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Energy effects of heat-island reduction strategies in Toronto, Canada

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Abstract

The effect of heat-island reduction (HIR) strategies on annual energy savings and peak-power avoidance of the building sector of the Greater Toronto Area is calculated, using an hourly building energy simulation model. Results show that ratepayers could realize potential annual energy savings of over $11M from the effects of HIR strategies. The residential sector accounts for over half (59%) of the total savings, offices 13% and retail stores 28%. Savings from cool roofs are about 20%, shade trees 30%, wind shielding of trees 37%, and ambient cooling by trees and reflective surfaces 12%. These results are preliminary and highly sensitive to the relative price of gas and electricity. Potential annual electrticity savings are estimated at about 150 GWh and potential peak power avoidance at 250 MW.
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1. Introduction

During the summer, solar-reflective roofs (also known as "high-albedo"[1] or "cool" roofs) reflect most of the incoming sunlight and reduce the amount of heat conduction into a building. Similarly, strategically placed trees, shading windows and walls of a building, reduce the amount of direct heat gain. The reduction in summer heat gain because of cool roofs and deciduous shade trees reduces the air-conditioning load of a building, improves thermal comfort, saves peak-demand electricity, and saves money. During the winter, cool roofs and the shading effects of trees may add to the heating load of a building. However, the heating-energy penalties are small, since typically most of the heating is required during the evening hours with

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[1] Albedo (â) is the ratio of the reflected over the incoming solar radiation.

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little or no sunshine, winter days are shorter and cloudier than summer days, and buildings may have snow on the roofs. Furthermore, trees can actually save heating-energy bills by shielding a building from cold winter wind [1].

Cool surfaces (roofs and pavements) together with urban vegetation (shade trees, park trees, lawn, etc.) can potentially cool the city by several degrees. Lowered urban air temperatures can further reduce cooling-energy demand. More importantly, cooler ambient conditions can slow the rate of smog (O_3) formation and have a significant effect on ambient air quality [2].

Summertime temperatures in Toronto have been steadily increasing with the expansion of the city [3]. In addition, most new buildings are equipped with air-conditioners. As a result, the local utility company has changed from a winter-peaking to a summer-peaking utility. The effect of higher temperatures in the summer can potentially make air-quality problems more severe.

Energy savings from the use of solar-reflective roofs and shade trees have been predicted through computer simulations and verified with measured data in both residential and commercial buildings. The majority of these studies have focused on reflective roofs. Konopacki et al. [4] used computer simulations to estimate the net direct energy savings (cooling-energy savings minus heat-energy penalties) from reflective roofs on residential and commercial buildings in 11 US metropolitan statistical areas (MSAs). Metropolitan-wide savings were as much as \$37 M for Phoenix and \$35 M in Los Angeles and as low as \$3 M in the heating-dominated climate of Philadelphia. The results showed that three major building types accounted for over 90% of the annual electricity and monetary savings: old residences (55%), new residences (15%), and old/new office buildings and retail stores together (25%).

In two recent studies, Konopacki and Akbari [5,6] have estimated the direct and indirect energy effects of all heat-island reduction (HIR) measures in five US metropolitan areas: Baton Rouge, Chicago, Houston, Sacramento and Salt Lake City. The analysis indicated potential net annual energy savings of \$15 M, \$30 M, \$82 M, \$26 M, and \$3.6 M, peak-power avoidance of 130 MW, 400 MW, 730 MW, 490 MW and 85 MW, for the five respective cities.

Akbari and Taha [1] have simulated the effect of reflective surfaces and trees in four Canadian cities (including Toronto). The simulations indicated that by increasing the vegetative cover by 30%, the heating-energy use in Toronto can be reduced by 10% in urban houses and 20% in houses located in open suburban areas (mostly because of the wind-shielding effect of trees). Results also showed that by increasing the albedo of houses by 0.2 (from moderate-dark to medium-light color), the cooling-energy use can be reduced by about 30–40%. Other studies using computer simulations to estimate the effect of reflective roofs and trees include Konopacki and Akbari [7], Akbari et al. [8], Parker et al. [9], and Taha et al. [10].

In addition to computer simulations, several field studies have documented measured air-conditioning (a/c) summertime energy savings resulting from the use of solar-reflective roofs. These studies were conducted in warm-weather climates (mostly in Florida and California). Konopacki and Akbari [11] have measured daily energy savings of 39 Wh/m^2 (11%) and peak-power reduction of 3.8 W/m^2 (14%) in a large retail store in Austin, Texas from the application of a reflective membrane. Akbari and Rainer [12] measured daily a/c energy savings of 33 Wh/m^2 (1%) in two Nevada telecommunication regeneration buildings. Konopacki et al. [13] monitored the effect of reflective roofs in three California commercial buildings, two medical offices and one retail store. Summertime daily a/c savings of 68, 39 and 4.3 Wh/m^2 (18, 13 and 2%) and reduced demand of 3.3, 2.4 and 1.6 W/m^2 (12, 8 and 9%) were measured. Akbari et al. [14]

have shown that an increase in roof reflectance in one monitored Sacramento house resulted in daily summertime cooling-energy savings of 14 Wh/m^2 (63%) and peak-power reduction of 3.6 W/m^2 (25%), and in a Sacramento school bungalow, cooling-energy savings of 47 Wh/m^2 (46%) and peak-power reduction of 6.8 W/m^2 (20%). In an office, a museum and a hospice with reflective roofs in Sacramento, Hildebrandt et al. [15] measured daily a/c savings of 10, 20 and 11 Wh/m^2 (17, 26 and 39%). Parker et al. [9] monitored the effects of reflective roofs in 11 Florida residences with daily savings ranging from 5–137 Wh/m^2 (2–43%) and peak-demand reduction of 1.5–7.7 W/m^2 (12–28%). Parker and Sheinkopf [16] measured daily energy savings of 17% from a reflective roof in a high-efficiency home in Florida. Parker et al. [17] have also monitored seven retail stores within a strip mall in Florida before and after applying a reflective roof coating and measured a 7.5 Wh/m^2 (25%) drop in daily summertime cooling-energy use and a 0.65 W/m^2 (29%) decrease in demand. Parker et al. [18] measured daily energy savings of 44 Wh/m^2 (25%) and peak-power reduction of 6.0 W/m^2 (30%) from a reflective roof on a school building in Florida. Akridge [19] reported daily savings of 75 Wh/m^2 (28%) for an education building in Georgia, the unpainted galvanized roof of which was coated with white acrylic. An office building in southern Mississippi was shown to save 22% after the application of a reflective roof coating [20].

In two monitored houses in Sacramento, Akbari et al. [21] have demonstrated that seasonal cooling-energy savings of 30% and peak-power savings of 35% can be realized with the placement of shade trees near the buildings.

