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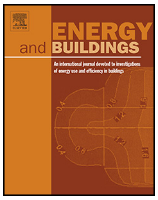

Effect of cool roofs on commercial buildings energy use in cold climates

Mirata Hosseini, Hashem Akbari*

Heat Island Group, Building, Civil, and Environmental Engineering Department, Concordia University, Montreal, Canada

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ABSTRACT

We used DOE-2.1E to simulate energy consumption for several prototype office and retail buildings in four cold-climate cities in North America: Anchorage, Milwaukee, Montreal, and Toronto. To simulate the effect of snow on the roof, we defined a function calculating the daily *U*-value and absorptivity of the roof. Cool roofs for the simulated buildings resulted in annual energy expenditure savings in all cold climates. In Anchorage, the simulated annual heating energy consumptions of the old retail building with a dark versus a cool roof (without snow) are 123.5 and 125.8 GJ/100 m^2, respectively (a 2.3 GJ/100 m^2 penalty for the cool roof). With snow, the heating penalties decreased to 1.2 GJ/100 m^2, leading to an annual energy savings of 7 \$/100 m^2 of roof area. For an old retail building in Montreal and Toronto, a cool roof can save up to 62 \$/100 m^2 and 37 \$/100 m^2, respectively. For a new, medium-sized office building with natural gas heating fuel, a cool roof would save 4 \$/100 m^2 in Montreal, 14 \$/100 m^2 in Milwaukee and Anchorage, and 10 \$/100 m^2 in Toronto. Cool roofs can reduce the peak electric demand of the retail buildings up to 1.9 and 5.4 W/m^2 in Toronto and Montreal, respectively.

1. Introduction

Heat gain through the roof is a major part of the cooling load for a single-story building during the cooling season. When solar radiation reaches an opaque roof, it is either absorbed or reflected. The energy that is absorbed by the roof is either transferred through convection to the air directly above the surface or emitted back to the sky, and the remaining heat is conducted into the building. Any improvement to a roof that limits the summertime solar heat gain will result in energy-cost savings for the building owner, as well as a reduction in the building's overall environmental impact.

A cool roof (high reflectivity and high emissivity) is a roof system that can reflect solar radiation and emit heat, consequently keeping the roof surface cool. A cooler roof surface reduces the cooling load during the summer, thereby reducing cooling costs. On a larger scale, cool roofs can moderate the air temperature surrounding a building, decrease greenhouse gas emissions like CO$_2$, and mitigate the urban heat island effect [1]. Many states in the United States prescribe cool roofs in the construction of new buildings and for re-roofing existing buildings. Akbari and Levinson [2] have summarized the status of cool roof standards in the U.S. and several other countries.

Some recent articles have comments that cool roofs may not work in cold climates, and others have gone so far as to try to promote dark (warm) roofs for cold climates. The concern about the use of a cool roof focuses on the condensation risk and heating energy penalties that can occur in cold regions. In cold climates, because of short summers, the lower surface temperature of cool roofs may increase the risk of condensation and, consequently, moisture accumulation, mold growth, and deterioration of the roof system. For instance, an annotation on the Huffington Post website [3] points out the risk of condensation and mold formation as a result of cool roofing. In addition, Bludau et al. [4] investigated the moisture performance of cool roofs in various climates, using a building hygrothermal performance computer program (WUFI). They applied two criteria to evaluate the moisture behavior of roofs: total moisture content and water content through the roof system. Their results indicate that, in Phoenix, a warm location, both typical and self-drying roofing systems can be used with either black or white surfaces. In Chicago, a temperate location, only white surfaces can be installed on the self-drying roofs, and in Anchorage, a very cold climate, black surfaces were recommended for both roofing systems.

Moghaddaszadeh Ahrab and Akbari [5] conducted a comprehensive study on the hygrothermal behavior of cool roofs in different

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* Corresponding author. Tel.: +1 514 848 2424x3201.
E-mail address: Hashem.Akbari@Concordia.ca (H. Akbari).

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Table 1
ASHRAE climatic data for the studied locations.

City	HDD18	CDD10	Zone
Anchorage	5872	382	7
Montreal	4603	1192	6
Milwaukee	4069	1327	6
Toronto	4059	1317	6

climates. In their study, they considered four different types of roofing systems: typical, smart, self-drying, and smart-vented roofs in both residential and commercial buildings. They found that the prototype office buildings never experienced moisture accumulation problems. However, there were some moisture accumulation problems in residential buildings with typical cool roofs in cold climates, which followed with lower condensation risk by using smart or self-drying cool roofs. Eventually the researchers demonstrated that, with the smart-vented system, cool roofs did not face any moisture accumulation, even in very cold weather like Anchorage. In addition, they showed that snow accumulation on the roof could effectively reduce the risk of condensation and moisture problems for cool roofs in cold climates.

Because of lower solar radiation absorption, cool roofs may increase heating energy consumption. Some recent studies have addressed concerns regarding white roofs' tendency in northern climates to increase average space heating usage more than they decrease average air conditioning usage [6–9].

