coloured painted steel roof, and one even lighter cool roof), two HVAC systems, and four thicknesses of ceiling insulation. Each simulation was run four times: i) with the revised above-roof temperature model, ii) with the roof condensation model, iii) with neither model, and iv) with both models. All simulations involved a 350×200 m^2 two-storey shopping centre building.

A comparison of simulation results indicated that rooftop dew and above-roof air temperature fields can affect BPS results significantly, especially in cases where multiple simulations are being compared to assess the relative effects of cool roofs. If both phenomena had been neglected in the cases investigated here, electricity savings would have been miscalculated by 3–71% (35% on average) and gas 'penalties' (i.e. extra gas consumption for heating of the building) would have been miscalculated by 12–46% (29% on average). When both models were implemented, calculated gas penalties attributable to the cool roof were consistently reduced and HVAC electricity savings were either reduced or increased, depending on the climate.

The value proposition of cool roofs depends on the unit costs and greenhouse gas emission factors of electricity and gas, as well as the climate, so a range of unit costs and emission factors were investigated in the economic analysis. Compared to the bare-metal roof, the cool roof provided a net saving in HVAC running costs and reduction in greenhouse gas emissions for the case-study building in almost all cases involving Darwin, Brisbane, Alice Springs and Sydney. In simulations of Dubbo, Melbourne and Canberra, running costs and emissions could be reduced or increased by the cool roof, depending on the unit costs and emission factors.

The net effect of rooftop dew and above-roof air temperature fields on predicted HVAC running cost savings and greenhouse gas emissions abatements for the cool roof varied, but was generally positive. When both models were implemented, the predicted cool roof benefits were consistently increased in simulations of Dubbo, Sydney, Melbourne and Canberra. In hotter climates (Darwin, Brisbane and Alice Springs), the combined effects of dew and above-roof temperatures were found to either increase or decrease the predicted cool roof benefits, depending on the emission factors and unit costs of electricity and gas.

Introduction

Background

'Cool' roofing materials are engineered to maximise the solar reflectance and thermal emittance of the roof top surface. Cool roofs tend to remain colder than those fabricated from conventional roofing materials, because they reflect a relatively large fraction of incoming short-wave solar radiation, and transmit a relatively large quantity of long-wave radiation to the sky (as compared to low-emissivity bare metal roofs). Such a reduction in surface temperature can reduce the amount of heat transmitted into a building during hot periods, thereby reducing the energy required for space cooling and/or improving the indoor comfort conditions. However, in cold conditions, cool roofs tend to reduce indoor thermal comfort and/or increase the energy required to heat indoor spaces—an effect often referred to as the cool roof 'heating penalty'. Thus, the suitability of cool roof technology depends on the local climate, as well as the building design and usage.

A recently completed research project entitled 'Driving Increased Utilisation of Cool Roofs on Large-Footprint Buildings' (RP1037) investigated previous claims that cool roofs may have additional effects on the performance of buildings with large roof surfaces (e.g. airport terminals and shopping centres) and rooftop heating, ventilation and air-conditioning (HVAC) equipment (Green *et al.*, 2018). In that study, it was confirmed experimentally that, in addition to the effects that cool roofs have on heat transmission through the roof structure, they can also significantly alter the temperature of air surrounding rooftop HVAC equipment. An empirical model was formed that can predict near-roof air temperatures, taking into account the influence of roof surface temperature, and the model was implemented in a set of building performance simulations (BPS). The simulation results indicated that the effect roof surface temperatures have on ventilation air inlet temperatures and rooftop heat exchanger efficiencies can cause changes in annual HVAC electricity and gas consumption of up to 5%. Moreover, in the cases investigated, these above-roof air temperature effects were found to account for approximately half of the benefits and penalties associated with cool roofs. Thus, if the near-roof air temperature field had not been modelled accurately (as is currently the conventional practice in BPS), the cooling savings and heating penalties associated with cool roofs would have been underestimated by approximately 50%.

The findings of RP1037 have provided valuable insight into the magnitude of effect that near-roof air temperatures can have, and the importance of these effects in the performance of cool roofs. The empirical above-roof temperature model has also provided a means for BPS practitioners to take near-roof air temperatures into account. However, the experiments on which the model was based were limited to three buildings and a relatively small set of weather conditions. Therefore, validation of the model with additional experimental data would be highly valuable, and users of the model should have a clear understanding of any limits to the range of conditions which it is valid for. In particular, the validity of the model for use in simulations of cold conditions is of interest, since the experiments were all conducted in warm summer/autumn conditions and the model has a large effect on predicted cool roof heating penalties, which arise in cold conditions. This issue has been investigated in the present work.

The second issue that has been investigated in the research reported here is that of water condensation on roof surfaces, and the effects that this phenomenon can have on the performance of cool roofs relative to roof constructed of more conventional roofing materials. When a roof surface temperature falls below the local dew-point temperature, water will condense on the surface, which could have two potentially significant effects on the thermal performance of roofing materials:

1. The release of latent heat during condensation and absorption of latent heat during evaporation could significantly influence roof surface temperatures.
2. Water droplets or films on the roof surface could significantly alter the roof radiative-optical properties, thereby influencing roof surface temperatures.

Prior to investigation, it was speculated that cool roofs and 'non-cool' roofs could reach very similar temperatures when covered in condensed water, and that this could significantly reduce cool roof heating penalties. In the present study, the authors have quantified the effects of condensation on cool and 'non-cool' roofs, in order to determine whether this could be true.

Aims

The aims of the current project have been outlined below:

1. Quantify the range of weather conditions for which the existing RP1037 above-roof temperature model can be applied, and develop a new model for cold weather conditions if needed.
2. Quantify the effects of condensation on cool roof thermal performance, relative to metal-coated ('non-cool') roofing materials.
3. Revise results from the RP1037 BPS, cost-benefit analysis and greenhouse gas emissions abatement calculations, to take into account any revisions to the above-roof temperature model, and the effects of condensation if they prove to be significant.
4. Ensure utilisation of research outcomes by producing technical design support resources, conducting a series of seminars for key user groups, and disseminating findings in appropriate industry and academic publications.

Method

The project has been divided into four primary activities:

1. Investigate the effects of condensation on cool roof performance, by:
    a. reviewing literature related to condensation on roofs and the physical phenomena involved in this process;
    b. analysing the existing RP1037 dataset, to determine how often condensation was likely to occur and whether there was a discernible effect on roof surface temperatures at those times;
    c. developing a model that can estimate the rate of water condensation and evaporation on a roof surface, as well as the effects of these processes on roof radiative-optical properties and the roof temperature; and
    d. conducting dynamic BPS, with and without the condensation model, of buildings with cool and ‘non-cool’ bare metal-coated steel roofs, to quantify the effect of condensation in several illustrative cases.
2. Address issues related to use of the existing above-roof temperature model in simulations of cold conditions, by:
    a. quantifying the range of weather conditions recorded during the RP1037 experiments and comparing this to the range of conditions predicted throughout a typical year in different Australian climates; and
    b. revising the above-roof temperature model if necessary.
3. Replicate BPS, cost-benefit analysis and greenhouse gas emissions abatement calculations from RP1037, incorporating the condensation model and revised above-roof temperature model, if necessary.
4. Disseminate research findings through publications, seminars, and summary design support resources.

Report outline

This is the second interim report for RP1037u1 ‘Above-Roof Temperature Impacts on Heating Penalties of Large Cool Roofs in Australian Climates’, an extension of the original project, RP1037. Activities covered by the first interim report have not been included in this report. In this report, the authors have outlined progress on:

- Application of the roof condensation model in dynamic building performance simulations;
- Evaluation of cool roof performance relative to a bare metal-coated steel roof when simulated on case study large-footprint buildings in Australian climates;
- Quantification of the financial and environmental value proposition of the cool roof in those test cases.

These three topics constitute the two main sections of this report. A short conclusion has also been included, to summarise the key preliminary findings reached since the first interim report.