The objective of this study was to make a preliminary assessment of the effects of HIR measures on building cooling- and heating-energy use and ambient air quality in the Greater Toronto Area (GTA). This paper summarizes our efforts to calculate the annual energy savings and peak-power avoidance resulting from the implementation of HIR strategies in the GTA. We focused on the effect of various HIR strategies on three major building types that offer the most savings potential: residence, office, and retail store. The HIR strategies included: (1) use of solar-reflective roofing material on buildings [*direct effect*]; (2) placement of deciduous shade trees near south and west walls of buildings [*direct effect*]; (3) placement of coniferous wind-shielding vegetation near buildings [*direct effect*]; (4) effect of ambient cooling by a large-scale program of urban reforestation with reflective building roofs and pavements [*indirect effect*]; and (5) combination of strategies 1–4 [*direct and indirect effects*].

2. Methodology

HIR measures have a significant effect on the energy use of low-rise residential and commercial buildings; they do not significantly affect the energy use of large multistorey commercial or apartment buildings typically located in the downtown area [4]. Hence, we focused our efforts mostly on single-family residential and low-rise commercial buildings (offices and retail stores).

We modeled a total of nine building prototypes including five residential [pre-1980 (old) single-family houses, 1980+ (new) single-family houses, R-2000 single-family houses, pre-1980 (old) row-houses, 1980+ (new) row-houses; all modeled with both gas- and electric-heating systems], two office buildings [pre-1980 (old) offices, 1980+ (new) offices; both modeled with gas- and electric-heating systems], and two retail store buildings [pre-1989 (old) retail buildings, 1980+ (new) retail buildings; both modeled with gas- and electric-heating systems].

A four-step methodology was used to access the potential effects of HIR measures on prototype buildings and metropolitan-wide energy use in the GTA.

1. We defined prototypical building characteristics in detail for pre-1980 and 1980+ construction (and R-2000 single-family residence).
2. We simulated annual cooling- and heating-energy use and peak demand using the DOE-2.1E model and determined direct and indirect energy and demand savings for each HIR strategy.
3. We estimated the total roof area of air-conditioned buildings in the GTA, using existing data sources.
4. We calculated the metropolitan-wide effects of HIR strategies.

3. Building and measure descriptions

Prototypical building data were identified and used to define construction, internal load, and cooling- and heating-equipment characteristics for residential, office, and retail store buildings. The buildings were characterized for old (pre-1980: built prior to 1980) and new (1980+: built in 1980 or later) construction vintages; an R-2000 residence was also modeled. The prototypes were developed with both gas- and electricity-heating fuels. Considered were the use of existing and reflective roofs, the placement of deciduous shade trees about the south and west sides of the building, and coniferous trees on the north side to shield the building from cold winter wind. These data then defined the characteristics of the prototype building used by the DOE-2.1E energy simulation computer program. Building data for residences were obtained primarily from NRCAN [22,23] and Akbari and Taha [1]. Specific building characteristics data were not available for office and retail store buildings in the GTA. Characteristics data were taken from previous research focusing on the effect of reflective roofs in eleven US metropolitan areas [4] and Energy Star® [27].

3.1. Residence

The residence was modeled in two configurations: (1) single-family detached and (2) single-family row-house. The single-family structure was also modeled for R-2000 design. According to NRCAN [22], about 60% of existing single-family detached (SFD) houses are two-storey and 23% single storey; the average floor area is about 280 m^2. The newer (1980+) SFD houses are about 90% two-storey and 7% three-storey (less than 3% are one-storey); the average floor area is about 350 m^2. For all existing row-houses, about 64% are two-storey and 27% three-storey; the average floor area is 170 m^2. The newer (1980+) row-houses were about 62% two-storey and 37% three-storey with an average floor area of about 150 m^2. Prototypes for all residential buildings were modeled as two-storey buildings. Other major characteristics of the residential prototypes are summarized in Table 1 [24].

The roof was constructed with asphalt shingles on a 20° sloped plywood deck, over a naturally ventilated and unconditioned attic, above a studded ceiling frame with fiberglass insulation (varying by vintage), and with a sheet of drywall beneath. The fractional-leakage-area of

Table 1
Single-family residence and row-house. Prototypical building description for the Greater Toronto Area

	Single-family residence			Row house	
	pre-1980	1980+	R-2000	pre-1980	1980+
Two-storey, non-directional					
Roof and floor area (m^2)	93/185	112/223	93/185	56/112	46/93
Zones					
Living (conditioned)					
Attic (unconditioned)					
Basement (unconditioned)					
Roof insulation (m^2K/W)	3.34 (R-19)	5.28 (R-30)	6.69 (R-38)	2.29 (R-13)	5.28 (R-30)
Wall construction					
Brick exterior					
Wood frame					
Insulation (m^2K/W)	1.23 (R-7)	2.46 (R-14)	3.52 (R-20)	1.06 (R-6)	2.64 (R-15)
Drywall interior					
Windows					
Clear with operable shades			low-ε		
Number of panes	<——2——>				
Window to wall ratio	<——0.08——>			<——0.11——>	
Fractional leakage area (cm^2/m^2)					
Living	2.8	1.4	1	2.8	0.7
Attic	5.6	2.8	2	6.2	2.1
Cooling equipment					
Central a/c, air-cooled					
Energy efficiency ratio (EER)	8	10	12	8	10
Capacity (MJ/h)	38.0	31.7	25.3	38.0	31.7
Cooling setpoint (°C)	<——25.6——>				
Natural ventilation available					
Heating equipment					
(1) Central forced air gas furnace					
Efficiency (%)	82	85	85	81	92
Capacity (MJ/h)	79.1	63,3	52.8	42.2	38.0
Heating setpoint (°C)	<——21.1——>				
11 p.m.–7 a.m. setback (°C)[a]	<——15.6——>				
(2) Electric	Central electric heat pump			Resistance	
Heating season performance factor (HSFP)	5	7	8	N/A	

[a] Although many houses may not use a heating setback, assuming a setback only affects the base heating energy use and not the potential heating penalties.

the attic and living quarters was dependent on vintage. Variable air infiltration was modeled by the Sherman-Grimsrud algorithm [25].

The prototype SFD residence was cooled and heated by a central air-conditioning system (with ducts located in the conditioned space), a constant volume fan, and without an economizer. Heating was modeled with both a gas furnace and an electric heat pump. The multi-family row-house was served by a ductless window or room a/c unit with heating provided by a gas wall furnace or electric resistance. Cooling through natural ventilation was available by window operation. System size and efficiency were selected for each vintage.

Modified part-load-ratio curves for a typical air-conditioner, heat pump and gas furnace were used in place of the standard DOE-2 curves, since they have been shown to model low-energy use more accurately [26]. Duct loads were simulated with a validated residential duct function [9] implemented into DOE-2 to better estimate the thermal interactions between the ducts and building thermal zones.

