Cool Roofs Savings and Penalties in Cold Climates: the Effect of Snow Accumulation on Roof

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Abstract

Utilizing a cool roof is an efficient way to reduce a building's usage of cooling energy, although it may increase the usage of heating energy in winter. In cold climates, during the winter, the sun angle is low, days are short, the sky is often 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 factors lead to wintertime heating penalties for cool roofs that are lower than what is commonly thought.

We used DOE-2.1E to simulate energy consumption in several prototype office and retail buildings in four cold-climate cities in North America: Anchorage (AK), Milwaukee (WI), Montreal (QC), and Toronto (ON). The effects 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 simulate four different types of snow on the roof, we defined a function consisting of the U-value and absorptivity of the roof on a daily basis. We used an average based on six years of meteorological data from the National Oceanic and Atmospheric Administration (NOAA) and Environment Canada to estimate the snow thickness on the roof.

In the very cold climate of Anchorage, AK, the simulated annual heating energy consumptions of the prototype old retail building with a dark (warm) versus a cool roof (without considering the snow) are 123548 and 125848 MJ/100 m^2, respectively (showing a 2300 MJ/100 m^2 penalty for the cool roof). These numbers reduce slightly to 123216 and 124409 MJ/100 m^2, respectively (showing 1193 MJ/100 m^2 penalty for the cool roof), when "late-winter packed" snow is considered. In this way, for an old retail building in Montreal, a cool roof can save up to \$62/100 m^2. For a new, medium-sized office building with electric cooling and natural gas as 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 roof also saves maximum of 37\$/100 m^2 for a retail store building in Toronto.

Cool roofs for the simulated buildings resulted in annual energy expenditure savings in all cold climate regions.

A cool roof also reduces the electricity peak demand of the building during the cooling season; this effect is considered to be a practical method to improve the reliability of grids and plants or to prevent unwanted

electricity shutdown on hot summer days. 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.

Most HVAC systems are designed based on the peak summer cooling load. A cool roof can reduce the summer cooling load, which would lead to downsizing of HVAC systems. A downsized HVAC system can operate more efficiently throughout the year, including during the heating season.

Acknowledgment

I would like to express my sincere gratitude to my supervisor, Dr. Hashem Akbari, for the guidance, direction, and pearls of wisdom, but more importantly, for offering encouragement precisely when needed without which it would have been nearly impossible to produce this research.
The friendship of Hatef Aria and Ali Gholizadeh is much appreciated and has led to many interesting and good-spirited discussions relating to this research.

Dedication

This thesis is dedicated to my parents, Farkhondeh and Mehdi for their love, dedication, encouragement, and the many years of support during my life. My aunt and uncle, Pat and Farhad receive my deepest gratitude and love for their infinite support during my study.

This thesis is also dedicated to all those who believe in the richness of learning.

Table of Contents

List of Figures

List of Tables

List of symbols

Symbol	Unit	Definition
A	m^2	Cross section area of material
C	kJ/kg.K	Thermal capacity
F_A	-	View factor
F_E	-	Emissivity factor
h	$W/m^2.K$	Convective heat transfer coefficient
h_r	$W/m^2.K$	Radiative heat transfer coefficient
I	W/m^2	Solar radiation intensity
k	W/m.K	Thermal conductivity
k_{eff}	W/m.K	Effective thermal conductivity of snow
L	W/m^2	Surface emitted long wave radiation
l	m	Material thickness
Q	W	Heat flow through material
q_{1-2}	W/m^2	Radiant heat transfer between surfaces 1 to 2
q_s	W/m^2	Absorbed solar radiation by surface
q_{rad}	W	Net radiation heat exchange between roof and sky
q_x	W	Convective heat rate
t	s	Time
T	K	Temperature
T_a	K	Ambient temperature
T_s	K	Roof surface temperature
T_∞	K	Fluid (air) temperature
T_{sky}	K	Sky absolute temperature
U	$W/m^2.K$	Material conductance
α	-	Surface solar absorptance
ε_s	-	Surface emissivity
σ	$W/m^2.K^4$	Stephane-Boltzmann constant= $5.67*10^{-8}$
ρ	kg/m^3	Material density
dT/dx	-	Temperature gradient in x direction
ΔT	K	Temperature difference between the initial and final stage
FILMU	Btu/(hr-ft^2-°F)	The combined radiative and convective outside surface conductance in
CLDAMT	-	Cloud amount in tenths
SKY	Btu/(hr-ft^2)	Heat loss by roof surface to sky
T_s	Rankin	Outside roof surface temperature
SOLI	Btu/(hr-ft^2)	Solar radiation incident on outside roof surface from direct, diffuse, and reflected radiation
α	-	Roof surface absorptivity
DBTR	Rankin	Outside surface temperature
U	Btu/(hr-ft^2-°F)	Conductance of the wall exclusive of the outside air film (includes a combined inside film coefficient
T_{zone}	Rankin	The constant space temperature
Q	Btu/hr	Heat flow through the inside roof surface
SAREA	ft^2	Surface area

List of Acronyms

Abb.	Full name
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CC	Cooling Capacity
CDD	Cooling Degree Days
COP	Coefficient Of Performance
DOE	Department OF Energy
HC	Heating Capacity
HDD	Heating Degree Days
HIR	Heat Island Reduction
HVAC	Heating, Ventilation, and air conditioning
LWP	Late Winter Packed
NECB	National Energy Code of Canada for Buildings
NFD	Newly Fallen Dry
NREL	National Renewable Energy Laboratory
PSZ	Packaged Single Zone
PTAC	Packaged Terminal Air Conditioner
TMY	Typical Meteorological Year
VAV	Variable Air Volume
VLN	Very Loose New
WP	Wind Packed

Chapter 1: Introduction

1.1 Motivation

Since the roof constitutes a large portion of the building enclosure, it provides considerable potential for energy efficiency. That is, any attempt to reduce the heat transfer through the roof may lead to saving a significant amount of energy.

Solar reflectance, infrared emittance, and thermal insulation are three parameters affecting heat transfer through the roof. Solar reflectance is the fraction of the solar radiation that is reflected back to the sky (in the 0.3–2.5 µm spectrum), thus lowering the solar energy that the roof absorbs. "When the roof absorbs solar radiation, it is transformed into heat and some of this heat is emitted back in the form of infrared radiation according to the infrared emittance property of the roof (in the 4–80 µm spectrum). Thus, a roof with a high solar reflectance and a high infrared emittance will absorb less energy and will be cooler than a regular roof" (Levinson and Akbari, 2010). A cool roof (high reflective or low absorptive) 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, and reducing cooling costs. On a larger scale, cool roofs can moderate the air temperature surrounding a building, decrease greenhouse gas emissions like CO2, and mitigate the urban heat island effect (Akbari et al., 2009).

Many states prescribe cool roofs in the construction of new buildings and for re-roofing existing buildings. Akbari and Levinson (2008) have summarized the status of cool roof standards in the United States and several other countries.

Some recent articles have claimed 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 (available at http://www.huffingtonpost.com/samir-ibrahim/white-roofs-green-myth_b_2901288.html) points out the risk of condensation and mold formation as a result of cool roofing. In addition, Bludau et al. (2009) investigated the moisture performance of cool roofs in various climates. They used WUFI, a building hygrothermal performance computer program, to simulate the buildings' roofs. 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 (2012) conducted a comprehensive study on the hygrothermal behavior of cool roofs in different 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 office buildings never experienced moisture accumulation problems. However, there were some moisture accumulation problems among 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 discovered that, with the smart-vented system, cool roofs did not face any moisture accumulation, even in very cold weather like Anchorage's. In addition, they realized 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 (Hutchinson, 2008; Ibrahim, 2009; Hutchinson, 2013; Yang et al., 2014).

Generally, using a cool roof in cold climates is not suggested because the heating penalty may be higher than the cooling savings. For example, ASHRAE has limited reflective-roof usage to Zones 1–3 (ASHRAE 90.1 and ASHRAE 90.2). Oleson et al. (2010) 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; however, Miller et al. (2004) stated that, for cold climates with a hot summer season, high emittance is preferred because the heating penalty during the year will be outweighed by the savings in summer. Konopacki et al. (1997), 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.

During winters in cold climates, the sun angle is low during the day, the days are short, the sky is cloudy most of the time, and most heating occurs during early morning or evening hours when the solar intensity is low. These conditions allow less solar radiation to affect the roof. Moreover, in cold climates the roof is covered by snow during most months of the heating season, which is the most important point not taken into account in previous studies.

Therefore, a negligible (if any) heating energy penalty is expected for a building with a cool roof when compared to the same building with a dark roof during the cold season. What is less clear and more controversial is whether or not cool roofing is beneficial in climates where, over the course of a year, heating energy loads are greater than cooling ones. In other words, can cool roofs be advantageous in cold climates?

1.2 Objectives of this research

The objective of this research 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 1-1 categorizes these locations based on ASHRAE climate zone, heating degree days (HDD18), and cooling degree days (CDD10).

Table 1-1. 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

1.3 Thesis organization

This thesis is organized in five other chapters beside this introductory chapter (chapter 1).

Chapter 2 offers a review of the literatures related to cool roofs performance in different climates especially in cold climates; Followed by discussing the cold climate condition and snow properties based on the literatures.

Chapter 3 discusses the methodology we have applied in order to achieve our goals. The first part discusses our input data and their sources; then, there would be a short summary about the software we used (DOE-2.1.E). This chapter will be concluded by a description of the functions we defined for the software.

Chapter 4 provides the complete description of scenarios and prototype buildings together with a summary of HVAC systems included in our research.

In Chapter 5 initial results are compared with previous works and standards to make sure about the accuracy and validation of subsequent results. Then all the results along with a comprehensive analysis are presented.

Chapter 6 consists of a summary and conclusion continued by references used through this research.

Chapter 2: Literature review

2.1 Introduction

Buildings are responsible for 72% of the annual electrical energy used in the United States (EIA, 2007). 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 and converted to heat is 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 this 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 is a roofing system that reflects the largest portion of solar radiation back into the atmosphere as infrared energy (whereas a dark roof absorbs solar radiation).

Solar reflectance and thermal emittance of the roof material, each ranging from 0 to 1, are two major parameters determining the roof's surface temperature. The larger the values of these two parameters are, the cooler the roof surface will be in the sun. Another way of measuring the coolness of a roof is with the solar reflectance index (SRI), which is calculated based on the solar reflectance and thermal emittance of the roof's surface material. The higher the SRI, the cooler the roof surface remains in the sun. Since 1999, several building energy efficiency standards, including ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code, and California's Title 24, have adopted cool-roof credits or requirements (Akbari and Levinson, 2008). According to California's Title 24 and ASTM (E1980, 1998), the minimum requirements for qualifying as a cool roof are as shown in Table 2–1, based on the slope of the roof. A low-sloped roof has a pitch of 9.5° or 2:12, and a steep-sloped roof has values greater than these.

Table 22-1. Cool roof requirements (International Code Council, 2010) (ASTM E1980, 1998)

Roof Type	Solar Reflectance (3 year aged)		Thermal Emmitance (3 year aged)		Solar reflectance index SRI (3 year aged)
Low Sloped	0.55	AND	0.75	OR	64
Steep Sloped	0.2		0.75		16

2.2 Benefits of cool roofs

Because a dark roof absorbs 90% or more of solar energy, it can reach 150°F (66°C), whereas a cool roof may stay at 100°F (38°C) or cooler (Urban and Roth, 2010). Reduced thermal stress can increase the lifetime of cool roofs, lessening maintenance and waste (Akbari et al., 2001) (Levinson et al., 2005). A cooler roof surface reduces the cooling energy consumption and peak power demand of the building during the summer. The energy-cost savings expected from a cool roof depends on factors such as climate, amount of roof insulation, type of building use, energy prices, and type and efficiency of its HVAC systems (Urban and Roth, 2010). Light-colored method is an efficient way to reduce the cooling load, peak demand, and urban heat island effect. Akbari et al. (1993) measured 40–50% cooling-energy savings and 30–40% peak power cooling reduction in different types of buildings in Sacramento, CA, using high albedo-coated roofs. Both 10–43% savings in daily air conditioning and 12–38% savings in utility costs during peak power periods were demonstrated in eight Florida homes using reflective-coating roofs (Parker et al., 1995). A simulation study in the Los Angeles Basin showed 20–40% savings during peak cooling times in residential areas and 5–10% in office buildings resulting from a 0.4 increase in roof albedo (Taha et al, 1996). Synnefa et al. (2007) found that increasing the roof albedo by 0.65 obtained cooling reductions of 9–48 kWh/m^2, with heating penalties of only 0.2–17 kWh/m^2. In a European case study, Synnefa et al. (2007) investigated a school in Athens, Greece, to estimate the impact of a cool roof on the energy performance and thermal behavior of the building. Their results show that the application of the cool roof decreased the annual cooling load by 40% (3 kWh/m^2) for the uninsulated building and 35% (1 kWh/m^2) for the insulated building. They also estimated the heating energy penalty. The application of the cool roof resulted in an increase in annual heating loads of 10% (2.6 kWh/m^2) and 4% (0.7 kWh/m^2) for the uninsulated and insulated buildings, respectively.

On a larger scale, Konopacki et al. (1997) used simulation-modeling strategies for their study of potential energy savings in 11 metropolitan areas across the United States, predicting savings of $37M for Phoenix and $35M in Los Angeles. They also found that cool roofs could achieve $3M in savings in the heating-dominated climate of Philadelphia.

Cool roofs also have many environmental benefits, such as reducing the heat island effect. A heat island is defined as an urban area with an air temperature higher than the surrounding rural environment (Akbari et al., 1999). Cool roofs can decrease local air temperatures, leading to better air quality and reductions in smog; they can reduce peak electric-power demands, preventing power outages; they can lower power plant emissions, including carbon dioxide, sulfur dioxide, nitrous oxides, and mercury, by reducing cooling energy-use in buildings; and they can reduce heat trapped in the atmosphere by reflecting more sunlight back into space and consequently slowing climate change (Levinson and Akbari, 2010). Most US cities have significant opportunities to increase the use of cool roofs and benefit from the resulting reduction in energy demands and the mitigation of the heat island effect because, in urban regions, roofs account for 20–25% of all urban land cover (L.S. Rose et al., 2003). In 2001, in response to electrical power shortages, California updated its building energy code (Title 24) by adding cool roofing as an energy-efficient option. In 2005, the cool roof provisions became mandatory statewide for all new nonresidential construction and re-roofing projects that involved more than 90 m^2 (969 ft^2) or 50% replacement (USEPA, 2009). Akbari and Taha (1992) studied the impacts of trees and white surfaces on residential buildings' cooling- and heating-energy usage in four Canadian cities: Edmonton, Montreal, Toronto, and Vancouver. They compared prototype buildings with moderate dark (albedo=0.3) and medium light (albedo=0.5) exterior walls and roofs in order to measure the effect of whitening exterior surfaces (roofs and walls). Their results show that the heating penalty associated with a cool roof is negligible (0.1 GJ/year or 0.2%).

In another numerical simulation-based study, Akbari and Konopacki (2004) investigated low-rise residential (single family) and commercial (office and retail) buildings using heat-island reduction (HIR) strategies including the use of solar-reflective roofing materials in a cold climate city like Toronto, Canada, in order to find the cooling and heating energy-use associated with each strategy. They applied the DOE-2.1E energy-simulation computer program to estimate the heating and cooling energy usage of the buildings. They assumed solar reflectance of 0.2 and 0.6 for a cool roof and dark roof, respectively, and they stated that this assumption was a good estimate for the summer savings but a slight overestimation for the heating penalty in winter because they did not consider the effect of snow (as both cool and dark roofs are covered with snow during most periods of the heating season). Their results show that applying a reflective roof instead of a non-reflective roof can save up to 522 kWh per 100 m^2 for an old retail flat roof and 0.26 kW/100m^2 peak power reduction for the same building (representing a \$40.7/100 m^2 savings with a cool roof). In contrast, DOE-2 can underestimate the cooling-energy savings potentials of cool roofs by as much as a factor of two (Akbari and Konopacki, 2004).

In none of the previous studies is snow taken into account as a covering layer that minimizes energy penalties for cool roofs in cold climates.

2.3 Cold climates characteristics

There are at least six reasons why the heating penalty associated with cool roofs is not as severe as it could be and why cooling-energy savings in summertime outweigh the winter heating-energy penalty in cold climates.

First, during the winter, the solar angle is low, so reflectivity and absorption are not that important. Reflectivity and absorption are more critical during the summer, when the solar angle is high and solar radiation is hitting the roof almost normally. Figures 2-1 and 2-2 show the average solar radiation on a horizontal surface in a variety of climates in the United States and Canada. Also, data for the typical meteorological year (TMY) for four cold-climate cities of North America demonstrate that solar intensity in winter is much lower than in summer.

Figure 2-3 shows the solar intensity in four cold-climate cities of North America: Anchorage (AK), Milwaukee (WI), Montreal (QC), and Toronto (ON).

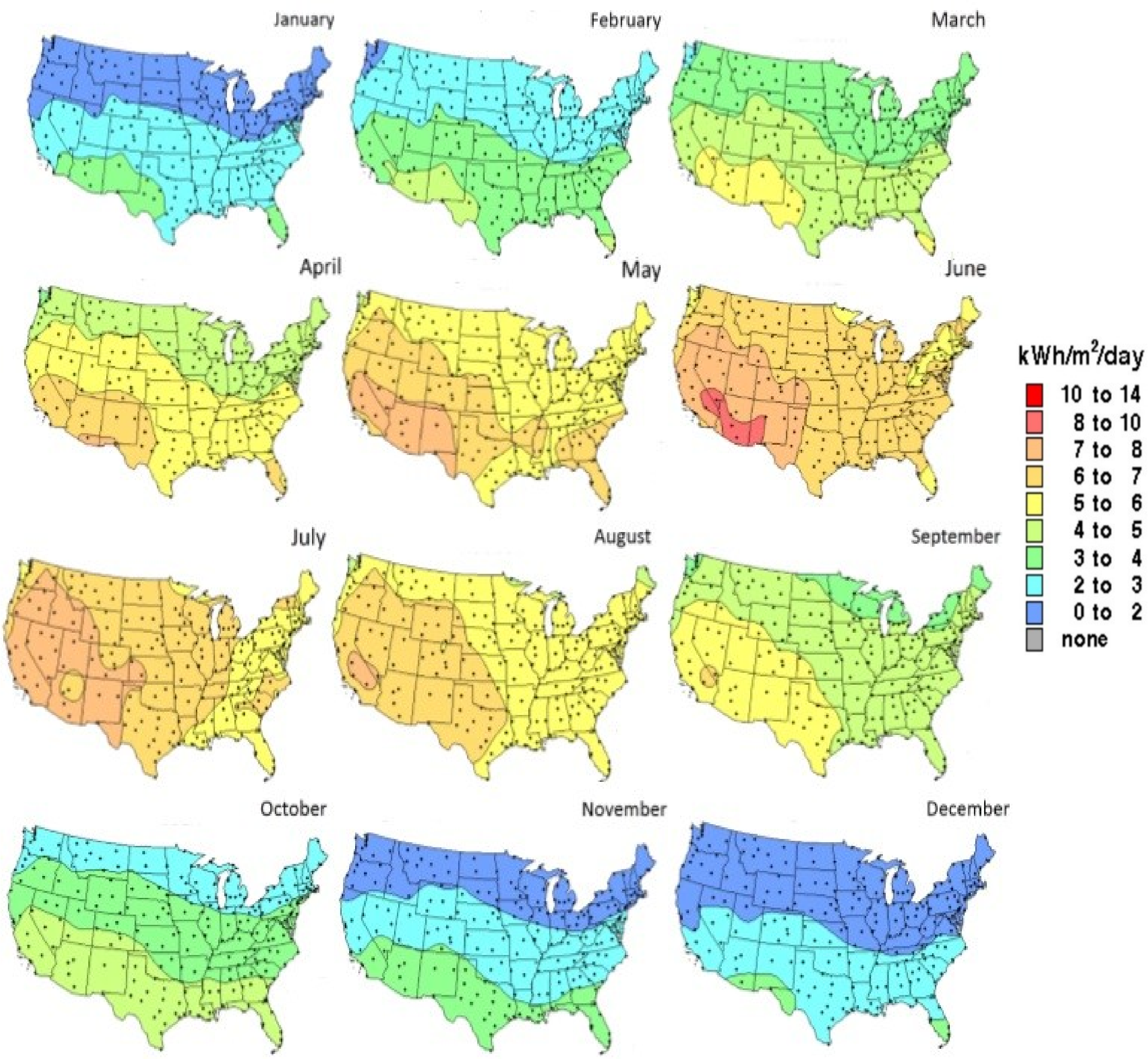


Figure 2-1. Average daily solar radiation on a horizontal surface for each month in The United States

Source:http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/

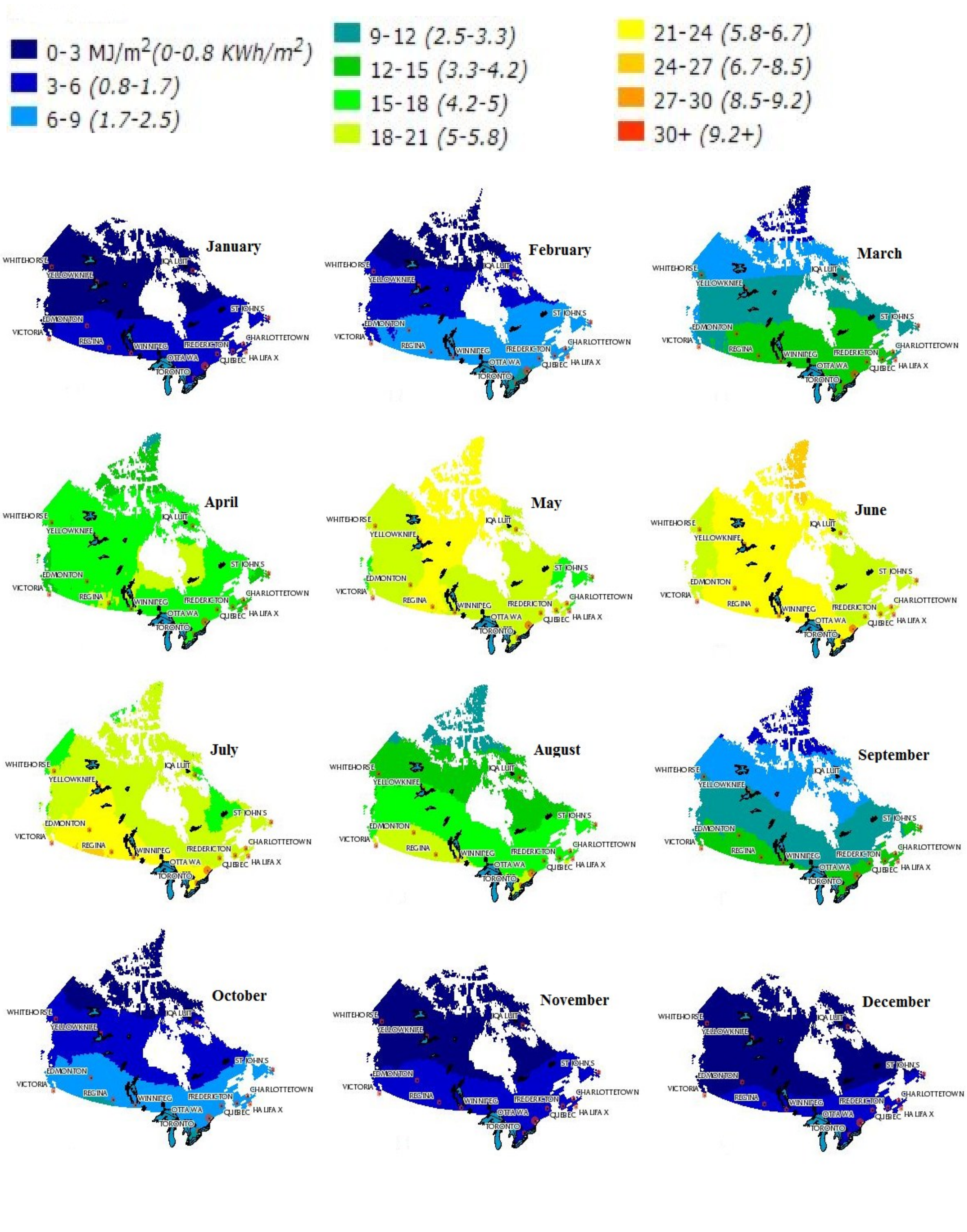


Figure 2-2. Average daily solar radiation on a horizontal surface for each month in Canada

Source: Natural Resources Canada

As figure 2-1 and 2-2 show, solar radiation is low during the heating seasons (October, November, December, January, and March) comparing with that for cooling seasons (April, May, June, July, August, and September).

