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THE IMPACT OF TREES AND WHITE SURFACES ON RESIDENTIAL HEATING AND COOLING ENERGY USE IN FOUR CANADIAN CITIES

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Abstract—We have investigated the potential of using vegetation and high-albedo materials in Toronto, Edmonton, Montreal, and Vancouver, Canada, to modify the urban microclimate, thereby saving residential heating and cooling energy use. Parametric computer simulations of microclimates and energy performance of prototypical houses were our primary analysis tools. The building prototypes included a detached one-story and a detached two-story single family house, as well as a row house. The simulations indicated that by increasing the vegetative cover of the neighborhood by 30% (corresponding to about three trees per house) and increasing the albedo of the houses by 20% (from moderate-dark to medium-light color), the heating energy in Toronto can be reduced by about 10% in urban houses and 20% in rural houses, whereas cooling energy can be reduced by 40 and 30%, respectively. The annual savings in heating and cooling costs for different houses ranged from $30 to $180 in urban areas and from $60 to $400 in rural zones. In urban houses of Edmonton, Montreal, and Vancouver, savings in heating energy use were about 10%. Cooling energy can be totally offset in Edmonton and Vancouver, and average savings of 35% can be achieved in Montreal.

INTRODUCTION

The Canadian climate is dominated by high heating demands during the winter and moderate cooling needs during the summer. But because of rapid penetration of residential air-conditioning, the cooling energy costs are also becoming important in the region. In fact, data from Ontario Hydro indicate that the system-wide peak load in the summer is comparable to the winter peak load. We need, therefore, to consider potential savings in heating and cooling energy equally. Microclimate modification strategies are especially suitable for this purpose. In particular, tree planting and high-albedo‡ materials appear to be two efficient and easily implemented strategies.[1,2]

City administrators are more aware of their urban climates and heat islands than they were a decade ago, and urban planners and policy makers are now more willing to implement strategies that can modify the urban climate and save energy on the city scale. Today, there is a trend towards urban tree planting and many cities have actually inaugurated such programs. A striking example is the city of Los Angeles, California, where 1 million trees were planted for the 1984 Olympics.§

While there has been considerable attention directed towards vegetation, urban reforestation, and research on the effects of trees on microclimate and energy use in buildings, little has been done to study and implement high-albedo materials in the built environment. So far, computer simulation of the effects of whiter surfaces has been the main tool for energy savings estimations.[2,3]

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‡The albedo is the space- and wavelength-integrated reflectivity. In this study, we are especially interested in the solar spectrum between 0.1 and 4 μm.

§Reports indicate that, unfortunately, many of the trees planted in Los Angeles in 1984 did not survive.

In this paper, we investigate both the influence of vegetation and whiter surfaces in the context of Canada's climate and building prototypes. We simulate the microclimate changes associated with increasing the vegetative cover and surface albedo in residential neighborhoods, using models that we developed to simulate the energy and moisture balance of tree microclimates and the effects of changing surface albedo in urban areas. To study the energy use of buildings in the various climates of Canada, we simulate several prototypes and thermal integrity/fuel options with the DOE-2.1D building energy analysis program. DOE-2.1D is a public domain program developed under the leadership of the Lawrence Berkeley Laboratory. It can be used to simulate the hourly performance of heating and cooling systems and the indoor environmental conditions for any building/system configuration.

PROTOTYPE HOUSE DESCRIPTIONS

We gathered information on common housing stock in the sector served by the Ontario Hydro utility. We used the most common house configurations based on information from Ontario Hydro, Ontario Ministry of Energy, and published literature.[4,5] The prototypes we simulated include detached one-story, detached two-story single family residences, and two-story row houses. Table 1 summarizes the general characteristics of the three prototypical buildings.

Table 2 shows the thermal integrity of each prototype, considering three fuel/integrity options: (a) gas-heated houses, (b) electric-heated houses, and (c) R-2000 gas houses. The given R-values correspond to additional insulation on walls or roofs. For example, the R-0 values at the exterior walls, basement walls, and basement floors of existing gas-heated homes indicate that there is no additional insulation on the concrete walls or floors. All prototypes have full basements, the detached houses are exposed on all four sides, whereas the row houses have only northern and southern exposures as their east and west walls are fully shielded by neighboring buildings (this latter assumption was made so that row buildings benefit from the south exposure).

Table 1. Building types (partly based on data from Ref. 4).

