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Energy impacts of heat island reduction strategies in the Greater Toronto Area, Canada

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Energy Impacts of Heat Island Reduction Strategies in the Greater Toronto Area, Canada

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Energy Impacts of Heat Island Reduction Strategies in Toronto, Canada

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Abstract

In 2000, the Toronto Atmospheric Fund (TAF) embarked on an initiative to quantify the potential benefits of Heat Island Reduction (HIR) strategies (shade trees, reflective roofs and pavements) in reducing cooling energy use in buildings, lowering the ambient air temperature and improve air quality. This report summarizes the efforts of Lawrence Berkeley National Laboratory (LBNL) to assess the impacts of HIR measures on building cooling- and heating-energy use.

We discuss our efforts to calculate annual energy savings and peak-power avoidance of HIR strategies in the building sector of the Greater Toronto Area. The analysis is focused on three major building types that offer most saving potentials: residence, office and retail store. Using an hourly building energy simulation model, we quantify the energy saving potentials of (1) using cool roofs on individual buildings [*direct effect*], (2) planting deciduous shade trees near south and west walls of building [*direct effect*], (3) planting coniferous wind-shielding vegetation near building [*direct effect*], (4) ambient cooling by a large-scale program of urban reforestation with reflective building roofs and pavements [*indirect effect*], (5) and the combined direct and indirect effects.

Results show potential annual energy savings of over $11M (with uniform residential and commercial electricity and gas prices of $0.084/kWh and $5.54/GJ) could be realized by ratepayers from the combined direct and indirect effects of HIR strategies. Of that total, about 88% was from the direct impact roughly divided equally among reflective roofs, shade trees and wind-shielding, and the remainder (12%) from the indirect impact of the cooler ambient air temperature. The residential sector accounts for over half (59%) of the total, offices 13% and retail stores 28%. Savings from cool roofs were about 20%, shade trees 30%, wind shielding of tree 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 about $10M; about 78% resulted from wind-shielding, 16% from shading by trees, and 5% from cool roofs.

Potential annual electricity savings were estimated at about 150GWh or over $12M, of that about 75% accrued from roofs and shade trees and only 2% from wind shielding. The indirect effect was 23%. Potential peak-power avoidance was estimated at 250MW with about 74% attributed to the direct impacts (roofs about 24%, shade trees 51% and wind-shielding a small negative %) and the remainder (26%) to the indirect impact. The greatest part of avoided peak power (about 83%) was because of the effects of the residences and the rest shared by offices (7%) and retail stores (9%).

Energy Impacts of Heat Island Reduction Strategies in Toronto, Canada

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Executive Summary

In 2000, the Toronto Atmospheric Fund (TAF) embarked on an initiative to quantify the potential benefits of Heat Island Reduction (HIR) strategies (i.e. shade trees, reflective roofs, reflective pavements and urban reforestation) to reduce cooling energy use in buildings, lower the ambient air temperature and improve air quality. This report summarizes the efforts of Lawrence Berkeley National Laboratory (LBNL) to assess the impacts of HIR measures on building cooling- and heating-energy use. A companion report will address the air quality aspect (Taha *et al.*, 2002).

Background

During the summer, solar-reflective roofs (also known as "high-albedo[§]" 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 gains because of cool roofs and 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 shade trees may add to the heating load of a building. However, the heating-energy penalties are fairly small, since most of the heating is required during the evening hours (when there is 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.

Cool surfaces (roofs and pavements) together with urban vegetation (shade trees, park trees, lawn, etc.) can potentially cool the city by a few degrees. Lowered urban air temperatures can further reduce cooling-energy demand. More importantly, cooler ambient conditions can also slow the rate of smog (O_3) formation and have a significant impact on ambient air quality. Observational data from Los Angeles, California indicate that the peak daily concentration of ozone increases by about 4–5% per ºC (2–3% per ºF) in the temperature range of 21–38^{o}C (70–100^{o}F) (Akbari *et al.*, 2001).

It is noted that summertime temperatures in Toronto have been steadily increasing with the expansion of the city. 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 impact of higher temperatures in the summer can potentially make air-quality problems more severe.

Project Objective

The objective of this project was to assess the impacts of Heat Island Reduction (HIR) measures on building cooling- and heating-energy use and ambient air quality in Toronto. This report summarizes our efforts to calculate annual energy savings and peak-power avoidance of HIR strategies in the Greater Toronto Area (GTA). In this analysis, we focused on the effect of vari-

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[§] When sunlight hits a surface some energy is reflected (albedo = â) and the remainder is absorbed (α = 1 –â). High-â surfaces become cooler than low-â surfaces and consequently lower the cooling load of a building.

ous HIR strategies on three major building types that offer most savings potential: residence, office and retail store. The HIR strategies include:

A. Use of solar-reflective roofing material on building [*direct effect*].

B. Placement of deciduous shade trees near south and west walls of building [*direct effect*].

C. Placement of coniferous wind-shielding vegetation near building [*direct effect*].

D. Urban reforestation with reflective building surfaces and pavements [*indirect effect*].

E. Combination of strategies A through D [*direct and indirect effects*].

Methodology

The focus of the project was to obtain an estimate of savings potentials of HIR measures. HIR measures have a significant effect on energy use of small residential and commercial buildings; HIR measures do not affect the energy use of large multistory commercial buildings typically located in the downtown area. Hence, we focused our efforts mostly on single-family residential and low-rise commercial buildings (office and retail store). In previous studies, these building types accounted for over 90% of potential savings of HIR measures.

A five-step methodology was developed to access the potential impact of HIR measures on building and metropolitan-wide energy use in Toronto.

1. Define prototypical-building characteristics in detail for pre-1980 and 1980+ construction.
2. Simulate annual energy use and peak demand using the DOE-2.1E model.
3. Determine direct and indirect energy and demand savings from each HIR strategy.
4. Identify the total roof area of air-conditioned buildings (residences, offices, and retail stores) in the GTA
5. Calculate the metropolitan-wide impact of HIR strategies.

We modeled a total of 20 prototypes including ten residential [pre-1980 (old) singles 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], four office buildings [pre-1980 (old) offices, 1980+ (new) offices; both modeled with gas and electric heating systems], and four retail buildings [pre-1980 (old) retail buildings, 1980+ (new) retail buildings; both modeled with gas and electric heating systems].

Building Energy Simulations

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

As expected, an increase in the heating energy use was found for all building types and in each HIR mitigation strategy with the exception of wind shielding, since this measure reduces the heating requirements of a building. The annual gas deficit for combined direct and indirect effects was 2–6$/100m^2 for residences, 11–12$/100m^2 for offices and only 0–3$/100m^2 for retails.

Simulated peak power reduction was significant for all building types and strategies, except for wind shielding. Combined direct and indirect peak-demand reduction in cooling electricity was 21–23% in residences and 13–16% in offices and retails. This translates into 0.57–

$0.61kW/100m^2$ for pre-1980 residences, $0.33–0.40kW/100m^2$ for 1980+ residences, $0.60–1.13kW/100m^2$ for old and new offices, and $0.36–0.71kW/100m^2$ for old and new retails.

Potential Metropolitan-Wide Benefits

The Greater Toronto Area (GTA) has a population of over 4.2 million with nearly 1.5 million households and is situated inland, on the northwestern edge of Lake Ontario. The Toronto summer is hot and brief with a cooling season from May through September. The winter is cold from November through March [Average summer peak temperature is 34°C and average winter minimum temperature is –24°C. Typically, there are about 320 cooling degree-days and 4200 heating degree-days, base 18.3°C]. Most residential buildings are two-story and commercial buildings are low-rises. The saturation of air-conditioning is high in both residential and commercial buildings. The total roof area of residential, office and retail buildings with air-conditioning was 40, 1.9 and $3.4Mm^2$, respectively, and about 75% built prior to 1980.

The potential metropolitan-wide benefits assume full implementation of HIR measures and were calculated in the form of annual energy savings [M$], annual electricity savings in giga watt-hour [GWh] and [M$], annual natural gas deficit in peca Joule [$PJ = 10^{15}J$] and [M$], and avoided peak power mega watt [MW].

Results show potential annual energy savings of over $11M (with uniform residential and commercial electricity and gas prices of $0.084/kWh and $5.54/GJ) could be realized by ratepayers from the combined direct and indirect effects of HIR strategies. Of that total, about 88% was from the direct impact roughly divided equally among reflective roofs, shade trees and wind-shielding, and the remainder (12%) from the indirect impact of the cooler ambient air temperature. The residential sector accounts for over half (59%) of the total, offices 13% and retail stores 28%. Savings from cool roofs were about 20%, shade trees 30%, wind shielding of tree 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 $10M; about 78% resulted from wind-shielding, 16% from shading by trees, and 5% from cool roofs. (These results are fairly intuitive, as the higher prices of gas make winter heating penalties more expensive.)

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

The potential annual natural gas deficit was estimated to be over 0.23PJ or just under $1–2M, with actual savings of over $4–8M from wind shielding and a combined penalty of under $3–7M. Residences accounted for about 94% of the gas deficit since these commercial buildings require very little heating.

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

Discussion

The results of this study are preliminary by nature. The objective of the project was to perform a preliminary analysis and to develop a database of potential energy- and peak-demand savings from the implementation of HIR measures (i.e., cool roofs, shade trees, and cool pavements). To perform such a study, we focused on three building types (residential, office, and retail) that offer the highest potential savings for the GTA. The primary reason we focused on these three building types was that these buildings constitute over 90% of the floor area of all building stock in 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

The analysis included both the direct and indirect effects of three heat-island reduction measures on heating- and cooling-energy use of several prototypical residential and commercial buildings. The prototypical savings were then extrapolated to obtain savings potentials for the Greater Toronto Area. 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 –$ penalties in heating-energy use) is 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 currently underestimates 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 saving potentials were only a small fraction of total potential savings. Hence, for energy saving potentials consideration, reflective roofs and shade trees that save energy both directly and indirectly should be given a higher priority than reflective pavements that only save energy indirectly.

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1. Introduction

During the summer, solar-reflective roofs (also known as "high-albedo[§]" 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 gains because of cool roofs and 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 shade trees may add to the heating load of a building. However, the heating-energy penalties are fairly small, since most of the heating is required during the evening hours (when there is 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 (Akbari *et al*., 1990).

Cool surfaces (roofs and pavements) together with urban vegetation (shade trees, park trees, lawn, etc.) can potentially cool the city by a few 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 impact on ambient air quality. Observational data from Los Angeles, California indicate that the peak daily concentration of ozone increases by about 4–5% per ºC (2–3% per ºF) in the temperature range of 21–38^{o}C (70–100^{o}F) (Akbari *et al.,* 2001).

It is noted that summertime temperatures in Toronto have been steadily increasing with the expansion of the city (Jessup, 2000). 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 impact of higher temperatures in the summer can potentially make air-quality problems more severe.

Literature Review

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.

In a pilot study, Konopacki *et al*. (1997) used computer simulations to estimate the direct energy impact from solar-reflective roofs in eleven U.S. Metropolitan Statistical Areas (MSAs). The study reported metropolitan-wide estimates of total residential and commercial annual energy and electricity savings, annual gas deficit (winter heating penalties), avoided peak power and annual carbon reduction. 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%). Furthermore, these three building types accounted for 93% of the total air-conditioned roof area. The metropolitan-wide savings were a function of energy savings in the air-conditioned buildings, stock of residential and commercial buildings, percentage of buildings that were air-conditioned, and the number of floors per building (roof area). Populous cities with an older low-rise building stock, in hot and sunny climates, and with a high level of a/c saturation provided the highest savings potential for HIR strategies. Metropolitan-wide savings were as much as $37M for Phoenix and $35M in Los Angeles and as low as $3M in the heating-dominated climate of Philadelphia.

[§] When sunlight hits a surface some energy is reflected (albedo = â) and the remainder is absorbed (α = 1 –â). High-â surfaces become cooler than low-â surfaces and consequently lower the cooling load of a building.

In a recent study using a methodology similar to the pilot project, Konopacki and Akbari (2000) have estimated the direct and indirect energy impacts of all HIR measures in three U.S. metropolitan areas: Baton Rouge, Sacramento and Salt Lake City. The analysis indicated that for the three respective cities, potential annual energy savings (cooling energy savings minus heating energy penalties) of \$15M, \$26M and \$3.6M, peak-power avoidance of 130MW, 490MW and 85MW, and annual carbon reduction of 40kt, 92kt and 20kt could be realized from full implementation of HIR measures.

