HEATING ENERGY PENALTIES OF COOL ROOFS: THE EFFECT OF SNOW ACCUMULATION ON ROOF

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ABSTRACT

Utilizing a cool roof is an efficient way to reduce the cooling energy use of a building. Cool roofs, however, may increase heating energy use in winter. 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 lower (than what is commonly thought) winter time heating penalties for cool roofs.

We used DOE-2.E to simulate energy consumption in an office building in four cold climate cities in North America: Anchorage (AK), Milwaukee (WI), Montreal (QC), and Toronto (ON). The effect of sun angle, clouds, daytime duration, and heating schedules can be modelled with 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 the effect of snow, we defined a function consisting of U-value and absorptivity of the roof on a daily basis to simulate four different types of snow on the roof. We used an average of six years meteorological data from National Oceanic and Atmospheric Administration (NOAA) and Environment Canada to estimate the snow thickness on the roof. Results show that the heating penalties of cool roof are significantly lower (than what is commonly thought) considering snow on the roof. Annual heating energy consumption of the building with dark and cool roof without considering the snow are 85 and 88 MJ/100 m^2, respectively (3 MJ/100 m^2 penalty for cool roof) in Anchorage whereas, the annual heating energy for the dark and cool roof considering the effect of Late-Winter Packed snow are 83 and 84 MJ/100 m^2, respectively (1 MJ/100 m^2 penalty for the cool roof). For a typical office building with electricity as cooling fuel and natural gas as heating fuel, cool roofs save $0.08/ m^2 in Montreal and in Toronto the saving for cool roof is $0.04/ m^2 (not accounting for the effect of peak demand savings and potential downsizing of the HVAC systems).

KEYWORDS

Cool Roof, Heating Energy, Cold Climate, Office Building, DOE-2.E

1 INTRODUCTION

Cool roofs reduce the heat flux penetration into a building through the roof. Solar reflectance, infrared emittance, and thermal insulation are three parameters affecting roof heat flux. When a roof absorbs solar radiation, it is transformed into heat and some of this heat is emitted back as 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 (Akbari and Levinson 2010). When a roof is cooler, the heat flux through the roof decreases, therefore, less cooling energy is needed to provide thermal comfort inside the building. Thermal insulation of the roof is the third parameter that influences the heat flux through the roof. During the winter, because of lower solar radiation absorption, a cool roof may increase the heating energy of the building.

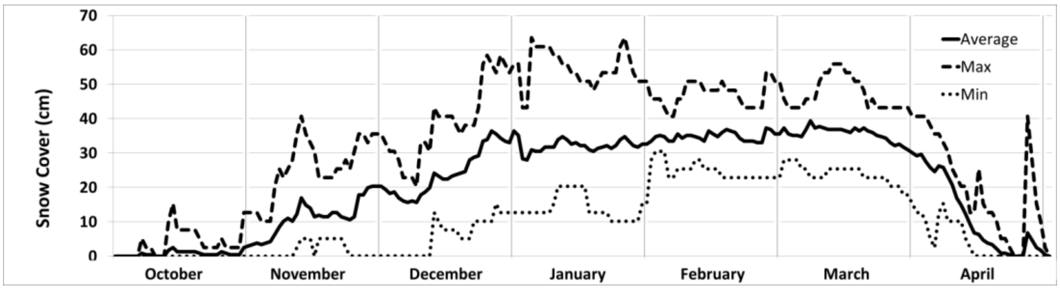
Akbari et al. (2004) state that for cold climates with hot summers, a roof with solar reflectance and high emmitance is preferred as the heating penalty during the year will be less important. In addition, for cold climates with no summer cooling, using cool roof is not suggested. Some factors that make the heating energy penalties small include: lower wintertime sun angle, shorter days (sun light hours), cloudy skies, and heating period (early in the morning and evening hours). In cold climates the roof may be covered by snow during some months of the heating season and there would not be a significant difference in heating energy use of a building with cool and dark roof. The focus of this study is to quantify the heating energy penalties of a cool roof accounting for the effect of roof snow.

