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Abstract

In 1997, the U.S. Environmental Protection Agency (EPA) established the "Heat Island Reduction Initiative" to quantify the potential benefits of Heat-Island Reduction (HIR) strategies (i.e., shade trees, reflective roofs, reflective pavements and urban vegetation) to reduce cooling-energy use in buildings, lower the ambient air temperature and improve urban air quality in cities, and reduce CO_2 emissions from power plants. Under this initiative, the Urban Heat Island Pilot Project (UHIPP) was created with the objective of investigating the potential of HIR strategies in residential and commercial buildings in three initial UHIPP cities: Baton Rouge, LA; Sacramento, CA; and Salt Lake City, UT. Later two other cities, Chicago, IL and Houston, TX were added to the UHIPP.

In an earlier report we summarized our efforts to calculate the annual energy savings, peak power avoidance, and annual CO_2 reduction obtainable from the introduction of HIR strategies in the initial three cities. This report summarizes the results of our study for Chicago and Houston. In this analysis, we focused on three building types that offer the highest potential savings: single-family residence, office and retail store. Each building type was characterized in detail by vintage and system type (i.e., old and new building constructions, and gas and electric heat). We used the prototypical building characteristics developed earlier 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. Our simulations included the impact of (1) strategically-placed shade trees near buildings [*direct effect*], (2) use of high-albedo roofing material on the building [*direct effect*], (3) urban reforestation with high-albedo pavements and building surfaces [*indirect effect*] and (4) combined strategies 1, 2, and 3 [*direct and indirect effects*]. We then estimated the total roof area of air-conditioned buildings in each city using readily obtainable data to calculate the metropolitan-wide impact of HIR strategies.

The results show that in Chicago, potential annual energy savings of $30M could be realized by ratepayers from the combined direct and indirect effects of HIR strategies. Additionally, peak power avoidance is estimated at 400 MW and the reduction in annual carbon emissions at 58 ktC. In Houston, the potential annual energy savings are estimated at $82M, with an avoidance of 730 MW in peak power and a reduction in annual carbon emissions of 170 ktC.

Acknowledgements

This work was supported by the U. S. Environmental Protection Agency under the Urban Heat Island Pilot Project (UHIPP) through the U. S. Department of Energy under contract DE-AC03-76SF00098. We acknowledge the support and guidance we received from Edgar Mercado, Eva Wong, and Jeanne Briskin of the EPA. The authors would like to thank Ronnen Levinson, Osman Sezgen, and Fred Winkelmann (LBNL) for their pre-publication reviews of this report.

Executive Summary

In 1997, the U.S. Environmental Protection Agency (EPA) 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 vegetation). The goals were to reduce cooling-energy use in buildings, lower the ambient air temperature, reduce CO_2 emissions from power plants, and improve air quality in urban areas. Under this initiative, entitled "The Heat Island Reduction Initiative," the EPA has been engaged in two major projects. The first is the Urban Heat Island Pilot Project (UHIPP), and the second is the Energy Star® Roof Products Program, a joint effort with the U.S. Department of Energy (DOE).

Project Objectives

The objective of the UHIPP is to investigate the use of HIR strategies for the reduction of cooling-energy use in buildings, and for the reduction of the ambient air temperature. Cooling the ambient air temperature has the additional benefit of reducing urban smog concentration, and hence improving urban air quality. In the initial phase of the UHIPP, three cities were selected: Baton Rouge, LA; Sacramento, CA; and Salt Lake City, UT. Later two other cities—Chicago, IL and Houston, TX—were added to UHIPP's list. Since the inception of the project, Lawrence Berkeley National Laboratory (LBNL) has conducted detailed studies to investigate the impact of HIR strategies on heating- and cooling-energy use of the three selected pilot cities. In addition, LBNL has collected urban surface characteristics data and conducted preliminary meteorology and urban smog simulations for the three pilot cities.

In an earlier report (Konopacki and Akbari, 2000), we summarized our efforts to calculate annual energy savings, peak power avoidance and annual CO_2 reduction obtainable from HIR strategies in Baton Rouge, Sacramento, and Salt Lake City. In this report, we extend the analysis to metropolitan Chicago and Houston. In these analyses, we focused on three major building types that offer the highest potential savings[*]: residence, office, and retail store. We have also updated the combined energy savings and the reduction in carbon emission for the other three cities.

This executive summary provides an overview of the results and analyses for all five cities. The body of this report, however, focuses on the more recent analyses for Chicago and Houston.

Methodology

To estimate the potential metropolitan-wide benefits of HIR strategies, a methodology was developed that incorporates readily obtainable data from building energy simulations, previous heat-island studies, and from the U.S. Census. The methodology consists of five parts:

1. define prototypical building characteristics in detail for old and new construction;
2. simulate annual energy use and peak power demand using the DOE-2.1E model;
3. determine direct and indirect energy savings from each HIR strategy;
4. identify the total roof area of air-conditioned buildings in each city; and

[*] These building types were selected based on an earlier detailed study of the direct energy-saving potential of highly reflective roofs in eleven U.S. metropolitan areas, which show that they account for over 90% of potential national energy savings in residential and commercial buildings (Konopacki *et al.,* 1997).

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

The building energy simulations are performed for a base case and four modified cases. The modified simulations include the impact of the following HIR strategies:

1. the *direct effect* on energy use of strategically-placed shade trees near building;
2. the *direct effect* on building energy use of using high-albedo roofing material;
3. the *indirect effect* on building energy use of ambient cooling (resulting from urban reforestation with highly reflective pavements and building surfaces); and
4. the combined strategies 1–3 [*direct and indirect effects*].

Results

The potential metropolitan-wide benefits of HIR strategies for all air-conditioned residential, office, and retail buildings are presented in **Table EX.1** and Figures **EX.1-3**. The estimates are in the forms of annual energy savings, annual electricity savings, annual natural gas deficit, peak power avoided, and annual carbon emissions reduction. Note that the following points should be considered when examining the results.

- Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential 0.5 and commercial 0.6).
- The conversion from giga Watt-hour (GWh) to carbon corresponds to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 tera Watt-hour (TWh) sold emitted 500 MtC (million metric tons of carbon). Thus, 1 GWh emits 167 tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm.

Baton Rouge is a metropolitan area of over 500,000 inhabitants and is situated inland, in southeastern Louisiana, where the climate is hot and humid, and with an April through October cooling season. 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 is 245, 13, and 18 Mft^2, respectively. The combined direct (85%) and indirect (15%) effects of HIR strategies can potentially yield ratepayer benefits of over $15M (79% residential; 6% office; 15% retail store) in total annual energy savings. This figure is derived from annual electricity savings of $18M minus a $3M natural gas deficit. Additionally, peak power avoidance is estimated at 135 MW (89%, 4%, and 7%) and the reduction in annual carbon emissions at 36 thousand tons of carbon (ktC) (79%, 6%, and 15%).

Chicago is a metropolitan area of over eight million inhabitants and is situated in northeastern Illinois on the edge of Lake Michigan. The climate is hot and humid in summer, with a cooling season from June through September. Most residential buildings are multi-story, and commercial buildings are a mix of low- and high-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 is 765, 120, and 124 Mft^2, respectively. The combined direct (82%) and indirect (18%) effects of HIR strategies can potentially yield ratepayer benefits of $30M (37% residential; 27% office; 36% retail store) in total annual energy savings. This figure is derived from annual electricity savings of $50M minus a $20M natural gas deficit. Additionally, peak power avoidance is estimated at 398 MW (63%, 22%, and 15%) and the reduction in annual carbon emissions at 58 ktC (28%, 31%, and 41%).

Houston is a metropolitan area of nearly four million inhabitants and is situated on the southeast gulf coast of Texas, where the climate is hot and humid, with a cooling season from May through October. 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 is 1228, 83, and 114 Mft^2, respectively. The combined direct (81%) and indirect (19%) effects of HIR strategies can potentially yield ratepayer benefits of $82M (79% residence, 7% office, and 14% retail store) in total annual energy savings. This figure is derived from annual electricity savings of $95M minus a $13M natural gas deficit. Additionally, peak power avoidance is estimated at 734 MW (83%, 7%, and 10%) and the reduction in annual carbon emissions at 170 ktC (76%, 8%, and 16%).

Sacramento is a metropolitan area of almost 1.5 million inhabitants and is situated inland, in the central valley of northern California, where the climate is hot and dry. The cooling season lasts from May through September. 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 is 648, 37, and 50 Mft^2, respectively. The combined direct (81%) and indirect (19%) effects of HIR strategies can potentially yield ratepayer benefits of $30M (51% residence, 16% office, and 32% retail store) in total annual energy savings. This figure is derived from annual electricity savings of $48M minus a $18M natural gas deficit. Additionally, peak power avoidance is estimated at 449 MW (84%, 6%, and 9%) and the reduction in annual carbon emissions at 59 ktC (49%, 17%, and 34%).

Salt Lake City is a metropolitan area of nearly 1.1 million inhabitants and is situated inland, in the high-desert terrain of northwestern Utah. The climate is hot and dry during the June through September cooling season, and cold during the long heating season, beginning in September and ending in May. Most residential buildings are one-story, and commercial buildings are low-rises. The saturation of air-conditioning is high in both residential (except in the older residences) and commercial buildings. The total roof area of residential, office, and retail buildings with air-conditioning is 120, 15, and 21 Mft^2, respectively. The combined direct (78%) and indirect (22%) effects of HIR strategies can potentially yield ratepayer benefits of $4M (11% residence, 31% office, and 58% retail store) in total annual energy savings. This figure is derived from annual electricity savings of $8M minus a $4M natural gas deficit. Additionally, peak power avoidance is estimated at 85 MW (65%, 17%, and 18%) and the reduction in annual carbon at 9 ktC (–4%, 37%, and 67%).

Of the overall annual energy savings for Baton Rouge, Chicago, Houston, Sacramento and Salt Lake City, savings from the indirect impact (cooler ambient air temperature) of HIR strategies were 15%, 18%, 19%, 19%, and 22%, respectively. Our climate simulations indicated a reduction in maximum air temperature of 2°F, 0°F, 2°F, 3°F, and 3°F, respectively, for these cities (Taha, 1996 and 1999b). The indirect savings potentials are a function of local climate and the possible degree of surface modification. For instance, the cooling seasons for Chicago, Sacramento, and Salt Lake City are fairly short, and the potential for ambient cooling by urban vegetation in Baton Rouge and Houston is limited because of their humid climates.

Discussion

Since roofs and shade trees offer a direct saving potential, from an energy-saving point of view programs should have highest priority that focus on reflective roofs and shade trees. However, when considering smog and air-quality issues, programs should have priority that focus on reflective surfaces (roofs and pavements) that can cool the ambient air in both humid and dry climate conditions. Urban trees also play a major role in directly sequestering CO_2 and thereby delaying global warming. A shade tree planted in an urban area avoids the combustion of carbon as well as sequestering carbon from atmosphere (as it would if growing in a forest). In this sense, a shade tree in urban area could be equivalent to several forest trees.