Other studies using computer simulations to estimate the impact of solar-reflective roofs include Konopacki and Akbari (1998a), Akbari *et al*. (1998), Parker *et al*. (1998a) and Gartland *et al*. (1996). Additionally, Taha *et al*. (1996) have modeled the impact of shade trees. Finally, Akbari and Taha (1992) have estimated the impact of reflective surfaces and trees in four Canadian cities (including Toronto). The building prototypes included a detached one-story and a detached two-story, and a two-story row-house. The simulations indicated that by increasing the vegetative cover by 30% and increasing the albedo of houses by 0.2 (from moderate-dark to medium-light color), the heating-energy use in Toronto can be reduced by 10% in urban houses and 20% in rural houses (mostly because of wind-shielding effect of trees). The cooling-energy use can be reduced by about 30%–40%.

In addition to computer simulations, several field studies have documented measured air-conditioning summertime energy savings that result from the use of solar-reflective roof systems. These studies were conducted in warm-weather climates, mostly in Florida and California, on residential and commercial buildings. In a recent study, Konopacki and Akbari (2001) have estimated daily energy savings of 39 Wh/m^2 (3.6Wh/ft^2) (11%) and peak-power reduction of 3.8W/m^2 (0.35W/ft^2) (14%) in a large retail store in Austin from the application of a reflective membrane. Akbari and Rainer (2000) measured daily a/c energy savings of 33Wh/m^2 (3.1Wh/ft^2) (1%) in two Nevada telecommunication regeneration buildings. Konopacki *et al*. (1998) have demonstrated the impact of reflective roofs in three California commercial buildings, two medical offices and one retail store, summertime daily air-conditioning savings of 68 Wh/m^2 (6.3 Wh/ft^2), 39 Wh/m^2 (3.6 Wh/ft^2) and 4.3Wh/m^2 (0.4Wh/ft^2) (18%, 13% and 2%) and reduced demand of 3.3 W/m^2 (0.31 W/ft^2), 2.4 W/m^2 (0.22 W/ft^2) and 1.6W/m^2 (0.15W/ft^2) (12%, 8% and 9%). Akbari *et al*. (1997a) have shown from an increase in roof reflectance in one monitored Sacramento house daily summertime cooling-energy savings of 14Wh/m^2 (1.3Wh/ft^2) (63%) and peak-power reduction of 3.6W/m^2 (0.33W/ft^2) (25%), and in a Sacramento school bungalow, cooling-energy savings of 47Wh/m^2 (4.4Wh/ft^2) (46%) and peak-power reduction of 6.8W/m^2 (0.63W/ft^2) (20%). In an office, museum and hospice with reflective roofs in Sacramento, Hildebrandt *et al*. (1998) measured daily a/c savings of 10 Wh/m^2 (0.9 Wh/ft^2), 20 Wh/m^2 (1.9 Wh/ft^2) and 11Wh/m^2 (1.0Wh/ft^2) (17%, 26% and 39%) . Parker *et al*. (1998a) have monitored the performance of reflective roofs in eleven Florida residences with daily savings ranging from 5–137Wh/m^2 (0.5–12.7Wh/ft^2) (2–43%) and peak-demand reduction of 1.5–7.7W/m^2 (0.14–0.72W/ft^2) (12–28%). Parker *et al*. (1999) measured daily energy savings of 17% from a reflective roof in a high-efficiency home in Florida. Parker *et al*. (1997) have also monitored seven retail stores within a strip mall in Florida before and after applying a reflective roof coating and measured a 7.5Wh/m^2 (0.7Wh/ft^2) (25%) drop in daily summertime cooling-energy use and a 0.65W/m^2 (0.06W/ft^2) (29%) decrease in demand. Parker *et al*. (1998b) measured daily energy savings of 44Wh/m^2 (4.1Wh/ft^2) (25%)and peak-power reduction of 6.0W/m^2 (0.56W/ft^2) (30%) from a reflective roof on a school building in Florida. Akridge (1998) reported daily savings of 75Wh/m^2 (7.0Wh/ft^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 (Boutwell and Salinas 1986).

In two monitored houses in Sacramento, Akbari *et al*. (1997b) 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.

Project Objective

The objective of this project was to assess the impacts of Heat Island Reduction (HIR) measures on building cooling- and heating-energy use and ambient air quality in the Greater Toronto Area (GTA). This report summarizes our efforts to calculate the annual energy savings and peak-power avoidance resulting from the implementation of HIR strategies in the GTA[§]. In this analysis, we focused on the effect of various HIR strategies on three major building types that offer most savings potential: residence, office and retail store. The HIR strategies include:

A. Use of solar-reflective roofing material on buildings [direct effect].

B. Placement of deciduous shade trees near south and west walls of buildings [direct effect].

C. Placement of coniferous wind-shielding vegetation near buildings [direct effect].

D. Urban reforestation with reflective building surfaces and pavements [indirect effect].

E. Combination of strategies A through D [direct and indirect effects].

2. Methodology

The focus of the project was to obtain an estimate of the savings potentials of HIR measures. HIR measures have a significant effect on the energy use of small residential and commercial buildings; HIR measures do not affect the energy use of large multistory commercial buildings typically located in the downtown area. Hence, we focused our efforts mostly on single-family residential and low-rise commercial building (office and retail store). In previous studies, these building types accounted for over 90% of the potential savings resulting from the implementation of HIR measures.

We modeled a total of 20 prototypes including ten 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], four office buildings [pre-1980 (old) offices, 1980+ (new) offices; both modeled with gas and electric heating systems], and four retail buildings [pre-1989 (old) retail buildings, 1980+ (new) retail buildings; both modeled with gas and electric heating systems].

A five-step methodology was developed to access the potential impact of HIR measures on building and metropolitan-wide energy use in the GTA.

1. Define prototypical building characteristics in detail for pre-1980 and 1980+ construction.

Prototypical building data were identified and used to define construction, internal load, and cooling and heating equipment characteristics for residential, office and retail buildings. The prototypes were developed for both pre-1980 and 1980+ construction vintages (and R-2000 for the residence) and with both gas and electricity heating fuels. The use of existing and reflective roofs, the placement of deciduous shade trees about the south and west sides of the building and northern wind-shielding were considered. These data then defined the characteristics of the Building Description Language used by the DOE-2.1E energy simulation computer program. Building data for residences were obtained from two primary sources. (Sources of data for building characteristics information are summarized in Appendix A.) The first is an analysis of a

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[§] A companion report will address the air quality aspect of HIR in the GTA (Taha *et al.,* 2002).

Natural Resources Canada survey of 1361 houses in the GTA (NRCAN, 2001a), and the second is a study by Akbari *et al*. (1992) that estimated the impact of trees and reflective roofs on residential cooling- and heating-energy use in four Canadian cities**.**

2. Simulate annual energy use and peak demand using the DOE-2.1E model.

The DOE-2 building-energy model was used to simulate the *direct* impact of reflective roofs, shade trees and wind-shielding on cooling- and heating-energy use for several prototypical buildings in the GTA. The DOE-2 model simulates energy use of a building for 8,760 hours of a year, using typical hourly weather data. The MM5 mesoscale meteorological model was used to simulate the impact of urban surface modifications on the cooling of the regional ambient air. Following that step, the Toronto Weather Year for Energy Consumption (WYEC2) data was modified to account for this ambient cooling. The rerun of the DOE-2 simulations with the modified weather data quantified the *indirect* impact of HIR measures on building-energy use. Local electricity and natural gas rates were applied to the simulation results to obtain total annual energy use in dollars.

3. Determine direct and indirect energy and demand savings from each HIR strategy.

Simulated annual cooling- and heating-energy savings and avoided peak power were calculated by comparing the base case energy use and demand to those of the HIR strategies.

4. Identify total roof area of air-conditioned buildings in the GTA.

Total air-conditioned roof area for the entire GTA was estimated for residential, office (including high-rises) and retail buildings. Residential roof area was calculated with data obtained from Statistics Canada (STATCAN, 1996), Natural Resources Canada (NRCAN, 2001a), ICLEI (1997) and the Survey of Household Energy Use (NRCAN, 1995). Commercial building roof area was calculated from a methodology described in Konopacki *et al*. (1997).

5. Calculate the metropolitan-wide impact of HIR strategies.

Savings from building-energy simulations were combined with the total air-conditioned roof area for each prototype and HIR strategy to determine metropolitan-wide impact.

3. Building and Measure Descriptions

Three major building prototypes were selected for investigation in this project: [1] residence [2] office [3] retail store. In a detailed study to quantify the impact of reflective roofs in eleven Metropolitan Statistical Areas (MSAs), Konopacki *et al*. (1997) showed that these three building types accounted for 93% of the residential and commercial air-conditioned roof area. 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. Two heating fuels were available for each prototype, natural gas and electricity. The prototype characteristics were written into Building Description Language (BDL) for DOE-2 modeling.

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 Natural Resources Canada (2001a), about 60% of existing single-family detached (SFD) houses are two-story and 23% single story; the average floor area is about 280 m^2 (3000 ft^2). The newer (post 1980) SFD houses are about 90% two-story and 7% three-story (less than 3% are one-story); the average floor area is about 350 m^2 (3800 ft^2). For all existing row-houses, about 64% are two-story and 27% three-story; the average floor area is 170 m^2 (1800 ft^2). The newer

(1980+) row-houses were about 62% two-story and 37% three-story with an average floor area of about 150 m^2 (1600 ft^2).

Changing the reflectance of the roof, mostly affects the heat transfer through the roof structure. We present the simulated data by normalizing the savings per 100m^2 of roof area. Then in calculating the savings for the GTA, we accounted for the number of stories of the building stock.

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 the attic and living quarters were dependent on vintage. Variable air infiltration was modeled by the Sherman-Grimsrud algorithm (Sherman *et al.,* 1986). The existing solar reflectance of the roof was 0.2, typical for asphalt shingles, and the albedo of the reflective roof was taken to be 0.5, the value for prototype white shingles and a typical value for aged white roof coatings. The thermal emittance of both roofs was 0.9.

The single-family detached 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. 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. A Seasonal Energy Efficiency Ratio (SEER) of 12 or greater is the standard for an Energy Star® qualifying central air-conditioner, and a Heating Season Performance Factor (HSPF) of 7 for an air-source heat pump (U.S.DOE 2001). The minimum SEER allowed today is 10.

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 (Henderson, 1998). Duct loads were simulated with a validated residential duct function (Parker *et al*., 1998a) implemented into DOE-2 to better estimate the thermal interactions between the ducts and space. The function was designed for the residential central system type (RESYS) in DOE-2 and for a single air-conditioned living space with an attic and basement. Since this function greatly improves cooling and heating energy use estimates and the top story of a building receives the primary benefits of a reflective roof, the single-story residential structure was modeled.

Building data for residences are shown in **Tables 3.1 (a,b)** and were obtained from several sources: an analysis of a Natural Resources Canada (NRCAN, 2001a) survey of 1361 houses in the GTA, and a study by Akbari *et al*. (1992), which estimated the impact of trees and reflective roofs on residential cooling and heating energy use in four Canadian cities. Additionally, characteristics for 1980+ construction homes were identified from DOE national appliance energy standards (NAECA, 1987), California's Title 24, the Model Energy Code, and Energy Star® (U.S.DOE, 2001).

Office

The office was modeled as a non-directional building with four perimeter zones and a core zone, also in two construction vintages, those built prior to 1980, those built in 1980 and after. The floor plan was a 21.3m by 21.3m (70' by 70') layout with a total air-conditioned floor area of 455m^2 (4900ft^2). The perimeter zone depth was 4.6m (15'). The building operated from 6am to 7pm 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. The existing solar reflectance of the roof was 0.2, typical for gray or tan built-up, and the albedo of the reflective roof was taken to be 0.6, typical for aged white roof coatings. The thermal emittance of both roofs was 0.9.

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. A Seasonal Energy Efficiency Ratio (SEER) of 12 or greater is the standard for an Energy Star® qualifying central air-conditioner, and a Heating Season Performance Factor (HSPF) of 7 for an air-source heat pump (U.S.DOE, 2001). The minimum currently allowed SEER is 10.

