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Optimized cool roofs: Integrating albedo and thermal emittance with *R*-value

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ABSTRACT

For cool roofs the combined effect of the three parameters that define heat gain and loss from a roof, namely solar albedo α, thermal emittance *E*, and sub-roof *R*-value, must be considered. An accurate contribution of night sky cooling, and hence humidity and total down-welling atmospheric radiation is needed. A systematic analysis of the contribution of a roof to average cooling load per day and to peak load reductions is presented for a temperate climate zone over 6 cooling months using an hour-by-hour analysis. Eighteen 3-parameter sets (α,*E*,*R*) demonstrate the over-riding importance of a high α, while sensitivity to *R*-value and *E* drops away as albedo rises. Up-front cost per unit reductions in peak demand or average energy use per day always rises strongly as *R* rises unless albedo is low. A moderate $R \sim 1.63$ is superior to high *R* unless a roof is dark, or winter heating demand is high. We indicate briefly why the roof typically does not present a dominant influence on average winter heating needs in most temperate zones, enhancing the benefits of cool roofs.

1. Introduction

"Cool roofs" have been of increasing interest recently [1,2] because they can increase summer interior average thermal comfort levels significantly under free-running (i.e non-air conditioned) conditions, or can reduce average power needed in conditioned spaces. Both are of interest but have different measures. Performance under free-running is determined by the number of discomfort days as measured by internal zone temperatures T_{zone} exceeding a desired maximum. Total power consumption for interior cooling needed to avoid exceeding a pre-set maximum T_{zone} (set at 25 °C in this study) provides a conditioned performance measure. Energy ratings based on either measure can differ significantly for the same building design though they tend to converge when power needs are very low, that is in the highest rating buildings [3]. In the case of conditioned spaces roofs also have a strong influence on peak summer power demand, which is of growing concern to utilities. Roof related heat gains peak when solar flux $\Phi_S(t)$ is the highest and cooling power demands usually peak an hour or two later, when electricity is the most expensive and blackouts may be a high risk. In this study we will consider average daily and monthly cooling loads for the whole cooling season, as well as peak summer loads.

"Cool roofs" are commonly defined as having a high solar reflectance or albedo α, and hence the focus has been on heat gains in the daytime. While this is a key feature, overall performance is also dictated by other material and design factors and what happens at night in terms of additional passive cooling. The other material parameters of main interest are the roof's external emittance *E* and the *R*-value (or *U*-value $=1/R$) of any insulation immediately under the roof. Roof and building thermal mass is relevant but is fixed in this study. Internal loads are also neglected so we can focus on heat flow impacts of the material and meteorological influences, including the sun, the atmosphere, and air flow or wind. Ceilings if present between the roof and the occupied space, and insulation on ceilings, as used in many homes can be considered separately but for simplicity in the core message in this report results are confined to the influence of the roof including sub-roof insulation, and roof surfaces as one unit. From an initial cost perspective it is desirable to achieve the maximum energy savings (or minimum discomfort days) per dollar invested in the overall roof structure, that is cost benefits or return-on-investment. Payback period from energy savings could also be included for conditioned spaces.

Traditionally building codes have focused on more roof insulation, i.e. increased *R*-values, but more recently the extent of energy saving, comfort, and environmental benefits of a high roof albedo in warm climates have come into prominence [1,2,4–7]. The impact of emittance and hence night sky cooling, though treated reasonably well from a physics/environmental perspective in some computer codes, is often modeled poorly and has been widely underrated in its impact. Raising roof *R*-values and hence cost of insulation reduces daytime heat gains, but at the expense of night-time heat losses. High *R* in combination with thermal mass can trap daytime heat gains over the following night unless much cool air ventilation is available and utilized. Making the most of all available night cooling opportunities is especially important in buildings with significant internal heat gains. A systematic study of how α and *E* combine with

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a range of *R*-values embodies useful lessons and insights for new designs and for retrofitting. Changing roof coatings or modifying *R*-values can be part of regular maintenance. They are relatively inexpensive and come with important little recognized bonus benefits some of which are outlined briefly in the next section. Other factors of importance include thermal mass, roof slope, roof-to-wall area ratio, orientation, time dependence, magnitude of internal loads, and air exchange rates. All are fixed in this report so we can focus on roof material properties.