Building type	Floor area (ft^2)	Exposed wall area[a] (ft^2)	Roof area[b] (ft^2)	Window area[c] (ft^2)	Door area (ft^2)	Wall perimeter length (ft)
Row houses[d]	1716	1956	846	108	35	118 (26×33)
Detached, 1-story	1084	1367	1200	100	35	134 (27.8×39)
Detached, 2-story	2170	2465	1200	215	35	134 (27.8×39)

All buildings have full basements. [a]This column includes the areas of windows and exterior doors; [b]this is the actual area of the gable (inclined) roof; [c]uniformly distributed on all exposed walls; [d]Row houses have two stories.

Table 2. Thermal integrity (partly based on data from Ref. 4). The R-values given here are for additional insulation on walls and roofs.

Building type	Roof ins. (R)	Exposed ceiling ins. (R)	Exterior walls ins. (R)	Windows[a] (R)	Doors (R)	Basement walls (R)	Basement floor (R)	Infiltration/ ventilation (cfm)
Existing (all-electric)	29	32	12	2	3.5[b]	6[c]	0.5	110
(gas-heated)	19	30	0	2	3.5[b]	0	0	110
R-2000 (electric and gas)[d]	40	32	20	2	4	12	5	10[e]

[a]Double glazing; [b]wood sash with storm; [c]average value; [d]instead of detailed envelope specification, the R-2000 code can be alternatively met by observing pre-set total annual energy targets in kWh/year (Ref. 4) as follows: Windsor - 18700, Toronto - 19600, Ottawa - 20700, North Bay - 21900, Thunder Bay - 22700, Timmins - 23500, Moosonee - 24900, Trout Lake - 26300; [e]cfm/room, or < 0.45 ach (whichever is smaller); additional requirements: leakage area = 1 $in^2/100\ ft^2$ (existing = 3 $in^2/100\ ft^2$).

We divided the housing stock into two groups—those under and those over 180 m² floor area. For prototype houses under 180 m² we assumed one 75,000 Btu/h gas furnace and one 36,000 Btu/h air conditioner. In electrical houses, the gas furnace was replaced with electric resistance heaters totaling 12 kW. Other equipment in the building amounted to a total of 0.5 average kW. In houses over 180 m², we assumed two 75,000 Btu/h gas furnaces and two 36,000 Btu/h air conditioners. In electric houses, the gas heaters were replaced with electric resistance heaters totaling 18 kW. Other electrical equipment amounted to 0.75 average kW.

We categorized the building stock as either existing standard or R-2000 standard. In the existing buildings, we assumed a gas furnace efficiency of 65%, an air conditioner coefficient of performance (COP) of 2.17, and electric resistance heater efficiency of 100%. In the R-2000 stock, we assumed a gas furnace efficiency of 78%, an air conditioner COP of 2.7, and electric heater efficiency of 100%. Finally, we assumed that each house has a lighting intensity of 5.4 W/m², a cooling thermostat setting of 25.5°C, and a heating thermostat setting of 21°C with a nighttime setback to 15.6°C between 11 p.m. and 7 a.m.

Our parametric simulations were performed using a SMART algorithm for air-conditioning control. We adopted the term SMART to indicate the operation of a building that is naturally cooled and ventilated by opening the windows whenever the outside temperature and moisture allowed such natural cooling of the building.

WEATHER DATA

In order to conduct our microclimate simulations, we used weather data for Toronto, Edmonton, Montreal, and Vancouver from WYEC (Weather Year for Energy Calculation) tapes. A weather summary for these cities is given in Table 3.

SIMULATION AND ASSUMPTIONS

Generally speaking, vegetation affects the microclimate via three major processes: shading, wind speed reduction (wind shielding), and evapotranspiration.[1,3] Albedo, on the other hand, affects the microclimate by reducing the absorbed solar radiation at the surface in question.[2] We first studied the effects of each process separately; then we studied the simultaneous impacts of a combination of these processes. As mentioned earlier, we used the DOE-2.1D building energy analysis program for the energy simulations and we used a weather processor that we developed through heat island research at the Lawrence Berkeley Laboratory to simulate the microclimate modifications.[2,3,6]

The attenuation of solar radiation by vegetation was accounted for by simulating the shadow case by trees on the walls and windows of the buildings. Since our simulations were intended to show average conditions for the majority of houses, we assumed that any given vegetative cover would be uniformly distributed on all orientations (in terms of cooling energy use, this is a conservative assumption since tree shade can be optimized to maximize energy savings by positioning the trees on the south and west sides of buildings). The trees let in 70% of the sunlight in winter but only 10% in summer.