In this study, we use the average retail prices of electricity for end-users given in $/kWh. The prices include the charges for peak demand. It is not accurate to use such average prices if the shape of the savings does not match the shape of demand for the whole end-use class (as is the case for residential and commercial buildings). Measures considered in this report save energy when the marginal cost of electricity is highest, and heating penalties are incurred when the marginal cost of electricity is lowest. This means that by using a flat electricity rate to estimate savings we are underestimating the dollar benefits of the measures considered in this report.

If retail deregulation of electricity is not in effect the end-user is typically exposed to a tariff that most likely includes peak demand charges. Since the measures considered here save more during the hours when the peaks occur, the bill reduction will be more than a proportional decrease based on an average kWh price and the kWh savings. With retail deregulation, the customer can more easily benefit from the reductions in energy use during peak hours when the wholesale prices are highest, since a peak-reducing customer can select a supplier providing prices that are more tightly coupled with the wholesale market (more closely approximate real-time pricing).

Finally, for these five pilot cities, we have estimated a potential 1.8GW reduction in peak electric power demand. Typically, the peaking power plants are considered ‘dirty’ and they are a source of air pollution during the time that air quality is worst. The HIR measures have the added benefit of reducing the need for these polluting sources of power generation.

Table EX.1. Metropolitan-wide estimates of annual energy savings, peak power avoided, and annual carbon emissions reduction from Heat-Island Reduction strategies for residential and commercial buildings in Baton Rouge, Chicago, Houston, Sacramento and Salt Lake City. Direct savings are from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings, and indirect savings include the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

Metropolitan Area and HIR Strategy	Annual Energy [M$]	Annual Electricity [GWh]	Annual Electricity [M$]	Annual Natural Gas [Mtherm]	Annual Natural Gas [M$]	Peak Power [MW]	Annual Carbon [ktC]
Baton Rouge							
Base Case	114.8	1,275	92.8	30.7	21.9	858	257
Savings							
Direct shade tree	5.2	94	6.9	(2.4)	(1.7)	62	12
Direct high albedo	8.0	120	8.7	(1.0)	(0.7)	60	19
Indirect	2.3	39	2.8	(0.7)	(0.5)	13	6
Combined	15.5	253	18.4	(4.1)	(2.9)	135	36
Chicago							
Base case	879.4	3,505	293.4	804.3	586.0	3,456	1,749
Savings							
Direct shade tree	13.5	293	25.0	(15.6)	(11.4)	128	26
Direct high albedo	10.9	224	18.9	(11.0)	(8.1)	237	21
Indirect	5.4	65	5.6	(0.3)	(0.2)	33	10
Combined	29.8	582	49.5	(26.9)	(19.7)	398	58
Houston							
Base case	696.6	7,230	572.0	169.7	124.7	5,158	1,453
Savings							
Direct shade tree	27.8	421	34.3	(8.8)	(6.5)	247	58
Direct high albedo	38.3	523	42.0	(5.0)	(3.7)	269	80
Indirect	15.6	236	19.1	(4.7)	(3.5)	218	33
Combined	81.8	1,181	95.4	(18.5)	(13.6)	734	170
Sacramento							
Base case	296.2	2,238	185.9	162.2	110.3	2,454	608
Savings							
Direct shade tree	9.8	247	20.6	(15.8)	(10.7)	180	18
Direct high albedo	14.6	220	18.3	(5.5)	(3.8)	163	29
Indirect	5.9	114	9.5	(5.3)	(3.6)	106	11
Combined	30.3	581	48.4	(26.6)	(18.1)	449	59
Salt Lake City							
Base case	67.0	511	31.4	70.8	35.6	488	188
Savings							
Direct shade tree	1.1	52	3.3	(4.2)	(2.2)	33	3
Direct high albedo	1.8	45	2.8	(2.0)	(1.0)	32	5
Indirect	0.8	25	1.6	(1.6)	(0.8)	20	2
Combined	3.7	122	7.7	(7.8)	(4.0)	85	9

a) Metropolitan-wide annual energy savings [M$ = Million$], annual electricity savings [M$ and GWh = Giga Watt-hour], annual natural gas deficit [M$ and Mtherm = Million therms], peak power avoided [MW = Mega Watt] and annual carbon emissions reduction [kt = thousand tons].

b) The methodology consisted of the following: [1] define prototypical building characteristics in detail for old and new construction, [2] simulate annual energy use and peak power demand using the DOE-2.1E model, [3] determine direct and indirect energy benefits from high-albedo surfaces (roofs and pavements) and trees, [4] identify the total roof area of air-conditioned buildings in each city, and [5] calculate the metropolitan-wide impact of HIR strategies.

c) Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

d) The conversion from GWh to carbon corresponds to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 TWh sold emitted 500 MtC (million metric tons of carbon); thus, 1 GWh emits 167 tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm.

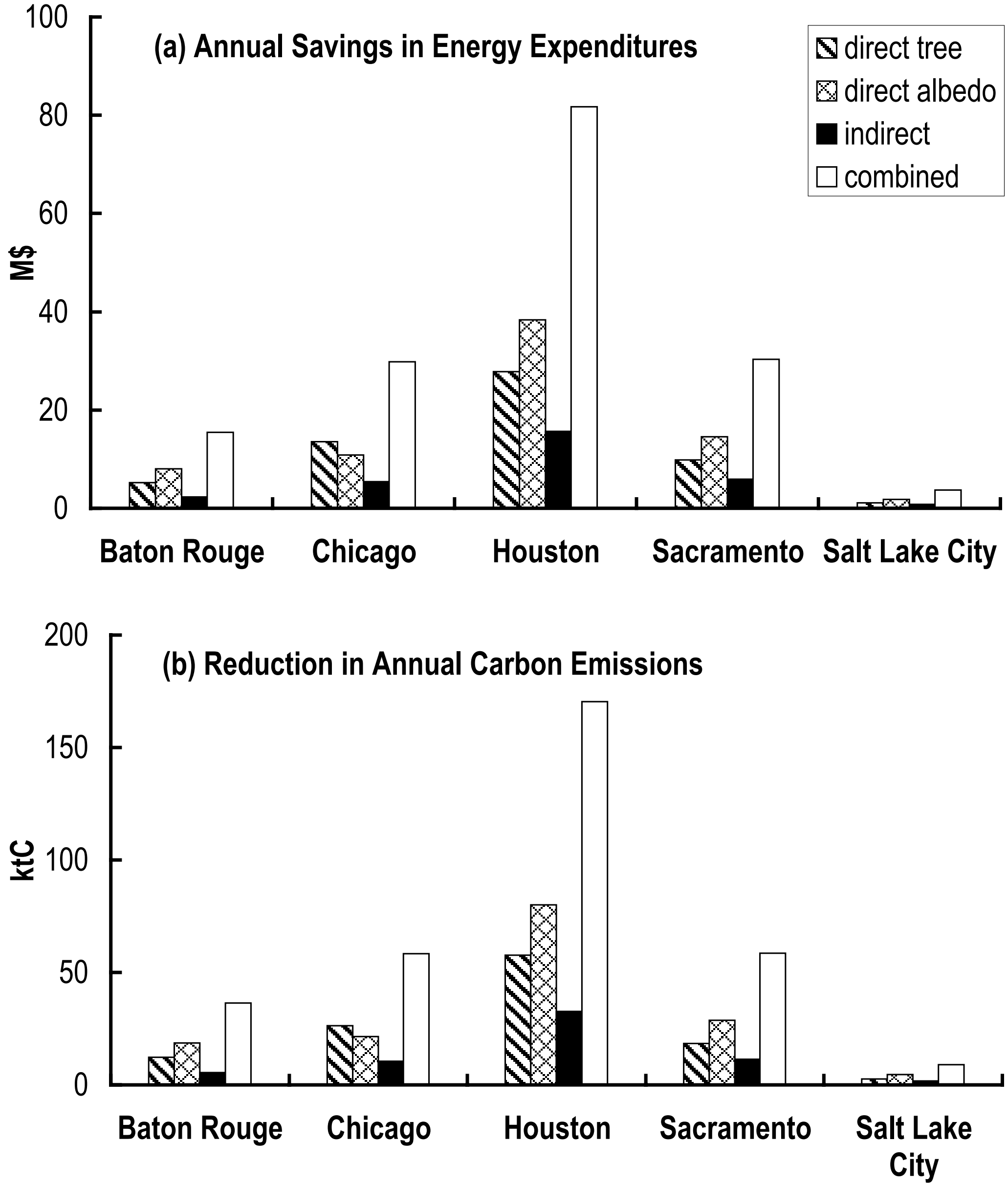

Figure EX.1. Savings in annual energy expenditures (a) and reduction in annual carbon emissions (b). Estimates are for (i) direct effect of planting shade trees, (ii) direct effect of increasing roof albedo, (iii) indirect effect of increasing urban vegetation and albedo of roofs and pavements, and (iv) combined direct and indirect effect of urban vegetation, roofs, and pavements.

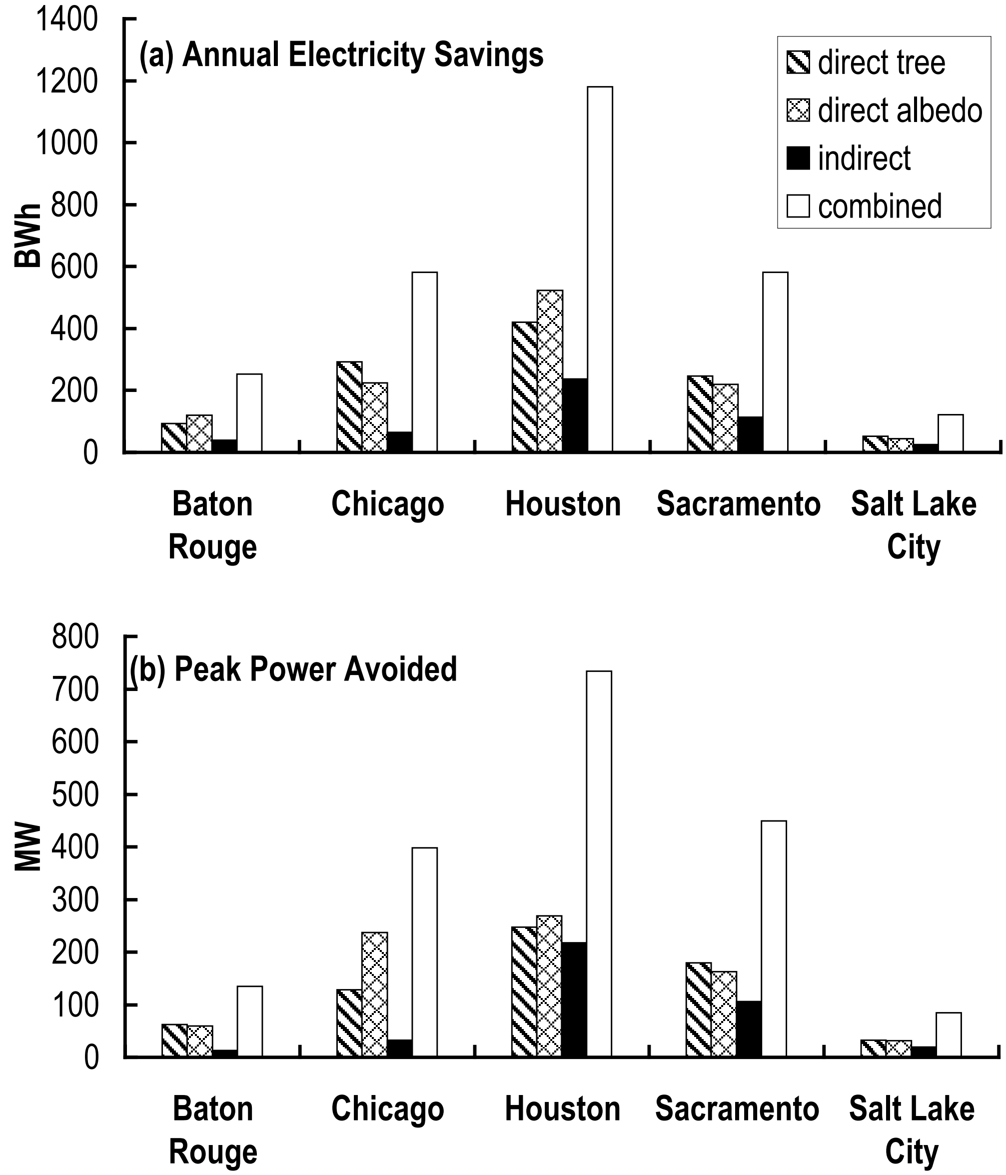

Figure EX.2. Savings in annual electricity use (a) and peak power avoided (b). Estimates are for (i) direct effect of planting shade trees, (ii) direct effect of increasing roof albedo, (iii) indirect effect of increasing urban vegetation and albedo of roofs and pavements, and (iv) combined direct and indirect effect of urban vegetation, roofs, and pavements.