Building performance simulations

A parametric BPS study was conducted, incorporating the roof condensation model and the revised above-roof temperature model, both of which were outlined in the previous interim report (Lin *et al.*, 2019). A similar set of cases were investigated as had been in the previous project, RP1037. The primary differences between this and the previous investigations were the inclusion of the roof condensation model, adoption of the revised above-roof temperature model, and revision of several HVAC sizing and control settings to form a more realistic representation of the large-footprint buildings of interest. Therefore, the results presented here should be considered to supersede those contained in the RP1037 final report (Green *et al.*, 2018).

Aims

The parametric study was conducted with three primary aims:

1. Quantify the influence of cool roofs on the annual energy demand of large-footprint buildings in Australian climates, taking into account:
    a) the effect of water condensation and evaporation on the roof external surface; and
    b) the effect of the near-roof air temperature field on rooftop HVAC equipment.
2. Quantify the difference between BPS results that do and do not take these phenomena into account.

In order to achieve the aims outlined above, simulations were run of a case-study large-footprint building operating in a variety of Australian climates over the period of one year. The simulations were replicated with different cool roofs and a ‘non-cool’ bare metal-coated steel roof, and different types of HVAC equipment. In order to quantify the effects of near-roof air temperature fields and dew, each simulation was run with both the above-roof temperature and roof condensation models, with each model individually, and with neither model.

Simulation methodology

The BPS software EnergyPlus v8.9 was used, with the simulation manager jEPlus v.1.7.2 (Zhang, 2011). The Energy Management System (EMS) feature in EnergyPlus provides a means to manipulate simulation variables using custom scripts, thereby allowing the effective integration of external models.

Implementation of the above-roof temperature model

The revised above-roof temperature model was implemented using the EMS. At each timestep in the simulations, the ambient air temperature (T_{amb}) and reference wind speed (u_{ref}) were obtained from the weather file, the representative building length scale (L) was set as the square root of the total building roof area, and the mean roof surface temperature (T_s) was obtained from the current building energy balance. Using this information, a corrected inlet air temperature (T_{HVAC}) was determined for rooftop HVAC equipment, assuming that the equipment inlets span from $z_1 = 0.5$ m to $z_2 = 2$ m above the roof surface. Figure 1 depicts this process schematically.

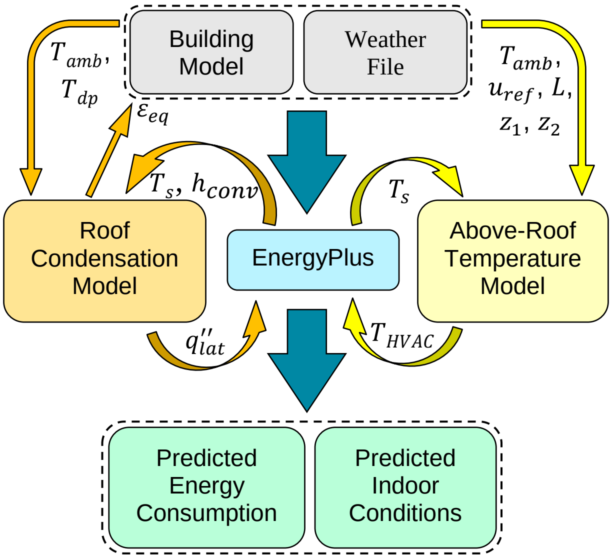

Figure 1: Schematic showing how the roof condensation and above-roof temperature models were integrated with EnergyPlus.

Implementation of the roof condensation model

The roof condensation model was implemented in EnergyPlus using the EMS, as shown in Figure 1. At each timestep within simulations, the current ambient temperature (T_{amb}) and dew-point temperature (T_{dp}) were obtained from the weather file, and the spatially averaged roof surface temperature (T_s) and roof convective heat transfer coefficient ($\bar{h}_{conv}$) were obtained from the previous timestep solution. These inputs were used to calculate: i) the latent heat released/absorbed due to condensation/evaporation of dew on the roof surface (q''_{lat}), and ii) the apparent roof thermal emittance taking into account the effect of any dew on the surface (ε_{eq}). A heat source term in the roof energy balance and the roof material thermal emittance could then be set to account for the effects of dew during the current timestep.

There was a risk that implementation of the roof condensation model in this way could cause instability in the simulations or incorrect results, since it uses an explicit method (i.e. uses variables from one timestep to estimate conditions at a future timestep). Therefore, it was important that an appropriately small timestep be used, to produce results that were timestep-independent and free of significant timestep-induced oscillations. A timestep sensitivity study was conducted to select an appropriate timestep for the proceeding simulations.

It was also important to check whether the thermal capacitance of dew on the roof could have a significant effect on the building performance, since the model implementation described above does not take such effects into account. Simulations were conducted in which the thermal capacitance of the roof sheet was modified at each timestep according to amount of dew present, and the results were compared to those obtained without taking dew thermal capacitance into account.

External convective heat transfer coefficients

In the previous interim report, various external convective heat transfer coefficient models were compared (Lin *et al.*, 2019), and it was shown that the 'ClearRoof' model (Clear *et al.*, 2003; Costanzo *et al.*, 2014) is an appropriate choice for simulations like that at hand. The ClearRoof model was applied to roof surfaces in the present work and the DOE-2 model was used for external vertical surfaces (i.e. walls).

Cases investigated

A case-study large-footprint shopping centre building was developed for the simulation study. It should be noted that no single building model can accurately represent the myriad different large-footprint buildings in existence, and that BPS results were found to be very sensitive to assumed building properties, operational schedules and loads, HVAC control and sizing strategies, etc. in the present investigation. An effort has been made to base the case study shopping centre on design standards and industry guidelines, where possible. However, the results presented here represent the performance of one typical building, and cannot necessarily be applied directly to all similar buildings.

Building details

The building model had plan dimensions of 350 m × 200 m and a double-pitched, low-angle roof, as shown in Figure 2. It was modelled with concrete walls, a metal deck roof and concrete slab on ground; 5% of the wall area was set as glazing and no roof glazing was included. The indoor space was divided into two storeys and one separate unconditioned roof cavity, each comprising a separate indoor zone.

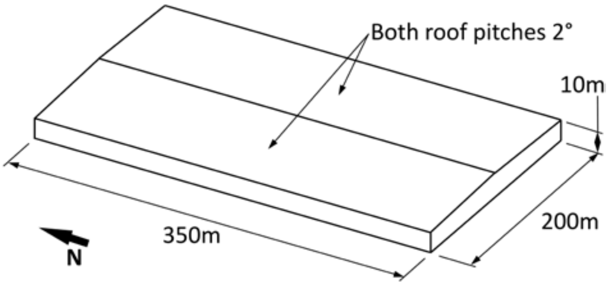

Figure 2: Diagram of the case-study building geometry.

The building fabric and construction details were set to meet minimum performance requirements outlined in the Australian National Construction Code of 2019 (NCC2019) for each climate investigated (Australian Building Codes Board, 2019). The thermal resistance (R-value) requirements for different climate zones can be found in Sections J1.3 and J1.5 of NCC2019. Additional simulations were run with a range of roof R-values, to investigate the importance of ceiling insulation in the relative benefits of cool roofs.

Very few previous studies were found that had quantified air infiltration rates for shopping centres. Jenkins (2008) noted that they could be expected to vary significantly over time and between different buildings; the author suggested values from 0.5 to 1.0 air changes per hour (ACH) at natural pressure. A value of 0.7 was set in the present investigation.

Roof radiative-optical properties

Three roof types were included in simulations: one representative of bare metal-coated steel sheet (e.g. zinc-aluminium coated steel), and two light-coloured painted steel sheet roofs, referred to herein as of 'light' and 'very light' roofs. Differences between the roofs are detailed in Table 1. In simulations incorporating the roof condensation model, the effective roof thermal emittance varied from the 'dry roof' values reported in Table 1 according to the amount of dew present on the roof.