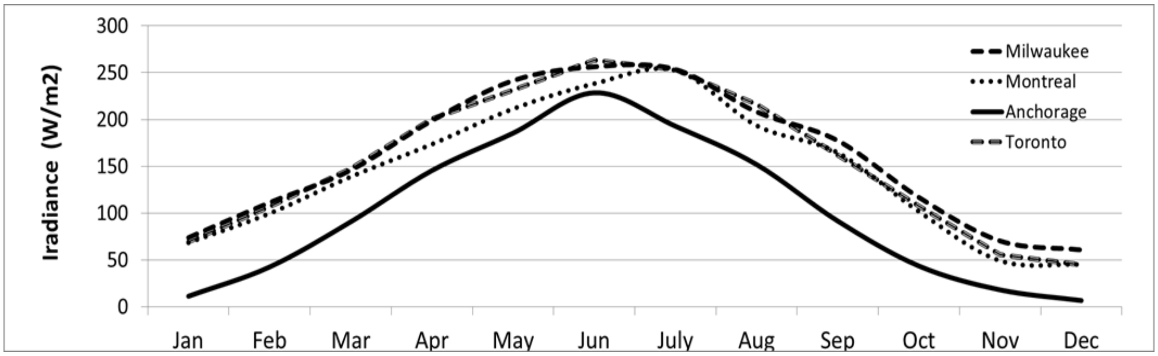


Figure 2-3. TMY Irradiance on a horizontal surface in four cold climate cities of North America

Figure 2-3 shows that Irradiance in December is much lower than that for July (by as much as a factor of almost 4) for Milwaukee, Montreal, and Toronto and this discrepancy is more intensive for Anchorage.

Second, the days during winter months are short, so there is less total radiation available on the roof to be absorbed or reflected than over the same period of time during the summer.

Third, the ratio of cloudy to sunny days increases during the winter, so again, not as much solar energy is striking the roof. Data collection from the TMY shows that, in cold climates, the sky is cloudy most days of the year, especially during heating-season days. Figure 2-4 shows the TMY cloud fraction for the four cold-climate cities in North America, while Figure 2-5 shows a winter cloudy day in a cold-climate region.

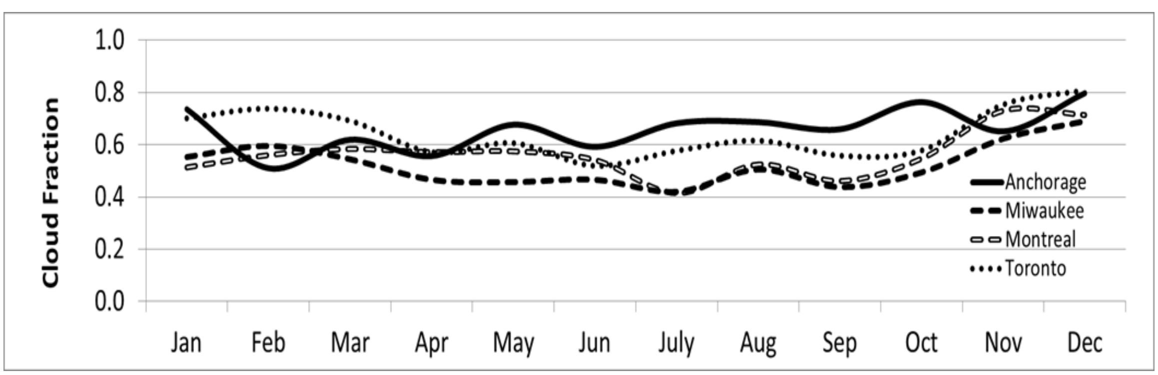


Figure 2-4. Average TMY Cloud fraction over a year in four cold cities

Figure 2-5. A winter cloudy day in cold climate region

Fourth, in most cases, heating resources like natural gas or oil are cheaper than cooling resources such as electricity (Levinson and Akbari, 2010). Table 2-2 shows the natural gas and electricity prices in four cold-climate cities of North America. In this research, actual utility tariffs that include demand charges are used to perform analysis of cool roofs (see Section 5.2.1).

Table 2-2. Electricity and natural gas rates in studied locations

	Small Office			Other Prototypes		
Location	**Electricity ($/kWh)**	**Electricity ($/GJ)**	**Natural Gas ($/GJ)**	**Electricity ($/kWh)**	**Electricity ($/GJ)**	**Natural Gas ($/GJ)**
Anchorage	0.15[a]	41.97	4.12[b]	0.096[a]	26.74	4.12[b]
Milwaukee	0.13[c]	38.73	6.89[d]	0.084[e]	23.38	5.91[d]
Montreal	0.09[f]	26.05	4.59[g]	0.047[h]	13.08	4.59[g]
Toronto	0.10[i]	28.05	8.43[j]	0.10[i]	28.05	8.43[j]

[a] Municipal Light and Power (2014), [b] ENSTAR Natural Gas Company (2014), [c] We Energies cg1 (2014), [d] We Energies natural gas tariff (2014), [e] We Energies cg3 (2014), [f] Hydro Quebec, Rate G (2014), [g] Gaz Metro (2014), [h] Hydro Quebec, Rate M (2014), [i] Toronto Hydro (2014), [j] Ontario Energy Board (2014).

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 or absorbent the roof is. Figure 2-6 shows the snow cover on a roof during the winter in Montreal.

Figure 2-6. Snow cover on a residential building roof during the winter in Montreal.

2.4 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 (Palm and Tveitereid, 1979). 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/m3, the thermal conductivity is about 0.045 Wm-1K-1 (more than six times less than that for soil), which means that, for the same depth, snow can insulate six times more effectively than soil (Pomeroy and Brun, 2001).

The thermal insulation of snow is highly dependent on the length of snow cover as well as the crystal structure and density of the surface layer. Sturm et al. (1997) studied the thermal conductivity of different types of snow. Their study showed that the effective thermal conductivity of snow varies from 0.05 $Wm^{-1}K^{-1}$ for low-density fresh snow (density=100 kg/m^3) to 0.6 $Wm^{-1}K^{-1}$ for dense drifted snow (density=500 kg/m^3). Figure 2-6 shows the thermal conductivity of different types of snow based on snow density (Sturm et al., 1997). They also suggested a regression equation to model snow's effective conductivity based on the density of the snow, as discussed below (Equation 1 and 2):

$k_{eff} = 0.138-1.01\,\rho+3.233\,\rho^2 \qquad \{0.156 < \rho < 0.6\}$

Equation 2-1

$k_{eff} = 0.023+ 0.234\,\rho \qquad \{\rho < 0.156\}$

Where ρ is in g cm^{-3} and k_{eff} is in W$m^{-1}\,K^{-1}$

A logarithmic expression can also be used:

$k_{eff} = 10^{(2.650\,\rho-1.652)} \qquad \{\rho < 0.6\}$ Equation 2-2

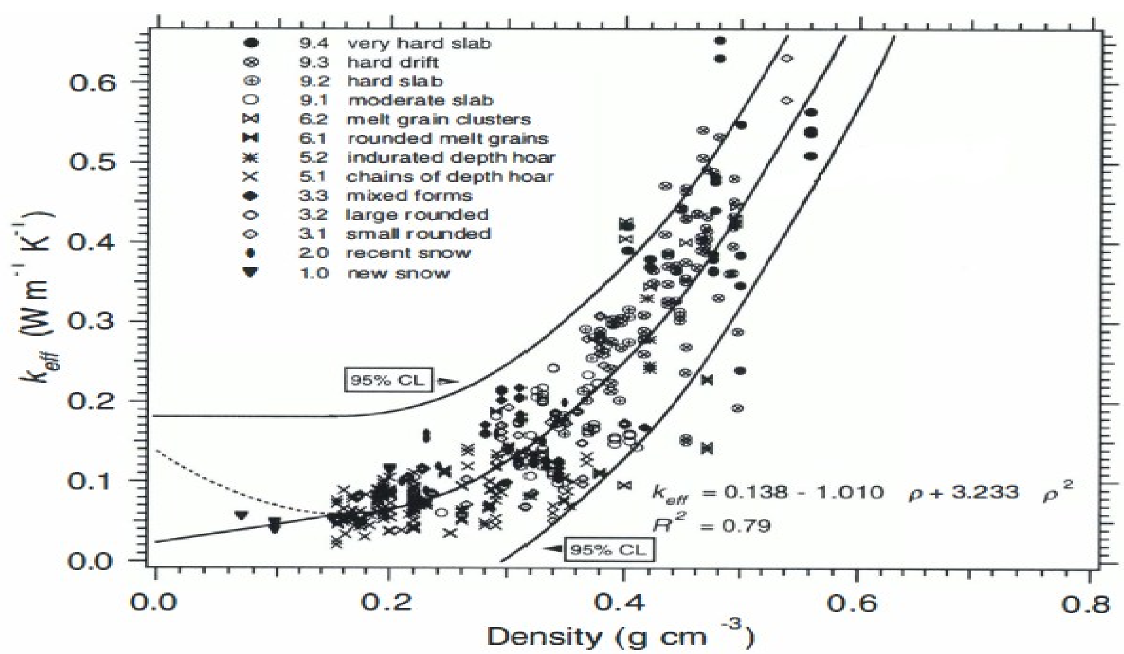


Figure 2-7. Effective thermal conductivity of snow based on crystal type and snow density courtesy by Sturm et al. (1997).

Snow reflects most shortwave radiation (it has a high albedo compared to soil), absorbs and reemits most long wave radiation (Male, 1980), and varies during the winter. The albedo of compact, dry, clean, and fresh snow is 0.8 to 0.9; it drops to 0.5 to 0.6 for aged, wet, and patchy snow; and it drops further to 0.3 to

0.4 for porous, dirty snow. A portion of shortwave radiation is not reflected and can penetrate the top 30 cm of snow cover (Pomeroy and Brun, 2001).

Gray (1970), as well as Raab and Vedin (1995), have offered the density for different types of snow as in Table 2-3:

Table 22-3: Different variety of snow density

Type of Snow	Raab and Vedin (kg/m^3)	Gray (g/cm^3)
Very loos new snow	<30	0.01-0.03
Newly-fallen dry snow	30-100	0.07-0.19
Wet, new snow	100-200	
Wind-packed snow	200	0.2-0.35
late-winter Packed snow	200-300	0.4-0.55
Thawing snow in spring	>400	0.6-0.7

Snow also acts almost as a black body; which means that snow absorbs long wave portion of solar radiation (thermal infrared) and emits it as thermal radiation. Emitted long wave radiation is depended to the fourth power of surface temperature of snow (Stefan Boltzmann law, Equation 3).

$$L = \varepsilon_s \, \sigma \, T_s^4 \qquad \text{Equation 3}$$

Where: ε_s is the surface emmisivity, σ is Stefan Boltzmann constant=5.67*10^{-8} $Wm^{-2}K^{-4}$, and T_s is the absolute surface temperature (K).

The thermal emissivity of snow varies from 0.975 to 0.995 within the wavelength of 3 to 15 μm and 0.96 to 0.99 with snow grain size for the wavelength above 15 μm (Warren, 1982). However, generally it is taken as 0.98 (Pomeroy and Brun, 2001).

Another physical properties of snow influences energy consumption of the building is the roughness of snow which impacts on the convection part of heat transfer through the roof. Snow covers are aerodynamically smooth (aerodynamic height of 0.01 to 0.7 mm) comparing most land surfaces, therefore the wind speed is greater on snow cover rather than vegetated surfaces (Pomeroy and Brun, 2001).

2.5 Conclusion

Cool roofing is a simple, energy-efficient way to effectively reduce a cooling load. It also lowers electricity usage during its peak demand and consequently reduces the electricity bill during summer air-conditioning usage while also decreasing the heat urban effect and greenhouse gas emissions.

Cool roofs, however, may increase heating-energy usage in winter. In cold climates during winter, the sun angle is lower, days are shorter, the sky is usually cloudy, and most heating occurs early in the morning or in the evening hours when the solar intensity is low. In addition, the roof may be covered with snow for most of the heating season. All of these factors lead to wintertime heating penalties for cool roofs that are far lower than what is commonly thought.

Snow, as a porous medium, has unique properties that can influence the heating-energy consumption of the building. Therefore, the current study has responded to the need to study the operation of cool roofs in cold climates and accurately demonstrate its associated energy and cost penalties or savings.

Chapter 3: Methodology

A simulation study performed to quantify the effect of roof snow on a building's energy consumption. In this chapter first the two major building-energy simulation models and their capabilities are presented. The fundamentals of the selected model, which is used for simulating the building prototypes with various characteristics in different cold-climate regions are also discussed. In the simulations, the original algorithm of the program is modified to account for the effect of snow regarding solar reflectance and thermal conductance.

3.1 Building energy simulation computer programs

There are many building-energy simulation computer programs in the building industry. The US Department of Energy has a list of 115 such programs (US Department of Energy, list of building energy simulation tools); however, some of them are not up-to-date, and others have not been free to the public in the last decade. DOE-2 and EnergyPlus have been two major building-energy simulation programs widely used by building-energy industry researchers.

3.1.1 DOE-2

DOE-2 is a freeware building energy analysis program; one of the most flexible hourly, building energy analysis program calculating energy performance. It can be used to model energy efficiency of existing buildings and new efficiency technologies. According to DOE-2 official website "it uses a description of the building layout, constructions, operating schedules, conditioning systems and utility rates provided by the user, along with weather data, to perform an hourly simulation of the building and to estimate utility bills. The source code as well as engineering manual are offered therefore, the users can add or modify components which are not considered in regular runs; that's why it is highly used by the researchers; however DOE-2 program is a "DOS box" or "batch" program which requires substantial experience to learn to use effectively" (DOE2 official website).

DOE-2 is widely used to predict energy consumption and costs of thousands of well-known buildings in the United States such as: The White House, World Trade Center, Sears Tower, Hirschhorn Museum, Boston City Hall, New York State Capitol, Texas State Capitol, Ronald Reagan Library, U.S. State Department, NREL Laboratory, Bank of Boston, Pacific Museum of Flight, Peachtree Place, One Magnificent Mile; and also some buildings in other countries such as: National Library (France), New Parliament House (Australia), Berlin Holocaust Center, Nestle' Headquarters (Switzerland), U.S. Embassy (Berlin) DOW Europe (Switzerland) Renault Technocenter (France), Citibank Plaza (Hong Kong) (LBL, Lawrence Berkeley National Lab, DOE-2 website).

3.1.2 EnergyPlus

EnergyPlus is the model that the US Department of Energy has committed to support. It is an accurate building energy simulation program with vast detailed simulation capabilities developed based on the most popular features of BLAST and DOE-2. According to department of energy website “the weather data for more than 1250 locations gives a big chance to worldwide users to simulate different types of Buildings”. However, EnergyPlus is a stand-alone simulation program without a user-friendly graphical interface. It reads input and writes output as text files which may increase the time of modeling (Department of energy website, EnergyPlus simulation software).

3.2 Selected simulation model

After studying different simulation models, DOE-2.1E was selected in order to demonstrate the energy behavior of cool roofs in cold climates because of: First, it’s one of the most accurate building energy simulation model (Zhu et al, 2012) and is widely used for building energy simulation in different climates. Second, it’s free and available to use for public. Third, the running time is short comparing with other simulation programs. Fourth, its flexibility let the researches to reach the source and add or modify majority of components which are not considered in normal runs (specifically in this study DOE-2 let the user to modify the roof heat equation to model the roof snow).

3.2.1 Governing equations

According to DOE-2 engineers manual (DOE-2 Engineers Manual, 1982) heat balance equation at the outside roof surface is as Equation 3-1:

$q_{out} = q_1 + q_2 - q_3$ Equation 3-1

Where:

q_1 The energy absorbed by the surface from direct solar radiation, diffuse sky radiation, and short wave radiation reflected from the ground; that is Equation 3-2. Table 3-1 shows all the parameter description.

q_1 = SOLI * α Equation 3-2

q_2 Energy from convective and long wave interchange with the air; that is Equation 4-3:

q_2 = FILMU * (DBTR -T_s) Equation 3-3

q_3 Long wave reradiation. 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 as Equation 3-4:

$q_{in} = q_{out}$ = U * (T_s - T_{zone}) Equation 3-4

Here, U is the combined conductance of the roof and inside film. Thus, it can be written as Equation 3-5:

U (T_s-T_{zone}) = (SOLI*α) + FILMU (DBTR-T_s) – SKY Equation 3-5

The long Wave reradiation to the sky is estimated by assuming that the clear sky from roof surface should be 63 W/m^2 (20 Btu/ (hr-ft^2)). When the sky is covered by clouds, the assumption is made that no reradiation 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-CLDAMT) Equation 3-6

Solving for T_s , the outside roof surface temperature yields

$$T_s = \frac{(SOLI*\alpha)+(FILMU*DBTR)+(U*T_{ZONE})-SKY}{(U+FILMU)}$$ Equation 3-7

Once T_s is known, the total heat flow at the inside surface can be written as Equation 3-8:

Q = U* SAREA * (T_s - T_{zone}) Equation 3-8

Equations 3-1 to 3-8 are solved simultaneously (for each hour) to calculate the heat gain throughout the roof.

Table 3-1 Variable list of heat balance equation on the roof

VARIABLE	DESCRIPTION
FILMU	The combined radiative and convective outside surface conductance in Btu/(hr-ft^2-°F)
CLDAMT	Cloud amount in tenths
SKY	Heat loss by roof surface to sky in Btu/(hr-ft^2)
T_s	Outside roof surface temperature in Rankin
SOLI	Solar radiation incident on outside roof surface from direct, diffuse, and reflected radiation in Btu/(hr-ft^2)
α	Roof surface absorptivity
DBTR	Outside surface temperature in Rankin
U	Conductance of the wall exclusive of the outside air film (includes a combined inside film coefficient in Btu/(hr-ft^2-°F)
T_{zone}	The constant space temperature in Rankin
Q	Heat flow through the inside roof surface in Btu/hr
SAREA	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.

3.2.2 Structure of DOE-2

DOE-2 consists of one translation subprogram (BDL processor) translating text input of user to the language known for the program and four simulation subprograms (LOADS, SYSTEMS, PLANT, and ECON) which are performed serially so that the output of LOADS become the input for HVAC (including SYSTEMS and PLANT) and its output is then the input for ECON, which predicts the conditioning expenditure.

Figure 3-1 shows the flowchart of DOE-2 (Lawrence Berkeley National Lab, DOE-2 website).

3.2.3 Required data input for simulations

The required input data generally consists of following components:

- The geometry and composition of building envelop
- Building materials and characteristics
- Internal zones characteristic
- Schedules
- Indoor and outdoor conditions
- HVAC characteristics
- Energy source prices

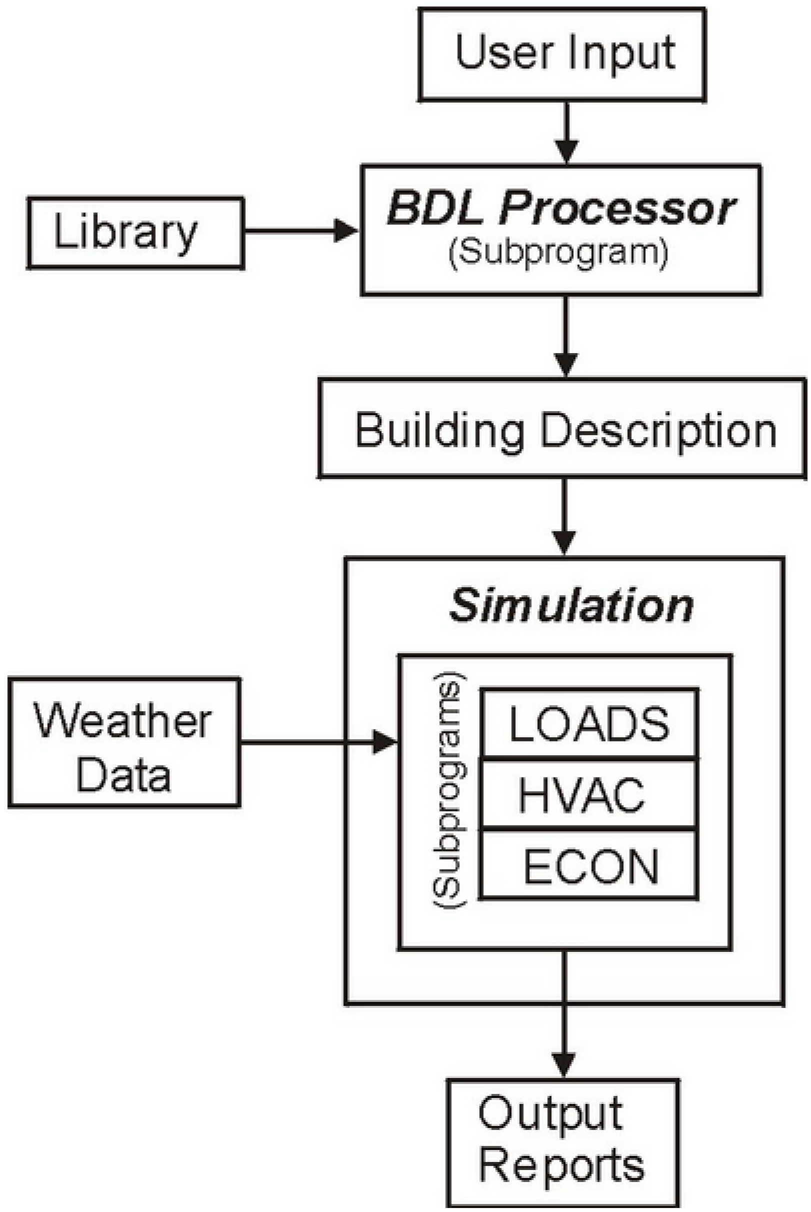


Figure 3-1. DOE-2 flowchart (Lawrence Berkeley National Lab, DOE-2 website)

3.3 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 covers, meteorological data previously provided by the National Oceanic and Atmospheric Administration were applied for the first two cities and

Environment Canada for the next two cities. Figures 3-2 and 3-3 show the outside air temperature and snow cover on a flat surface in the studied locations. Note that snow covers flat surfaces from mid-October to mid-April in Anchorage.

Different types of snow have different thermal conductivity, specific heat and also may have different absorptivity (or reflectivity).

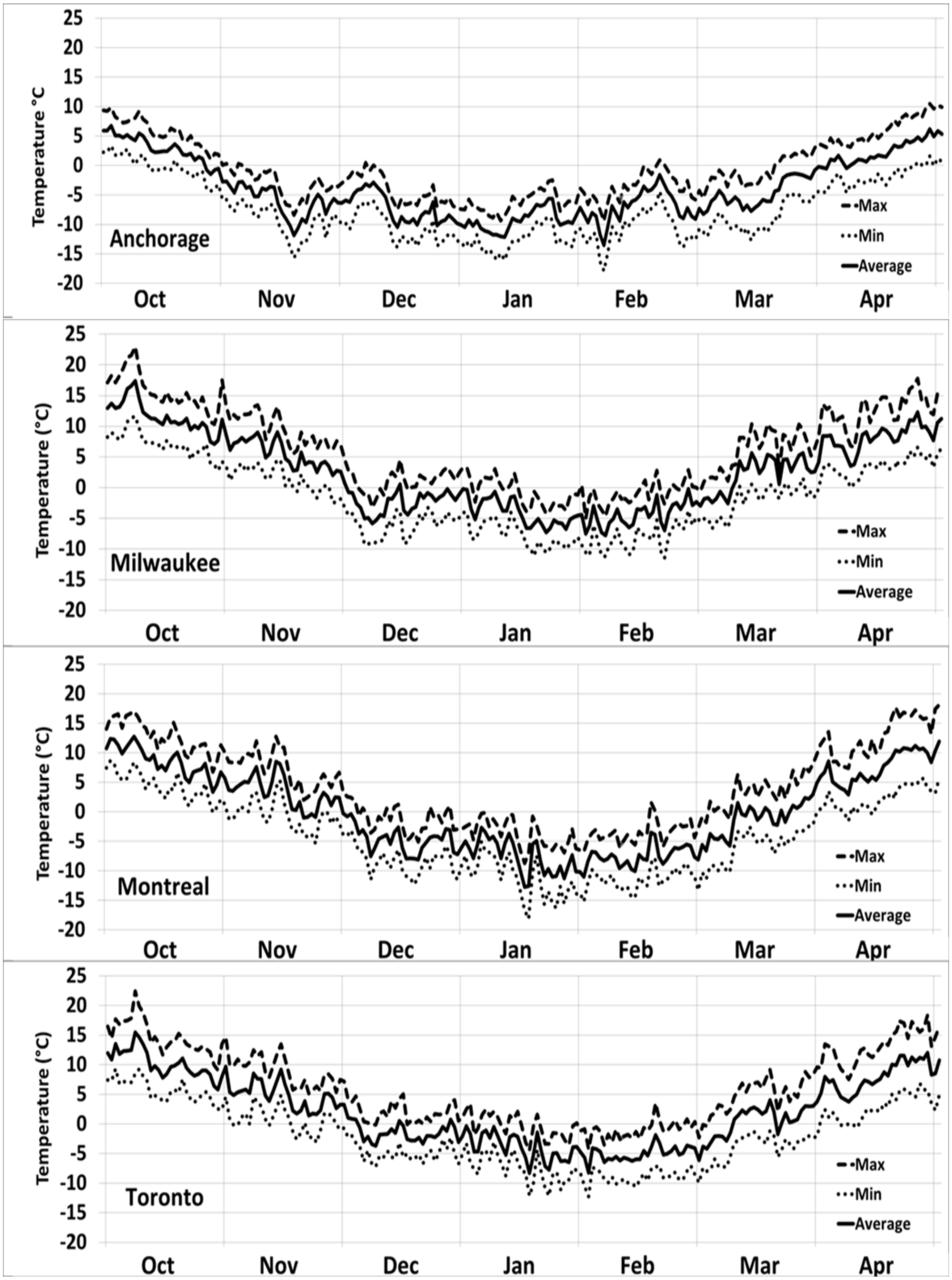
3.3.1 Thermal conductivity of snow

In this study, four types of snow were considered based on density. Depending on density, different snow has different thermal conductivity. Gray (1970) and Sturm et al. (1977) provide data for the thermal conductivity of different snow types, summarized in Table 3-2 (also see Equation 2-1 and Table 2-3).