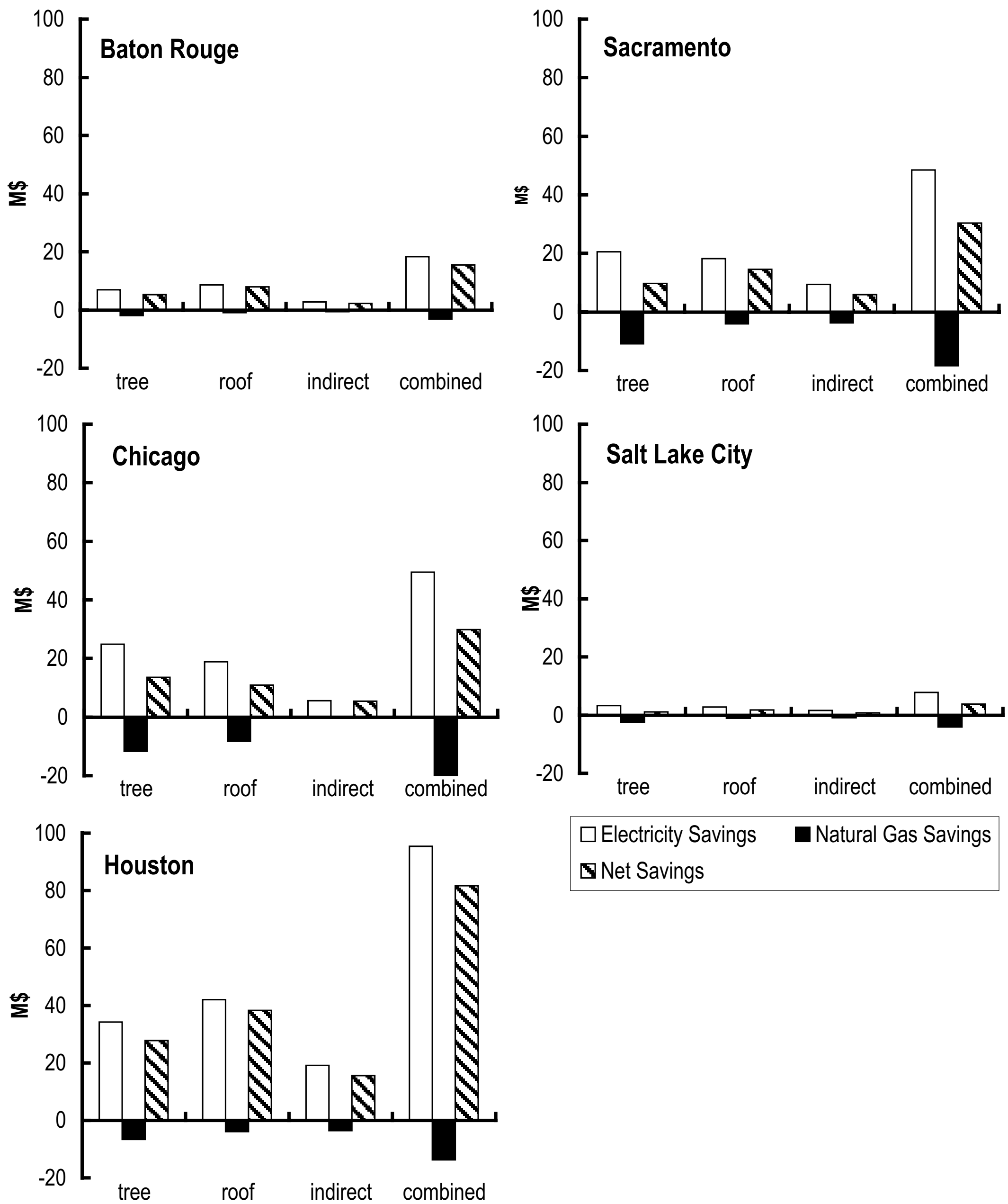

Figure EX.3. Annual electricity, natural gas deficit, and resulting savings in net cooling- and heating-energy use for Baton Rouge, Chicago, Houston, Sacramento, and Salt Lake City. Estimates are for (i) direct effect of planting shade trees, (ii) direct effect of increasing roof albedo, (iii) indirect effect of increasing urban vegetation and albedo of roofs and pavements, and (iv) combined direct and indirect effect of urban vegetation, roofs, and pavements.

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1. Introduction

Urban areas tend to have higher air temperatures than their rural surroundings as a result of gradual surface modifications that include replacing the natural vegetation with buildings and roads. The term "Urban Heat Island" describes this phenomenon. The surfaces of buildings and pavements absorb solar radiation and become hot, in turn warming the surrounding air. Cities that have been "paved over" do not receive the benefit from the natural cooling effect of vegetation.[*] As the air temperature rises, so does the demand for air-conditioning (a/c), leading to higher emissions by power plants and increased smog formation at higher temperatures. Strategies to reverse the heat-island effect include planting shade trees and other vegetation and incorporating high-albedo[†] roofs and pavements into the urban landscape.

In 1997, the U.S. Environmental Protection Agency (EPA) 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 vegetation) to reduce cooling-energy use in cities, improve urban air quality and lower CO_2 emissions from power plants. Under this initiative, entitled "the Heat Island Reduction Initiative," EPA has been engaged in two major projects. The first is the Urban Heat Island Pilot Project (UHIPP) and the second is the Energy Star® Roof Products Program, a joint effort with the U.S. Department of Energy (DOE).

The objective of the UHIPP is to investigate the use of HIR strategies for the reduction of cooling-energy use in buildings and for the reduction of the ambient air temperature. Cooling the ambient air temperature has the additional benefit of reducing urban smog concentration, and hence, improving urban air quality. In the initial phase of the UHIPP, three cities were selected: Baton Rouge, LA; Sacramento, CA; and Salt Lake City, UT. Later two other cities—Chicago, IL and Houston, TX—were added to UHIPP's list. Since the inception of the project, Lawrence Berkeley National Laboratory (LBNL) has conducted detailed studies to investigate the impact of HIR strategies on heating- and cooling-energy use of the three selected pilot cities. In addition, LBNL has collected urban surface characteristic data and conducted preliminary meteorology and urban smog simulations for the pilot cities.

In an earlier report, we summarized our efforts to calculate the annual energy savings, peak power avoidance and annual CO_2 reduction of HIR strategies in Baton Rouge, Sacramento and Salt Lake City (Konopacki and Akbari, 2000). In this report, we extend the analysis to the cities of Chicago and Houston. In these analyses, we focused on three major building types that offer the greatest potential savings:[‡] residence, office and retail store.

In this study, we followed the same methodology used for analysis of the first three cities. The methodology consisted of (1) defining prototypical buildings for each city; (2) simulating the base heating- and cooling-energy use for each prototype; (3) simulating the energy effects of shade trees and reflective roofs for each prototype; (4) simulating the effect of ambient cooling

[*] Evaporation of liquid water occurs at the leaf surface and lowers the local air temperature.

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

[‡] These building types were selected based on an earlier detailed study of the direct energy savings potential of highly reflective roofs in eleven U.S. metropolitan areas, in which these three building types were determined to account for over 90% of the national energy savings potential (Konopacki *et al.*, 1997).

on heating- and cooling-energy use of each prototype; (5) estimating the total roof area for each prototype by metropolitans area; and (6) estimating energy savings by metropolitan regions. In Appendix A, we have reproduced the relevant section of Konopacki and Akbari (2000). The reader is referred to Appendix A for a more detailed description of the calculation methodology and description of prototypical buildings. Appendix A also provides detailed descriptions of our approach in simulating direct and indirect energy effects, and modeling details of shade trees and high-albedo roofs.

As in the earlier study, we focused on three major building types that offer the greatest potential savings: residence, office and retail store. Each of these three types of buildings was characterized with four different prototypes: old construction with a gas heating system, old construction with an electric heat pump system, new construction with a gas heating system, and new construction with an electric heat pump system (see Appendix A). We prepared input data for each set of prototypical-building characteristics and simulated the impact of HIR strategies on building cooling- and heating-energy use. The simulations included:

1. the *direct effect* of strategically-placed shade trees near building on energy use;
2. the *direct effect* of using high-albedo roofing material on building energy use;
3. the *indirect effect* of ambient cooling (resulting from urban reforestation with highly reflective pavements and building surfaces) on building energy use; and
4. the combined strategies 1–3 [*direct and indirect effects*].

2. Typical Weather Data for Chicago and Houston

Local full-year hourly weather data are required as input to the DOE-2 simulation program. For Houston, we used the Typical Meteorological Years (TMY) format and for Chicago, we used the Weather Year for Energy Computation (WYEC2) format. It is important to remark that TMY and WYEC2 formats represent typical rather than extreme weather conditions.

Two sets of weather data were utilized in this exercise: [1] standard, and [2] modified. As discussed in Appendix A, the modified data represent a decrease in hourly drybulb temperature as a result of HIR strategies. This change in temperature is termed the indirect effect. The modified weather data for Chicago and Houston were obtained from an earlier study by Taha *et al.* (1996). The maximum air temperature and degree-days of the standard weather data are compared to those of the modified data and are presented in **Table 1**.

The standard weather data for Houston had three times as many annual cooling degree-days[*] (2878 calculated at the base temperature of 65°F) than Chicago (979). Also, Chicago is heating-dominated with 6264 heating degree-days at 65°F, compared to 1363 for Houston. Long-term annual average maximum temperatures in Chicago and Houston are 94°F, and 99°F, respectively.

