Use of special solar reflective and low emissivity coatings on single-skin and lightly-insulated metal clad buildings in India to reduce cooling and heating loads

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***Abstract*— India has many single-skin or lightly insulated metal clad commercial, retail and industrial buildings. It is predicted that, given the size of the population and warm climate, use of air conditioning will grow significantly but adjustments to building design and specification may mitigate some of the additional energy demand. The total number of potential 'Cooling Degree Days' in India has been calculated to be 3906, which compares to 279 in the USA. Absolute demand is therefore extremely high. If this load is met conventionally there are adverse environmental impacts (much of India's power generation relies on coal fired power stations), and considerable stress will be placed on electricity generation and distribution infrastructures (as reflected in the power blackouts of 2012 attributed to a surge in power demand caused by air conditioning).**

The effective use of innovative advanced coatings for building envelopes could significantly reduce cooling needs, including in relation to industrial buildings. These coatings can increase solar reflectance on the outside of buildings (materially reducing 'through fabric' heat transfer), and reduce emissivity on the inside surfaces such that heat exchange between building and the occupants/internal spaces is reduced. Savings can be made by adjusting thermostat settings with no loss of thermal comfort. Critically, these coatings are economic, can be used in conjunction with other simple passive measures, and unlike many insulation techniques, have little or no adverse effect in terms of increasing the embodied energy of the building fabric.

This paper examines the effects of solar reflective and low emissivity coatings on electricity use for air conditioning (and heating), peak cooling load, and roof surface temperatures for single skin or lightly insulated metal clad buildings in three Indian climates.

A typical metal clad retail building has been modelled using dynamic thermal simulation software, to assess the effect that different roof cladding reflectance values have on cooling and heating loads. It has been found, for example, that air conditioning loads can be reduced by as much as 18% for single skin buildings in Mumbai when the solar reflectivity of the roof is increased to 65%, with similarly significant effects in other highly developed locations in India. Significantly, it has also been identified that peak cooling loads can also be reduced by over 25%. This reduction could play a significant role in reducing the potential risk of power outages associated with periods of high grid energy demand, and in reducing the imperative to continually increase grid capacity in relation to exponentially expanding demand.

***Index Terms*—Solar reflectance; low emissivity; coating; building; air conditioning**

INTRODUCTION

Efficient mitigation of global warming requires energy-efficient technologies to reduce CO_2 emissions, which are now proved to be the key cause of global warming. As buildings are responsible globally for a large proportion of total CO_2 emissions (greater than sectors such as transport and industrial production), it is critical to reduce their operational energy requirements, and internationally considerable effort is presently being invested into improving standards. For example, in the UK building regulations the present Part L has introduced whole-building carbon dioxide emissions approaches for both domestic and non-domestic buildings. Similar policies apply in mainland Europe, the United States and Asia. One of the features of these latest approaches is that many building envelope characteristics can be properly accounted for in carbon calculations including factors such as air-tightness and U values, but also the important role that coatings can have in 'through fabric' heat transfer. A general characteristic of all active buildings is that energy is required to run their heating and cooling systems. Buildings exhibit differences in solar gain throughout the year, due obviously to the effects of glazed openings, but also as a consequence of heating of external roof and wall surfaces. Measures to reduce 'through fabric' effects can be as significant in magnitude as solar control of glass and shading of windows.

The thermal resistance value R_{ow} of an external wall (similar rules apply for roofs) can be described as:

$$R_{ow}=\frac{1}{h_{r,i}}+\frac{1}{h_{c,i}}+R_w+\frac{1}{h_{r,o}}+\frac{1}{h_{c,o}} \qquad (1)$$

where h is heat transfer coefficient, W/m2K; R is thermal resistance, m2K/W; subscripts i and o denote inside and outside; subscripts r and c denote radiative and convective; subscript w denotes wall. An increase in overall thermal resistance can be achieved by increasing the reflectance of the surface, as well as by the more common strategy of reducing thermal conductance, normally by increasing insulation thickness). Reflective

Table 1 Locations of retail shed

City	Latitude	Longitude	Altitude (m)
New Delhi	28.62	77.22	213
Mumbai	18.98	72.85	0
Chennai	13.08	80.28	15

techniques typically involve organic coating materials with high solar reflectance in the near infrared region of the spectrum.