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 (DOE-2 Basics, 1991). 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 modelled as a quick wall rather than a delay wall; therefore, the thermal storage effect of the roof materials and snow is ignored.

Table 3-2. Effective thermal conduction for different snow type

Type of Snow	$\boldsymbol{k_{eff}(Wm^{-1}\,K^{-1})}$
Very loos new snow	0.0276
Newly-fallen dry snow	0.059
Wind-packed snow	0.1259
Late-winter Packed snow	0.4412



. *Figure 3-2: Six years average of outside air temperature in different locations*

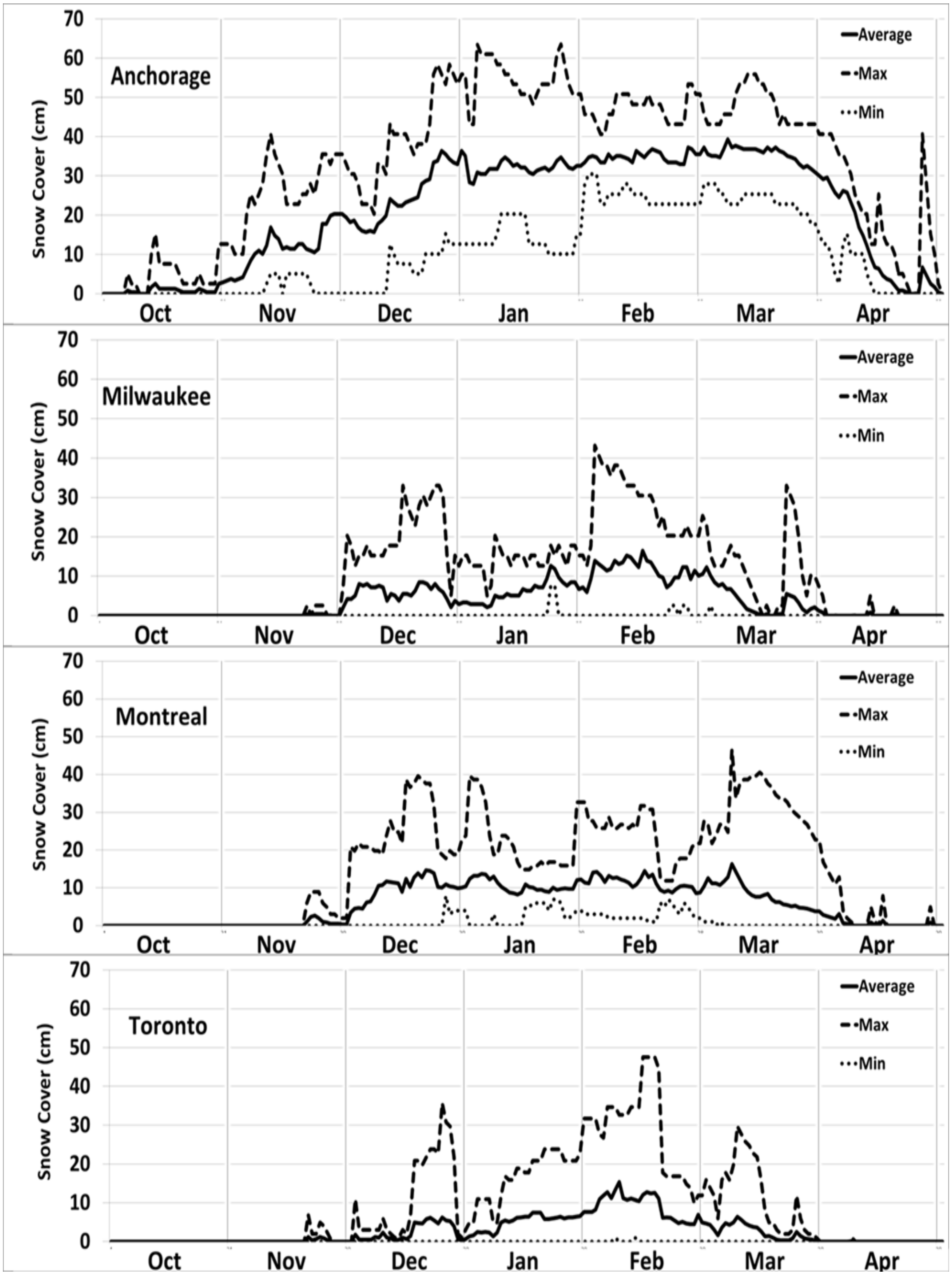


Figure 3-3. Six years average of snow thickness in different locations

For finding the overall U-value of the roof considering the snow, the following equation was used:

$R_{overall} = R_{roof} + R_{snow}$ Equation 3-9

Where: $R_{overall}$ The overall thermal resistance of the roof

R_{roof} Thermal resistance of the roof including inside film resistance (but not outside film resistance)

R_{snow} Thermal resistance of snow. From the previous equation:

$$\frac{1}{U_{overall}} = \frac{1}{U_{roof}} + \frac{1}{U_{snow}}$$ Equation 3-10

$$U_{snow} = \frac{k_{eff}}{l}$$ Equation 3-11

Where: k_{eff} thermal conductivity of snow from Table 3-2, and l is daily thickness of snow (Figure 3-3).

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

3.3.2 Solar reflectivity of snow

Snow on the roof also changes its solar reflectivity. As mentioned earlier, 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 length of the snow as well as the solar reflectivity of the roof surface. SNICAR (SNICAR-online website), 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. Figure 3-4 shows various snow-types' solar reflectance based on the snow thickness and type of roof (cool or dark) calculated using SNICAR.

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

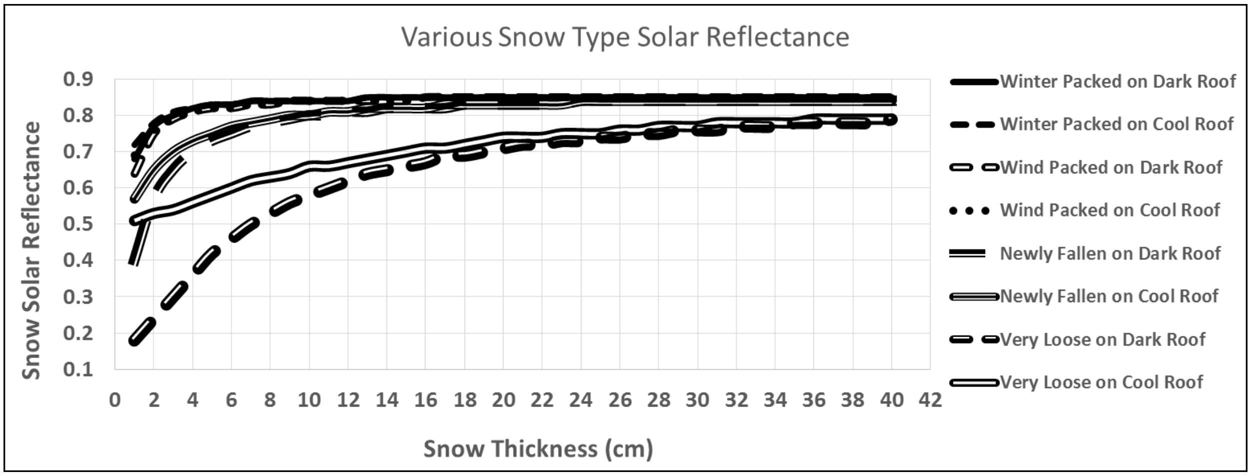


Figure 3-4. Various snow type solar reflectance with respect to snow thickness and the type of roof

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. Figure 3-5 shows the snow-modeling process flowchart. First, the average snow thickness was calculated in an Excel file. Then, for each snowy day, solar reflectance was calculated using SNICAR software, 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 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.

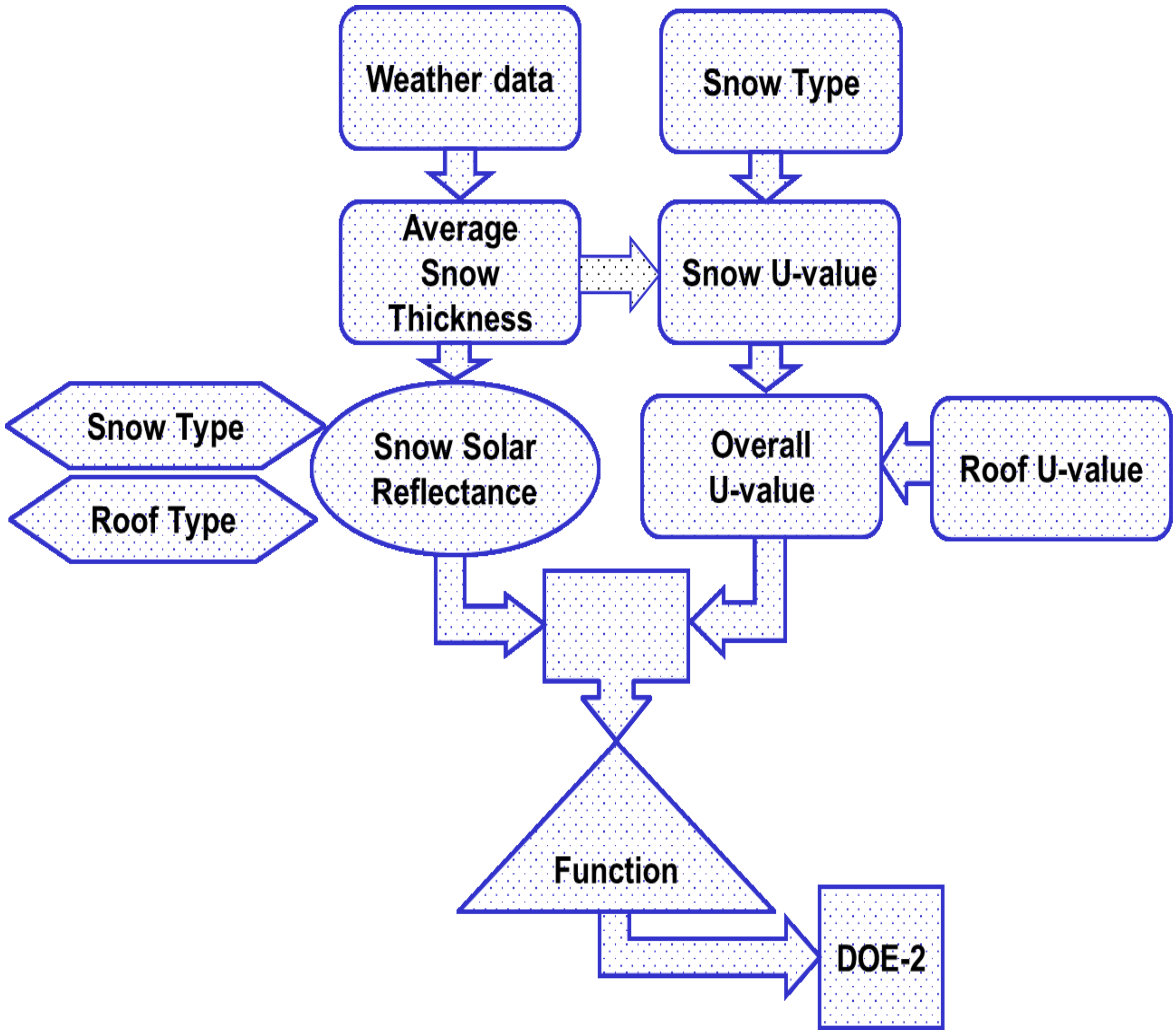


Figure 3-5. Snow modeling process flowchart

Roof slope can be an important factor in the effect of snow on a building's energy consumption. If the slope of the roof changes, solar radiation absorbed by the roof changes, too. Also, slope may help the snow disappear sooner and thus impact the duration of snow accumulation on the roof. It should be mentioned that only flat roofs were considered for the buildings in this study.

Chapter 4: Prototypical Building Characteristics

A small single story (511 m²), a medium three-story (4985 m^2), a large three-story (14515 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 (http://www.energycodes.gov/commercial-prototype-building-models). The new small office prototype offered by DOE is modelled with slope roof; however, since in this study it is focused on the flat roofs, the new small office is modelled 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 (Deru et al., 2011). For new construction, we used ASHRAE standard 90.1 (ASHRAE 90.1, 2007) for Anchorage and Milwaukee. Data from the National Energy Code of Canada was used for Buildings (NECB, 2011) with new constructions in Montreal and Toronto.

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 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 4-1 to 4-20 show the prototypes' characteristics in each location. 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.

Tables 4-21 to 4-24 show the buildings' operation schedules. The schedules for each office building are the same; however, the old and new prototypes have different operation schedules and set points.

Table 4-1.Old and new small office shape

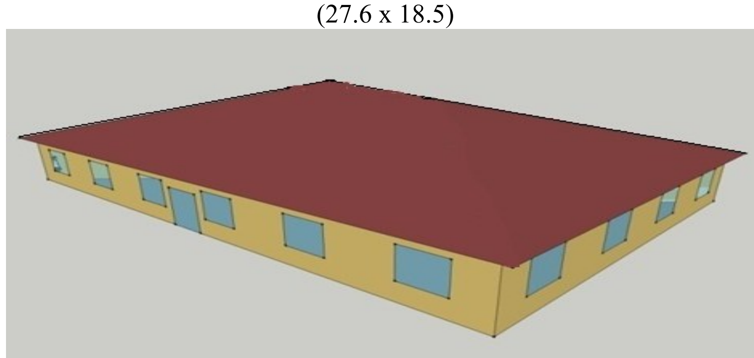
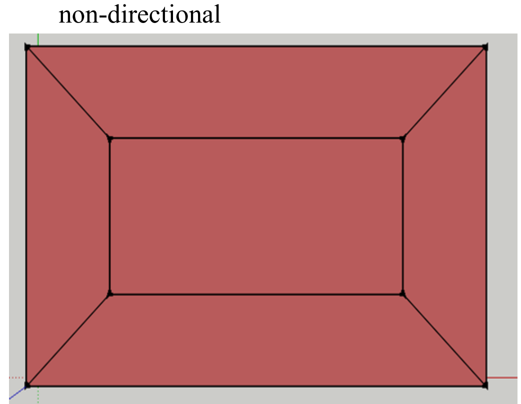
Item	Descriptions
General	
Vintage	Old and new construction
Location	Anchorage, Milwaukee, Montreal, Toronto
Available fuel types	gas, electricity
Building Type (Principal Building Function)	office
Building Prototype	small Office
Form	
Total Floor Area (sq meter)	511 (27.6 x 18.5)
Building shape	
Aspect Ratio	1.5
Number of Floors	1
Window Fraction (Window-to-Wall Ratio)	24.4% for South and 19.8% for the other three orientations (Window Dimensions: 1.8 m x 1.5 m punch windows for all facades)
Window Locations	evenly distributed along four facades
Azimuth	non-directional
Thermal Zoning	Perimeter zone depth: 5 m Four perimeter zones, one core zone and one plenum zone Percentages of floor area: Perimeter 70%, Core 30% 
Floor to roof height (meter)	3
Floor to ceiling height (meter)	no ceiling for old construction, 2.7 for new construction
Glazing sill height (meter)	0.9 (top of the window is 2.4 high with 1.5 high glass)

Table 4-2. Old small office envelope

Envelope	
Exterior walls	
Construction	Steel Frame Wood Siding,Insulation,1/2 in Gypsum Board
U-factor (W/m^2K)	0.845, for Anchorage 0.788
Roof	
Construction	Built-up Roof: roof membrane + roof insulation + metal decking
U-factor (W/m^2K)	0.35
Tilts and orientations	horizontal
Window	
Dimensions	punch window, each 1.5 m high by 1.8 m wide
Number of Panes	2
U-factor (W/m^2K)	2.96
Shading Coefficient	0.47
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	8" Heavy weight concrete slab poured directly on to the earth
Thermal properties for ground level floor U-factor (W/m^2K)	0.17
Interior Partitions	
Construction	2 x 4 uninsulated stud wall
Air Barrier System	
Infiltration	0.00167 $m^3/s/m^2$ of floor area

Table 4-3. Old small office HVAC characteristics

HVAC	
System Type 1	
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
Air Conditioning COP	Deru et. Al, 2011
Heating Efficiency	78%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 40°C, Minimum 14°C
Economizers	No
Ventilation (outdoor air liter/minutes/person)	595
Supply Fan	
Supply Fan Mechanical Efficiency (%)	65%
Supply Fan Pressure Rise (Pa)	747
Lighting	
Average power density (W/m^2)	19.3
Plug load	
Average power density (W/m^2)	8
Occupancy	
Area (m^2)/Person	18.5

Table 4-4. New small office envelope

Envelope	
Exterior walls	
Construction	Wood-Frame Walls (2X4 16IN OC) 1in. Stucco + 5/8 in. gypsum board + wall Insulation+ 5/8 in. gypsum board
U-factor (W/m^2K)	0.289, for Montreal and Toronto 0.244
Roof	
Construction	Built-up Roof: roof membrane +roof insulation + metal decking
U-factor (W/m^2K)	0.27, for Montreal and Toronto 0.18
Tilts and orientations	horizontal
Window	
Dimensions	punch window, each 1.5 m high by 1.8 m wide
Number of Panes	2
U-factor (W/m^2K)	for Milwaukee 2.25, for Anchorage 2.02, for Montreal and Toronto 1.969
Shading Coefficient	0.44, for Anchorage 0.51
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	8" Heavy weight concrete slab poured directly on to the earth
Thermal properties for ground level floor U-factor (W/m^2K)	0.12, for Anchorage 0.09
Interior Partitions	
Construction	2 x 4 uninsulated stud wall
Air Barrier System	
Infiltration	0.001024 $m^3/s/m^2$ of above ground envelope area

Table 4-5. New small office HVAC characteristics

HVAC	
System Type 1	
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
HVAC Efficiency	
Air Conditioning COP	ASHRAE 90.1
Heating Efficiency	80%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 40°C, Minimum 13°C
Economizers	No
Ventilation (outdoor air liter/minutes)	3880,2917,1727,2917,1727 for Core and Zones 1 to 4
Supply Fan	
Supply Fan Total Efficiency (%)	53
Supply Fan Pressure Rise (Pa)	623
Internal Loads & Schedules	
Lighting	
Average power density (W/m^2)	10.7
Plug load	
Average power density (W/m^2)	6.7
Occupancy	
Area (m^2)/Person	16.5

Table 4-6. Old and new medium office shape

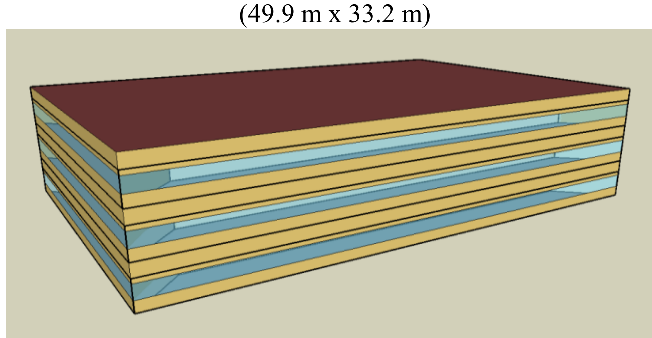
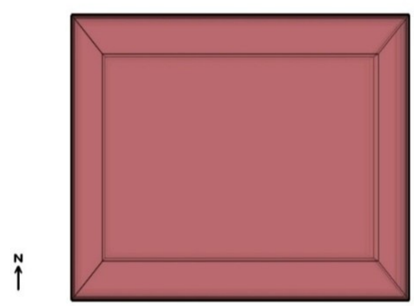
Item	Descriptions
General	
Vintage	Old and new construction
Location	Anchorage, Milwaukee, Montreal, Toronto
Available fuel types	gas, electricity
Building Type (Principal Building Function)	office
Building Prototype	medium office
Form	
Total Floor Area (sq meter)	4985 (49.9 m x 33.2 m)
Building shape	
Aspect Ratio	1.5
Number of Floors	3
Window Fraction (Window-to-Wall Ratio)	33% (Window Dimensions: 49.9 m x 1.3 m on the long side of facade 33.2 m x 1.3 m on the short side of the façade)
Window Locations	even distribution among all four sides
Azimuth	non-directional
Thermal Zoning	Perimeter zone depth: 4.57 m Each floor has four perimeter zones and one core zone. Percentages of floor area: Perimeter 40%, Core 60% 
Floor to roof height (meter)	3.96
Floor to ceiling height (meter)	2.75 (1.2 m above-ceiling plenum)
Glazing sill height (meter)	1 m (top of the window is 2.3 m high with 1.3 m high glass)

Table 4-7. Old medium office envelope

Envelope	
Exterior walls	
Construction	Steel-Frame Walls Wood Siding + wall Insulation+1/2 in Gypsum Board.
U-factor (W/m^2K)	0.817, for Anchorage 0.771
Roof	
Construction	Built-up Roof: roof membrane + roof insulation + metal decking
U-factor (W/m^2K)	0.35
Tilts and orientations	horizontal
Window	
Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
Number of Panes	2
U-factor (W/m^2K)	2.96
Shading Coefficient	0.47
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	4" Heavy weight concrete slab poured directly on to the earth
Thermal properties for ground level floor U-factor (W/m^2K)	0.28
Interior Partitions	
Construction	2 x 4 uninsulated stud wall
Air Barrier System	
Infiltration	0.0076 $m^3/s/m^2$ of above ground envelope area

Table 4-8. Old medium office HVAC characteristics

HVAC	
System Type 1	
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
HVAC Efficiency	
Air Conditioning COP	Deru et. al, 2011
Heating Efficiency	78%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 40°C, Minimum 14°C
Economizers	Limit Temperature = 24° C
Ventilation (outdoor air liter/minute/person)	595
Supply Fan	
Supply Fan Total Efficiency (%)	54
Supply Fan Pressure Rise (Pa)	747
Lighting	
Average power density (W/m^2)	16.8
Plug load	
Average power density (W/m^2)	8
Occupancy	
Area (m^2)/Person	18.5

Table 4-9. New medium office envelope

Envelope	
Exterior walls	
Construction	Steel-Frame Walls 0.4 in. Stucco+5/8 in. gypsum board + wall Insulation+5/8 in.
U-factor (W/m^2K)	0.346, for Montreal and Toronto 0.244
Roof	
Construction	Built-up Roof: roof membrane + roof insulation + metal decking
U-factor (W/m^2K)	0.27, for Montreal and Toronto 0.18
Tilts and orientations	horizontal
Window	
Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
Number of Panes	2
U-factor (W/m^2K)	For Milwaukee 2.25, for Anchorage 2.02, for Montreal and Toronto 1.969
Shading Coefficient	0.44, for Anchorage 0.51
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	8" concrete slab poured directly on to the earth
Thermal properties for ground level floor U-factor (W/m^2K)	0.13
Interior Partitions	
Construction	2 x 4 uninsulated stud wall
Air Barrier System	
Infiltration	0.001024 $m^3/s/m^2$ of above ground envelope area

Table 4-10. New medium office HVAC characteristics

HVAC	
System Type 1	
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
HVAC Efficiency	
Air Conditioning COP	ASHRAE 90.1
Heating Efficiency	80%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 40°C, Minimum 13°C
Economizers	No
Ventilation (outdoor air liter/minutes/person)	566
Supply Fan	
Supply Fan Total Efficiency (%)	62
Supply Fan Pressure Rise (Pa)	623
Lighting	
Average power density (W/m^2)	10.7
Plug load	
Average power density (W/m^2)	6.7
Occupancy	
Area (m^2)/Person	16.5

