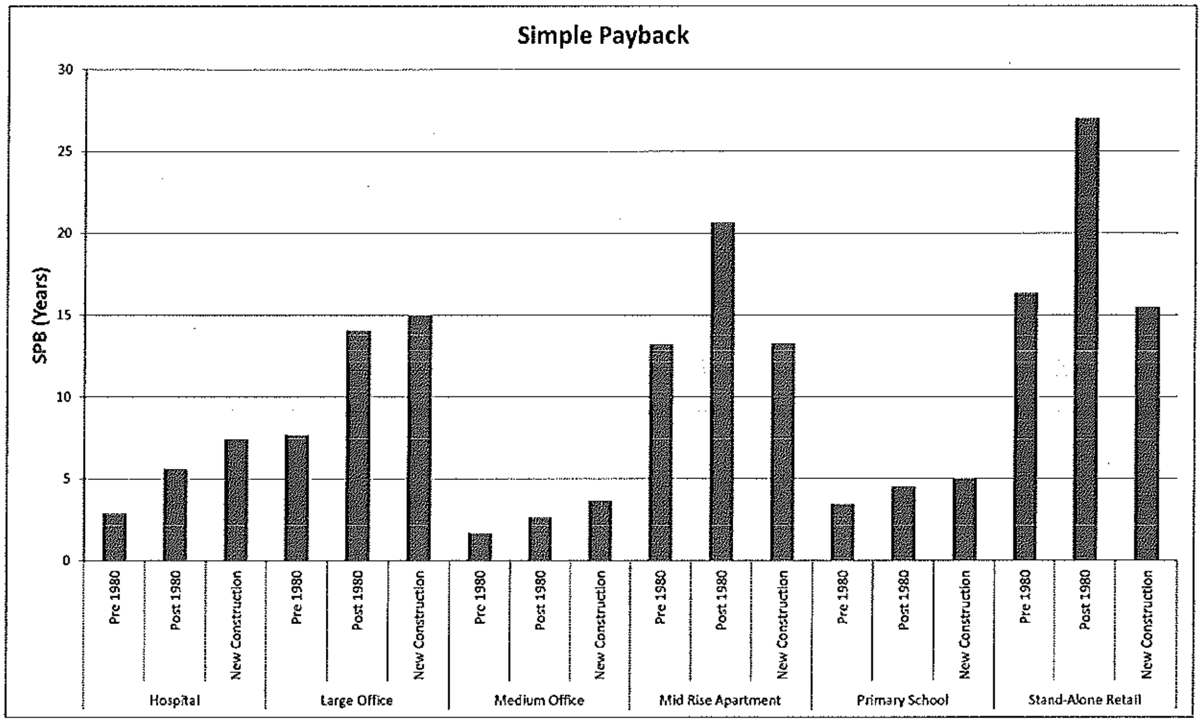
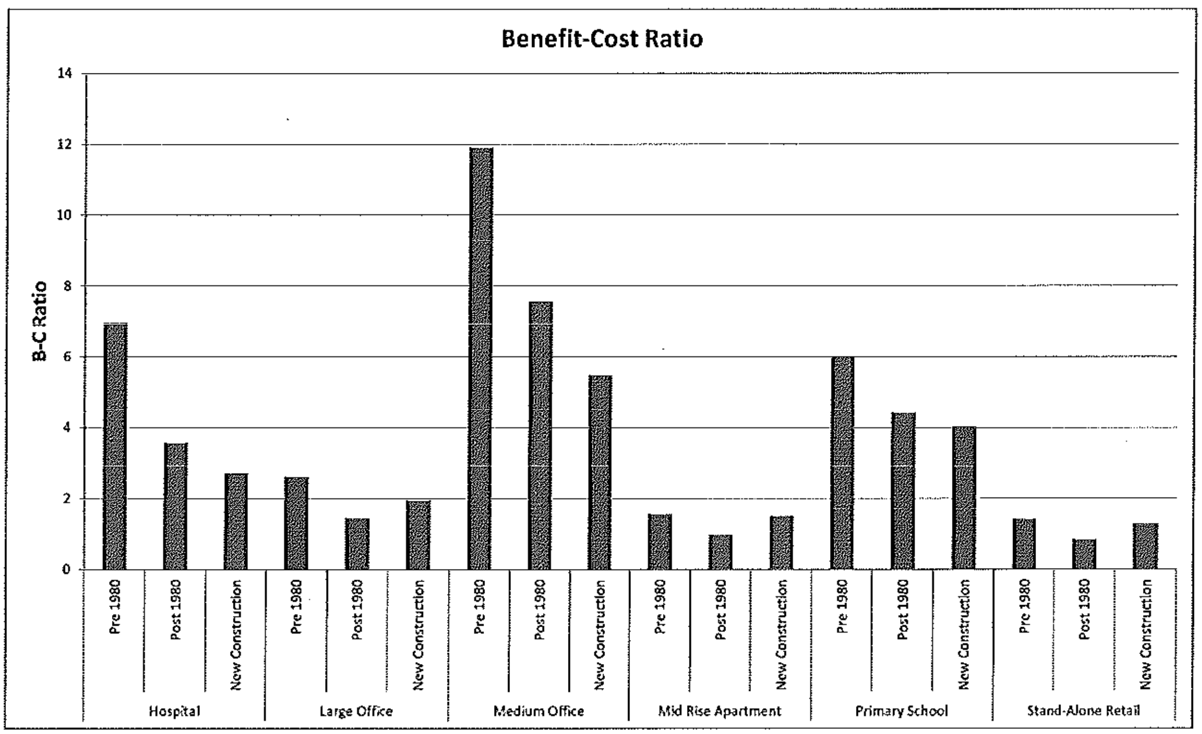
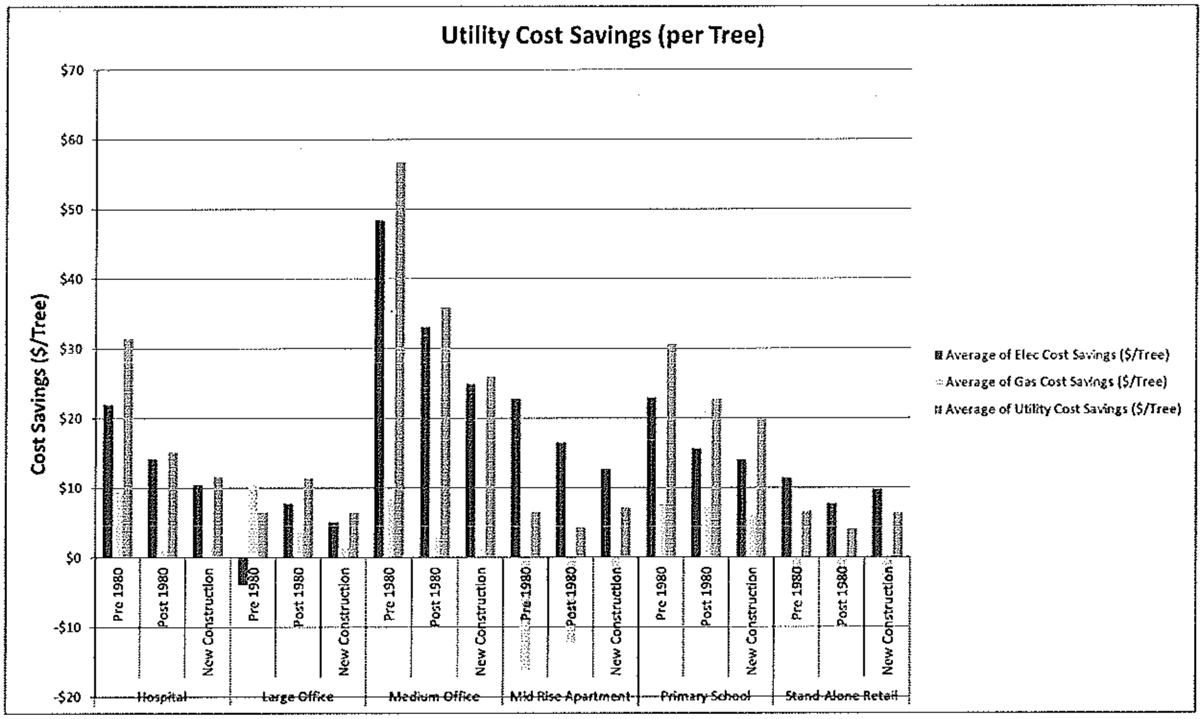
Measure CS-2

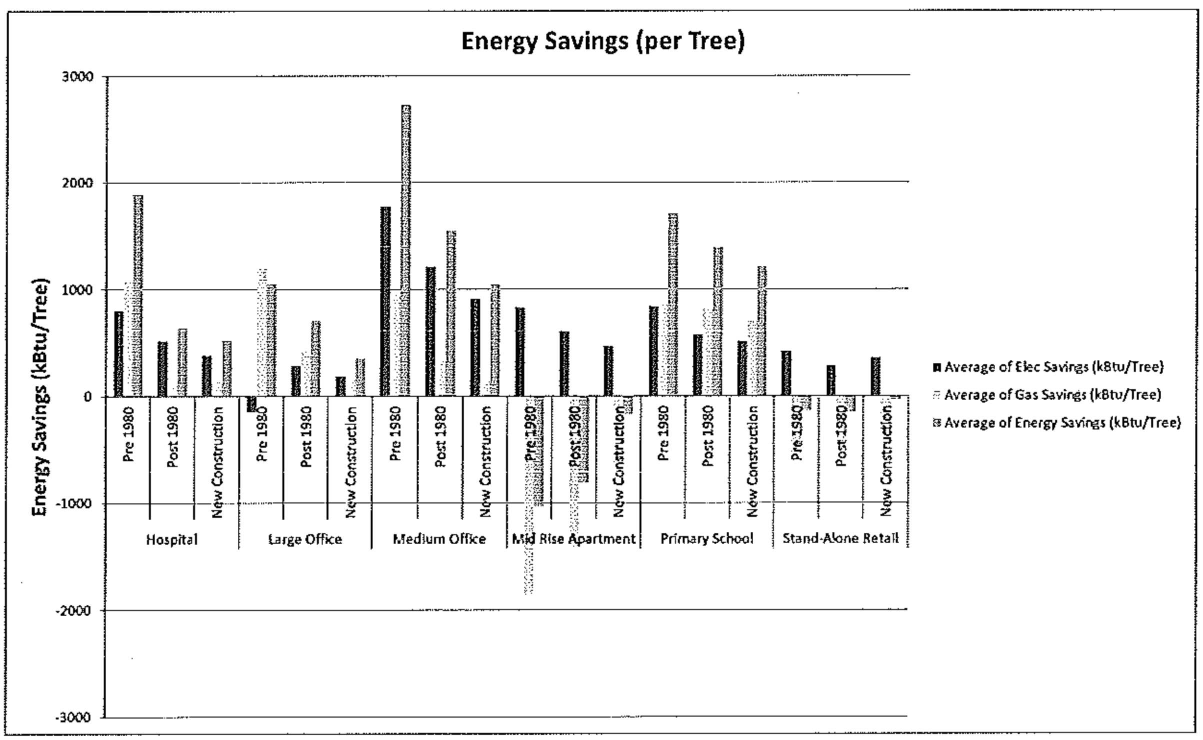