2 METHODOLOGY

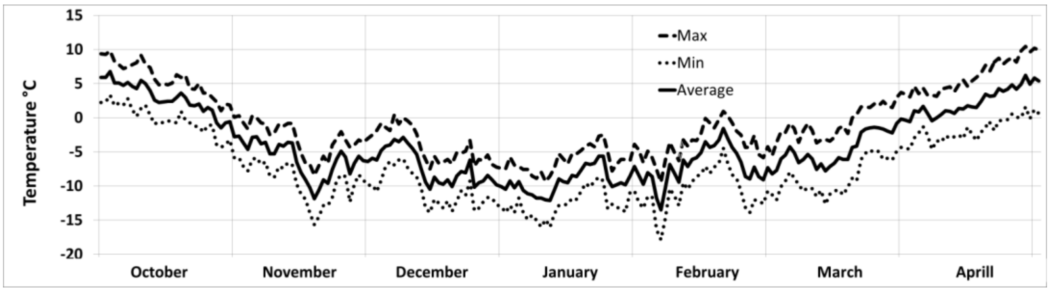
The effect of sun angle, clouds, daytime duration, and heating schedules can be modelled with existing capabilities of DOE-2. Snow on the roof provides an additional layer of insulation and increases the solar reflectance of the roof. To simulate the effect of snow, we defined a function consisting of U-value and absorptivity of the roof on a daily basis to simulate four different types of snow on the roof. We used an average of six years meteorological data to estimate the snow thickness on the roof.

2.1 Study sites and data

We studied four cold climate cities in North America: Anchorage (AK), Milwaukee (WI), Toronto (ON), and Montreal (QC). In order to estimate the thicknesses of snow cover, we applied previous meteorological data provided by National Oceanic and Atmospheric Administration (NOAA) for the first two cities and Environment Canada for the next two cities. Figure 1 shows the snow cover on a flat surface and outside air temperature in Anchorage. Note that snow is covering a flat surface from mid-October to mid-April.



a) Snow cover



b) Outdoor air temperature

Figure 1. Snow cover and outdoor air temperature in Anchorage, AK

2.2 Snow Properties

Gray (1970) and Raab and Vedin (1995) have documented the density for different types of snow as in Table 1.

Table 1: Density of different type of snow (kg/m^3)

Type of Snow	Raab and Vedin	Gray
Very loos new snow	<30	10-30
Newly-fallen dry snow	30-100	70-190
Wet, new snow	100-200	
Wind-packed snow	200	200-350
Late-winter Packed snow	200-300	400-550
Thawing snow in spring	>400	600-700

Hedstrom and Pomeroy (1998) provide an equation to calculate the density of fresh and dry snow based on the air temperature as follow:

$$\rho_s = 67.9+51.25\ e^{Ta/2.59} \tag{1}$$

Where: ρ_s is density of snow in kg/m^3 and T_a is the air temperature in °C.

Sturm et al. (1997) provide an equation for to calculate the snow effective conductivity based on the density of snow as below:

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

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

Where ρ is in g cm^{-3} and k_{eff} is in Wm^{-1} K^{-1}.

The heat transport through the snow has three components: (1) conduction through the ice lattice, (2) conduction through the air in the pore spaces, and (3) latent heat transport across pore spaces because of vapour sublimation and condensation. Radiation and convection heat transfer is considered small and ignored in our analysis. An effective thermal conductivity (k_{eff}) is used to combine all three main mechanisms (Sturm et al, 1997). We calculated k_{eff} of for snow using Eq. 2 and density of snow listed in Table 1 (see Table 2).

Table 2: Effective thermal conduction for different snow type

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

In this study we considered four types of snow based on thermal conductivity. Since in our methodology we change the U-value of the roof on a daily basis, we modelled the roof as a quick wall in DOE-2 (this approach ignores thermal storage effect of the roof materials). Much of the shortwave radiation incident on a snow surface is reflected, with albedos as high as 0.9 for compact, dry, clean snow, dropping to 0.5-0.6 for wet snow (Pomeroy and Brun, 2001). Hence, the absorptance of the snow was assumed to be as 0.2 as an average.

