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

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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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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].

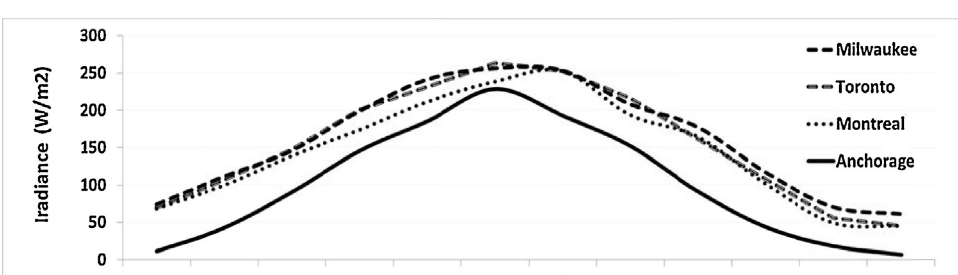

Fig. 1. TMY Irradiance on a horizontal surface in four cold climate cities of North America.

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Table 2
Variable list of heat balance equation on the roof.

Variable	Description
U_{FILM}	The combined radiative and convective outside surface conductance in Btu/(h ft^2 °F)
CLD	Cloud amount in tenths
SKY	Heat loss by roof surface to sky in Btu/(h ft^2)
T_s	Outside roof surface temperature in Rankine
I_{SOL}	Solar radiation incident on outside roof surface from direct, diffuse, and reflected radiation in Btu/(h ft^2)
α	Roof surface absorptivity
T_{DB}	Outside surface temperature in Rankine
U	Conductance of the wall exclusive of the outside air film (includes a combined inside film coefficient in Btu/(h ft^2 °F)
T_{zone}	The constant space temperature in Rankine
Q	Heat flow through the inside roof surface in Btu/h
A	Surface area in ft^2

Note: DOE-2 typically performs the calculations based on imperial units (as it exists in DOE-2 Engineering Manual); however it let the user input based on SI units.

3. Methodology

The methodology in this study is the same as Hosseini and Akbari [18]. A simulation study performed to quantify the effect of roof snow on a building's energy consumption. In the simulations, the original algorithm of the program is modified to account for the effect of snow regarding solar reflectance and thermal conductance. DOE-2.1E is used to perform simulations because its flexibility let the researchers to define algorithms for component energy calculations.

In previous study, it was assumed a constant solar reflectance of 0.2 for snow, whereas it may change depending on the thickness of snow cover, type of snow, and solar reflectance of the roof (as it is discussed later). Also, simulations were conducted just for a small office in previous study [18], whereas the simulations are expanded for other prototypes as well in this study.

3.1. Roof heat transfer governing equations of DOE-2

DOE-2 [19] calculates the heat balance on the outside roof surface using Eq. (1). (Table 2 shows all the parameter description.) Eqs. (1)–(8) all are in imperial units.

$$q_{out} = q_1 + q_2 - q_3 \tag{1}$$

where q_1 is the energy absorbed by the surface from direct solar radiation, diffuse sky radiation, and short wave radiation reflected from the ground; that is

$$q_1 = I_{SOL} * \alpha \tag{2}$$

q_2 is the energy from convective and long wave exchange with the air; that is Eq. (3):

$$q_2 = U_{FILM} * (T_{DB} - T_s) \tag{3}$$

q_3 is the long wave re-radiation. That is, the difference between the long wave radiation incident on the surface, from the sky and the ground, and the radiation emitted by a black body at the outdoor air temperature.

For the roof with no heat capacity, the heat flow at the outside surface must equal the heat flow at the inside surface:

$$q_{in} = q_{out} = U * (T_s - T_{zone}) \tag{4}$$

Here, U is the combined conductance of the roof and inside film. Thus, Eq. (1) can be written:

$$U(T_s - T_{zone}) = (I_{SOL} * \alpha) + U_{FILM}(T_{DB} - T_s) - SKY \tag{5}$$

Table 3
Effective thermal conduction for different snow type.

Type of snow	k_{eff} (W m^{-1} K^{-1})
Very loose new snow	0.0276
Newly fallen dry snow	0.059
Wind-packed snow	0.1259
Late-winter packed snow	0.4412

The long wave re-radiation to the sky is calculated by assuming a clear sky radiation deficit of 63 W/m^2 (20 Btu/(h ft^2)). When the sky is covered by clouds, the assumption is made that no re-radiation occurs; i.e., that the clouds and the surface are at approximately the same temperature. For partial cloud covers, a linear interpolation is made, expressed as,

$$SKY = 2(10 - CLD) \quad (\text{in Btu/(h ft}^2)) \tag{6}$$

Solving for T_s, the outside roof surface temperature yields

$$T_s = \frac{(I_{SOL} * \alpha) + (U_{FILM} * T_{DB}) + (U * T_{zone}) - SKY}{(U + U_{FILM})} \tag{7}$$

Once T_s is known, the total heat flow at the inside surface can be written as Eq. (8):

$$Q = U * A * (T_s - T_{zone}) \tag{8}$$

Eqs. (1)–(8) are solved simultaneously (for each hour) to calculate the heat gain throughout the roof. DOE-2 typically performs the calculations based on imperial units (as it exists in DOE-2 Engineering Manual); however it let the user input based on SI units.

3.2. Effect of snow on roof

The effect of sun angle, clouds, daytime duration, and heating schedules can be modeled with the existing capabilities of DOE-2. Snow on the roof provides an additional layer of insulation and increases the solar reflectance of the roof. To estimate the thicknesses of the snow cover, historical meteorological data provided by the National Oceanic and Atmospheric Administration were used for the two U.S. cities and Environment Canada for the next two Canadian cities (see Figs. 1 and 2 of Hosseini and Akbari [18]).

The thermal conductivity, specific heat, and solar reflectance varies with snow type.

3.2.1. Thermal conductivity of snow

Four types of snow were considered based on density. Gray [20] and Sturm et al. [16] provide data for the thermal conductivity of different snow types, summarized in Table 3.

DOE-2 considers the heat capacity of the exterior wall and roof materials (delayed heat transfer) using complex heat-transfer equations. A less accurate method to model the exterior wall is to define the U-value of the construction. When the construction has little heat capacitance (such as through doors and windows) and the heat flow is not delayed, DOE-2 uses steady-state or quick calculation methods [21]. Since DOE-2 lets the user change only the U-value (not the heat capacitance), U-value of the roof was changed on a daily basis and the roof was modeled as a quick wall rather than a delay wall; therefore, the thermal storage effect of the roof materials and snow is ignored.

To find the overall U-value of the roof considering the snow, the following equation was used:

$$R_{overall} = R_{roof} + R_{snow} \tag{9}$$

where $R_{overall}$ the overall thermal resistance of the roof, R_{roof} thermal resistance of the roof including inside film resistance (but not

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Table 4
Common prototype office and retail buildings characteristics.