Simple Payback
SPB (Years)
30
25
20
15
10
5
0
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail


Benefit-Cost Ratio
B-C Ratio
14
12
10
8
6
4
2
0
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail

Measure CS-3

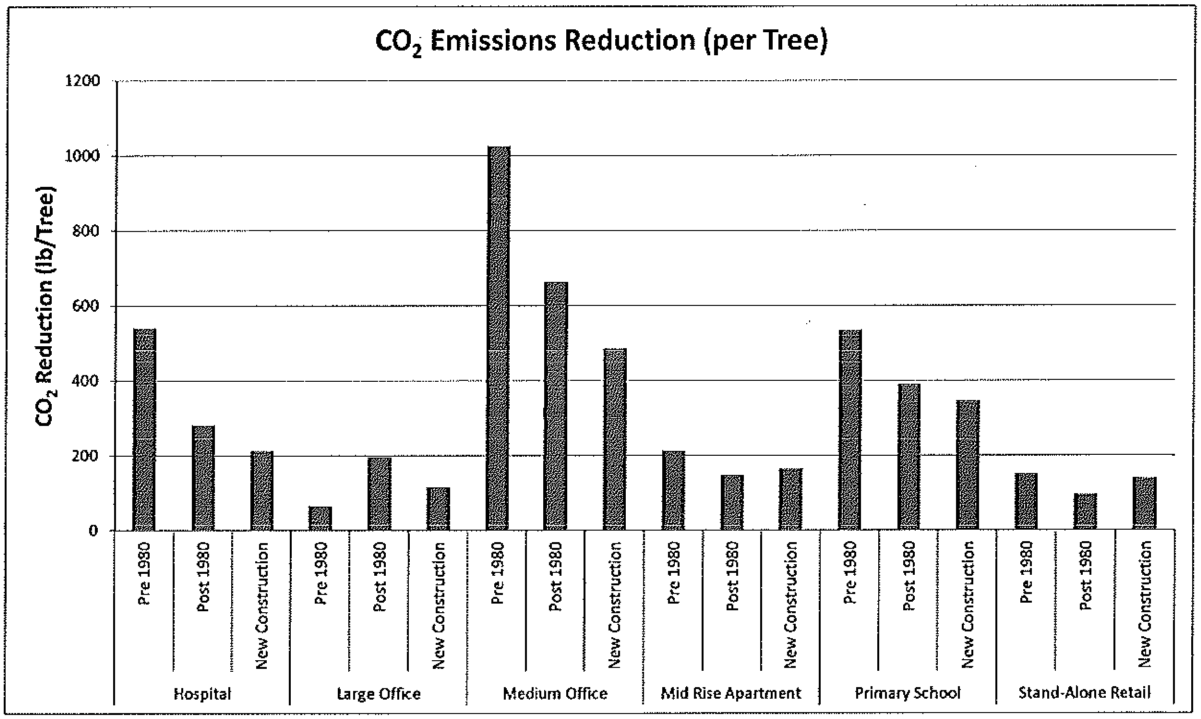


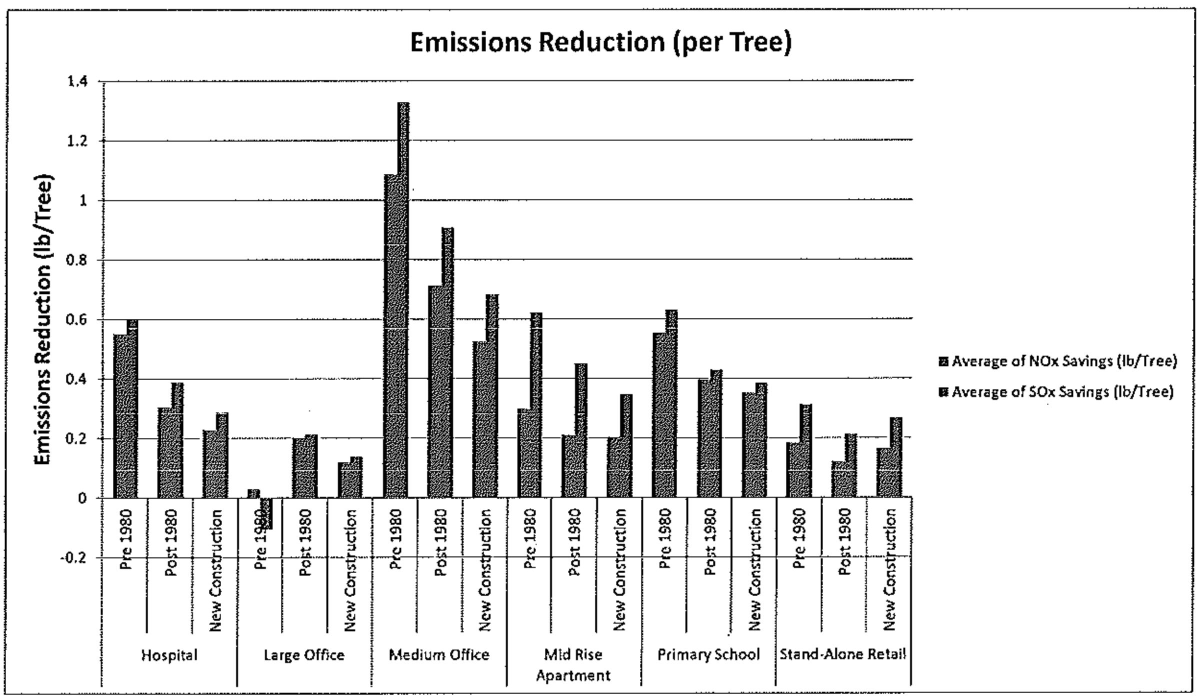
Utility Cost Savings (per Tree)