2.3 Simulated building characteristics

We studied a small (465 m²) office as prototype Building with flat roof consisting of six zones (four perimeters, one central, and a plenum zone). A VAV system with natural gas boiler together with an electric chiller as one case and a packaged variable volume variable temperature with heat pump system (using electricity for both heating and cooling) as second system serve the building. For the period that snow exists on the roof, we assumed that the absorptance of the roof is 0.2 and when snow disappears, the absorptance would be 0.85 and 0.4 for dark roof and cool roof, respectively. Table 3 presents the characteristics of the prototype building and HVAC system.

2.4 DOE-2 simulations

To simulate the effect of snow, we defined a function consisting of U-value and absorptivity of the roof on a daily basis to simulate four different types of snow on the roof.

2.4.1 Overall U-value of the roof with snow

In our modelling effort, we calculate the U-value of the snow based on its thermal conductivity and thickness. We considered density of four snow types (Late-winter packed, Wind packed, Newly-fallen dry, and Very loose new snow) and simulated the building energy consumption using DOE-2.E.

In order to find the overall U-value of the roof considering the snow, we used the following equation:

$$\frac{1}{U_{overall}} = \frac{1}{U_{roof}} + \frac{1}{U_{snow}} \tag{4}$$

Where, $U_{overall}$ is the overall U-value of the roof with snow, U_{roof} is U-value of the roof including inside film resistance (but not outside film resistance), and U_{snow} is U-value of snow. $U_{snow} = \frac{k_{eff}}{d}$, k_{eff} is thermal conductivity of snow from Table 2 which is result of equation 2, and d is daily thickness of snow. Thus, depend on the type and the thickness of snow we assumed a particular $U_{overall}$ for each day.

2.4.2 Duration of snow

Among the four cold-climate cities, in Anchorage the roof of the building is covered by snow for six months: mid-October to mid-April. Whereas, in other three cities the roof is covered by snow for almost four months and half: November 21 to April 8.

2.4.3 Slope of the roof

Here, we simulate the effect of the snow on flat roofs. Sloped roofs are designed to shed snow. Hence the period of snow cover on the roof is shorter and depends on the roof slope and frequency of snow storm.

2.4.4 Snow thickness

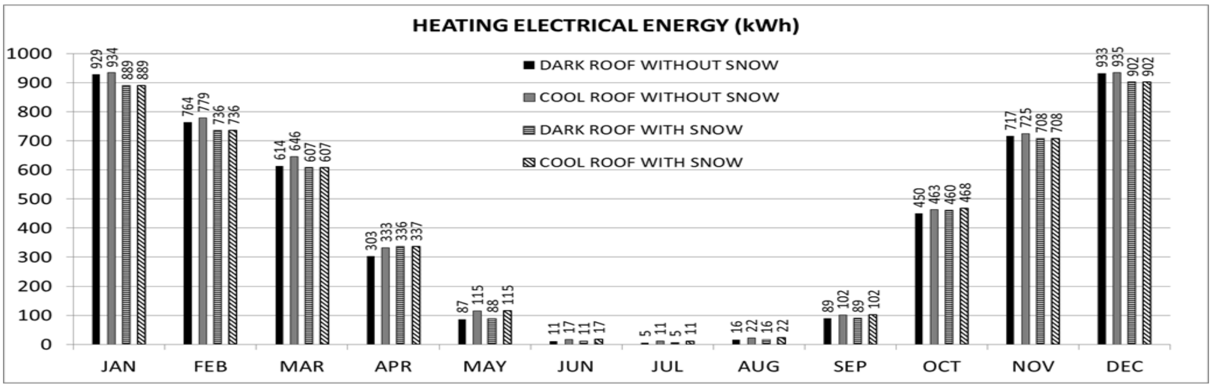
For all four simulated climate regions, we calculated the six-year daily average thickness snow cover on the surface and used the data to simulate the prototype building heating energy use with the snow on the roof.