Theoretically, the solar radiation striking the earth's atmosphere equates to 1.5 kW per square metre per hour (measured normal to the sun's rays).Part of this is reflected by the atmosphere, part is scattered and part is absorbed. Although terrestrial radiation is many times less intense than outer atmosphere solar radiation, the annual net radiation is still comparatively high. As the implications of solar radiation on building envelope performance become more appreciated, there is considerable world-wide research concerning how building envelope reflectivity can be better calculated and the role of more highly reflective coatings in reducing building energy demand. For example, Luxmoore et al. [1] used a demonstration house to investigate indoor thermal performance as well as heat island and global warming effects.

Considerable research has also been conducted concerning reflectance estimations and solar radiation calculations in urban areas to perform a systematic analysis of the various factors on relflectance of surfaces [2–9]. Tang [10] discussed the intensity of direct solar radiation and the effect of building orientation on radiant performance, and also presented a study of the influence of building form on solar gain. Studies have been carried out regarding the cooling potential of reflective coatings on the roofs of buildings. Givoni and Hoffman [11] compared the temperatures inside buildings by coating exterior walls in white or grey. The effect of external surface colour (hence the reflectance) on the thermal performance of the buildings was also investigated [12– 15]. In addition, cool roof technology has been developed based on the similar fundamental theory of using reflective materials. Synnefa et al. [16] reported on the use of cool materials for commercial cool roof applications.

This paper investigates the thermal behaviour, in particular the energy savings, by means of a dynamic computer simulation for a one-storey retail shed after application of reflective coatings on exterior wall and roof surfaces.

Some degree of energy saving can also be achieved, especially in single skin buildings, by use of low emissivity (e) coatings on the inner surface. A low emissivity means that less radiant energy is transferred to building occupants and other surfaces from the walls and roof, decreasing the temperature that is sensed by occupants. Two values of emissivity are investigated in this paper: 0.85 (standard) and 0.3 (low).

DESCRIPTION OF BUILDING AND CONDITIONS

The building

A retail building with a pitched roof (shown in Fig. 1) is assumed, constructed on a steel portal frame, 50m long x, 40m wide and 8m high. The building has a 2000m^2 floor area and

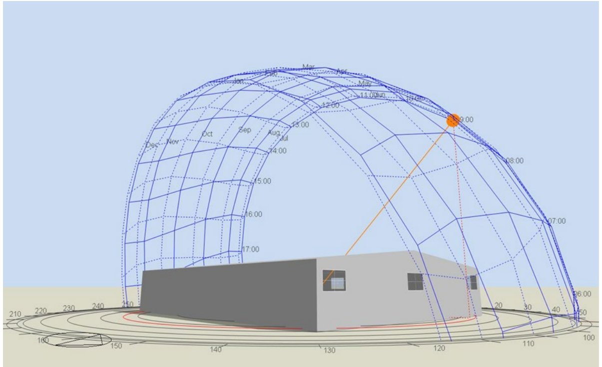


Figure 1 Designbuilder retail shed model

approximately 19050m^3 internal volume. The building has a 200mm ground-bearing concrete slab and 10% double glazing window area (four 4.0m x 2.5m windows) on the front and side elevations. The roof angle is 6°.

The walls and roofs of the building are clad with either single-skin sheeting comprising one 0.7mm metal layer (U-value 5.8W/m^{2}K) or composite panels comprising two 0.7mm metal layers (internal and external surfaces) and a 25 mm polyurethane core (U-value 0.88W/m^{2}K).

Figure 2 Locations modelled

Locations/climates

The performance estimation was undertaken for three locations in India (New Delhi, Mumbai, and Chennai, detailed in Table1.) A dynamic model was run using real recorded hourly weather data taken from the weather database software Meteonorm 6.1. As an example, the weather of Chennai on 1st

May is shown in Fig.3, indicating dry bulb temperature and solar radiation levels.

Internal conditions

The breakdown of internal conditions is listed in Table 2. The building is designed to be air-conditioned, heated to 20°C in winter and cooled to 21°C in summer. In the computer simulation it is assumed that electric heaters are 100% efficient and a cooling coefficient of performance (COP) is 2.5.

The air-conditioning system is operated 07:00–18:00h Mondays to Saturdays. The lighting gain refers to the heat gain inside the building due to artificial lighting, which is fixed because daylight control is not applied. Occupant sensible and latent gains are the heat and moisture gains in relation to the metabolism of the occupants.

Coatings

Five coating materials with different solar reflectances (ranging from 0.05 to 0.65) were investigated together with two internal coatings of different emissivity: 0.85 (standard) and 0.3 (low).