The modified weather data had the greatest indirect effect in Houston, where the maximum drybulb temperature decreased by 2°F, annual cooling degree-days by 135, and annual heating degree-days increased by 35. For Chicago, the HIR measures did not result in a reduction in the

[*] Typically, heating and cooling degree-days are calculated using average daily temperatures. To obtain a more accurate estimate of heating and cooling degree-days, we calculated the heating and cooling degree-hours (using hourly temperature data) and divided the results by 24.

maximum temperature, but resulted in 39 fewer annual cooling degree-days and 28 more annual heating degree-days.

Table 1. Maximum air temperature and degree-days data for standard and modified weather (Δ = modified –standard).

Temperature and Degree-Hour Data	Chicago, IL (WYEC2) Standard	Δ	Houston , TX (TMY) Standard	Δ
Maximum temperature [°F][a]	94	0	99	–2
Cooling degree-days [65°F]				
June	185	–7	509	–19
July	284	–11	560	–22
August	286	–7	538	–18
Annual	979	–39	2878	–135
Heating degree-days [65°F]				
January	1307	0	357	6
February	1050	2	312	6
December	1106	1	373	6
Annual	6264	28	1363	35

a. The maximum standard ambient air temperature and the maximum modified temperature decrease are non-concurrent.

3. Energy Prices

The local average prices of electricity for 1999 and natural gas for 2000 were obtained from the Energy Information Administration web page (EIA, 2001) for residential and commercial sectors, as displayed in **Table 2**. These were utilized to calculate the annual combined cost of cooling- and heating-energy use. EIA (2001) lists the average price of electricity ($/kWh) for the utility serving the locality and the average price of gas by state.

Table 2. Average prices of electricity (1999) and natural gas (2000) for residential and commercial sectors.

Location	Residential		Commercial	
	Electricity [$/kWh][a]	Gas [$/therm][b]	Electricity [$/kWh][c]	Gas [$/therm][b]
Chicago, IL	0.093	0.733	0.075	0.690
Houston, TX	0.084	0.741	0.069	0.574

a. Energy Information Administration (EIA, 2001). Table 14. Class of ownership, number of ultimate consumers, revenue, sales, and average revenue per kilowatt-hour for the residential sector by state and utility, 1999. http://www.eia.doe.gov/cneaf/electricity/esr/t14.txt.

b. Energy Information Administration (EIA, 2001). Table 24. Average price of natural gas delivered to consumers by state, and sector, 2000. http://www.eia.doe.gov/oil_gas/natural_gas/nat_frame.html.

c. Energy Information Administration (EIA, 2001). Table 15. Class of ownership, number of ultimate consumers, revenue, sales, and average revenue per kilowatt-hour for the commercial sector by state and utility, 1999. http://www.eia.doe.gov/cneaf/electricity/esr/t15.txt.

4. Simulated Energy Use and Savings, and Peak Power Demand and Savings

Annual cooling- and heating-energy use and cooling peak power demand were simulated with the DOE-2.1E building energy simulation program (BESG, 1990 and 1993) using typical weather data for residential, office and retail store prototypical buildings. The residential building description was adapted with a validated attic-duct function developed by Parker *et al.* (1998) to better estimate the thermal interactions between the ducts and attic space. Each prototype was characterized by old (pre-1980: built prior to 1980) or new (1980^{+}: built 1980 or later) construction, electric cooling system, and with either a gas furnace or an electric heat pump heating system. The simulations were performed for a base case, defined as a building without shade trees and a low-albedo roof of 0.2, and four modified cases as discussed earlier.

The modified cases had a roof albedo of 0.5 for residence and 0.6 for commercial buildings. For purposes of our simulations, we assumed eight shade trees for the building categories residence and office, and four for retail store.

The simulations provided estimates of annual cooling- and heating-electricity use [kWh/1000ft^2], annual heating natural gas use [therms/1000ft^2] and cooling peak power demand [kW/1000ft^2]. From the simulations, the annual total expenditures for cooling and heating energy [\$/1000ft^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 the savings are presented in **Tables 3(a, b)** and **4(a, b)**. Tables (a) show the savings in absolute terms [\$/1000ft^2 or kW/1000ft^2] and (b) as a percentage. Consider points a–e upon examination of the tables.

a. Results are calculated per 1000ft^2 of roof area and can be applied to multi-story buildings.
b. Linear interpolation can be used to estimate savings or penalties for other net changes in albedo ($\Delta \hat{a}_2$) than presented here ($\Delta \hat{a}_1$) (Konopacki *et al.,* 1997). Therefore, the results presented in the tables can be simply adjusted by the ratio $\Delta \hat{a}_2 / \Delta \hat{a}_1$ to obtain estimates for other combinations of albedo. Linear interpolation is also valid for shade trees.
c. Savings will increase for buildings with less roof insulation than that specified in these prototypes (R-11 for old construction and R-30 for new). Conversely, savings will decrease for those with more roof insulation.
d. These buildings have a/c ducts in either the attic or plenum space. Savings will decrease for buildings with a/c ducts in the conditioned space and for those without ducts.
e. Savings in peak power make it clear that an air-conditioner can be downsized when HIR strategies are considered.

In **Chicago**, the simulations predicted combined direct and indirect savings in annual total energy of 19 and 5 \$/1000ft^2 (2% and 1%) and in peak power of 0.56 and 0.35 kW/1000ft^2 (12% and 8%) for old and new gas-heated residences, 80 and 30 \$/1000ft^2 (8% and 6%) and 0.84 and 0.31 kW/1000ft^2 (11% and 9%) for old and new gas-heated offices, and 99 and 37 \$/1000ft^2 (12% and 11%) and 0.58 to 0.27 kW/1000ft^2 (12% and 10%) for old and new gas-heated retail stores. The indirect effect accounted for 0–2% of these savings. The annual natural gas deficit for the combined direct and indirect effects of the old residence was 60% of the 48 \$/1000ft^2 in electricity savings, 77% of 22 \$/1000ft^2 for the new residence, 10% of 89 \$/1000ft^2 for the old office, 21% of 38 \$/1000ft^2 for the new office, 4% of 103 \$/1000ft^2 for the old retail, and 10% of 41 \$/1000ft^2 for the new retail.

In **Houston**, the simulations predicted combined direct and indirect savings in annual total energy of 60 and 35 $/1000ft^2 (12% and 14%) and in peak power of 0.56 and 0.35 kW/1000ft^2 (15% and 16%) for old and new gas-heated residences, 90 and 37 $/1000ft^2 (10 and 8%) and 0.81 and 0.31 kW/1000ft^2 (11% and 8%) for old and new gas-heated offices, and 110 and 46 $/1000ft^2 (11% and 10%) and 0.67 to 0.31 kW/1000ft^2 (13% and 11%) for old and new gas-heated retail stores. The indirect effect accounted for 2–5% of these savings. The annual natural gas deficit for the combined direct and indirect effects of the old residence was 20% of the 75 $/1000ft^2 in electricity savings, 13% of 40 $/1000ft^2 for the new residence, 3% of 93 $/1000ft^2 for the old office, 2% of 38 $/1000ft^2 for the new office, 1% of 111 $/1000ft^2 for the old retail, and less than 1% of 46 $/1000ft^2 for the new retail.

Table 3(a). Chicago: Simulated cooling and heating annual base energy expenditures and savings [\$/1000ft^2], and peak power demand and savings [kW/1000ft^2] from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

Building Type and Mitigation Strategy	**Annual Total Energy [\$/1000ft^2]**				**Annual Electricity [\$/1000ft^2]**		**Annual Gas [\$/1000ft^2]**		**Peak Power [kW/1000ft^2]**	
	Gas Heat		Electric Heat		Gas Heat		Gas Heat		Gas and Electric Heat	
	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$
Residence										
Base case	1040	492	1728	801	204	103	836	389	3.19	1.72
Savings										
Direct shade tree	7	3	–23	–4	24	13	–17	–10	0.09	0.04
Direct high albedo	6	1	–6	–2	18	7	–12	–6	0.30	0.10
Indirect	6	1	6	3	6	2	0	–1	0.01	0.00
Combined	19	5	–23	–3	48	22	–29	–17	0.40	0.14
Office										
Base case	992	503	1184	582	604	320	388	183	7.44	4.19
Savings										
Direct shade tree	46	19	46	18	47	22	–1	–3	0.42	0.23
Direct high albedo	25	6	22	4	33	11	–8	–5	0.26	0.09
Indirect	9	5	9	4	9	5	0	0	0.16	0.09
Combined	80	30	77	26	89	38	–9	–8	0.84	0.41
Retail store										
Base case	831	340	831	340	675	303	156	37	5.10	2.62
Savings										
Direct shade tree	47	21	48	21	46	22	1	–1	0.24	0.13
Direct high albedo	44	11	44	11	49	14	–5	–3	0.24	0.09
Indirect	8	5	9	4	8	5	0	0	0.10	0.05
Combined	99	37	101	36	103	41	–4	–4	0.58	0.27

Note: Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential: 0.5 and commercial: 0.6). To estimate direct savings for other changes in albedo ($\Delta\hat{a}$) multiply the savings by the ratio $\Delta\hat{a}/0.3$ for residences and $\Delta\hat{a}/0.4$ for commercial buildings.

Table 3(b). Chicago: Simulated cooling and heating annual base energy expenditures [\$/1000ft^2] and savings [%], and peak power demand [kW/1000ft^2] and savings [%] from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

Building Type and Mitigation Strategy	**Annual Total Energy** Gas Heat pre-1980	Gas Heat 1980$^+$	Electric Heat pre-1980	Electric Heat 1980$^+$	**Annual Electricity** Gas Heat pre-1980	Gas Heat 1980$^+$	**Annual Gas** Gas Heat pre-1980	Gas Heat 1980$^+$	**Peak Power** Gas and Electric Heat pre-1980	Gas and Electric Heat 1980$^+$
Residence										
Base case	1040	492	1728	801	2194	1108	1141	531	3.19	1.72
Savings [%]										
Direct shade tree	1	1	–1	0	12	13	–2	–3	3	2
Direct high albedo	1	0	0	0	9	7	–1	–2	9	6
Indirect	1	0	0	0	3	2	0	0	0	0
Combined	2	1	–1	0	24	21	–3	–4	12	8
Office										
Base case	992	503	1184	582	8053	4267	562	265	7.44	4.19
Savings [%]										
Direct shade tree	5	4	4	3	8	7	0	–2	6	5
Direct high albedo	3	1	2	1	5	3	–2	–3	3	2
Indirect	1	1	1	1	1	2	0	0	2	2
Combined	8	6	7	5	15	12	–2	–4	11	9
Retail store										
Base case	831	340	831	340	9000	4040	226	54	5.1	2.62
Savings [%]										
Direct shade tree	6	6	6	6	7	7	1	–3	5	5
Direct high albedo	5	3	5	3	7	5	–3	–8	5	3
Indirect	1	1	1	1	1	2	0	0	2	2
Combined	12	11	12	10	15	14	–3	–11	12	10

Note: Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential: 0.5 and commercial: 0.6). To estimate direct savings for other changes in albedo (Δâ) multiply the savings by the ratio Δâ/0.3 for residences and Δâ/0.4 for commercial buildings.