It is important to note that the properties of roof materials can change significantly over time. The effect of such ageing depends on the local exposure conditions and the properties of the roof product, but light-coloured painted roofs have been shown to exhibit significant decreases in solar reflectance, even within the first three years of installation, and bare metal roofs tend to increase in thermal emittance (California Energy Commission, 2015; Paolini *et al.*, 2016; Cool Roof Rating Council, 2018). Factory-applied cool coatings, such as those on which the roofs in the present work were based, have been shown to change less over time than field-applied coatings, in the absence of biological growth (Sleiman *et al.*, 2011). However, the results of the present study should still be considered to represent building performance at a particular point in time, not a consistent performance that could be expected over the entire life of a roofing product.

Table 1: Radiative-optical properties of the roof products investigated.

Roof Type	Solar Reflectance	Thermal Emittance
Bare metal	0.67	0.3
Light-coloured	0.68	0.85
Very light-coloured	0.77	0.87

Building operation

Air conditioning and heating were used to maintain the indoor air temperature within 22.0–24.5°C between 7:00 and 18:00 every day, and no air conditioning was used outside of these periods. The majority of internal heat load magnitudes and schedules were defined as per the requirements for Class 6 buildings in NCC2019 (see Table 2). NCC2016 did not provide a maximum occupant density for such buildings, so a value from were Energy Action (2018) was used. The equipment load was set to 10 W m^{-2}, which is larger than the NCC2016 value of 5 W m^{-2}, to account for loads that are common in shopping centres but not within the typical retail shop, e.g. vending machines, cooking equipment in food courts and any refrigeration in supermarkets that is not conditioned by rooftop units.

Table 2: Internal loads and schedules applied to the two case-study buildings.

Parameter	**Setting**
Lighting load [W m^{-2}]	22
Equipment load [W m^{-2}]	10
Maximum (inverse) occupant density [m^{2} person^{-1}]	3
Occupant thermal load [W person^{-1}]	75 sensible, 55 latent
Lighting schedule	100% from 7:00 and 19:00, 10% otherwise
Equipment schedule	70% from 7:00 and 19:00, 10% otherwise
Occupancy schedule	Varies, maximum of 25% reached during 11:00–13:00
HVAC schedule	On between 7:00 and 18:00

HVAC systems

Detailed variable-air-volume HVAC systems were included in the building models (see Figure 4) based on design guidelines from ASHRAE Standard 90.1-2010 (ASHRAE 2010). They were comprised of one 'parallel fan-powered box' air handling unit per floor, each connected to four staged chillers and four gas boilers. Each simulation was run twice, once with air-cooled chillers and once with two wet cooling towers per chiller, to investigate whether above-roof temperature fields affect such systems differently.

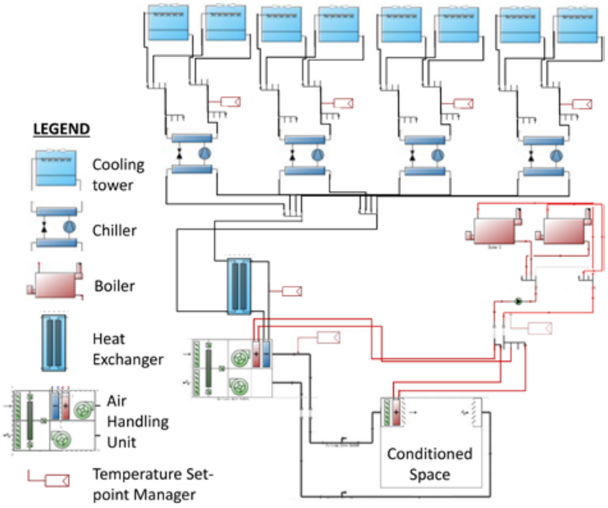

Figure 3: Schematic diagram of the detailed HVAC systems included in the building model; two such systems were used, one for each storey of the building. Simulations were also run with equivalent systems, except that the chillers were air-cooled (i.e. wet cooling towers were not included).

All HVAC components were automatically sized, based on simulations of 'extreme' summer and winter weeks specified in the weather data files. The nominal system cooling and heating capacities were set 1.15 and 1.25 times the maximum cooling and heating demands, respectively; these design factors were based on the recommendations of ASHRAE (DesignBuilder, 2018). Therefore, HVAC components were different sizes in each simulation and did not necessarily achieve the same coefficient of performance (COP) in each case.

Weather

Seven sets of weather conditions were simulated, representing typical conditions in major Australian cities located within climate zones 1–7, as described in the NCC2019 (see Figure 4 and Table 3). International Weather for Energy Calculation (IWEC) typical weather data files were used for all simulations except those of climate zones 3 and 4; IWEC weather data was not available for those locations, so reference meteorological year (RMY) data was used instead. It should be noted that some spatial variations in climate also exist within the climate zones, so the results presented here do not represent all Australian climates exactly.

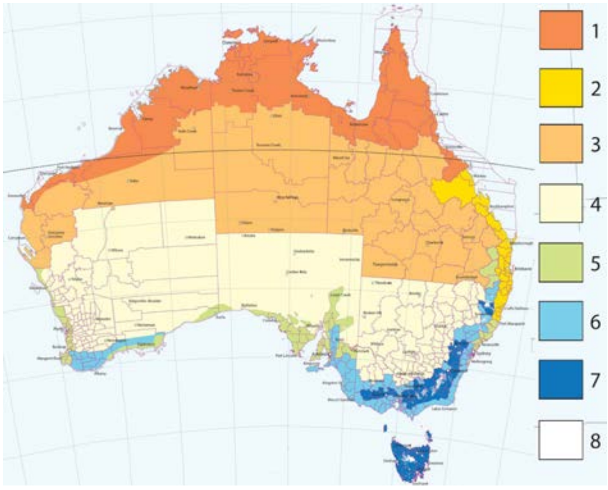

Figure 4: Australian climate zones, adapted from Australian Building Codes Board (2016); zones 1–7 were included in the BPS study.

Table 3: Australian cities that were used to represent each of the seven climate zones investigated.

Zone	**Description**	**City**
1	High humidity summer, warm winter	Darwin
2	Warm humid summer, mild winter	Brisbane
3	Hot dry summer, warm winter	Alice Springs
4	Hot dry summer, cool winter	Dubbo
5	Warm temperate	Sydney
6	Mild temperate	Melbourne
7	Cool temperate	Canberra

Results and discussion

Timestep sensitivity

Preliminary simulations were run with three different timestep values: 6, 2 and 1 min, all with the roof condensation model, bare metal roof, air-cooled chillers and weather data representing Sydney. Results from all three simulations were very similar. The RMS deviation between roof surface temperatures, dew mass loadings and latent heat fluxes obtained using timesteps of 6 min and 1 min were 0.31°C, 3.7 g m^{-2} and 8.1 W m^{-2}, respectively; between results obtained using timesteps of 2 min and 1 min, the corresponding RMS deviations were 0.054°C, 0.65 g m^{-2} and 1.0 W m^{-2}, respectively. Based on these indications of timestep sensitivity, it appeared timesteps as large as 6 min could be used without affecting results significantly. However, some signs of instability were observed in the spatially averaged roof surface temperatures obtained using a 6 min timestep (see Figure 5). Such instability could cause large inaccuracies, so subsequent simulations were conducted with a timestep of 2 min.

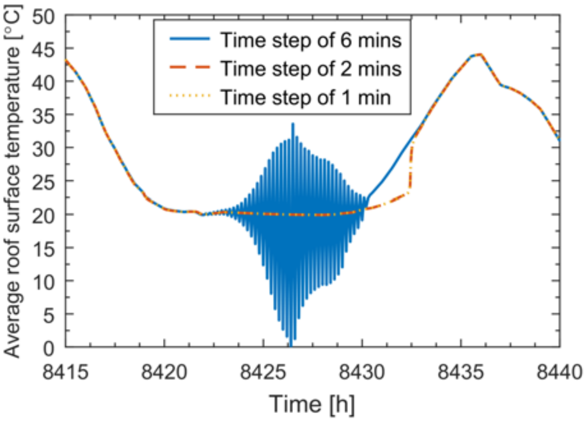

Figure 5: Example of unstable results produced using 6 min timesteps, compared to the corresponding results obtained with 2 and 1 min timesteps.