3 RESULTS

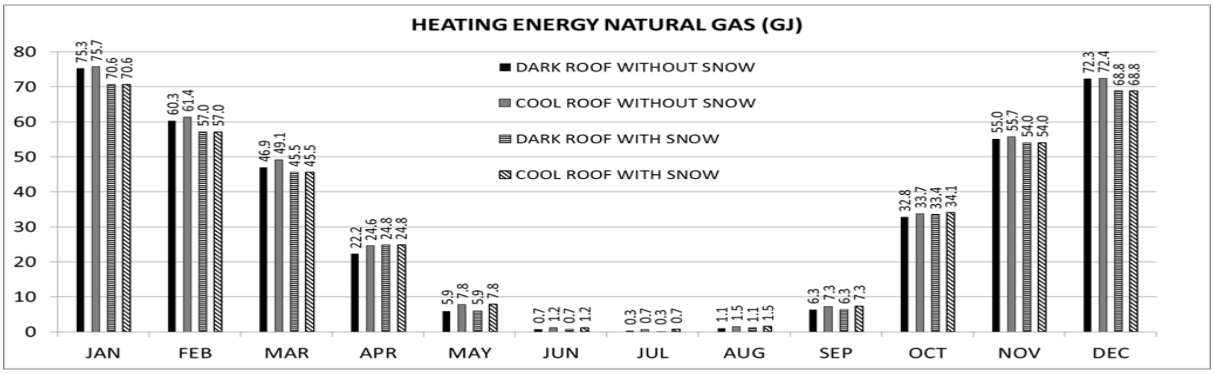
We first simulated the office building with dark and cool roof without snow to compare heating and cooling energy consumption. Then, we simulated the effect of snow, taking into account as a layer of the roof.

Table 3: Prototype office building and HVAC system characteristics

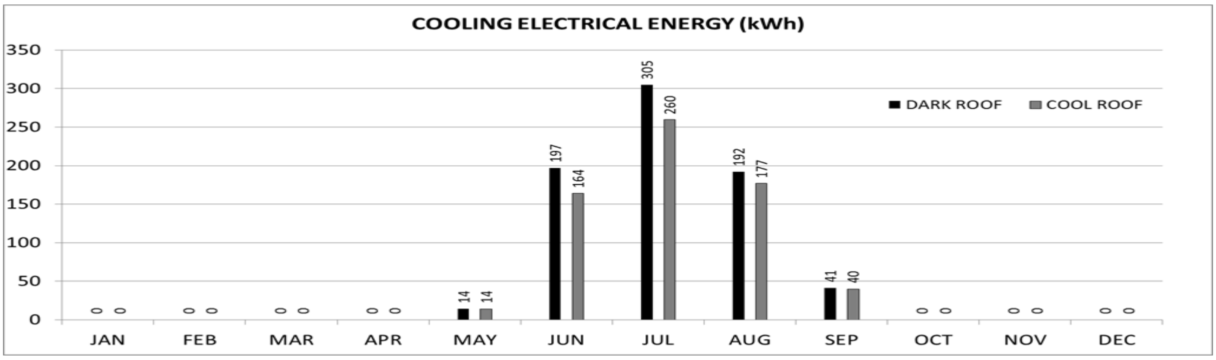
Characteristic	Old Vintage	Old Vintage New HVAC	New Vintage
Construction			
Floor Area (m^2)	464.5		
Number of Floors	1		
Floor Materials	4IN Concrete Slab-On-Grade		
Roof Materials	Roof Gravel, Built-up-roof, R-7 Mineral Board insulation, Wood Sheathing (U-Value=0.63W/m^2K)		R-20 insulation(U-Value=0.251W/m^2K)
Wall Materials	Wood Shingles, Plywood, R-7 Fiber insulation, Gypsum Board (U-Value=0.555W/m^2K)		R-19 insulation (U-Value=0.241W/m^2K)
Window Characteristics			
Number of Panes	2	2	2
Shading Coefficient	0.76	0.76	0.76
Interior Loads			
Occupancy (Person)	50		
Interior Lights (W/m^2)	16.14		
Miscellaneous (W/m^2)	10.76		
HVAC System			
Type 1	Variable Air Volume (VAV)		
Schedule	8 am – 9 pm Weekdays Jan1 – Dec 31		
Ventilation	Supply		
Capacity	Zonal/Local	Zonal/Local	Zonal/Local
Efficiency	0.55		
Economizer	Temperature		
Economizer Limit Temperature(°C)	18.3		
Outside Air (m^3/h/person)	34		
Natural Ventilation	No		
Cooling			
Type	Air-Cooled Hermetic Reciprocating Chiller		
Capacity	Zonal/Local	Zonal/Local	Zonal/Local
COP	3.65	4.54	4.54
Setpoint (°C)	25		
Setup (°C)	37		
Heating			
Type	Natural Gas Hot Water boiler		
Capacity	Zonal/Local	Zonal/Local	Zonal/Local
Efficiency (%)	80	84	84
Setpoint (°C)	21		
Setup (°C)	13		
Type 2	Packaged Variable Volume and Temperature (VVT)		
Cooling			
Type	Direct-Expansion		
Capacity	Zonal/Local	Zonal/Local	Zonal/Local
COP	2.77	3.57	3.57
Setpoint (°C)	25		
Setup (°C)	37		
Heating			
Type	Heat Pump		
Capacity	Zonal/Local	Zonal/Local	Zonal/Local
COP	2.7	3.5	3.5
Setpoint (°C)	21		
Setup (°C)	13		



