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

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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 these properties is shown to affect the energy performance of buildings and to vary with the context.

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

1. Introduction

Roofs are often the surfaces in buildings on which the highest amount of solar radiation per m^2 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 recognised 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 their 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, etc.]. 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 about 0.6 and the original reflectance was about 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 high reflectance roofs typically yielded measured summertime daily air-conditioning savings and peak demand reductions of about 10–30%. Other studies for which measurements were taken for high reflectance coatings in hot American climates have reported similar benefits [5, 6, 7, 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 independently 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 by 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.

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 for the energy performance of internal and external roof coatings were done in hot and sunny climates, while their effect of such coatings on heating season has not been discussed thoroughly 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. The next section will provide the details of the method used for obtaining the required for the comparisons results.

2. Methodology

2.1 Simulation Tool

The ESP-r open-source simulation program [11] was used for assessing the energy performance of the building in this study. In ESP-r, the finite volume approach is used where the model is 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] summarises 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 since 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 building model used for the evaluations was based on a school 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 be individually analysed which provides insight into the effect of the coatings in a variety of situations. Fig. 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 horizontal or tilted with a small angle in several directions. In particular, about 30% of the roof surfaces face south with a tilted angle of less than 15^o.

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

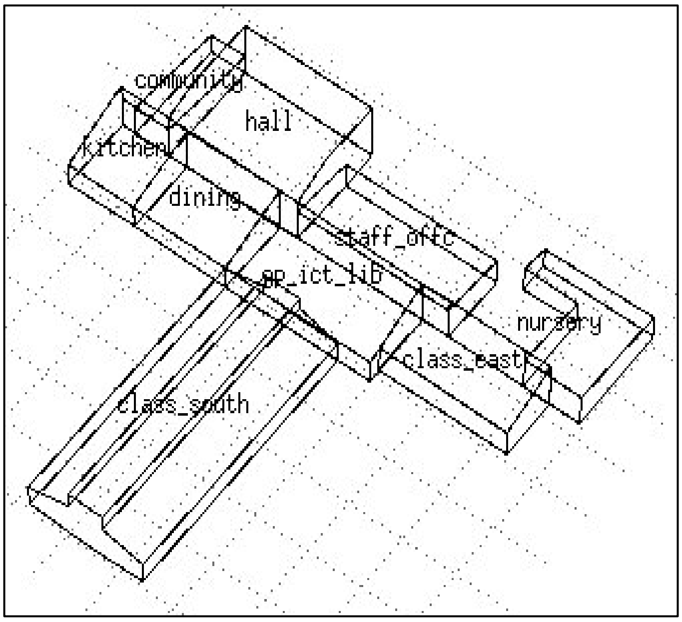

Figure 1. 3-D wireframe overview of the building used in this study

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 in order to provide a general idea for the different conditions of the three locations.

TABLE 1: SUMMARY STATISTICS OF THE THREE CLIMATES

Parameter	London, UK	Athens, Greece	Ningbo, China
Latitude & 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 (W/m^2)	113	251	179

2.4 Coating Combinations

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

TABLE 2: EXTERNAL COATING PROPERTIES

External coating:	Reflectance	Emittance
Aluminium sheeting (Average value from CIBSE guide A [15])	0.47	0.24
Standard Lt Grey	0.39	0.87
Thermal Control Lt Grey	0.62	0.88
Standard Dk Grey	0.10	0.91
Thermal Control Dk Grey	0.43	0.91

TABLE 3: INTERNAL COATING PROPERTIES

Internal coating:	Reflectance	Emittance
Standard Internal (Average value from CIBSE guide A [15])	0.6	0.91
Thermal Control Internal	0.6	0.57

The tables below (Tables 4 and 5) give some of the references that were used to set the values for the standard aluminium external and the white internal surfaces. It should be noted that aluminium comes in a wide range of finishes and that the mean of the CIBSE range for dull or rough polished was used.

TABLE 4: REFERENCE VALUES FOR ALUMINIUM

Aluminium reference:	Reflectance	Emittance
CIBSE Guide A [15] (dull, rough polish)	0.35 – 0.6	0.18 - 0.3
CIBSE Guide A [15] (roofing)	-	0.23

TABLE 5: REFERENCES FOR STANDARD INTERNAL COATINGS

Internal surface reference:	Reflectance	Emittance
CIBSE guide A [15]: white painted plaster.	0.5 – 0.7	0.91

The analysis was initially carried out for 7 combinations of internal and external surface; each of these combinations incorporated 180mm 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 50mm of mineral wool and also without any roof insulation;

It is worth noting that the 180mm mineral wool construction gave U-values around 0.21 W/m^2K, while 50mm of mineral wool construction gave U-values around 0.7 W/m^2K 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^2K.