Characteristic	Old vintage	Old vintage new HVAC	New vintage
Construction			
Floor materials	0.20 m (8″) heavy concrete slab-on-grade		
Roof *U*-value (W/m^2 K)	0.35		0.27, Mo and To 0.18
Wall *U*-value (W/m^2 K)	0.845, An 0.788		0.289, Mo and To 0.244
Window characteristics			
Number of panes	2	2	2
Shading coefficient	0.47		0.44, An 0.51
Glass *U*-value (W/m^2 K)	2.96		2.25, An 2.02, Mo and To 1.969
Interior loads			
Occupancy (m^2/person)	18.5		16.5
Interior lights (W/m^2)	19.3		10.7, Mo and To 9.6
Miscellaneous (W/m^2)	8		6.7
HVAC System 1	Variable air volume		
Office schedule	7 am–10 pm weekdays, 7 am–6 pm Saturday; Jan 1–Dec 31		
Ventilation	Supply		
Capacity	Zonal/local		
Efficiency	0.58	0.61	
Economizer	Temperature		
Economizer limit temperature (°C)	28		
Outside air (m^3/h/person)	36		
Natural ventilation	No		
Cooling type	Air-cooled hermetic reciprocating chiller		
Capacity	Zonal/local		
COP	5.12	6.09	
Setpoint (°C)	24		
Setup (°C)	30		26.7
Heating type	Natural gas hot water boiler		
Capacity	Zonal/local		
Efficiency (%)	76	80	
Setpoint (°C)	21		
Setup (°C)	15.6		
HVAC System 2	Packaged single zone		
Cooling type	Direct-expansion		
Capacity	Zonal/local		
COP	See Deru et al. [24]	ASHRAE 90.1	
Heating type	Gas furnace		
Capacity	Zonal/local		
Efficiency (%)	78	80	
HVAC System 3	Packaged terminal air conditioner		
Cooling type	Direct-expansion		
Capacity	Zonal/local		
COP	See Deru et al. [24]	ASHRAE 90.1	
Heating type	Heat pump		
Capacity	Zonal/local		
COP	See Deru et al. [24]	ASHRAE 90.1	

Note 1: Most building and systems characteristics for old vintage (with Old and New HVAC) are the same, only changes are shown.
Note 2: Most characteristics in all the locations are the same except those with An indicating just for Anchorage, Mi just for Milwaukee, and those with Mo and To indicating just for Montreal and Toronto.

outside film resistance), R_{snow} thermal resistance of snow. From the previous equation:

$$\frac{1}{U_{overall}} = \frac{1}{U_{roof}} + \frac{1}{U_{snow}} \tag{10}$$

$$U_{snow} = \frac{k_{eff}}{l} \tag{11}$$

where k_{eff} thermal conductivity of snow from Table 3, and l is daily thickness of snow (Fig. 2 of Hosseini and Akbari [18]).

Thus, depending on the type and the thickness of snow a particular $U_{overall}$ for each day was calculated.

3.2.2. Solar reflectivity of snow

Snow on the roof also changes its solar reflectivity. The part of the solar shortwave radiation that is not reflected can penetrate the top 30 cm of snow depth; therefore, the solar reflectivity of snow changes depending on the type (density) and the depth of the snow as well as the solar reflectivity of the roof surface. SNICAR [22], an online snow solar reflectivity calculator provided by the University of Michigan, was used to calculate the daily solar reflectivity of snow on the roof. Different types of snow with different snow thicknesses were applied: one for a cool roof and one for a dark roof. Solar reflectance of 0.6 and 0.15 were assumed for the cool and dark roofs, respectively. Fig. 2 shows the calculated solar reflectance based on snow type, snow thickness and, under-laying roof (cool or dark), using SNICAR.

As long as snow exists on the roof, thermal insulation and solar reflectance of the roof change daily.

For simulating the effect of snow using DOE-2, a function consisting of the *U*-value and absorptivity of the roof on a daily basis is defined to simulate four different types of snow on the roof. Fig. 3 shows the snow-modeling process flowchart. First, the average snow thickness was calculated in a spreadsheet file. Then, for each snowy day, solar reflectance was calculated using SNICAR, based on snow density, roof solar reflectance, and thickness of the snow layer.

The *U*-value of the snow was calculated based on snow thickness and thermal conductance. Then, the overall roof *U*-value was calculated by combining the *U*-value of the snow with the *U*-value of the roof. We then used the calculated roof *U*-value and solar reflectance

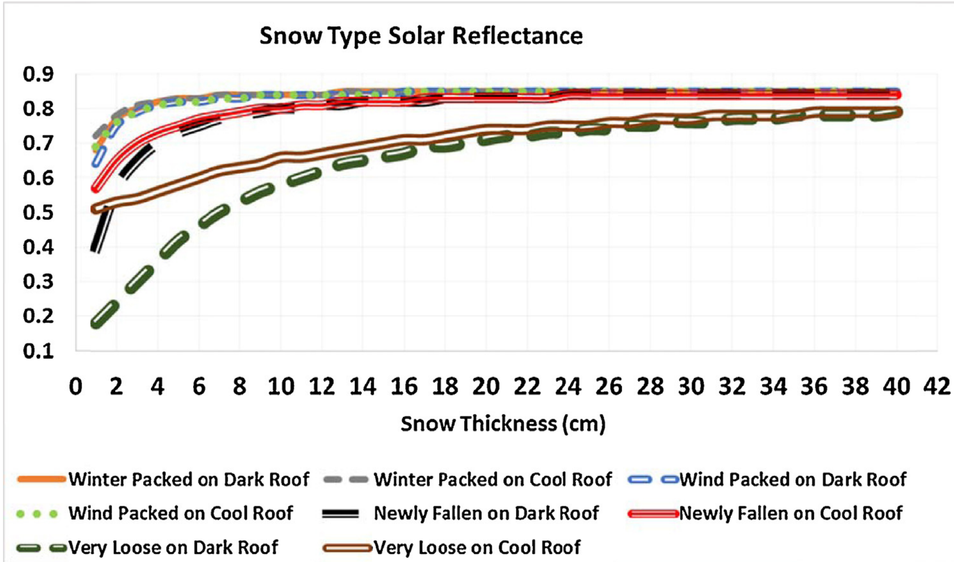

Fig. 2. Various snow type solar reflectance with respect to snow thickness and the type of roof.

to modify the roof properties in DOE-2 using the function option in DOE-2.1E. Once the function file was prepared, it was used for the building simulation.

4. Prototypical building characteristics

A small single story (511 m^2), a medium three story (4985 m^2), a large three story (14,515 m^2) office and a medium single story retail store (2299 m^2) were studied as prototype buildings with flat roofs (prototypes are available at DOE website [23]). The new small office prototype offered by DOE is modeled with slope roof; however, in this study the new small office is modeled with flat roof. In addition, for the large office building, the same medium office was enlarged because the large office prototype on the aforementioned website was a thirteen-story building and the roof has inconsiderable portion of heat transfer compared to the entire building's heat transfer.

Three vintages were considered for each building: old construction with old HVAC systems (pre-1980), old construction with new HVAC systems, and new construction with new HVAC systems. The prototype data for each old construction site was obtained from an NREL technical report [24]. For new construction, ASHRAE standard 90.1 [10] are used for Anchorage and Milwaukee. Data from the National Energy Code of Canada was used for Buildings [25] with new constructions in Montreal and Toronto.

The four cold climate-North American cities have some number of cooling degree days and air conditioning systems are mostly used in commercial buildings (see Table 1). Each of the office prototypes consists of six zones for each floor (four perimeters, one central, and a plenum zone) except for the old small office in which the plenum zone is eliminated. The retail building has five zones (core, front, back space, point of sale, and entry) and no plenum. Each prototype is simulated once with gas heating and electric cooling (using variable air volume for large offices and packaged single zone for

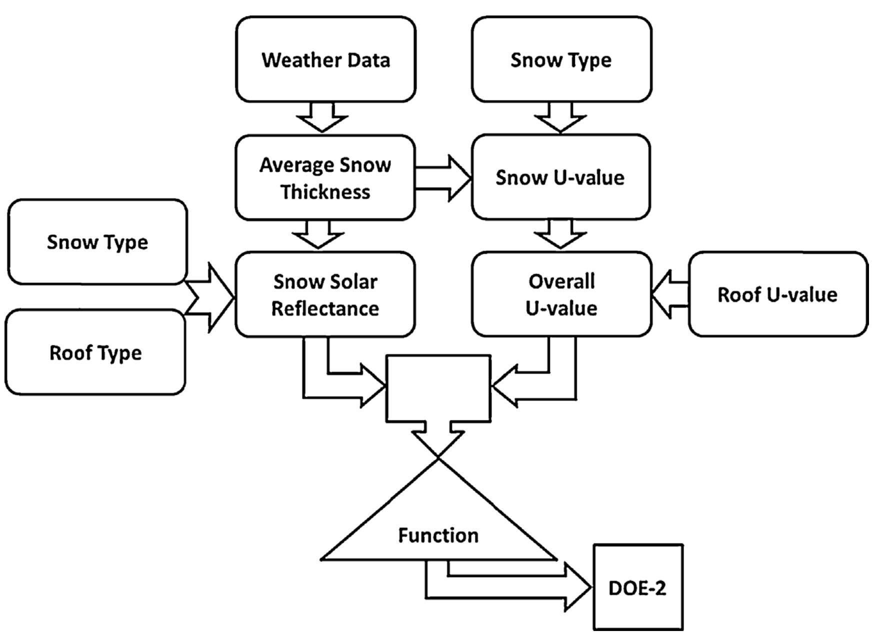

Fig. 3. Snow modeling process flowchart.