Table 4-11. Old and new large office shape

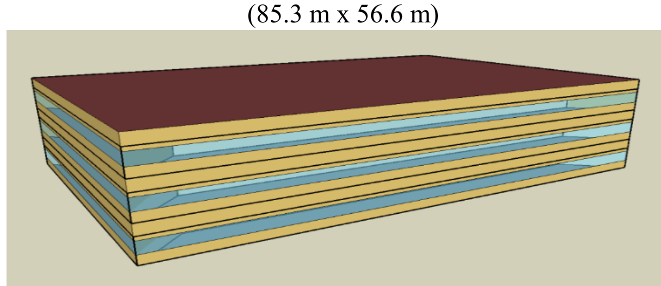
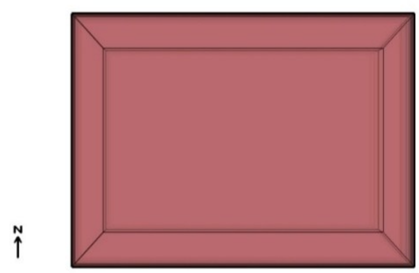
Item	Descriptions
General	
Vintage	old and new construction
Location	Anchorage, Milwaukee, Montreal, Toronto
Available fuel types	gas, electricity
Building Type (Principal Building Function)	office
Building Prototype	Large office
Form	
Total Floor Area (sq meter)	14515 (85.3 m x 56.6 m)
Building shape	
Aspect Ratio	1.5
Number of Floors	3
Window Fraction (Window-to-Wall Ratio)	33% (Window Dimensions: 85.3 m x 1.3 m on the long side of facade 56.6 m x 1.3 m on the short side of the façade)
Window Locations	even distribution among all four sides
Azimuth	non-directional
Thermal Zoning	Perimeter zone depth: 4.57 m Each floor has four perimeter zones and one core zone. Percentages of floor area: Perimeter 40%, Core 60% 
Floor to roof height (meter)	3.96
Floor to ceiling height (meter)	2.75 (1.2 m above-ceiling plenum)
Glazing sill height (meter)	1 m (top of the window is 2.3 m high with 1.3 m high glass)

Table 4-12. Old large office envelope

General	
Exterior walls	
Construction	Wood-Frame Walls (2X4 16IN OC) 1in. Stucco + 5/8 in. gypsum board + wall Insulation+ 5/8 in. gypsum board
U-factor (W/m^2K)	0.822, for Anchorage 0.771
Roof	
Construction	Built-up Roof: roof membrane + roof insulation + metal decking
U-factor (W/m^2K)	0.35
Dimensions	based on floor area and aspect ratio
Tilts and orientations	horizontal
Window	
Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
Number of Panes	2
U-factor (W/m^2K)	2.96
Shading Coefficient	0.47
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	8" Heavy weight concrete slab poured directly on to the earth
Thermal properties for ground level floor U-factor (W/m^2K)	0.28
Interior Partitions	
Construction	2 x 4 uninsulated stud wall
Air Barrier System	
Infiltration	0.0076 $m^3/s/m^2$ of above ground envelope area

Table 4-13. Old large office HVAC characteristics

HVAC	
System Type 1	
Heating type	VAV Central Heating with Gas Fired Boiler
Cooling type	VAV Central Cooling with Hermetic Reciprocating Chiller
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
HVAC Efficiency	
Air Conditioning COP	5.12
Heating Efficiency	76%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 40°C, Minimum 13°C
Economizers	Limit Temperature = 28° C
Ventilation (outdoor air liter/minute/person)	597
Supply Fan	
Supply Fan Total Efficiency (%)	61
Supply Fan Pressure Rise (Pa)	1018
Lighting	
Average power density (W/m^2)	16.1
Plug load	
Average power density (W/m^2)	8
Occupancy	
Area (m^2)/Person	18.5

Table 4-14. New large office envelope

Envelope	
Exterior walls	
Construction	Wood-Frame Walls (2X4 16IN OC) 1in. Stucco + 5/8 in. gypsum board + wall Insulation+ 5/8 in. gypsum board
U-factor (W/m^{2}K)	0.289, for Montreal and Toronto 0.244
Roof	
Construction	Built-up Roof: roof membrane + roof insulation + metal decking
U-factor (W/m^{2}K)	0.27, for Montreal and Toronto 0.18
Tilts and orientations	horizontal
Window	
Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
Number of Panes	2
U-factor (W/m^{2}K)	for Milwaukee 2.25, for Anchorage 2.02, for Montreal and Toronto 1.969
Shading Coefficient	0.44, for Anchorage 0.51
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	8" Heavy weight concrete slab poured directly on to the earth
Thermal properties for ground level floor U-factor (W/m^{2}K)	0.14, for Anchorage 0.11
Interior Partitions	
Construction	2 x 4 uninsulated stud wall
Air Barrier System	
Infiltration	0.001024 m^3/s/m^2 of above ground envelope area

Table 4-15. New large office HVAC characteristics

HVAC	
System Type 1	
Heating type	VAV Central Heating with Gas Fired Boiler
Cooling type	VAV Central Cooling with Hermetic Reciprocating Chiller
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
HVAC Efficiency	
System 1 Air Conditioning COP	6.09
System 1 Heating Efficiency	80%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 50 °C, Minimum 13 °C
Economizers	Limit Temperature = 16 °C
Ventilation (outdoor air liter/minutes/person)	566
Supply Fan	
Supply Fan Total Efficiency (%)	61
Supply Fan Pressure Rise (Pa)	1018
Lighting	
Average power density (W/m^2)	10.7
Plug load	
Average power density (W/m^2)	6.7
Occupancy	
Area (m^2)/Person	16.5

Table 4-16. Old and new retail shape

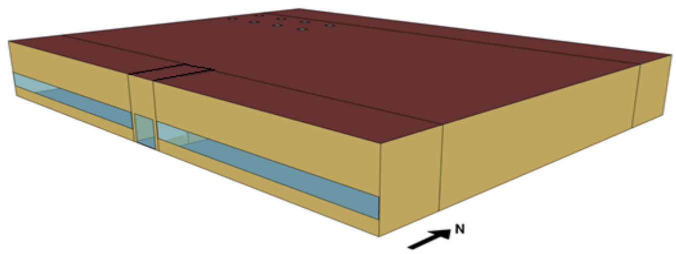
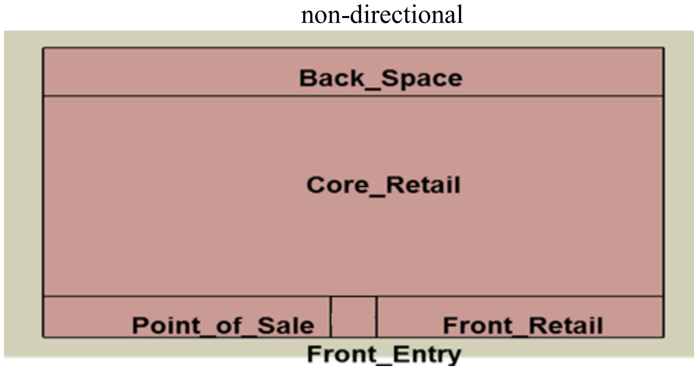
Item	Descriptions
General	
Vintage	old and new construction
Location	Anchorage, Milwaukee, Montreal, Toronto
Available fuel types	gas, electricity
Building Type (Principal Building Function)	retail
Building Prototype	standalone retail
Form	
Total Floor Area (sq meter)	2299 (54.2 m x 42.3 m)
Building shape	
Aspect Ratio	1.28
Number of Floors	1
Window Fraction (Window-to-Wall Ratio)	7.1% (Window Dimensions: 25 m x 1.5 m, 3 m x 2.6 m and 25 m x 1.5 m on the street facing facade)
Window Locations	Windows only on the street facing façade (25.4% WWR)
Azimuth	non-directional
Thermal Zoning	
Floor to roof height (meter)	6.1
Floor to ceiling height (meter)	No ceiling
Glazing sill height (feet)	1.5 m (top of the window is 2.6 m high with 1.1 m high glass)

Table 4-17. Old retail envelope

Envelope	
Exterior walls	
Construction	Steel-Frame Walls Wood Siding + wall Insulation+1/2 in Gypsum Board.
U-factor (W/m^{2}K)	0.822, for Anchorage 0.771
Roof	
Construction	Built-up Roof: roof membrane + roof insulation + metal decking
U-factor (W/m^{2}K)	0.35
Tilts and orientations	horizontal
Window	
Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
Number of Panes	2
U-factor (W/m^{2}K)	2.96
Shading Coefficient	0.47
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	6" concrete slab poured directly on to the earth with carpet
Thermal properties for ground level floor U-factor (W/m^{2}K)	0.17
Interior Partitions	
Construction	0.5 in gypsum board + 0.5 in gypsum board
Air Barrier System	
Infiltration	0.0076 m^3/s/m^2 of above ground envelope area

Table 4-18. Old retail HVAC characteristics

HVAC	
System Type 1	
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
HVAC Efficiency	
Air Conditioning COP	Deru et. Al, 2011
Heating Efficiency	78%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 40°C, Minimum 14°C
Economizers	Limit Temperature = 28° C
Ventilation (outdoor air liter/minute/person)	597
Supply Fan	
Supply Fan Total Efficiency (%)	Core 58, Point of sale and Front retail, and Entry 52, Back space 54
Supply Fan Pressure Rise (Pa)	623, Entry 498
Lighting	
Average power density (W/m^2)	12.5, Core zone 36.2
Plug load	
Average power density (W/m^2)	3.2, Point of sale 21.5 and back space 8
Occupancy	
Area (m^2)/Person	6.2, back space 27.8

Table 4-19. New retail envelope

Envelope	
Exterior walls	
Construction	Concrete Block Wall: 8 in. CMU + Wall Insulation + 0.5 in. gypsum board
U-factor (W/m^2K)	for Milwaukee 0.45, for Anchorage 0.4, for Montreal and Toronto 0.244
Roof	
Construction	Built-up Roof: roof membrane + roof insulation + metal decking
U-factor (W/m^2K)	0.27, for Montreal and Toronto 0.18
Tilts and orientations	horizontal
Window	
Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
Number of Panes	2
U-factor (W/m^2K)	for Milwaukee 2.25, for Anchorage 2.02, for Montreal and Toronto 1.969
Shading Coefficient	0.44, for Anchorage 0.51
Foundation	
Foundation Type	Slab-on-grade floors (unheated)
Construction	6" concrete slab poured directly on to the earth with carpet
Thermal properties for ground level floor U-factor (W/m^2K)	0.17, for Anchorage 0.08
Interior Partitions	
Construction	0.5 in gypsum board + 0.5 in gypsum board
Air Barrier System	
Infiltration	0.001024 $m^3/s/m^2$ of above ground envelope area

Table 4-20. New retail HVAC characteristics

HVAC	
System Type 1	
Heating type	Gas furnace inside the packaged air conditioning unit
Cooling type	Packaged air conditioning unit
System Type 2	
Heating type	Packaged terminal air conditioner with heat pump
Cooling type	Packaged terminal air conditioner
HVAC Sizing	
Air Conditioning	autosized to weather file
Heating	autosized to weather file
HVAC Efficiency	
Air Conditioning COP	ASHRAE 90.1
Heating Efficiency	80%
HVAC Control	
Thermostat Setpoint	24°C Cooling/21°C Heating
Thermostat Setback	30°C Cooling/16°C Heating
Supply air temperature	Maximum 40°C, Minimum 13°C
Economizers	Limit Temperature = 28° C
Ventilation (outdoor air liter/minutes)	Core 111285, Point of sale 10675, Entry 1700, Front retail 10788, Back space 13903
Supply Fan	
Supply Fan Total Efficiency (%)	Core 59, Point of sale and Front retail, and Entry 54, Back space 55
Supply Fan Pressure Rise (Pa)	623, Core 1018
Lighting	
Average power density (W/m^2)	Core, Point of sale, and Front retail 18.3, Entry 14, Back space 8.6
Plug load	
Average power density (W/m^2)	3.2, Point of sale 21.5 and 8 for Back space 8
Occupancy	
Area (m^2)/Person	6.2

Table 4-21. Old office schedule through December 31

Schedule	Hour	1	2	3	4	5	6	7	8	9	10	11	Noon
Internal Loads													
Lighting (fraction)	Weekday	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.3	0.9	0.9	0.9	0.9
	Saturday	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.3	0.3	0.3	0.3
	Sun, Hol	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Equipment (fraction)	Weekday	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.9
	Saturday	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5
	Sun, Hol	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Occupancy (fraction)	Weekday	0	0	0	0	0	0	0.1	0.2	0.95	0.95	0.95	0.95
	Saturday	0	0	0	0	0	0	0.1	0.1	0.3	0.3	0.3	0.3
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0
Infiltration													
Infiltration (fraction)	Weekday	1	1	1	1	1	1	0	0	0	0	0	0
	Saturday	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	1	1	1	1	1	1	1	1	1	1	1	1
HVAC													
Operation (On/Off))	Weekday	0	0	0	0	0	0	1	1	1	1	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0
Heating setpoint °C	Weekday	15.6	15.6	15.6	15.6	15.6	21	21	21	21	21	21	21
	Saturday	15.6	15.6	15.6	15.6	15.6	15.6	21	21	21	21	21	21
	Sun, Hol	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Cooling setpoint °C	Weekday	30	30	30	30	30	30	24	24	24	24	24	24
	Saturday	30	30	30	30	30	30	30	24	24	24	24	24
	Sun, Hol	30	30	30	30	30	30	30	30	30	30	30	30
Min Outdoor air	Weekday	0	0	0	0	0	0	0	1	1	1	1	1
	Saturday	0	0	0	0	0	0	0	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0

Schedule	Hour	13	14	15	16	17	18	19	20	21	22	23	24
Internal Loads													
Lighting (fraction)	Weekday	0.9	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.2	0.2	0.1	0.05
	Saturday	0.15	0.15	0.15	0.15	0.15	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Sun, Hol	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Equipment (fraction)	Weekday	0.8	0.9	0.9	0.9	0.9	0.5	0.4	0.4	0.4	0.4	0.4	0.4
	Saturday	0.35	0.35	0.35	0.35	0.35	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Sun, Hol	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Occupancy (fraction)	Weekday	0.5	0.95	0.95	0.95	0.95	0.3	0.1	0.1	0.1	0.1	0.05	0.05
	Saturday	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0
Infiltration													
Infiltration (fraction)	Weekday	0	0	0	0	0	0	0	0	0	0	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	1	1	1	1	1	1	1	1	1	1	1	1
HVAC													
Operation (On/Off))	Weekday	1	1	1	1	1	1	1	1	1	1	0	0
	Saturday	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0
Heating setpoint °C	Weekday	21	21	21	21	21	21	15.6	15.6	15.6	15.6	15.6	15.6
	Saturday	21	21	21	21	21	15.6	15.6	15.6	15.6	15.6	15.6	15.6
	Sun, Hol	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Cooling setpoint °C	Weekday	24	24	24	24	24	24	24	24	24	24	30	30
	Saturday	24	24	24	24	24	24	30	30	30	30	30	30
	Sun, Hol	30	30	30	30	30	30	30	30	30	30	30	30
Min Outdoor air	Weekday	1	1	1	1	1	1	1	1	1	1	0	0
	Saturday	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0

Key: Sun: Sunday, Hol: Holliday

Table 4-22. New office schedule through December 31

Schedule	Hour	1	2	3	4	5	6	7	8	9	10	11	Noon
Internal Loads													
Lighting (fraction)	Weekday	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.3	0.9	0.9	0.9	0.9
	Saturday	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.3	0.3	0.3	0.3
	Sun, Hol	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Equipment (fraction)	Weekday	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.9
	Saturday	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5
	Sun, Hol	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Occupancy (fraction)	Weekday	0	0	0	0	0	0	0.1	0.2	0.95	0.95	0.95	0.95
	Saturday	0	0	0	0	0	0	0.1	0.1	0.3	0.3	0.3	0.3
	Sun, Hol	0	0	0	0	0	0	0.05	0.05	0.05	0.05	0.05	0.05
Infiltration													
Infiltration (fraction)	Weekday	1	1	1	1	1	1	0	0	0	0	0	0
	Saturday	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	1	1	1	1	1	1	1	1	1	1	1	1
HVAC													
Operation (On/Off))	Weekday	0	0	0	0	0	0	1	1	1	1	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0
Heating setpoint °C	Weekday	15.6	15.6	15.6	15.6	15.6	17.6	19.6	21	21	21	21	21
	Saturday	15.6	15.6	15.6	15.6	15.6	17.6	19.6	21	21	21	21	21
	Sun, Hol	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Cooling setpoint °C	Weekday	26.7	26.7	26.7	26.7	26.7	25.7	25	24	24	24	24	24
	Saturday	26.7	26.7	26.7	26.7	26.7	25.7	25	24	24	24	24	24
	Sun, Hol	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
Min Outdoor air	Weekday	0	0	0	0	0	0	0	1	1	1	1	1
	Saturday	0	0	0	0	0	0	0	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0

Schedule	Hour	13	14	15	16	17	18	19	20	21	22	23	24
Internal Loads													
Lighting (fraction)	Weekday	0.9	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.2	0.2	0.1	0.05
	Saturday	0.15	0.15	0.15	0.15	0.15	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Sun, Hol	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Equipment (fraction)	Weekday	0.8	0.9	0.9	0.9	0.9	0.5	0.4	0.4	0.4	0.4	0.4	0.4
	Saturday	0.35	0.35	0.35	0.35	0.35	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Sun, Hol	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Occupancy (fraction)	Weekday	0.5	0.95	0.95	0.95	0.95	0.3	0.1	0.1	0.1	0.1	0.05	0.05
	Saturday	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0	0	0	0	0
	Sun, Hol	0.05	0.05	0.05	0.05	0.05	0.05	0	0	0	0	0	0
Infiltration													
Infiltration (fraction)	Weekday	0	0	0	0	0	0	0	0	0	0	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	1	1	1	1	1	1	1	1	1	1	1	1
HVAC													
Operation (On/Off))	Weekday	1	1	1	1	1	1	1	1	1	1	0	0
	Saturday	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0
Heating setpoint °C	Weekday	21	21	21	21	21	21	21	21	21	21	15.6	15.6
	Saturday	21	21	21	21	21	15.6	15.6	15.6	15.6	15.6	15.6	15.6
	Sun, Hol	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Cooling setpoint °C	Weekday	24	24	24	24	24	24	24	24	24	24	26.7	26.7
	Saturday	24	24	24	24	24	26.7	26.7	26.7	26.7	26.7	26.7	26.7
	Sun, Hol	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7	26.7
Min Outdoor air	Weekday	1	1	1	1	1	1	1	1	1	1	0	0
	Saturday	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	0	0	0	0	0	0	0	0	0	0	0	0

Key: Sun: Sunday, Hol: Holliday

Table 4-23. Old retail store schedule through December 31

Schedule	Hour	1	2	3	4	5	6	7	8	9	10	11	Noon
Internal Loads													
Lighting (fraction)	Weekday	0.05	0.05	0.05	0.05	0.05	0.05	0.2	0.5	0.9	0.9	0.9	0.9
	Saturday	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.3	0.3	0.6	0.3	0.9
	Sun, Hol	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.1	0.4	0.4
Equipment (fraction)	Weekday	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.7	0.9	0.9	0.9	0.9
	Saturday	0.15	0.15	0.15	0.15	0.15	0.15	0.3	0.5	0.8	0.9	0.9	0.9
	Sun, Hol	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.3	0.3	0.6	0.6	0.3
Occupancy (fraction)	Weekday	0	0	0	0	0	0	0.1	0.2	0.5	0.5	0.7	0.7
	Saturday	0	0	0	0	0	0	0.1	0.2	0.5	0.6	0.8	0.8
	Sun, Hol	0	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2
Infiltration													
Infiltration (fraction)	Weekday	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5
	Saturday	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5
	Sun, Hol	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5
HVAC													
Operation (On/Off))	Weekday	0	0	0	0	0	0	1	1	1	1	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	0	1	1	1	1	1
Heating setpoint °C	Weekday	15.6	15.6	15.6	15.6	15.6	17.6	19.6	21	21	21	21	21
	Saturday	15.6	15.6	15.6	15.6	15.6	17.6	19.6	21	21	21	21	21
	Sun, Hol	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Cooling setpoint °C	Weekday	30	30	30	30	30	30	24	24	24	24	24	24
	Saturday	30	30	30	30	30	30	24	24	24	24	24	24
	Sun, Hol	30	30	30	30	30	30	30	30	24	24	24	24
Min Outdoor air	Weekday	0	0	0	0	0	0	1	1	1	1	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	1	1	1	1	1	1

Schedule	Hour	13	14	15	16	17	18	19	20	21	22	23	24
Internal Loads													
Lighting (fraction)	Weekday	0.9	0.9	0.9	0.9	0.9	0.5	0.6	0.6	0.5	0.2	0.05	0.05
	Saturday	0.9	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.05	0.1	0.05	0.05
	Sun, Hol	0.6	0.6	0.6	0.6	0.4	0.2	0.05	0.05	0.05	0.05	0.05	0.05
Equipment (fraction)	Weekday	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.7	0.4	0.2	0.2	0.2
	Saturday	0.8	0.9	0.9	0.9	0.9	0.7	0.5	0.5	0.3	0.15	0.15	0.15
	Sun, Hol	0.8	0.8	0.8	0.8	0.6	0.4	0.3	0.15	0.15	0.15	0.15	0.15
Occupancy (fraction)	Weekday	0.7	0.7	0.8	0.7	0.95	0.5	0.5	0.1	0.3	0.3	0	0
	Saturday	0.8	0.8	0.8	0.8	0.6	0.2	0.2	0.2	0.1	0	0	0
	Sun, Hol	0.4	0.4	0.4	0.4	0.2	0.1	0.1	0	0	0	0	0
Infiltration													
Infiltration (fraction)	Weekday	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1
	Saturday	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1
	Sun, Hol	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1	1
HVAC													
Operation (On/Off))	Weekday	1	1	1	1	1	1	1	1	0	0	0	0
	Saturday	1	1	1	1	1	1	1	1	1	1	0	0
	Sun, Hol	1	1	1	1	1	1	0	0	0	0	0	0
Heating setpoint °C	Weekday	21	21	21	21	21	21	21	21	21	21	15.6	15.6
	Saturday	21	21	21	21	21	15.6	15.6	15.6	15.6	15.6	15.6	15.6
	Sun, Hol	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Cooling setpoint °C	Weekday	24	24	24	24	24	24	24	24	24	30	30	30
	Saturday	24	24	24	24	24	24	24	24	24	24	30	30
	Sun, Hol	24	24	24	24	24	24	24	30	30	30	30	30
Min Outdoor air	Weekday	1	1	1	1	1	1	1	1	1	0	0	0
	Saturday	1	1	1	1	1	1	1	1	1	1	0	0
	Sun, Hol	1	1	1	1	1	1	0	0	0	0	0	0

Key: Sun: Sunday, Hol: Holliday

Table 4-24. New retail store schedule through December 31

Schedule	Hour	1	2	3	4	5	6	7	8	9	10	11	Noon
Internal Loads													
Lighting (fraction)	Weekday	0.05	0.05	0.05	0.05	0.05	0.05	0.2	0.4	0.6	0.9	0.9	0.9
	Saturday	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.3	0.6	0.9	0.9	0.9
	Sun, Hol	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.1	0.4	0.4	0.6
Equipment (fraction)	Weekday	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.6	0.9	0.9	0.9	0.9
	Saturday	0.15	0.15	0.15	0.15	0.15	0.15	0.3	0.5	0.8	0.9	0.9	0.9
	Sun, Hol	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.3	0.6	0.6	0.8
Occupancy (fraction)	Weekday	0	0	0	0	0	0	0.1	0.2	0.5	0.5	0.7	0.7
	Saturday	0	0	0	0	0	0	0.1	0.2	0.5	0.6	0.8	0.8
	Sun, Hol	0	0	0	0	0	0	0	0	0.1	0.2	0.2	0.4
Infiltration													
Infiltration (fraction)	Weekday	1	1	1	1	1	1	0	0	0	0	0	0
	Saturday	1	1	1	1	1	1	0	0	0	0	0	0
	Sun, Hol	1	1	1	1	1	1	1	0	0	0	0	0
HVAC													
Operation (On/Off))	Weekday	0	0	0	0	0	0	1	1	1	1	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	0	1	1	1	1	1
Heating setpoint °C	Weekday	15.6	15.6	15.6	15.6	15.6	17.6	21	21	21	21	21	21
	Saturday	15.6	15.6	15.6	15.6	15.6	17.6	21	21	21	21	21	21
	Sun, Hol	15.6	15.6	15.6	15.6	15.6	15.6	15.6	17.6	21	21	21	21
Cooling setpoint °C	Weekday	30	30	30	30	30	26.6	25	24	24	24	24	24
	Saturday	30	30	30	30	30	26.6	25	25	25	25	25	25
	Sun, Hol	30	30	30	30	30	30	30	26.6	24	24	24	24
Minimum Outdoor air	Weekday	0	0	0	0	0	0	1	1	1	1	1	1
	Saturday	0	0	0	0	0	0	1	1	1	1	1	1
	Sun, Hol	0	0	0	0	0	0	0	1	1	1	1	1

Schedule	Hour	13	14	15	16	17	18	19	20	21	22	23	24
Internal Loads													
Lighting (fraction)	Weekday	0.9	0.9	0.9	0.9	0.9	0.5	0.5	0.5	0.2	0.05	0.05	0.05
	Saturday	0.9	0.9	0.9	0.9	0.9	0.5	0.3	0.3	0.2	0.2	0.1	0.05
	Sun, Hol	0.6	0.6	0.6	0.6	0.4	0.2	0.05	0.05	0.05	0.05	0.05	0.05
Equipment (fraction)	Weekday	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.2	0.2	0.2	0.2
	Saturday	0.9	0.9	0.9	0.9	0.9	0.7	0.5	0.5	0.3	0.15	0.15	0.15
	Sun, Hol	0.8	0.8	0.8	0.8	0.6	0.4	0.3	0.15	0.15	0.15	0.15	0.15
Occupancy (fraction)	Weekday	0.7	0.7	0.8	0.7	0.5	0.5	0.3	0.3	0	0	0	0
	Saturday	0.8	0.8	0.8	0.8	0.6	0.2	0.2	0.2	0.1	0	0	0
	Sun, Hol	0.4	0.4	0.4	0.4	0.2	0.1	0	0	0	0	0	0
Infiltration													
Infiltration (fraction)	Weekday	0	0	0	0	0	0	0	0	1	1	1	1
	Saturday	0	0	0	0	0	0	0	0	0	1	1	1
	Sun, Hol	0	0	0	0	0	0	1	1	1	1	1	1
HVAC													
Operation (On/Off))	Weekday	1	1	1	1	1	1	1	1	0	0	0	0
	Saturday	1	1	1	1	1	1	1	1	1	0	0	0
	Sun, Hol	1	1	1	1	1	1	0	0	0	0	0	0
Heating setpoint °C	Weekday	21	21	21	21	21	21	21	21	21	15.6	15.6	15.6
	Saturday	21	21	21	21	21	21	21	21	21	21	15.6	15.6
	Sun, Hol	21	21	21	21	21	21	15.6	15.6	15.6	15.6	15.6	15.6
Cooling setpoint °C	Weekday	24	24	24	24	24	24	24	24	30	30	30	30
	Saturday	25	25	25	25	25	25	25	25	25	30	30	30
	Sun, Hol	24	24	24	24	24	24	30	30	30	30	30	30
Minimum Outdoor air	Weekday	1	1	1	1	1	1	1	1	0	0	0	0
	Saturday	1	1	1	1	1	1	1	1	1	0	0	0
	Sun, Hol	1	1	1	1	1	1	0	0	0	0	0	0

Key: Sun: Sunday, Hol: Holliday

Chapter 5: Simulated Heating and Cooling Energy Use

5.1 Validation of prototype buildings

Calibrated and validated prototype models are available from DOE across all US climate zones. These models are prepared for EnergyPlus simulations (http://www.energycodes.gov/commercial-prototype-building-models). EnergyPlus is the model that the US 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 input model, we simulated the same prototype with EnergyPlus and DOE-2 and compared the results. Because of some inconsistencies 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 negligible error. The most notable inconsistency occurred when we modeled the infiltration rate.