Table 3. Weather data summary.

Parameter	Edmonton	Montreal	Toronto	Vancouver
Avg. Drybulb Temp. (F)	34.7	43.7	45.9	49.6
Avg. Wetbulb Temp. (F)	30.8	39.6	42.2	46.4
Max. Drybulb Temp. (F)	83	89	93	78
Min. Drybulb Temp. (F)	-34	-17	-10	18
No. of Cloudy Days	84	78	80	83
Heating Deg. Days (Base 65)	11247	8244	7547	5734
Cooling Deg. Days (Base 65)	20	346	372	33

The wind reduction (shielding) caused by trees was simulated based on empirical correlations between tree/building density and wind speed in residential neighborhoods. The empirical data distinguish between the wind effects of trees in full leaf and the effects of trees with no leaves. For this purpose, we assumed that trees are in full leaf between 1 April and 1 October.

The effects of evapotranspiration were accounted for by simulating the impact of trees' evaporative cooling on ambient air temperature and atmospheric moisture.[1] For this purpose, we assumed that trees transpire only above ambient air temperatures of 10°C, and that evapotranspiration is insignificant between October and April.

Only the direct effect of changing albedo were simulated by modifying the color of a building's walls and roof from moderate dark (albedo = 30%) to medium light (albedo = 50%).

We analyzed the cost savings of trees and light-colored surfaces only for Toronto, using a rate of 6¢/kWh for electricity and a base rate of $6/month plus 19¢/m^3 for gas.[8]

BASE CASES VS PARAMETRIC SIMULATIONS

In addition to various building types and fuel/thermal integrity variants, we defined two climate base cases for Toronto. The first climate base case corresponds to an urban residential area devoid of trees (no shade or evapotranspiration effects) but with a building cover equivalent to 20%. The buildings have an albedo of 30%, which corresponds to a dark brown or dark gray color.

The second climate base case is more similar in characteristics to an airport location with small roughness or tree effects. This base case thus corresponds to a vegetation-free rural residential neighborhood that is relatively more open (sparse buildings) than the urban residential neighborhood. The buildings have an albedo of 30%.

For Toronto, we performed simulations for both urban and rural houses. For the other cities (Edmonton, Montreal, and Vancouver), we performed simulations for urban houses only. The vegetation parametric simulations were performed with the assumption that a 30% uniformly distributed tree cover was installed at the site. This cover, corresponding to about three trees per house, causes shading, wind shielding, and evapotranspiration effects. In the urban neighborhoods, the 30% foliage increase in cover is added to the 20% equivalent building cover in the base case, and that results in a total cover of 50% for wind speed reduction calculations. In the rural neighborhoods, the 30% increase in cover is the only addition relative to the base case.

In the albedo parametric simulations, the albedo of the buildings was increased from 30 to 50%, with the latter corresponding to a medium-light color such as cream or yellow.

RESULTS

Toronto (urban residential sites)

Tables 4 and 5 summarize our simulation results for residential sites in the urban and rural areas of Toronto. Table 4 presents the energy and peak implications of climate modifications via the processes mentioned earlier, whereas Table 5 gives results for combined simulations as well as corresponding energy costs and savings. In Table 4, the first column represents the base case energy consumption or peak power for heating and cooling for each prototype. The next five columns relate to trees. The columns labeled "Shade", "Shield", and "Evapo." give the relative changes in energy or peak power, with respect to the base case, resulting from shading, wind shielding, and evapotranspiration of trees. The numbers indicate energy savings; numbers in parentheses () indicate energy penalties rather than savings. The column labeled "Total" gives the total effect of trees on energy use or peak power. This total includes the simultaneous effects of shading, wind shielding, and evapotranspiration. The columns labeled "Δ" and "Δ%" give absolute and percentage changes from the base case. Finally, the column labeled

Table 4. Simulated energy use and peak power demand for the *urban sites* in Toronto.