Table 5
Specific prototype characteristics for office and retail buildings.

Characteristic	Old vintage	Old vintage new HVAC	New vintage
Medium office wall *U*-value (W/m^2 K)	–		An 0.346, Mi 0.346
Large office wall *U*-value (W/m^2 K)	0.822, An 0.771	–	–
Retail store			
Construction			
Wall *U*-value (W/m^2 K)	0.817, An 0.771		Mi 0.45, An 0.4, Mo and To 0.244
Interior loads			
Occupancy (m^2/person)	6.1, back space 27.8		6.1
Interior lights (W/m^2)	36.1, back space 12.4		18.2, back space 8.6, Mo and To 15
Miscellaneous (W/m^2)	Core and front 3.2, point of sale 21.5, back space 8		
Schedule	7 am–8 pm weekdays, 7 am–10 pm Saturday, 8 am–6 pm Sunday; Jan 1–Dec 31		

Note 1: Most building and systems characteristics for old vintage (with old and new HVAC) are the same, only changes are shown.
Note 2: Most characteristics in all the locations are the same except those with An indicating just for Anchorage, Mi just for Milwaukee, and those with Mo and To indicating just for Montreal and Toronto.

others) and once with all-electric HVAC (using packaged terminal air conditioner with heat pump for heating) systems.

For the retail building with a gas heating system, the entry zone is heated by an electric unit heater in the old construction and a furnace unit heater in the new construction.

For medium office building with old construction, fifteen systems serve the fifteen zones whereas, in the new construction there are only 3 systems serving the zones (the core zones as the main control zones and the perimeters as subzones). Core zones are heated by gas furnace and perimeters are heated by electric reheat coils. Tables 4 and 5 summarize the prototypes' characteristics and operation schedules in each location (for details see Hosseini [26]). Note that the shape and geometry of the old and new constructions are the same; however, the building envelope characteristics and the HVAC systems are different.

4.1. Validation of prototype buildings

Calibrated and validated prototype models are available from DOE across all U.S. climate zones, prepared for EnergyPlus simulations [27]. EnergyPlus is the model that the U.S. Department of Energy supports; it is the next-generation building simulation tool, and many of its algorithms are the same as DOE-2. To simulate the effect of snow on the roof, we used DOE-2.1E, which allows user-introduced functions that can simulate the effect of snow. Hence, to validate our DOE-2 protope input model, we simulated the same prototype with EnergyPlus and DOE-2 and compared the results. Because of some differences in the EnergyPlus and DOE-2.1E calculations, the DOE-2.1E results are not exactly the same as the EnergyPlus results but still acceptable with less than 5% difference [26]. Once we made sure that our DOE-2 model was calibrated with the EnergyPlus model, we modified the building characteristics as outlined in our prototype building description to simulate the heating- and cooling-energy usage of the prototype buildings in the four climate regions of interest.

5. Results

We used the following criteria to evaluate the effect of cool roofs on building: annual energy consumption, overall building energy expenditure, peak demand, and HVAC system size.

5.1. Building overall energy expenditure

Prototypes are simulated once with dark roof and white roof without considering the effect of snow (regular DOE-2 run). Then, different types of snow are considered by defining a specific function for each run and simulations were repeated (separate functions

Table 6
Electricity prices for all prototypes and utilities rate schedules for demand charges.

Location	Electricity energy rate ($/kWh)	Electricity demand rate ($/kW)
a. All prototypes (except small office)		
Anchorage	0.096274 [28]	16.96 [28]
Milwaukee	0.08419 [31]	13.385 [31]
Montreal	0.0471 [33]	14.7 [33]
Toronto	0.101 [34]	1.9253 [34]
b. Small office with gas-heating HVAC system		
Anchorage	0.151124 [28]	0 [28]
Milwaukee	0.13945 [29]	0 [29]
Montreal	0.0938 [32]	0 [32]
Toronto	0.101 [34]	0 [34]
c. Small office with all-electric HVAC system		
Anchorage	0.096274 [28]	16.96 [28]
Milwaukee old building	0.12421 [30]	6.761 [30]
Milwaukee new building	0.139 [29]	0 [29]
Montreal	0.0471 [33]	14.07 [33]
Toronto	0.101 [34]	1.9253 [34]
d. Terms of demand charge		
Anchorage	Monthly peak demand exceeds 20 kW for three consecutive months	
Milwaukee	Monthly electricity energy exceeds 10,000 kWh	
Montreal	Monthly peak demand exceeds 50 kW at least once a year	
Toronto	Monthly peak demand exceeds 50 kW	

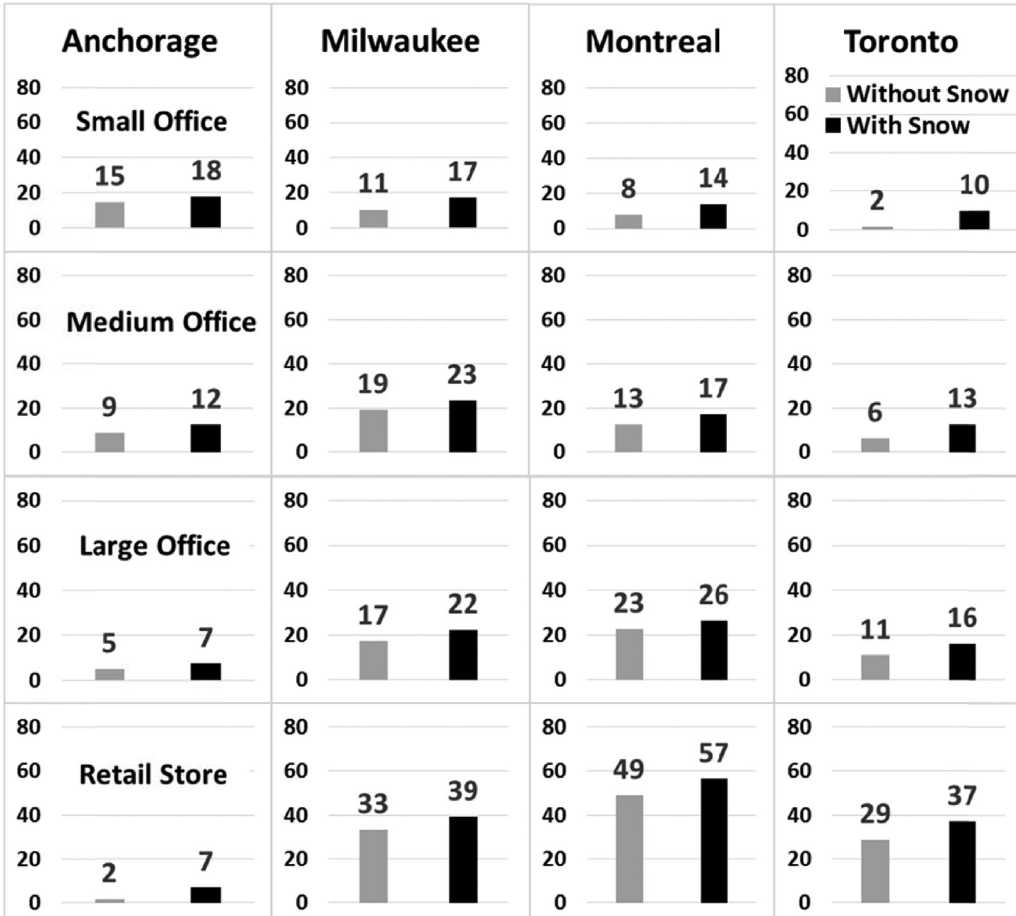

Fig. 4. Annual savings ($/100 m^2) of cool roofs with and without the effect of snow for the old buildings with gas-heating HVAC systems.

for dark or white and deferent snow type). The simulations were carried out once with gas-heating and electricity-cooling systems and once with all electric heat pump systems. Among gas-heating systems, for new medium office only core zone is heated by gas and the other zones are heated by electricity (reheat electric coils). In calculating the overall expenditure, electricity and natural gas expenditures are calculated separately then summed and presented as one number.