Influence of dew thermal capacitance

During the timestep sensitivity study, it was observed that a significant quantity (in the order of 100 g m^{-2}) of dew could accumulate on the roof under dynamic conditions. Since water has a relatively high specific heat capacity of approximately 4.2×10^3 J kg^{-1} K^{-1}, a dew mass loading of 150 g m^{-2} would have one third of the thermal capacitance of the 0.5 mm-thick steel roof sheet. Therefore, it was prudent to assess whether the thermal capacitance of accumulated dew should be accounted for in simulations.

A simulation in which the roof sheet thermal capacitance was overridden at each timestep, to include the additional capacitance of any dew that was present, was compared to a simulation in which this was not done. Results from the two simulations were in close agreement; the RMS deviation between the simulated roof surface temperatures, dew mass loadings and latent heat fluxes were 0.093°C, 6.4 g m^{-2} and 1.1 W m^{-2}, respectively. Such small effects would not influence building performance significantly, so the effect of dew on roof thermal capacitance was not accounted for in subsequent simulations.

Dew condensation/evaporation dynamics

During approximately half of the nights simulated with Sydney weather, the roof surface temperature fell below the dewpoint temperature, which caused dew to form. On these occasions, dew continued to accumulate until the roof surface rose above the dewpoint temperature, at which time evaporation began. Typically, the dew was completely evaporated relatively quickly once evaporation began (see Figure 6); on average, it was completely evaporated within 2.2 h in simulations of Sydney. However, on a small number of days the solar heat flux did not raise the roof surface temperature high enough to completely evaporate all dew that was present, so the model predicted that some dew persisted over a period of several days.

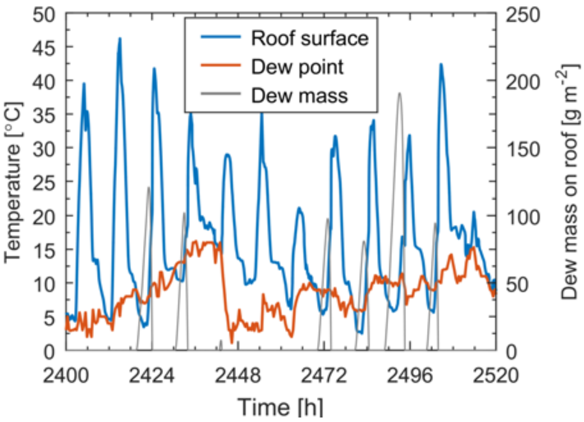

Figure 6: Example of the dynamic dew condensation/evaporation process over a period of 12 days, driven by the difference between roof surface temperature and dew-point temperature.

Dew effect on roof apparent thermal emittance

Over the course of the simulated year of Sydney weather, the bare metal roof apparent thermal emittance often rose to approximately 0.96 (see Figure 7). Any dew mass loading greater than ~20 g m^{-2} would have this effect. Such conditions were typically reached in the early morning (~2:00–8:00). During these periods, the thermal performance of the bare metal roof and painted roofs would be quite similar, since both would have a high apparent thermal emittance, and differences in solar reflectance would have little effect due to the low solar heat flux. Conventional BPS practices (i.e. those ignoring the effects of dew) would not account for this phenomenon, so would be likely to overestimate the degree to which high-emissivity roofs (e.g. cool roofs) are colder than low-emissivity roofs (e.g. bare metal roofs) in the early morning.

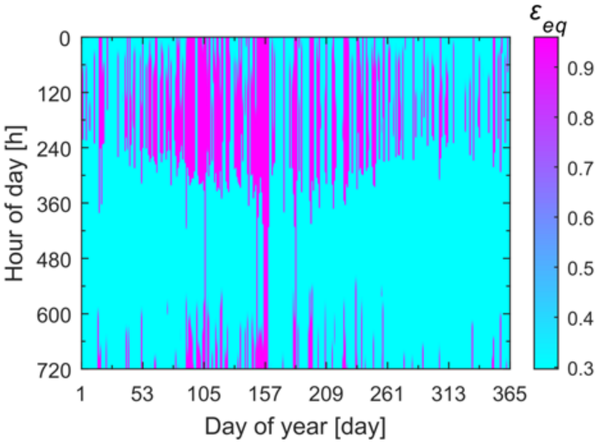

Figure 7: Apparent thermal emittance (ε_{eq}) of the bare metal roof during simulations of Sydney weather.

Dew effect on roof surface temperatures

The roof condensation model decreased the temperature of the bare metal roof by several degrees during many mornings in simulations, and tended to increase the very light roof temperature during the early morning and decrease it during the late morning (see Figure 8). On some extreme occasions, the bare-metal roof surface temperature was reduced by over 15°C by dew.

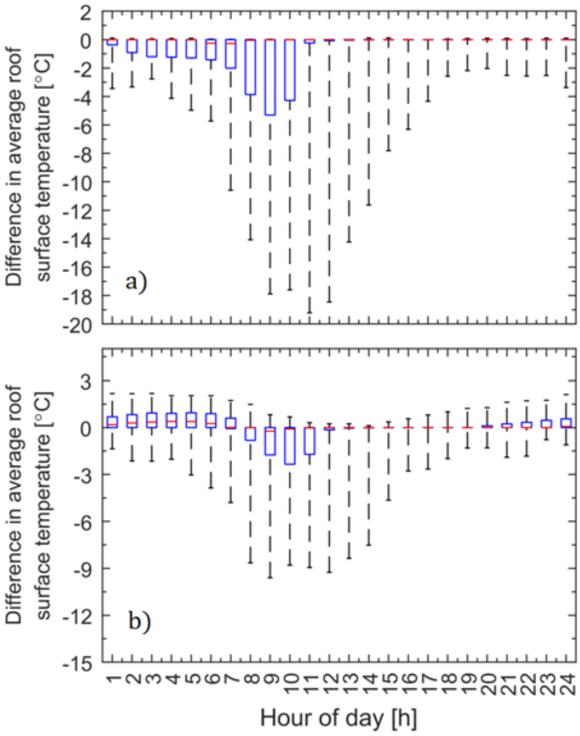

Figure 8: Effect of the roof condensation model on roof surface temperatures at different times of day, for the a) bare metal roof and b) very light roof in Sydney. Each red line indicates the distribution median, the blue 'boxes' bound the 2nd and 3rd quartiles, and the 'whiskers' extend to the minimum and maximum values within each distribution.

The effect of latent heat fluxes are clearly evident in results from the very light roof (Figure 8b); roof surface temperatures were typically driven warmer as dew condensed in the early morning, and colder in the late morning (~8:00–10:00) as dew evaporated. In simulations of the bare metal roof, the effects of dew on roof apparent thermal emittance were much more pronounced, since the dry-roof emittance was much lower than in other cases. The bare-metal roof surface was almost always made colder by dew. During the early morning, enhanced radiant heat exchange with the sky appears to have overpowered the warming effect of latent heat release during condensation, and the complimentary effects of latent heat absorption and enhanced radiant heat exchange with the sky combined to drive the bare metal roof temperature down in the late morning.

To investigate the relative importance of the two effects of dew (latent heat fluxes and modified roof thermal emittance) on roof surface temperatures, simulations were run in which only one of the two effects was imposed. The results revealed that, in simulations of the bare metal roof in Sydney, the effect of dew on the roof apparent thermal emittance was the primary cause of changes in roof surface temperature (see Figure 9).

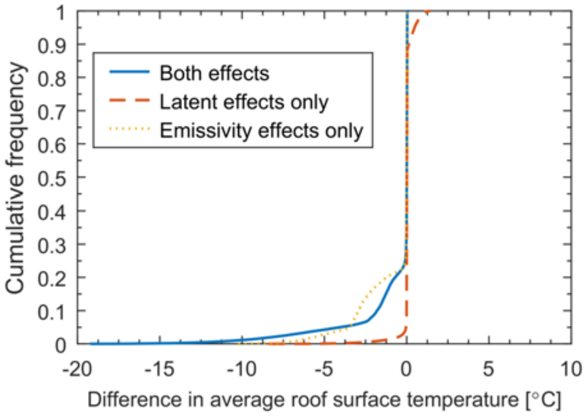

Figure 9: Effects of dew on the bare metal roof temperature, when taking either the latent heat effects, emissivity effects, or both effects into account.