	Basecase	TREES Shade Δ	TREES Shield Δ	TREES Evapo. Δ	TREES Total Δ	TREES Total Δ%	Albedo w/snow Δ	Albedo w/snow Δ%
DETACHED, 1-STORY, GAS								
Heating gas consumption GJ yr^{-1}	151.8	(0.7)	10.0	(0.4)	8.9	5.8	(0.7)	(0.5)
Cooling electricity GJ yr^{-1}	1.76	0.41	(0.08)	0.49	0.70	39.7	0.37	21.0
Peak heating gas kW equivalent	24.3	0	1.4	0	1.43	5.9	0	0
Peak cooling electricity kW	2.3	0.3	0.07	0.2	0.52	22.8	0.2	8.3
DETACHED, 2-STORY, GAS								
Heating gas consumption GJ yr^{-1}	263.4	(1.2)	18.5	(0.8)	16.4	6.2	(1.2)	(0.5)
Cooling electricity GJ yr^{-1}	4.47	0.82	(0.14)	1.08	1.52	34.0	0.72	16.1
Peak heating gas kW equivalent	45.2	0	2.5	0	2.51	5.6	0	0
Peak cooling electricity kW	4.4	0.5	0.2	0.3	0.98	22.0	0.3	7.2
DETACHED, 1-STORY, ELEC.								
Heating electricity GJ yr^{-1}	53.4	(0.5)	5.4	(0.2)	4.7	8.6	(0.2)	(0.3)
Cooling electricity GJ yr^{-1}	1.35	0.36	(0.01)	0.29	0.50	37.0	0.17	12.6
Peak heating electricity kW	10.0	0	0.8	0	0.81	8.0	0	0
Peak cooling electricity kW	1.7	0.3	0.1	0.1	0.55	31.5	0.1	5.8
DETACHED, 2-STORY, ELEC.								
Heating electricity GJ yr^{-1}	82.8	(0.7)	9.8	(0.3)	8.7	10.2	(0.3)	(0.3)
Cooling electricity GJ yr^{-1}	3.55	0.75	0	0.66	1.10	31.0	0.30	8.5
Peak heating electricity kW	17.8	0	1.3	0	1.30	7.3	0	0
Peak cooling electricity kW	3.3	0.6	0.2	0.2	0.95	29.0	0.1	4.5
DETACHED, 1-STORY, R-2000								
Heating gas consumption GJ yr^{-1}	51.0	(0.6)	3.7	(0.1)	2.94	5.6	(0.2)	(0.3)
Cooling electricity GJ yr^{-1}	1.09	0.24	(0.01)	0.17	0.33	30.3	0.09	8.3
Peak heating gas kW equivalent	11.5	0	0.6	0	0.59	5.2	0	0
Peak cooling electricity kW	1.1	0.2	0.04	0.07	0.32	28.7	0.06	5.1
DETACHED, 2-STORY, R-2000								
Heating gas consumption GJ yr^{-1}	79.0	(1)	6.9	(0.5)	5.3	6.5	(0.3)	(0.3)
Cooling electricity GJ yr^{-1}	3.05	0.60	0	0.44	0.81	26.6	0.19	6.2
Peak heating gas kW equivalent	21.0	0	1.0	0	1.10	5.0	0	0
Peak cooling electricity kW	2.2	0.4	0.09	0.1	0.64	29.0	0.09	4.0
ROW-HOUSE, GAS								
Heating gas consumption GJ yr^{-1}	110.9	(0.7)	13.0	(0.5)	12.0	10.6	(0.4)	(0.4)
Cooling electricity GJ yr^{-1}	3.18	0.35	0	0.46	0.65	20.4	0.25	7.9
Peak heating gas kW equivalent	24.2	0	2.1	0	2.13	8.8	0	0
Peak cooling electricity kW	2.3	0.2	0.2	0.1	0.46	19.8	0.1	5.3
ROW-HOUSE, ELECTRIC								
Heating electricity GJ yr^{-1}	42.9	(0.4)	7.4	(0.2)	6.7	15.0	(0.1)	(0.2)
Cooling electricity GJ yr^{-1}	2.86	0.30	0	0.28	0.49	17.1	0.11	3.8
Peak heating electricity kW	11.5	0	1.2	0	1.2	10.2	0	0
Peak cooling electricity kW	2.0	0.2	0.2	0.1	0.44	22.5	0.06	3.1
ROW-HOUSE, R-2000								
Heating gas consumption GJ yr^{-1}	36.9	(0.5)	5.0	(0.3)	4.2	10.8	(0.1)	(0.3)
Cooling electricity GJ yr^{-1}	2.72	0.30	0	0.24	0.43	15.8	0.08	2.9
Peak heating gas kW equivalent	12.8	0	0.9	0	0.87	6.9	0	0
Peak cooling electricity kW	1.4	0.1	0.09	0.07	0.29	21.1	0.04	2.9

The houses labeled GAS are heated with a gas heater and cooled with an electric air-conditioner. The houses labeled ELEC. are all-electric homes. We assumed that the R-2000 houses are gas-heated. The basecase column reports the energy use of buildings without any microclimate control strategy. The following columns report the absolute change in energy use (Δ) and the percent change in energy use (Δ%) compared to the basecase column. The bracketed numbers indicate a penalty (increase) rather than savings in energy use.