Overall expenditure is calculated based on the local electricity and natural gas rates as it is shown in Tables 6 and 7. The overall electricity expenditure is calculated considering the demand charge as Eqs. (13)–(15):

$$\text{Electricity expenditure} = \text{monthly electricity energy cost} + \text{monthly demand charge} \quad (12)$$

where electricity expenditure ($).

$$\text{Monthly electricity energy cost} = \text{monthly consumption (kWh)} * \text{energy rate (\$/kWh)} \quad (13)$$

Table 7
Natural gas prices.

Location	Natural gas price ($/GJ)
Anchorage	4.12 [35]
Milwaukee	6.89 [36]
Montreal	4.59 [37]
Toronto	8.43 [38]

$$\text{Monthly demand charge} = \text{monthly peak demand (kW)} * \text{peak demand rate (\$/kW)} \quad (14)$$

According to utilities' electricity rates and tariffs, all prototypes except small offices have demand charges (Table 6(a)). However for the small office prototype with gas-heating HVAC system, demand charges are not taken into account because for these prototypes either monthly electricity consumption or monthly peak electricity demand is under the base rate limit (Table 6(b)). On the contrary, most small office buildings with all-electric HVAC systems exceed the base rate limit, hence, for these prototypes demand charges are considered as well (Table 6(c)). Utility demand charge rates schedule are shown in Table 6(d).

Table 8 shows the heating, cooling, ventilation energy, and the overall expenditure normalized per 100 m^2 of the roof area for the small office in Anchorage. For complete results on heating, cooling, ventilation energy, and the overall expenditure for all the prototypes in all the locations see Tables 5-7 to 5-38 of Hosseini [26]. Note that the overall expenditure is the entire building energy expenditure including air-conditioning, lighting, and equipment. Also note that the numbers in the tables are rounded, hence, there might be ±1 discrepancy in savings.

Table 8 shows that in Anchorage for small office with gas-heating system, the heating penalty of cool roof reduced by 1 GJ/100 m^2 when snow is taken into account. Figs. 4–7 summarize the savings of cool roofs (normalized per 100 m^2) for the

Table 8
Annual heating, cooling, ventilation energy use and energy expenditure for the small office prototype with gas-heating system in Anchorage.

Case	Gas heating (heating in GJ/100 m², cooling in kWh/100 m²)														
	No snow on roof			LWP snow on roof			WP snow on roof			NFD snow on roof			VLN snow on roof		
	D	W	S	D	W	S	D	W	S	D	W	S	D	W	S
Old construction with old systems															
Heating energy	82	85	−2	82	83	−1	80	81	−1	78	79	−1	75	77	−1
Cooling energy	385	287	98	379	282	97	370	273	97	364	267	96	358	262	96
Ventilation energy	4456	4459	−2	4342	4342	0	4189	4189	0	4087	4087	0	4006	4006	0
Expenditure ($)	2497	2482	15	2478	2461	18	2452	2434	18	2432	2415	17	1091	1083	8
Old construction with new systems															
Heating energy	81	83	−2	81	82	−1	78	79	−1	76	77	−1	74	75	−1
Cooling energy	330	246	84	324	241	83	317	234	83	311	229	82	306	224	82
Ventilation energy	4450	4453	−3	4336	4336	0	4184	4184	0	4081	4081	0	4001	4001	0
Expenditure ($)	2470	2460	10	2451	2437	14	2425	2411	14	2406	2392	14	1070	1065	5
New construction with new systems															
Heating energy	37	38	−1	37	37	0	34	35	0	32	33	0	30	31	0
Cooling energy	385	317	67	383	317	66	383	317	66	384	318	66	385	318	67
Ventilation energy	1198	1201	−3	1195	1196	0	1182	1183	−1	1172	1173	−1	1162	1163	−1
Expenditure ($)	979	976	3	977	972	6	967	962	5	958	953	5	949	944	5

Notes: D, W, and S indicate dark roof, white (cool) roof, and savings, respectively. (−) shows penalty. LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow, respectively.

prototypes with gas-heating systems with and without considering the effect of late winter packed snow (see [26] for all type of snow).

In Anchorage for old small office with gas-heating system, snow increased the annual overall expenditure savings of cool roof from 15 to 18 $/100 m². For a small office with all-electric system in Montreal cool roof increased annual energy expenditure by 23 $/100 m² when simulated without the effect of snow on the roof. When the effect of roof snow is considered, this penalty changed to saving of 12 $/100 m² (35 $/100 m² difference for the effect of snow).

For the retail store building with gas-heating system cool roof never experienced any penalty in overall expenditure. For the new construction, cool roof saved up to 61 $/100 m² in Anchorage (Fig. 5).

For medium office with all-electric system in Anchorage, the penalty of cool roof was 20 $/100 m² without considering the roof

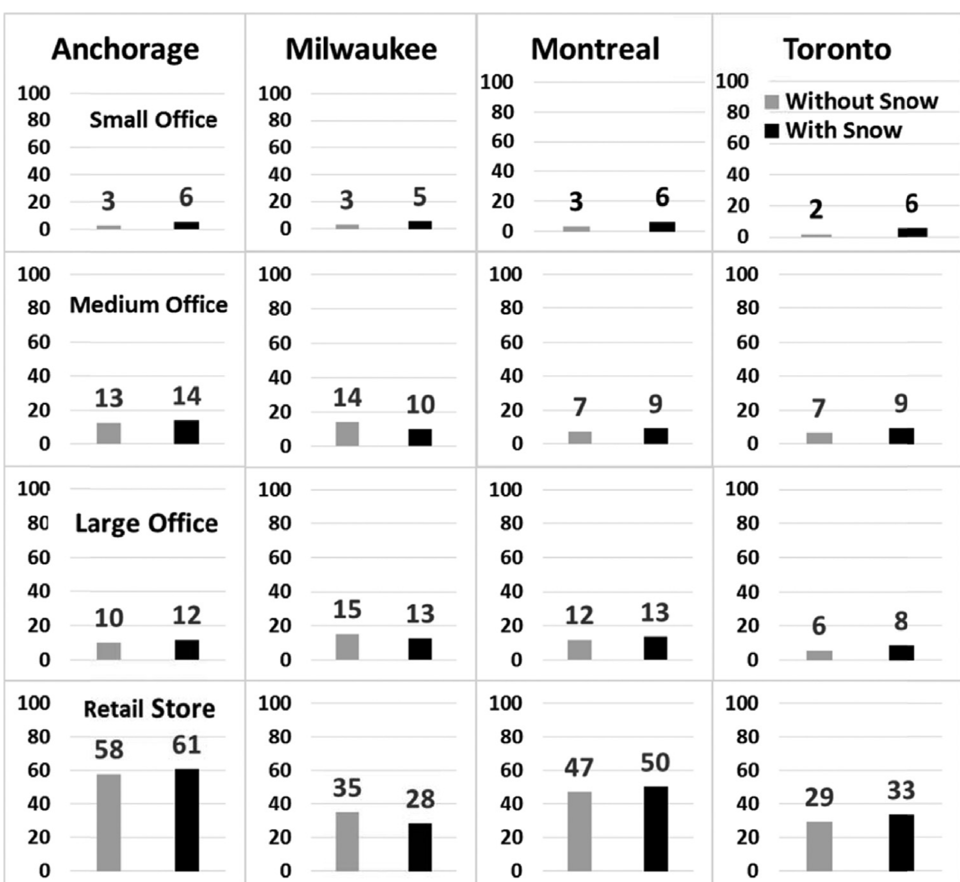

Fig. 5. Annual savings ($/100 m²) of cool roofs with and without the effect of snow for the new buildings with gas-heating HVAC systems.