Table 4(a). Houston: Simulated cooling and heating annual base energy expenditures and savings [$/1000ft^2], and peak power demand and savings [kW/1000ft^2] from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

Building Type and Mitigation Strategy	Annual Total Energy [$/1000ft^2] Gas Heat		Annual Total Energy [$/1000ft^2] Electric Heat		Annual Electricity [$/1000ft^2] Gas Heat		Annual Gas [$/1000ft^2] Gas Heat		Peak Power [kW/1000ft^2] Gas and Electric Heat	
	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$
Residence										
Base case	494	256	603	280	360	207	134	49	3.75	2.23
Savings										
Direct shade tree	20	15	23	16	27	18	–7	–3	0.19	0.15
Direct high albedo	29	13	26	12	33	14	–4	–1	0.21	0.09
Indirect	11	7	11	7	15	8	–4	–1	0.16	0.11
Combined	60	35	60	35	75	40	–15	–5	0.56	0.35
Office										
Base case	977	496	992	499	927	486	50	10	7.89	4.13
Savings										
Direct shade tree	21	11	21	12	22	11	–1	0	0.13	0.05
Direct high albedo	44	14	45	15	46	15	–2	–1	0.38	0.12
Indirect	25	12	25	12	25	12	0	0	0.34	0.14
Combined	90	37	91	39	93	38	–3	–1	0.85	0.31
Retail store										
Base case	969	450	969	450	957	450	12	0	5.43	2.81
Savings										
Direct shade tree	32	16	32	16	32	16	0	0	0.19	0.11
Direct high albedo	60	20	60	20	61	20	–1	0	0.31	0.11
Indirect	18	10	19	11	18	10	0	0	0.17	0.09
Combined	110	46	111	47	111	46	–1	0	0.67	0.31

Note: Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential: 0.5 and commercial: 0.6). To estimate direct savings for other changes in albedo (Δâ) multiply the savings by the ratio Δâ/0.3 for residences and Δâ/0.4 for commercial buildings.

Table 4(b). Houston: Simulated cooling and heating annual base energy expenditures [$/1000ft^2] and savings [%], and peak power demand [kW/1000ft^2] and savings [%] from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

Building Type and Mitigation Strategy	**Annual Total Energy**				**Annual Electricity**		**Annual Gas**		**Peak Power**	
	Gas Heat		Electric Heat		Gas Heat		Gas Heat		Gas and Electric Heat	
	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$	pre-1980	1980$^+$
Residence										
Base case	494	256	603	280	4286	2464	181	66	3.75	2.23
Savings [%]										
Direct shade tree	4	6	4	6	8	9	–5	–6	5	7
Direct high albedo	6	5	4	4	9	7	–3	–2	6	4
Indirect	2	3	2	2	4	4	–3	–2	4	5
Combined	12	14	10	12	21	19	–11	–10	15	16
Office										
Base case	977	496	992	499	13435	7043	87	17	7.89	4.13
Savings [%]										
Direct shade tree	2	2	2	2	2	2	–2	0	2	1
Direct high albedo	5	3	5	3	5	3	–4	–10	5	3
Indirect	3	2	3	2	3	2	0	0	4	4
Combined	9	7	10	7	10	8	–6	–10	11	8
Retail store										
Base case	969	450	969	450	13870	6522	21	0	5.43	2.81
Savings [%]										
Direct shade tree	3	4	3	4	3	4	0	0	4	4
Direct high albedo	6	4	6	4	6	4	–8	0	6	4
Indirect	2	2	2	2	2	2	0	0	3	3
Combined	11	10	11	10	12	10	–8	0	13	11

Note: Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential: 0.5 and commercial: 0.6). To estimate direct savings for other changes in albedo (Δâ) multiply the savings by the ratio Δâ/0.3 for residences and Δâ/0.4 for commercial buildings.

5. Air-Conditioned Roof Area for Metropolitan Chicago and Houston

The data for the total commercial and residential air-conditioned roof areas in metropolitan Chicago and Houston were obtained from a detailed analysis of the stock of buildings in eleven metropolitan areas in the U.S. (Konopacki *et al*., 1997). The stock of existing roof area is summarized in **Table 5.** In Chicago, the saturation of air-conditioning in pre-1980 residential building is 39% and for post-1980 (1980^+) 84%. In Houston, 76% of pre-1980 residences and 94% of post-1980 residences are air-conditioned. Almost all offices in both metropolitan areas are air-conditioned. In Chicago, 63–69% and in Houston 79–85% of retail stores are air-conditioned. Over 90% of all commercial and residential buildings in both metropolitan areas are heated with natural gas.

Table 5. Air-conditioned flat roof area, residential and commercial buildings.

Metropolitan Area and Building Type	Total Roof Area [Mft^2]	HVAC Saturation [%]			Conditioned Roof Area [Mft^2]	
		AC	Gas	HP	AC & Gas	AC & HP
Residence pre-1980						
Chicago	1426.4	39	98	2	545.2	11.1
Houston	1140.2	76	91	9	788.6	78.0
Residence 1980^+						
Chicago	248.2	84	96	4	200.1	8.3
Houston	384.0	94	86	14	310.4	50.5
Office pre-1980						
Chicago	93.5	95	94	6	83.5	5.3
Houston	50.8	100	95	5	48.3	2.5
Office 1980^+						
Chicago	31.6	100	95	5	30.0	1.6
Houston	32.1	100	85	15	27.3	4.8
Retail store pre-1980						
Chicago	132.2	63	100	0	83.3	0.0
Houston	111.9	85	95	5	90.4	4.8
Retail store 1980^+						
Chicago	58.5	69	99	1	40.0	0.4
Houston	24.0	79	100	0	19.0	0.0

Notes: **AC:** Air-conditioned; **Gas:** Heated with natural gas; **HP:** Heated with electric heat pump.

6. Metropolitan-Wide Impact of Heat-Island Reduction Strategies

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

The metropolitan-wide results 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 city. These results are presented in **Tables 6(a)** and **7(a)**, for each prototype by vintage and system type (i.e., for old and new building constructions, and for gas and electric heat). Metropolitan-wide annual energy savings [M$], annual electricity savings [GWh and M$], annual natural gas deficit [Mtherms and M$], peak power avoided [MW] and annual carbon emissions reduction [kt] are presented in **Tables 6(b)** and **7(b)**, for residences, office buildings, retail stores, and the total is shown for each HIR strategy and pilot city. The level of carbon (as CO_2) emitted as a consequence of electricity production should decrease as demand is lowered, as a consequence of the implementation of HIR strategies. On an annualized basis 1 GWh of electricity emits 167 tC (metric tons of carbon) (EIA, 1997).* The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm (EIA, 1997). We have also recalculated the reduction in the rate of carbon emissions for Baton Rouge, Sacramento, and Salt Lake City; Appendix B shows the updated tables.

Chicago is a metropolitan area of over eight million inhabitants and is situated in northeastern Illinois on the edge of Lake Michigan. The climate is hot and humid in summer, with a cooling season from June through September. Most residential buildings are multi-story, and commercial buildings are a mix of low- and high-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 is 765, 120, and 124 Mft^2, respectively. The combined direct (82%) and indirect (18%) effects of HIR strategies can potentially yield ratepayer benefits of $30M (37% residential; 27% office; 36% retail store) in total annual energy savings. This figure is derived from annual electricity savings of $50M minus a $20M natural gas deficit. Additionally, peak power avoidance is estimated at 398 MW (63%, 22%, and 15%), and the reduction in annual carbon emissions at 58 ktC (28%, 31%, and 41%).

Houston is a metropolitan area of nearly four million inhabitants and is situated on the southeast gulf coast of Texas, where the climate is hot and humid, with a cooling season from May through October. 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 is 1228, 83, and 114 Mft^2, respectively. The combined direct (81%) and indirect (19%) effects of HIR strategies can potentially yield ratepayer benefits of $82M (79% residence, 7% office, and 14% retail store) in total annual energy savings. This figure is derived from annual electricity savings of $95M minus a $13M natural gas deficit. Additionally, peak power avoidance is estimated at 734 MW (83%, 7%, and 10%) and the reduction in annual carbon emissions at 170 ktC (76%, 8%, and 16%).

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* The conversion from GWh to carbon corresponds to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 TWh sold emitted 500MtC (million metric tons of carbon), thus 1 GWh emits 167 tC.

Table 6(a). Chicago: Metropolitan-wide estimates of cooling and heating annual base energy expenditures and savings [1000$], and peak power demand and savings [MW] from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

Building Type And Mitigation Strategy	Annual Total Energy [M$]				Annual Electricity [M$]		Annual Gas [M$]		Peak Power [MW]			
	Gas Heat		Electric Heat		Gas Heat		Gas Heat		Gas Heat		Electric Heat	
	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+
Residence												
Base case	567.0	98.4	19.2	6.6	111.2	20.6	455.8	77.8	1739	344	35	14
Savings												
Direct shade tree	3.8	0.6	–0.3	0.0	13.1	2.6	–9.3	–2.0	49	8	1	0
Direct high albedo	3.3	0.2	–0.1	0.0	9.8	1.4	–6.5	–1.2	164	20	3	1
Indirect	3.3	0.2	0.1	0.0	3.3	0.4	0.0	–0.2	5	0	0	0
Combined	10.4	1.0	–0.3	0.0	26.2	4.4	–15.8	–3.4	218	28	4	1
Office												
Base case	82.8	15.1	6.3	0.9	50.4	9.6	32.4	5.5	621	126	39	7
Savings												
Direct shade tree	3.8	0.6	0.2	0.0	3.9	0.7	–0.1	–0.1	35	7	2	0
Direct high albedo	2.1	0.2	0.1	0.0	2.8	0.3	–0.7	–0.2	22	3	1	0
Indirect	0.8	0.2	0.0	0.0	0.8	0.2	0.0	0.0	13	3	1	0
Combined	6.7	0.9	0.4	0.0	7.4	1.1	–0.8	–0.2	70	12	4	1
Retail store												
Base case	69.2	13.6	0.0	0.1	56.2	12.1	13.0	1.5	425	105	0	1
Savings												
Direct shade tree	3.9	0.8	0.0	0.0	3.8	0.9	0.1	0.0	20	5	0	0
Direct high albedo	3.7	0.4	0.0	0.0	4.1	0.6	–0.4	–0.1	20	4	0	0
Indirect	0.7	0.2	0.0	0.0	0.7	0.2	0.0	0.0	8	2	0	0
Combined	8.2	1.5	0.0	0.0	8.6	1.6	–0.3	–0.2	48	11	0	0

Note: Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

Table 6(b). Chicago: Metropolitan-wide estimates of energy savings, avoided peak power and carbon emissions reduction from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from urban reforestation and high-albedo surfaces.