Specific building characteristics data for the commercial sector in the GTA were not available. Office characteristics were taken from previous research focusing on the impact of reflective roofs in eleven U.S. metropolitan areas (Konopacki *et al*., 1997) and Energy Star® (U.S.DOE, 2001). These office building characteristics are displayed in **Table 3.2**.

Retail Store

The retail store was modeled as a non-directional building with a single zone, also in two construction vintages, those built prior to 1980 (pre-1980), those built in 1980 and after (1980+). The floor plan was a 90' by 90' layout with 8100ft^2 of total air-conditioned floor area. The building operated from 8am to 9pm on weekdays and from 10am to 5pm 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. The existing solar reflectance of the roof was 0.2, typical for gray or tan built-up, and the albedo of the reflective roof was taken to be 0.6, typical for aged white roof coatings. The thermal emittance of both roofs was 0.9.

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. A Seasonal Energy Efficiency Ratio (SEER) of 12 or greater is the standard for an Energy Star® qualifying central air-conditioner, and a Heating Season Performance Factor (HSPF) of 7 for an air-source heat pump (U.S.DOE, 2001). The minimum SEER allowed today is 10.

Specific building characteristic data for the commercial sector in the GTA were not available. Retail store characteristics were taken from previous research focusing on the impact of reflective roofs in 11 U.S. metropolitan areas (Konopacki *et al*., 1997) and Energy Star® (U.S.DOE, 2001). These retail store building characteristics are displayed in **Table 3.3**.

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 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 (CRMD, 2001) developed at LBNL, 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 0.2–0.25. 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.

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. In DOE-2 the *ABSORPTANCE* keyword for roof construction was 0.8 for the base case and was changed to 0.5 and 0.4 for residential and commercial reflective roofs, respectively.

Bretz and Akbari (1997) 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, rainfall can cleanse a roof and in most cases have the same effect as a thorough washing.

A "generic white" asphalt shingle has a laboratory tested initial albedo of 0.25 (CRMD, 2001). 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 (CRMD, 2001). The roofs—built-up asphalt capsheet with light-gray granules—of three commercial buildings in California were coated with a white-elastomeric material, where the measured pre-coated albedo ranged from 0.16 to 0.24, the initial post-coated albedo was 0.6, the unwashed albedo ranged from 0.47 to 0.56, and the washed albedo was 0.59 (Konopacki and Akbari, 1998b).

Shade Trees

Shade trees block incoming sunlight to the windows and walls of a building and effectively lower cooling demand. Deciduous shade trees shed their leaves in the winter to allow sunlight to warm the building. Mature deciduous shade trees were modeled in DOE-2 with the *BUILDING-SHADE* keyword as a box-shaped building shade with seasonal transmittance[ξ]. The summertime transmittance was 0.1 for 1 April through 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 $21m^2$ ($225ft^2$), 4.6m by 4.6m (15' by 15'), a depth of 3m (10'), and a canopy height of 4.6m (15'). They were placed outside the south and west walls near the windows (with 0.6m of clearance from the building) in order to maximize the impact 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.

Wind-Shielding

Trees and shrubbery 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 cold northerly winds, and to locate deciduous foliage on the south and west sides. In a heating-dominant climate such as Toronto, the net effect yielded savings in annual energy ex-

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

penditures. The shielding impact on reducing seasonal heating expenditures was greater than the slight increase in cooling costs.

The wind-shielding effect on cooling and heating use was modeled within DOE-2 by altering the three following BDL Building-Location keywords: [1] *SHIELDING-COEFFICIENT* [2] *TERRAIN-PAR1* [3] *TERRAIN-PAR2* (Winklemann *et al*., 1993). 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 the wind pressure caused by local obstructions. A value of 0.19 representing typical suburban shielding was used for base simulations; this was altered to 0.17. The wind speed was also modified 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.

Table 3.1(a). Prototypical building description for the Greater Toronto Area: Single-Family Residence.

Single-Family Residence	**Pre-1980**	**1980+**	**R-2000**
Two-story, non-directional			
Roof & floor area (m^2)	93/185	112/223	93/185
Zones			
Living (conditioned)			
Attic (unconditioned)			
Basement (unconditioned)			
Roof construction			
20^o slope			
6.3 mm (1/4") asphalt shingle			
1.9 cm (3/4") plywood deck w/ 5.8 cm x 25.2 cm (2" x 6") rafters			
Naturally ventilated attic			
1.9 cm (3/4") plywood deck w/ 5.8 cm x 25.2 cm (2" x 6") rafters (15%)			
Fiberglass insulation (85%) (m2K/W)	3.34 (R-19)	5.28 (R-30)	6.69 (R-38)
1.3 cm (1/2") drywall			
Roof solar reflectance			
Pre	0.2		
Post	0.5		
Roof thermal emittance	**0.9**		
Wall construction			
Brick exterior			
Wood frame (15%)			
Fiberglass insulation (85%) (m2K/W)	1.23 (R-7)	2.46 (R-14)	3.52 (R-20)
1.3 cm (1/2") drywall interior			
Windows			
Clear with operable shades			low-□
Number of panes	2		
Window to wall ratio	0.08		
Fractional leakage area (cm^2/m^2)			
Living	2.8	1.4	1
Attic	5.6	2.8	2
Air-conditioning equipment			
Central a/c, direct expansion, air-cooled			
Seasonal energy efficiency ratio (SEER)	8	10	12
Coefficient of performance (COP)	2.3	2.9	3.5
Capacity (kJ/h)	38,000	31,700	25,300
Cooling setpoint (^{o}C)	25.6		
Natural ventilation available			
Heating equipment			
1) central forced air gas furnace			
Efficiency (%)	82	85	85
Capacity (kJ/h)	79,100	63,300	52,800
Heating setpoint (^{o}C)	21.1		
11pm–7am setback (^{o}C)	15.6		
2) central electric heat pump			
Heating season performance factor (HSFP)	5	7	8
Duct air leakage (%)	**20**	**10**	**5**

Table 3.1(b). Prototypical building description for the Greater Toronto Area: Row-House Residence.

Row-House Residence	**Pre-1980**	**1980+**	**R2000**
Two-story, non-directional			
Roof & floor area (m^2)	56/112	46/93	56/112
Zones			
Living (conditioned)			
Attic (unconditioned)			
Basement (unconditioned)			
Roof construction			
20o slope			
6.3 mm (1/4") asphalt shingle			
1.9 cm (3/4") plywood deck w/ 5.8 cm x 15.2 cm (2" x 6") rafters			
Naturally ventilated attic			
1.9 cm (3/4") plywood deck w/ 5.8 cm x 15.2 cm (2" x 6") rafters (15%)			
Fiberglass insulation (85%) (m2K/W)	2.29 (R-13)	5.28 (R-30)	6.69 (R-38)
1.3 cm (1/2") drywall			
Roof solar reflectance			
Pre	0.2		
Post	0.5		
Roof thermal emittance	**0.9**		
Wall construction			
Brick exterior			
wood frame (15%)			
Fiberglass insulation (85%) (m2K/W)	1.06 (R-6)	2.64 (R-15)	3.52 (R-20)
1.3 cm (1/2") drywall interior			
Windows			
Clear with operable shades			
Number of panes	2		
window to wall ratio	0.11		
Fractional leakage area (cm^2/m^2)			
Living	2.8	0.7	0.7
Attic	6.2	2.1	1.4
Air-conditioning equipment			
window or room a/c, direct expansion			
Seasonal energy efficiency ratio (SEER)	6	10	12
Coefficient of performance (COP)	2.3	2.9	3.5
Capacity (kJ/h)	38,000	31,700	25,300
Cooling setpoint (^oC)	25.6		
Natural ventilation available			
Heating equipment			
1) wall mounted gas furnace			
Efficiency (%)	81	92	92
Capacity (kJ/h)	42,200	38,000	31,700
Heating setpoint (^oC)	21.1		
11pm–7am setback (^oC)	15.6		
2) electric resistance			
Duct air leakage (%)	-	-	

Table 3.2. Prototypical Building Description for the Greater Toronto Area: Office.

Single-Story Office	**Pre-1980**	**1980+**
Non-directional		
5 zones (conditioned)		
Roof & floor area (m^2)	455	
Roof construction		
Built-up roofing		
1.9 cm (3/4") plywood decking (0o slope)		
Plenum (unconditioned)		
Roof solar reflectance		
Pre	0.2	
Post	0.6	
Roof thermal emittance	**0.9**	
Ceiling construction		
5.8 cm x 25.2 cm (2"x 6") studded frame (15%)		
Fiberglass insulation (85%) (m2K/W)	3.34 (R-19)	5.28 (R-30)
1.3 cm (1/2") drywall		
Wall construction		
Brick exterior		
Wood frame (15%)		
Fiberglass insulation (85%) (m2K/W)	1.06 (R-6)	2.29 (R-13)
1.3 cm (1/2") drywall		
Foundation		
Slab-on-grade with carpet and pad		
Windows		
Clear with operable shades		
Number of panes	1	2
Window to wall ratio	0.5	
Air-conditioning equipment		
Packaged a/c, direct expansion, air-cooled		
Seasonal energy efficiency ration (SEER)	8	10
Coefficient of performance (COP)	2.3	2.9
Heating equipment		
(1) gas furnace		
Efficiency (%)	70	74
(2) electric heat pump		
Heating season performance factor (HSPF)	5	7
Distribution		
Constant-volume forced air system		
Economizer	fixed	temperature
Duct leakage (%)	20	10
Duct temperature drop (^oC)	1.1	0.6
Thermostat		
Weekday operation (6am–7pm)		
Cooling setpoint (^oC)	25.6	
Heating setpoint (^oC)	21.1	
Interior load		
Infiltration (air-change/hour)	0.5	
Lighting (W/m^2)	20.4	15.1
Equipment (W/m^2)	18.3	16.1
Occupants	25	

Table 3.3. Prototypical Building Description for the Greater Toronto Area: **Retail Store**.

Single-Story Office	**Pre-1980**	**1980+**
Non-directional		
5 zones (conditioned)		
Roof & floor area (m^2)	750	
Roof construction		
Built-up roofing		
1.9 cm (3/4") plywood decking (0o slope)		
Plenum (unconditioned)		
Roof solar reflectance		
Pre	0.2	
Post	0.6	
Roof thermal emittance	**0.9**	
Ceiling construction		
5.8 cm x 25.2 cm (2"x 6") studded frame (15%)		
Fiberglass insulation (85%) (m2K/W)	3.34 (R-19)	5.28 (R-30)
1.3 cm (1/2") drywall		
Wall construction		
Brick exterior		
Wood frame (15%)		
Fiberglass insulation (85%) (m2K/W)	0.70 (R-4)	2.29 (R-13)
1.3 cm (1/2") drywall		
Foundation		
Slab-on-grade with carpet and pad		
Windows		
Clear with operable shades		
Number of panes	1	2
Window to wall ratio	0.17	
Air-conditioning equipment		
Packaged a/c, direct expansion, air-cooled		
Seasonal energy efficiency ration (SEER)	8	10
Coefficient of performance (COP)	2.3	2.9
Heating equipment		
(1) gas furnace		
Efficiency (%)	70	74
(2) electric heat pump		
Heating season performance factor (HSPF)	5	7
Distribution		
Constant-volume forced air system		
Economizer	fixed	temperature
Duct leakage (%)	20	10
Duct temperature drop (^oC)	3	1
Thermostat		
Weekday operation (6am–7pm)		
Weekend operation (10am–5pm)		
Cooling setpoint (^oC)	25.6	
Heating setpoint (^oC)	21.1	
Interior load		
Infiltration (air-change/hour)	0.5	
Lighting (W/m^2)	25.8	18.3
Equipment (W/m^2)	7.5	6.5
Occupants	16	

4. Energy Simulations

Annual cooling- and heating-energy use and peak-power demand were simulated on an hourly time-step with the DOE-2.1E building-energy simulation program (BESG, 1990) using Toronto climate data for residential, office and retail store building prototypes, and for each Heat Island Reduction (HIR) strategy. Local residential and commercial electricity and natural gas rates were applied to the simulation results to obtain total annual energy use in dollars.