3.2. Office

The office was modeled as a single-storey non-directional building with four perimeter zones and a core zone, also in two construction vintages: pre-1980 and 1980+. The floor plan was a 21.3 by 21.3 m layout with a total air-conditioned floor area of 455 m^2. The perimeter zone depth was 4.6 m. The building operated from 6 a.m. to 7 p.m. on weekdays only. The roof was constructed with built-up materials on a flat plywood deck, over an unventilated and unconditioned plenum, above a studded ceiling frame with fiberglass insulation (varying by vintage), and with a sheet of drywall beneath. Other major characteristics of the office prototypes are summarized in Table 2 [24].

The building was cooled and heated by five rooftop, constant-volume, packaged-single-zone systems, each one servicing a single zone. The systems were sized based on peak-cooling and -heating loads as determined by DOE-2, which allowed for peak loads to be met and for maximum savings to be calculated. Duct loads were simulated by specifying air leakage and temperature drop. An economizer was also implemented.

3.3. Retail store

The retail store was modeled as a single-storey non-directional building with a single zone, also in two construction vintages: pre-1980 and 1980+. The floor plan was a 27.4 by 27.4 m layout with 750 m^2 of total air-conditioned floor area. The building operated from 8 a.m. to 9 p.m. on weekdays and from 10 a.m. to 5 p.m. on weekends and holidays. The roof was constructed with built-up materials on a flat plywood deck, over an unventilated and unconditioned plenum, above a studded ceiling frame with fiberglass insulation, and with a sheet of drywall beneath. Other major characteristics of the retail store prototypes are summarized in Table 2 [24].

The building was cooled and heated by a single rooftop, constant volume packaged-single-zone system. The system was sized based on peak-cooling and -heating loads as determined by DOE-2, which allowed for peak loads to be met and for maximum savings to be calculated. Duct loads were simulated by specifying air leakage and temperature drop. An economizer was also implemented.

3.4. Solar-reflective roofs

A solar-reflective roof is typically light in color and absorbs less sunlight than a conventional dark-colored roof. Less absorbed sunlight means a lower surface temperature, which directly reduces heat gain through the roof and air-conditioning demand. Typical values of albedo for

Table 2
Office and retail store prototypical building description for the Greater Toronto Area

	Office		Retail store	
	pre-1980	1980+	pre-1980	1980+
Single-storey, non-directional				
Roof and floor area (m^2)	455		750	
Zones: 5 zones (conditioned) plenum (unconditioned)				
Ceiling insulation (m^2K/W)	3.34 (R-19)	5.2 (R-30)	3.34 (R-19)	5.28 (R-30)
Wall construction				
Brick exterior				
Wood frame				
Insulation (m^2K/W)	1.06 (R-6)	2.29 (R-13)	0.70 (R-4)	2.29 (R-13)
Drywall				
Windows				
Clear with operable shades				
Number of panes	1	2	1	2
Window to wall ratio	0.5		0.17	
Cooling equipment				
Packaged a/c, air-cooled				
Energy efficiency ration (EER)	8	10	8	10
Heating equipment				
(1) Gas furnace				
Efficiency (%)	70	74	70	74
(2) Electric heat pump				
Heating season performance factor (HSPF)	5	7	5	7
Distribution				
Constant-volume forced air system				
Economizer	Fixed	Temperature	Fixed	Temperature
Duct leakage (%)	20	10	20	10
Duct temperature drop (°C)	1.1	0.6	3	1
Thermostat				
Weekday operation	6am–7pm		6am–7pm	
Weekend operation	setback		10am–5pm	
Cooling setpoint (°C)	25.6		25.6	
Heating setpoint (°C)	21.1		21.1	
Interior load				
Infiltration (air-change/hour)	0.5		0.5	
Lighting (W/m^2)	20.4	15.1	25.8	18.3
Equipment (W/m^2)	18.3	16.1	7.5	6.5
Occupants	25		16	

low- and high-albedo roofs were selected to cover the wide range of commercially available roofing materials (shingles, tiles, membranes and coatings) and the effects of weathering and aging. These were obtained primarily from the Cool Roofing Materials Database [28], containing measured values of roof absorptance across the solar spectrum.

For the sloped-roof residential sector, commercially available high-reflective materials are scarce. White asphalt shingles are available, but have a relatively low albedo of 0.25–0.27. White coatings can be applied to shingles or tiles to obtain an aged albedo of about 0.5. Some high-reflective white shingles are being developed, but are only in the prototype stage. Also, some reflective tiles are available. Conversely, high-reflective materials for the low-slope commercial sector are on the market. White acrylic, elastomeric and cementatious coatings can now be applied to built-up roofs to achieve an aged solar-reflectance of 0.6 and likewise for white thermoplastic membranes. A "generic white" asphalt shingle has a laboratory tested initial albedo of 0.25 [28]. A "generic gray" asphalt shingle has a laboratory tested initial albedo of 0.22, and the albedo of a green or brown shingle is about 0.12–0.15 [28].

The values of roof albedo were chosen to be 0.2 and 0.5 for residential roofs and 0.2 and 0.6 for commercial roofs, which represent low- and high-albedo materials. The long-wave thermal emittance of these materials was a uniform 0.9. We only accounted for the changes of the roof reflectance during the summer and did not model the effect of snow on the roof during the winter season. This assumption provides a good estimate of summertime saving potentials and slightly overestimates the wintertime heating penalties of the reflective roofs (i.e. both reflective and non-reflective roofs are covered by snow during winter).

Bretz and Akbari [29] have reported that the albedo of white-coated roof surfaces can degrade up to 20% over a period of several years as a result of weathering and accumulation of dirt and debris (microbial growth can contribute to degradation in humid climates), and by washing the roof, the albedo can be restored to 90–100% of the initial value. Note that rainfall can cleanse a roof and in most cases have the same effect as a thorough washing.

3.5. Shade trees

Shade trees were modeled in DOE-2 with the *BUILDING-SHADE* keyword as a box-shaped building shade with seasonal transmittance.[2] The summertime transmittance was 0.1 for 1 April to 31 October and wintertime was 0.9 for the remainder of the year. The geometry of the modeled tree consisted of a square cross-sectional area of 21 m^2, 4.6 by 4.6 m, a depth of 3 m, and a canopy height of 4.6 m. They were placed outside the south and west walls near the windows (with 0.6 m of clearance from the building) in order to maximize the effect on the building-cooling load. The fully-grown trees shade a portion of the roof during low sun hours, but do not cover any of it during high sun hours. The number of shade trees modeled were 4, 8 and 10 for the residence, office, and retail store, respectively.