Building Type And HIR Strategy	Annual Energy	Annual Electricity		Annual Natural Gas		Peak Power	Annual Carbon
	[M$]	[GWh]	[M$]	[Mtherm]	[M$]	[MW]	[ktC]
Residence							
Base Case	691.3	1695	157.7	728	533.6	2133	1337
Savings							
Direct Shade Tree	4.1	166	15.4	–15	–11.3	58	5
Direct High Albedo	3.4	120	11.1	–11	–7.7	188	5
Indirect	3.6	40	3.8	0	–0.2	6	6
Combined	11.1	326	30.3	–26	–19.2	252	16
Office							
Base Case	105.1	897	67.2	55	37.9	793	229
Savings							
Direct Shade Tree	4.7	65	4.9	0	–0.2	45	10
Direct High Albedo	2.4	43	3.2	–1	–0.8	26	5
Indirect	1.0	13	1.0	0	0.0	17	2
Combined	8.0	120	9.0	–1	–1.0	88	18
Retail store							
Base Case	83.0	913	68.5	21	14.5	530	183
Savings							
Direct Shade Tree	4.7	63	4.7	0	0	25	10
Direct High Albedo	5.1	61	4.6	1	0.5	24	11
Indirect	0.9	12	0.9	0	0	10	2
Combined	10.7	136	10.2	1	0.5	59	24
Total							
Base Case	879.4	3505	293.4	804	586.0	3456	1749
Savings							
Direct Shade Tree	13.5	293	25.0	–16	–11.4	128	26
Direct High Albedo	10.9	224	18.9	–11	–8.1	237	21
Indirect	5.4	65	5.6	0	–0.2	33	10
Combined	29.8	582	49.5	–27	–19.7	398	58

a. Metropolitan-wide annual energy savings [M$ = Million$], annual electricity savings [M$ and GWh = Giga Watt-hour], annual natural gas deficit [M$ and Mtherm = Million therms], peak power avoided [MW = Mega Watt] and annual carbon emissions reduction [kt = thousand tons].

b. Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

c. The conversion from GWh to carbon corresponds to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 TWh sold emitted 500 MtC (million metric tons of carbon), thus 1 GWh emits 167 tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm.

Table 7(a). Houston: Metropolitan-wide estimates of cooling and heating annual base energy expenditures and savings [1000$], and peak power demand and savings [MW] from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

Building Type and Mitigation Strategy	Annual Total Energy [M$]				Annual Electricity [M$]		Annual Gas [M$]		Peak Power [MW]			
	Gas Heat		Electric Heat		Gas Heat		Gas Heat		Gas Heat		Electric Heat	
	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+	pre-1980	1980+
Residence												
Base case	389.6	79.5	47.0	14.1	283.9	64.3	105.7	15.2	2957	692	293	113
Savings												
Direct shade tree	16.6	4.7	1.8	0.8	21.3	5.6	–5.5	–0.9	150	47	15	8
Direct high albedo	22.9	4.0	2.0	0.6	26.0	4.3	–3.2	–0.3	166	28	16	5
Indirect	8.7	2.5	0.9	0.4	11.8	2.5	–3.2	–0.3	126	34	12	6
Combined	48.1	11.2	4.7	1.8	59.1	12.4	–11.8	–1.6	442	109	44	18
Office												
Base case	47.2	13.5	2.5	2.4	44.8	13.3	2.4	0.3	381	113	20	20
Savings												
Direct shade tree	1.0	0.3	0.1	0.1	1.1	0.3	0.0	0.0	6	1	0	0
Direct high albedo	2.1	0.4	0.1	0.1	2.2	0.4	–0.1	0.0	18	3	1	1
Indirect	1.2	0.3	0.1	0.1	1.2	0.3	0.0	0.0	16	4	1	1
Combined	4.3	1.0	0.2	0.2	4.5	1.0	–0.1	0.0	41	8	2	1
Retail store												
Base case	87.6	8.6	4.7	0.0	86.5	8.6	1.1	0.0	491	53	26	0
Savings												
Direct shade tree	2.9	0.3	0.2	0.0	2.9	0.3	0.0	0.0	17	2	1	0
Direct high albedo	5.4	0.4	0.3	0.0	5.5	0.4	–0.1	0.0	28	2	1	0
Indirect	1.6	0.2	0.1	0.0	1.6	0.2	0.0	0.0	15	2	1	0
Combined	9.9	0.9	0.5	0.0	10.0	0.9	–0.1	0.0	61	6	3	0

Note: Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

Table 7(b). Houston: Metropolitan-wide estimates of energy savings, avoided peak power and carbon emissions reduction from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from urban reforestation and high-albedo surfaces.

Building Type And HIR Strategy	Annual Energy [M$]	Annual Electricity [GWh]	[M$]	Annual Natural Gas [Mtherm]	[M$]	Peak Power [MW]	Annual Carbon [ktC]
Residence							
Base Case	530.2	4873	409.3	163	120.9	4055	1050
Savings							
Direct Shade Tree	23.0	351	29.5	–9	–6.5	219	46
Direct High Albedo	29.5	393	33.0	–5	–3.5	214	59
Indirect	12.1	185	15.5	–5	–3.5	178	24
Combined	64.6	929	78.0	–18	–13.4	612	129
Office							
Base Case	65.6	912	62.9	5	2.7	533	159
Savings							
Direct Shade Tree	1.4	21	1.5	0	0.0	8	3
Direct High Albedo	2.7	41	2.8	0	–0.1	23	7
Indirect	1.7	24	1.7	0	0.0	22	4
Combined	5.8	86	5.9	0	–0.2	53	14
Retail store							
Base Case	100.8	1445	99.7	2	1.1	570	244
Savings							
Direct Shade Tree	3.4	49	3.4	0	0.0	20	8
Direct High Albedo	6.1	90	6.2	0	–0.1	32	15
Indirect	1.9	28	1.9	0	0.0	18	5
Combined	11.4	166	11.4	0	–0.1	70	27
Total							
Base Case	696.6	7230	572.0	170	124.7	5158	1453
Savings							
Direct Shade Tree	27.8	421	34.3	–9	–6.5	247	58
Direct High Albedo	38.3	523	42.0	–5	–3.7	269	80
Indirect	15.6	236	19.1	–5	–3.5	218	33
Combined	81.8	1181	95.4	–19	–13.6	734	170

a. Metropolitan-wide annual energy savings [M$ = Million$], annual electricity savings [M$ and GWh = Giga Watt-hour], annual natural gas deficit [M$ and Mtherm = Million therms], peak power avoided [MW = Mega Watt] and annual carbon emissions reduction [kt = thousand tons].

b. Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail store: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

c. The conversion from GWh to carbon corresponds to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 TWh sold emitted 500 MtC (million metric tons of carbon), thus 1 GWh emits 167 tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm.

7. Conclusions

In this study, we investigated the potential of Heat-Island Reduction (HIR) strategies (i.e., shade trees, reflective roofs, reflective pavements, and urban vegetation) to reduce cooling-energy use in buildings in two cities: Chicago, IL and Houston, TX. 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 greatest potential savings: single-family residence, office and retail store. Each building type was characterized in detail by vintage (old or new construction) and heating equipment (gas furnace or electric heat pump. We defined prototypical-building 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. Our simulations included the impact of (1) strategically-placed shade trees near buildings [*direct effect*]; (2) use of high-albedo roofing material on building [*direct effect*]; (3) cooling of the ambient air by the placement of urban vegetation and the use of high-albedo surfaces (pavements and roofs surfaces) [*indirect effect*]; and (4) combined strategies 1–3 [*direct and indirect effects*]. We then estimated the total roof area of air-conditioned buildings in each city using readily obtainable data to calculate the metropolitan-wide impact of HIR strategies.

The results show that in Chicago, potential annual energy savings of \$30M could be realized by ratepayers from the combined direct and indirect effects of HIR strategies. Additionally, peak power avoidance is estimated at 400 MW and the reduction in annual carbon emissions at 58 ktC. In Houston, the potential annual energy savings are estimated at \$82M, with an avoidance of 730 MW in peak power and a reduction of 170 ktC in annual carbon emissions.

Savings from the indirect impact (cooler ambient air temperature) of HIR strategies were 18% and 19% of the total savings for Chicago and Houston, respectively.

Since roofs and shade trees offer a direct savings potential, from an energy-saving point of view programs should have highest priority that focus on reflective roofs and shade trees. However, when considering smog and air-quality issues, programs should have priority that focus on reflective surfaces (roofs and pavements) that can cool the ambient air in both humid and dry climate conditions. Urban trees also play a major role in directly sequestering CO_2 and thereby delaying global warming. A shade tree planted in an urban area avoids the combustion of carbon as well as sequestering carbon from atmosphere (as it would if growing in a forest). In this sense, a shade tree in urban area could be equivalent to several forest trees.

In this study, we used the average retail prices of electricity for end-users given in \$/kWh. The prices include the charges for peak demand. It is not accurate to use such average prices if the shape of the savings does not match the shape of demand for the whole end-use class (as is the case for residential and commercial buildings). Measures considered in this report save energy when the marginal cost of electricity is highest and heating penalties are incurred when the marginal cost of electricity is lowest. This means that by using a flat electricity rate to estimate savings we are underestimating the dollar benefits of the measures considered in this report.

If retail deregulation of electricity is not in effect the end-user is typically exposed to a tariff that most likely includes peak demand charges. Since the measures considered here save more during the hours when the peaks occur, the bill reduction will be more than a proportional decrease based on an average kWh price and the kWh savings. With retail deregulation, the customer can more easily benefit form the reductions in energy use during peak hours when the wholesale prices are highest, since a peak-reducing customer can select a supplier offering prices that are more tightly coupled with the wholesale market (more closely approximate real-time pricing).

Finally, for these five pilot cities, we have estimated a potential 1.8GW reduction in peak electric power demand. Typically, the peaking power plants are considered '"dirty," and they are a source of air pollution during the time that air quality is worst. The HIR measures have the added benefit of reducing the need for these polluting sources of power generation.

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Appendix A.

[Reproduction of relevant sections of Konopacki and Akbari (2000): Methodology, Building Description, Direct and Indirect, Shade Trees, and Roof Albedo]

A.1. Methodology

A methodology was developed that incorporates readily obtainable data from building energy simulations, previous heat-island studies and the U.S. Census to estimate the potential metropolitan-wide benefits of HIR strategies.

1. **Define prototypical-building characteristics in detail for old and new 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 placement of shade trees around the building and the use of low and high-albedo roofs were considered. These data then defined the characteristics of the building description language used by the DOE-2.1E energy simulation program.
2. **Simulate annual energy use and peak power demand using the DOE-2.1E model**. Annual cooling and heating energy use and peak power demand were simulated with DOE-2 using Typical Meteorological Year (TMY2) weather data and modified TMY2 (represents the indirect effect) for all building prototypes, HIR scenarios and pilot cities. Local residential and commercial electricity and natural gas prices for 1997 were applied to the simulation results to obtain total annual energy use in dollars.
3. **Determine direct and indirect energy 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 HIR strategies.
4. **Identify the total roof area of air-conditioned buildings in each city.** Total air-conditioned roof area for the entire metropolitan area was estimated for residential, office and retail buildings. Residential roof area was calculated with normalized roof area from Konopacki *et al.* (1997), data obtained from the 1990 U.S. Census and the American Housing Survey (AHS). Commercial building roof areas were derived from the Konopacki *et al.* (1997) commercial estimates and residential roof area calculated in this report.
5. **Calculate the metropolitan-wide impact of HIR strategies**. Combine building energy simulations with total air-conditioned roof area for each prototype and strategy.