Above-roof air temperatures

Corrected HVAC inlet temperatures (T_{HVAC}) calculated by the above-roof temperature model typically differed from the ambient air temperature (T_{amb}) by 0–1.2°C (see Figure 10). Air close to all three roofs was typically driven hotter than T_{amb} during daylight hours, when the sun heated the roof surfaces, and colder than T_{amb} at night-time, when radiant heat exchange with the sky drove T_s below T_{amb}. The light and very light roofs tended to remain colder than the bare metal roof due to their higher solar reflectance and thermal emittance, so T_{HVAC} also tended to be colder in simulations of those roofs. These results were commensurate with experimentally measured and simulated values from project RP1037 (Green *et al.*, 2018).

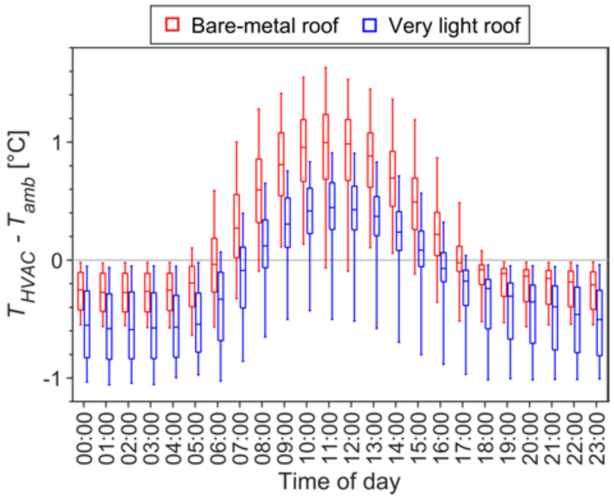

Figure 10: Effect of the above-roof temperature model on HVAC inlet temperatures, in simulations of Sydney, neglecting the effects of dew. Each 'box' and set of 'whiskers' represent the distribution of values recorded during the specified hour of day throughout the entire year-long simulation.

Annual cooling and heating requirements

The above-roof temperature model increased annual cooling requirements by 4–23% and decreased annual heating requirements by 6–12% for the building with a bare metal roof (see Figure 11). The roof condensation model had a much smaller effect on the annual thermal HVAC loads (less than 0.6% and 2% for cooling and heating, respectively).

The effect of the two models on thermal loads in simulations of light and very light roofs was similar to that reported for the bare metal roof, above, except that above-roof temperatures tended to have less of an effect and dew tended to have a larger effect. In simulations of the two painted roofs, the above-roof temperature model caused annual cooling to increase by 1.3–16% and annual heating to either decrease or increase by 0.4–4.9%. The roof condensation model caused annual cooling to increase by 0.6–2.3% and annual heating to decrease by 1.3–4.9%.

Annual electricity and gas consumption

The annual HVAC electricity and gas consumption calculated in simulations of the building with air-cooled chillers are presented in Figure 12. Chillers with wet cooling towers typically performed with higher COPs than the corresponding air-cooled chillers, leading to a reduction in total annual HVAC electricity consumption of 11–30% (and no effect on gas consumption).

The effects of above-roof air temperatures and dew on electricity and gas consumption were generally similar to their effect on cooling and heating loads. The above-roof temperature model tended to increase HVAC electricity consumption and decrease gas consumption, and affected the building with bare metal roof more than those with painted roofs. The roof condensation model typically had very small effect in simulations of the bare metal roof, and tended to increase electricity consumption slightly and decrease gas consumption in cases involving the light and very light roofs.

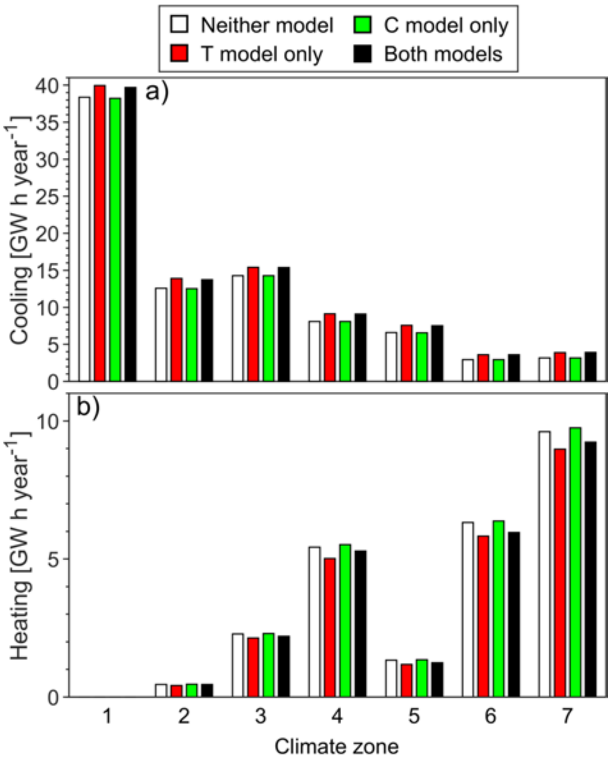

Figure 11: Annual a) cooling and b) heating requirements of the building with bare metal roof. Results are presented from simulations with the above-roof temperature model (T model), roof condensation model (C model), both models, and neither model.

The combined effects of the two models when implemented together did not equate to the sum of effects caused by each model individually. The roof condensation model influenced roof surface temperatures and, thereby, above-roof air temperatures, so the effects of dew were amplified by the above-roof temperature model. Typically, the two models had opposing effects on HVAC energy consumption in cases with the bare metal roof, and complimentary effects in cases with the light and very light roofs. These trends can be understood by considering that the bare metal roof was typically cooled by dew during mornings, so T_{HVAC} was lower, mitigating above-roof temperature effects (which would otherwise tend to increase HVAC energy consumption when cooling was required and decrease it when heating was required). In cases with either of the painted roofs, the roof condensation model had a relatively large effect on thermal loads, which caused changes in electricity and gas consumption that complemented the effects of above-roof air temperatures.

