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Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions

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Abstract

The impact from using cool roof coatings on the cooling and heating loads and the indoor thermal comfort conditions of residential buildings for various climatic conditions is estimated. The energy cooling loads and peak cooling demands are estimated for different values of roof solar reflectance and roof *U*-value. The results show that increasing the roof solar reflectance reduces cooling loads by 18–93% and peak cooling demand in air-conditioned buildings by 11–27%. The indoor thermal comfort conditions were improved by decreasing the hours of discomfort by 9–100% and the maximum temperatures in non air-conditioned residential buildings by 1.2–3.3 °C. These reductions were found to be more important for poorly or non-insulated buildings. For the locations studied, the heating penalty (0.2–17 kWh/m^2 year) was less important than the cooling load reduction (9–48 kWh/m^2 year). The application of cool roof coatings is an effective, minimal cost and easy to use technique that contributes to the energy efficiency and the thermal comfort of buildings.

Keywords: Roof solar reflectance; Cooling energy savings; Indoor temperature; Roof *U*-value; Passive cooling

1. Introduction

In most countries, energy use in the building sector represents about one third of the total energy consumption. The contribution of building sector electricity use to that of the total electricity use of the country is even higher. In 2003, nearly 60% of total net electricity consumption in the OECD (Organisation for Economic Co-operation and Development) economies was in the building sector both residential and commercial, each representing about half of this electricity consumption [1]. In developing countries the residential building sector accounts for more than half of the electricity consumption [2]. Furthermore, the robust economic growth in many of the non-OECD countries is expected to boost residential demand for electricity, supporting a major transformation in living standards as electric lighting, air-conditioning and other appliances, and new technologies become available to an increasing share of the world's population [3]. Energy consumption for residential cooling shows an increasing trend worldwide and is, therefore, of primary concern not only for countries that are characterized by hot climatic conditions but also for cities suffering from the heat island effect. Urban heat islands with daytime average air temperatures 2–5 °C higher than the surrounding rural areas are present in many cities around the world. In Athens, Greece, according to climatic measurements performed at 30 urban and suburban stations during the summer of 1997, the daily heat island intensity under the canopy was found to be close to 10 °C [4–7]. Apart from the thermal discomfort, heat islands are an energy efficiency concern because increased air temperatures, raise air-conditioning loads in buildings, in turn raising energy consumption, peak electricity demand and energy prices [8–10]. According to the International Energy Administration (IEA 2005), from 1978 to 1997 the electricity use for residential air-conditioning in the US rose from 3.27×10^{17} to 4.43×10^{17} J and nearly 75% of all households had air-conditioners. In the OECD countries, electricity demand for residential space cooling has increased by 13% from 1990 to

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2000 [1]. Furthermore, the total demand for air-conditioners, at an international level, has increased by 6.8% during the period of 1999–2002 [11]. This extensive use of air-conditioning apart from being an energy efficiency concern is also an economic concern. Increasing electricity demand for cooling also increases peak electricity utility loads which forces utilities to burn more fossil, increasing energy costs and pollution levels. In addition, problems with indoor air quality related to the use of air-conditioners are of serious concern [7,8].

To decrease the demand for air-conditioning use, cool materials have gained a lot of interest during the past few years [12–14]. Cool materials are characterized by high solar reflectance (SR) and high thermal emittance values [15]. A number of white or light colored materials are currently commercially available for rooftops having high solar reflectance values ranging from 0.4 to 0.85. The thermal emissivity of these materials was measured to be about 0.9. For peak solar conditions (about 1000 W/m^2), for an insulated surface, and under a low wind condition, the temperature of a black surface with solar reflectance of 0.05 is about 50 °C higher than ambient air temperature. For a white surface with solar reflectance of 0.8, the temperature rise is about 10 °C. Surface temperature measurements demonstrated that a cool coating can reduce a concrete tile's surface temperature by 7.5 °C and it can be 15 °C cooler than a silver grey coating [16,17]. Furthermore, new cool colored materials that are highly reflective in the near infrared, are being developed for the cases where the aesthetics of darker colors is preferred [18,19]. The maximum difference between the solar reflectance of a cool and conventional color matched coating was found to be 0.22 with a corresponding surface temperature difference of 10.2 °C [18]. Another study reports that the solar reflectance of commercially available products has increased to 0.30–0.45 from 0.05–0.25 [19].