Direct vs. Indirect Effect

Strategies to cool cities and mitigate urban heat islands include planting shade trees around buildings, planting other urban vegetation in parks and along roadways, and using solar-reflective roofs and pavements. Trees shade buildings, and reflective roofs reflect solar energy from buildings, *directly* reducing demand for air-conditioning (a/c). Vegetation can reduce wind velocity near a building and consequently reduce heat loss; thus, wind-shielding *directly* increases a/c use and decreases heating demand. Urban vegetation and reflective surfaces (roofs and pavements) alter the surface-energy balance of an area through the evapotranspiration provided by vegetation and by the reflection of incident solar energy, lowering the ambient temperature and hence *indirectly* reducing a/c use (Akbari *et al.,* 1990).

Weather Data

Local full-year hourly weather data are required as input to the DOE-2 simulation program. The data used for this simulation were those for Toronto in the Weather Year for Energy Consumption (WYEC2) format. It is important to remark that this format represents normal rather than extreme weather conditions.

The direct energy impacts are simulated with the building-energy software DOE-2 and the standard WYEC2 climate data. The indirect energy impacts were estimated in a two-step process. First, a modified WYEC2 weather data was created to represent the impact of HIR strategies. Second, the prototypes were simulated with the modified weather tape to calculate the impact of the reduced ambient air temperature on cooling and heating energy use.

To quantify the ambient cooling from the indirect effect, a modified urban fabric (fraction of urban surfaces) is first created from the present fabric with increased urban vegetation, the planting of shade trees, and the use of reflective roofs and pavements. Second, the effect of the modified urban fabric on climate is simulated using the PSU/NCAR MM5 (Grell *et al*., 1994), from which a modified average dry-bulb air temperature is obtained from 15 locations within the boundaries of the model over 72-hour winter (Jan 15–17) and summer (July 15–17) episodes; discussed in detail by Taha *et al.* (2002). The modified temperature is then calculated for each hour of the year, using an algorithm based on a statistical analysis of temperature change (ΔT) as a function of solar intensity (I) (see Eq. 1). Because ΔT is solely a function of solar intensity, ΔT is zero during hours without sunlight. Finally, ΔT is used to modify the standard WYEC2 weather data to create modified temperature data for the building energy simulations.

$$\Delta T\ [^{\circ}C] = -0.0018\ I\ [W/m^2] \qquad \text{EQ. 1.}$$

In **Table 4.1**, cooling and heating degree-days (base 18.3°C) and the maximum air temperature have been tallied monthly for the standard and both modified WYEC2 weather data. The difference between the modified and the standard data is denoted by ΔT in the table. Ambient cooling from urban fabric modification was observed mostly during June, July and August with 64, 106 and 91 fewer cooling degree-days during those months. On an annual basis, 324 cooling-degree-days were reduced by 45. The effect on heating-degree-days was seen throughout the entire year;

annually there were 54 more degree-days. The greatest reduction in maximum ambient air temperature was recorded as 1.7°C from a high of 34°C in July.

Table 4.1. Standard and modified Toronto WYEC2 weather data with cooling- and heating-degree-days and maximum air temperature tallied monthly (ΔT = modified—standard).

	Cooling degree-days [base 18.3°C]		**Heating degree-days [base 18.3°C]**		**Maximum air temperature [°C]**	
Month	**Standard**	**Δ**	**Standard**	**Δ**	**Standard**	**Δ**
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**		

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

Energy Prices

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 (ICLEI 2001) and were \$0.084/kWh and \$5.54/GJ (\$0.206/m^3). Specific residential rates were obtained by inspecting the monthly utility bill for a typical house (Ligeti, 2002). The electricity rate was essentially the same as the commercial rates based on a comparison of Toronto Hydro Electric System rate schedules (THES, 2001). The gas rate was \$10.84/GJ (Total without customer charge \$0.404/m^3: gas supply charge \$0.202/m^3, gas delivery charge \$0.149/m^3, and gas storage charge \$0.052/m^3). The price of gas has changed significantly over the last few years. To perform a preliminary analysis of the impact 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.

DOE-2.1E Energy Simulations

The simulations provided estimates of annual cooling- and heating-electricity use [kWh/100m^2], annual heating natural gas use [GJ/100m^2] and cooling peak-power demand [kW/100m^2]. From the simulations, the annual total expenditures for cooling and heating energy [\$/100m^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 4.2(a, b, c)**. Table 4.2(a) shows the savings in absolute terms [kWh/100m^2, GJ/100m^2 & kW/100m^2], Table 4.2(b and c) show the savings in dollars with two prices for residential gas.

Base energy expenditures and peak-power demand were simulated using standard Toronto weather data for buildings with a dark roof (reflectance 0.2) and without shade trees or wind-shielding. Direct savings were simulated for a reflective roof (residential 0.5 and commercial 0.6), the placement of shade trees (residence 4, office 8 and retail 10) and wind-shielding. Indirect savings were simulated with modified weather data for the base case and each of the three direct cases. To estimate direct savings from increased roof reflectance ($\Delta\hat{a}$) other than those specified in Table 4, multiply the savings by the ratio $\Delta\hat{a}/0.3$ for residences and $\Delta\hat{a}/0.4$ for commercial buildings[§]. Linear interpolation can also be applied to direct shade tree savings. Savings will increase for buildings with less roof insulation than that specified in these prototypes (R-19 for old construction & R-30 for new). Conversely, savings will decrease for those with more roof insulation. Savings in peak power make it clear that the required air-conditioner can be downsized when HIR strategies are considered.

The simulations predicted annual total energy savings of about 3–5% from combined direct and indirect effects for old 17–22$/100m^2 and new 9$/100m^2 gas-heated single-family and row-house residences. This number increased to 10% for offices [40$/100m^2 for new and 100$/100m^2 for old] and 12% for retail buildings [40$/100m^2 for new and 100$/100m^2 for old]. Electric-heated units did not fair so well, where savings of 0–2% were observed for residences and 5–9% for the office and retail buildings because the higher cost of electric heating than that of gas heating.

As expected, an annual natural gas deficit was found for all building types and in each HIR mitigation strategy with the exception of wind-shielding, since this measure reduces the heating requirements of a building. The annual gas deficit for combined direct and indirect effects was 2–6$/100m^2 for residences,11–12$/100m^2 for offices and only 0–3$/100m^2 for retails.

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 retails. This translates into 0.57–0.61kW/100m^2 for pre-1980 residences, 0.33–0.40kW/100m^2 for 1980+ residences, 0.60–1.13kW/100m^2 for old and new offices, and 0.36–0.71kW/100m^2 for old and new retails.

[§] 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 ($\Delta\hat{a}_1$) (Konopacki *et al.*, 1997). 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 4.2(a). Toronto simulated cooling and heating annual base expenditures and savings [electricity: kWh/100m^2, gas: GJ/100m^2], and peak-power demand and savings [kW/100m^2] from heat-island reduction strategies for residential and commercial buildings. Direct savings are from the use of solar-reflective roofs, strategic placement of deciduous shade trees and wind-shielding vegetation, and indirect savings include the impact of reduced ambient air temperature from a modified urban fabric. Simulations are presented per 100m^2 of air-conditioned roof area.

Building type & Mitigation strategy	Gas heat				Electric heat		Gas & electric heat	
	Electricity (kWh/100m^2)		Gas (GJ/100m^2)		Electricity (kWh/100m^2)		Peak power (kW/100m^2)	
	Pre-1980	1980+	Pre-1980	1980+	Pre-1980	1980+	Pre-1980	1980+
Residence: Single-Family								
Base expenditure & demand	1057	629	75.0	49.3	14785	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								
Base expenditure & 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								
Base expenditure & 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								
Base expenditure & demand	7276	3842	57.3	27.5	16934	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								
Base expenditure & 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 4.2(b). Toronto simulated cooling and heating annual base expenditures and savings [\$/100m^2] from heat-island reduction strategies for residential and commercial buildings (residential gas price of \$5.54/GJ). Direct savings are from the use of solar-reflective roofs, strategic placement of deciduous shade trees and wind-shielding vegetation, and indirect savings include the impact of reduced ambient air temperature from a modified urban fabric. Simulations are presented per 100m^2 of air-conditioned roof area.

Building type & Mitigation strategy	**Annual energy and savings (\$/100m^2)**				**Annual energy (\$/100m^2) and savings (%)**			
	Gas heat		**Electric heat**		**Gas heat**		**Electric heat**	
	Pre-1980	1980+	Pre-1980	1980+	Pre-1980	1980+	Pre-1980	1980+
Residence: Single-Family								
Base expenditure & demand	504	325	1242	705	504	325	1242	705
Savings								
Reflective roof savings	2.5	1.5	-5.2	-1.7	0.5	0.5	-0.4	-0.2
Shade tree savings	5.6	2.0	-2.0	-0.7	1.1	0.6	-0.2	-0.1
Wind shield savings	11.6	4.4	31.8	11.2	2.3	1.4	2.6	1.6
Indirect savings	2.7	1.3	-8.4	-5.0	0.5	0.4	-0.7	-0.7
Combined savings	22.5	9.3	16.2	3.9	4.5	2.8	1.3	0.6
Residence: R-2000								
Base expenditure & demand	n/a	216	n/a	482	n/a	216	n/a	482
Savings								
Reflective roof savings	n/a	-0.3	n/a	-2.8	n/a	-0.1	n/a	-0.6
Shade tree savings	n/a	1.7	n/a	-0.7	n/a	0.8	n/a	-0.2
Wind shield savings	n/a	1.5	n/a	6.3	n/a	0.7	n/a	1.3
Indirect savings	n/a	0.8	n/a	-3.3	n/a	0.4	n/a	-0.7
Combined savings	n/a	3.7	n/a	-0.5	n/a	1.7	n/a	-0.1
Residence: Row-House								
Base expenditure & demand	498	236	1555	705	498	236	1555	705
Savings								
Reflective roof savings	3.4	1.9	-9.3	-5.1	0.7	0.8	-0.6	-0.7
Shade tree savings	5.8	3.6	-2.9	-0.9	1.2	1.5	-0.2	-0.1
Wind shield savings	4.4	0.6	16.3	3.8	0.9	0.3	1.0	0.5
Indirect savings	3.0	2.7	-11.6	-4.2	0.6	1.1	-0.7	-0.6
Combined savings	16.7	8.9	-7.5	-6.3	3.3	3.8	-0.5	-0.9
Office								
Base expenditure & demand	929	475	1422	681	929	475	1422	681
Savings								
Reflective roof savings	29.5	10.3	22.9	5.1	3.2	2.2	1.6	0.7
Shade tree savings	48.5	17.5	40.8	10.9	5.2	3.7	2.9	1.6
Wind shield savings	0.8	3.1	7.4	8.1	0.1	0.6	0.5	1.2
Indirect savings	20.9	11.2	13.5	5.4	2.3	2.4	0.9	0.8
Combined savings	99.6	42.1	84.6	29.4	10.7	8.8	5.9	4.3
Retail Store								
Base expenditure & demand	802	338	1070	415	802	338	1070	415
Savings								
Reflective roof savings	40.7	13.0	36.0	8.6	5.1	3.9	3.4	2.1
Shade tree savings	35.6	13.2	35.5	12.3	4.4	3.9	3.3	3.0
wind shield savings	2.1	3.3	11.6	9.4	0.3	1.0	1.1	2.3
Indirect savings	19.8	9.3	15.1	6.9	2.5	2.8	1.4	1.7
Combined savings	98.9	39.4	98.2	37.1	12.3	11.7	9.2	8.9

Table 4.2(c). Toronto simulated cooling and heating annual base expenditures and savings [\$/100m^2] from heat-island reduction strategies for residential and commercial buildings (residential gas price of \$10.84/GJ). Direct savings are from the use of solar-reflective roofs, strategic placement of deciduous shade trees and wind-shielding vegetation, and indirect savings include the impact of reduced ambient air temperature from a modified urban fabric. Simulations are presented per 100m^2 of air-conditioned roof area.