Using a cool roof in cold climates is typically not suggested based on the presumption that the heating penalties may be higher than the cooling savings. For example, ASHRAE has limited reflective-roof usage to Zones 1–3 [10,11]. Oleson et al. [12] developed a model to estimate the effects of white roofs on urban temperature in a global climate. They stated that, with cool roofing, global space heating increased more than air conditioning decreased, and concluded that end-use energy costs must be considered when evaluating the benefits of white roofs. On the other hand, Konopacki et al. [13], through a simulation study, concluded that for most climate regions that require air conditioning in the summer, having a cool roof decreases the annual energy expenditure. All previous studies have not accounted for the effect of snow on the roof.

The objective of this study is to quantify the heating energy penalties of a cool roof accounting for the effect of roof snow and analysis of energy savings and penalties associated with them for commercial buildings in four cold climate cities of North America namely, Anchorage (AK), Milwaukee (WI), Toronto (ON), and Montreal (QC).

Table 1 categorizes these locations based on ASHRAE climate zone, heating degree days (HDD18), and cooling degree days (CDD10).

2. Cold climates characteristics

There are at least six reasons why the heating penalties associated with cool roofs (particularly low-sloped or flat) may not be as severe as it is commonly thought and why cooling-energy savings in summertime outweigh the winter heating-energy penalties in cold climates. First, during the winter, the solar angle is low making the incident solar energy on a flat roof small and, hence, the solar reflectivity of the roof is less important in winter than summer. Reflectivity and absorption are more critical during the summer, when the solar angle is high and solar radiation is hitting the roof almost normally. Fig. 1 shows the solar intensity in four cold-climate cities of North America: Anchorage (AK), Milwaukee (WI), Montreal (QC), and Toronto (ON). The irradiance in December is much lower than that in July (by as much as a factor of 4, for Anchorage the ratio of summer to winter irradiance is even higher).

Second, the days during winter months are short, so there is less total radiation available on the roof to be absorbed compared to summer. Third, the ratio of cloudy to sunny days increases during the winter, so again, not as much solar energy is striking the roof. Fourth, in most cases, heating resources like natural gas or oil are cheaper than cooling resources such as electricity [1]. Fifth, most heating occurs early morning or late evening, when the sun angle is low (solar radiation on the roof is low). Sixth, in cold climates, a roof covered with snow during the majority of the winter reflects the sun's energy; therefore, it is less important how reflective the roof is.

2.1. Snow properties

As a porous medium with high air content, snow can act as an insulator to protect humans, microorganisms, animals, and plants from wind and severely low temperatures [14]. For instance, Eskimos often used snow to insulate their igloos, which were constructed from whalebone and hides. Outside, temperatures may have been as low as −45 °C, but inside, the temperatures ranged from −7 to 16 °C when warmed by body heat alone.

Thermal conductivity of snow is low compared with that of soil and also varies in density and water content. For dry snow with a density of 100 kg/m^3, the thermal conductivity is about 0.045 W m^{-1} K^{-1} (more than six times less than that for soil) [15]. The thermal insulation of snow is highly dependent on the thickness of snow cover as well as the crystal structure and density of the surface layer. Sturm et al. [16] studied the thermal conductivity of different types of snow. Their study showed that the effective thermal conductivity of snow varies from 0.05 W m^{-1} K^{-1} for low-density fresh snow (density = 100 kg/m^3) to 0.6 W m^{-1} K^{-1} for dense drifted snow (density = 500 kg/m^3).

Snow reflects most shortwave radiation (it has a high albedo compared to soil), absorbs and reemits most long wave radiation [17], and varies during the winter. The albedo of compact, dry, clean, and fresh snow is 0.8–0.9; it drops to 0.5–0.6 for aged, wet, and patchy snow; and it drops further to 0.3–0.4 for porous, dirty snow. A portion of shortwave radiation that is not reflected can penetrate the top 30 cm of snow cover [15].

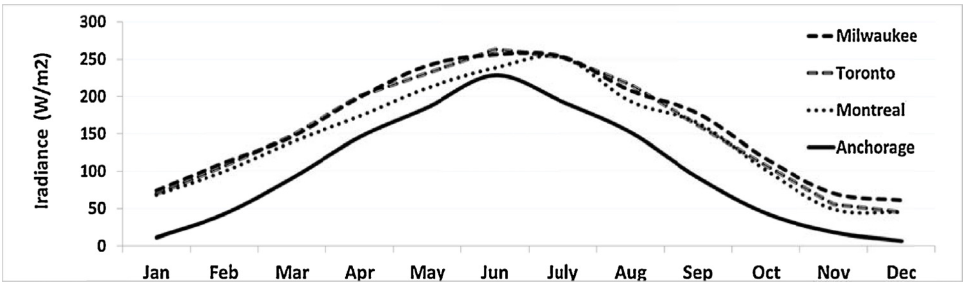

Fig. 1. TMY Irradiance on a horizontal surface in four cold climate cities of North America.