Among the climate zones, Duluth (zone7) represents the climate for Anchorage (also zone 7), and Minneapolis (zone 6) represents those for Milwaukee, Montreal, and Toronto (each also zone 6).

Air infiltration through the building envelope plays an important role in the building's heating energy, especially in cold regions. The DOE-2 infiltration methodology uses a reference wind speed of 10 mph, whereas EnergyPlus does not account for wind speed. DOE uses 0.0076 $m^3/s/m^2$ of above-ground envelope area (wall and roof) for old (pre-1980) buildings and 0.001024 $m^3/s/m^2$ of above-ground envelope area for new buildings in EnergyPlus models; however, we converted these numbers to either cfm/ft^2 of floor area or air-changes/hour to calibrate our DOE-2 model with the EnergyPlus modeling.

Tables 5-1 and 5-2 show the heating, cooling, and ventilation energy consumption of the prototypes modeled by EnergyPlus (provided by the Department of Energy) and the DOE-2.1E model.

As mentioned in the previous chapter, we modified the new small office and all large office prototypes; hence, these prototypes are not compared to the original models.

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.

Table 5-1. Calibration results of the DOE-2.1E model with EnergyPlus model (provided by DOE). Duluth (zone 7) weather file

	EnergyPlus	**DOE-2.1E**	**Difference (%)**
Old Small Office			
Cooling Energy (GJ)	14	15	
Heating Energy (GJ)	351	375	
Fan (GJ)	108	104	
Total (GJ)	473	494	4
Old Medium Office			
Cooling Energy (GJ)	114	115	
Heating Energy (GJ)	1727	1777	
Fan (GJ)	747	663	
Total (GJ)	2588	2555	1
New Medium Office			
Cooling Energy (GJ)	175	159	
Heating Energy (GJ)	507 gas+586 electricity	844 gas+229 electricity	
Fan (GJ)	90	93	
Total (GJ)	1358	1325	2
Old Retail			
Cooling Energy (GJ)	51	79	
Heating Energy (GJ)	2545 gas+12 electricity	2683 gas+19 electricity	
Fan (GJ)	577	526	
Total (GJ)	3185	3307	4
New Retail			
Cooling Energy (GJ)	80	95	
Heating Energy (GJ)	843	941	
Fan (GJ)	363	310	
Total (GJ)	1286	1346	4

Note: Cooling and fan energy is electricity; heating energy is natural gas except for new medium office and old retail store which heating is both natural gas and electricity

Table 5-2. Calibration results of the DOE-2.1E model with EnergyPlus model (provided by DOE). Minneapolis (zone 6) weather file

	EnergyPlus	DOE-2.1E	Difference (%)
Old Small Office			
Cooling Energy (GJ)	27	28	
Heating Energy (GJ)	295	312	
Fan (GJ)	100	104	
Total (GJ)	421	444	5
Old Medium Office			
Cooling Energy (GJ)	230	240	
Heating Energy (GJ)	1450	1376	
Fan (GJ)	710	695	
Total (GJ)	2390	2311	3
New Medium Office			
Cooling Energy (GJ)	205	215	
Heating Energy (GJ)	482 gas+301 electricity	614 gas+219 electricity	
Fan (GJ)	80	93	
Total (GJ)	1068	1141	6
Old Retail			
Cooling Energy (GJ)	139	214	
Heating Energy (GJ)	2144 gas+10 electricity	2182 gas+14 electricity	
Fan (GJ)	557	540	
Total (GJ)	2850	2950	3
New Retail			
Cooling Energy (GJ)	135	152	
Heating Energy (GJ)	745	793	
Fan (GJ)	322	331	
Total (GJ)	1202	1276	6

Note: Cooling and fan energy is electricity; heating energy is natural gas except for new medium office and old retail store which heating is both natural gas and electricity

5.2 Results and discussion

The main goal in this study is evaluating the use of cool roofs in cold climates more accurately. The criteria is the effect of cool roofs on building annual energy consumption, overall building energy expenditure, peak demand, and HVAC system size.

5.2.1 Building conditioning energy and overall 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 repeated the simulations. (Separate functions for dark or white and deferent snow type). The simulations are run once with gas-heating and electricity-cooling systems and once with all electric heat pump systems. Among the 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).

Tables 5-7 to 5-38 show the heating, cooling, ventilation energy, and the overall expenditure normalized per 100 m^2 of the roof area for each prototype, including old construction with old system, old construction with new system and new construction with new system. Note that the overall expenditure is the entire building energy expenditure including air-conditioning, lighting, and equipment.

Overall expenditure is calculated based on the local electricity and natural gas rates as it is shown in Tables 5-3 to 5-5 (also Table 2-2 for natural gas). The overall electricity expenditure is calculated considering the demand charge as equations 5-1 to 5-3:

Electricity expenditure = monthly electricity energy cost + monthly demand charge Equation 5-1

Where:

Electricity expenditure in $

Monthly electricity energy cost = monthly consumption (kWh) * energy rate ($/kWh) Equation 5-2

Monthly demand charge = monthly peak demand (kW) * peak demand rate ($/kW) Equation 5-3

According to utilities' electricity rates and tariffs, all prototypes except small offices have demand charges (Table 5-3). 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 5-4). 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 5-5). Utility demand charge rates are shown in Table 5-6.

Table 5-3. Electricity prices for all the prototypes except small office buildings

	All prototypes (except small office)	
Location	**electricity energy rate ($/kWh)**	**electricity demand rate ($/kW)**
Anchorage	[a] 0.096274	[a] 16.96
Milwaukee	[e] 0.08419	[e] 13.385
Montreal	[g] 0.0471	[g] 14.7
Toronto	[i] 0.101	[i] 1.9253

Table 5-4. Electricity prices for small office buildings with gas-heating HVAC system

	Small Office with gas-heating HVAC system	
Location	**electricity energy rate ($/kWh)**	**electricity demand rate ($/kW)**
Anchorage	[b] 0.151124	[b] 0
Milwaukee	[c] 0.13945	[c] 0
Montreal	[f] 0.0938	[f] 0
Toronto	[h] 0.101	[h] 0

Table 5-5. Electricity prices for small office buildings with all-electric HVAC system

	Small Office with all-electric HVAC system	
Location	**electricity energy rate ($/kWh)**	**electricity demand rate ($/kW)**
Anchorage	[a] 0.096274	[a] 16.96
Milwaukee old building	[d] 0.12421	[d] 6.761
Milwaukee new building	[c] 0.139	[c] 0
Montreal	[g] 0.0471	[g] 14.07
Toronto	[i] 0.101	[i] 1.9253

[a] Municipal Light and Power for large commercial costumers (2014), [b] Municipal Light and Power for small commercial costumers (2014) [c] We Energies cg1 (2014), [d] We Energies cg2 (2014), [e] We Energies cg3 (2014), [f] Hydro Quebec, Rate G (2014), [g] Hydro Quebec, Rate M (2014), [h] Toronto Hydro for costumers with monthly demand less than 50 kW (2014), [i] Toronto Hydro for costumers with monthly demand between 50 and 999 kW (2014)

Table 5-6. Utilities rate schedules for demand charges

Location	Term of demand charge
Anchorage	Monthly peak demand exceeds 20 kW for three consecutive months
Milwaukee	Monthly electricity energy exceeds 10000 kWh
Montreal	Monthly peak demand exceeds 50 kW at least once a year
Toronto	Monthly peak demand exceeds 50 kW

Note that just for the case of new the prototype medium office with gas-heating system, heating energy is the summation of natural gas and electricity use. However, in calculating the overall expenditure, electricity and natural gas prices are calculated separately then summed and presented as one number. Also note that the numbers in the tables are rounded hence, there might be ±1 discrepancy in savings.

Table 5-7.Small office 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

Table 5-8.Small office with all-electric system in Anchorage

Case	Heat pump (heating and 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	16955	17322	-368	16801	16951	-150	16110	16258	-148	15566	15723	-157	15058	15231	-173
Cooling energy	296	188	109	292	185	107	286	181	105	283	179	104	280	177	103
Ventilation energy	240	240	-1	234	234	-1	226	226	-1	220	221	-1	216	216	-1
Expenditure ($)	5595	5640	-45	5550	5570	-19	5432	5452	-19	5338	5354	-16	5248	5265	-17
Old construction with new systems															
Heating energy	16838	17186	-348	16679	16816	-137	15992	16125	-133	15450	15594	-144	14944	15105	-161
Cooling energy	260	165	95	257	163	94	252	159	93	249	157	92	246	155	91
Ventilation energy	227	229	-3	221	222	0	214	214	-1	208	209	-1	204	205	-1
Expenditure ($)	5568	5611	-43	5523	5537	-14	5405	5416	-11	5312	5325	-13	5217	5238	-21
New construction with new systems															
Heating energy	6220	6375	-155	6182	6208	-25	5786	5812	-26	5422	5453	-31	5037	5080	-43
Cooling energy	407	336	71	405	335	69	405	335	69	406	336	69	407	337	70
Ventilation energy	62	61	1	62	61	1	62	61	1	62	61	1	62	61	1
Expenditure ($)	2678	2701	-23	2688	2688	0	2648	2648	0	2604	2606	-2	2551	2559	-8

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-9. Medium office 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	102	103	-1	101	102	0	98	99	0	96	96	0	93	94	0
Cooling energy	562	508	55	562	508	55	562	508	55	562	508	55	562	508	55
Ventilation energy	8119	8123	-4	8113	8114	-1	8100	8101	-1	8090	8091	-1	8081	8083	-1
Expenditure ($)	5605	5596	9	5601	5589	12	5587	5575	12	5576	5563	12	5565	5553	12
Old construction with new systems															
Heating energy	100	102	-1	100	100	0	97	97	0	94	94	0	92	92	0
Cooling energy	489	441	48	489	441	48	489	441	48	489	441	48	489	441	48
Ventilation energy	7930	7934	-4	7924	7925	-1	7911	7912	-1	7902	7903	-1	7893	7895	-2
Expenditure ($)	5541	5534	7	5561	5526	34	5547	5513	34	5536	5502	34	5525	5491	34
New construction with new systems															
Heating energy	67	68	-1	67	67	0	65	65	0	63	63	0	61	61	0
Cooling energy	1527	1448	79	1526	1448	78	1526	1448	78	1526	1448	78	1527	1448	79
Ventilation energy	1228	1225	3	1228	1225	3	1228	1225	3	1228	1225	3	1228	1225	3
Expenditure ($)	4394	4381	13	4396	4383	14	4393	4379	14	4389	4375	14	4384	4370	13

Table 5-10. Medium office with all-electric system in Anchorage

Case	Heat pump (heating and 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	21136	21323	-186	20988	21019	-31	20403	20434	-31	19915	19952	-38	19437	19489	-52
Cooling energy	1863	1758	105	1862	1758	104	1862	1758	104	1862	1758	104	1863	1758	105
Ventilation energy	278	277	1	279	277	2	279	277	2	278	277	2	278	276	2
Expenditure ($)	9245	9265	-20	9240	9234	6	9175	9170	6	9116	9112	3	9048	9050	-2
Old construction with new systems															
Heating energy	21115	21297	-183	20965	20994	-29	20379	20409	-29	19892	19928	-36	19416	19465	-50
Cooling energy	1646	1553	93	1644	1552	92	1644	1552	92	1645	1553	92	1646	1553	93
Ventilation energy	263	262	1	264	262	1	263	262	1	263	262	1	263	262	1
Expenditure ($)	9206	9226	-21	9200	9196	4	9136	9132	4	9076	9074	2	9008	9012	-4
New construction with new systems															
Heating energy	15153	15299	-147	15054	15069	-15	14561	14577	-15	14118	14139	-21	13659	13691	-33
Cooling energy	2080	1997	83	2077	1996	81	2077	1997	81	2079	1998	81	2081	1999	82
Ventilation energy	225	223	2	225	223	2	225	223	2	225	223	2	225	223	2
Expenditure ($)	6887	6896	-9	6876	6865	11	6808	6797	11	6744	6734	10	6666	6659	7

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-11. Large office 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	91	92	-1	90	91	0	87	87	0	84	84	0	82	82	0
Cooling energy	324	317	8	324	317	8	324	317	8	324	317	8	324	316	9
Ventilation energy	1505	1477	28	1501	1476	25	1501	1476	25	1503	1477	25	1507	1481	26
Expenditure ($)	4612	4607	5	4607	4599	7	4593	4585	7	4581	4574	7	4571	4564	7
Old construction with new systems															
Heating energy	87	88	-1	86	86	0	83	83	0	80	80	0	78	78	0
Cooling energy	271	265	6	271	265	6	271	265	6	271	265	6	271	265	6
Ventilation energy	1455	1428	27	1451	1427	24	1451	1426	24	1452	1428	25	1457	1431	25
Expenditure ($)	4567	4562	4	4561	4555	7	4548	4542	7	4537	4531	7	4528	4522	6
New construction with new systems															
Heating energy	67	68	-1	66	67	0	64	64	0	62	62	0	60	60	0
Cooling energy	470	449	21	470	449	21	470	449	21	470	449	21	470	449	21
Ventilation energy	1375	1339	35	1370	1339	31	1374	1343	31	1382	1351	32	1395	1363	33
Expenditure ($)	3691	3681	10	3688	3677	12	3679	3667	12	3671	3660	12	3663	3652	11

Table 5-12. Large office with all-electric system in Anchorage

Case	Heat pump (heating and 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	14177	14358	-181	14007	14030	-23	13377	13400	-23	12848	12878	-30	12333	12376	-43
Cooling energy	2217	2100	116	2212	2099	113	2213	2100	113	2215	2102	113	2219	2104	115
Ventilation energy	229	227	2	229	227	2	229	226	2	228	226	2	228	226	2
Expenditure ($)	7656	7666	-10	7644	7629	15	7583	7568	14	7493	7480	13	7412	7402	10
Old construction with new systems															
Heating energy	14174	14353	-179	14003	14025	-22	13373	13395	-22	12845	12874	-29	12331	12373	-42
Cooling energy	2104	1995	110	2100	1993	107	2101	1994	107	2103	1995	108	2107	1998	109
Ventilation energy	216	215	2	217	215	2	216	214	2	216	214	2	215	213	2
Expenditure ($)	7633	7644	-11	7620	7607	14	7560	7546	14	7470	7458	13	7389	7380	10
New construction with new systems															
Heating energy	11553	11697	-144	11445	11458	-13	10938	10951	-13	10483	10501	-18	10009	10038	-29
Cooling energy	1975	1894	81	1971	1893	78	1972	1894	79	1973	1895	79	1976	1896	80
Ventilation energy	187	184	2	187	184	2	187	184	2	186	184	2	186	184	2
Expenditure ($)	6075	6085	-10	6062	6051	11	6013	6003	11	5898	5889	10	5807	5801	6

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-13. Retail store 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	124	126	-2	123	124	-1	123	124	-1	120	122	-2	117	119	-2
Cooling energy	129	93	36	131	94	37	150	110	40	150	112	38	150	113	36
Ventilation energy	4634	4637	-3	4521	4521	0	4460	4420	40	4438	4315	123	4419	4231	188
Expenditure ($)	3316	3314	2	3298	3292	7	3299	3286	13	3284	3260	24	3270	3238	31
Old construction with new systems															
Heating energy	124	126	-2	123	124	-1	120	121	-1	117	119	-2	115	117	-2
Cooling energy	129	93	36	131	94	37	132	96	36	131	98	33	131	99	32
Ventilation energy	4634	4637	-3	4521	4521	0	4408	4368	40	4386	4264	122	4366	4180	187
Expenditure ($)	3316	3314	2	3298	3292	7	3269	3257	12	3254	3232	22	3239	3210	30
New construction with new systems															
Heating energy	44	46	-2	44	45	-1	40	42	-2	38	39	-2	35	37	-2
Cooling energy	402	348	54	400	347	52	400	348	53	402	349	53	403	350	53
Ventilation energy	3597	3189	408	3588	3179	409	3581	3172	409	3580	3171	409	3577	3169	408
Expenditure ($)	1973	1915	58	1968	1908	61	1955	1895	61	1945	1884	61	1935	1875	60

Table 5-14. Retail store with all-electric system in Anchorage

Case	Heat pump (heating and 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	25873	26296	-423	25638	25842	-204	24833	25033	-200	24205	24409	-204	23619	23843	-224
Cooling energy	496	398	98	491	394	97	484	388	96	479	384	95	474	381	93
Ventilation energy	244	244	0	239	238	1	231	230	1	226	225	1	221	221	1
Expenditure ($)	6818	6850	-32	6757	6768	-10	6618	6631	-13	6511	6525	-14	6413	6432	-20
Old construction with new systems															
Heating energy	25737	26142	-405	25500	25689	-189	24695	24884	-189	24068	24263	-195	23487	23698	-210
Cooling energy	468	374	93	462	369	93	455	364	92	451	360	91	446	357	89
Ventilation energy	231	231	0	226	225	1	218	217	1	213	212	1	209	208	1
Expenditure ($)	6795	6826	-31	6734	6743	-9	6595	6607	-13	6488	6501	-13	6390	6409	-19
New construction with new systems															
Heating energy	10189	10426	-237	10032	10106	-74	9385	9461	-76	8839	8924	-85	8290	8392	-102
Cooling energy	809	619	190	805	618	187	806	619	187	808	621	187	810	622	188
Ventilation energy	132	119	13	132	119	13	131	118	13	131	118	13	131	118	13
Expenditure ($)	3244	3244	-1	3204	3186	18	3090	3072	19	2998	2982	17	2907	2893	14

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-15. Small office with gas-heating system in Milwaukee

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	57	59	-2	58	59	-1	57	58	-1	56	57	-1	55	56	-1
Cooling energy	1764	1592	173	1762	1590	172	1759	1586	172	1754	1582	172	1746	1575	171
Ventilation energy	4398	4400	-2	4388	4388	0	4359	4359	0	4320	4320	0	4256	4258	-1
Expenditure ($)	2554	2544	11	2559	2542	17	2549	2532	17	2536	2519	17	2516	2501	15
Old construction with new systems															
Heating energy	56	58	-2	57	58	-1	56	57	-1	55	56	-1	53	55	-1
Cooling energy	1512	1364	148	1510	1363	148	1507	1360	147	1503	1356	147	1496	1350	147
Ventilation energy	4398	4400	-2	4388	4388	0	4359	4359	0	4320	4320	0	4256	4258	-1
Expenditure ($)	2511	2504	7	2516	2502	14	2506	2492	14	2493	2480	13	2473	2461	12
New construction with new systems															
Heating energy	30	31	-1	27	27	0	27	27	0	27	27	0	26	26	0
Cooling energy	1027	948	79	1032	983	49	1032	983	49	1033	983	50	1033	983	50
Ventilation energy	1338	1343	-5	1323	1323	0	1322	1323	0	1320	1321	0	1317	1318	-1
Expenditure ($)	1503	1500	3	1484	1479	5	1483	1477	5	1480	1475	5	1475	1471	4

Table 5-16. Small office with all-electric system in Milwaukee

Case	Heat pump (heating and 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	11447	11814	-367	11638	11815	-177	11047	11212	-165	10806	10985	-179	10471	10682	-211
Cooling energy	1517	1286	231	1513	1282	231	1617	1426	191	1613	1423	191	1607	1417	190
Ventilation energy	196	196	0	194	195	0	197	197	0	195	195	0	193	193	0
Expenditure ($)	3884	3907	-23	3906	3904	2	3758	3756	1	3720	3721	-1	3669	3675	-6
Old construction with new systems															
Heating energy	10914	11252	-338	11097	11252	-155	10910	11065	-155	10670	10838	-168	10339	10538	-199
Cooling energy	1429	1260	169	1428	1259	169	1425	1257	168	1422	1254	168	1416	1249	168
Ventilation energy	188	188	0	191	188	3	189	187	3	188	185	3	185	182	3
Expenditure ($)	3710	3738	-28	3737	3738	0	3709	3709	0	3671	3674	-3	3621	3629	-7
New construction with new systems															
Heating energy	4379	4546	-167	3968	4001	-33	3932	3965	-33	3871	3910	-39	3769	3821	-52
Cooling energy	993	913	81	997	946	51	997	946	51	997	946	51	997	946	51
Ventilation energy	69	67	2	68	67	1	68	67	1	68	67	1	68	67	1
Expenditure ($)	1695	1707	-12	1638	1635	3	1633	1630	3	1624	1622	2	1610	1610	0

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-17. Medium office with gas-heating system in Milwaukee

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	77	78	-1	78	78	0	77	77	0	76	76	0	74	75	-1
Cooling energy	4653	4532	121	4653	4532	121	4653	4532	121	4653	4532	121	4653	4532	121
Ventilation energy	9567	9572	-4	9569	9571	-2	9564	9566	-2	9558	9560	-2	9550	9553	-3
Expenditure ($)	5716	5697	19	5720	5696	23	5714	5691	23	5707	5684	23	5698	5675	22
Old construction with new systems															
Heating energy	76	77	-1	77	77	0	76	76	0	75	75	0	73	74	-1
Cooling energy	3980	3876	104	3980	3876	104	3980	3876	104	3980	3876	104	3980	3876	104
Ventilation energy	9324	9329	-5	9326	9329	-2	7911	7912	-1	9315	9318	-2	9308	9311	-3
Expenditure ($)	5548	5533	15	5552	5533	19	5547	5528	19	5540	5521	19	5530	5512	18
New construction with new systems															
Heating energy	48	49	-1	46	46	0	45	46	0	45	45	0	44	45	0
Cooling energy	4440	4322	118	4448	4376	73	4448	4376	73	4448	4376	73	4448	4376	73
Ventilation energy	1505	1496	9	1505	1499	5	1505	1499	5	1505	1499	5	1228	1225	3
Expenditure ($)	4140	4126	14	4131	4121	10	4130	4121	10	4129	4119	10	4126	4117	9