a) Monthly electrical heating energy consumption



b) Monthly natural gas heating energy consumption



c) Monthly electrical cooling energy consumption

Figure 3: Small office building monthly electrical and gas heating energy (a,b) and electrical cooling (c) consumption in Anchorage

For Anchorage, Figure 3 shows that using a cool roof for the building is associated with heating energy consumption penalties primarily during October through April. Accounting for the effect of snow, these penalties no longer exists for six months (Nov-Apr) of the year and the heating energy for the building with cool and dark roofs are the same. Cooling energy use (and hence savings) are fairly small.

We calculated annual expenditure for electricity and natural gas using local cost as in Table 4 for all the four cities.

Table 4: energy rates in the four locations

	Anchorage[1]	**Milwaukee**[1]	**Montreal**	**Toronto**
Electricity ($/kWh)	0.116	0.077	0.089 (HydroQuebec)	0.078 (OntarioHydro)
Natural Gas ($/therm)	0.49	1.01	0.31(Gaz Metro)	0.57 (Energy Shop)

1. Akbari and Levinson (2010)

Table 5 shows the annual heating penalties and cooling savings for cool roof with and without snow, for the building with VAV and PVVT system in all four cities. Considering the effect of snow on the roof, conditioning cost penalties for cool roof decreased in Anchorage (from 0.14 to 0.04 $/m^2$ for gas-heating system and from 0.29 to 0 $/m^2$ for electric-heating system). In Milwaukee for gas-heating system, conditioning penalties for cool roof reduced from 0.16 to 0.01 $/m^2$ and for electric-heating system from 0.13 to 0.07 $/m^2$.

Accounting for the effect of snow in Montreal, conditioning savings for cool roof increased from 0.01 to 0.08 $/m^2$ for gas-heating system and 0.18 $/m^2$ penalties for cool roof reached to 0.13 $/m^2$ savings for that of electric-heating system. In Toronto, for gas-heating system 0.05 $/m^2$ penalties for cool roof altered to a 0.04 $/m^2$ savings.

As the roof insulation in buildings increases (new construction), the energy consumption differences between dark roof and cool roof decreased significantly. For instance, in Anchorage penalties for cool roof decreased from 0.04 to 0.01$/m^2$ and in Milwaukee this amount reduced from 0.01 to 0 $/m^2$. For Montreal and Toronto also savings for cool roof decreased from 0.08 to 0.03 $/m^2$ and from 0.04 to 0.01 $/m^2$, respectively. These same results are obtained by Syneffa et al. (2007).