The following table (Table 6) shows the different combinations that were included in this study.

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

All seven cases of the above table (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 be easily extracted from the software as required.

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

From the graphs shown in Figs 2 to 4 it can be seen that the selection of roof coatings is more significant for roof constructions of low insulation levels. The trend of the change on 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 for Case 7 with the standard external aluminium 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 lost through radiative exchange with the sky. Emissivity appears to have a larger effect than the solar reflectance in this case. 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 the ~1% improvement over the standard internal surface (Case 1) is due to the reduced radiative losses through the roof. It should be noted here that a roof construction of 180mm 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 180mm of insulation.

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

It can be seen from Fig. 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 around 5.5% compared to the Standard Dark Grey (Case 4).

However, for the climate of London the overall demand for heating and cooling (Fig. 4) is mainly dominated by the heating demand. The decisions for selecting roof coatings in such climates should be therefore 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 Figs 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 50mm of roof insulation are more typical for buildings located in Athens than those using 180mm.

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 around 1 to 2% on both heating and cooling energy requirements (i.e. compare case 7 against case 1 and case 6 against case 4 in Figs 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.

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 = 180mm)	119965	123797	126380	120992	124284	119488	118419
Ningbo, China (roof insulation = 50mm)	126143	137780	146092	129605	139279	129458	125824
Ningbo, China (NI: roof insulation = 0mm)	208445	277292	316748	245363	284302	244860	208752
Annual Cooling (kWh)							
Ningbo, China (roof insulation = 180mm)	61113	59567	57959	61472	59268	61341	61002
Ningbo, China (roof insulation = 50mm)	81116	74639	67394	83799	73263	82447	79898
Ningbo, China (NI: roof insulation = 0mm)	181529	153310	109922	215020	144692	182631	157840
Total Annual Heating + Cooling (kWh)							
Ningbo, China (roof insulation = 180mm)	181078	183364	184339	182464	183552	180829	179421
Ningbo, China (roof insulation = 50mm)	207259	212419	213486	213404	212542	211905	205722
Ningbo, China (NI: roof insulation = 0mm)	389974	430602	426670	460383	428994	427491	366592

4. Results compared to 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. [16] used the DOE Cool Roof calculator [17] 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 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 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 about 1 to 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.

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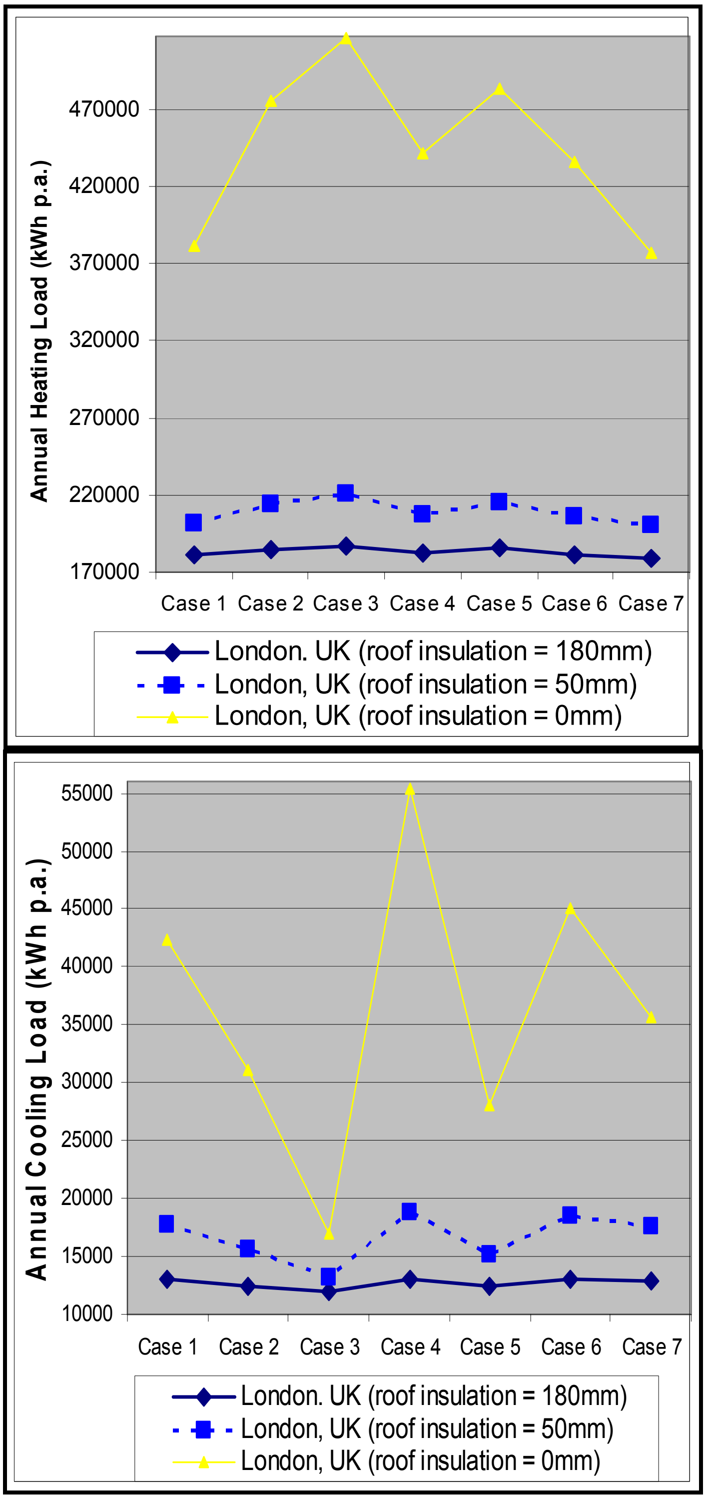