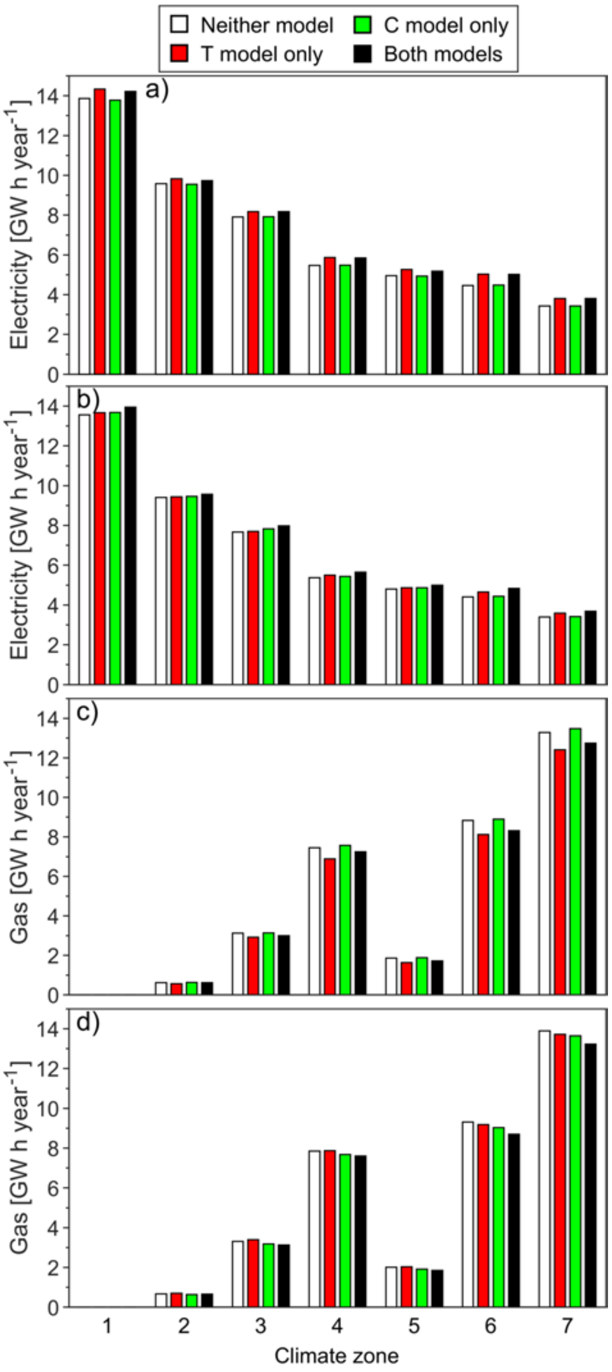

Figure 12: Annual HVAC electricity (a-b) and gas (c-d) consumption of the building with air-cooled chillers and either a bare metal roof (a, c) or very light roof (b, d). Results are presented from simulations with the above-roof temperature model (T model), roof condensation model (C model), both models, and neither model.

Cool roof electricity savings and gas penalties

In order to quantify the value proposition of cool roofs in the cases investigated, simulations of the very light roof (a cool roof) and the bare metal roof (a typical 'non-cool' roof) were compared. Figure 14 presents this comparison for buildings with air-cooled chillers, and Figure 15 shows the same results for buildings with wet cooling towers. The magnitude of electricity savings and gas penalties corresponded quite closely to the annual HVAC electricity and gas consumption, respectively. Cool roof savings/benefits obtained with air-cooled chillers were very similar to those obtained with wet cooling towers, but were slightly higher in some cases.

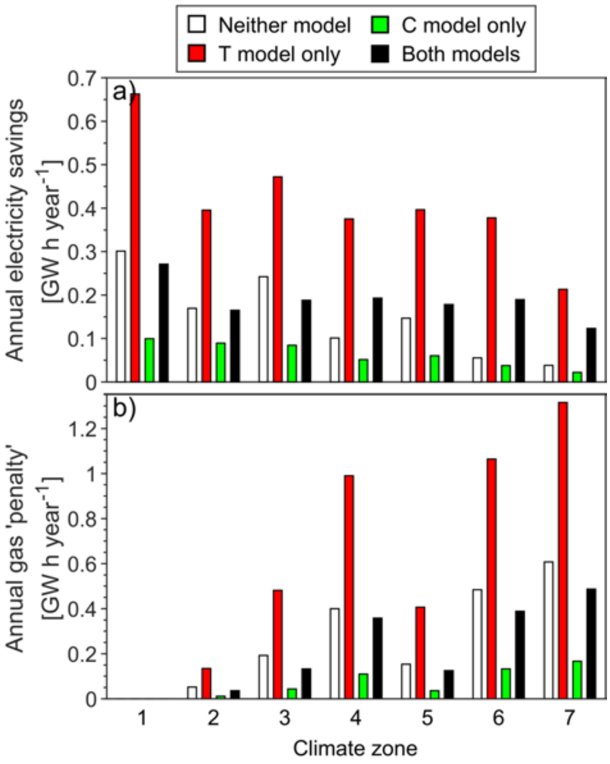

Figure 13: Annual a) electricity savings and b) gas 'penalties' attributable to the use of the very light roof rather than the bare metal roof, for the building with air-cooled chillers. Results are presented from simulations with the above-roof temperature model (T model), roof condensation model (C model), both models, and neither model.

Above-roof air temperatures and dew both had a large effect on the electricity savings and gas penalties attributable to the cool roof. The two models had opposing effects on the savings/penalties in all cases; the above-roof temperature model consistently increased electricity savings and gas penalties, and the roof condensation model consistently decreased them. When both models were implemented their combined effect varied; gas penalties were reduced in all climates, as were electricity savings in hot climates (zones 1–3), with the exception of climate zone 2 when wet cooling towers were included, and electricity savings were increased in temperate climates (zones 4–7).

The magnitude of effect that the models had on predicted electricity savings and gas penalties demonstrates the importance of these phenomena in the performance of technologies like cool roofs. If conventional BPS practices were adhered to, both above-roof temperature and dew effects would be neglected. While such simplifications would have only affected annual energy consumption by several percent in the cases investigated here, the relative performance of a cool roof compared to a 'non-cool' roof could have been miscalculated by a much larger fraction. In the cases investigated here, the effects of above-roof air temperatures and dew on annual savings/penalties tended to cancel each other out, to a degree. However, simulations with different building geometries, construction details, internal loads, usage schedules and/or climates could be affected differently.

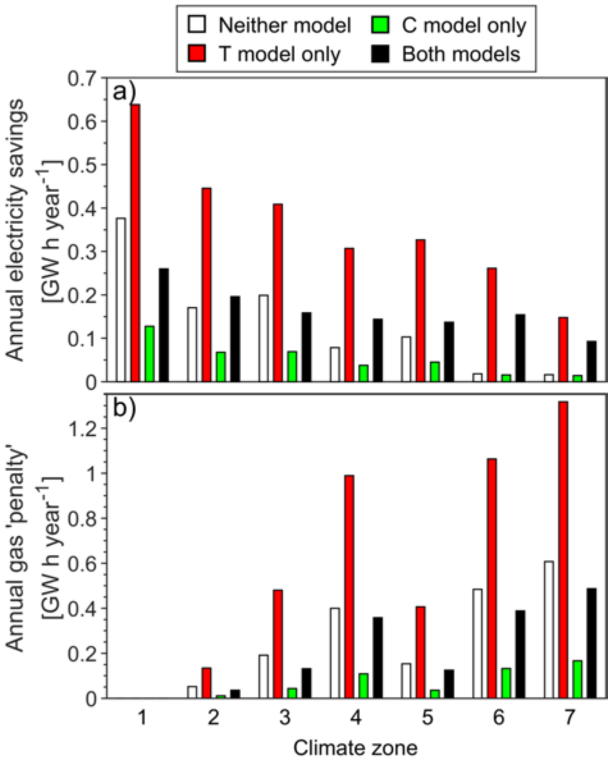

Figure 14: Annual a) electricity savings and b) gas 'penalties' attributable to the use of the very light roof rather than the bare metal roof, for the building with water-cooled chillers. Results are presented from simulations with the above-roof temperature model (T model), roof condensation model (C model), both models, and neither model.

Sensitivity to ceiling insulation thickness

Results from simulations with different amounts of ceiling insulation were compared, to investigate how each model affected results with roof R-values higher or lower than the values specified in NCC2019. Such cases have relevance to existing buildings that do not meet current building code requirements, and to buildings with more ceiling/roof insulation than is required. Results from this comparison also provided additional insight into how each model influenced the simulated building.

HVAC electricity savings and gas penalties attributable to the cool roof both tended to increase with decreasing roof R-value (see Figure 15), since differences in roof surface temperature had a larger effect on the heat flux through the roof structure. In most cases, the two models affected annual energy savings/penalties by a similar magnitude, regardless of the roof R-value. However, when very little ceiling insulation was included, reducing the total roof R-value to ~0.5, the roof condensation model reduced gas penalties by a much larger amount (see Figure 15b). Such a trend could be explained by the effects of dew on roof surface temperatures, which can influence HVAC energy consumption via two pathways: i) driving heat transmission through the roof structure, and ii) influencing air temperatures at the inlet to rooftop HVAC equipment. When less ceiling insulation is installed, the first of these pathways is enhanced, so the effects of dew are also enhanced. By contrast, the above-roof temperature model provides a means to include the second pathway in simulations, but does not affect temperatures within the simulation directly.