Building type & Mitigation strategy	Annual energy and savings (\$/100m^2) Gas heat Pre-1980	Gas heat 1980+	Electric heat Pre-1980	Electric heat 1980+	Annual energy (\$/100m^2) and savings (%) Gas heat Pre-1980	Gas heat 1980+	Electric heat Pre-1980	Electric heat 1980+
Residence: Single-Family								
Base expenditure & demand	898	584	1242	705	898	584	1242	705
Savings								
Reflective roof savings	-2.5	-1.1	-5.2	-1.7	-0.3	-0.2	-0.4	-0.2
Shade tree savings	0.3	-2.0	-2.0	-0.7	0.0	-0.3	-0.2	-0.1
Wind shield savings	25.1	10.6	31.8	11.2	2.8	1.8	2.6	1.6
Indirect savings	-1.7	-1.6	-8.4	-5.0	-0.2	-0.3	-0.7	-0.7
Combined savings	21.2	5.9	16.2	3.9	2.4	1.0	1.3	0.6
Residence: R-2000								
Base expenditure & demand	n/a	386	n/a	482	n/a	386	n/a	482
Savings								
Reflective roof savings	n/a	-2.9	n/a	-2.8	n/a	-0.8	n/a	-0.6
Shade tree savings	n/a	-1.3	n/a	-0.7	n/a	-0.3	n/a	-0.2
Wind shield savings	n/a	4.6	n/a	6.3	n/a	1.2	n/a	1.3
Indirect savings	n/a	-1.3	n/a	-3.3	n/a	-0.3	n/a	-0.7
Combined savings	n/a	-0.9	n/a	-0.5	n/a	-0.2	n/a	-0.1
Residence: Row-House								
Base expenditure & demand	868	408	1555	705	868	408	1555	705
Savings								
Reflective roof savings	-2.3	-0.4	-9.3	-5.1	-0.3	-0.1	-0.6	-0.7
Shade tree savings	1.2	1.1	-2.9	-0.9	0.1	0.3	-0.2	-0.1
Wind shield savings	10.0	2.3	16.3	3.8	1.1	0.6	1.0	0.5
Indirect savings	-0.8	1.3	-11.6	-4.2	-0.1	0.3	-0.7	-0.6
Combined savings	8.2	4.3	-7.5	-6.3	0.9	1.0	-0.5	-0.9
Office								
Base expenditure & demand	929	475	1422	681	929	475	1422	681
Savings								
Reflective roof savings	29.5	10.3	22.9	5.1	3.2	2.2	1.6	0.7
Shade tree savings	48.5	17.5	40.8	10.9	5.2	3.7	2.9	1.6
Wind shield savings	0.8	3.1	7.4	8.1	0.1	0.6	0.5	1.2
Indirect savings	20.9	11.2	13.5	5.4	2.3	2.4	0.9	0.8
Combined savings	99.6	42.1	84.6	29.4	10.7	8.8	5.9	4.3
Retail Store								
Base expenditure & demand	802	338	1070	415	802	338	1070	415
Savings								
Reflective roof savings	40.7	13.0	36.0	8.6	5.1	3.9	3.4	2.1
Shade tree savings	35.6	13.2	35.5	12.3	4.4	3.9	3.3	3.0
Wind shield savings	2.1	3.3	11.6	9.4	0.3	1.0	1.1	2.3
Indirect savings	19.8	9.3	15.1	6.9	2.5	2.8	1.4	1.7
Combined savings	98.9	39.4	98.2	37.1	12.3	11.7	9.2	8.9

5. Air-Conditioned Roof Area Calculations

The stock of air-conditioned (a/c) residential, office and retail 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 persons residing in 1,488,370 households (STATCAN, 1996).

Residential

The total roof area for the stock of residences with a/c was calculated from integrating data from the following sources: Statistics Canada (STATCAN, 1996), ICLEI Energy Services (ICLEI, 1997), Natural Resources Canada (NRCAN, 2001a) and the Survey of Household Energy Use (NRCAN, 1995). 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 [6] was estimated to be 39.8Mm^2 (428Mft^2) (77% single-family, 20% row-house and 3% apartment) from elements [1–5] arranged in Equation 2 and highlighted in **Table 5.1**. Since the apartment accounted for only 3% of the total a/c roof area in the residential sector a DOE-2 prototype was not developed.

[1] The number of occupied private dwellings (households) by period of construction and structural type were obtained from Statistics Canada for the 1996 census (STATCAN, 1996). The total number of dwellings listed are 1,488,370 and those built through 1980 are 72% or 1,074,000 and from 1981–1996 is 28% or 414,400. The total number of single-family detached houses was 43% or 646,330, row-house multi-family units (listed as other) were 28% or 421,675 and apartments (five or more stories) were 28% or 419,750.

[2] The average floor area per dwelling unit was obtained from an analysis of housing in the city of Toronto for 1990 (ICLEI, 1997). The housing stock was disaggregated into single-detached, semi-detached, row-house and apartment units (apartments in mixed use were classified as row-house). For this analysis single- and semi-detached were combined into the category of single-family. The average floor area was listed as 128m^2 (1380ft^2), 97m^2 (1040ft^2) and 82m^2 (880ft^2) for the single-family, row-house and apartment dwellings, respectively. (Note that the average floor areas from NRCAN data are much larger.)

[3] The height of the building was identified from a statistical analysis of Natural Resources Canada data[§] (NRCAN, 2001a). The analysis shows that about 69.1% of buildings are single-family detached, 28.2% are row-houses, and 2.7% are double or attached houses. The number of stories of the houses was determined to be 1.8 for pre-1980 single-family, 2.0 for 1980+ single-family, 2.2 for pre-1980 row-house and 2.4 for 1980+ row-house. Apartments were assumed to be five story buildings.

[4] Air-conditioner equipment saturation for Ontario was found to be 46.5%, 64.1% for central a/c or heat pump units and 35.9% for window or room units (NRCAN, 1995). Also, the age of appliance was given to be 7.6 years for all air-conditioners, 6.9 years for central and 9.0 for window units. It was assumed that the single-family dwellings had only central a/c systems and the row-house/apartment dwellings had only window/room units.

§ Natural Resources Canada has conducted a survey and compiled characteristic data for 1361 houses in the Toronto metropolitan area. The building data collected included: construction year, floor area, building foot print area, heating furnace type, furnace efficiency, furnace fuel, domestic hot water type, efficiency, fuel, type of house (single-family detached, attached, row houses), ceiling insulation, foundation wall insulation, walls insulation, number of stories, total occupancy, plan shape, basement heating temperature, main floor heating temperature, volume of house, infiltration rate, existence of central ventilation, and annual electricity and gas consumption. The data provided to us did not explicitly show any information of windows and cooling systems.

[5] Natural gas was the dominant heating fuel and was surveyed in 86.0% of pre-1980 and 98.2% of 1980+ single-family homes, as well as 92.3% of pre-1980 and 46.5% of 1980+ row-houses. Similarly, electricity was surveyed in 6.2% of pre-1980 and 1.8% of 1980+ single-family homes, as well as 4.8% of pre-1980 and 53.5% of 1980+ row-houses (NRCAN, 2001a). Electricity is most likely used for electric resistance heaters and heat pumps. For the purpose of this analysis electric resistance heaters were considered exclusively in the row-house and apartment buildings.

[6] GTA A/C Roof Area $_{residence}$ [Mm^2] = [1] * [2] * [4] * [5] / [3] EQ. 2.

R-2000 residences were not included in the GTA calculations because so few have been built. Natural Resources Canada (NRCAN, 2001b) states that since the program began in 1982, 8000 R-2000 houses have been certified. The GTA with 12.6% of the 1996 Canadian population (STATCAN, 1996) would thus have only 1000 R-2000 houses, about a tenth of 1% of the total housing stock of the GTA.

Office and Retail

The total roof area for the stock of office buildings and retail stores with a/c were calculated for pre1980 and 1980+ construction vintag es from integrating data from the above residential sector estimates and from Konopacki *et al*. (1997). Office and retail air-conditioned roof area for the GTA [10] was estimated to be 5.3Mm^2 (57Mft^2) (1.9Mm^2 for offices and 3.4Mm^2 for retail stores) from elements [6–9] arranged in Equation 3 and highlighted in Table 5.2.

[6] GTA residential a/c roof area for each vintage from equation 1 in Mm^2.

[7] Konopacki *et al*. (1997) observed that the fraction of commercial to residential roof area was fairly constant when arranged by the general height of a city. Low-rise cities, such as the GTA, were found to have a fractional roof area (compared to the residential sector) of 4 and 7% for pre-1980 and 1980+ offices, and 10 and 5% for pre-1980 and 1980+ retail stores.

[8] Air-conditioner equipment saturation was not available; therefore, it was assumed to be 100% for both construction vintages, office and retail. This was also supported by Konopacki *et al*. (1997).

[9] Heating fuel type was not available; therefore, it was assumed to be 100% natural gas for both construction vintages, office and retail. This was also supported by Konopacki *et al*. (1997).

[10] GTA A/C Roof Area $_{office\_retail}$ [Mm^2] = [6] * [7] * [8] * [9] EQ. 3.

Table 5.1. Calculation of **air-conditioned roof area** [Mm^2] for residential buildings in the Greater Toronto Area.

	Pre-1980	1980+	Total	Source
1996 Population				
Persons [1000s]	-	-	4218	STATCAN, 1996
Residence: single-family				
[1] housing units [1000s]	466	180	646	STATCAN, 1996
[2] average floor area [m^2/hu]	-	-	128	ICLEI, 1997: table 1
[3] building height [fls/hu]	1.8	2	-	NRCAN, 2001a
[4] air-conditioner saturation [%]	-	-	68.7	Calculation
Central or heat pump	-	-	100	Assumption
[5] heating fuel [%]				
Natural gas	86	98.2	-	NRCAN, 2001a
Electricity	14	1.8	-	NRCAN, 2001a + Assumption
[6] **air-conditioned roof area** [Mm^2]				
W/ gas furnace	19.6	7.8	27.4	[1] * [2] * [4] * [5] / [3]
W/ heat pump	3.2	0.2	3.4	[1] * [2] * [4] * [5] / [3]
Total	22.8	8.0	30.8	
Residence: row-house				
[1] housing units [1000s]	305	117	422	
[2] average floor area [m^2/hu]	-	-	97	
[3] building height [fls/hu]	2.2	2.4	-	
[4] air-conditioner saturation [%]	-	-	44.1	
Window or room	-	-	100	
[5] heating fuel [%]				
Natural gas	92.3	46.5	-	
Electricity	7.7	53.5	-	
[6] **air-conditioned roof area** [Mm^2]				
W/ gas furnace	5.5	0.9	6.4	
W/ heat pump	0.5	1.1	1.6	
Total	6.0	2.0	8.0	
Residence: apartment				
[1] housing units [1000s]	303	117	420	
[2] average floor area [m^2/hu]	-	-	82	
[3] building height [fls/hu]	5	5	-	
[4] air-conditioner saturation [%]	-	-	14.8	
Window or room	-	-	100	
[5] heating fuel [%]				
Natural gas	92.3	46.5	-	
Electricity	7.7	53.5	-	
[6] **air-conditioned roof area** [Mm^2]				
W/ gas furnace	0.7	0.1	0.9	
W/ heat pump	0.1	0.2	0.2	
Total	0.8	0.3	1.1	
Residence: total				
[1] housing units [1000s]	1074	414	1488	
[2] average floor area [m^2/hu]	-	-	94	
[4] air-conditioner saturation [%]	-	-	46.5	NRCAN, 1995
Central or heat pump	-	-	64.1	NRCAN, 1995
Window or room	-	-	35.9	NRCAN, 1995
[6] air-conditioned roof area [Mm^2]				
W/ gas furnace	25.7	8.8	34.5	Σ [6] single-family_row-house_apartment
W/ heat pump	3.7	1.4	5.1	Σ [6] single-family_row-house_apartment
Total	**29.4**	**10.2**	**39.6**	

Table 5.2. Calculation of **air-conditioned roof area** [Mm^2] for office and retail buildings in the Greater Toronto Area.