"Albedo, w/snow" represent the impact of albedo modifications with respect to a base case with snow cover in winter.

The effect of lightening the color of a building on heating energy is almost nil because the building's albedo is high in winter anyway as the roofs and portions of walls get covered with snow. Hence, for all practical purposes, lightening the color of a house reduces summer cooling loads without significantly affecting winter heating energy needs. On the other hand, if buildings have no snow cover, the effect of higher albedo on winter heating energy is relatively higher.

Some general observations can be made for Table 4. One can see that the total effect of trees is always a net saving. The negative effects (penalties) of albedo on heating energy is about 0.4%. The effects of all strategies on peak power are always net savings.

In the urban sites of Toronto, the simultaneous implementation of trees and albedo strategies in detached one- and two-story gas-heated homes saves an average 6% in heating

Table 5. Energy and cost savings of trees and white surfaces for the *urban and rural sites* in Toronto.

	Urban sites					Rural sites				
	Basecase		Savings (Trees + Albedo[a])			Basecase		Savings (Trees + Albedo[a])		
	Energy	Cost[b]	Energy		Cost	Energy	Cost[b]	Energy		Cost
	GJ yr^{-1}	$/Yr	GJ yr^{-1}	Δ%	$/Yr	GJ yr^{-1}	$/Yr	GJ yr^{-1}	Δ%	$/Yr
DETACHED, 1-STORY, GAS										
Heating gas consumption	151.8	846	8.2	5.4	42	168.2	930	22.6	13.3	115
Cooling electricity	1.76	29	1.08	61.3	18	1.68	28	0.79	47.0	13
Total	153.6	875	9.3	6.1	60	169.9	958	23.4	13.8	128
DETACHED, 2-STORY, GAS										
Heating gas consumption	263.4	1415	15.2	5.7	77	293.7	1570	41.9	14.2	213
Cooling electricity	4.47	2.24	74	50.1	37	4.32	72	1.75	40.5	29
Total	267.9	912	17.4	6.5	114	298.0	1642	43.7	14.7	242
DETACHED, 1-STORY, ELEC.										
Heating electricity	53.4	890	4.5	8.3	75	62.5	1042	12.9	20.3	215
Cooling electricity	1.35	22	0.67	49.6	11	1.35	22	0.55	40.7	9
Total	54.8	912	5.2	9.5	86	63.9	1064	13.5	13.5	224
DETACHED, 2-STORY, ELEC.										
Heating electricity	82.8	1379	8.5	10.0	141	99.4	1657	23.5	23.1	391
Cooling electricity	3.55	60	1.41	39.7	24	3.62	60	1.26	34.8	21
Total	86.6	1439	9.9	11.4	165	103.0	1717	24.8	24.1	412
DETACHED, 1-STORY, R-2000										
Heating gas consumption	51.0	332	2.8	5.6	14	57.3	364	9.4	16.0	48
Cooling electricity	1.09	18	0.42	38.5	7	1.09	18	0.34	31.2	8
Total	52.1	350	3.2	6.1	21	58.4	382	9.7	16.6	56
DETACHED, 2-STORY, R-2000										
Heating gas consumption	79.0	475	5.1	6.2	26	90.4	533	17.3	18.5	88
Cooling electricity	3.05	52	1.00	32.8	17	3.13	52	0.91	29.1	15
Total	82.1	527	6.1	7.4	43	93.4	585	18.2	19.5	103
ROW-HOUSE, GAS										
Heating gas consumption	110.9	638	11.6	10.3	59	133.0	750	30.7	22.7	157
Cooling electricity	3.18	53	0.91	28.6	15	3.19	53	0.79	24.8	13
Total	114.1	691	12.5	11.0	74	136.2	803	31.5	23.1	170
ROW-HOUSE, ELECTRIC										
Heating electricity	42.9	715	6.6	14.7	110	55.6	927	17.7	30.9	296
Cooling electricity	2.86	48	0.60	20.9	10	2.91	48	0.61	20.9	10
Total	45.8	763	7.2	15.7	120	58.5	975	18.3	31.3	306
ROW-HOUSE, R-2000										
Heating gas consumption	36.9	260	4.1	10.4	21	45.4	303	12.7	26.5	65
Cooling electricity	2.72	45	0.51	18.7	9	2.74	46	0.48	17.5	8
Total	39.6	305	4.6	11.6	30	48.1	349	13.2	27.4	73