Table 5-18. Medium office with all-electric system in Milwaukee

Case	Heat pump (heating and 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	15355	15563	-208	15477	15557	-80	15332	15413	-81	15142	15232	-90	14871	14983	-113
Cooling energy	5698	5555	143	5698	5555	143	5698	5555	143	5698	5555	143	5699	5556	143
Ventilation energy	300	298	2	300	298	2	300	298	2	300	298	2	300	298	2
Expenditure ($)	7569	7574	-5	7580	7573	7	7566	7560	7	7549	7543	6	7524	7520	3
Old construction with new systems															
Heating energy	15265	15465	-200	15385	15459	-74	15241	15316	-75	15051	15135	-84	14782	14889	-107
Cooling energy	4979	4853	126	4979	4853	125	4979	4853	125	4979	4854	125	4979	4854	125
Ventilation energy	285	283	2	285	283	2	285	283	2	285	283	2	285	282	2
Expenditure ($)	7444	7449	-5	7455	7449	7	7442	7435	6	7424	7419	6	7399	7396	3
New construction with new systems															
Heating energy	10519	10682	-163	9948	9974	-26	9902	9928	-26	9828	9860	-31	9703	9749	-45
Cooling energy	4260	4153	107	4289	4220	69	4289	4220	69	4289	4220	69	4290	4220	70
Ventilation energy	207	205	2	206	205	1	206	205	1	206	205	1	206	205	1
Expenditure ($)	5376	5383	-7	5298	5294	5	5293	5289	4	5285	5281	4	5271	5269	1

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-19. Large office with gas-heating system in Milwaukee

Case	Gas heating (heating in GJ/100 m^2, cooling in kWh/100 m^2)														
	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	70	72	-1	71	72	0	70	71	0	69	70	-1	68	68	-1
Cooling energy	3600	3534	66	3600	3534	66	3600	3534	66	3600	3534	66	3600	3534	66
Ventilation energy	1614	1580	35	1614	1579	35	1614	1579	35	1613	1579	35	1613	1578	35
Expenditure ($)	4816	4798	17	4820	4798	22	4815	4792	22	4809	4787	22	4799	4778	21
Old construction with new systems															
Heating energy	67	68	-1	68	68	0	67	67	0	66	66	-1	64	65	-1
Cooling energy	3021	2965	55	3021	2965	55	3021	2965	55	3021	2965	55	3021	2965	55
Ventilation energy	1560	1527	34	1560	1527	34	1560	1526	34	1559	1526	34	1559	1525	34
Expenditure ($)	4674	4659	15	4678	4659	20	4673	4653	20	4668	4648	19	4658	4640	18
New construction with new systems															
Heating energy	49	50	-1	46	46	0	46	46	0	45	45	0	45	45	0
Cooling energy	2337	2276	61	2328	2288	40	2328	2288	40	2328	2288	40	2328	2288	41
Ventilation energy	1404	1368	37	1419	1396	22	1419	1397	23	1420	1397	23	1422	1399	23
Expenditure ($)	3614	3599	15	3595	3583	13	3593	3580	13	3590	3578	12	3588	3576	12

Table 5-20. Large office with all-electric system in Milwaukee

Case	Heat pump (heating and cooling in kWh/100 m^2)														
	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	10469	10666	-197	10591	10657	-65	10435	10501	-66	10233	10309	-76	9943	10042	-99
Cooling energy	5694	5533	162	5693	5533	161	5693	5533	161	5694	5533	161	5695	5534	161
Ventilation energy	235	232	2	235	232	2	235	232	2	234	232	2	234	232	2
Expenditure ($)	6494	6496	-2	6506	6495	11	6490	6479	11	6470	6460	10	6440	6433	7
Old construction with new systems															
Heating energy	10439	10632	-194	10560	10623	-63	10404	10468	-64	10202	10275	-73	9913	10009	-96
Cooling energy	5388	5234	154	5387	5234	153	5387	5234	152	5387	5235	153	5388	5235	153
Ventilation energy	222	220	2	222	220	2	222	220	2	222	220	2	221	219	2
Expenditure ($)	6442	6444	-2	6454	6443	11	6438	6428	11	6418	6408	10	6388	6381	7
New construction with new systems															
Heating energy	8177	8337	-160	7605	7626	-21	7557	7579	-22	7482	7509	-27	7353	7395	-41
Cooling energy	4642	4517	125	4691	4606	85	4691	4606	85	4691	4606	85	4691	4607	85
Ventilation energy	168	166	1	167	166	1	167	166	1	167	166	1	167	166	1
Expenditure ($)	4931	4934	-3	4853	4845	8	4848	4840	8	4838	4832	7	4822	4817	4

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-21. Retail store with gas-heating system in Milwaukee

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	91	93	-2	92	93	-1	91	92	-1	90	91	-1	88	89	-2
Cooling energy	2595	2410	185	2595	2410	185	2595	2409	186	2595	2409	186	2594	2409	186
Ventilation energy	5348	5197	151	5345	5193	152	5336	5184	152	5324	5171	152	5301	5149	152
Expenditure ($)	3463	3430	33	3468	3429	39	3461	3422	39	3452	3413	39	3438	3401	37
Old construction with new systems															
Heating energy	89	91	-2	90	91	-1	89	90	-1	88	89	-1	86	87	-2
Cooling energy	2331	2162	168	2331	2162	168	2331	2162	169	2331	2162	169	2330	2162	169
Ventilation energy	5235	5086	149	5231	5083	149	5222	5074	149	5210	5061	149	5188	5040	148
Expenditure ($)	3383	3352	30	3388	3352	36	3380	3344	36	3371	3335	36	3358	3323	35
New construction with new systems															
Heating energy	32	34	-2	29	30	-1	29	29	-1	28	29	-1	27	28	-1
Cooling energy	1614	1536	77	1705	1633	72	1704	1633	71	1705	1633	72	1705	1634	72
Ventilation energy	3620	3307	313	3286	3109	177	3285	3108	177	3283	3106	177	3280	3103	177
Expenditure ($)	1890	1855	35	1848	1820	28	1846	1818	28	1844	1816	28	1839	1812	27

Table 5-22. Retail store with all-electric system in Milwaukee

Case	Heat pump (heating and 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	18515	18866	-351	18696	18855	-159	18478	18639	-160	18202	18377	-175	17820	18028	-208
Cooling energy	3334	3056	277	3333	3056	277	3332	3055	277	3331	3054	277	3329	3052	276
Ventilation energy	224	218	6	224	218	6	224	217	6	223	217	6	222	216	6
Expenditure ($)	5227	5226	0	5242	5222	20	5218	5193	24	5188	5162	25	5146	5125	21
Old construction with new systems															
Heating energy	18366	18705	-339	18545	18694	-149	18328	18478	-149	18053	18216	-164	17673	17870	-197
Cooling energy	3197	2930	267	3196	2929	267	3195	2929	266	3194	2928	266	3192	2926	266
Ventilation energy	212	206	6	212	206	6	212	205	6	211	205	6	210	204	6
Expenditure ($)	5192	5198	-7	5207	5194	13	5183	5165	17	5153	5134	19	5111	5097	15
New construction with new systems															
Heating energy	6964	7202	-237	6178	6242	-65	6120	6185	-65	6029	6100	-71	5874	5963	-89
Cooling energy	2380	2137	244	2323	2182	141	2323	2182	141	2323	2182	141	2323	2182	141
Ventilation energy	129	119	10	118	113	6	118	113	6	118	113	6	118	112	6
Expenditure ($)	2515	2521	-5	2371	2362	9	2363	2354	9	2351	2342	8	2330	2324	6

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-23. Small office with gas-heating system in Montreal

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	69	71	-2	70	71	-1	69	70	-1	67	68	-1	66	67	-1
Cooling energy	1519	1329	191	1516	1325	191	1506	1316	190	1495	1306	189	1481	1293	189
Ventilation energy	4989	4996	-7	4962	4962	0	4883	4883	0	4794	4794	0	4679	4680	-1
Expenditure ($)	1804	1796	8	1806	1792	14	1792	1779	14	1777	1763	13	1756	1744	12
Old construction with new systems															
Heating energy	67	69	-2	69	69	-1	67	68	-1	66	67	-1	64	65	-1
Cooling energy	1302	1139	163	1299	1135	164	1291	1128	163	1282	1120	162	1270	1108	162
Ventilation energy	4989	4996	-7	4962	4962	0	4883	4883	0	4794	4794	0	4679	4680	-1
Expenditure ($)	1776	1771	5	1779	1768	11	1766	1754	11	1750	1739	11	1730	1720	10
New construction with new systems															
Heating energy	31	32	-1	32	32	0	32	32	0	31	31	0	30	30	0
Cooling energy	961	884	77	961	884	77	961	884	77	961	884	77	961	884	77
Ventilation energy	1513	1516	-3	1517	1517	0	1515	1514	0	1511	1511	0	1505	1505	-1
Expenditure ($)	994	990	3	997	991	6	995	988	6	991	985	6	985	980	6

Table 5-24. Small office with all-electric system in Montreal

Case	Heat pump (heating and 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	69	71	-2	70	71	-1	69	70	-1	67	68	-1	66	67	-1
Cooling energy	1519	1329	191	1516	1325	191	1506	1316	190	1495	1306	189	1481	1293	189
Ventilation energy	4989	4996	-7	4962	4962	0	4883	4883	0	4794	4794	0	4679	4680	-1
Expenditure ($)	3684	3704	-20	3705	3693	12	3668	3656	12	3623	3612	10	3554	3552	2
Old construction with new systems															
Heating energy	67	69	-2	69	69	-1	67	68	-1	66	67	-1	64	65	-1
Cooling energy	1302	1139	163	1299	1135	164	1291	1128	163	1282	1120	162	1270	1108	162
Ventilation energy	4989	4996	-7	4962	4962	0	4883	4883	0	4794	4794	0	4679	4680	-1
Expenditure ($)	3654	3669	-15	3670	3666	4	3632	3625	7	3587	3582	5	3525	3525	0
New construction with new systems															
Heating energy	31	32	-1	32	32	0	32	32	0	31	31	0	30	30	0
Cooling energy	961	884	77	961	884	77	961	884	77	961	884	77	961	884	77
Ventilation energy	1513	1516	-3	1517	1517	0	1515	1514	0	1511	1511	0	1505	1505	-1
Expenditure ($)	1863	1867	-5	1873	1869	4	1868	1864	4	1859	1857	3	1845	1844	1

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-25. Medium office with gas-heating system in Montreal

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	97	98	-1	98	98	0	96	97	0	95	95	0	92	93	-1
Cooling energy	3736	3589	147	3736	3589	147	3736	3589	147	3736	3589	147	3736	3589	147
Ventilation energy	10164	10169	-4	10166	10168	-2	10160	10161	-2	10153	10155	-2	10143	10146	-2
Expenditure ($)	1100	1100	1	1104	1099	5	1097	1092	5	1089	1084	5	1078	1074	4
Old construction with new systems															
Heating energy	95	97	-1	96	96	0	95	95	0	93	93	0	91	91	-1
Cooling energy	3159	3034	125	3159	3034	125	3159	3034	125	3159	3034	125	3159	3034	125
Ventilation energy	9900	9904	-4	9902	9903	-1	9895	9897	-2	9889	9891	-2	9880	9882	-2
Expenditure ($)	1054	1054	0	1057	1053	4	1051	1046	4	1043	1039	4	1032	1029	3
New construction with new systems															
Heating energy	53	54	-1	53	54	0	53	53	0	52	53	0	51	52	0
Cooling energy	3944	3845	99	3944	3845	99	3944	3845	99	3944	3845	99	3944	3845	99
Ventilation energy	1621	1616	6	1621	1616	6	1621	1616	6	1621	1616	6	1621	1616	6
Expenditure ($)	609	607	2	611	607	4	610	606	4	607	603	4	603	600	4

Table 5-26. Medium office with all-electric system in Montreal

Case	Heat pump (heating and 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	19389	19628	-239	19543	19604	-61	19302	19363	-61	19008	19079	-71	18610	18707	-97
Cooling energy	5050	4874	176	5050	4874	176	5050	4874	175	5050	4874	176	5050	4874	176
Ventilation energy	344	341	3	344	341	3	344	341	3	344	341	3	344	341	3
Expenditure ($)	6846	6852	-6	6860	6851	9	6844	6835	9	6821	6813	8	6789	6784	5
Old construction with new systems															
Heating energy	19346	19582	-235	19500	19557	-57	19259	19317	-58	18965	19033	-68	18568	18661	-93
Cooling energy	4411	4257	154	4411	4257	153	4411	4257	154	4411	4257	154	4411	4257	154
Ventilation energy	326	324	3	326	324	3	326	324	3	326	324	3	326	324	3
Expenditure ($)	6770	6777	-7	6784	6776	8	6768	6760	8	6745	6739	6	6713	6710	3
New construction with new systems															
Heating energy	12138	12276	-138	12257	12286	-29	12152	12181	-29	12002	12038	-35	11764	11817	-54
Cooling energy	3674	3592	82	3673	3592	81	3673	3592	81	3674	3592	82	3674	3592	82
Ventilation energy	219	217	2	219	217	2	219	217	2	219	217	2	219	217	2
Expenditure ($)	4495	4501	-6	4506	4502	4	4498	4494	4	4485	4482	3	4464	4464	1

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-27. Large office with gas-heating system in Montreal

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	90	91	-1	91	91	0	89	89	0	87	88	0	85	86	-1
Cooling energy	2940	2859	81	2940	2859	81	2940	2859	81	2940	2859	81	2940	2859	81
Ventilation energy	1604	1564	40	1603	1563	40	1602	1563	40	1602	1562	40	1602	1562	40
Expenditure ($)	3672	3649	23	3676	3650	26	3668	3642	26	3660	3634	26	3650	3624	26
Old construction with new systems															
Heating energy	86	87	-1	86	87	0	85	85	0	83	83	0	81	81	-1
Cooling energy	2466	2398	68	2466	2398	68	2466	2398	68	2466	2398	68	2466	2398	68
Ventilation energy	1550	1511	39	1549	1511	38	1549	1510	38	1548	1510	39	1548	1510	39
Expenditure ($)	3557	3537	20	3560	3537	24	3553	3530	24	3545	3522	23	3536	3513	23
New construction with new systems															
Heating energy	55	56	-1	56	56	0	55	55	0	54	55	0	53	54	0
Cooling energy	1937	1881	56	1937	1881	56	1937	1881	56	1937	1881	56	1937	1881	56
Ventilation energy	1353	1323	30	1351	1322	29	1352	1323	29	1353	1324	29	1355	1325	30
Expenditure ($)	2536	2524	12	2537	2524	13	2534	2521	13	2532	2519	13	2526	2514	12

Table 5-28. Large office with all-electric system in Montreal

Case	Heat pump (heating and 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	13378	13614	-235	13532	13583	-51	13271	13323	-51	12954	13015	-61	12523	12611	-88
Cooling energy	5050	4866	184	5049	4866	183	5049	4866	183	5049	4866	183	5050	4866	184
Ventilation energy	268	265	3	268	265	3	268	265	3	268	264	3	267	264	3
Expenditure ($)	5720	5725	-4	5735	5723	12	5714	5701	12	5686	5675	11	5645	5637	8
Old construction with new systems															
Heating energy	13365	13598	-234	13518	13567	-49	13257	13307	-50	12940	13000	-60	12510	12596	-86
Cooling energy	4783	4607	175	4782	4607	175	4782	4607	175	4782	4607	175	4783	4607	175
Ventilation energy	253	250	3	253	250	3	253	250	3	253	250	3	253	250	3
Expenditure ($)	5688	5693	-5	5703	5691	11	5682	5670	11	5654	5643	10	5613	5606	7
New construction with new systems															
Heating energy	9258	9396	-138	9378	9405	-27	9270	9297	-27	9115	9149	-34	8869	8921	-52
Cooling energy	3934	3844	90	3934	3844	90	3934	3844	90	3934	3844	90	3934	3844	90
Ventilation energy	177	175	2	177	175	2	177	175	2	177	175	2	177	175	2
Expenditure ($)	3987	3994	-7	3999	3995	4	3990	3986	4	3974	3971	3	3949	3948	0

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-29. Retail store with gas-heating system in Montreal

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	108	113	-5	109	113	-3	108	111	-4	106	110	-4	104	108	-4
Cooling energy	1928	1770	158	1928	1769	159	1929	1772	157	1928	1772	156	1927	1772	155
Ventilation energy	6280	5684	597	6268	5643	625	6240	5551	690	6209	5448	761	6170	5328	841
Expenditure ($)	2628	2579	49	2632	2575	57	2624	2565	59	2614	2553	61	2601	2539	62
Old construction with new systems															
Heating energy	107	110	-4	108	110	-3	106	109	-3	104	108	-3	102	106	-4
Cooling energy	1730	1583	147	1730	1586	143	1730	1586	144	1730	1589	141	1729	1588	141
Ventilation energy	6146	5563	583	6135	5523	611	6107	5434	673	6076	5333	743	6038	5216	822
Expenditure ($)	2572	2524	49	2576	2520	56	2568	2510	58	2558	2498	60	2546	2484	62
New construction with new systems															
Heating energy	36	38	-2	37	38	-1	37	38	-1	36	37	-1	34	35	-1
Cooling energy	1686	1501	184	1685	1501	184	1684	1500	184	1683	1500	184	1683	1499	184
Ventilation energy	3349	3097	253	3348	3095	253	3343	3089	253	3336	3083	253	3327	3073	253
Expenditure ($)	1367	1320	47	1369	1319	50	1366	1316	50	1362	1312	50	1355	1305	49

Table 5-30. Retail store with all-electric system in Montreal

Case	Heat pump (heating and 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	23161	23528	-367	23365	23477	-113	23006	23116	-109	22587	22710	-123	22054	22205	-151
Cooling energy	2711	2385	326	2707	2382	326	2698	2367	331	2685	2359	326	2674	2342	331
Ventilation energy	273	274	-1	272	272	-1	267	269	-1	262	264	-1	258	258	0
Expenditure ($)	4532	4537	-5	4543	4527	16	4502	4485	17	4454	4438	16	4395	4376	19
Old construction with new systems															
Heating energy	23064	23429	-365	23267	23377	-111	22907	23018	-111	22490	22613	-123	21958	22108	-151
Cooling energy	2597	2282	315	2593	2279	315	2584	2266	318	2571	2258	313	2559	2242	317
Ventilation energy	258	259	-1	257	257	-1	253	253	-1	248	249	-1	244	243	1
Expenditure ($)	4514	4520	-6	4525	4511	15	4484	4468	16	4437	4422	15	4377	4360	18
New construction with new systems															
Heating energy	7959	8159	-200	8100	8168	-69	7966	8036	-69	7781	7858	-77	7491	7590	-99
Cooling energy	1761	1557	204	1760	1557	203	1760	1557	203	1760	1556	203	1760	1556	204
Ventilation energy	135	127	9	135	127	9	135	126	9	135	126	9	134	126	9
Expenditure ($)	1944	1943	1	1954	1942	12	1938	1926	12	1917	1906	11	1884	1874	9

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-31. Small office with gas-heating system in Toronto

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	58	60	-2	59	60	-1	59	60	-1	58	59	-1	57	58	-1
Cooling energy	1586	1397	190	1581	1391	190	1570	1380	190	1559	1370	190	1548	1358	190
Ventilation energy	4249	4253	-3	4205	4205	0	4113	4113	0	4022	4022	0	3928	3928	0
Expenditure ($)	2023	2021	2	2028	2018	10	2013	2004	10	1997	1988	9	1976	1969	7
Old construction with new systems															
Heating energy	57	59	-2	58	59	-1	58	59	-1	57	58	-1	56	57	-1
Cooling energy	1360	1197	163	1355	1192	163	1346	1183	163	1336	1174	162	1327	1164	163
Ventilation energy	4249	4253	-3	4205	4205	0	4113	4113	0	4022	4022	0	3928	3928	0
Expenditure ($)	1990	1991	-1	1994	1987	7	1980	1973	7	1964	1958	6	1944	1939	4
New construction with new systems															
Heating energy	25	26	-1	26	26	0	25	26	0	25	25	0	24	25	0
Cooling energy	1049	969	80	1049	969	79	1049	969	79	1049	969	79	1049	969	80
Ventilation energy	1439	1440	-1	1442	1441	1	1441	1440	1	1439	1438	1	1434	1434	0
Expenditure ($)	1127	1125	2	1132	1126	6	1130	1124	6	1126	1121	5	1120	1116	4

Table 5-32. Small office with all-electric system in Toronto

Case	Heat pump (heating and 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	11447	11814	-367	11648	11831	-183	11494	11675	-181	11275	11471	-196	10965	11200	-235
Cooling energy	1517	1286	231	1512	1281	231	1503	1272	231	1493	1264	229	1483	1256	227
Ventilation energy	196	196	0	194	194	0	190	190	0	186	186	0	182	182	0
Expenditure ($)	2567	2583	-16	2587	2583	4	2568	2564	4	2542	2540	2	2507	2509	-2
Old construction with new systems															
Heating energy	11320	11673	-353	11520	11688	-168	11366	11532	-165	11148	11332	-184	10840	11062	-222
Cooling energy	1337	1133	204	1333	1129	204	1325	1121	204	1316	1114	203	1307	1106	201
Ventilation energy	186	186	0	184	184	0	180	180	0	176	176	0	172	172	0
Expenditure ($)	2533	2551	-17	2553	2551	2	2535	2532	2	2509	2509	0	2474	2478	-4
New construction with new systems															
Heating energy	3847	3978	-132	3949	4000	-51	3909	3961	-51	3838	3898	-60	3718	3798	-80
Cooling energy	1041	965	76	1041	965	76	1041	965	76	1041	965	76	1041	965	76
Ventilation energy	70	68	2	70	68	2	70	68	2	70	68	2	70	68	2
Expenditure ($)	1307	1314	-7	1318	1317	1	1314	1313	1	1307	1306	0	1294	1296	-2

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-33. Medium office with gas-heating system in Toronto

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	73	74	-1	74	74	0	73	74	0	72	73	-1	71	72	-1
Cooling energy	4373	4225	148	4373	4225	148	4373	4225	148	4373	4225	148	4373	4225	148
Ventilation energy	10474	10478	-4	10477	10478	-1	10474	10475	-1	10471	10472	-2	10466	10468	-1
Expenditure ($)	4965	4959	6	4972	4960	13	4967	4954	13	4958	4946	12	4946	4935	11
Old construction with new systems															
Heating energy	95	97	-1	73	73	0	72	73	0	71	72	-1	70	71	-1
Cooling energy	3702	3578	124	3702	3578	124	3702	3578	124	3702	3578	124	3702	3578	124
Ventilation energy	10194	10197	-4	10196	10197	-1	10194	10195	-1	10191	10192	-1	10186	10187	-1
Expenditure ($)	5044	5041	3	4855	4845	10	4850	4839	10	4841	4831	10	4829	4821	8
New construction with new systems															
Heating energy	40	40	-1	40	40	0	40	40	0	39	40	0	39	39	0
Cooling energy	4383	4279	104	4383	4279	104	4383	4279	104	4383	4279	104	4383	4279	104
Ventilation energy	1747	1743	5	1747	1743	5	1747	1743	5	1747	1743	5	1747	1743	5
Expenditure ($)	3382	3375	7	3385	3376	9	3384	3374	10	3381	3372	9	3376	3367	8

Table 5-34. Medium office with all-electric system in Toronto

Case	Heat pump (heating and 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	15152	15379	-227	15299	15392	-92	15183	15277	-93	15015	15121	-106	14762	14899	-138
Cooling energy	5579	5391	189	5579	5391	188	5579	5391	188	5579	5391	188	5579	5391	188
Ventilation energy	339	337	3	339	337	3	339	337	3	339	336	3	339	336	3
Expenditure ($)	5255	5261	-6	5270	5263	7	5258	5251	7	5241	5235	6	5215	5212	3
Old construction with new systems															
Heating energy	15091	15314	-222	15238	15326	-88	15123	15212	-89	14954	15056	-102	14702	14834	-132
Cooling energy	4872	4707	165	4872	4707	165	4872	4707	165	4872	4707	165	4872	4707	165
Ventilation energy	322	319	3	322	319	3	322	319	3	322	319	3	322	319	3
Expenditure ($)	5044	5041	3	4855	4845	10	4850	4839	10	4841	4831	10	4829	4821	8
New construction with new systems															
Heating energy	9035	9156	-121	9136	9175	-39	9088	9127	-39	9005	9052	-47	8864	8933	-69
Cooling energy	4042	3947	95	4041	3947	95	4041	3947	95	4042	3947	95	4042	3947	95
Ventilation energy	213	211	2	213	211	2	213	211	2	213	211	2	213	211	2
Expenditure ($)	3382	3375	7	3385	3376	9	3384	3374	10	3381	3372	9	3376	3367	8

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-35. Large office with gas-heating system in Toronto

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	68	69	-1	69	69	-1	68	68	-1	67	68	-1	66	66	-1
Cooling energy	3360	3267	93	3360	3267	93	3360	3267	93	3360	3267	93	3360	3267	93
Ventilation energy	1632	1588	43	1631	1588	43	1631	1588	43	1631	1588	43	1631	1587	44
Expenditure ($)	4046	4035	11	4052	4036	16	4047	4031	16	4039	4023	16	4028	4013	14
Old construction with new systems															
Heating energy	65	66	-1	65	66	0	65	65	-1	64	64	-1	63	63	-1
Cooling energy	2826	2741	85	2819	2741	78	2819	2741	78	2819	2741	78	2819	2741	78
Ventilation energy	1632	1535	97	1577	1535	42	1577	1535	42	1577	1535	42	1576	1534	42
Expenditure ($)	3954	3938	16	3953	3939	14	3948	3934	14	3941	3927	14	3930	3917	12
New construction with new systems															
Heating energy	41	42	-1	42	42	0	42	42	0	41	42	0	41	41	0
Cooling energy	2132	2084	47	2132	2084	47	2132	2084	47	2132	2084	47	2132	2084	47
Ventilation energy	1405	1372	33	1403	1372	31	1404	1372	31	1405	1373	32	1407	1375	32
Expenditure ($)	2929	2923	6	2932	2924	8	2930	2922	8	2927	2919	8	2922	2915	7