	Pre-1980	1980 +	Total	Source
Office				
[7] fraction of residence total roof area [%]	4	7	-	Konopacki *et al*., 1997
[8] air-conditioner saturation [%]	-	-	100	Konopacki *et al*., 1997 + Assumption
[9] heating fuel [%]				
Natural gas	-	-	100	Konopacki *et al*., 1997 + Assumption
Electricity	-	-	0	Konopacki *et al*., 1997 + Assumption
[10] **air-conditioned roof area** [Mm^2]				
w/ gas furnace	**1.2**	**0.7**	**1.9**	[6] $_{\text{residence: total}}$ * [7] * [8] * [9]
w/ heat pump	**-**	**-**	**-**	[6] $_{\text{residence: total}}$ * [7] * [8] * [9]
Total	**1.2**	**0.7**	**1.9**	
retail store				
[7] fraction of residence total roof area [%]	10	5	-	
[8] air-conditioner saturation [%]	-	-	100	
[9] heating fuel [%]				
Natural gas	-	-	100	
Electricity	-	-	0	
[10] **air-conditioned roof area** [Mm^2]				
w/ gas furnace	**3.0**	**0.5**	**3.5**	
w/ heat pump	**-**	**-**	**-**	
Total	**3.0**	**0.5**	**3.5**	

6. Estimates of Savings for the Greater Toronto Area

The potential metropolitan-wide benefits of Heat Island Reduction (HIR) strategies (i.e., shade trees, reflective roofs, reflective pavements and urban vegetation) in the GTA for residential, office and retail buildings with air-conditioning were estimated in the forms of annual energy savings, annual electricity savings, annual natural gas deficit, peak power avoided and annual carbon reduction.

The Greater Toronto Area has a population of over 4.2 million with nearly 1.5 million households and is situated inland, on the northwestern edge of Lake Ontario. The Toronto summer is hot and brief with a May through September cooling season, and the winter is cold from November through March (Average summer peak temperature is 34°C and average winter minimum temperature is –24°C. Typically, there are about 320 cooling degree-days and 4200 heating degree-days base 18.3°C). Most residential buildings are two story and commercial buildings are low-rises. The saturation of air-conditioning is high in both residential and commercial buildings. The total roof area of residential, office and retail buildings with air-conditioning was 40, 1.9 and 3.5Mm^2, respectively, and 75% built prior to 1980.

Metropolitan-wide annual electricity savings [GWh], annual natural gas deficit [PJ], and peak power avoided [MW] are presented in **Table 6.1** for residences, office buildings, retail stores, and the total for each HIR strategy. Metropolitan-wide estimates of annual energy savings [M$] were calculated for residences, office buildings and retail stores. The estimates were obtained by combining the simulated energy and power savings from HIR strategies by the total air-conditioned roof area for each building type in the GTA. These results are presented in **Table 6.2(a, b)** with two prices for residential gas for each prototype by vintage and system type (i.e., for old and new building constructions and for gas and electric heat).

With uniform gas prices for commercial and residential buildings, annual electricity savings of \$12.6M less a 10% natural gas deficit combine for a potential ratepayer benefit of over \$11M. Of that total, about 88% was from the direct impact roughly divided equally among reflective roofs, shade trees and wind-shielding, and the remainder (12%) from the indirect impact of the cooler ambient air temperature. The residential sector accounts for over half (about 59%) of the total, offices 13% and retail stores 27%. Savings from cool roofs were about 20%, shade trees 30%, wind-shielding of tree 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 \$10M; about 78% resulted from wind-shielding, 16% from shading by trees, and 5% from cool roofs.

Potential annual electricity savings were estimated at about 150GWh or over \$12M, of which about 75% accrued from roofs and shade trees and only 2% from wind-shielding. The indirect effect from a modified urban fabric 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 \$1–2M, with actual savings of over \$4–8M from wind-shielding and a combined penalty of under \$3–7M. Residences accounted for about 94% of the gas deficit since these commercial buildings require very little heating.

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

Table 6.1. The Greater Toronto Area estimates of cooling and heating annual energy savings and avoided peak power from heat-island reduction strategies for residential and commercial buildings. Direct savings are from the use of solar-reflective roofs, strategic placement of deciduous shade trees and wind-shielding vegetation. Indirect savings include the effect of reduced ambient air temperature from a modified urban fabric.

Building type	Gas heat				Electric heat		Gas & electric heat	
&	Electricity (GWh)		Gas (PJ)		Electricity (GWh)		Peak power (MW)	
Mitigation strategy	Pre-1980	1980+	Pre-	1980+	Pre-	1980+	Pre-1980	1980+
Residence: Single-Family								
Base expenditure & 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								
Base expenditure & 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								
Base expenditure & 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								
Base expenditure & 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								
Base expenditure & 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								
Base expenditure & 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 6.2a. 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 (residential gas price of $5.54/GJ). Direct savings are from the use of solar-reflective roofs, strategic placement of deciduous shade trees and wind-shielding vegetation. Indirect savings include the effect of reduced ambient air temperature from a modified urban fabric.

Building type & Mitigation strategy	Annual energy and savings (M$) Gas heat Pre-1980	Gas heat 1980+	Electric heat Pre-1980	Electric heat 1980+	Total (M$)
Residence: Single-Family					
Base expenditure & demand	99	25	39	1	165
Savings					
Reflective roof savings	0.5	0.1	-0.2	0.0	0.5
Shade tree savings	1.1	0.2	-0.1	0.0	1.2
Wind shield savings	2.3	0.3	1.0	0.0	3.6
Indirect savings	0.5	0.1	-0.3	0.0	0.4
Combined savings	4.4	0.7	0.5	0.0	5.6
Apartment					
Base expenditure & demand	3	0	1	1	6
Savings					
Reflective roof savings	0.0	0.0	0.0	0.0	0.0
Shade tree savings	0.0	0.0	0.0	0.0	0.0
Wind shield savings	0.0	0.0	0.0	0.0	0.1
Indirect savings	0.0	0.0	0.0	0.0	0.0
Combined savings	0.1	0.0	0.0	0.0	0.1
Residence: Row-House					
Base expenditure & demand	27	2	7	8	45
Savings					
Reflective roof savings	0.2	0.0	0.0	-0.1	0.1
Shade tree savings	0.3	0.0	0.0	0.0	0.3
Wind shield savings	0.2	0.0	0.1	0.0	0.4
Indirect savings	0.2	0.0	-0.1	0.0	0.1
Combined savings	0.9	0.1	0.0	-0.1	0.9
Office					
Base expenditure & demand	11	4	0	0	15
Savings					
Reflective roof savings	0.4	0.1	0.0	0.0	0.4
Shade tree savings	0.6	0.1	0.0	0.0	0.7
Wind shield savings	0.0	0.0	0.0	0.0	0.0
Indirect savings	0.3	0.1	0.0	0.0	0.3
Combined savings	1.2	0.3	0.0	0.0	1.5
Retail Store					
Base expenditure & demand	24	2	0	0	26
Savings					
Reflective roof savings	1.2	0.1	0.0	0.0	1.3
Shade tree savings	1.1	0.1	0.0	0.0	1.1
Wind shield savings	0.1	0.0	0.0	0.0	0.1
Indirect savings	0.6	0.1	0.0	0.0	0.6
Combined savings	2.9	0.2	0.0	0.0	3.1
All Buildings					
Base expenditure & demand	164	33	48	10	256
Savings					
Reflective roof savings	2.3	0.3	-0.2	-0.1	2.3
Shade tree savings	3.1	0.4	-0.1	0.0	3.4
Wind shield savings	2.6	0.4	1.1	0.1	4.2
Indirect savings	1.6	0.3	-0.3	-0.1	1.4
Combined savings	9.6	1.3	0.5	-0.1	11.3

Table 6.2b. 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 (residential gas price of $10.84/GJ). Direct savings are from the use of solar-reflective roofs, strategic placement of deciduous shade trees and wind-shielding vegetation. Indirect savings include the effect of reduced ambient air temperature from a modified urban fabric.

Building type & Mitigation strategy	Annual energy and savings (M$)				Total (M$)
	Gas heat		Electric heat		
	Pre-1980	1980+	Pre-1980	1980+	
Residence: Single-Family					
Base expenditure & demand	176	46	39	1	262
Savings					
Reflective roof savings	-0.5	-0.1	-0.2	0.0	-0.7
Shade tree savings	0.1	-0.2	-0.1	0.0	-0.2
Wind shield savings	4.9	0.8	1.0	0.0	6.8
Indirect savings	-0.3	-0.1	-0.3	0.0	-0.7
Combined savings	4.2	0.5	0.5	0.0	5.1
Apartment					
Base expenditure & demand	6	0	1	1	9
Savings					
Reflective roof savings	0.0	0.0	0.0	0.0	0.0
Shade tree savings	0.0	0.0	0.0	0.0	0.0
Wind shield savings	0.1	0.0	0.0	0.0	0.1
Indirect savings	0.0	0.0	0.0	0.0	0.0
Combined savings	0.1	0.0	0.0	0.0	0.0
Residence: Row-House					
Base expenditure & demand	48	4	7	8	66
Savings					
Reflective roof savings	-0.1	0.0	0.0	-0.1	-0.2
Shade tree savings	0.1	0.0	0.0	0.0	0.1
Wind shield savings	0.5	0.0	0.1	0.0	0.7
Indirect savings	0.0	0.0	-0.1	0.0	-0.1
Combined savings	0.4	0.0	0.0	-0.1	0.4
Office					
Base expenditure & demand	11	4	0	0	15
Savings					
Reflective roof savings	0.4	0.1	0.0	0.0	0.4
Shade tree savings	0.6	0.1	0.0	0.0	0.7
Wind shield savings	0.0	0.0	0.0	0.0	0.0
Indirect savings	0.3	0.1	0.0	0.0	0.3
Combined savings	1.2	0.3	0.0	0.0	1.5
Retail Store					
Base expenditure & demand	24	2	0	0	26
Savings					
Reflective roof savings	1.2	0.1	0.0	0.0	1.3
Shade tree savings	1.1	0.1	0.0	0.0	1.1
Wind shield savings	0.1	0.0	0.0	0.0	0.1
Indirect savings	0.6	0.1	0.0	0.0	0.6
Combined savings	2.9	0.2	0.0	0.0	3.1
All Buildings					
Base expenditure & demand	273	57	48	10	388
Savings					
Reflective roof savings	0.8	0.0	-0.2	-0.1	0.5
Shade tree savings	1.7	0.0	-0.1	0.0	1.6
Wind shield savings	5.8	0.9	1.1	0.1	7.9
Indirect savings	0.4	0.0	-0.3	-0.1	0.0
Combined savings	8.7	1.0	0.5	-0.1	10.1

7. Discussion

This analysis included the direct and indirect effects of three heat-island reduction measures (shade trees, reflective roofs, and reflective paved surfaces) on heating- and cooling-energy use of several prototypical residential and commercial buildings. The prototypical savings were then extrapolated to obtain savings potentials for the Greater Toronto Area. 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 –$ penalties in heating-energy use) is 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 currently underestimates 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 saving potentials were only a small fraction of total potential savings. Hence, for energy saving potentials consideration, reflective roofs and shade trees that save energy both directly and indirectly should be given a higher priority than reflective pavements that only save energy indirectly.

8. Conclusion

In this study, we have investigated 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. The impact of both direct effect (reducing heat gain through the building shell) and indirect effect (reducing the ambient air temperature) was addressed.

To perform this analysis, we identified three building types that offer the most savings potential: residence (single-family and row-house), office and retail store. Each building type was characterized in detail by pre-1980 (old) or 1980+ (new) construction vintage and with natural gas or electricity as heating fuel. We defined prototypical characteristics for each building type and simulated the impact of HIR strategies on building cooling and heating energy use and peak-power demand using the DOE-2.1E model and Toronto WYEC2 weather data. Our simulations included the impact of HIR strategies outlined below.

A. Use of solar-reflective roofing material on building [*direct effect*].

B. Placement of deciduous shade trees near south and west walls of building [*direct effect*].

C. Placement of coniferous wind-shielding vegetation near building [*direct effect*].

D. Urban reforestation with reflective building surfaces and pavements *[indirect effect*].

E. Combination of strategies A through D [*direct and indirect effects*].

We then estimated the total roof area of air-conditioned residential, office and retail buildings in the GTA to scale the energy simulations in order to calculate the metropolitan-wide impact of HIR strategies.

Toronto is a metropolitan area of over 4.2 million with nearly 1.5 million households and is situated inland, on the northwestern edge of Lake Ontario. The Toronto summer is hot and brief with a May through September cooling season, and the winter is cold from November through March (Average summer peak temperature is 34°C and average winter minimum temperature is –24°C. Typically, there are about 320 cooling degree-days and 4200 heating degree-days base 18.3°C). Most residential buildings are one story and commercial buildings are low-rises. The saturation of air-conditioning is high in both residential and commercial buildings. The total roof area of residential, office and retail buildings with air-conditioning was 428, 20 and 37Mft^2, respectively, and 75% built prior to 1980.