4 CONCLUSIONS

Utilizing cool roof is an efficient way to reduce building cooling energy use and urban heat island. Cool roofs, however, may increase the heating energy use. In this study, we simulated the annual heating and cooling energy use in conventional and cool roof buildings in four cities in cold climates. Results show that annual energy expenditure for an small office prototype building in cold climates with cool roofs is lower than those of dark roofs.

Accounting for the effect of roof snow, conditioning cost penalty for cool roof reduced dramatically in Anchorage (0.14 to 0.04 $/m^2$ for gas-heating system and 0.29 to 0 $/m^2$ for electric heating system). In Milwaukee for gas-heating system, conditioning penalties for cool roof reduced from 0.16 to 0.01 $/m^2$ whereas for electric-heating system 0.13 $/m^2$ penalty for cool roof altered to a 0.07 $/m^2$ savings.

In Montreal also conditioning savings for cool roof increased from 0.01 to 0.08 $/m^2$ for gas-heating system and 0.18 $/m^2$ penalty for cool roof changed to 0.13 $/m^2$ savings for electric-heating system. In Toronto for using gas-heating system, 0.05 $/m^2$ penalties for cool roof altered to a 0.04 $/m^2$ savings.

These simulations show that penalties for cool roofs in cold climates are very small, if any. Cool roofs also save peak demand electricity use during the summer (saving $) and potentially lead to down-sizing of the HVAC equipment (saving more $). Accounting for the peak demand savings and downsizing will only make cool roofs more economical. Also, it should be noted that a cool roof replacing a dark roof leads to cooling of the globe. The heat island reduction and air quality benefits of cool roof are also significant.

5 ACKNOWLEDGEMENTS

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Table 6: Annual heating penalty and cooling saving for cool roof with and without snow in the building with VAV and PVVT system