A.2. Building Descriptions

Three major building prototypes have been selected for investigation in this project: residence, office, and retail store. Konopacki *et al.* (1997), in a detailed study to quantify the impact of high-albedo roofs in eleven Metropolitan Statistical Areas (MSAs), showed that these three building types accounted for 93% of the residential and commercial conditioned roof area. The buildings were characterized for old (built prior to 1980) or new (built 1980 or later) construction and with a gas furnace or an electric heat pump. Detailed construction, equipment, and interior load data were available from studies of Northern California commercial buildings (Akbari *et al.*, 1993) and Sacramento residential and commercial buildings (CEC, 1994), and were used to define the prototypes in all three cities (quality data were unavailable for old-construction buildings in Baton Rouge and Salt Lake city). Characteristics for new-construction residences were identified from DOE national appliance energy standards (NAECA, 1987), California's Title 24, and the Model Energy Code. All three buildings were single-story prototypes with either an attic or plenum space that contains a/c ducts. Old-construction buildings were modeled with R-11 attic/plenum insulation and the new with R-30.

Residence

The residence was modeled as a single-family, ranch-style building with a detached garage, with characteristics identified in Table 2.1. The exterior dimensions were 55 by 28 ft with a total conditioned floor area of 1540 ft^2. The exposed wall area was 1328 ft^2. Distinct windows were placed on each wall with a window-to-wall ratio of 0.17. Operable shades were employed on the windows. The residence operated from 7am to 10pm seven days a week.

The roof was constructed with asphalt shingles on a 20^o sloped plywood deck, over a naturally ventilated and unconditioned attic, above a studded ceiling frame with fiberglass insulation, and with a sheet of drywall beneath. The attic ventilation to floor area ratio was set at 1:400 and variable air infiltration was modeled by the Sherman-Grimsrud algorithm (Sherman, 1986).

The residence was cooled and heated by a central air-conditioning system with ducts located in the attic, a constant volume fan and without an economizer. 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-load energy use more accurately (Henderson, 1998). 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 with a validated residential attic-duct function[*] (Parker *et al*., 1998) implemented into DOE-2 to better estimate the thermal interactions between the ducts and the attic space. Cooling through natural ventilation was available through window operation.

Office

The office was modeled as a rectangular building with four perimeter zones and a core zone, with characteristics identified in Table 2.2. The exterior dimensions were 80 by 50 ft with a total conditioned floor area of 4000 ft^2. The perimeter zone depth was 15 ft. The exposed wall area was 2340 ft^2 and the windows wrapped continuously around the building with a window-to-wall ratio of 0.5. Operable shades were employed on the windows. The building operated from 6am to 7pm on weekdays.

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 building was cooled and heated by five rooftop, direct expansion, constant volume, packaged-single-zone systems, each one servicing a single zone. The systems were sized based

[*] The function calculates attic temperature, supply and return duct losses, and temperature-dependent heat conduction through the insulation. It was documented to provide reasonable agreement with measured attic temperature and air-conditioning electricity use data taken from Florida test homes.

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.

Retail Store

The retail store was modeled as a rectangular building with a single zone, as part of a strip mall with other buildings on two sides, with characteristics identified in Table 2.3. The exterior dimensions were 100 by 80 ft with a total conditioned floor area of 8000 ft^2. The exposed wall area was 1800 ft^2 (unexposed 1440 ft^2), and a continuous window was situated only on the south wall (north facing orientation) with a window-to-wall ratio of 0.6. Operable shades were not employed on the windows. The building operated from 8am to 9pm on weekdays and from 10am to 5pm on weekends or 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 building was cooled and heated by a single rooftop, direct expansion, constant volume, packaged-single-zone system. 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.3. Direct vs. Indirect Effect

Strategies to cool cities and mitigate urban heat islands include placing shade trees around buildings, placing other urban vegetation in parks and along roadways, and using high-albedo roofs and pavements. Trees shade buildings and high-albedo roofs reflect solar energy from buildings, directly reducing demand for air-conditioning (a/c). Urban vegetation and reflective surfaces (high-albedo roofs and pavements) alter the surface energy balance of an area through evapotranspiration of vegetation and by reflecting incident solar energy, lowering the ambient temperature and hence indirectly reducing a/c use.

The direct energy impacts are simulated with the building energy software DOE-2. The indirect energy impacts are estimated in a two-step process. First, a modified TMY2 weather tape was created to represent the impact of HIR strategies. Second, the prototypes were simulated with the modified weather tape to calculate the impact of ambient cooling on heating- and cooling-energy use.

To quantify the ambient cooling from the indirect effect, first, a modified urban fabric is created from the present fabric with increased urban vegetation, the placement of shade trees, and the use of high-albedo roofs and pavements. Second, the impact of the modified urban fabric on climate is simulated using the Colorado State Urban Meteorological Model (CSUMM), from which a modified average drybulb air temperature is obtained from several locations within the boundaries of the model over the 48 hour episode beginning 27 July; discussed in detail by Taha and Chang (1999a). Then, the modified temperature is calculated for each hour of the year using an algorithm developed by Taha (1999b) based on a statistical analysis of temperature change as a function of solar intensity; because ΔT is solely a function of solar, ΔT is zero during hours without sunlight. Finally, ΔT is used to modify the standard TMY2 weather data to create modified temperature data for the building energy simulations.

A lower air temperature as a result of the urban fabric modification may also occur during non-solar hours and could mostly affect residential cooling- and heating-energy use, as the office and retail buildings typically do not operate late evening and early morning. The lowered air temperature in the evening/morning would add to residential cooling-energy savings and heating-energy penalties, unless natural ventilation or evening venting were cooling the building during these hours. The extrapolation of episodic ΔT to an annual scale is being studied further.

A.4. Shade Trees

Mature deciduous shade trees were modeled as a box-shaped building shade with seasonal transmittance* (summertime transmittance is 0.1 for April 1 through October 31; wintertime transmittance is 0.9 for the remainder of the year), a cross-section of 15 by 15 ft (21 ft radius), a depth of 10 ft, and a canopy height of 15 ft. They were placed near windows (with 2 ft 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 the roof.

A total of eight residential shade trees were situated near the east, south, and west walls directly in front of the windows, whereby the placement differed for north/south and east/west orientations. A total of eight office shade trees were situated near the east, south, and west walls (continuous windows), whereby placement differed for north/south and east/west orientations. A total of four retail store shade trees were situated near the south wall (only wall with windows), whereby placement was the same for all three orientations.

A.5. Roof Albedo

Typical values of albedo for low- and high-albedo roofs were selected that 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) developed at LBNL that contains measured values of roof absorptance across the solar spectrum.† The roof albedos were 0.2 and 0.5 for residential roofs and 0.2 and 0.6 for commercial roofs, representing low- and high-albedo materials as shown in Table 5.1. The long-wave thermal emittance of these materials was a uniform 0.9.

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 such as Baton Rouge), and by washing the roof, the albedo can be restored to 90–100% of the initial value. Note: rainfall can cleanse a roof effectively and have the same effect as a thorough washing.

A few examples of real materials are shown in the table. A “generic white” asphalt shingle has a laboratory tested initial albedo of 0.25 (CRMD, 1998). 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, 1998). The roofs—built-up asphalt capsheet with light-gray granules—of three commercial buildings in California were coated with a white elastomeric material, where

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* The fraction of light that passes through the tree is the transmittance.

† The on-line database can be found at http://eetd.lbl.gov/coolroof (CRMD, 1998).

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, 1998).

Table A.1. [Same as Table 2.1 of Konopacki and Akbari (2000)**.**] Residence prototypical construction, equipment, and interior load characteristics.

Construction	Characteristic	Old	New
Zones	Living (conditioned)		
	Attic (unconditioned)		
Floor Area	1540ft^2 (conditioned)		
Aspect Ratio	2		
Roof Construction	¼” asphalt shingle		
	3/4” plywood decking (20^o slope)		
Ceiling Construction	2”x4” studded frame (15%)		
	Fiberglass insulation	R-11	R-30
	1/2” drywall		
Wall Construction	Brick		
	2”x4” studded frame (15%)		
	Fiberglass insulation 5		13
	1/2” drywall		
Foundation	Slab-on-grade with carpet and pad		
Windows	231ft^2		
	Clear with operable shades		
	Layers	1	2
Equipment			
Cooling	Direct expansion		
	SEER[a]	8.5	10
Heating	Gas furnace		
	Efficiency (η)	0.70	0.78
	Heat pump		
	HSPF[b]	4.7	6.8
Distribution	Constant-volume forced air system		
	Attic ducts: R-value	2	4
	Supply duct area = 370 ft^2		
	Return duct area = 69 ft^2		
	Duct leakage: % 20	10	
Thermostat Cooling	Setpoint = 78°F		
	Heating setpoint = 70°F (7am–10pm)		
	Heating setback = 64°F		
Natural Ventilation	Window operation available		
Interior Load			
Infiltration	Sherman-Grimsrud:		
	Fla = 0.0005 (living)		
	Fla = 0.0025 (attic)		
Lighting	0.4 W/ft^2		
Equipment	0.8 W/ft^2		
Occupants	3		

[a]Seasonal Energy Efficiency Ratio

[b]Heating Seasonal Performance Factor

Table A.2. [Same as Table 2.2 of Konopacki and Akbari (2000).] Office prototypical construction, equipment, and interior load characteristics.

Construction	Characteristic	Old	New
Zones	5 (conditioned)		
Floor Area	4000ft^2 (conditioned)		
Aspect Ratio	1.6		
Roof Construction	Built-up roofing		
	¾" plywood decking (0^o slope)		
	Plenum (unconditioned)		
Ceiling Construction	2"x4" studded frame (15%)		
	Fiberglass insulation	R-11	R-30
	½" drywall		
Wall Construction	Brick		
	2"x4" studded frame (15%)		
	Fiberglass insulation	6	13
	½" drywall		
Foundation	Slab-on-grade with carpet and pad		
Windows	1170ft^2		
	Clear with operable shades		
	Layers	1	2
Equipment			
Cooling	Direct expansion		
	COP	2.25	2.9
Heating	Gas furnace		
	Efficiency (η)	0.70	0.74
	Heat pump		
	COP	2.25	2.9
Distribution	Constant-volume forced air system		
	Economizer	fixed	temperature
	Duct leakage: %	20	10
	Duct temperature drop: °F	2	1
Thermostat	Weekday operation (6am–7pm)		
	Cooling setpoint = 78°F		
	Heating setpoint = 70°F		
Interior Load			
Infiltration Air	Change/hour = 0.5		
Lighting	W/ft^2	1.9	1.4
Equipment	W/ft^2	1.7	1.5
Occupants	25		

Table A.3. [Same as Table 2.3 of Konopacki and Akbari (2000)**.**] Retail Store prototypical construction, equipment, and interior load characteristics.