The simulations predicted annual total energy savings of about 3–5% from combined direct and indirect effects for old $17–22\$/100\text{m}^2$ and new $9\$/100\text{m}^2$ gas-heated single-family and row-house residences. This number increased to 10% for offices [$40\$/100\text{m}^2$ for new and $100\$/100\text{m}^2$ for old] and 12% for retail stores [$40\$/100\text{m}^2$ for new and $100\$/100\text{m}^2$ for old]. Electric-heated units did not fair so well, where savings of 0–2% were observed for residences and 5–9% for offices and retail stores because the electric heating penalty is more expensive than that of gas.

As expected, an annual natural gas deficit was found for all building types and in each HIR mitigation strategy with the exception of wind-shielding, since this measure reduces the heating requirements of a building. The annual gas deficit for combined direct and indirect effects was $2–6\$/100\text{m}^2$ for residences,$11–12\$/100\text{m}^2$ for offices and only $0–3\$/100\text{m}^2$ for retails.

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 retails. This translates into $0.57–0.61\text{kW}/100\text{m}^2$ for pre-1980 residences, $0.33–0.40\text{kW}/100\text{m}^2$ for 1980+ residences, $0.60–1.13\text{kW}/100\text{m}^2$ for old and new offices, and $0.36–0.71\text{kW}/100\text{m}^2$ for old and new retails.

The potential metropolitan-wide benefits assume the full implementation of HIR measures and were calculated in the form of annual energy savings [M$], annual electricity savings [GWh & M$], annual natural gas deficit [PJ & M$], and avoided peak power [MW].

The potential metropolitan-wide benefits assume full implementation of HIR measures and were calculated in the form of annual energy savings [M$], annual electricity savings [GWh & M$], annual natural gas deficit [PJ & M$], and avoided peak power [MW].

Results show potential annual energy savings of over $11M (with uniform residential and commercial electricity and gas prices of $0.084/kWh and $5.54/GJ) could be realized by ratepayers from the combined direct and indirect effects of HIR strategies. Of that total, about 88% was from the direct impact roughly divided equally among reflective roofs, shade trees and wind-shielding, and the remainder (12%) from the indirect impact of the cooler ambient air temperature. The residential sector accounts for over half (about 59%) of the total, offices 13% and retail stores 27%. Savings from cool roofs were about 20%, shade trees 30%, wind-shielding of tree 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 $10M; about 78% resulted from wind-shielding, 16% from shading by trees, and 5% from cool roofs.

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

The potential annual natural gas deficit was estimated to be over 0.23 PJ or just under $1–2M, with actual savings of over $4–8M from wind-shielding and a combined penalty of under $3–7M. Residences accounted for about 94% of the gas deficit since these commercial buildings require very little heating.

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

By their nature, the results of this study are preliminary. The objective of the project was to perform a preliminary analysis and to develop a database of potential energy and peak-demand savings from the implementation of heat-island-reduction technologies (i.e., cool roofs, shade trees, and cool pavements). To perform such a study, we focused on three building types (residential, office, and retail) that offer the highest potential savings for the GTA. We focused on these three building types primarily because they constitute over 90% of the floor area of the total building stock in the GTA. The 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 of additional savings for the entire metropolitan Toronto.

References

Akbari, H., A. Rosenfeld, and H. Taha. 1990. "Summer Heat Islands, Urban Trees, and White Surfaces," *ASHRAE Transactions*, 96(1).

Akbari, H. and H. Taha. 1992. "The Impact of Trees and White Surfaces on Residential Heating and Cooling Energy Use in Four Canadian Cities." *Energy* 17:141–150.

Akbari, H., S. Bretz, D. Kurn and J. Hanford. 1997a. "Peak Power and Cooling Energy Savings of High-Albedo Roofs." *Energy and Buildings* 25:117–126.

Akbari, H., D. Kurn, S. Bretz and J. Hanford. 1997b. "Peak Power and Cooling Energy Savings of Shade Trees." *Energy and Buildings* 25:139–148.

Akbari, H., S. Konopacki, C. Eley, B. Wilcox, M. Van Geem and D. Parker. 1998. "Calculations for Reflective Roofs in Support of Standard 90.1." *ASHRAE Transactions* 104(1):984–995.

Akbari, H. and L. Rainer. 2000. "Measured Energy Savings from the Application of Reflective Roofs in 3 AT&T Regeneration Buildings." Lawrence Berkeley National Laboratory Report LBNL-47075. Berkeley, CA.

Akbari, H., M. Pomerantz and H. Taha. 2001 "Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas." *Solar Energy* 70(3):295–310.

Akridge, J. 1998. "High-Albedo Roof Coatings—Impact on Energy Consumption." *ASHRAE Technical Data Bulletin* 14(2).

Boutwell, C. and Y. Salinas. 1986. "Building for the Future—Phase I: An Energy Saving Materials Research Project." Oxford: Mississippi Power Co., Rohm and Haas Co. and the University of Mississippi.

Bretz, S. and H. Akbari. 1997. "Long-Term Performance of High-Albedo Roof Coatings." *Energy and Buildings* 25:159–167.

Building Energy Simulation Group (BESG). 1990. "Overview of the DOE-2 Building Energy Analysis Program, Version 2.1D." Lawrence Berkeley National Laboratory Report LBL-19735, Rev. 1. Berkeley, CA.

Cool Roofing Materials Database (CRMD). 2001. http://eetd.lbl.gov/coolroof. Lawrence Berkeley National Laboratory. Berkeley, CA.

Energy Information Administration (EIA). 1997. DOE/EIA-0383(97) *Annual Energy Outlook 1997*. Tables A8 and A19. Washington, DC.

Gartland, L., S. Konopacki and H. Akbari. 1996. "Modeling the Effects of Reflective Roofing." *ACEEE Summer Study on Energy Efficiency in Buildings* 4:117–124. Pacific Grove, CA.

Grell, G., J. Dudhia and D. Stauffer. 1994. "A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)." National Center for Atmospheric Research Technical Note NCAR/TN-398 + STR. Boulder, CO.

Henderson, H. 1998. "Part Load Curves for Use in DOE-2." Draft report prepared for Lawrence Berkeley National Laboratory and Florida Solar Energy Center. CDH Energy Corp. Cazenovia, NY. January 16, 1998.

Hildebrandt, E., W. Bos and R. Moore. 1998."Assessing the Impacts of White Roofs on Building Energy Loads" *ASHRAE Technical Data Bulletin* 14(2).

International Council for Local Environmental Initiatives Energy Services (ICLEI). 1997. "Realizing Toronto's Target for Greenhouse Gas Emission Reductions – Current Trends and Outlook." Torrie Smith Associates. Toronto, Ontario.

International Council for Local Environmental Initiatives Energy Services (ICLEI). 2001. "Summary Report Opportunities for Budget Cost Savings in the City of Toronto's Corporate Facilities – Technical Reference: Data and Analysis." Toronto, Ontario.

Jessup, P. 2000. Private communication. Toronto Atmospheric Fund, Toronto, Canada.

Konopacki, S., H. Akbari, M. Pomerantz, S. Gabersek and L. Gartland. 1997. "Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas." Lawrence Berkeley National Laboratory Report LBNL-39433. Berkeley, CA.

Konopacki, S., H. Akbari, L. Gartland and L. Rainer. 1998. "Demonstration of Energy Savings of Cool Roofs." Lawrence Berkeley National Laboratory Report LBNL-40673. Berkeley, CA.

Konopacki, S. and H. Akbari. 1998a. "Simulated Impact of Roof Surface Solar Absorptance, Attic, and Duct Insulation on Cooling and Heating Energy Use in Single-Family New Residential Buildings." Lawrence Berkeley National Laboratory Report LBNL-41834. Berkeley, CA.

Konopacki, S. and H. Akbari. 1998b. "Demonstration of Energy Savings of Cool Roofs: Phase II." Lawrence Berkeley National Laboratory—Heat Island Group Technical Note. Berkeley, CA.

Konopacki, S. and H. Akbari. 2000. "Energy Savings Calculations for Heat Island Reduction Strategies in Baton Rouge, Sacramento and Salt Lake City." Lawrence Berkeley National Laboratory Report LBNL-42890. Berkeley, CA.

Konopacki, S. and H. Akbari. 2001. "Measured Energy Savings and Demand Reduction from a Reflective Roof Membrane on a Large Retail Store in Austin." Lawrence Berkeley National Laboratory Report LBNL-47149. Berkeley, CA.

Ligeti, E. 2002. Private communication. Obtained copy of electricity and gas utility bills for a single-family residence. Toronto Atmospheric Fund, Toronto, Canada.

National Appliance Energy Conservation Act of 1987 (NAECA). 1987. DOE Publication. www.eren.doe.gov/buildings/codes_standards/notices/pdfs/furn_boiler_notice.pdf. U.S. Department of Energy, Washington, D.C.

Natural Resources Canada (NRCAN). 1995. "1993 Survey of Household Energy Use." Energy Publications. Ottawa, Ontario.

Natural Resources Canada (NRCAN). 2001a. "Toronto Survey of 1361 Homes." Office of Energy Efficiency, Ottawa, Ontario.

Natural Resource Canada (NRCAN). 2001b. "R-2000 Program." Office of Energy Efficiency. http://oee.nrcan.gc.ca/english/newhouses_r2000.cfm.

Parker, D., J. Sonne and J. Sherwin. 1997. "Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Retail Strip Mall." Florida Solar Energy Center Report FSEC-CR-964-97. Cocoa, Fl.

Parker, D., J. Huang, S. Konopacki, L. Gartland, J. Sherwin and L. Gu. 1998a. "Measured and Simulated Performance of Reflective Roofing Systems in Residential Buildings." ASHRAE Transactions 104(1):963–975.

Parker, D., J. Sherwin and J. Sonne. 1998b. "Measured Performance of a Reflective Roofing System in a Florida Commercial Building." *ASHRAE Technical Data Bulletin* 14(2).

Parker, D. and K. Sheinkopf. 1999. "Cool Home Features Bring Peak Energy Savings." *Home Energy* 16:22–27.

Sherman, M., D. Wilson and D. Kiel. 1986. "Variability in Residential Air Leakage." *Measured Air Leakage in Buildings ASTM STP-904*. Philadelphia, PA.

Statistics Canada (STATCAN). 1996. http://www.statcan.ca.

Taha, H., S. Konopacki and S. Gabersek. 1996. "Modeling the Meteorological and Energy Effects of Urban Heat Islands and Their Mitigation: a 10 Region Study." Lawrence Berkeley National Laboratory Draft Report LBNL-39335. Berkeley, CA.

Taha, H., S.C. Chang, and H. Akbari. 2002. "Air Quality Impacts of Heat Island Reduction Strategies in Toronto, Canada." Lawrence Berkeley National Laboratory Draft Report LBNL-49210. Berkeley, CA.

Toronto Hydro Electric System (THES). 2001. "Rates." www.torontohydro.com/ electricsystem/business/rates.htm. www.torontohydro.com/electricsystem/residential/rates.htm

U.S. Department of Energy (U.S.DOE). 2001. "Choosing or Upgrading Your Central Air-conditioner." Office of Building Technology, State and Community Programs." http://www.eren.doe.gov/buildings/heatcool_cenair.html.

Winklemann, F., B. Birdsall, W. Buhl, K. Ellington and A. Erdem. 1993. "DOE-2 Supplement Version 2.1E." Lawrence Berkeley National Laboratory Report LBNL-34947. Berkeley, CA.

Appendix A. Building Information Data Sources

We contacted various agencies and individuals in regards to obtaining building data for the Greater Toronto area. In general, obtaining detailed building characteristics data proved to be more difficult than anticipated. Two sources provided detailed data for the housing sector. To date, we have not identified any relevant data for the commercial sector in Toronto.

Natural Resources Canada (NRCAN, 2001a) has conducted a survey and compiled characteristic data for 1361 houses in the Greater Toronto Area. The building data collected included: construction year, floor area, building foot print area, heating furnace type, furnace efficiency, furnace fuel, domestic hot water type, efficiency, fuel, type of house (single-family detached, attached, row-houses), ceiling insulation, foundation wall insulation, walls insulation, number of stories, total occupancy, plan shape, basement heating temperature, main floor heating temperature, volume of house, infiltration rate, existence of central ventilation, and annual electricity and gas consumption. The data provided to us does not explicitly show any information of windows and cooling systems; we have contacted NRCAN regarding this additional data.