City	Gas heating (heating in GJ/100 m2, cooling in kWh/100 m2)										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		No snow on roof		LWP snow on roof		WP snow on roof		NFD snow on roof		VLN snow on roof	
	D*	C*	D	C	D	C	D	C	D	C	D	C	D	C	D	C	D	C	D	C
a) Anchorage										**Old construction with old systems**										
Heating energy use	85	88	83	84	77	78	73	74	70	71	12468	12800	11792	11885	10511	10604	9678	9771	8994	9086
Cooling energy use	161	141	161	141	161	141	161	141	161	141	216	135	227	135	227	135	227	135	227	135
Conditioning expenditure ($)	520	534	508	512	474	479	451	455	431	435	1471	1500	1394	1394	1246	1246	1149	1149	1070	1070
										Old construction with new systems										
Heating energy use	81	84	79	80	74	75	70	71	66	67	11545	11874	10916	10990	9685	9758	8888	8961	8238	8311
Cooling energy use	129	113	129	113	129	113	129	113	129	113	176	105	176	105	176	105	176	105	176	105
Conditioning expenditure ($)	498	512	487	491	454	459	432	436	413	417	1360	1390	1287	1287	1144	1144	1051	1052	976	976
										New construction with new systems										
Heating energy use	60	61	60	61	58	58	56	56	54	54	8084	8225	8001	8023	7571	7593	7192	7214	6801	6823
Cooling energy use	126	116	126	116	126	116	126	116	126	116	187	148	187	148	187	148	187	148	187	148
Conditioning expenditure ($)	373	378	372	373	360	361	349	350	337	338	959	971	950	948	900	898	856	854	811	809
b) Milwaukee										**Old construction with old systems**										
Heating energy use	54	57	55	56	53	55	52	53	49	50	7043	7399	7215	7318	6844	6948	6470	6574	6030	6134
Cooling energy use	1385	1252	1385	1252	1385	1252	1385	1252	1385	1252	1359	1167	1359	1167	1359	1167	1359	1167	1359	1167
Conditioning expenditure ($)	654	670	666	667	647	648	628	629	604	605	647	660	660	653	632	625	603	596	569	562
										Old construction with new systems										
Heating energy use	52	54	53	54	51	52	49	50	47	48	6410	6730	6560	6646	6197	6282	5837	5922	5419	5504
Cooling energy use	1112	1005	1112	1005	1112	1005	1112	1005	1112	1005	1067	912	1067	912	1067	912	1067	912	1067	912
Conditioning expenditure ($)	609	626	621	623	603	605	584	587	562	564	576	588	587	582	559	554	532	526	499	494
										New construction with new systems										
Heating energy use	37	38	38	38	37	38	37	37	36	36	4329	4460	4436	4465	4348	4377	4243	4271	4084	4113
Cooling energy use	1046	994	1046	994	1046	994	1046	994	1046	994	1047	971	1047	971	1047	971	1047	971	1047	971
Conditioning expenditure ($)	458	465	465	465	460	460	453	453	443	443	414	418	422	419	415	412	407	404	395	391
c) Montreal										**Old construction with old systems**										
Heating energy use	70	73	71	72	68	69	65	66	62	63	10054	10492	10194	10289	9537	9631	8930	9025	8279	8374
Cooling energy use	1176	1029	1176	1029	1176	1029	1176	1029	1176	1029	1176	938	1176	938	1176	938	1176	938	1176	938
Conditioning expenditure ($)	377	376	381	373	370	362	359	351	347	339	999	1017	1012	999	953	941	899	887	841	829
										Old construction with new systems										
Heating energy use	67	70	68	69	65	66	62	63	59	60	9318	9712	9357	9516	8808	8884	8227	8303	7602	7678
Cooling energy use	944	826	944	826	944	826	944	826	944	826	918	730	918	730	918	730	918	730	918	730
Conditioning expenditure ($)	347	349	351	345	341	335	330	324	319	313	911	929	914	912	866	856	814	804	758	748
										New construction with new systems										
Heating energy use	50	51	51	51	50	50	49	49	47	48	6623	6798	6760	6788	6605	6633	6418	6446	6140	6168
Cooling energy use	874	818	874	818	874	818	874	818	874	818	854	766	854	766	854	766	854	766	854	766
Conditioning expenditure ($)	274	274	277	274	275	271	271	267	265	262	665	673	678	672	664	658	647	642	622	617
d) Toronto										**Old construction with old systems**										
Heating energy use	54	57	56	57	54	56	53	54	51	52	6502	6884	6724	6850	6426	6552	6106	6232	5715	5841
Cooling energy use	1365	1204	1365	1204	1365	1204	1365	1204	1365	1204	1435	1182	1435	1182	1435	1182	1435	1182	1435	1182
Conditioning expenditure ($)	440	445	449	445	440	436	431	427	418	414	619	629	636	627	613	603	588	578	558	548
										Old construction with new systems										
Heating energy use	51	54	52	54	51	52	50	51	48	49	5686	6056	5883	6020	5601	5734	5304	5435	4943	5061
Cooling energy use	1109	978	1109	978	1109	978	1109	978	1109	978	1117	891	1117	891	1117	891	1117	891	1117	891
Conditioning expenditure ($)	400	406	409	407	401	399	392	390	380	378	531	542	546	539	524	517	501	493	473	464
										New construction with new systems										
Heating energy use	37	38	37	38	37	38	37	37	36	36	4156	4304	4286	4325	4222	4261	4136	4175	3999	4038
Cooling energy use	1024	963	1024	963	1024	963	1024	963	1024	963	942	866	942	866	942	866	942	866	942	866
Conditioning expenditure ($)	305	308	310	309	308	307	305	304	300	299	398	403	408	405	403	400	396	393	385	383

***LWP=Late Winter Packed WP=Wind Packed NFD=Newly Fallen Dry VLN=Very Loose New D=Dark C=Cool**

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