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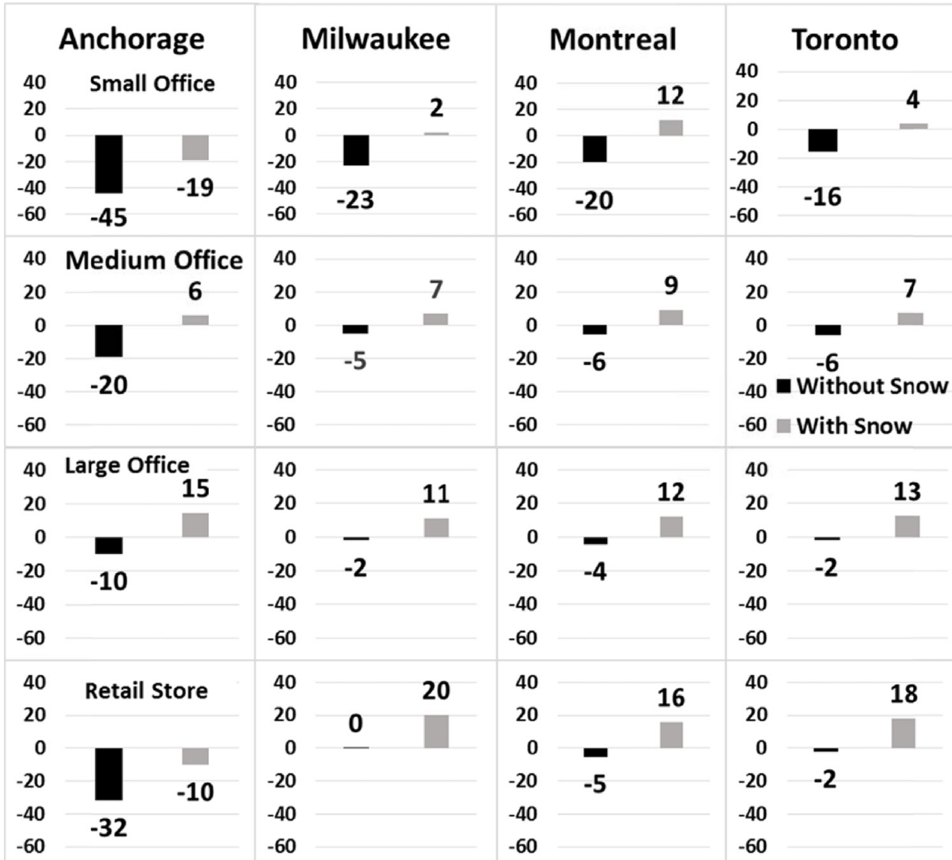

Fig. 6. Annual savings ($/100 m^2) of cool roofs with and without the effect of snow for the old buildings with all-electric HVAC systems.

snow, decreasing to 6 $/100 m^2 with snow (Fig. 6). In Montreal for small office, depending on the construction, cool roof can save 4–12 $/100 m^2 for buildings with all-electric system (Figs. 6 and 7). In Toronto, for small office, Fig. 6 shows that snow changed 16 $/100 m^2 penalty of cool roof to 4 $/100 m^2 savings (20 $/100 m^2 effect of snow). For medium office, cool roof saved up to 13 $/100 m^2 considering snow on the roof (Fig. 4). For large office cool roof saved up to 16 $/100 m^2 (Fig. 4) and for retail store building, cool roof could save maximum of 37 $/100 m^2 (Fig. 4).

5.2. Peak demand reduction by cool roof

Most utilities offer two electricity tariffs as time-of-use prices to their clients. During off-peak hours, electricity consumption is lower and electricity prices are cheaper, as well. But during peak hours, which usually occur in the afternoons and evenings of summer days, electricity consumption is considerably higher and the electricity rate is more expensive as well (we assumed a constant off-peak price in our annual energy price calculations).

Table 9
Electricity peak demand (W/m^2) for buildings with gas-heating systems.

Case	Small office			Medium office			Large office			Retail store		
	D	W	S	D	W	S	D	W	S	D	W	S
I. Anchorage												
(a) Old construction/old systems	47.2	45.4	1.8	115.3	114.7	0.7	93.9	93.1	0.8	60.5	59.5	1.0
(b) Old construction/new systems	45.2	43.8	1.4	111.0	110.3	0.6	91.1	90.4	0.7	59.9	58.9	1.0
(c) New construction/new systems	28.8	28.6	0.2	84.4	84.4	0.1	75.0	74.4	0.6	35.6	34.7	0.9
II. Milwaukee												
(a) Old construction/old systems	64.4	62.6	1.8	166.8	165.8	1.0	145.3	144.0	1.3	95.7	93.9	1.8
(b) Old construction/new systems	60.1	58.5	1.6	155.0	154.2	0.8	135.6	134.4	1.3	91.0	89.5	1.5
(c) New construction/new systems	36.0	36.0	0.0	123.0	122.5	0.5	94.4	93.4	1.0	46.5	45.5	1.0
III. Montreal												
(a) Old construction/old systems	64.8	62.2	2.5	160.6	159.7	0.8	161.2	157.3	4.0	91.4	88.2	3.2
(b) Old construction/new systems	60.5	58.3	2.2	149.3	148.6	0.7	149.6	146.1	3.5	86.8	83.8	3.0
(c) New construction/new systems	38.0	37.8	0.2	113.8	113.6	0.2	87.7	86.4	1.3	50.7	45.4	5.4
IV. Toronto												
(a) Old construction/old systems	64.0	62.4	1.6	167.6	166.2	1.4	153.2	149.9	3.3	98.1	96.2	1.9
(b) Old construction/new systems	59.7	58.3	1.4	155.4	154.2	1.2	143.0	139.6	3.3	93.6	91.9	1.7
(c) New construction/new systems	38.7	38.4	0.4	119.3	118.9	0.4	88.7	88.1	0.5	53.9	52.8	1.1

Note: D, W, and S indicate dark roof, white (cool) roof, and saving respectively.