We performed a statistical analysis of the NRCAN data; the results are summarized in **Table A.1**. NRCAN database shows that about 69.1% of buildings are single-family detached, 28.2% are row houses, and 2.7% are double or attached houses. These data clearly support development of two prototypes of single-family detached and row houses. In addition, 87.1% of houses are heated with gas, 7.8% with electricity, and 5.1% with oil. About 16.9% of houses are single-story, 60.6% two stories, and 20.5% two and a half or three stories. Finally, 97.9% of buildings have no mechanical ventilation systems.

The integrity and insulation level in houses varies with age (see **Figure A.1**). It appears that most houses have lower insulation both on ceilings and walls prior to 1970s. We partitioned the data for Pre-1980 and 1980+ for an analysis of housing insulation. Indeed, the average roof and wall insulation for the 1980+ period is larger than the Pre-1980 period. We also observe that the infiltration rate (as measured by Air Change per Hour, ACH) is much lower for 1980+ than Pre-1980, indicating better-built and tighter houses. The heating furnace efficiency is also higher for 1980+ than Pre-1980 period. Most houses are heated with gas, except 1980+ row houses that are about 50% heated with gas and 50% electricity.

Another data source for residential buildings was Akbari *et al.* (1992). This study analyzed and estimated the impact of trees and reflective roofs on residential heating and cooling energy use in four Canadian cities. The study also summarized detailed building characteristics data for single-family one-story detached houses, single-family two-story detached houses, single-family one-story detached R-2000 houses, single-family two-story detached R-2000 houses, two-story row houses, and two-story R-2000 row houses. The characteristics of these prototypes are listed in **Tables A.2–4**.

The building characteristic data available from NRCAN database and Akbari *et al.* (1992) are sufficient to define prototypical-building description. The prototypes to be developed will include: single-family detached houses (old and new), row houses (old and new), and a R-2000 home. To date, we have been able to locate no specific information for characteristics of commercial buildings in Toronto. Previous research, focused on estimating the impact of reflective roofs in eleven U.S. metropolitan areas, has shown that offices (new and old) and retail stores (new and old) offer the greatest potential cooling energy savings (Konopacki *et al.,* 1997). For this study, we intend to focus on collecting data primarily for these two building types.

Table A.1. Housing characteristics in the Greater Toronto Area (Source: NRCAN, 2001a).

Parameter	Single-Family Houses All	Single-Family Houses Pre-1980	Single-Family Houses 1980+	Row-Houses All	Row-Houses Pre-1980	Row-Houses 1980+
Year Built	1951	1943	1989	1935	1924	1984
Floor Area (m^2)	292	272	382	183	189	159
Footprint (m^2)	97	93	113	53	55	45
Furnace SS Eff (%)	82	82	85	83	81	92
DHW Energy Fac	0.60	0.61	0.58	0.61	0.59	0.70
Ceiling Ins (K.m2/W)*	3.70	3.42	4.99	2.73	2.24	4.92
Fnd Wall Ins (K.m2/W)	1.01	0.90	1.52	0.87	0.74	1.46
Main Wall Ins (K.m2/W)	1.46	1.23	2.48	1.42	1.13	2.71
Total Occupants	3.7	3.6	4.0	3.6	3.6	3.6
Temp Bsmt (C)	20.1	20.1	20.2	20.2	20.1	20.5
Temp Main (C)	21.0	21.0	21.1	21.0	20.9	21.2
Volume (m^3)	730	681	954	458	472	397
ACH @ 50 Pa	8.0	8.7	5.0	12.4	13.2	8.7
ELA @ 10 Pa (cm2)	2132	2218	1740	2197	2412	1249
Number of Stories						
% 1-story	23.0	27.4	2.9	3.1	3.8	0.0
% 1½ -stories	2.7	3.1	0.6	0.5	0.6	0.0
% 2-stories	59.6	53.0	89.4	63.5	63.9	62.0
% 2½ -stories:	5.4	6.6	0.0	5.7	6.7	1.4
% 3-stories	9.4	9.9	7.1	27.1	24.9	36.6
Heating Fuel						
% Natural Gas	88.2	86.0	98.2	83.9	92.3	46.5
% Oil	6.4	7.8	0.0	2.3	2.9	0.0
% Electricity	5.4	6.2	1.8	13.8	4.8	53.5
% Propane	0.0	0.0	0.0	0.0	0.0	0.0
% Wood	0.0	0.0	0.0	0.0	0.0	0.0
DHW Fuel						
% Natural Gas	83.0	80.8	92.9	81.8	90.1	45.1
% Oil	0.3	0.4	0.0	0.0	0.0	0.0
% Electricity	16.7	18.8	7.1	18.2	9.9	54.9
% Propane	0.0	0.0	0.0	0.0	0.0	0.0
% Wood	0.0	0.0	0.0	0.0	0.0	0.0

* To convert to British units multiply by 5.68.

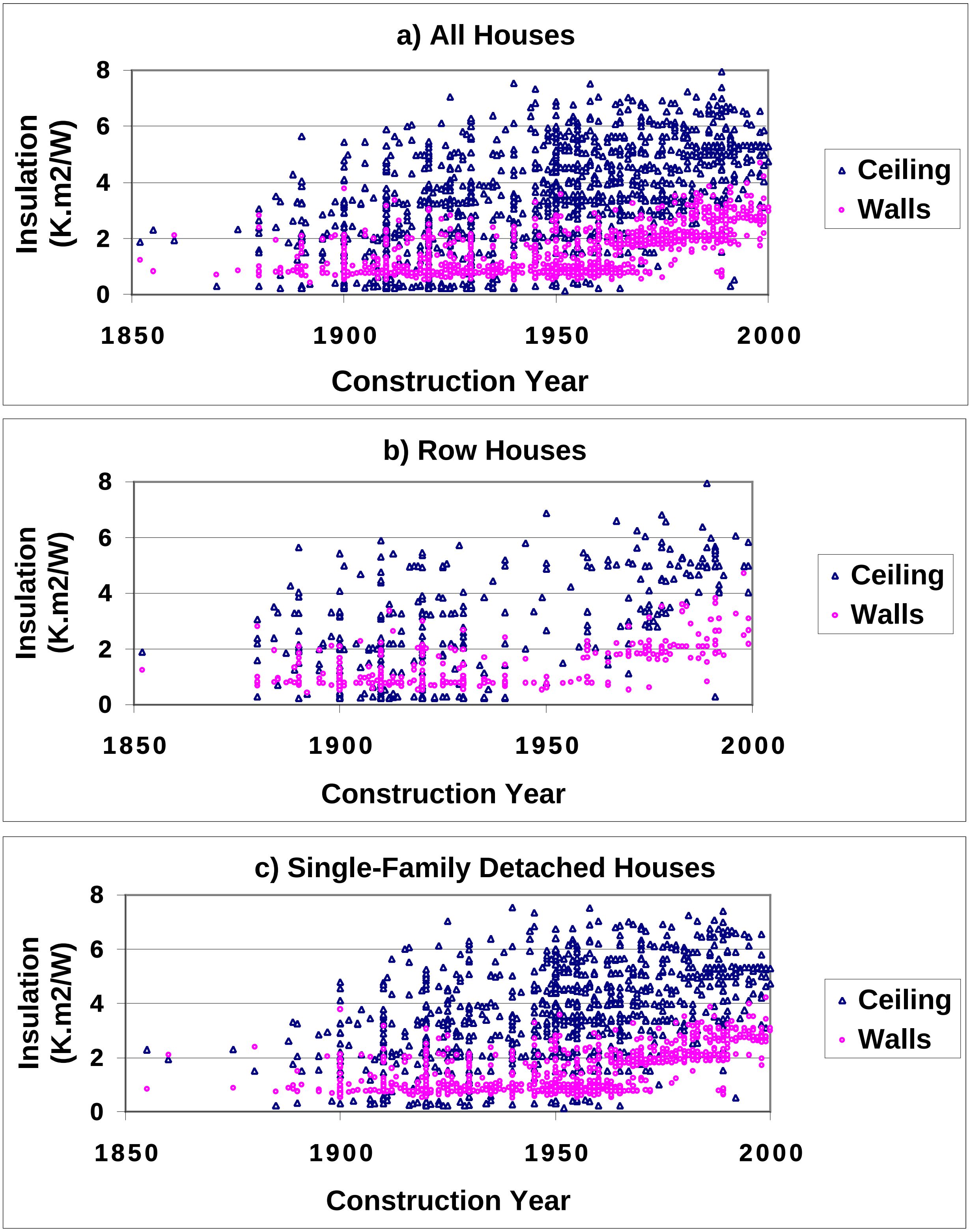

Figure A.1. Ceiling and wall insulation for a) all houses, b) row-houses, c) single-family-detached houses.

Table A.2. Building types (partly based on data from draft report 89-78-K, Ontario Hydro Research Division).

Type of building	Floor area (ft^2)	Foundation type	Exposed wall area (ft^2) [1]	Roof area (ft^2) [2]	Total window area (ft^2) [3]	Total door area (ft^2)	Number of stories	Wall perimeter length (ft)
Row- houses	1716	Full basement	956	946	108	35	2	118 (26x33)
Detached, one-story	1084	Full basement	1367	1200	100	35	1	134 (27.8x39)
Detached, two-story	2170	Full basement	2465	1200	215	35	2	134 (27.8x39)

1 This includes the areas of windows and exterior doors

2 This is the actual area of the gable (inclined) roof

3 Uniformly distributed on all exposed walls

Table A.3. Thermal integrity (partly based on data from draft report 89-78-K, Ontario Hydro Research Division).

Type of building	Roof ins. (R)	Exposed ceiling ins. (R)	Exterior walls ins. (R)	Windows (R)	Doors (R)	Basement walls (R)	Basement floor (R)	Infiltration/ ventilation
Existing(all-electric)	29	32	12	2 [4]	3.5 [5]	6 [6]	0.5	110 cfm
(gas-heated)	19	30	0	2 [4]	3.5 [5]	0	0	110 cfm
R-2000 (electric and gas)	40 [7]	32 [7]	20 [7, 8]	2 [7, 9]	4 [7]	12 [7, 10]	5	10 cfm/room [11]

4 Double glazing

5 Wood sash with storm

6 Average value

7 Instead of detailed envelope specification, the R-2000 code can be met by observing pre-set total annual energy targets in kWh/year (Source: House Wrap, Conference and Exhibition on Innovative Residential Building Products, Dec. 1988 EnerMark):

Windsor: 18700 Toronto: 19600 Ottawa: 20700 North Bay: 21900 Thunder Bay: 22700

Timmins: 23500 Moosones: 24900 Trout Lake: 26300

8 R-24 for Timmins and North

9 Double glazing (and R-2.6 for Timmins and North)

10 To floor

11 or < 0.45 ach (whichever is smaller). Additional requirements: leakage area = 1 $in^2/100\ ft^2$ (existing = 3 $in^2/100\ ft^2$).

Table A.4. Internal loads, equipment, and thermostat settings.

THERMOSTAT SETTING*:*

Heating thermostat setting: 21 ºC (night set back to 15.6 ºC, 11 pm through 7 am) Cooling thermostat setting: 25.5 ºC

INTERNAL LOAD*:*

3.2 people per house (time average) lights (~5.4 W/m^2)

HEATING AND COOLING EQUIPMENT

Houses under 180 m^2

- 75,000 Btu/h gas-furnace
- 36,000 Btu/h air-conditioner
- Maximum, electric heaters = 12 kW
- Maximum, other equipment = 0.5 kW

Houses over 180 m^2

- Two 75,000 Btu/h gas-furnaces
- Two 36,000 Btu/h air-conditioners
- Maximum, electric heaters = 18 kW
- Total, other equipment = 0.75 kW

EFFICIENCY*:*

Existing stock:gas furnace eff.: 60%

- Air-conditioner c.o.p: 2.17
- Electric resistance heater eff.: 100%

R-2000 stock: gas furnace eff.: 78%

- Air-conditioner c.o.p: 2.7
- Electric resistance heater eff.: 1 00%

HOT WATER HEATER:

40 gallons capacity (located in basement).