[a]Albedo with snow; [b]formula for annual gas costs: \$72 + 19¢/m^3 (we assumed 35300 Btu/m^3 of gas); for electricity costs, we used 6¢/kWh. In these simulations, vegetation and albedo parameters were simultaneously changed. The energy saving columns show the corresponding changes in energy use with respect to the basecase.

gas and 55% in cooling electricity (see Table 5). In the detached electrical homes, the savings are about 9 and 45% for heating and cooling electricity, respectively. Since the R-2000 houses are better insulated than the gas and electric ones, the percentage savings are lower, 6 and 40% on heating gas and cooling electricity. In the gas-heated row houses, these savings are 10 and 29% on heating gas and cooling electricity, in electric row houses the savings are 15 and 21% on heating electricity and cooling electricity, respectively. Finally, in the R-2000 row-houses, the savings are 10 and 19% on heating gas and cooling electricity.

In terms of peak power, the savings are also considerable. In the detached gas homes, the average savings in heating peak power and cooling peak power are, respectively, 6 and 30%. In the detached electrical homes, the savings are 8 and 35% for the heating peak and cooling peak, respectively. In the detached R-2000 houses, these savings are 5 and 33%; in the gas-heated row houses, they are 9 and 25% on heating and cooling peaks, respectively. In electric row houses, the savings are 10 and 26% and in the R-2000 row-houses, the savings are 7 and 24% for the heating and cooling peaks, respectively.

Table 5 also contains energy costs associated with operating these buildings and the savings resulting from applying the strategies mentioned earlier. The "Cost" column under "Basecase" represents the annual dollar amounts required to heat and cool the buildings whereas the "\$/Yr" column under "Savings" gives the annual dollars saved by applying the combined strategies. The first five columns in Table 5 indicate possible energy savings of up to 15% in heating energy and up to 61% in cooling energy use for the urban sites. The mean is 8%

savings in heating energy and 37% savings in cooling energy. The total annual dollar savings can be as high as $165 and the mean is $79. Of course, one has to weigh these savings by building stock size to estimate potential savings for the entire city.

Toronto (rural residential sites)

Table 5 also summarizes the results of our simulations for the Toronto rural areas. The *net* impact of microclimate modification on energy use is larger in rural areas than in urban zones. Savings in heating energy in rural Toronto can be as high as 31% (compared to 15%) and savings in cooling energy can be as large as 47% (compared to 61%). The mean savings are 21% in heating energy (compared to 8%) and 31% in cooling energy (compared to 37%). The main reason why rural areas have larger heating energy savings but smaller cooling energy savings is because of the larger impact of wind shielding in open rural areas than in denser urban zones. Slower winds relieve the need for heating in winter but increase the need for cooling in summer.

The implementation of trees and albedo strategies in detached one- and two-story gas homes saves about 14% in heating gas and 44% in cooling electricity. In the detached electrical homes, the savings are about 22 and 38% for heating and cooling electricity, respectively. In the detached R-2000 houses, these savings approach 17 and 30% on heating gas and cooling electricity. In the gas-heated row houses, these savings are 23 and 25% on heating gas and cooling electricity, in electric row houses the savings are 31 and 21% on heating electricity and cooling electricity, respectively. Finally, in the R-2000 row-houses, the savings are 27 and 17% on heating gas and cooling electricity.

Rural peak power savings are also substantial (not shown in table). In the detached gas-heated homes the savings in heating peak power and cooling peak power are respectively about 12 and 35%. In the detached electrical homes, the savings are on average 10 and 37% for heating and cooling peak, respectively. In the detached R-2000 houses, these savings are about 11 and 35% on heating and cooling peaks; and in the gas-heated row houses, they are 18 and 32% on heating and cooling peaks, respectively. In electric row houses the savings are 20 and 30%, and in the R-2000 row-houses, the savings are 14 and 27% on heating and cooling peaks, respectively.