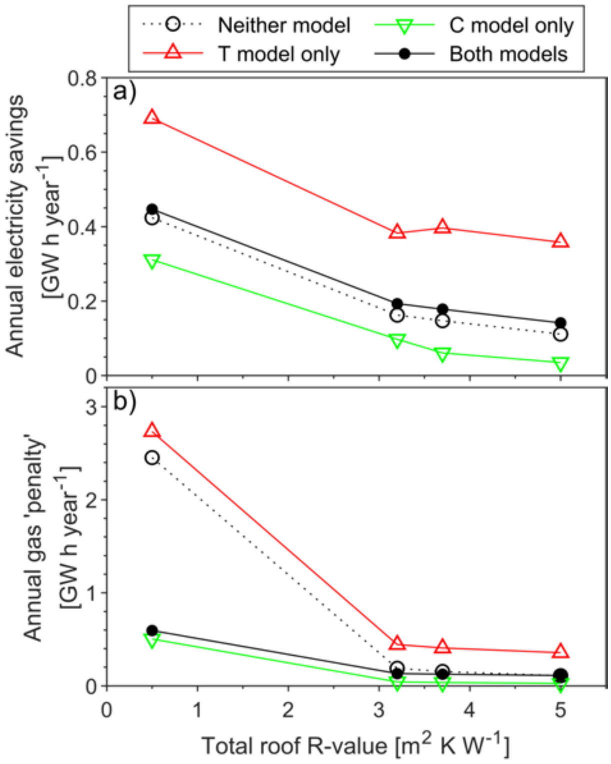

Figure 15: Influence of ceiling insulation on the annual HVAC electricity savings and gas 'penalties' attributable to the use of the very light roof rather than the bare metal roof in Sydney. Results are presented from simulations with the above-roof temperature model (T model), roof condensation model (C model), both models, and neither model.

Economic analysis

The net effect of electricity savings and gas penalties on the overall value proposition of cool roofs depends on the unit financial costs and greenhouse gas emission factors of gas and electricity. To investigate these dependencies and quantify the net cool roof value proposition for the cases investigated, a cost-benefit analysis and greenhouse gas emissions abatement estimate were conducted.

Operational cost savings

In order to compare electricity savings and gas penalties on a financial basis, each value needed to be multiplied by a unit cost. In reality, electricity and gas pricing structures are often complex. Unit prices can vary according to time of use, and other tariffs associated with the customer peak demand may also be applied. The scope of the current project did not permit time for a comprehensive analysis of the impact of pricing structures on the value proposition for cool roofs. The analysis presented here has been based on single unit costs for both gas and electricity, which provided an indicative range of results for the building investigated. To fully explore the value proposition for cool roofs accurately, the hourly results of BPS would need to be analysed alongside the energy supply contracts in place for a particular building.

A range of electricity and gas unit costs were included in the analysis, in order to provide results that are widely applicable, despite the significant variations in electricity and gas costs across different Australian jurisdictions, and the high probability that such costs will change significantly over time. The ratio of electricity price to gas price (both expressed in units of $\$\ \mathrm{kW}^{-1}\ \mathrm{h}^{-1}$), ω, was used to relate the two unit prices in graphs.

Figure 16 presents the running cost savings per unit floor area attributable to the use of the very light roof rather than the bare metal roof (see definitions of these roofs in the previous section of this report) on the case-study shopping centre building. In order to quantify the effects of the above-roof temperature and roof condensation models, results from simulations conducted with both models and those conducted with neither model have both been plotted.

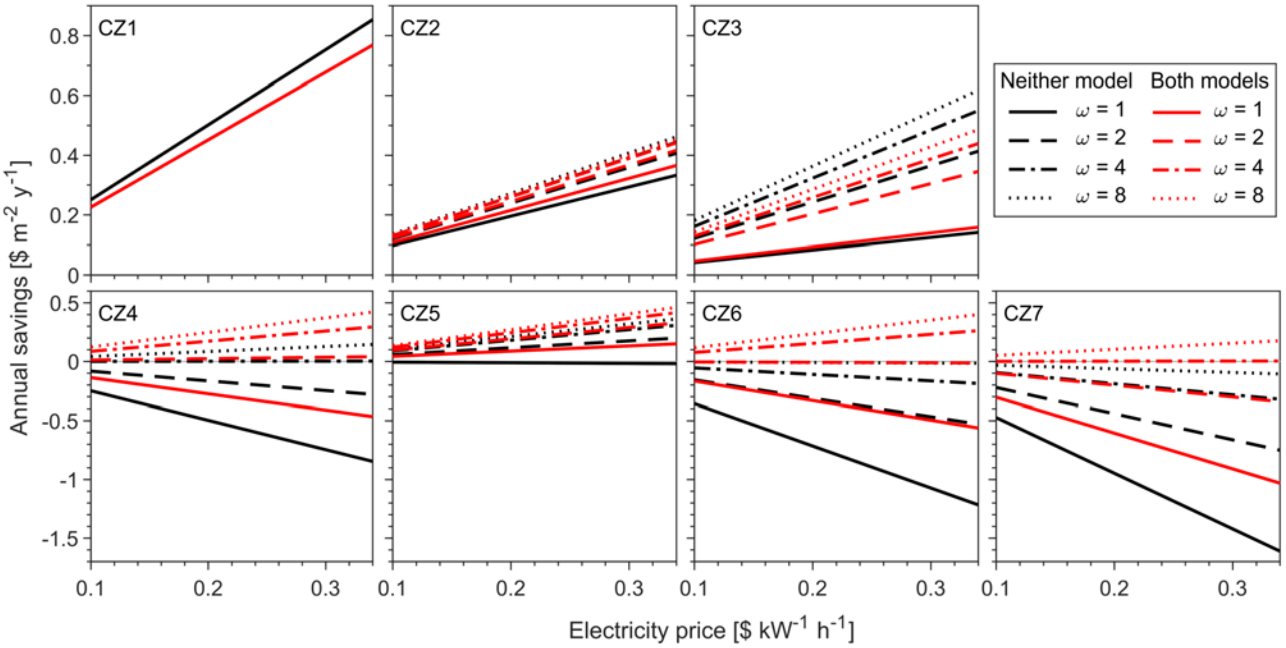

Figure 16: Annual HVAC running cost savings per unit floor area attributable to the use of the very light roof rather than the bare metal roof, calculated for the case-study shopping centre building with air-cooled chillers in seven climate zones (CZ1–7), for different electricity-gas cost ratios (ω), and with both the above-roof temperature and roof condensation models, or with neither model.

A net saving in running costs was calculated for all cases in climate zones 1, 2, 3 and 5. The magnitude of cost saving increased with ratio of unit costs for electricity and gas (ω), and with the magnitude of those unit costs for a given value of ω. In climate zones 4, 6 and 7, the cool roof was predicted to either decrease or increase running costs, depending on the value of ω. The magnitude of predicted savings/losses was significant in most cases. An annual saving per unit floor area of 0.1 [$\$\ \mathrm{m}^{-2}\ \mathrm{y}^{-1}$] would amount to a total operational saving of \$280,000 for the case-study building considered here, if it is assumed that the roof products have a service life of 20 years. The operational saving over the service life of the roof could be compared to the upfront cost difference between the different roof types to help determine which is most cost-effective.

The combined effect of the above-roof temperature and roof condensation models was to increase HVAC running cost savings in the four climate zones where electricity savings had been increased (4–7). In other climates, the combined effect of the models depended on ω, since gas penalties had been decreased but electricity savings had also been decreased, resulting in opposing effects on running cost savings.

It is important to note that the results presented here do not necessarily apply to all large-footprint buildings in the climate zones specified. The value proposition of cool roofs to real buildings is likely to vary significantly, depending on the building construction details, usage, HVAC equipment, and location. Furthermore, the ageing of roof materials and changes in electricity and gas prices are likely to change the annual savings attributable to cool roofs over time. However, the results presented here for the case-study shopping centre building at one point in time do demonstrate the importance of dew and above-roof air temperature effects in assessments of this type. If these phenomena had not been included in the analyses presented here, the value proposition of the cool roof would have been miscalculated by over 50% in many cases, and a net loss could have been predicted in climate zones 4, 6 or 7, when in fact a net saving had been possible.