Figure 2. London climate: Annual heating and cooling loads for different roof coatings and insulation levels

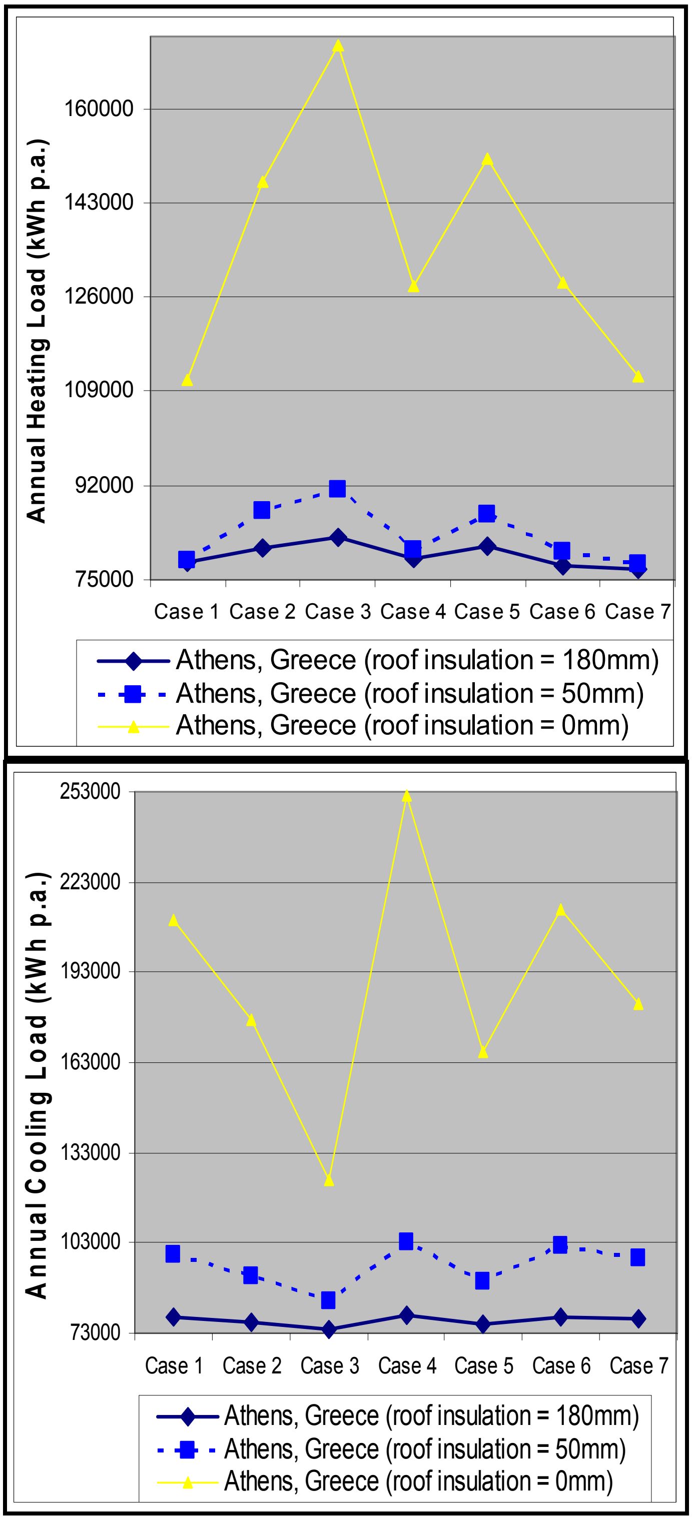

Figure 3. Athens climate: Annual heating and cooling loads