3.6. Wind-shielding

Trees shield the walls and portions of the roof from wind directly reducing wind speed, thus reducing outside air film conductance and wind-speed dependent infiltration. The tree-planting strategy consists in placing coniferous vegetation on the north side of a building to shield from cold northerly winds, and to locate deciduous foliage on the south and west sides.

The wind-shielding effect on cooling- and heating-energy use from a 20% increase in vegetation cover around buildings was modeled within DOE-2 by altering the three DOE-2 key-

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[2] The fraction of light that passes through the tree is the transmittance.

words: (1) *SHIELDING-COEFFICIENT*, (2) *TERRAIN-PAR1*, and (3) *TERRAIN-PAR2* [30]. The shielding-coefficient value is used in calculating the Sherman–Grimsrud infiltration. The coefficient modifies the wind speed term in the model to account for changes in wind pressure caused by local obstructions. DOE-2 assigns a shielding coefficient of 0.19 for "typical suburban shielding—heavy shielding, obstructions around most of perimeter, buildings or trees within 30 feet in most directions" and a coefficient of 0.10 for "typical downtown shielding—very heavy shielding, large obstructions surrounding perimeter within two house heights". The value of 0.19 representing typical suburban shielding was used for base simulations; this was altered to 0.17 (a 20% adjustment from 0.19 to 0.10, i.e. $0.19–0.2 \times (0.19 - 0.10) = 0.17$).

The same methodology was used to modify the wind speed for terrain and space height effects at the building site using the keywords *TERRAIN-PAR1* and *TERRAIN-PAR2*. Values of 0.85 and 0.20 representing rural area with low buildings and trees were altered to 0.81 and 0.21 (a 20% adjustment from "rural" to "urban" areas as defined by DOE-2 [30]).

4. Energy simulations

The DOE-2 model simulates energy use of a building for 8760 h per year, using typical hourly weather data [31]. Using Toronto Weather Year for Energy Consumption (WYEC2) data, annual cooling- and heating-energy use and peak-power demand were simulated for residential, office and retail store building prototypes, and savings were calculated for each HIR strategy. To estimate the effect of heat-island reduction measures on the ambient temperature, we used the PSU/NCAR MM5 mesoscale meteorological model to simulate changes in the temperature field over the GTA [32]. We then estimated changes in an average dry-bulb air temperature from 15 locations within the boundaries of the model over 72-h winter (January 15–17) and summer (July 15–17) episodes. The changes in ambient temperature (ΔT) were then regressed as a function of solar intensity (I) (see Eq.(1)).

$$\Delta T\ [\mathrm{K}] = -0.0018\ I\ [\mathrm{W/m^2}] \tag{1}$$

Because ΔT is solely a function of solar intensity, ΔT is zero during hours without sunlight. Finally, we modified the standard WYEC2 weather data ($T_{\mathrm{modified}} = T_{\mathrm{standard}} + \Delta T$) to create modified temperature data for the building energy simulations. The rerun of the DOE-2 simulations with the modified weather data quantified the *indirect* effect of HIR measures on building-energy use.

In Table 3, cooling and heating degree-days (base 18.3 °C) and the maximum air temperature have been tallied monthly for both standard and modified WYEC2 weather data. The difference between the modified and the standard data is denoted by ΔT in the table. Ambient cooling from urban surface modification was observed mostly during June, July and August with 64, 106 and 91 fewer cooling degree-days during those months. The annual 324 cooling-degree-days were reduced by 45 and the annual heating-degree-days was increased by 54. The greatest reduction in maximum ambient air temperature was simulated as 1.7 °K from a high of 34 °C in July.

Local residential and commercial electricity and natural gas rates were applied to the simulation results to obtain total annual energy use in dollars. Average commercial rates for electricity and natural gas consumption were available from a 1998 City of Toronto facility analysis [33] and were \$0.084/kWh and \$5.54/GJ (\$0.206/m^3). Specific residential rates were obtained

Table 3
Standard and modified Toronto WYEC2 weather data with cooling- and heating-degree-days and maximum air temperature tallied monthly ($\Delta T = T_{modified} - T_{standard}$)

Month	Cooling degree-days (base 18.3 °C)		Heating degree-days (base 18.3 °C)		Maximum air temperature	
	Standard	Δ	Standard	Δ	Standard (°C)	Δ (K)
January	0	0	750	3	7	0.0
February	0	0	671	5	5	0.0
March	0	0	577	8	18	−0.6
April	2	−1	359	11	24	−1.1
May	29	−5	209	7	30	−1.1
June	64	−10	68	9	33	−1.1
July	106	−13	28	1	34	−1.7
August	91	−11	40	1	32	−0.6
September	32	−5	121	3	28	−0.6
October	1	0	269	6	21	−0.6
November	0	0	444	3	17	−0.6
December	0	0	662	2	8	0.0
Total	324	−45	4198	54		

Maximum standard ambient air temperature and maximum modified temperature decrease are non-concurrent.

by inspecting the monthly utility bill for a typical house [34]. Based on a comparison of Toronto Hydro Electric System rate schedules, we found that the residential and commercial electricity rate were essentially the same [35]. The gas rate was \$10.84/GJ. The price of gas has changed significantly over the last few years. To perform a preliminary analysis of the effect of the gas price on potential savings, we also calculated the net savings with a uniform price of \$5.54/GJ for both residential and commercial buildings.

4.1. Results of DOE-2.1E energy simulations

The simulations provided estimates of annual cooling- and heating-electricity use [kWh/100 m^2], annual heating natural gas use [GJ/100 m^2] and cooling peak-power demand [kW/100 m^2], all normalized per 100 m^2 of flat roof area. From the simulations, the annual total expenditures for cooling and heating energy [\$/100 m^2] could then be calculated using local energy prices. Using the base case as a reference, annual energy and peak-power savings were determined for each HIR strategy. The base expenditure and demand and savings are presented in Tables 4 and 5.[3] Table 4 shows the energy and demand savings in absolute terms [kWh/100 m^2, GJ/100 m^2 and kW/100 m^2], and Table 5 shows the dollar saving in with two prices for residential gas.

The simulations predicted net annual energy savings of about 3–5% from combined direct and indirect effects [17–22\$/100 m^2 for old and 9\$/100 m^2 for new] in gas-heated single-family

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[3] Linear interpolation can be used to estimate savings or penalties for other net changes in roof reflectance ($\Delta\hat{a}_2$) than presented in the tables ($\Delta\hat{a}_1$) [4]. Therefore, these results can be simply adjusted by the ratio $\Delta\hat{a}_2/\Delta\hat{a}_1$ to obtain estimates for other reflective roof scenarios.

Table 4
Simulated cooling and heating annual base energy use and savings (electricity: kWh/(100 m^2), gas: GJ/(100 m^2)), and peak-power demand and savings (kW/(100 m^2)) from Heat Island Reduction strategies for prototype residential and commercial buildings.