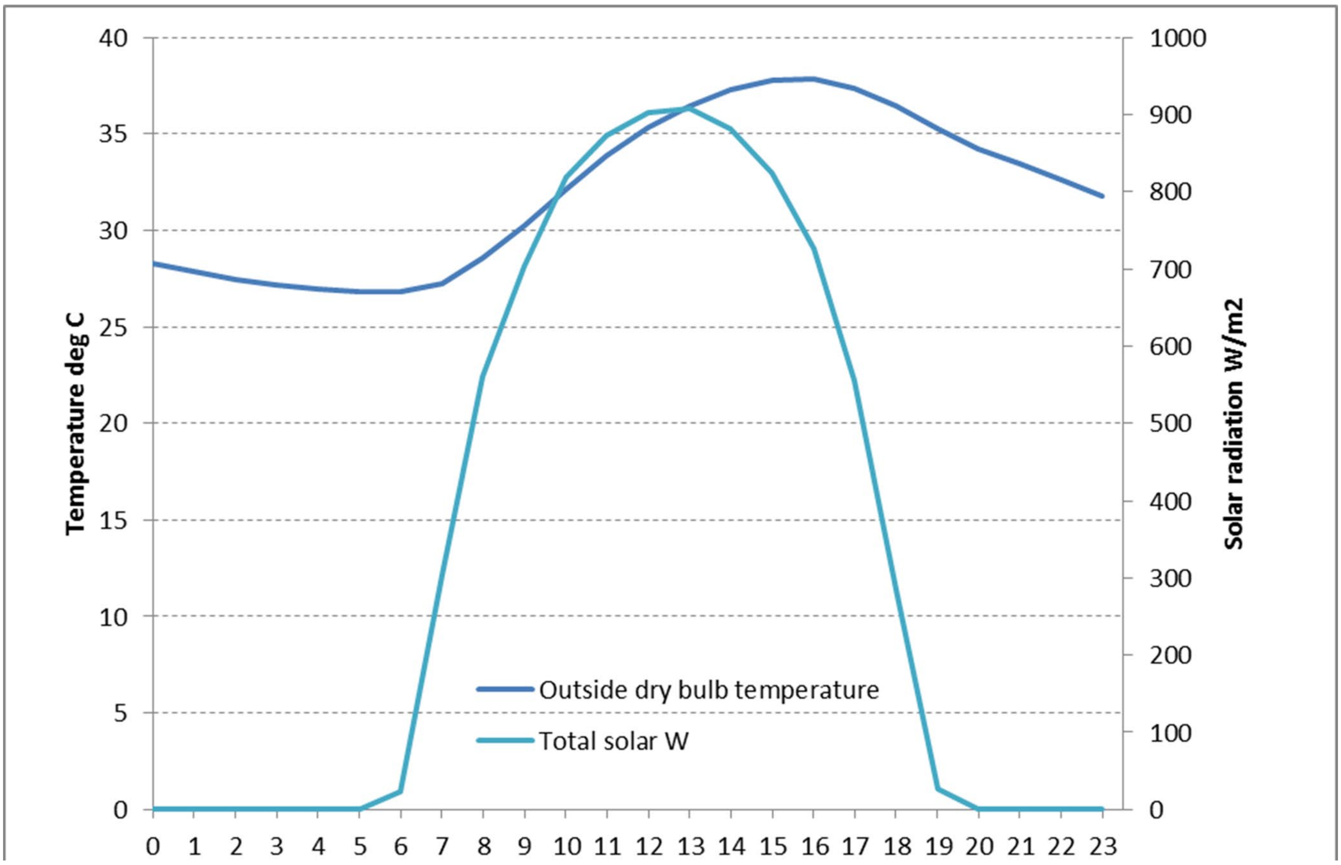


Figure 3 Temperature and solar gain, Chennai, 1st May of weather data

Table 2 Heat gains and air infiltration

Lighting gains	10W/m^2
Equipment gains	3W/m^2
Occupant gains	0.8W/m^2 sensible; 0.4W/m^2 latent
Air infiltration	0.33 air changes per hour

METHODOLOGY

Dynamic thermal simulation software ‘Designbuilder’ was used to build a geometrically precise model of a typical retail shed. Thermo-physical properties of the material are assigned to all construction elements. Internal heat gains, air infiltration and plant set-points are allocated before real recorded hourly weather data is applied and the software is run to assess dynamic performance.

The effect of envelope surface reflectance on thermal performance of buildings depends on various parameters, such as the composition of the wall, the orientation of the building and the attributes of windows. The computer modelling is performed on the basis of different locations (with regard to different climates) and cladding types, to predict the cooling/heating loads and indoor environments throughout the year. The model accommodates complex heating/cooling controls, different ventilation schemes, lighting/internal gains and solar loads as well as different aperture configurations using different functional zones.

Thermal environment and solar radiation control

The building (being active) relies on the use of electrical heating and cooling to maintain the internal environment at thermally comfortable levels. Fig. 4 depicts the interaction between building and environment illustrating typical heat gains and heat transfer pathways. Attention should be given to the cooling load shown in the figure, which should be considered as a heat sink rather than a heat source, but for the sake of easy description, the cooling load is illustrated in a similar way to the heat gain.

Mechanical ventilation refers to a fan-driven ventilation system, which provides fresh air to the rooms in the building and also expels air from the building to satisfy the fresh air requirements defined by hygiene/health standards. Taking into account the direct solar radiation through window panes into the building and their higher U-value compared to the wall, glazing on the front and side elevations has a significant impact on overall thermal behaviour.

Reflective coating

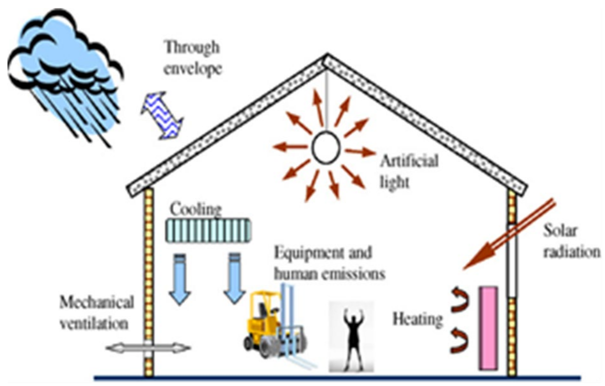


Figure 4 Thermal environment of a building

Reflective coating is the barrier to heat transfer created by the wall/roof surfaces where reflective materials are applied. The factors affecting the performance of a reflective coating can be summarised as follows [17]: (1) the reflectivity of the coating material: the higher value of the reflectivity, the higher the reflective heat (hence the better the 'insulation'); (2) the emissivity of the material; (3) the radiation angle of incidence on the reflective surface (different pitched roof angles); (4) the orientation of the buildings and (5) the direction of heat flow.

Performance estimation

The pre-processed 3-D model of the building is incorporated into a computer model using Designbuilder to transfer the problem into a mathematical description. The thermal performance of the building is therefore analysed throughout the whole year in an hourly dynamic computer simulation.

Theoretically, electricity consumption ε is calculated by the following equation:

$$\varepsilon = \frac{CL}{\eta_{cooling}} + \frac{HL}{\eta_{heating}} \quad (2)$$

where CL and HL are cooling load and heating load, respectively, $\eta_{cooling}$ and $\eta_{heating}$ refer to the cooling and heating efficiency. The performance estimation, commonly based on the electricity consumption, will be carried out in the next section in this paper.

RESULTS AND DISCUSSION

Cooling, heating and total electricity consumption: effect of skin type, reflectance and emissivity

It is very important to estimate the whole-building electricity consumption throughout the year based on heating and cooling requirements, particularly reflecting the energy associated with air-conditioning. Electricity consumption is defined as the

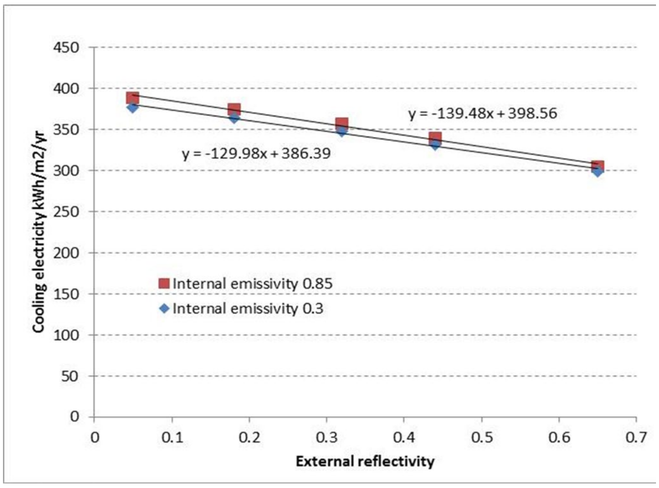


Figure 5 NEW DELHI, annual cooling electricity for the single skin building

summation of cooling and heating load, each divided by their respective efficiencies.

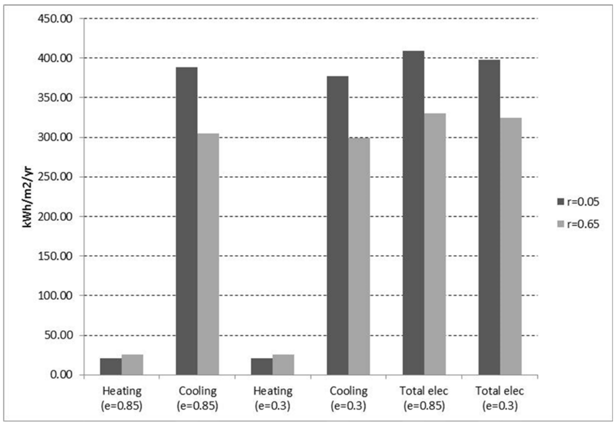


Figure 6 NEW DELHI, Single skin building: Effect of reflectivity and internal emissivity on annual heating and cooling electricity

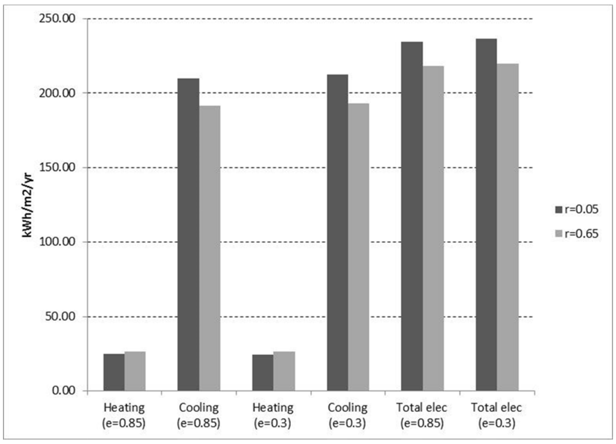


Figure 7 NEW DELHI, lightly insulated building: Effect of reflectivity and internal emissivity on annual heating and cooling electricity

New Delhi is the most northerly climate and, unlike the other two locations, requires some heating for a small part of the year. All results conform to simple straight line graphs of the form y=mx+c, (m=gradient, c = y intercept) for the range of reflectances modelled. As an example, the cooling electricity required for the New Delhi building is shown plotted in Figure 5.

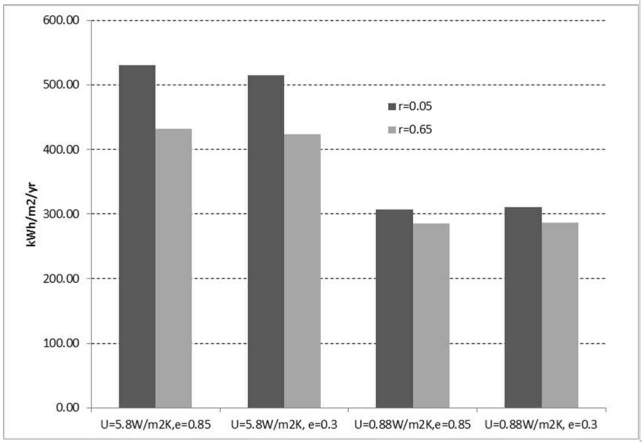
These straight line equations can be used to obtain the air conditioning electricity requirement across the whole range of possible reflectances, enabling a simplified model to be developed if required, in which the parameters modelled can be linked to reflectance for the particular building studied.

As seen in Figure 6, for a single skin building in New Delhi, increasing roof reflectance (r) from 0.05 to 0.65 adds to the heating electricity by about 5kWh/m^2 per year because less solar radiation is absorbed during the heating season. However, the cooling electricity demand is reduced by 84kWh/m^2 per year for an internal emissivity of 0.85 (25% decrease). Reducing emissivity to 0.3 alone has small effect on heating load, but reduces cooling electricity demand 10kWh/m^2 per year (3%). When the small increase in heating energy is taken into account, the total electricity saving for increasing reflectance to 0.65 from 0.05 is 19% (e=0.85) and 18% (for e = 0.3). Adding a low emissivity (e) coating to the inner surface reduces total electricity demand by just under 3% for the same reflectance on the outer surface.

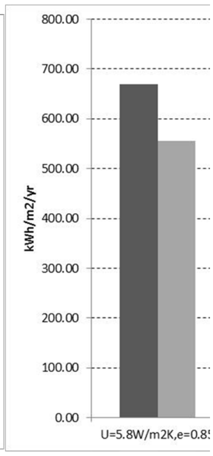
Referring to Figure 7, predictably, an insulated building uses approximately half the electricity to cool than one clad with a single metal skin, although the heating energy is very similar (indicating the beneficial effect of solar gain on single skin buildings in this climate). Again, as solar gain has less effect on internal climate when an insulated skin is used, the effects of high reflectance coating are reduced. Cooling electricity is reduced by high reflectance coatings by 8-9%, leading to an overall saving overall of about 7% once the small heating energy increase is taken into account. In the case of a lightly insulated building, the cooling electricity is little influenced by emissivity, the inner skin temperature being already significantly lower as a result of the insulation.

Both Mumbai and Chennai do not require heating of the building so the total electricity requirement for temperature regulation is associated with cooling only. From Figure 8, it is apparent that the single skin building in Mumbai with a high reflective coating (0.65) used in conjunction with either high or low emissivity inner linings, leads to a reduction in the electricity used for cooling of approximately 17-18% . For Chennai, this figure is 15-17%, although for a higher cooling load so the kWh savings are greater. Small reductions of 2-3% in cooling electricity are predicted when low emissivity coatings are used.

For a lightly insulated building, cooling electricity is reduced by 42% and 39% for Mumbai and Chennai respectively over a single skin building, showing that the single biggest influential factor is fabric insulation. The high reflectance coating has a smaller effect for these buildings, showing a reduction in cooling electricity of around 7% and 8% for Mumbai and Chennai respectively. Once again, low emissivity internal coatings have little effect once insulation is added to the building fabric.

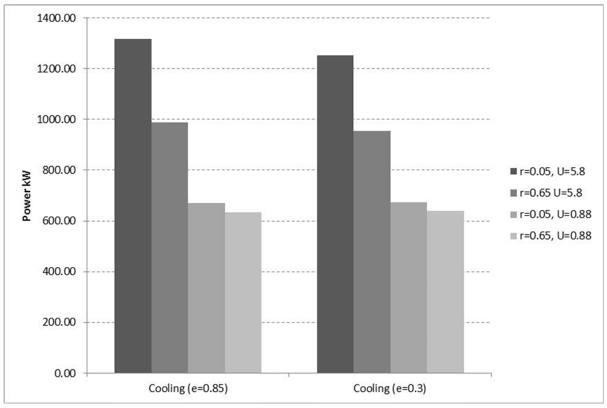


(a) Mumbai

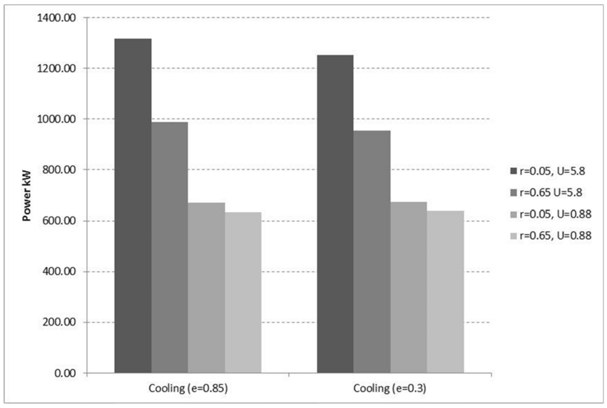


(b) Chennai

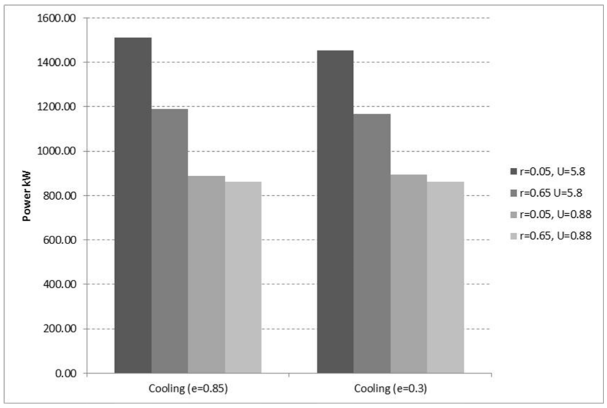
Figure 8 MUMBAI and CHENNAI: Effect of reflectivity and internal emissivity



(a) New Delhi



(b) Mumbai



(c) Chennai

Figure 1 NEW DELHI: effect of reflectance, insulation and emissivity on PEAK cooling power requirement

Effect of reflectance on peak cooling load

Peak cooling load dictates the chiller plant size that must be installed to provide the expected internal temperature conditions within the building all year round. A smaller chiller reduces capital cost, and can run more efficiently throughout the year as it will be at part load for less of the time. Lower peak demand on the electricity infrastructure will create less stress on the system, reducing the chances of demand exceeding supply and inevitable power outages at times of peak demand.

A roof solar reflectance of 0.65 reduces peak cooling power demand by 20-25% for all three of the climates studied when using a single skin cladding. A lightly insulated building will not get such a benefit, with reductions in peak load of 5%, 2%, and 3% for New Delhi, Mumbai and Chennai respectively.

A low emissivity coating has a smaller effect, reducing peak cooling demand by 2-5% for the three climates studied.

Effect of reflectivity on maximum roof temperature

Roof surfaces can achieve very high temperatures in these climates, having implications for excessive thermal expansion, for longevity of coatings, and for urban heat island effects in which temperatures are locally elevated in large conurbations by hot surfaces of buildings and roads. Reducing roof temperatures can contribute to less thermal movement (and less stress on fixings, or buckling of skins), a longer lifespan of coatings and claddings, and crucially, to lower inner city temperatures.

Adding insulation to a roof cladding leads to higher roof surface temperatures as the heat absorbed from solar radiation is not conducted so efficiently to the inside. All three climates show the same trends. The roof temperature data for New Delhi is shown in Figure 9.

Maximum roof temperature is reduced from 76°C to 58°C for single skin construction (standard internal emissivity of 0.85) when the reflectance of the coating is increased from 0.05 to 0.65. Decreasing internal emissivity to 0.3 elevates roof temperature as less heat is radiated to surrounding internal

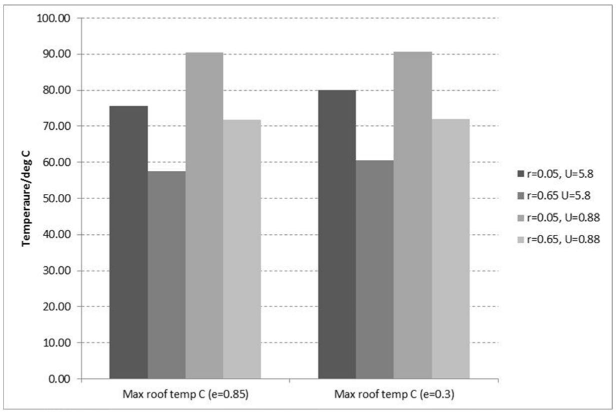


Figure 2 NEW DELHI: effect of reflectivity, insulation and emissivity on MAXIMUM roof surface temperature

surfaces. In this case, the maximum roof temperature for New Delhi rises to 80°C for a reflectance of 0.05, and is reduced to 61°C with the 0.65 reflectance coating.

For double skin sandwich construction, lightly insulated, the maximum roof temperature rises from 76°C for the single skin roof to 91°C (both at 0.05 reflectance), and using a coating of 0.65 reflectance brings this down to 72°C (all at standard internal emissivity). Reducing emissivity in this case increases the maximum external surface temperature very little as the thermal resistance of the cladding is already relatively high.

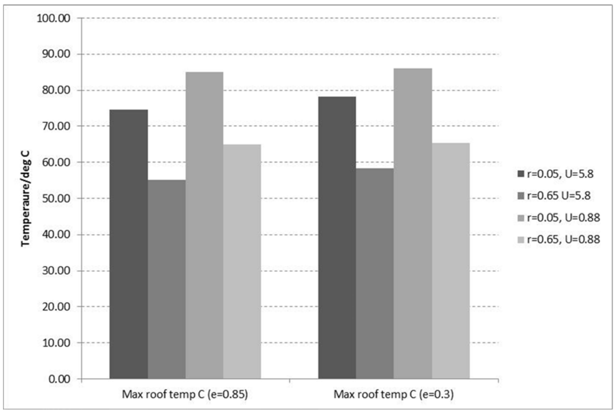


Figure 3 MUMBAI: effect of reflectivity, insulation and emissivity on MAXIMUM roof surface temperature

Similar trends are evident in Figure 10 (Mumbai) and in Figure 11 (Chennai).

In addition to operating cost savings and reduction in risks of power outages, increasing roof reflectance produces large savings in CO_2 emissions. About 65% of the electricity used in India is produced from thermal power stations, the majority burning coal (of which the country has vast reserves). Consequently, the CO_2 intensity of electricity in India (emission factor) is high, at 0.81824 kgCO_2e/ kWh, and the potential savings are also significant.

Table 3 summarises the results discussed above, and also shows the resulting savings in CO_2 emissions for the building modelled.

CONCLUSIONS

Demands to reduce energy consumption and use efficient technology become increasingly urgent due to environmental problems associated with global warming. This paper, focusing on a model retail building, has demonstrated the potential for energy reduction by use of solar reflective coatings on the external walls/roofs. The analyses suggest ways of reducing energy consumption and, importantly for India and similar climates, reducing periods of peak energy consumption where electricity demand for cooling can reach levels where power grids cannot meet demand, and where both generation and distribution capacity may become problematic.

The work suggests that modern coatings with differently engineered solar reflectivity and emissivity have potential to considerably reduce operational energy, particularly associated with use of electrical energy for cooling. They are complementary to conventional approaches to improving building envelope efficiency which involve introducing, or increasing the thickness of insulation materials. Key potential advantages include simplicity, as coatings are required and those analysed represent a straightforward substitution of existing finishes, cost, as the bulk use of the coating analysed is unlikely to significantly increase costs, and there are potential embodied energy benefits as the insulation materials they substitute have high embodied energy ratings. These coatings can fulfil cool roof requirements, as they successfully mitigate urban heat island effects in areas where this is of concern. The analyses strongly support further investigation across climatic zones and building types both within India and in similar climatic areas.

The modelling has also demonstrated how low emissivity (0.3) internal coatings can be used on single skin buildings to make smaller incremental savings in cooling electricity.

the higher of these figures. This translates to a market for metal cladding that already exceeds 200 million m^2 per year.

Whilst this growth in the use of metal roofing and cladding systems is in line with international markets and based on desirable structural and architectural characteristics, in warm climates such as India metal roofing can, depending on the design and specification of systems lead to higher internal building temperatures and increased cooling loads. This is a particular issue in single skin systems where the lack of insulation means that solar radiation can be readily conducted through the sheet and the inside roof surface can transfer heat through radiative and other forms of heat transfer. Warm external roof surfaces also create undesirable heat island effects which can see Indian cities experiencing temperatures circa 10°C higher than surrounding rural regions.

Table 3 Annual ***reduction*** *in total electricity use and CO_2 emissions for heating/cooling when roof reflectance increased from 0.05 to 0.65 for a 2000m^2 retail shed*

	Single skin e=0.85	Single skin e=0.3	Insulated e=0.85	Insulated e=0.3
NEW DELHI				
kWh	158350	146980	32660	34220
KgCO_2e	129568	120265	26724	28000
% reduction	19.3	18.5	7.0	7.2
MUMBAI				
kWh	197040	184000	42000	46000
KgCO_2e	161226	150556	34366	37639
% reduction	18.6	17.9	6.9	7.4
CHENNAI				
kWh	230000	200000	69060	73040
KgCO_2e	188195	163648	56508	59764
% reduction	17.2	15.4	8.4	8.8

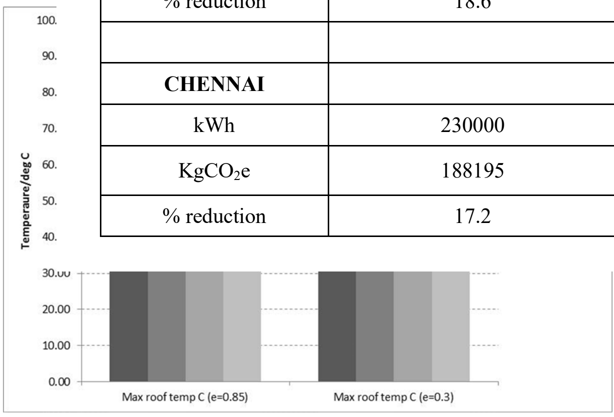


Figure 4 CHENNAI: effect of reflectivity, insulation and emissivity on MAXIMUM roof surface temperature

SIGNIFICANCE OF THE RESEARCH

The use of single layer and insulated metal roofing systems in India is increasing significantly. Until relatively recently markets were dominated by reinforced concrete roof structures, clay tiling and fibre cement sheeting, with market shares believed to be approximately 55%, 18% and 11% respectively although accurate data is difficult to assemble. Metal roofing systems began to achieve market penetration 40 years ago as an alternative to fibre cement. Since then they have gained particular acceptance in developed regions and cities, especially those subject to rapid urbanisation. Whilst the technology is used in many building types, growth has been supported by increased use of pre-engineered steel buildings frames for commercial and industrial applications. Presently the market for steel roof and wall cladding in India is estimated to be between 1 and 2 million tonnes per year, with the most recent estimates verging toward

Excessive use of electrically driven air conditioning systems is also now acknowledged to be a cause of summertime grid issues, where available power generation capacity can be insufficient to reliably meet the increased peak demand.

Given that use of metal roofing systems appears likely to continue to increase in India, the adoption of coating materials which reduce both internal and external cladding temperatures has strong strategic merit. These coatings reduce all three of the key thermal problems: internal temperature and cooling demand, heat island effects and collateral issues relating to power generation and related CO_2 emissions.

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