Greenhouse gas emissions abatement

The abatement of greenhouse gas emissions was estimated using emission factors from the Australian Government July 2017 National Greenhouse Accounts Factors report (Australian Government Department of the Environment and Energy and Energy, 2017). As had been the case for electricity and gas unit prices, the analysis was highly sensitive to the emissions factors chosen, and significant variations in emissions factors existed within Australia. For these reasons, a range of electricity emissions factors were included in the analysis. The emissions factor for natural gas was much more consistent within Australia, so it was fixed at the national average specified in the National Greenhouse Accounts Factors report (0.214 kg CO_2-e kW^{-1} h^{-1}).

Figure 17 presents the estimated greenhouse gas emissions abatement attributable to the very light roof, as compared to the bare metal roof, for the case-study shopping centre building with air-cooled chillers in all seven climate zones. Negative abatements (i.e. increased emissions) were possible in all climate zones where heating (using gas) was required, given very low electricity emission factors. However the 'break even' point (above which the cool roof was predicted to cause a net decrease in emissions) was very low in climate zones 1, 2, 3 and 5, so the cool roof would reduce emissions in those climates unless electricity was available with an extremely low emission factor ($\lesssim$0.15 kg CO_2-e kW^{-1} h^{-1}).

The effect of the above-roof temperature and roof condensation models on greenhouse gas emissions abatements was similar to the effect they had on operational cost savings. In climate zones 4–7, the models increased the electricity savings and decreased the gas penalties attributable to the cool roof, which produced a net decrease in predicted greenhouse gas emissions (i.e. increase in predicted abatement). In climate zones 2 and 3, the effect of dew and above-roof air temperatures depended on the electricity emission factor, and in climate zone 1 the models reduced electricity savings, thereby reducing predicted emissions abatements. The high sensitivity of greenhouse gas emissions abatement estimates to dew and above-roof air temperature fields is clearly visible in Figure 17. For instance, neglecting these factors in the present cases would have caused the cool roof to appear inappropriate for climate zones 6 and 7, when it could be beneficial in reality, depending on the electricity emission factor.

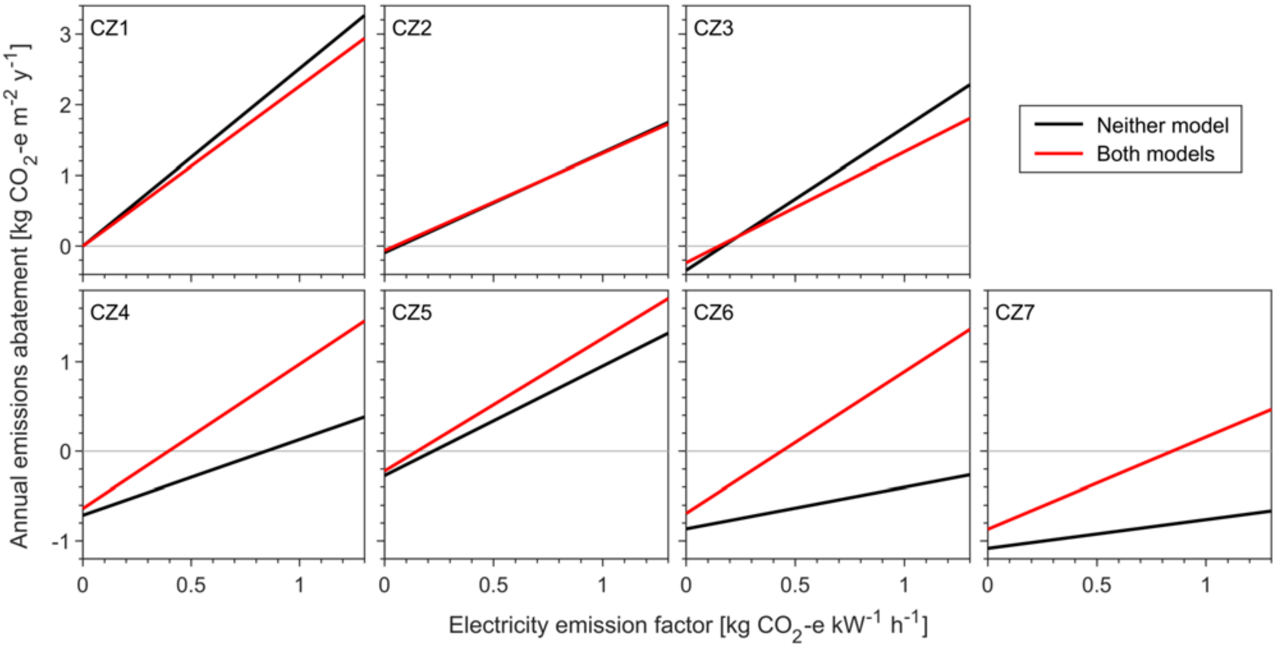

Figure 17: Annual greenhouse gas emissions abatement per unit floor area due changes in HVAC electricity and gas consumption if a very light roof were installed rather than a bare metal roof. Results are presented for the case-study shopping centre building with air-cooled chillers in seven climate zones (CZ1–7), with both the above-roof temperature and roof condensation models, and with neither model.

Conclusion

To the authors' knowledge, this has been the first study to publish such in-depth analysis of the effects of dew on building thermal performance. Dew was predicted to form on the building roof on the majority of nights in the cases simulated, which matched observations of roof surface and dew-point temperatures from the RP1037 experimental study. The relative importance of: i) latent heat absorption/release and ii) changes in apparent thermal emittance, in the effect of dew on roof surface temperatures, was found to depend on the type of roof. Changes in thermal emittance had a larger effect in simulations of the low-emittance bare metal roof than for painted roofs. The results of the present study indicate that both effects should be included if the influence of dew is to be accurately modelled.

The revised above-roof temperature model produced corrected HVAC inlet temperatures that were commensurate with experimental and simulated values from RP1037 (Green *et al.*, 2018). Changes made to the model are likely to have had a relatively small effect on BPS results, but the values presented here should be considered to supersede those in the RP1037 final report.

The effect of the two models on individual BPS was significant but relatively small in the cases investigated here. The roof condensation model typically altered T_s by less than 5°C, and the above-roof temperature model typically influenced T_{HVAC} by less than 1.2°C. Annual HVAC electricity and gas consumption were affected by 0.3–13% (6% on average) when both models were implemented together. However, when BPS was used to assess the performance of a cool roof relative to a bare metal roof, the two models had a much more pronounced effect on results. If conventional BPS practices had been adhered to in the present cases (i.e. if dew and above-roof temperature fields had been neglected), electricity savings would have been miscalculated by 3–71% (35% on average) and gas penalties would have been miscalculated by 12–46% (29% on average). There is a significant probability that such large errors could cause cool roofs to be erroneous deemed cost-effective or not. Therefore, both dew and above-roof air temperatures should be considered in simulation studies that compare cool roofs to other roofing products.

The present study had several limitations, which should be understood:

1. Only one case-study building was investigated in the BPS study and economic analysis. Results were found to be highly sensitive to modelling assumptions (e.g. building construction details, internal loads, usage schedules, etc.), so the results presented here should not be considered to represent all large-footprint buildings.
2. Roof radiative-optical properties are known to change over time. Such 'ageing' was not taken into account in the present work, so the results are not necessarily accurate for the entire service life of a roof.
3. The above-roof temperature model was based on experimental data from three buildings. Limitations in the applicability of the above-roof temperature model were assessed in the previous interim report (Lin *et al.*, 2019), and it was determined to be valid for the cases presented here. Nevertheless, further validation of this model would be valuable.
4. Two important assumptions were made during the development and application of the roof condensation model: i) dew was assumed to form a continuous film on the roof surface, and ii) condensation was only modelled on the roof external surface. It would be worthwhile to investigate the impact of these assumptions.

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