Construction	**Characteristic**	**Old**	**New**
Zones	1 (conditioned)		
Floor Area	8000ft^2 (conditioned)		
Aspect Ratio	1.25		
Roof Construction	Built-up roofing		
	¾” plywood decking (0^o slope)		
	Plenum (unconditioned)		
Ceiling Construction	2”x4” studded frame (15%)		
	Fiberglass insulation	R-11	R-30
	½” drywall		
Wall Construction	Brick		
	2”x4” studded frame (15%)		
	Fiberglass insulation	4	13
	½” drywall		
Foundation	Slab-on-grade with carpet and pad		
Windows	540ft^2 (south)		
	Clear without operable shades		
	Layers	1	2
Equipment			
Cooling	Direct expansion		
	COP	2.25	2.9
Heating	Gas furnace		
	Efficiency (η)	0.70	0.74
	Heat pump		
	COP	2.25	2.9
Distribution	Constant-volume forced air system		
	Economizer	fixed	temperature
	Duct leakage: %	20	10
	Duct temperature drop: °F	3	1
Thermostat	Weekday operation (8am–9pm)		
	Weekend operation (10am–5pm)		
	Cooling setpoint = 78°F		
	Heating setpoint = 70°F		
Interior Load			
Infiltration	Air-change/hour = 0.5		
Lighting	W/ft^2	2.4	1.7
Equipment	W/ft^2	0.7	0.6
Occupants	16		

Table A.4. [Same as Table 5.1 of Konopacki and Akbari (2000).] Roof materials and weathered albedo for residential and commercial buildings.

Building	Roof Material	Roof Albedo
Residential		
Low	Typical light- or dark-colored asphalt shingle	0.2
Medium	Premium white-algaecide or typical 1960s white shingle	0.3
High	Prototype six-coat TiO white shingle	0.5
Commercial		
Low	high-albedo granules on asphalt capsheet	0.2
Medium	dirty white-elastomeric coating on asphalt capsheet	0.4
High	white-elastomeric coating on asphalt capsheet	0.6

Appendix B.

Updated **Tables 10.1(b), 10.2(b), and 10.3(b)** from Konopacki and Akbari (2000). The estimated reductions in carbon emissions are modified to account for the effect of winter heating penalties.

Table B.1. [Updated Table 10.1(b) of Konopacki and Akbari (2000).] Baton Rouge metropolitan-wide estimates of energy savings, avoided peak power and carbon emissions reduction from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from urban reforestation and high-albedo surfaces.

Building Type And Mitigation Strategy	Annual Energy Savings [M$]	Annual Electricity Savings [GWh]	Annual Electricity Savings [M$]	Annual Natural Gas Deficit [Mth]	Annual Natural Gas Deficit [M$]	Peak Power Avoided [MW]	Annual Carbon Reduction [ktC]
Residence							
Base case	89.8	925.0	68.4	29.9	21.4	698.2	197.7
Direct shade tree	4.3	81.4	6.0	2.4	1.7	59.9	10.1
Direct high albedo	6.5	96.8	7.2	0.9	0.7	52.0	14.9
Direct combined	10.5	174.1	12.9	3.3	2.4	109.4	24.3
Indirect	1.9	32.9	2.4	0.7	0.5	9.3	4.5
Direct and indirect	11.9	202.4	15.0	4.2	3.0	118.6	27.7
Office							
Base case	9.6	131.9	9.2	0.6	0.4	78.2	22.9
Direct shade tree	0.3	4.1	0.3	0	0	0.7	0.7
Direct high albedo	0.4	6.4	0.4	0	0	2.2	1.1
Direct combined	0.7	10.1	0.7	0	0	3.3	1.7
Indirect	0.2	2.7	0.2	0	0	2.2	0.5
Direct and indirect	0.9	14.1	1.0	0.1	0	5.6	2.2
Retail store							
Base case	15.4	218.5	15.3	0.2	0.1	81.7	36.8
Direct shade tree	0.6	8.7	0.6	0	0	1.5	1.5
Direct high albedo	1.1	16.4	1.1	0	0	5.4	2.7
Direct combined	1.7	25.4	1.8	0	0	7.6	4.2
Indirect	0.2	3.1	0.2	0	0	1.3	0.5
Direct and indirect	2.2	31.2	2.2	0	0	8.8	5.2
Total							
Base case	114.8	1275.3	92.8	30.7	21.9	858.1	257.4
Direct shade tree	5.2	94.2	6.9	2.4	1.7	62.1	12.3
Direct high albedo	8.0	119.6	8.7	1.0	0.7	59.6	18.5
Direct combined	12.9	209.6	15.3	3.4	2.4	120.3	30.1
Indirect	2.3	38.7	2.8	0.7	0.5	12.8	5.5
Direct and indirect	15.0	247.7	18.1	4.3	3.1	133	35.1

a. Metropolitan-wide annual energy savings [M$ = Million$], annual electricity savings [M$ and GWh = Giga Watt-hour], annual natural gas deficit [M$ and Mth = Million therms], peak power avoided [MW = Mega Watt] and annual carbon emissions reduction [kt = thousand tons].

b. Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

c. The conversion from GWh to carbon correspond to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 TWh sold emitted 500 MtC (million metric tons of carbon), thus 1 GWh emits 167 tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm.

Table B.2. [Update Table 10.2(b) of Konopacki and Akbari (2000)**.**] **Sacramento** metropolitan-wide estimates of energy savings, avoided peak power and carbon emissions reduction from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from urban reforestation and high-albedo surfaces.

Building Type and Mitigation Strategy	Annual Energy Savings [M$]	Annual Electricity Savings [GWh]	[M$]	Annual Natural Gas Deficit [Mth]	[M$]	Peak Power Avoided [MW]	Annual Carbon Reduction [ktC]
Residence							
Base Case	223.0	1383.2	115.5	157.8	107.5	1957.7	459.3
Direct Shade Tree	4.7	184.2	15.4	15.8	10.7	154.7	7.9
Direct High Albedo	9.2	153.2	12.8	5.3	3.6	132.7	17.9
Direct Combined	12.9	332.4	27.8	21.8	14.9	313.1	24.0
Indirect	3.7	87.0	7.3	5.3	3.6	87.9	6.9
Direct and Indirect	13.4	396.9	33.1	29.0	19.8	409.7	24.3
Office							
Base Case	27.0	303.0	25.0	3.2	2.1	228.6	55.2
Direct Shade Tree	1.9	23.8	2.0	0	0	10.9	4.0
Direct High Albedo	1.4	18.8	1.6	0.2	0.1	10.6	2.9
Direct Combined	3.4	42.4	3.5	0.2	0.1	22.1	6.8
Indirect	1.0	12.4	1.0	0	0	9.9	2.1
Direct and Indirect	4.3	54.0	4.5	0.2	0.1	31.3	8.7
Retail store							
Base Case	46.1	551.5	45.4	1.1	0.7	267.3	93.7
Direct Shade Tree	3.2	39.2	3.2	0	0	14.2	6.5
Direct High Albedo	3.9	48.2	4.0	0.1	0.1	19.3	7.9
Direct Combined	7.3	89.3	7.4	0.1	0.1	35.8	14.8
Indirect	1.2	14.7	1.2	0	0	8.2	2.5
Direct and Indirect	8.4	102.8	8.5	0.1	0.1	44.5	17.0
Total							
Base Case	296.2	2237.7	185.9	162.2	110.3	2453.6	608.4
Direct Shade Tree	9.8	247.2	20.6	15.8	10.7	179.8	18.4
Direct High Albedo	14.6	220.2	18.3	5.5	3.8	162.6	28.8
Direct Combined	23.5	464.2	38.6	22.1	15.1	371.0	45.5
Indirect	5.9	114.1	9.5	5.3	3.6	106.0	11.4
Direct and indirect	26.1	553.7	46.1	29.4	20.0	485.5	49.9

a. Metropolitan-wide annual energy savings [M$ = Million$], annual electricity savings [M$ and GWh = Giga Watt-hour], annual natural gas deficit [M$ and Mth = Million therms], peak power avoided [MW = Mega Watt] and annual carbon emissions reduction [kt = thousand tons].

b. Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

c. The conversion from GWh to carbon correspond to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 TWh sold emitted 500 MtC (million metric tons of carbon), thus 1 GWh emits 167 tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm

Table B.3. [Updated Table 10.3(b) of Konopacki and Akbari (2000).] **Salt Lake City** metropolitan-wide estimates of energy savings, avoided peak power and carbon emissions reduction from urban heat-island mitigation strategies for residential and commercial buildings. Direct savings result from the strategic placement of shade trees and the use of high-albedo roofs on individual buildings. Indirect savings derive from urban reforestation and high-albedo surfaces.

Building Type and Mitigation Strategy	Annual Energy Savings [M$]	Annual Electricity Savings [GWh]	Annual Electricity Savings [M$]	Annual Natural Gas Deficit [Mth]	Annual Natural Gas Deficit [M$]	Peak Power Avoided [MW]	Annual Carbon Reduction [ktC]
Residence							
Base Case	47.9	210.4	14.6	64.9	33.3	299.7	129.0
Direct Shade Tree	–0.2	27.7	1.9	4.2	2.1	21.5	–1.5
Direct High Albedo	0.6	20.9	1.4	1.7	0.9	21.6	1.0
Direct Combined	0.3	45.7	3.2	5.6	2.8	42.4	–0.5
Indirect	0.2	14.2	1.0	1.5	0.8	12.8	0.2
Direct and Indirect	0.4	57.6	4.0	6.9	3.5	55.2	–0.4
Office							
Base Case	7.6	106.6	60.0	4.1	1.6	90.0	23.7
Direct Shade Tree	0.6	10.2	0.6	0	0	6.8	1.7
Direct High Albedo	0.3	6.6	0.4	0.2	0.1	3.9	0.8
Direct Combined	0.9	16.6	0.9	0.2	0.1	10.4	2.5
Indirect	0.2	4.8	0.3	0.1	0	4.3	0.7
Direct and Indirect	1.1	21.2	1.2	0.2	0.1	14.7	3.3
Retail store							
Base Case	11.5	193.8	10.9	1.7	0.7	98.2	34.8
Direct Shade Tree	0.8	13.7	0.8	0	0	4.6	2.3
Direct High Albedo	0.9	17.1	1.0	0.1	0.1	6.5	2.7
Direct Combined	1.7	32.1	1.8	0.1	0.1	12.4	5.2
Indirect	0.3	5.9	0.3	0	0	2.7	1.0
Direct and Indirect	2.1	37.8	2.1	0.2	0.1	15.0	6.0
Total							
Base Case	67.0	510.8	31.4	70.8	35.6	487.9	187.8
Direct Shade Tree	1.1	51.6	3.3	4.2	2.2	32.9	2.5
Direct High Albedo	1.8	44.6	2.8	2.0	1.0	32.0	4.6
Direct Combined	2.9	94.5	5.9	5.9	3.0	65.2	7.2
Indirect	0.8	25.0	1.6	1.6	0.8	19.8	1.9
Direct and Indirect	3.6	116.5	7.3	7.3	3.7	84.9	8.9

a. Metropolitan-wide annual energy savings [M$ = Million$], annual electricity savings [M$ and GWh = Giga Watt-hour], annual natural gas deficit [M$ and Mth = Million therms], peak power avoided [MW = Mega Watt] and annual carbon emissions reduction [kt = thousand tons].

b. Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail: four) and a high-albedo roof (residential 0.5 and commercial 0.6).

c. The conversion from GWh to carbon correspond to the U.S. mix of electricity. In 1995, DOE/EIA-0383(97) (EIA, 1997) shows that 3000 TWh sold emitted 500 MtC (million metric tons of carbon), thus 1 GWh emits 167 tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm