Impact of material surface properties on building performance across a variety of climates

Georgios Kokogiannakis[1*], **Paul Tuohy**[2] **and Jo Darkwa**[1]
[1]*Centre for Sustainable Energy Technologies (CSET), The University of Nottingham, Ningbo, China;* [2]*Energy Systems Research Unit (ESRU), University of Strathclyde, Glasgow, UK*

Abstract

Reflective coatings have been promoted for improved energy performance of buildings and are considered in some building regulations such as the California Title 24 standard. This paper provides an analysis of the energy impact of different internal and external surface coatings on heating and cooling energy performance across a variety of climates, constructions and building types. The analysis is undertaken with the ESP-r-integrated whole-building simulation program. The results are compared with other studies and conclusions are drawn. The effect of the reflectivity and emissivity of roof surfaces is shown to affect the energy performance of buildings and to vary with the context.

Keywords: reflective coatings; heating and cooling loads; modelling; emissivity and reflectivity

*Corresponding author: georgios.kokogiannakis@nottingham.edu.cn

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1 INTRODUCTION

Roofs are often the surfaces in buildings on which the highest amount of solar radiation per square metre falls over the year. The properties of internal and external roof coatings could impact the way solar radiation is affecting heating and cooling loads in buildings. This has been recognized in some building Standards such as the California Title 24 standard [1] in which there are prescriptive requirements for the reflectance and emittance of roof materials. Reflectance is a property of materials that defines their ability to reflect sunlight while thermal emittance is the property that defines their ability to radiate heat in the form of long-wave radiation. Previous studies have shown that roofs with external coatings of high solar reflectance and high thermal transmittance tend to stay cool in sunny climates [2, 3]. In particular, most of the previous studies were done for hot American climates with long cooling load periods. For example, measurements were taken on daily air-conditioning energy savings and peak power demand reduction from the use of high reflectance roofs on non-residential buildings in several warm-weather climates, including California, Florida and Texas [4]. In most buildings of this study, the roofs had a roof coating with reflectance of ~0.6 and the original reflectance was ~0.25. The measurements for making the comparisons in this study were taken at different periods (i.e. different outdoor climate conditions), but it was found that roofs with high reflectance typically yielded measurable summertime daily air-conditioning savings and peak demand reductions of ~10–30%. Other studies in which measurements were taken for high reflectance coatings in hot American climates have reported similar benefits [5–8]. A more credible comparison could be done with dynamic integrated simulation, instead of measurements, so that the effect of high reflectance external roof coatings on building thermal loads could be assessed against the same outdoor climate conditions. A simplified analytical study of extremely high reflective roof coatings (i.e. reflectance of 0.9) in warm climates could also be found in the literature [9], in which the roof constructions were assessed independent of the building and in which the heat storage of the roof was ignored. In this analytical study, it was found that the high reflective external coatings could drastically reduce the heat flux that reaches the internal part of the roof and also reduce the external surface temperature of the roof. Moreover, a detailed study in which a comparison was done between asphalt external roof coating and a high reflective external coating (reflectance = 0.88) reports the benefits of these coatings during the cooling season of a moderate French climate [10]. This study was done using a simulation model that was calibrated with monitoring data, and it was concluded that high reflective external roof coatings could reduce the external roof temperature, but the effect on actual building's cooling load will be small if the roof is heavily insulated.

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All of the above studies are focusing on external roof coatings. However, limited research has been done on the potential energy savings from the properties of internal roof coatings and most of the previous studies of the energy performance of internal and external roof coatings were done in hot and sunny climates, while the effect of such coatings on heating season has not thoroughly been discussed in the literature.

This paper will investigate the effect of internal and external roof coatings on annual heating and cooling loads for both warm and cold climates. A number of commercial roof coatings are compared by using an integrated modelling tool and a whole-building energy performance analysis is done. Section 2 provides the details of the method used for obtaining the required for the comparisons results.

2 METHODOLOGY

2.1 Simulation tool

In this study, the ESP-r open-source simulation program [11] was used for assessing the energy performance of a building. In ESP-r, the finite-volume approach was used where the model was described by a number of control volumes (or nodes), to which the principles of conservation of energy, mass and momentum can be applied. Buildings modelled using this technique may require the use of many thousands of control volumes to describe its fundamental characteristics: opaque and transparent structure, plant components, fluid volumes, etc. Clarke [12] summarizes this technique that has been implemented in ESP-r and identifies typical control volume (or node) types for this purpose. ESP-r has been the subject of numerous validation studies over the period of almost three decades. A summary of all the main validation studies is given by Strachan *et al.* [13]. This comprises studies included as part of European projects, within several IEA Annexes/Tasks, within national studies and as part of PhD theses.

In particular, for the purposes of this paper, ESP-r is an appropriate tool for comparing internal and external coatings as it accounts for complex indoor and outdoor radiation processes by considering the reflectance and the emittance of materials and by integrating these processes in an energy balance with the rest of the heat transfer processes in the building thermal domain. Clarke [12] provides the details of this method that has been adopted in ESP-r.

2.2 Overview of the building

The model used in this study for the evaluations is a school building, which contains a sports hall, a computer suite and a classroom as well as other zones such as offices and kitchen etc. Each of the different zones can individually be analysed, which provides insight into the effect of the coatings in a variety of situations. Figure 1 shows a 3-D wireframe overview of the building and the different spaces in it. The design is based on a real school, and the roof surfaces are either

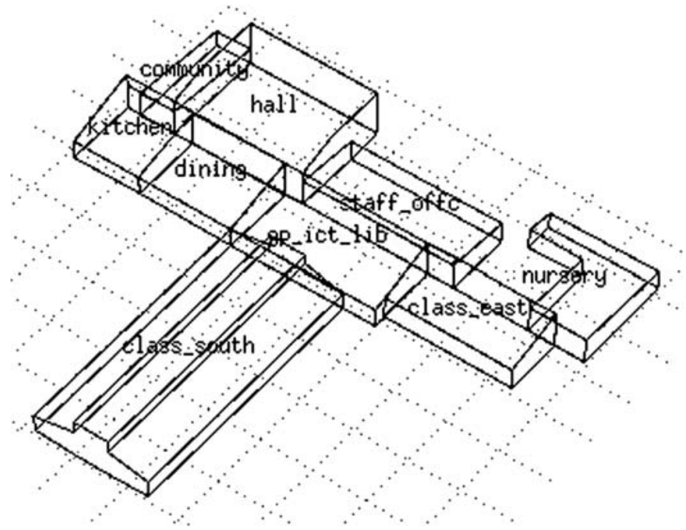

Figure 1. *3-D wireframe overview of the building used in this study.*

horizontal or tilted with a small angle in several directions. In particular, ∼30% of the roof surfaces face south with a tilted angle of $<15^\circ$.

The operational and constructional details of the building were based on UK characteristics (external wall *U*-value of 0.3 W/m^2 K, external double glazing with *U*-value of 2 W/m^2 K and uninsulated concrete slab floors with *U*-value of 1.1 W/m^2 K), but the roof coatings were studied under three different climates and under different roof insulation levels. The following section will briefly introduce the three climates used in the annual simulations.

2.3 Climates

The simulations were run with hourly climate data for the locations of London (UK), Athens (Greece) and Ningbo (China). It should be mentioned here that the climate of Ningbo was derived with the METEONORM software [14] from interpolated data between Hangzhou and Shanghai. The resulted climate involves a certain degree of uncertainty with some of the data to be identical for different periods of the year. However, the climate file of Ningbo is still sufficient for the purposes of the comparisons between the roof surface coatings.

A summary of relevant statistics that are taken out from the three climate files is presented in Table 1 to provide a general idea about the different conditions of the three locations.

2.4 Coating combinations

The roof constructions of the building were modelled with external and internal coating combinations as given in Tables 2 and 3, respectively. All the coatings are commercially available in the market.