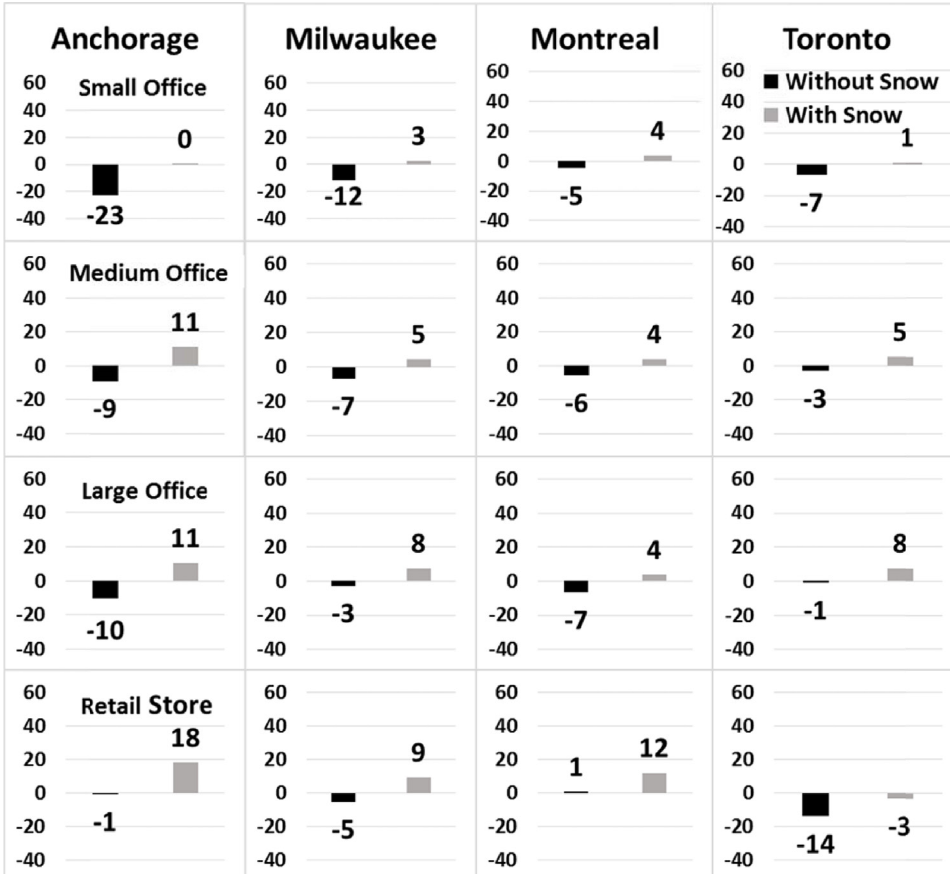

Fig. 7. Annual savings ($/100 m^2) of cool roofs with and without the effect of snow for the new buildings with all-electric HVAC systems.

Using a cool roof instead of a typical dark roof decreases the electricity peak demand during the cooling season. The cool roof not only reduces the monthly electricity bill but also increases the reliability of grids and plants. Table 9 shows the electricity peak demand (occurring in the afternoon in the studied locations) normalized to 1 m^2 of the building's roof. As the table indicates, a cool roof can reduce the peak electric demand of the retail buildings by up to 1.9 and 5.4 W/m^2 in Toronto and Montreal, respectively.

5.3. HVAC system size

In most climates, HVAC systems are sized based on peak summer cooling load. So that, amount of required air volume satisfying cooling load is calculated followed by computing the cooling coil capacity. A cool roof can reduce the summer cooling load leading to downsizing of HVAC systems. The extent to which an HVAC system can be downsized by using a cool roof is highly dependent on the size, type, and construction of the building, as well as on climate conditions and the type of HVAC system. A downsized HVAC system can operate more efficiently throughout the year including during heating season (system part load ratio would be closer to the optimum operation condition).

6. Discussion

Savings of cool roofs in cold climates are highly dependent on roof insulation, building type, HVAC system type, energy prices, snow thickness, snow type, and snow duration on roof. Cool roof resulted in overall energy expenditure savings for gas-heating systems in all studied cold climate regions even without the effect of roof snow. However, snow effectively reduced the heating penalty of cool roof contributing to an increase in annual overall energy expenditure savings for cool roof. In addition, cool roofs savings for retail store buildings were significantly higher than for other prototypes. The prototype retail store buildings did not include plenum zone; as a consequence the heat conducts directly from roof to the zones and the roof heat gain difference between dark roof and cool roof were greater. Moreover the retail store buildings operated even during the weekends with longer working hours resulting in comparatively higher savings.

For the simulated buildings with all-electric systems, considering the effect of snow on the roof, cool roof saved annual energy expenditure in all locations except for the old small and retail store in Anchorage and the new retail store in Toronto. As Figs. 4–7 show, in most cases cool roofs on old buildings with lower level of roof insulation resulted in higher savings. However, for buildings with all electric systems in Anchorage, cool roofs for old small office and retail store buildings showed some overall expenditure penalties. This penalty is mainly because of short and mild summer of Anchorage when there is not a significant cooling energy consumption. Moreover for the new buildings in Anchorage, the net annual expenditure is lower for cool roofs. This is because, during spring and fall season (when the outdoor temperature is lower than indoor, a higher level of roof insulation reduces the heat lose through the roof and actually lead to a higher cooling energy use.

Energy price plays an important role in cool roof saving. Results show that cool roofs have considerably higher savings for air-conditioned buildings with gas-heating HVAC systems since the heating source (natural gas) is cheaper than cooling source (electricity). Moreover, since heat pump system uses electricity throughout the year, low peak demand price in Toronto (only 1.9 $/kW) results in lower cooling expenditure savings for cool roofs

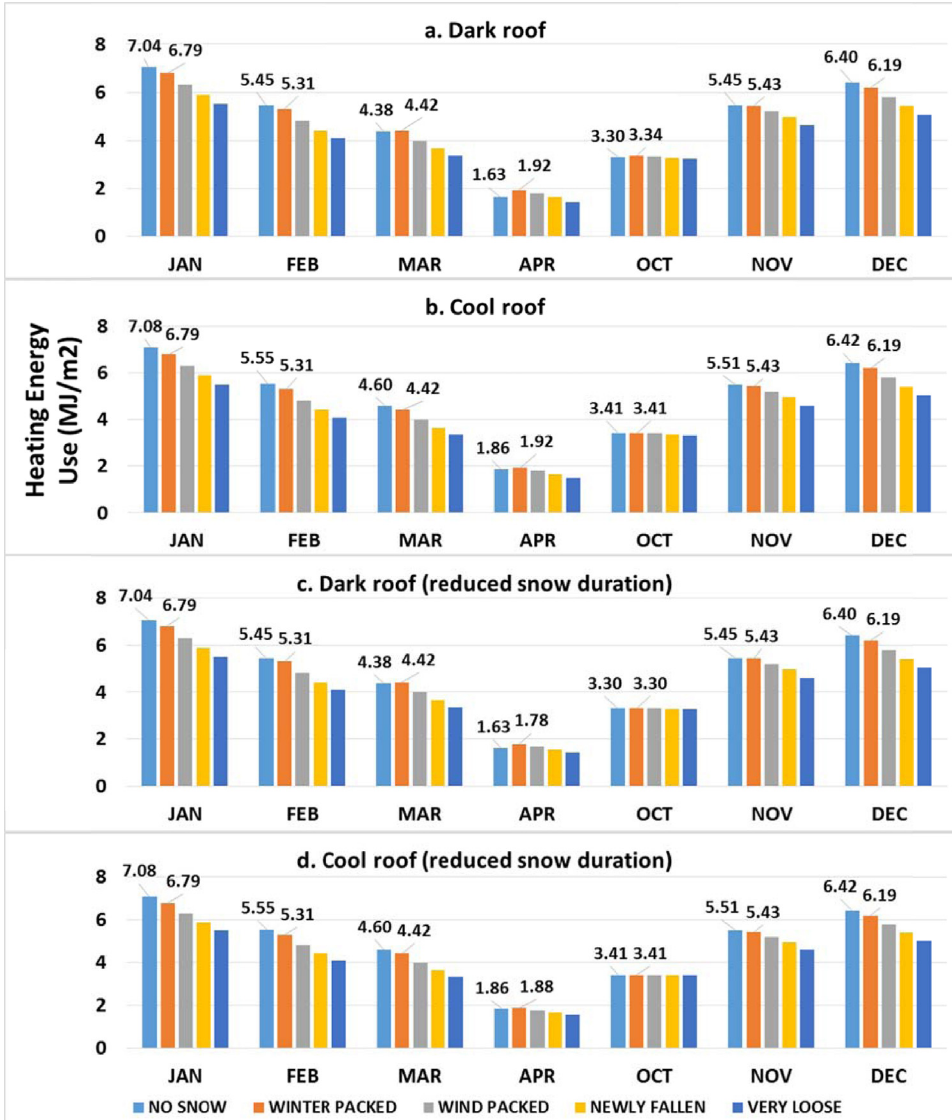

Fig. 8. Monthly heating energy consumption (MJ/m^2) of the new small office building in Anchorage without and with different snow types on dark roof.

and consequently more overall expenditure penalty for the new retail store. Snow on the roof also may increase the cooling energy consumption of the building. In Milwaukee, for a few days in April snow exists on the roof. When the interior cooling load is high HVAC system starts to operate and because of snow insulation cooling energy consumption increases. However the difference between the cooling energy of the dark roof and cool roof would be smaller compared to when there is no snow on the roof. That is why the cool roof with snow has less savings compared with cool roof without snow for new medium and large office and also new retail store buildings in Milwaukee.