Finally, the net dollar savings are much higher in the rural sites than in the urban ones. The annual dollar savings can be as high as $412 (compared to $165); the mean for all prototypes is $190.

Edmonton, Montreal, and Vancouver (urban residential sites)

Table 6 summarizes the energy performance of buildings in Edmonton, Montreal, and Vancouver. In Edmonton, only a small amount of cooling is needed in detached two-story houses; the other prototypes can be cooled with natural ventilation. Also, because this city is the coldest of the four considered, the addition of trees offsets the cooling needs in the two prototypes. After trees have been added, there is no need to use high albedo on building surfaces (to save cooling energy) because the cooling load is either non-existent or is already met by the shading and evaporative cooling effects of trees. The heating energy use, of course, is higher than that in Toronto. The savings in heating energy use resulting from wind-shielding effect of trees can be as high as 11%. The average savings in heating energy in detached one- and two-story gas houses is 5%, whereas the savings in the electric houses are 8% on average. In the R-2000 houses the average savings are 4.5%. In the gas row houses, the savings are 8%, in the electric row-houses, they are 12%, and in the R-2000 row houses, the savings in heating energy are 8% on average. For those prototypes where cooling energy was not met with trees alone, high-albedo materials were used (see "Trees + Albedo" column).

Montreal has a climate that is closer to that of Toronto and, as a result, we see somewhat the same kind of energy performance and savings. In terms of heating energy, savings from trees can be as high as 14% and savings in cooling energy as high as 100% (completely offset). The

Table 6. Energy savings for the *urban sites* in Edmonton, Montreal, and Vancouver.

	Edmonton[a]			Montreal					Vancouver[a]		
	Basecase	Savings Trees		Basecase	Savings Trees		Savings Trees + Albedo[b]		Basecase	Savings Trees	
	GJ yr^{-1}	GJ yr^{-1}	Δ%	GJ yr^{-1}	GJ yr^{-1}	Δ%	GJ yr^{-1}	Δ%	GJ yr^{-1}	GJ yr^{-1}	Δ%
DETACHED, 1-STORY, GAS											
Heating gas consumption	221.13	9.72	4.38	173.35	9.94	5.70	9.26	5.31	101.32	4.11	4.00
Cooling electricity	0.00	-	-	1.02	0.48	46.81	0.76	75.18	0.00	-	-
DETACHED, 2-STORY, GAS											
Heating gas consumption	375.80	18.08	4.78	299.72	18.46	6.11	17.32	5.73	176.78	7.35	4.09
Cooling electricity	0.69	0.69	100.0	2.27	1.55	68.30	2.11	92.71	0.00	-	-
DETACHED, 1-STORY, ELEC.											
Heating electricity	83.51	5.19	6.36	62.50	5.38	8.47	-	-	32.41	2.19	6.50
Cooling electricity	0.00	-	-	0.78	0.78	100.0	-	-	0.00	-	-
DETACHED, 2-STORY, ELEC.											
Heating electricity	125.18	9.61	7.77	96.80	10.02	10.12	9.76	9.85	49.31	4.00	7.65
Cooling electricity	0.55	0.55	100.0	1.80	1.26	69.66	1.49	82.63	0.00	-	-
DETACHED, 1-STORY, R-2000											
Heating gas consumption	81.85	3.26	3.90	60.32	3.39	5.47	-	-	30.46	0.97	2.98
Cooling electricity	0.00	-	-	0.63	0.63	100.0	-	-	0.00	-	-
DETACHED, 2-STORY, R-2000											
Heating gas consumption	123.59	6.28	4.94	93.23	6.42	6.63	-	-	46.42	2.15	4.21
Cooling electricity	0.00	-	-	1.48	1.48	100.0	-	-	0.00	-	-
ROW-HOUSE, GAS											
Heating gas consumption	163.61	13.49	8.11	129.56	13.86	10.50	13.42	10.16	64.85	5.90	8.66
Cooling electricity	0.00	-	-	1.50	0.90	60.10	1.50	100.0	0.00	-	-
ROW-HOUSE, ELECTRIC											
Heating electricity	65.41	7.52	11.11	51.67	7.80	14.50	7.70	14.32	21.52	3.20	13.20
Cooling electricity	0.00	-	-	0.84	0.30	35.19	0.37	44.64	0.00	-	-
ROW-HOUSE, R-2000											
Heating gas consumption	62.36	5.00	7.58	45.59	4.99	10.28	-	-	17.05	1.79	8.66
Cooling electricity	0.00	-	-	0.73	0.73	100.0	-	-	0.00	-	-