Tables 4 and 5 give some of the references that were used to set the values for the standard aluminium external and the

Table 1. *Summary statistics of the three climates.*

Parameter	London, UK	Athens, Greece	Ningbo, China
Latitude and longitude (decimals are per hundred units)	51.5N, 0.4W	37.9N, 23.7E	29.88N, 121.55E
Heating degree days (base temperature = 15.5°C)	1973	719	1351
Cooling degree hours (base temperature = 18°C)	3498.2	26870.2	26216.2
Mean annual ambient dry bulb temperature (°C)	10.9	17.9	16
Mean annual global solar radiation on horizontal roofs (W/m^2)	113	251	179

Table 2. *External coating properties.*

External coating	Reflectance	Emittance
Aluminium sheeting (average value from CIBSE guide A [17])	0.47	0.24
Standard light grey	0.39	0.87
Thermal control light grey	0.62	0.88
Standard dark grey	0.10	0.91
Thermal control dark grey	0.43	0.91

Table 3. *Internal coating properties.*

Internal coating	Reflectance	Emittance
Standard internal (average value from CIBSE guide A [17])	0.6	0.91
Thermal control internal	0.6	0.57

white internal surfaces. It should be noted that aluminium is available in a wide range of finishes and that the mean of the Chartered Institution of Building Services Engineers (CIBSE) range for dull or rough polished was used.

The analysis was initially carried out for seven combinations of internal and external surfaces; each of these combinations incorporated 180 mm of mineral wool insulation having a conductivity of 0.04 W/mK. This initial evaluation was for a typical UK climate.

To investigate further some of the variables, the same model was run but with the roof insulation reduced to 50 mm of mineral wool and also without any roof insulation.

It is worth noting that the 180-mm mineral wool construction gave *U*-value of ~0.21 W/m^2 K, whereas 50 mm of mineral wool construction gave *U*-value of ~0.7 W/m^2 K and the cases without any roof insulation (i.e. using only the coatings and a thin concrete layer for the roof construction) gave a theoretical *U*-value of 6.5 W/m^2 K.

Table 6 shows the different combinations included in this study.

Table 4. *Reference values for aluminium.*

Aluminium reference	Reflectance	Emittance
CIBSE Guide A [17] (dull, rough polish)	0.35–0.6	0.18 - 0.3
CIBSE Guide A [17] (roofing)	–	0.23

Table 5. *References for standard internal coatings.*

Internal surface reference	Reflectance	Emittance
CIBSE guide A [17]: white painted plaster	0.5–0.7	0.91

Table 6. *Coating combinations for modelling.*

Combination	Internal surface	External surface
Case 1	Standard internal	Aluminium
Case 2	Standard internal	Standard light grey
Case 3	Standard internal	Thermal control light grey
Case 4	Standard internal	Standard dark grey
Case 5	Standard internal	Thermal control dark grey
Case 6	Thermal control	Standard dark grey
Case 7	Thermal control	Aluminium

The seven cases mentioned in Table 6 were simulated with two roof insulation thicknesses and without roof insulation in all three climates that were previously mentioned, i.e. a UK climate (London), a typical southern European climate (Athens, Greece) and a subtropical Chinese climate (Ningbo, China).

3 RESULTS AND DISCUSSION

3.1 Coatings and roof insulation levels

In this paper, the results are presented only for the total building but results for individual building components (sports hall, computer suite, classrooms etc.) can easily be extracted from the software as required.

The heating and cooling demands from the London simulations are given in Figure 2, whereas the results for Athens are given in Figure 3. Table 7 provides the overall simulation results for the location of Ningbo.

From the graphs shown in Figures 2–4, it can be seen that the selection of roof coatings is more significant for roof constructions of low insulation levels. The trend in the change in the energy demand of the seven roof constructions is the same for the different insulation levels, but the degree of the change is higher for the roof that does not include an insulation layer.

3.2 Results for London

For the cool climate of London, the lowest heating energy requirement is Case 7 with the standard external aluminium

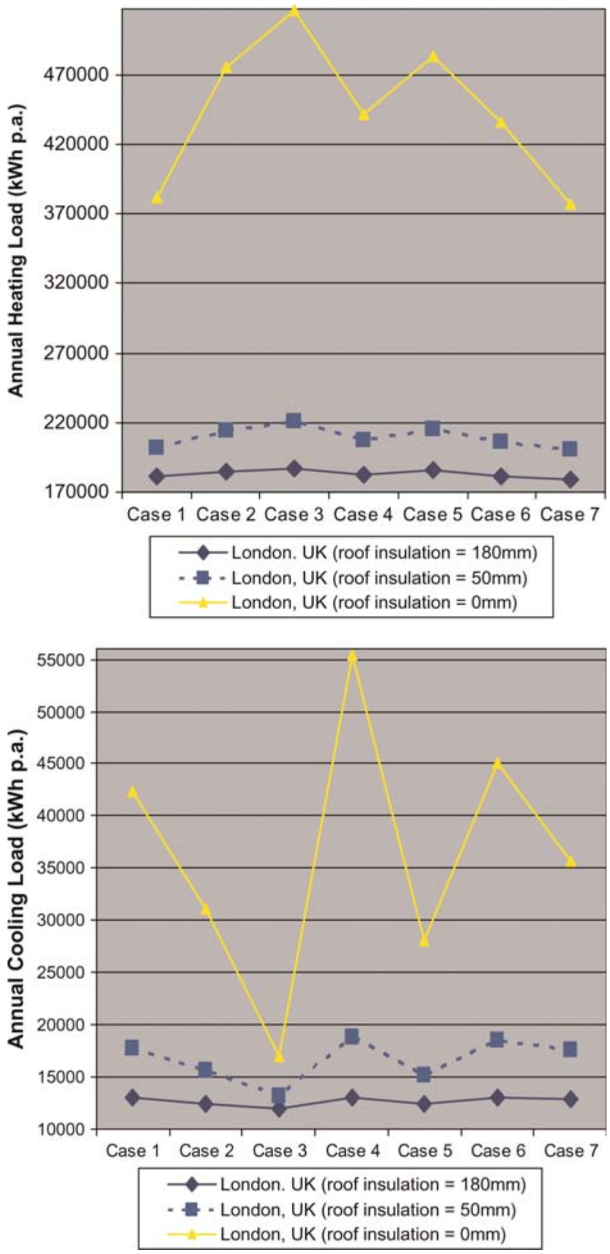

Figure 2. *London climate: annual heating and cooling loads for different roof coatings and insulation levels.*

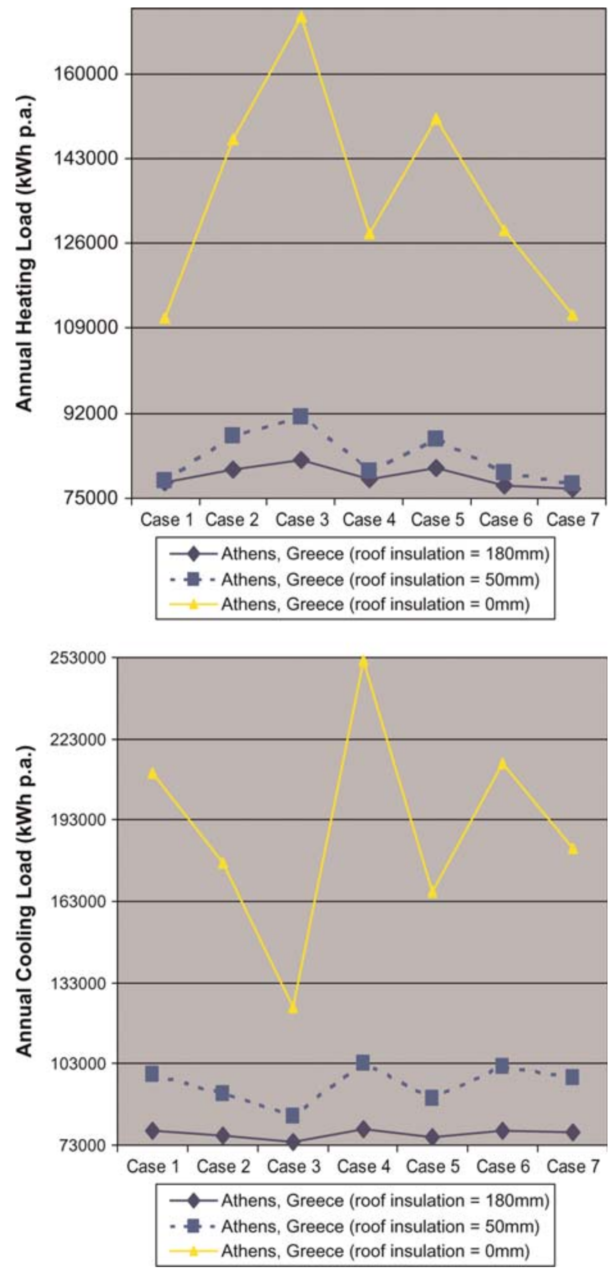

Figure 3. *Athens climate: annual heating and cooling loads for different roof coatings and insulation levels.*

coating and the low emissivity internal thermal control coating. This is due to the low emissivity of the aluminium on the external face reducing the heat loss through radiative exchange with the sky. In this case, emissivity appears to have a larger effect than the solar reflectance. The internal low emissivity coating does also slightly contribute in reducing the heating requirements for such climate (i.e. compare heating results for Case 1 against Case 7). In this case, ~1% improvement over the standard internal surface (Case 1) is due to the reduced radiative loss through the roof. It should be noted here that a roof construction of 180 mm is currently typical for UK climates and the cases of this study with the lower insulation levels are unrealistic for new buildings.

The reflective external coatings reduce the solar gain and lead to higher heating demands, i.e. thermal control light grey (Case 3) has higher heat demand than the standard light grey (Case 2), thermal control dark grey (Case 5) has higher heating demand than the standard dark grey (Case 4).

The level of variation in heating demand is 4.4% between the best (Case 7) and worst (Case 3) combination for the roof that includes 180 mm of insulation.

Table 7. *Simulation results for the roof coatings applied in Ningbo's climate.*

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Annual heating (kWh)							
Ningbo, China (roof insulation = 180 mm)	119 965	123 797	126 380	120 992	124 284	119 488	118 419
Ningbo, China (roof insulation = 50 mm)	126 143	137 780	146 092	129 605	139 279	129 458	125 824
Ningbo, China (NI: roof insulation = 0 mm)	208 445	277 292	316 748	245 363	284 302	244 860	208 752
Annual cooling (kWh)							
Ningbo, China (roof insulation = 180 mm)	61 113	59 567	57 959	61 472	59 268	61 341	61 002
Ningbo, China (roof insulation = 50 mm)	81 116	74 639	67 394	83 799	73 263	82 447	79 898
Ningbo, China (NI: roof insulation = 0 mm)	181 529	153 310	109 922	215 020	144 692	182 631	157 840
Total annual heating + cooling (kWh)							
Ningbo, China (roof insulation = 180 mm)	181 078	183 364	184 339	182 464	183 552	180 829	179 421
Ningbo, China (roof insulation = 50 mm)	207 259	212 419	213 486	213 404	212 542	211 905	205 722
Ningbo, China (NI: roof insulation = 0 mm)	389 974	430 602	426 670	460 383	428 994	427 491	366 592

The cooling demands from the simulations of the London cases are also given in Figure 2. The calculations for cooling assume that the building is mechanically cooled to 24°C during the occupied hours. It should be noted that, in most cases in the UK climate, the appropriate use of solar shading, ventilation and thermal mass and adaptive behaviour can eliminate the need for mechanical cooling.

It can be seen from Figure 2 that, if mechanical cooling is applied, then the reflective external coatings show a large reduction in cooling energy requirement. For example, the thermal control dark grey (Case 5) reduces the cooling load by ~5.5% compared with the standard dark grey (Case 4).

However, for the London climate, the overall demand for heating and cooling (Figure 4) is mainly dominated by the heating demand. The decisions for selecting roof coatings in such climates should therefore be based on the savings with regard to the heating demand.

3.3 Results for Athens

The balance between heating and cooling load is shifted in the warmer climate of Athens as would be expected.

It can be seen from Figures 3 and 4 that the same effects as discussed above for the London climate are also evident for the Athens climate. However, the cases that use 50 mm of roof insulation are more typical for buildings located in Athens than those using 180 mm.

It can be projected that, in climates where the cooling load is greater than the heating load, then the reflective external coatings will become beneficial. This can be noticed from the cooling load results of Case 3 (i.e. reflectance = 0.62).

The low emissivity internal coating shows a consistent benefit of ~1–2% on both heating and cooling energy requirements (i.e. compare Case 7 against Case 1 and Case 6 against Case 4 in Figures 3 and 4) for all the roof constructions that included an insulation layer. This benefit is larger for the uninsulated roof cases.

3.4 Results for Ningbo

The cases for the Ningbo climate demonstrate both high heating and cooling demands. The conclusions drawn previously for the other two climates are confirmed and the tabulated outputs are only therefore displayed in Table 7.

4 RESULTS COMPARED WITH PREVIOUS STUDIES FOR EXTERNAL COATINGS

A limited number of previous studies that assess the benefits of the external coatings exist in the literature. In particular, Petrie *et al.* [15] used the DOE Cool Roof calculator [16] to assess the savings from roof coatings across a range of American climates and insulation thicknesses. The authors drew similar conclusions as those in this paper.

The benefit the external reflective coatings give in terms of cooling loads in the Phoenix, Florida and Texas calculations are similar to the improvements that we see here for the poorer insulation construction in the Athens climate. The benefit of the coating in these situations should be appraised in conjunction with the potential negative impact of the coating on the heating load.

The DOE tool used in the prior studies gives results consistent with this ESP-r investigation.

5 CONCLUSIONS

A dynamic simulation program was used to assess the benefits from the application of different internal and external roof coatings on annual heating and cooling loads for warm and cold climates and under different roof insulation levels.

A number of commercial roof coatings were compared, and the simulations have shown that, in the UK context, the reflective external coatings tend to have a generally negative impact on overall energy consumption. However, they could be

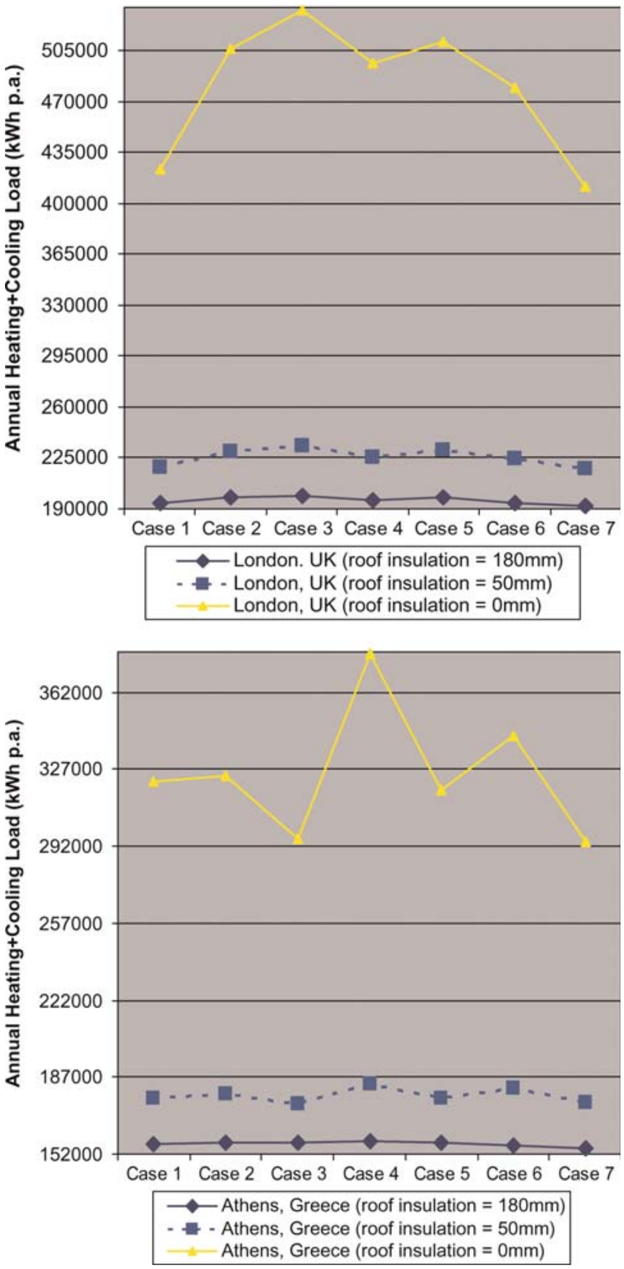

Figure 4. *London and Athens climate: total annual heating + cooling loads for different roof coatings and insulation levels.*

beneficial in climates with higher amounts of solar radiation such as those for the south Mediterranean regions.

The internal low emissivity roof coating does offer ∼1–2% annual energy savings in all climates.

In any case, roof coatings can have a major effect on the energy performance of buildings for roof constructions of low insulation levels.

REFERENCES

[1] California's Energy Efficiency Standards for Residential and Nonresidential Buildings, Title 24, Part 6 of the California Code of Regulations. 2010. http://www.energy.ca.gov/2008publications/CEC-400-2008-001/CEC-400-2008-001-CMF.PDF (26 February 2012, date last accessed).

[2] Levinson R, Akbari H, Konopacki S, *et al*. Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements. *Energy Policy* 2005;**33**:151–70.

[3] Rosenfeld H, Akbari S, Bretz B, *et al*. Mitigation of urban heat islands: materials, utility programs, updates. *Energy Build* 1995;**22**:255–65.

[4] Konopacki S, Gartland L, Akbari H, *et al*. *Demonstration of Energy Savings of Cool Roofs*. LBNL-40673. Lawrence Berkeley National Laboratory, 1998.

[5] Hildebrandt E, Bos W, Moore R. Assessing the impacts of white roofs on building energy loads. *ASHRAE Tech Data Bull* 1998;**14**:28–36.

[6] Konopacki S, Akbari H. *Measured Energy Savings and Demand Reduction from a Reflective Roof Membrane on a Large Retail Store in Austin*. LBNL-47149. Lawrence Berkeley National Laboratory, 2001.

[7] Parker D, Sonne J, Sherwin J. *Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Retail Strip Mall*. FSEC CR-964–97. Florida Solar Energy Center, 1997.

[8] Parker D, Sherwin J, Sonne J. Measured performance of a reflective roofing system in a Florida commercial building. *ASHRAE Tech Data Bull* 1998;**14**:7–12.

[9] Filho J, Henriquez J, Dutra J. Effects of coefficients of solar reflectivity and infrared emissivity on the temperature and heat flux of horizontal flat roofs of artificially conditioned nonresidential buildings. *Energy Build* 2011;**43**:440–5.

[10] Bozonnet E, Doya M, Allard F. Cool roofs impact on building thermal response: a French case study. *Energy Build* 2011;**43**:3006–12.

[11] ESP-r 11.11, 2011. *Building Energy Simulation Program*. University of Strathclyde. http://www.esru.strath.ac.uk (26 February 2012, date last accessed).

[12] Clarke J. *Energy Simulation in Building Design*, 2nd edn. Butterworth-Heinemann. 2001. ISBN 0-750-65082-6.

[13] Strachan P, Kokogiannakis G, Macdonald I. History and development of validation with the ESP-r simulation program. *Build Environ* 2008;**43**:601–9.

[14] METEONORM 6.1. Meteorological Reference Program. METEOTEST. http://www.meteonorm.com (26 February 2012, date last accessed).

[15] Petrie T, Wilkes K, Desjarlais A. Effect of solar radiation control on electricity demand costs—an addition to the DOE Cool Roof calculator, performance of exterior envelopes of whole buildings. In: *IX International Conference*, 2004.

[16] DOE Roof Calculator 1.2. *Calculation Program for Flat Roof Energy Savings*. U.S. Department of Energy's Oak Ridge National Laboratory. http://www.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm (26 February 2012, date last accessed).

[17] CIBSE (Chartered Institution of Building Services Engineers). *CIBSE Guide A: Environmental Design*, 7th edn. 2006. CIBSE Publications. ISBN: 1-903287-66-9.