Building type and mitigation strategy	Gas heat				Electric heat		Gas and electric heat	
	Electricity (kWh/100 m^2)		Gas (GJ/100 m^2)		Electricity (kWh/100 m^2)		Peak power (kW/100 m^2)	
	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+
Residence: Single-Family								
Energy use & demand	1057	629	75.0	49.3	14,785	8391	2.70	1.71
Savings								
reflective roof savings	94	52	−0.9	−0.5	−62	−20	0.12	0.08
shade tree savings	133	74	−1.1	−0.7	−24	−8	0.32	0.18
wind shield savings	−32	−25	2.5	1.2	379	134	0.00	−0.02
indirect savings	88	51	−0.8	−0.5	−100	−59	0.13	0.09
combined savings	283	152	−0.2	−0.6	193	47	0.57	0.33
Residence: R-2000								
Energy use and demand	n/a	440	n/a	307.0	n/a	5737	n/a	1.27
Savings								
reflective roof savings	n/a	29	n/a	−5.0	n/a	−33	n/a	0.05
shade tree savings	n/a	57	n/a	−5.0	n/a	−9	n/a	0.17
wind shield savings	n/a	−20	n/a	6.0	n/a	75	n/a	0.00
indirect savings	n/a	36	n/a	−4.0	n/a	−39	n/a	0.02
combined savings	n/a	101	n/a	−8.0	n/a	−5	n/a	0.25
Residence: row-house								
Energy use and demand	1277	643	70.6	32.8	18509	8393	3.01	1.87
Savings								
reflective roof savings	113	52	−1.1	−0.4	−111	−60	0.16	0.09
shade tree savings	127	75	−0.8	−0.5	−34	−11	0.29	0.22
wind shield savings	−18	−13	1.1	0.3	194	45	−0.02	−0.01
indirect savings	82	49	−0.7	−0.3	−138	−49	0.18	0.10
combined savings	305	164	−1.6	−0.8	−90	−75	0.61	0.40
Office								
Energy use and demand	7276	3842	57.3	27.5	16,934	8108	7.12	4.20
Savings								
reflective roof savings	388	160	−0.5	−0.5	273	60	0.26	0.14
shade tree savings	637	260	−0.9	−0.8	485	129	0.43	0.23
wind shield savings	−36	−1	0.6	0.5	88	96	0.02	0.01
indirect savings	271	164	−0.3	−0.4	160	64	0.42	0.23
combined savings	1260	583	−1.2	−1.3	1007	350	1.13	0.60
Retail store								
Energy use and demand	7493	3356	31.1	10.1	12733	4944	4.90	2.63
Savings								
reflective roof savings	522	200	−0.5	−0.6	429	102	0.26	0.14
shade tree savings	439	172	−0.2	−0.2	423	146	0.19	0.10
wind shield savings	−42	−13	1.1	0.8	138	111	0.02	0.01
indirect savings	258	133	−0.3	−0.3	179	82	0.24	0.11
combined savings	1177	492	0.0	−0.3	1170	442	0.71	0.36

Table 5
Simulated cooling and heating annual base expenditures and savings [$/(100 m^2)] from heat island reduction strategies for prototype residential and commercial buildings. The numbers in parentheses show % savings.

Building type and mitigation strategy	Residential gas price of $5.54/GJ				Residential gas price of $10.84/GJ			
	Gas heat		Electric heat		Gas heat		Electric heat	
	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+
Residence: single-family								
Base energy expenditure	504	325	1242	705	898	584	1242	705
Savings								
reflective roof savings	2.5(0.5)	1.5(0.5)	−5.2(−0.4)	−1.7(−0.2)	−2.5(−0.3)	−1.1(−0.2)	−5.2(−0.4)	−1.7(−0.2)
shade tree savings	5.6(1.1)	2.0(0.6)	−2.0(−0.2)	−0.7(−0.1)	0.3(0.0)	−2.0(−0.3)	−2.0(−0.2)	−0.7(−0.1)
wind shield savings	11.6(2.3)	4.4(1.4)	31.8(2.6)	11.2(1.6)	25.1(2.8)	10.6(1.8)	31.8(2.6)	11.2(1.6)
indirect savings	2.7(0.5)	1.3(0.4)	−8.4(−0.7)	−5.0(−0.7)	−1.7(−0.2)	−1.6(−0.3)	−8.4(−0.7)	−5.0(−0.7)
combined savings	22.5(4.5)	9.3(2.8)	16.2(1.3)	3.9(0.6)	21.2(2.4)	5.9(1.0)	16.2(1.3)	3.9(0.6)
Residence: R-2000								
Base energy expenditure	n/a	216	n/a	482	n/a	386	n/a	482
Savings								
reflective roof savings	n/a	−0.3(−0.1)	n/a	−2.8(−0.6)	n/a	−2.9(−0.8)	n/a	−2.8(−0.6)
shade tree savings	n/a	1.7(0.8)	n/a	−0.7(−0.2)	n/a	−1.3(−0.3)	n/a	−0.7(−0.2)
wind shield savings	n/a	1.5(0.7)	n/a	6.3(1.3)	n/a	4.6(1.2)	n/a	6.3(1.3)
indirect savings	n/a	0.8(0.4)	n/a	−3.3(−0.7)	n/a	−1.3(−0.3)	n/a	−3.3(−0.7)
combined savings	n/a	3.7(1.7)	n/a	−0.5(−0.1)	n/a	−0.9(−0.2)	n/a	−0.5(−0.1)
Residence: row-house								
Base energy expenditure	498	236	1555	705	868	408	1555	705
Savings								
reflective roof savings	3.4(0.7)	1.9(0.8)	−9.3(−0.6)	−5.1(−0.7)	−2.3(−0.3)	−0.4(−0.1)	−9.3(−0.6)	−5.1(−0.7)
shade tree savings	5.8(1.2)	3.6(1.5)	−2.9(−0.2)	−0.9(−0.1)	1.2(0.1)	1.1(0.3)	−2.9(−0.2)	−0.9(−0.1)
wind shield savings	4.4(0.9)	0.6(0.3)	16.3(1.0)	3.8(0.5)	10.0(1.1)	2.3(0.6)	16.3(1.0)	3.8(0.5)
indirect savings	3.0(0.6)	2.7(1.1)	−11.6(−0.7)	−4.2(−0.6)	−0.8(−0.1)	1.3(0.3)	−11.6(−0.7)	−4.2(−0.6)
combined savings	16.7(3.3)	8.9(3.8)	−7.5(−0.5)	−6.3(−0.9)	8.2(0.9)	4.3(1.0)	−7.5(−0.5)	−6.3(−0.9)
Office								
Base energy expenditure	929	475	1422	681	929	475	1422	681
Savings								
reflective roof savings	29.5(3.2)	10.3(2.2)	22.9(1.6)	5.1(0.7)	29.5(3.2)	10.3(2.2)	22.9(1.6)	5.1(0.7)
shade tree savings	48.5(5.2)	17.5(3.7)	40.8(2.9)	10.9(1.6)	48.5(5.2)	17.5(3.7)	40.8(2.9)	10.9(1.6)
wind shield savings	0.8(0.1)	3.1(0.6)	7.4(0.5)	8.1(1.2)	0.8(0.1)	3.1(0.6)	7.4(0.5)	8.1(1.2)
indirect savings	20.9(2.3)	11.2(2.4)	13.5(0.9)	5.4(0.8)	20.9(2.3)	11.2(2.4)	13.5(0.9)	5.4(0.8)
combined savings	99.6(10.7)	42.1(8.8)	84.6(5.9)	29.4(4.3)	99.6(10.7)	42.1(8.8)	84.6(5.9)	29.4(4.3)
Retail Store								
Base energy expenditure	802	338	1070	415	802	338	1070	415
Savings								
reflective roof savings	40.7(5.1)	13.0(3.9)	36.0(3.4)	8.6(2.1)	40.7(5.1)	13.0(3.9)	36.0(3.4)	8.6(2.1)
shade tree savings	35.6(4.4)	13.2(3.9)	35.5(3.3)	12.3(3.0)	35.6(4.4)	13.2(3.9)	35.5(3.3)	12.3(3.0)
wind shield savings	2.1(0.3)	3.3(1.0)	11.6(1.1)	9.4(2.3)	2.1(0.3)	3.3(1.0)	11.6(1.1)	9.4(2.3)
indirect savings	19.8(2.5)	9.3(2.8)	15.1(1.4)	6.9(1.7)	19.8(2.5)	9.3(2.8)	15.1(1.4)	6.9(1.7)
combined savings	98.9(12.3)	39.4(11.7)	98.2(9.2)	37.1(8.9)	98.9(12.3)	39.4(11.7)	98.2(9.2)	37.1(8.9)