for different roof coatings and insulation levels

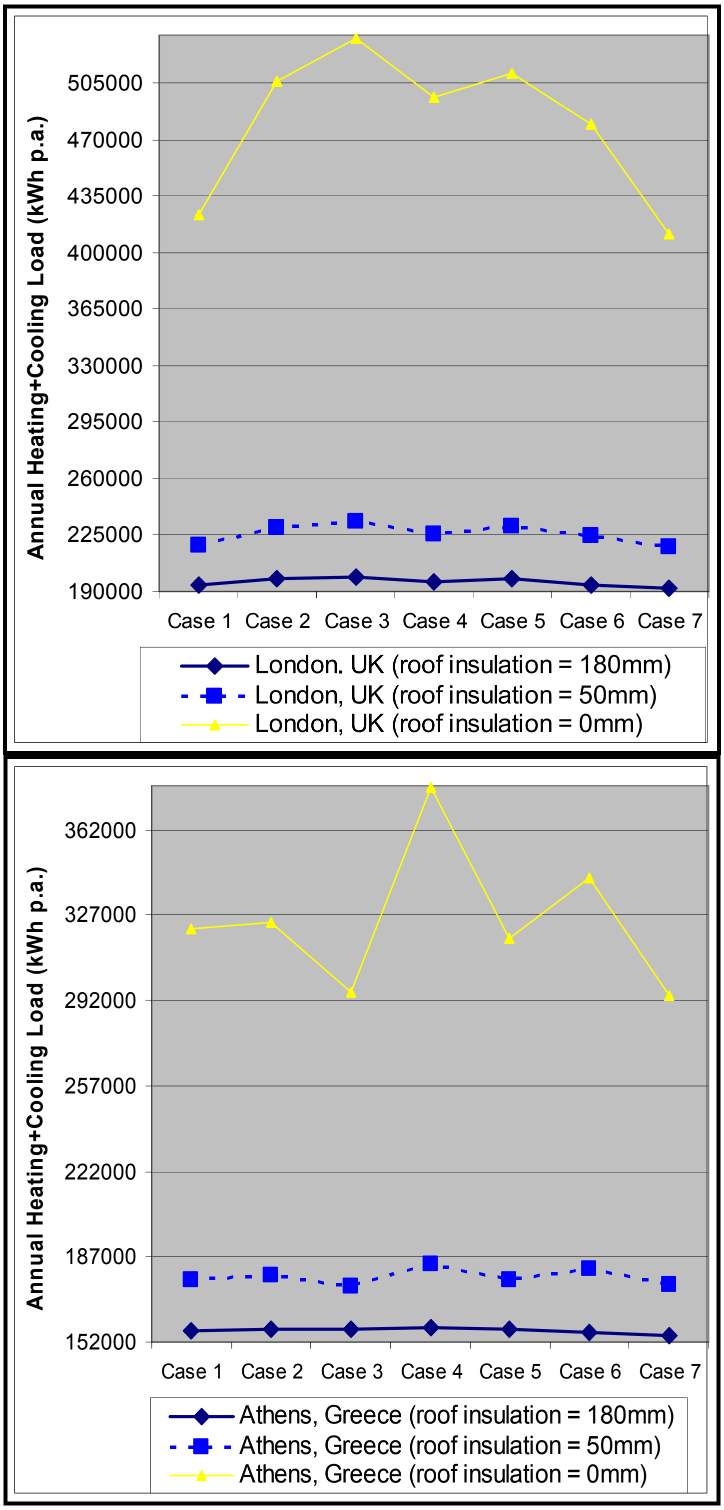

Figure 4. London and Athens climate: Total Annual heating+cooling loads for different roof coatings and insulation levels