Then a systematic study of the way the three parameters (α,*E*,*R*) in combination dictate the overall cooling demand and peak load contributions of a roof, along with the initial cost benefits of varying *R* for different (α,*E*) combinations, provides important guidelines on how to achieve maximum savings per dollar invested in buildings where cooling demand is needed either over just 6 months or most of a year. One common misconception is that *R*-values should be as high as possible. We will show clearly that is not the case though *R* does need to rise for "non-cool roofs". We confine results in this report to cooling demand over six dominant cooling months in a temperate zone. The central insights that follow can be readily extended to even warmer climates where cooling demand extends over nearly a full year according to limited results we have to date. These are interesting in their own right, especially in terms of night-time effects even in hot–humid zones, and will be reported separately. In temperate climates like those in most Australian cities, total electric power or gas energy use for winter heating in homes can be present at two to three times higher than summer cooling demand in well established homes. Why is this and does it mean optimally that to maximize year round savings less high roof solar absorptance may be required? Two points are relevant in such climates. First while the roof contribution to cooling demand in summer is very sensitive to changing albedo we find its contribution to winter heating demand varies only slightly with the same changes. For example raising albedo by 0.4 typically reduces total cooling demand by a factor 2–3 but raises heating demand by around only 10% or less. Secondly the roof contributes at most 1/4th to 1/3rd of total heating demand in winter in most established Australian homes. The remainder is primarily due to excessive cold air infiltration, along with the fact that heating is needed more at night, when people are home. This is the key finding of a detailed study on the influence of air infiltration rates on cooling and heating demands. While some modern Australian homes designed for energy efficiency have improved air tightness, we are aware of no examples (though they probably exist in our alpine regions where few reside) that employ established cold climate techniques where heat exchangers warm incoming air. In sub-tropical and warmer climates, and in commercial, industrial, retail, and institutional buildings with large internal heat loads, cooling needs extend for longer periods and cool roof design is even more important. Two facts are clear already in temperate zones: (i) the benefits of a bias to cool roofs persist on an annual analysis in most building types and (ii) in homes in temperate zones, reductions in air exchange rates in winter can strongly reduce heating needs and should be an additional high priority to cooler roofs. Coupled with cool roofs large total annual savings will follow.

1.1. *Bonus benefits of optimized cool roofs*

Cool roofs can have substantial additional benefits beyond the direct thermal impacts within a single building that we examine in detail in this study. These bonuses arise even when the direct energy savings from changes to the roof parameters are moderate fractions of total annual energy use in that building. Peak demand reductions are one bonus already mentioned. Meeting peak demand on a handful of days is demanding on capital investment in grid capacity, power sources, and chiller capacity. It involves inefficient energy use in stand-by power stations, which have to run at low output in readiness. Current high peak demand growth in summer is of growing concern to utilities, homes, and businesses. If widely implemented, cool roofs could lower peak summer demand significantly in various ways. Much of the recent growth in air conditioning use in temperate countries like Australia is attributable to avoiding overheating discomfort on a handful of worst days each year so its amelioration with better building design, including ideally variable ventilation, can mean that the alternative, comfortable free-running is often quite viable. Then in most homes, air conditioners would be unnecessary.

Another bonus from high α, high *E* roofs in addition to cutting peak demand and overall energy use is worth consideration, despite not yet being quantified. It involves improvements in microclimates around each building and probably in the local urban or industrial precincts if most buildings therein have cool roofs. This opens up a mean of amelioration of the urban heat island problem [4,8–11], which adds significantly to cooling demand in various ways, especially via air exchange. First raising average local albedo reduces thermal storage in buildings and provides cooler air close to the building. Secondly sub-ambient roofing at night resulting from high *E* leads to cool air just above a roof, which can flow by natural convection off the roof to cool walls and surrounds. High α roofs also have much cooler air just above them in the daytime, which can raise the coefficient-of-performance (COP) in air conditioners. More free-running comfortable buildings mean less pumping of heat from interiors into the outside, which adds to the urban heat island (UHI) problem. Cooler precincts mean lower cooling demand in all neighboring buildings.

Finally at the very large scale, direct global cooling can result if a high enough percentage of the world's roofs are made "cool" [1,5]. Other global impacts associated with reduced need for compressor driven cooling [12] include lower emission of two greenhouse gases CO_2, and refrigerant gases via leakage. It is interesting in this context and worthy of detailed future study to compare to cool roofs the cost and impact on peak demand, the UHI and the local and global environments of the following growing approaches for air conditioning aimed at lower CO_2 emissions: (i) cooling compressors driven by photovoltaic generated solar power, (ii) solar thermal driven absorption cycle chillers, and (iii) bi-generation and tri-generation plants using gas driven local power and absorption cycle chillers. Solar output also peaks in performance an hour or two before peak demand but the cost per each MW of peak demand reduction is much lower for a cool roof than for solar PV power systems [5]. Normal inefficiencies in roof-mounted solar systems, both PV and thermal, add heat to the UHI. Local gas fired power plants add heat and moisture to a precinct, while absorption chillers have low COP near 1.0 and hence pump a lot more heat nearby than typical modern electric compressors. This may include nearly all the solar energy falling on a roof covered with efficient solar thermal collectors if they supply heat to the chiller. This could be up to 8–9 times the precinct or UHI heat load addition from a cool roof. PV (ignoring cost) is likely to be the more attractive option of these three, apart from a cool roof. A combination of cool roof and PV is also of interest. PV systems suitably mounted onto otherwise cool roofs should perform with higher efficiency due to cooler air near them as shown in another cell cooling approach recently [13]. Less cells will be needed anyway if cooling demand is reduced.

2. Material properties and roof heat flows

High *E* requires high infra-red absorptance across the Planck spectrum of black body wavelengths for near ambient temperatures. Combining the ideal high solar reflectance and high IR absorptance