and row-house residences. This number increased to 10% for offices [40\$/100 m^2 for new and 100\$/100 m^2 for old] and 12% for retail store buildings [40\$/100 m^2 for new and 100\$/100 m^2 for old]. Electric-heated units did not fair so well, where savings of 0–2% were simulated for residences and 5–9% for the office and retail store buildings because the higher cost of electric heating than that of gas heating.

An annual natural gas deficit was found for all building types and in each HIR mitigation strategy with the exception of wind-shielding; wind-shielding reduced the heating requirements of the buildings. The annual gas deficit for combined direct and indirect effects was \$2–6/100 m^2 for residences, \$11–12/100 m^2 for offices and only \$0–3/100 m^2 for retail stores.

Simulated peak-power reduction was significant for all building types and strategies (wind-shielding was the exception). Combined direct and indirect peak-demand reduction in cooling electricity was 21–23% in residences and 13–16% in offices and retail stores. This translates into 0.57–0.61 kW/100 m^2 for pre-1980 residences, 0.33–0.40 kW/100 m^2 for 1980+ residences, 0.60–1.13 kW/100 m^2 for old and new offices, and 0.36–0.71 kW/100 m^2 for old and new retail stores.

5. Air-conditioned roof area for the GTA

The stock of air-conditioned residential, office and retail store buildings in the GTA were estimated for both pre-1980 and 1980+ construction vintages and both natural gas and electricity heating fuels. The 1996 population for the GTA was 4,218,465 residing in 1,488,370 households [36].

The total roof area for the stock of residences with a/c was calculated from integrating data from Statistics Canada [36], ICLEI Energy Services [37], and NRCAN [22,38]. The residential stock was disaggregated into single-family, row-house (multi-family) and apartment structure types for pre-1980 and 1980+ construction vintages. The total residential air-conditioned roof area for the GTA was estimated to be 39.8 Mm^2 (77% single-family, 20% row-house and 3% apartment) [24].

The total roof area for the stock of office buildings and retail stores with a/c was calculated for pre-1980 and 1980+ construction vintages from integrating data from the above residential sector estimates and from Konopacki et al. [4]. Office and retail air-conditioned roof area for the GTA was estimated to be 5.3 Mm^2 (1.9 Mm^2 for offices and 3.4 Mm^2 for retail stores) [24].

6. Metropolitan-area estimates

Metropolitan-wide potential annual electricity savings [GWh], annual natural gas deficit [PJ], and peak power avoided [MW] are presented in Table 6. Metropolitan-wide estimates of annual energy-use expenditure and savings [M\$] are presented in Table 7 with two prices for residential gas. With uniform gas prices for commercial and residential buildings, annual electricity savings of \$12.6 M less a 10% natural gas deficit combine for a potential rate-payer benefit of over \$11 M. Of that total, about 88% derived from the direct effects, divided roughly equally among reflective roofs, shade trees, and wind-shielding, and the

Table 6
Estimates of cooling and heating annual energy savings and avoided peak power from heat island reduction strategies for residential and commercial buildings in the Greater Toronto Area.