Increasing the solar reflectance lowers a surface's temperature since solar radiation is reflected rather than absorbed. In turn this decreases the heat penetrating into the building. During the summer, this results in lower cooling loads if it is an air-conditioned building, or in more comfortable thermal conditions if the building is not air-conditioned. The large-scale use of cool materials in an urban area leads also to indirect energy savings due to the increased solar reflectance that contributes to the reduction of the air temperature because of surface heat balance at the urban level. The indirect benefits arise from this ambient cooling of a city or neighborhood that will in turn decrease the need for air-conditioning [20,21].

Many experiments have been undertaken demonstrating the effectiveness of cool roofs in reducing cooling-energy use in residential buildings. Akbari et al. [22] measured cooling energy savings of about 2.2 kWh/day from changing the roof albedo of a residence in Sacramento, California from 0.18 to 0.73. Reductions in total and peak air-conditioning load of approximately 5% were measured for two identical white ($SR \approx 0.75$) compared to gray ($SR \approx 0.30$) and silver ($SR \approx 0.50$) roofed scale model buildings in Tucson Arizona [23]. In another study [24], the average seasonal electricity savings resulting from application of highly reflective roofs on 11 residences in Florida was found to be 19%. In addition to field studies, computer simulations of cooling energy savings from an increased roof albedo have been documented for residential buildings. A simulation study performed for two mild and hot climates, showed that as the absorbtance varies from 1 to 0, the total energy load decreases by 32% and 47%, respectively for not insulated buildings and by 26% and 32% for insulated buildings [25]. The study concluded that the absorptance of a flat roof has an important effect on heating and cooling loads and the introduction of light colors especially on the roof decreases the total load. A comparative analysis that was conducted for new residential buildings in various cities in the U.S. showed that a residence with a cool roof could utilize a lower level of insulation than one with a dark roof with zero net change in the annual energy bill [26]. A study on the energy efficient envelope design for high-rise apartments in Hong Kong showed that a 30% reduction in solar absorptance can achieve 12% saving in annual required cooling energy [27]. Using cool roofing colored materials it was demonstrated that increasing the roofs reflectance from 0.08 to 0.3 and 0.5 decreases the consumed energy by 15% and 30%, respectively in Miami and Dallas [28] Cheng and Givoni [29] studied the effect of color on indoor temperatures in hot humid climates. They experimented with test cells and reported that for lightweight construction, the maximum air temperature inside the black cell was higher by about 12 °C than that of the white cell. Additionally the air temperature inside the white cell was only 2–3 °C higher than the outdoor.

This study aims to evaluate by means of simulation the potential energy savings and the impact on thermal comfort from the use of cool roof coatings in residential buildings in various climatic conditions worldwide. A parametric analysis is also carried out in order to estimate the impact of solar reflectance and insulation on cooling and heating loads as well as peak cooling loads.

2. Description of methodology

In order to estimate the effect of the use of cool and cool colored materials on the residential energy load, simulations were performed for 27 cities around the world representing different climatic conditions, including Mediterranean, humid continental, subtropical arid, desert conditions, etc. Table 1 gives the latitude and the longitude of the selected cities. TRNSYS thermal simulation software [30] was used for the simulations. The calculations were performed with an hourly time step. The meteorological data were taken from the METEONORM [31] database.

The base case building used in the simulation is a single story, flat roof house with a roof area of 100 m^2. It is non-directional, in the sense that its length and width are equal (10 m). Its height is assumed to be 3 m. Each wall has a glazing of 4 m^2 (13.3% of the wall area), a *U*-value of 5.8 W/m^2 K and it is well shaded (external shading factor 0.7). The *U*-value of the walls was considered to be 2.2 W/m^2 K and the *U*-value of the roof equal to 0.84 W/m^2 K. Infiltration and ventilation rates were both set equal to 0.8 ach. Regarding internal gains, the