To better characterize the effect of snow on building energy consumption, some parametric simulations were performed before carrying out the main simulations. For the new small office building in Anchorage when the dark roof without snow and the dark roof with snow are compared, it is observed that all the snow types lower the heating energy consumption of the building in five months of the snow season (January, February, March, November and December). However, the choice of the snow type may lead to a slight increase in the simulated heating energy consumption of the building in April and October. During April and October there is a very thin layer of snow on roof. For a thin layer of packed snow, high solar reflectance dominates low thermal conductance and as a result affects thermal performance of the roof. Fig. 8(a) and (b) shows the monthly heating energy consumption of the new small office building in Anchorage without and with different snow types on dark and cool roof.

In the simulations, snow collection on the roof was assumed based on the meteorological data that are collected for snow on a flat surface. Snow on a flat roof may melt faster than the snow on the ground and may disappear for a duration of time throughout the winter because of heat conduction from the buildings. In our analysis, a continuous snow cover is assumed on the roof. To better understand the effect of the duration of snow on the roof, parametric simulations were performed by reducing the period of snow on the roof by 15 days at the beginning (October to December) and at the end (January to April) of snow collection on the roof (30 days reduction overall). Shorter duration of snow may slightly increase the penalties of cool roofs. Fig. 8(c) and (d) shows the results for reduced snow duration. As Fig. 8(a) and (b) shows, during the month of April the heating energy penalty of cool roof with winter-packed snow in non-reduced duration is zero (1.92 MJ/m^2 for both) whereas Fig. 8(c) and (d) illustrates that this penalty increases to 0.1 MJ/m^2 (1.78 MJ/m^2 for dark roof and 1.88 MJ/m^2 for cool roof)

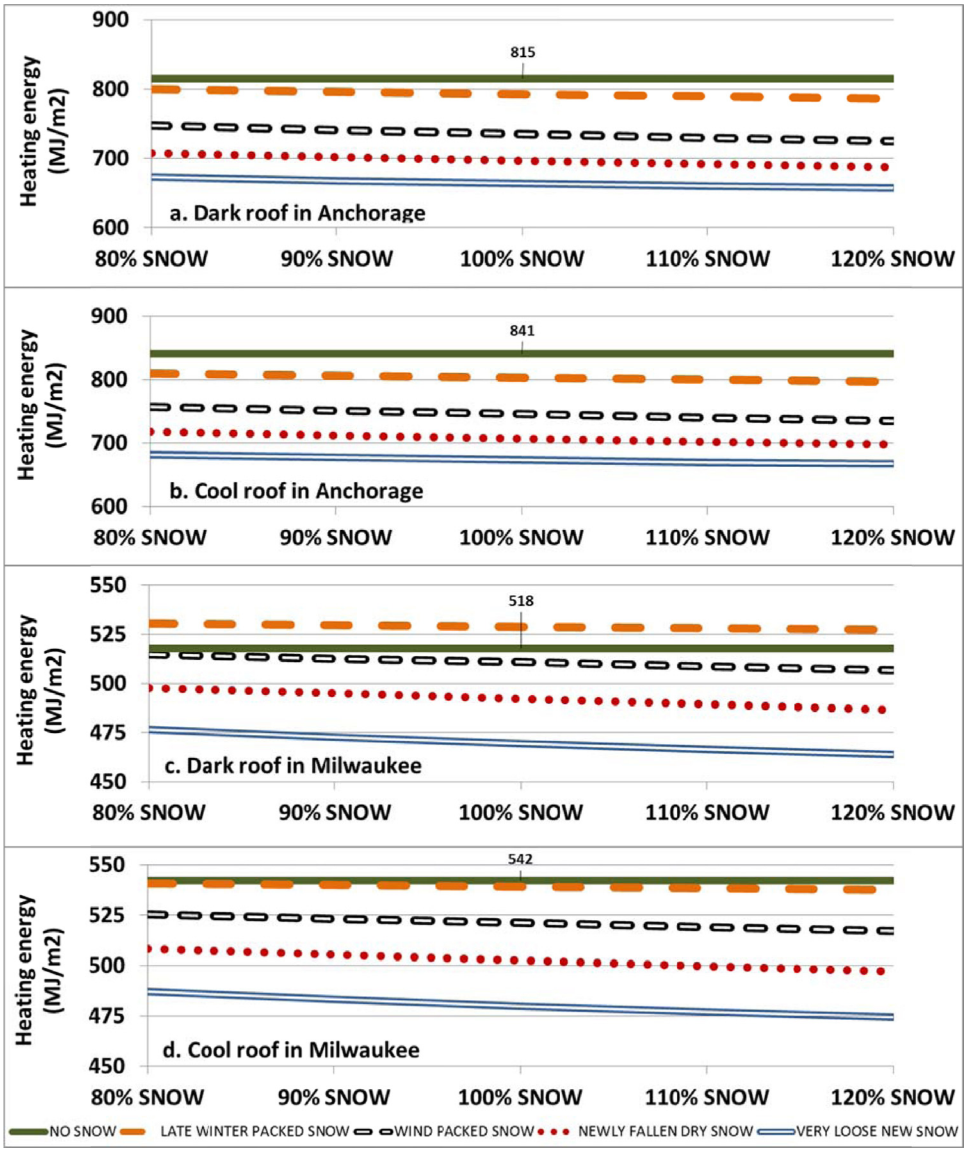

Fig. 9. Effect of different types of snow on heating energy considering the snow thickness for dark roof in Anchorage and Milwaukee.

when snow duration decreased by as much as 30 days. Moreover, the insulation of very loose snow is higher than other snow types, hence, a lower heating energy use during the year. During April, winter packed snow on the roof has actually caused a small increase in heating energy use, as a competing result of a thin layer of snow (low insulation value) and higher albedo of roof (with snow).

Some additional parametric simulations were performed to better understand the effect of snow thickness on the roof. For these parametric simulations, we analyzed the effect of the snow thickness on a single story small office building (465 m^2 roof area) with a constant snow solar reflectance of 0.8. We simulated the building with a central VAV system. The 6-year average of daily snow thickness was changed from 80% to 120%, in 10% intervals. As Fig. 9 illustrates there is a linear negative correlation between the snow thickness and annual heating energy of the building in Anchorage. Fig. 9(a) and (b) shows that annual natural gas heating energy consumption of the building with dark and cool roof without snow in Anchorage are 815 and 841 MJ/m^2, respectively, while these amounts for dark and cool roofs considering the winter packed snow are 794 and 802 MJ/m^2, respectively. Therefore, annual heating energy penalty for cool roof decreases from 26 to 8 MJ/m^2.

All types of snow reduce annual heating energy in Anchorage; however, late winter packed snow can increase the heating energy consumption for Milwaukee. Fig. 9(c) and (d) presents the annual heating energy consumption for dark and cool roofs in Milwaukee. Annual heating energy consumption of the building with dark and cool roofs without snow in Milwaukee are 241 and 252 GJ (518 and 542 MJ/m^2) while these amounts for dark and cool roofs considering the winter packed snow are 246 and 251 GJ (529 and 540 MJ/m^2). Therefore, annual heating energy penalty for cool roof decreases from 24 to 11 MJ/m^2.