Building type and mitigation strategy	Gas heat				Electric heat		Gas and electric heat	
	Electricity (GWh)		Gas (PJ)		Electricity (GWh)		Peak power (MW)	
	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+
Residence: single-family								
Energy use and demand	207	49	14.8	3.8	467	16	615	137
Savings								
reflective roof savings	18.4	4.1	−0.19	−0.04	−2.0	0.0	27	6
shade tree savings	26.2	5.8	−0.20	−0.06	−0.7	0.0	74	14
wind shield savings	−6.3	−2.0	0.51	0.09	12.0	0.2	0	−1
indirect savings	17.3	4.0	−0.17	−0.04	−3.2	−0.1	29	7
combined savings	55.5	11.9	−0.04	−0.05	6.1	0.1	130	26
Apartment								
Energy use and demand	8	1	0.4	0.0	17	16	22	5
Savings								
reflective roof savings	0.7	0.0	−0.01	0.00	−0.1	−0.1	1	0
shade tree savings	0.8	0.1	−0.01	0.00	0.0	0.0	2	1
wind shield savings	−0.1	0.0	0.01	0.00	0.2	0.1	0	0
indirect savings	0.5	0.0	0.00	0.00	−0.1	−0.1	1	0
combined savings	2.0	0.2	−0.01	0.00	−0.1	−0.1	5	1
Residence: row-house								
Energy use and demand	70	6	3.9	0.3	86	94	179	38
Savings								
reflective roof savings	6.2	0.5	−0.06	0.00	−0.5	−0.7	9	2
shade tree savings	7.0	0.7	−0.05	0.00	−0.2	−0.1	17	4
wind shield savings	−1.0	−0.1	0.06	0.00	0.9	0.5	−1	0
indirect savings	4.5	0.5	−0.04	0.00	−0.6	−0.6	11	2
combined savings	16.7	1.5	−0.08	−0.01	−0.4	−0.8	36	8
Office								
Energy use and demand	88	29	0.7	0.2	0	0	86	31
Savings								
reflective roof savings	4.7	1.2	−0.01	0.00	0.0	0.0	3	1
shade tree savings	7.7	1.9	−0.01	−0.01	0.0	0.0	5	2
wind shield savings	−0.4	0.0	0.01	0.00	0.0	0.0	0	0
indirect savings	3.3	1.2	0.00	0.00	0.0	0.0	5	2
combined savings	15.2	4.3	−0.01	−0.01	0.0	0.0	14	4
Retail store								
Energy use and demand	223	19	0.9	0.1	0	0	146	15
Savings								
reflective roof savings	15.5	1.1	−0.02	0.00	0.0	0.0	8	1
shade tree savings	13.1	1.0	−0.01	0.00	0.0	0.0	6	1
wind shield savings	−1.2	−0.1	0.03	0.00	0.0	0.0	1	0
indirect savings	7.7	0.7	−0.01	0.00	0.0	0.0	7	1
combined savings	35.0	2.7	0.00	0.00	0.0	0.0	21	2
Total								
Energy use and demand	596	103	20.7	4.4	570	125	1048	226
Savings								
reflective roof savings	45.5	6.9	−0.27	−0.05	−2.6	−0.8	48.4	10.0
shade tree savings	54.7	9.5	−0.27	−0.07	−0.9	−0.2	103.8	21.8
wind shield savings	−9.1	−2.2	0.61	0.11	13.0	0.8	−0.3	−1.4
indirect savings	33.3	6.5	−0.22	−0.05	−3.9	−0.8	53.5	11.5
combined savings	124.4	20.7	−0.16	−0.07	5.6	−0.9	205	42

Table 7
The Greater Toronto Area estimates of cooling and heating annual base energy expenditures and savings (M$) from heat island reduction strategies for residential and commercial buildings.

Building type and mitigation strategy	Residential gas price of $5.54/GJ					Residential gas price of $10.84/GJ				
	Annual energy and savings (M$)				Total (M$)	Annual energy and savings (M$)				Total (M$)
	Gas heat		Electric heat			Gas heat		Electric heat		
	pre-1980	1980+	pre-1980	1980+		pre-1980	1980+	pre-1980	1980+	
Residence: single-family										
Base energy expenditure	99	25	39	1	165	176	46	39	1	262
Savings										
reflective roof savings	0.5	0.1	−0.2	0.0	0.5	−0.5	−0.1	−0.2	0.0	−0.7
shade tree savings	1.1	0.2	−0.1	0.0	1.2	0.1	−0.2	−0.1	0.0	−0.2
wind shield savings	2.3	0.3	1.0	0.0	3.6	4.9	0.8	1.0	0.0	6.8
indirect savings	0.5	0.1	−0.3	0.0	0.4	-0.3	−0.1	−0.3	0.0	−0.7
combined savings	4.4	0.7	0.5	0.0	5.6	4.2	0.5	0.5	0.0	5.1
Apartment										
Base energy expenditure	3	0	1	1	6	6	0	1	1	9
Savings										
reflective roof savings	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
shade tree savings	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
wind shield savings	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1
indirect savings	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
combined savings	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0
Residence: row-house										
Base energy expenditure	27	2	7	8	45	48	4	7	8	66
Savings										
reflective roof savings	0.2	0.0	0.0	-0.1	0.1	-0.1	0.0	0.0	-0.1	-0.2
shade tree savings	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1
wind shield savings	0.2	0.0	0.1	0.0	0.4	0.5	0.0	0.1	0.0	0.7
indirect savings	0.2	0.0	-0.1	0.0	0.1	0.0	0.0	-0.1	0.0	-0.1
combined savings	0.9	0.1	0.0	-0.1	0.9	0.4	0.0	0.0	-0.1	0.4
Office										
Base energy expenditure	11	4	0	0	15	11	4	0	0	15
Savings										
reflective roof savings	0.4	0.1	0.0	0.0	0.4	0.4	0.1	0.0	0.0	0.4
shade tree savings	0.6	0.1	0.0	0.0	0.7	0.6	0.1	0.0	0.0	0.7
wind shield savings	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
indirect savings	0.3	0.1	0.0	0.0	0.3	0.3	0.1	0.0	0.0	0.3
combined savings	1.2	0.3	0.0	0.0	1.5	1.2	0.3	0.0	0.0	1.5
Retail store										
Base energy expenditure	24	2	0	0	26	24	2	0	0	26
Savings										
reflective roof savings	1.2	0.1	0.0	0.0	1.3	1.2	0.1	0.0	0.0	1.3
shade tree savings	1.1	0.1	0.0	0.0	1.1	1.1	0.1	0.0	0.0	1.1
wind shield savings	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1
indirect savings	0.6	0.1	0.0	0.0	0.6	0.6	0.1	0.0	0.0	0.6
combined savings	2.9	0.2	0.0	0.0	3.1	2.9	0.2	0.0	0.0	3.1

(continued on next page)

Table 7 (*continued*)

Building type and mitigation strategy	Residential gas price of \$5.54/GJ					Residential gas price of \$10.84/GJ				
	Annual energy and savings (M\$)				Total (M\$)	Annual energy and savings (M\$)				Total (M\$)
	Gas heat		Electric heat			Gas heat		Electric heat		
	pre-1980	1980+	pre-1980	1980+		pre-1980	1980+	pre-1980	1980+	
Total										
Base energy expenditure	164	33	48	10	256	273	57	48	10	388
Savings										
reflective roof savings	2.3	0.3	−0.2	−0.1	2.3	0.8	0.0	−0.2	−0.1	0.5
shade tree savings	3.1	0.4	−0.1	0.0	3.4	1.7	0.0	−0.1	0.0	1.6
wind shield savings	2.6	0.4	1.1	0.1	4.2	5.8	0.9	1.1	0.1	7.9
indirect savings	1.6	0.3	−0.3	−0.1	1.4	0.4	0.0	−0.3	−0.1	0.0
combined savings	9.6	1.3	0.5	−0.1	11.3	8.7	1.0	0.5	−0.1	10.1

remainder (12%) from the indirect effects of the cooler ambient air temperature. The residential sector accounts for over half (about 59%) of the total savings, offices 13% and retail stores 27%. Savings from cool roofs were about 20%, shade trees 30%, wind-shielding of trees 37%, and indirect effect 12%. These results are highly sensitive to the price of gas. Assuming a residential gas price of \$10.84/GJ (gas price during December 2001), the net annual savings are reduced to \$10 M; about 78% resulted from wind-shielding, 16% from shading by trees, and 5% from cool roofs.