Table 5-36. Large office with all-electric system in Toronto

Case	Heat pump (heating and 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	10164	10382	-218	10314	10392	-78	10191	10270	-79	10010	10104	-94	9740	9865	-125
Cooling energy	5597	5397	200	5596	5397	199	5596	5397	199	5597	5397	199	5597	5397	200
Ventilation energy	266	263	3	266	263	3	266	263	3	266	262	3	265	262	3
Expenditure ($)	4615	4617	-2	4630	4618	13	4618	4605	12	4599	4588	11	4571	4563	8
Old construction with new systems															
Heating energy	10145	10360	-215	10295	10371	-76	10172	10249	-76	9991	10082	-91	9723	9844	-121
Cooling energy	5303	5113	190	5303	5113	190	5303	5113	190	5303	5113	190	5303	5113	190
Ventilation energy	251	248	3	251	248	3	251	248	3	251	248	3	251	248	3
Expenditure ($)	4579	4582	-3	4595	4583	12	4582	4570	12	4563	4553	10	4535	4528	7
New construction with new systems															
Heating energy	6762	6880	-118	6865	6899	-35	6815	6850	-35	6730	6774	-44	6585	6651	-65
Cooling energy	4391	4277	114	4390	4277	113	4390	4277	113	4391	4277	114	4391	4277	114
Ventilation energy	173	172	2	173	172	2	173	172	2	173	172	2	173	172	2
Expenditure ($)	3375	3376	-1	3386	3378	8	3380	3373	8	3371	3365	7	3356	3351	4

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-37. Retail store with gas-heating system in Toronto

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	90	93	-3	91	93	-2	90	92	-2	89	91	-2	88	90	-2
Cooling energy	2443	2220	223	2443	2220	223	2441	2219	223	2440	2217	223	2439	2216	223
Ventilation energy	5484	5236	248	5475	5226	249	5455	5206	249	5434	5186	248	5409	5160	249
Expenditure ($)	3155	3126	29	3163	3126	37	3154	3118	37	3143	3107	36	3127	3093	34
Old construction with new systems															
Heating energy	88	91	-3	89	91	-2	88	90	-2	87	89	-2	86	88	-2
Cooling energy	2190	1993	198	2190	1992	198	2189	1991	198	2189	1990	199	2188	1989	199
Ventilation energy	5367	5125	242	5358	5115	243	5339	5095	244	5318	5075	243	5292	5049	243
Expenditure ($)	3098	3072	26	3105	3071	34	3097	3063	34	3086	3053	33	3070	3039	31
New construction with new systems															
Heating energy	27	29	-2	28	29	-1	27	28	-1	27	28	-1	26	27	-1
Cooling energy	1906	1755	151	1905	1755	150	1905	1755	150	1905	1755	150	1905	1755	151
Ventilation energy	3272	3029	243	3272	3029	243	3271	3028	243	3270	3027	243	3267	3025	243
Expenditure ($)	1621	1592	29	1626	1593	33	1624	1590	33	1619	1586	33	1612	1581	32

Table 5-38. Retail store with all-electric system in Toronto

Case	Heat pump (heating and 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	18525	18895	-371	18734	18909	-175	18565	18740	-175	18324	18519	-195	17975	18215	-240
Cooling energy	3075	2750	325	3074	2749	325	3073	2748	325	3071	2746	325	3069	2744	325
Ventilation energy	234	224	10	233	223	10	233	222	10	232	221	10	230	220	10
Expenditure ($)	3970	3973	-2	3992	3974	18	3974	3955	18	3948	3932	16	3910	3900	11
Old construction with new systems															
Heating energy	18391	18751	-360	18598	18764	-167	18429	18596	-167	18189	18374	-186	17842	18071	-229
Cooling energy	2947	2632	314	2946	2631	315	2945	2630	315	2943	2629	314	2941	2627	314
Ventilation energy	221	211	10	221	211	10	220	210	10	219	209	10	218	208	10
Expenditure ($)	3942	3944	-2	3963	3945	18	3945	3927	18	3919	3903	16	3882	3871	11
New construction with new systems															
Heating energy	5845	6049	-204	5970	6072	-103	5909	6012	-103	5805	5919	-114	5633	5772	-139
Cooling energy	1977	1905	72	1976	1904	71	1976	1905	71	1976	1905	72	1976	1905	71
Ventilation energy	122	109	13	123	109	13	122	109	13	122	109	13	122	109	13
Expenditure ($)	1727	1740	-14	1739	1743	-3	1733	1736	-3	1721	1726	-5	1703	1710	-7

Note1: D, W, and S indicate dark roof, white (cool) roof, and saving respectively. (-) shows penalty.
Note2: LWP, WP, NFD, and VLN indicate late winter packed, wind packed, newly fallen dry, and very loose new snow respectively.

Table 5-7 shows that in Anchorage for new small office with gas-heating system, the heating penalty of cool roof reduced from 1GJ/100m^2 to zero when snow is taken into account. Snow also increased the annual overall expenditure saving of cool roof from 15 to 18 \$/100m^2 for old construction. Table 5-8 shows with all-electric system cool roof increased annual energy expenditure by 23 \$/100 m^2 when simulated without the effect of snow on the roof. When the effect of roof snow is considered, this penalty removed (23 \$/100 m^2 difference for the effect of snow).

For medium office with gas-heating system cool roof simulated with roof snow had a penalty of 1 GJ/100m^2 but accounting for the effect of roof snow reduced the penalties to zero (Table 5-9). Cool roof resulted in annual energy saving expenditure when the effect of snow was considered (Table 5-10).

For large office even without considering the effect of snow, cool roof can save 10 \$/100m^2 for new construction (Table 5-11). For 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 \$/100m^2 (Table 5-13).

In Milwaukee, for small office with gas-heating system, snow decreases 1 GJ/100m^2 penalty of cool roof; this contributed to 5-17 \$/100m^2 saving for cool roof (Table 5-15). Table 5-16 shows for the new small office with all-electric system heating energy penalties of cool roof reduced from 167 to 33 kWh/100 m^2 when snow is taken into account and for old construction snow decreased this penalty by 25 \$/100m^2 (23 \$/100m^2 penalty to 2 \$/100m^2 savings).

For medium office with all-electric system the penalty of cool roof was 208 kWh/100m^2 without considering the roof snow whereas, it reduced to 80 kWh/100m^2 and this reduction contributed to 7 \$/100m^2 saving for cool roof. For large office, cool roof saved 4 to 22 \$/100m^2 considering snow on the roof (Tables 5-19 and 5-20). In addition, for the retail store, cool roof can save up to 39 \$/100m^2. (Tables 5-21 and 5-22).

In Montreal, for small office, depending on the construction, cool roof can save 14 \$/100m^2 for buildings with gas-heating system and 12 \$/100m^2 with all-electric system (Tables 5-23 and 5-24). For old medium office with all-electric system Table 5-26 shows that the heating penalty of cool roof was 239 kWh/100m^2 when snow was not considered, when it simulated with roof snow this penalty reduced to 61 kWh/100m^2 (6 \$/100m^2 penalty to 9 \$/100m^2 savings). For large office simulating snow on the roof, cool roof can save 3 to 26 \$/100m^2 (Tables 5-27 and 5-28) also cool roof on retail store building resulted in saving of up to 62 \$/100m^2 for old construction (Table 5-29).

In Toronto, for small office, Table 5-32 shows that snow changed 16 $/100m^2 penalty of cool roof to 4 $/100m^2 saving (20 $/100m^2 effect of snow). For medium office, cool roof saved 3 to 13 $/100m^2 considering snow on the roof (Tables 5-33 and 5-34). For large office cool roof saved 4 to 16 $/100m^2 (Tables 5-35 and 5-36) and for retail store building, cool roof could save maximum of 37 $/100m^2 (Table 5-37).

Figures 5-1 to 5-4 summarize the savings of cool roofs for the prototypes with gas-heating systems without and with considering the effect of snow (Late winter packed) in the locations of interest.

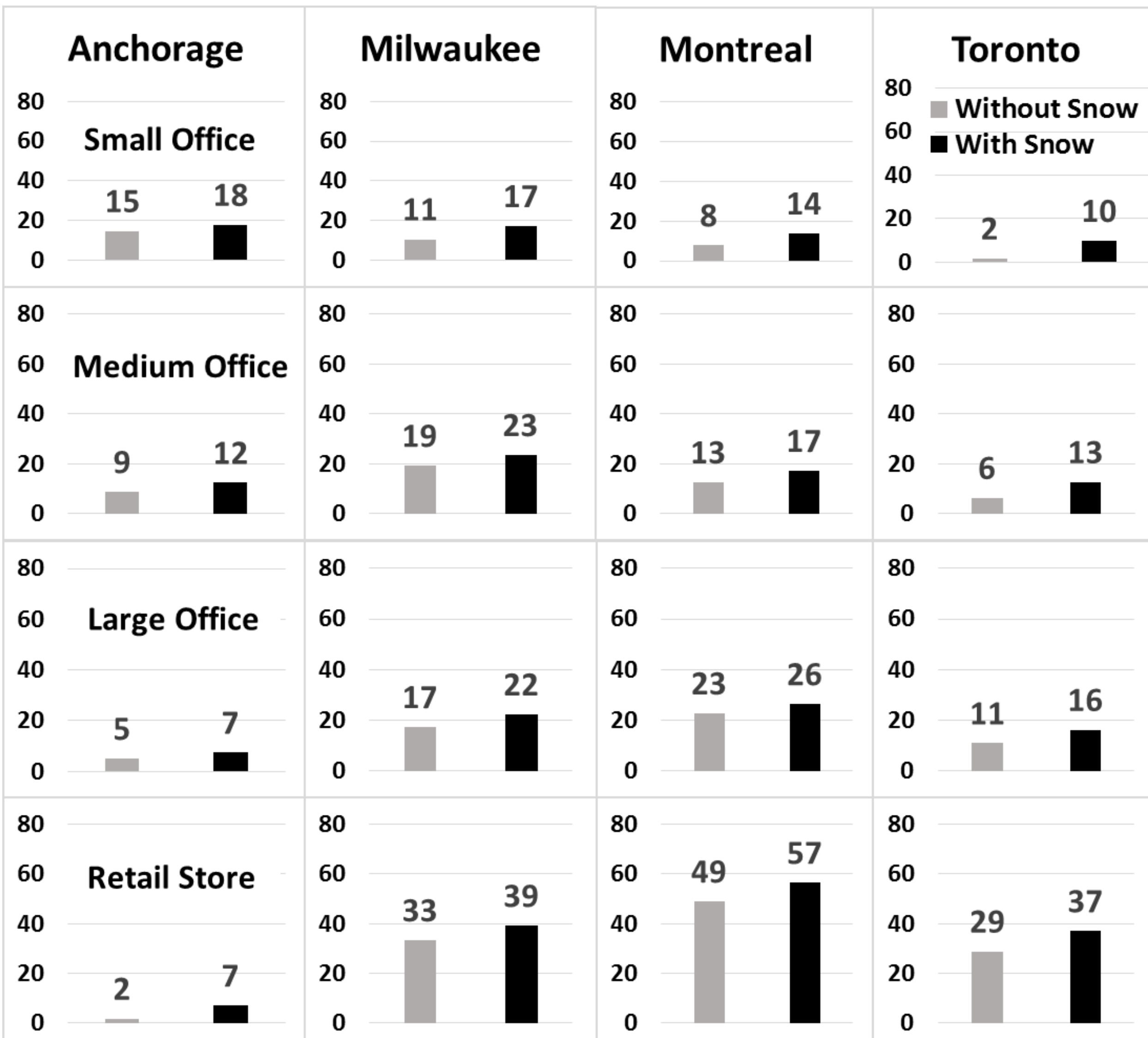


Figure 5-1. Savings of cool roofs with and without the effect of snow for the old buildings with gas-heating HVAC systems

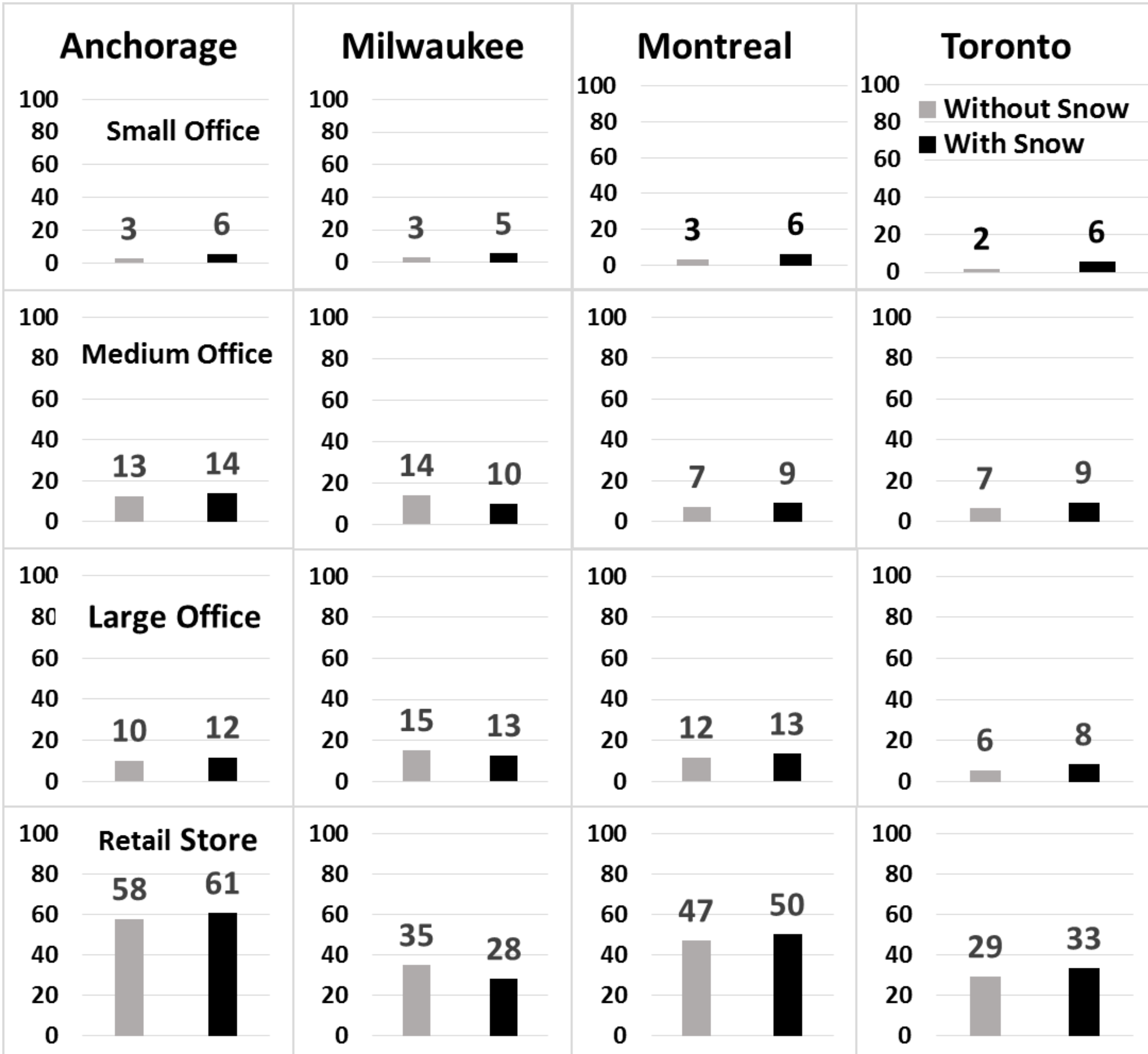


Figure 5-2. Savings of cool roofs with and without the effect of snow for the new buildings with gas-heating HVAC systems

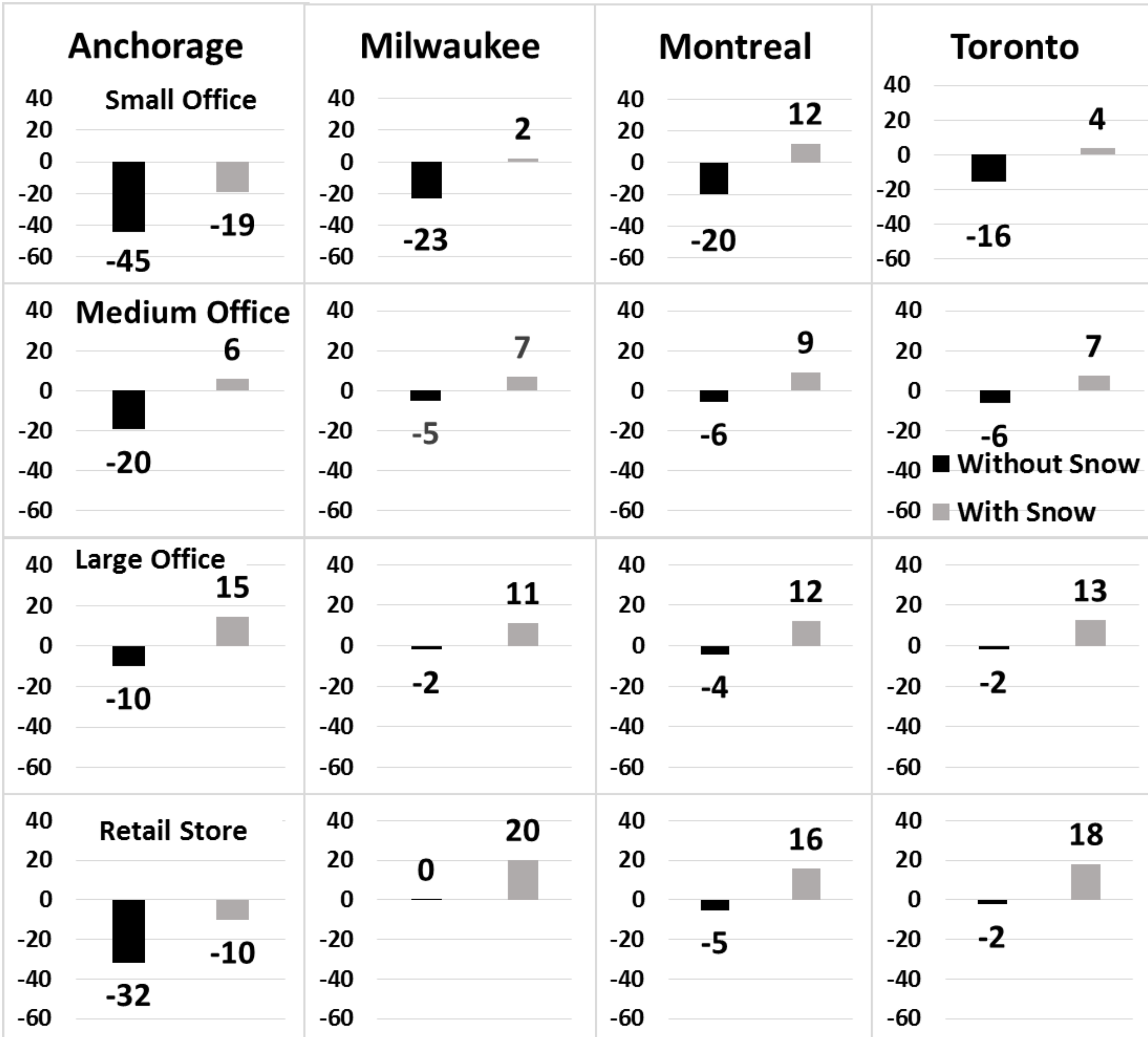


Figure 5-3. Savings of cool roofs with and without the effect of snow for the old buildings with all-electric HVAC systems

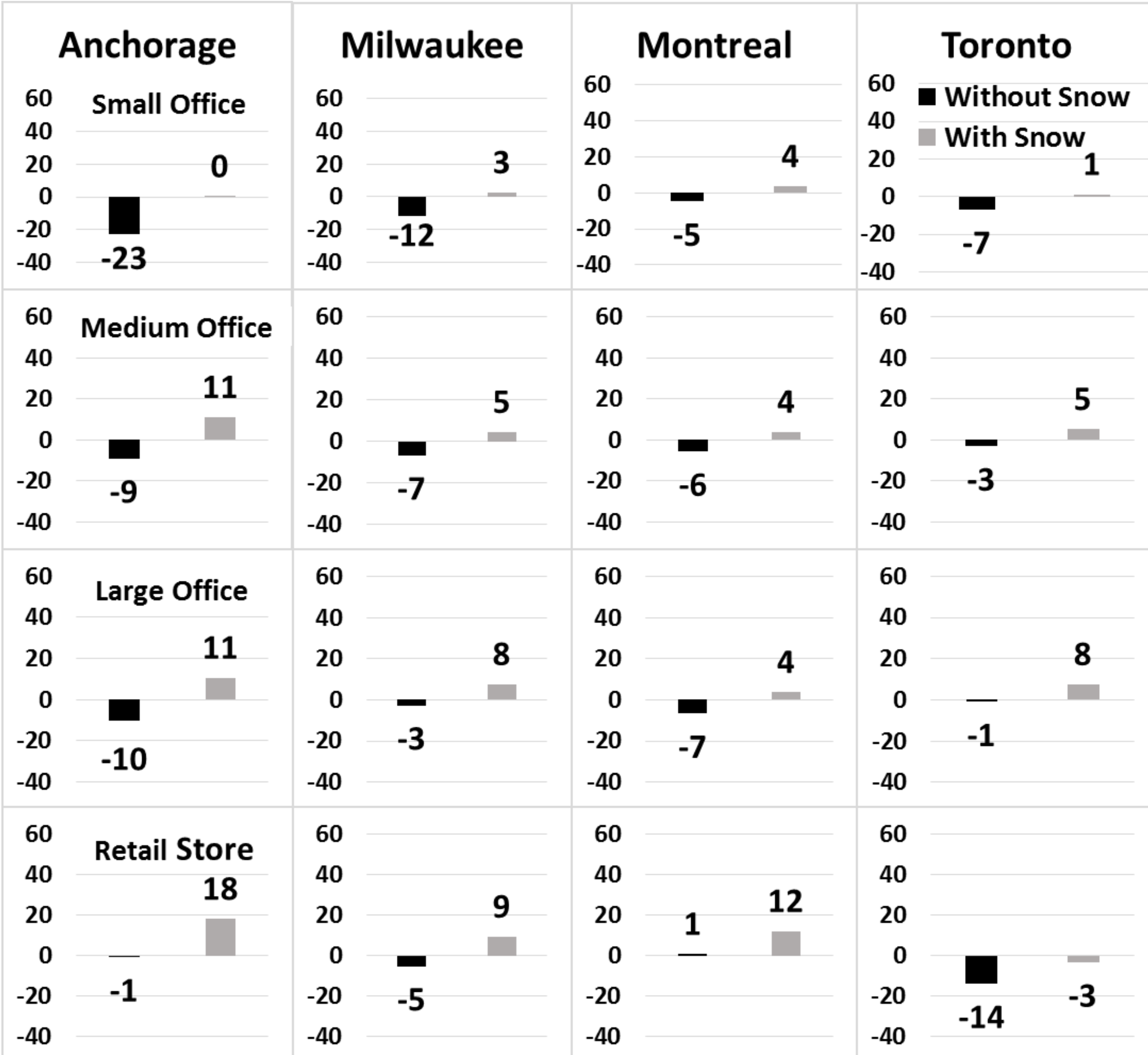


Figure 5-4. Savings of cool roofs with and without the effect of snow for the new buildings with all-electric HVAC systems

5.2.2 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).

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 5-35 shows the electricity peak demand (occurring in the afternoon in the studied locations) normalized to 1m2 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/m2 in Toronto and Montreal, respectively.

Table 5-39. Building electricity peak demand for buildings with gas-heating systems

Case	Small Office			Medium Office			Large Office			Retail Store		
	W/m^2			W/m^2			W/m^2			W/m^2		
	D	W	S	D	W	S	D	W	S	D	W	S
I. Anchorage												
a) Old construction with old systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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 with old systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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 with old systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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 with old systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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 with new systems												
Building Peak Demand	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

5.2.3 HVAC system size

Most 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. Then, this system size may be used to calculate the heating coil capacity as well. 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).

5.3 Discussion

The result show that savings of cool roofs in cold climates are highly dependent to 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 the 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 operate even during the weekends with longer working hours resulting in comparatively higher savings.