7. Summary and conclusion

In cold climates, during the winter the sun angle is lower, days are shorter, sky is cloudy, and most heating occurs during early morning or evening hours when the solar intensity is low. In addition, the roof may be covered with snow for most of the heating season. All these lead to a negligible winter time heating penalties for cool roofs. For most building types and in most climates, our simulations show that a cool roof saves in annul overall energy expenditure even without the effect of snow. However, snow can effectively reduce the heating penalties for buildings with cool roofs—as seen in all simulated climate regions—contributing to increase in annual energy expenditure savings. Cool roofs saved annually up to about 60 $/100 m^2 of the roof area for a retail store building in Anchorage and Montreal.

A cool roof also reduces the electricity peak demand of the building during the cooling season; this makes the use of a cool roof a practical method to improve the reliability of grids and generation power plants and to prevent unwanted electricity shutdowns on hot summer days. Cool roof reduced the peak electric demand of a retail store building up to about 5 W/m^2 of the roof area in Montreal. Moreover, most HVAC systems are designed based on peak summer cooling loads, which can be reduced by a cool roof, leading to the downsizing of HVAC systems. A downsized HVAC system can operate more efficiently throughout the year, including the heating season. It should be mentioned that these results are just the direct effect of using cool roofs on building energy use. Using cool roofs for buildings on a larger scale, may moderate local climate. Hence, savings of cool roofs may even increase when indirect effects are considered.

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References

[1] R. Levinson, H. Akbari, Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants, Energy Effic. 3 (2010) 53–109.
[2] H. Akbari, R. Levinson, Evolution of cool-roof standards in the US, Adv. Build. Energy Res. 2 (2008) 1–32.
[3] S. Ibrahim, Annotation in Huffington Post. Available from: http://www.huffingtonpost.com/samir-ibrahim/white-roofs-green-myth_b_2901288.html
[4] C. Bludau, D. Zirkelback, H.M. Kunzel, Condensation problems in cool roofs, Interface 27 (7) (2009) 11–16.
[5] M. Moghaddaszadeh Ahrab, H. Akbari, Hygrothermal behavior of flat cool and standard roofs on residential and commercial buildings in North America, Build. Environ. 60 (2013) 1–11.
[6] T.W. Hutchinson, A matter of opinion: a roofing industry professional shares his views about current issues facing the industry, Professional Roofing (2008, October) 32–38.
[7] T.W. Hutchinson, Questioning cool roofs, Commer. Build. Prod. 11 (1) (2013) 19–21.
[8] S. Ibrahim, Sustainable roof design: more than a black-and-white issue, in: Symposium on Building Envelope Technology, 2009, October.
[9] J. Yang, Z. Wang, K.E. Kaloush, Unintended Consequences, a Research Synthesis Examining the Use of Reflective Pavements to Mitigate the Urban Heat Island Effect, Arizona State University National Center of Excellence for SMART Innovations, 2014.
[10] ASHRAE 90.1, ASHRAE STANDARD, Energy Standard for Building Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2007.
[11] ASHRAE 90.2, Energy-Efficient Design of Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2007.
[12] K.W. Oleson, G.B. Bonan, J. Feddema, Effects of white roofs on urban temperature in a global climate model, Geophys. Res. Lett. 37 (2010) L03701, http://dx.doi.org/10.1029/2009GL042194
[13] S. Konopacki, H. Akbari, M. Pomerantz, S. Gabersek, L. Gartland, Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 US Metropolitan Areas, LBNL-39433, Lawrence Berkeley National Laboratory, 1997.
[14] E. Palm, M. Tveitereid, On heat and mass flow through dry snow, Geophys. Res. 84 (2) (1979) 745–749.
[15] J.W. Pomeroy, E. Brun, Physical properties of snow", in: H.G. Jones, J.W. Pomeroy, D.A. Walker, R.W. Hoham (Eds.), Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems, Cambridge University Press, Cambridge, 2001, pp. 45–118.
[16] M. Sturm, J. Holmgren, M. Konig, K. Morris, The thermal conductivity of seasonal snow", Glaciology 43 (143) (1997) 26–41.
[17] D.H. Male, S. Colbeck (Eds.), The Seasonal Snow Cover. Dynamics of Snow and Ice Masses, Academic Press, Toronto, 1980, pp. 305–395.
[18] M. Hosseini, H. Akbari, Heating energy penalties of cool roofs: the effect of snow accumulation on roofs", Adv. Build. Energy Res. (2014), http://dx.doi.org/10.1080/17512549.2014.890541
[19] DOE-2 Engineers Manual, Version 2.1A, LBL 11353, Lawrence Berkeley Laboratory, 1982.
[20] D.M. Gray (Ed.), Handbook on the Principles of Hydrology, Canadian National Committee for the International Hydrological Decade, Ottawa, 1970.
[21] DOE-2 Basics, version 2.1E, LBL 29140, Lawrence Berkeley Laboratory, 1991.
[22] SNICAR Online: Snow Albedo Simulation, http://snow.engin.umich.edu/
[23] DOE Website for Prototype Building Models, http://www.energycodes.gov/commercial-prototype-building-models
[24] M. Deru, K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, M. Rosenberg, M. Yazdanian, J. Huang, D. Crawley, U.S. Department of Energy Commercial Reference Building Models of the National Building Stock, Technical Report NREL/TP-5500-46861, February, 2011.
[25] National Energy Code of Canada for Buildings (NECB), Performance Simulation of Proposed Changes to NECB Relative to MNECB and ASHRAE 90.1-2007, Prepared by Caneta Research Inc., Mississauga, Ontario, 2011, Prepared for National Research Council.
[26] M. Hosseini, Cool Roofs Savings and Penalties in Cold Climates: The Effect of Snow Accumulation on Roof (Master thesis), Concordia University, Montreal, Canada, 2014.
[27] EnergyPlus Prototypical Building Simulations, http://www.energycodes.gov/commercial-prototype-building-models
[28] Municipal Light and Power, http://www.mlandp.com/redesign/rates_and_tariff.htm (accessed 1.05.14).
[29] We Energies cg1, http://www.we-energies.com/pdfs/etariffs/wisconsin/ewi_sheet35-36.pdf (accessed 1.05.14).
[30] We Energies cg2, http://www.we-energies.com/pdfs/etariffs/wisconsin/ewi_sheet37-39.pdf (accessed 1.05.14).
[31] We Energies cg3, http://www.we-energies.com/pdfs/etariffs/wisconsin/ewi_sheet40-42.pdf (accessed 1.05.14).
[32] Hydro Quebec, Rate G, http://www.hydroquebec.com/business/rates-and-billing/rates/electricity-rates-business-customers/rate-g/ (accessed 1.05.14).
[33] Hydro Quebec, Rate M, http://www.hydroquebec.com/business/rates-and-billing/rates/electricity-rates-business-customers/rate-m/ (accessed 1.05.14).
[34] Toronto Hydro, https://www.torontohydro.com/sites/electricsystem/business/yourbilloverview/Pages/ElectricityRates.aspx (accessed 1.05.14).
[35] ENSTAR Natural Gas Company, http://www.enstarnaturalgas.com/about-enstar/rates-regulatory/ (accessed 1.05.14).
[36] We Energies Natural Gas Tariff, http://www.we-energies.com/pdfs/tariffs_vol7/WGCtariffbk_vol7.pdf (accessed 1.05.14).
[37] Gaz Metro, http://www.gazmetro.com/Popup/Prix-gaz.aspx (accessed 1.05.14).
[38] Ontario Energy Board, http://www.ontarioenergyboard.ca/OEB/Consumers/Natural+Gas/Natural+Gas+Rates#prices (accessed 1.05.14).

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