Potential annual electricity savings were estimated at about 150 GWh or over \$12 M, of which about 75% accrued from roofs and shade trees and only 2% from wind-shielding. The indirect effect was 23%. The savings distributed among buildings is similar to those cited above.

The potential annual natural gas deficit was estimated to be over 0.232 PJ or just under \$1–2 M, with actual savings of over \$4–8 M from wind-shielding and a combined penalty of under \$3–7 M. Residences accounted for about 94% of the gas deficit.

Potential peak-power avoidance was estimated at about 250 MW with about 74% attributed to the direct effects (roofs about 24%, shade trees 51% and wind-shielding a small negative fraction) and the remainder (26%) to the indirect effect. About 83% of the avoided peak power resulted from the effects of the residences. The remainder was shared by offices (7%) and retail stores (9%).

7. Discussion

In this study, we focused on three building types (residential, office, and retail store) that offer the highest potential savings for the GTA. HIR technologies are also very effective on other building types such as hospitals, schools, restaurants, grocery stores, etc. However, the potential savings from these other buildings only contribute a few percent additional savings for the entire GTA.

In reviewing the results of this analysis, the following should be considered:

1. Reflective roofs and shade trees reduce summer cooling-energy use and also potentially increase winter heating-energy use. The net savings ($ savings in cooling energy use minus $ penalties in heating-energy use) are highly sensitive to prices of cooling- and heating-energy fuels. In the residential building prototypes cooled and heated with electricity, we found that most of the cooling-energy savings are written off by the penalties in heating-energy use. Since reflective roofs and shade trees affect the energy performance of a building typically for 20–30 years, a better understanding of long-term trends in energy prices would lead to better estimates of savings potentials.
2. Trees affect the energy use of a building by shading and wind shielding. Our capabilities to simulate the shading effects of trees are typically more refined than simulating the wind-shielding effects. Future studies to investigate further the wind-shielding effects of trees on heating-energy use would improve the current estimates.
3. DOE-2 can underestimate the cooling-energy saving potentials of reflective roofs by as much as a factor of two. Hence, the saving potentials shown for reflective roofs should be considered as conservative. Furthermore, during the winter, some of the roofs are covered with snow. Hence, the heating penalties of reflective roofs are potentially overestimated. A few monitoring and demonstration projects at the GTA would lead to a better understanding of the actual saving potentials in the region.
4. Although the simulations were performed for office, retail store, and residential prototypes, the results are normalized by roof area for each prototype. These results can be used to estimate savings potentials in other building types. For instance, one can comfortably estimate savings for a hospital based on the results obtained for office buildings.
5. The total roof area for commercial buildings in the GTA was estimated using an approach based on the population and the residential roof area. A more direct estimate of the actual roof area for commercial buildings can improve the accuracy of the estimates.
6. The indirect savings potential was only a small fraction of total potential savings. Hence, for consideration of energy-savings potentials, reflective roofs and shade trees that save energy both directly and indirectly should be given a higher priority than reflective pavements that save energy only indirectly.

8. Conclusion

We simulated the potential of heat island reduction (HIR) strategies (i.e. solar-reflective roofs, shade trees, wind-shielding, reflective pavements and urban vegetation) to reduce cooling-energy use in buildings in the Greater Toronto Area, Canada. Both direct effect (reducing heat gain through the building shell) and indirect effect (reducing the ambient air temperature) was addressed.

For gas-heated residential prototypes, the simulations predicted annual total energy savings of about 3–5% from combined direct and indirect effects [\$17–22/100 m^2 for old and \$9/100 m^2 for new residences]. This number increased to 10% for offices [\$40/100 m^2 for new and \$100/100 m^2 for old] and 12% for retail stores [\$40/100 m^2 for new and \$100/100 m^2 for old]. Electrically-heated units did not fare so well, because the electric heating penalty is more expensive than that of gas. Savings of 0–2% were observed for these residences and 5–9% for offices and retail stores.

An annual natural gas deficit was found for all building types and in each HIR strategy with the exception of wind-shielding; wind-shielding reduced the heating requirements of all buildings. The annual gas deficit for combined direct and indirect effects was \$2–6/100 m^2 for residences, \$11–12/100 m^2 for offices and only \$0–3/100 m^2 for retail stores.

Simulated peak-power reduction was significant for all building types and strategies (wind-shielding was the exception). Combined direct and indirect peak-demand reduction in cooling electricity was 21–23% in residences and 13–16% in offices and retail stores. This translates into 0.57–0.61 kW/100 m^2 for pre-1980 residences, 0.33–0.40 kW/100 m^2 for 1980+ residences, 0.60–1.13 kW/100 m^2 for old and new offices, and 0.36–0.71 kW/100 m^2 for old and new retail stores.

For the entire GTA, potential annual energy savings of over \$11 M (with uniform residential and commercial electricity and gas prices of \$0.084/kWh and \$5.54/GJ) could be realized by rate-payers from the combined direct and indirect effects of HIR strategies. Of that total, about 88% was from the direct effects and 12% from the indirect effect of the cooler ambient air temperature. The residential sector accounts for over half (about 59%) of the total savings, offices 13%, and retail stores 27%. Savings from cool roofs were about 20%, shade trees 30%, wind-shielding by trees 37%, and indirect effects 12%. These results were highly sensitive to the price of gas. Assuming a residential gas price of \$10.84/GJ (gas price during December 2001), the net annual savings are reduced to \$10 M; about 78% resulted from wind-shielding, 16% from shading by trees, and 5% from cool roofs.

Potential annual electricity savings were estimated at about 150 GWh or over \$12 M, of that about 75% accrued from roofs and shade trees and only 2% from wind-shielding. The indirect effect was 23%. The potential annual natural gas deficit was estimated to be over 0.23 PJ or just under \$1–2 M, with actual savings of over \$4–8 M from wind-shielding and a combined penalty of under \$3–7 M. Residences accounted for about 94% of the gas deficit.

Potential avoided peak-power was estimated at about 250 MW, with about 74% attributed to direct and 26% to indirect effects. About 83% of the avoided peak power occurred in the residences and the rest was shared by offices (7%) and retail stores (9%).

By their nature, the results of this study are preliminary. Our objective was to perform a preliminary analysis and provide an estimate of potential energy and peak-demand savings from the implementation of HIR measures. We focused on three building types (residential, office, and retail) that offer the highest potential savings for the GTA, and these three building types constitute over 90% of the floor area of the total building stock in the GTA. The HIR technologies are also very effective in other building types such as hospitals, schools, restaurants, grocery stores, etc. However, the potential savings from these other buildings only contribute a few percent of additional savings for the entire metropolitan Toronto.

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