For the simulated buildings with all-electric system, considering the effect of snow on the roof, cool roof saved in annual overall energy expenditure in all locations except for the old small and retail store in Anchorage and the new retail store in Toronto. As Figures 5-1 to 5-4 show, in most cases cool roofs on old buildings with lower level of roof insulation have 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, a higher level of roof insulation 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; because the heating source (natural gas) is much 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 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 compared, it is observed that all the snow types lower the heating energy consumption of the building in four month 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 winter packed or wind packed snow, high solar reflectance dominates low thermal conductance of that and as a result affect thermal performance of the roof. Figures 5-5 and 5-6 show the monthly heating energy consumption of the small office building in Anchorage without and with different snow types on dark and cool roof.

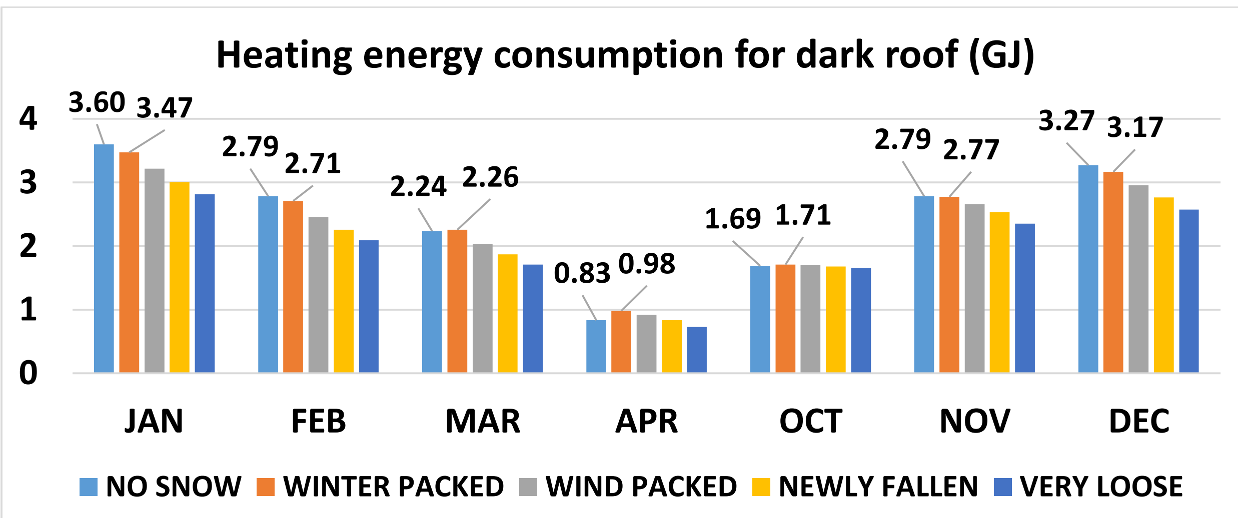


Figure 5-5. Monthly heating energy consumption of the small office building in Anchorage without and with different snow types on dark roof

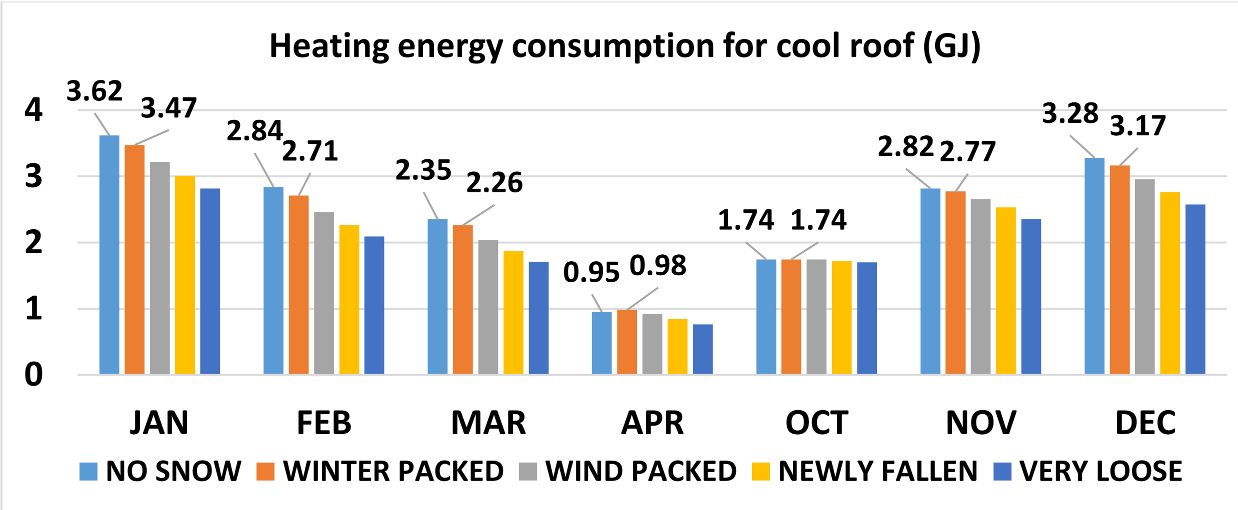


Figure 5-6. Monthly heating energy consumption of the small office building in Anchorage without and with different snow types on dark roof

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 down faster than the snow on the ground, because of heat conduction from the buildings. To better understand the effect of the snow on the roof, parametric simulations were performed by reducing the period of snow on the roof by 15 days on the beginning (October to December) and end (January to April) of snow collection on the roof (30 days reduction overall). Figures 5-7 and 5-8 show the results for reduced duration of snow. As the figures show, 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).

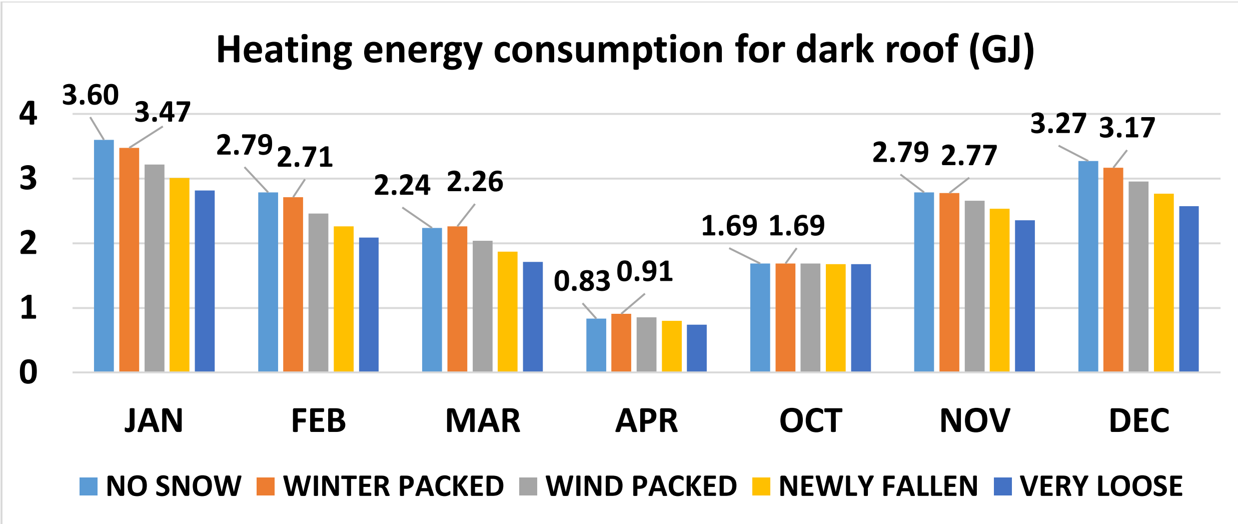


Figure 5-7. Monthly heating energy consumption of the small office building in Anchorage without and with different snow types on dark roof for 30 days reduced snow duration

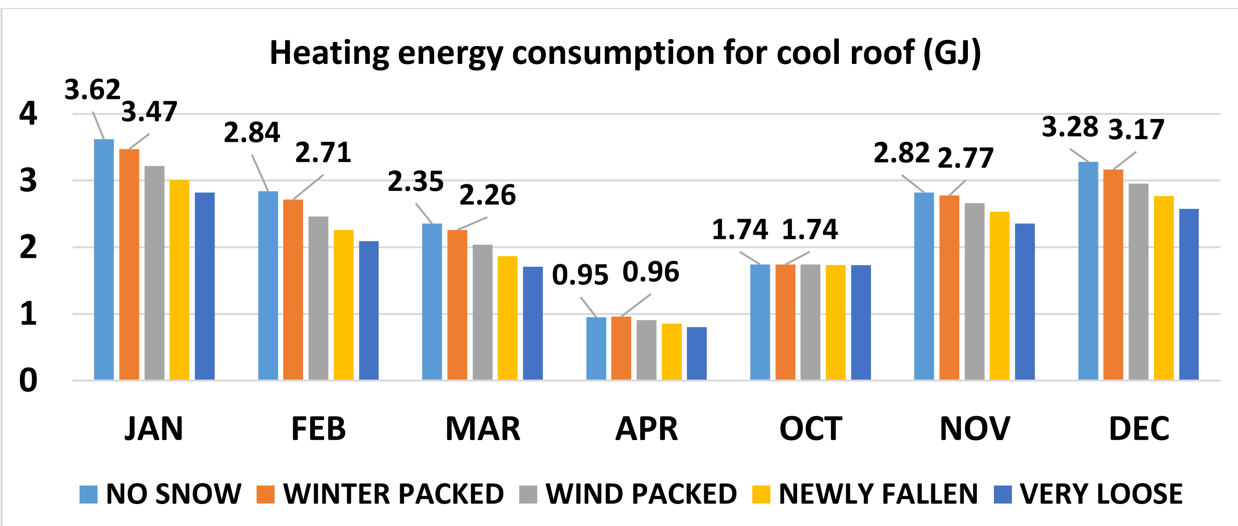


Figure 5-8. Monthly heating energy consumption of the small office building in Anchorage without and with different snow types on cool roof for 30 days reduced snow duration

Moreover, some parametric simulations were performed to better understand the effect of snow thickness on the roof; for these parametric simulations, the effect of snow, assuming a constant snow solar reflectance of 0.8, was simulated on a single story small office building (465 m^2 roof area). A VAV system was used as a central HVAC system for this building. First the six year average of daily snow thickness was changed to 80% and 120% for various snow types. As Figures 5-8 and 5-9 illustrate there is a linear correlation between the snow thickness and annual heating energy of the building in Anchorage.

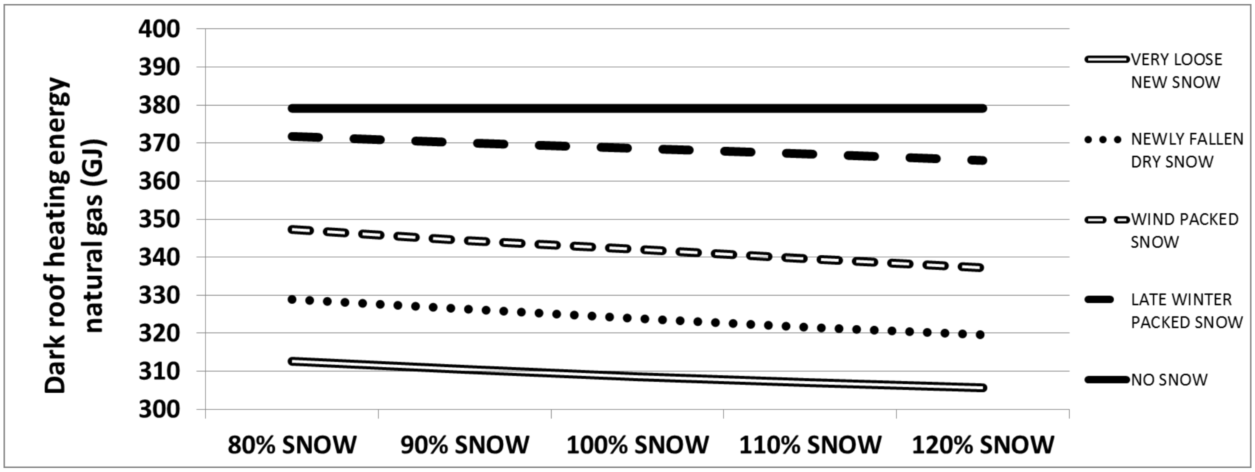


Figure 5-9. Effect of different types of snow on heating energy considering the snow thickness for dark roof in Anchorage

Figures 5-8 and 5-9 show that annual natural gas heating energy consumption of the building with dark and cool roof without snow in Anchorage are 379 and 391GJ respectively (815 and 841 MJ/m^2) while these amounts for dark and cool roofs considering the winter packed snow are 369 and 373 GJ respectively (794 and 802 MJ/m^2). Therefore, annual heating energy penalty for cool roof decreases from 26 to 8 MJ/m^2.

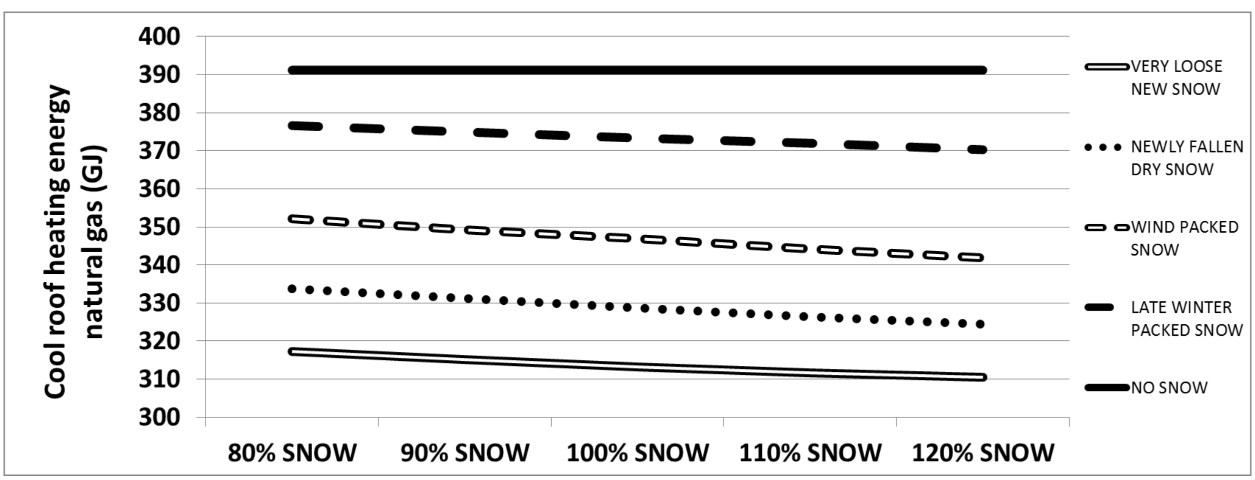


Figure 5-10. Effect of different types of snow on heating energy considering the snow thickness for cool roof in Anchorage

All types of snow reduce annual heating energy in Anchorage; however, late winter packed snow can increase the heating energy consumption for Milwaukee. Figures 5-10 and 5-11 present the annual heating energy consumption for dark and cool roof in Milwaukee.

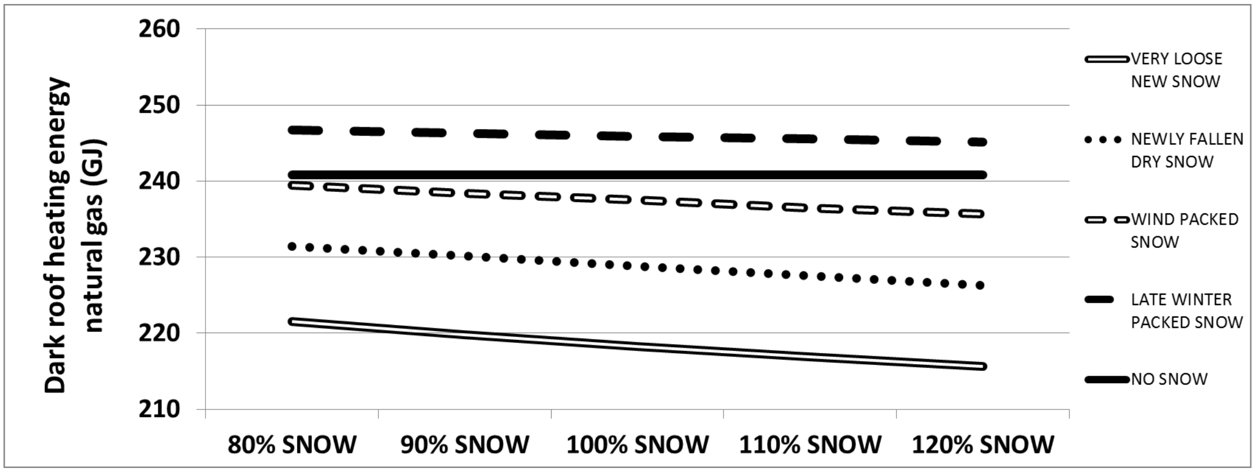


Figure 5-11. Effect of different types of snow on heating energy considering the snow thickness for dark roof in Milwaukee

From Figures 5-10 and 5-11, 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 540MJ/m^2). Therefore, annual heating energy penalty for cool roof decreases from 24 to 11 MJ/m^2.

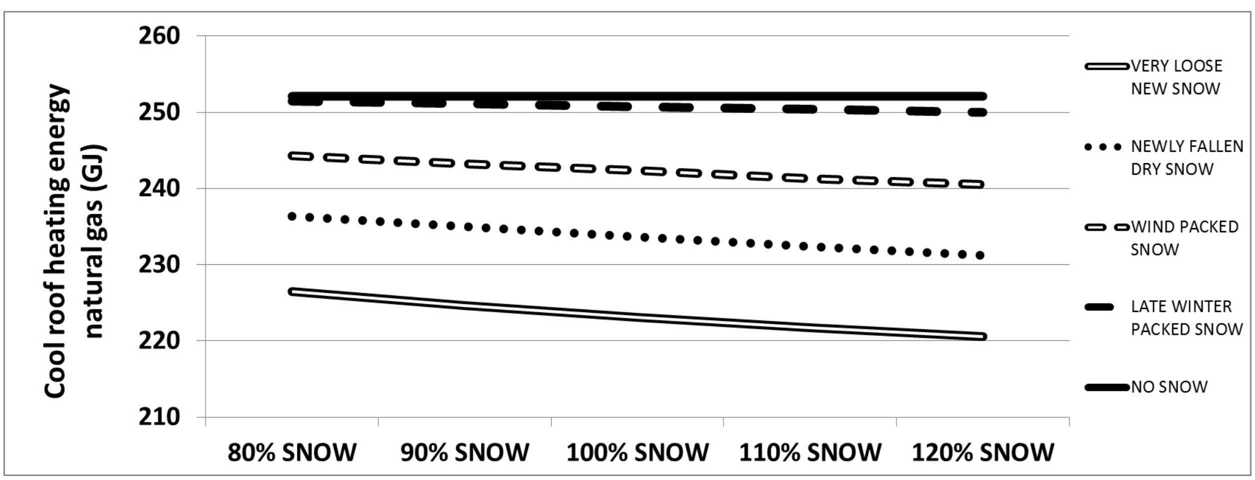


Figure 5-12. Effect of different types of snow on heating energy considering the snow thickness for cool roof in Milwaukee

Chapter 6: Summary and conclusion

Cool roof is a roof system which can reflect solar radiation and emits the heat and consequently keeps the roof surface cool; Since a dark roof absorbs 90% or more of solar energy, it can reach to 150 °F (66 °C) while a cool roof may stay only at 100 °F (38 °C) or cooler. A cooler roof surface, reduces the cooling load during the summer conditioning and cutting down cooling costs. Utilizing a cool roof is an efficient way to reduce the cooling energy use of a building. It provides a better thermal Comfort for non-conditioned building and lower cooling energy for conditioned buildings.

In cold climates, during the winter the sun angle is lower, days are shorter, sky is cloudy, and most heating occur 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.

Snow can play an important role in heat flux through the roof of the building. Thermal conductivity of snow is low comparing with that for the soil and varies with density and water content of that. For a dry snow with density of 100 kg/m^3, thermal conductivity of snow is about 0.045 $Wm^{-1}K^{-1}$ (more than six times smaller than that for soil) which means that at a constant length, snow can insulate six times more effectively than soil. Moreover, snow reflects most short wave radiation (high albedo comparing with soil), absorbs and reemits most long wave radiation and varies during the winter. The albedo of compact dry clean fresh snow is 0.8 to 0.9 dropping to 0.5 to 0.6 for the aged wet patchy and to 0.3 to 0.4 for porous dirty snow. A portion of short wave radiation is not reflected can penetrate to the top 30 cm of snow cover. Snow also acts almost as a black body; which means that snow absorbs long wave portion of solar radiation (thermal infrared) and emits it as thermal radiation. In this study we considered four types of snow based on density and consequently thermal conductivity. For simulating the effect of snow by DOE-2, a function consisting of U-value and absorptivity of the roof on a daily basis was defined to simulate four different types of snow on the roof.

The energy cost savings expected from a cool roof depends on many factors such as climate; the amount of roof insulation; the type of building use; energy prices; and the type and efficiency of HVAC systems therefore, a small single story, a medium three-story, a large three-story office and a large single story retail store were studied as prototype buildings with flat roofs. Three scenarios were considered for each building: old construction with old HVAC system (pre-1980), old construction with new HVAC systems, and new construction with new HVAC systems.

In this study it is mainly focused on quantifying the heating energy penalties of a cool roof accounting for the effect of roof snow. The results show that snow effectively reduces the heating penalties of cool roofs in cold regions. Although the type of snow plays an important role in heating energy consumption, it does not have a great impact on the amount of cool roof saving, in other words, cool roof has almost a constant amount of saving with any type of snow. For instance, in Anchorage for new small office with gas-heating system, the heating penalty of cool roof reduced from 1GJ/100m^2 to zero when snow is taken into account. Snow also decreased the annual overall energy expenditure penalty of cool roof from 23 to 0 \$/100m^2 for old construction with all-electric HVAC system (23 \$/100 m^2 difference for the effect of snow).

For medium office with gas-heating system, cool roof simulated without roof snow had a penalty of 1 GJ/100m^2 but accounting for the effect of roof snow reduced the penalties to zero. Cool roof resulted in annual energy saving expenditure when the effect of snow was considered.

For large office even without considering the effect of snow, cool roof can save 10 \$/100m^2 for new construction. For retail store building with gas-heating system in Anchorage, cool roof never experience any penalty in overall energy expenditure. For the new construction cool roof saves up to 61 \$/100m^2.

In Milwaukee, for small office with gas-heating system, snow decreases 1 GJ/100m^2 penalty of cool roof; this contributes to 5-17 \$/100m^2 saving for cool roof. For the new small office with all-electric system heating energy penalties of cool roof reduced from 167 to 33 kWh/100 m^2 when snow is taken into account and for old construction snow decreased this penalty by 25 \$/100m^2 (23 \$/100m^2 penalty to 2 \$/100m^2 saving). For medium office with all-electric system the penalty of cool roof was 208 kWh/100m^2 without considering the roof snow whereas, it reduced to 80 kWh/100m^2 and this reduction contributed to 7 \$/100m^2 saving for cool roof. For large office, cool roof saves maximum of 22 \$/100m^2 considering snow on the roof. In addition, for the retail store, cool roof can save up to 39 \$/100m$^{2.}$

In Montreal, for small office, depending on the construction, cool roof can save 14\$/m^2 for buildings with gas-heating system and 12 \$/100m^2 with all-electric system. For old medium office with all-electric system the heating penalty of cool roof was 239 kWh/100m^2 when snow was not considered, when it was simulated with roof snow this penalty reduced to 61 kWh/100m^2 (6 \$/100m^2 penalty to 9 \$/100m^2 saving). For large office by simulating snow on the roof, cool roof can save 3 to 26 \$/100m^2. Cool roof also resulted in up to 62 \$/100m^2 saving for old retail store.

In Toronto, for small office, snow changes 16 \$/100m^2 penalty of cool roof to 4 \$/100m^2 saving (20 \$/100m^2 effect of snow). For medium office, cool roof save 3 to 13 \$/100m^2 considering snow on the roof. For large office cool roof can save 4 to 16 \$/100m^2 and for retail store building, cool roof can save maximum of 37 \$/100m^2.

Cool roof can reduces the peak electric demand of the retail store buildings up to 1.9 and 5.4 W/m^2 in Toronto and Montreal respectively.

6.1 Contribution

The results show that snow can effectively reduce the heating penalty for buildings with cool roofs—as seen in all the simulated climate regions—contributing to annual energy expenditure savings. 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 plants and to prevent unwanted electricity shutdowns on hot summer days. 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. Therefore, a cool roof can be used in cold climates without concern for annual energy consumption or expenditures. For these reasons and due to the great environmental benefits of a cool roof, we highly recommend cool roofs be used instead of the more typical dark roofs, even in cold climates.

6.2 Future work

Because most low-rise residential buildings have steep, sloped roofs, they provide a great opportunity to evaluate the savings and penalties of cool roofs for steep-sloped residential buildings in cold climates. Steep-sloped roofs are designed to shed snow accumulation, and they must be modeled with precision. Future work should investigate these conditions to provide further recommendations for cool roofs.

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