[a] Note that in this case, we do not need to use light-colored materials because there is generally no cooling need (all but two cases) and when there is one, trees offset all the cooling need. Besides being useless in further decreasing the cooling load, the implementation of high albedo will increase the heating load and result in penalties; [b] albedo with snow.

average savings in heating energy in detached one- and two-story gas houses are 6% and the savings in the electric houses are 9% on average. In the R-2000 houses the average savings are 6% and in the gas row houses, the savings are 11%. In the electric row-houses, savings are 15%, and in the R-2000 row houses, the savings in heating energy are 10% on average.

In Vancouver, all the cooling loads are totally met with natural ventilation, so neither trees nor high albedo are needed for further cooling energy savings. However, trees can still save heating energy, and in this case, the savings can be as high as 13%. The average savings in heating energy in detached one- and two-story gas houses are 4%, whereas the savings in the electric houses are 7%. In the R-2000 houses the average savings are 3%. In the gas row houses, the savings are 9%, whereas in the electric row-houses, they are 13%. In the R-2000 row houses, the average savings in heating energy are 9%.

Cost of conserved energy

In an earlier report, Akbari et al[1] have estimated a cost of conserved energy of less than 1¢/kWh for urban shade trees and white surfaces. A thorough cost-benefit analysis for the Canadian cities is beyond the scope of the present study; however, in the absence of a detailed analysis, the following simplified discussion is presented.

Most houses are painted every 5–10 years; house owners could be encouraged to re-paint their houses in light colors. Therefore, one can argue that the incremental cost of changing the color of houses is nil. Also, many people plant trees in their yards for aesthetic reasons. In a low-cost information program, house owners can be advised of the most effective species and planting locations. The initial and maintenance costs of a tree can vary from zero to over $100, depending on the tree species, the planter and the maintainer of the tree. Most literature, however, site cost figures in the range of $5–50 for a tree. Assuming these costs, the simple payback period for urban houses in Toronto is in the range of 2 weeks–2 years.

CONCLUSIONS

We first note that the simulation results reported in this study involved only moderate changes in tree cover and albedo. Had these modifications been made larger, which is easily possible, higher savings would have resulted. Increased vegetation cover of up to 60 or 80% in other climates produced substantial savings in the heating and cooling energy use in buildings. Similarly, the albedo of houses can be increased to larger values than 50%. We have investigated the cooling energy savings of surface colors up to 90% reflective, and the results indicate large savings as well. In this study, we only simulated the direct effects of albedo. The work of Taha et al[2] has indicated that the indirect effects of albedo are even more effective in reducing cooling energy demand than the direct effects.† We investigated the impacts of only moderate changes in vegetation cover and albedo to give conservative results and also to suit the climate of Canada, where larger changes may not be needed. The changes in tree cover and albedo must be balanced to avoid energy penalties resulting from overdoing one or the other. Also, the simulations were performed with our assumption that there exists a nighttime setback in the heating thermostat setting (from 21 to 15.6°C). Without this setback, the savings in heating energy would be much larger. Also, it can be argued that the case without nighttime setback is more likely to be closer to the actual operation of the buildings.

Our simulations indicate that by implementing such simple strategies as tree planting and color changes, there is potential for large savings in building energy consumption in Canada. The results show that heating energy in Toronto can be reduced by an average 10% in urban residential neighborhoods and an average 20% in rural neighborhoods. Cooling energy, on the other hand, can be reduced by 40 and 30%, respectively. The annual savings in heating and cooling costs range from $30 to $180 in urban areas and from $60 to $400 in rural zones. In urban residential neighborhoods of Edmonton, Montreal, and Vancouver, average savings in heating energy use are 8, 11, and 10%, respectively. Cooling energy can be totally offset in Edmonton and Vancouver and average savings of 35% can be achieved in Montreal.

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†By "direct" effects of albedo we mean those effects on energy use of a building resulting from modifying the albedo of the building itself. By "indirect" effects we mean the effects on energy use resulting from modifications in urban air temperature caused by changing the albedo of an entire neighborhood.