Cost Savings ($/Tree)
$70
$60
$50
$40
$30
$20
$10
$0
-$10
-$20
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail
Average of Elec Cost Savings ($/Tree)
Average of Gas Cost Savings ($/Tree)
Average of Utility Cost Savings ($/Tree)



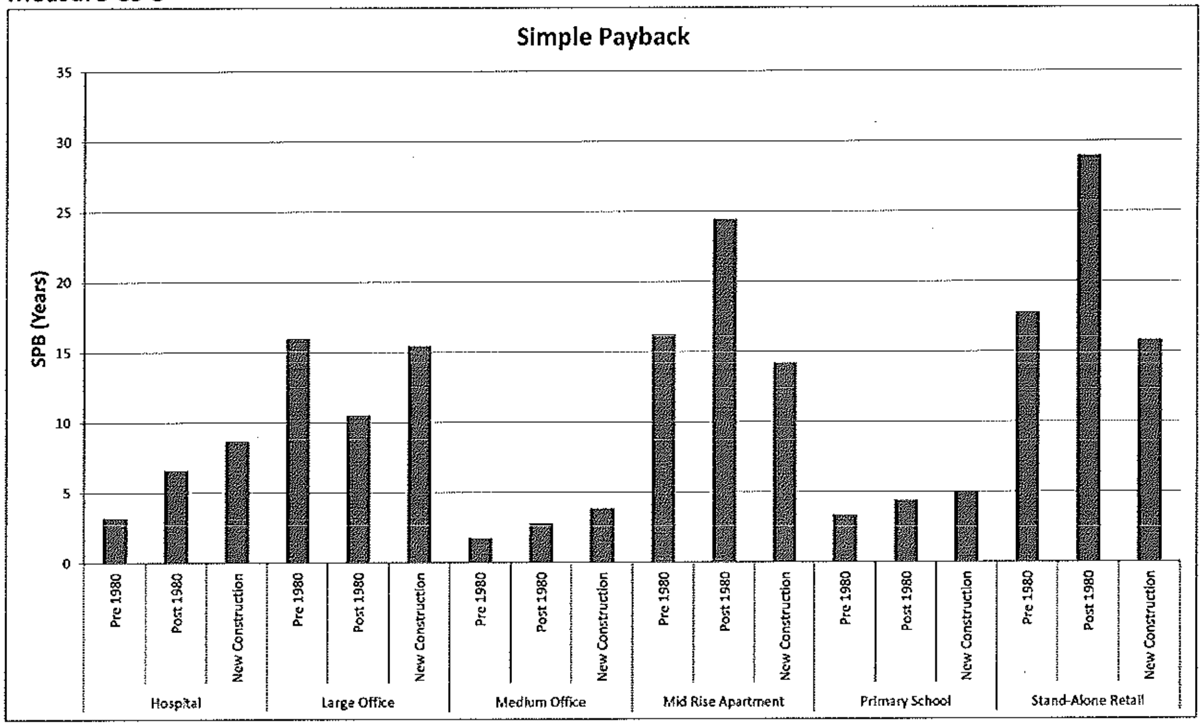
Energy Savings (per Tree)
Energy Savings (kBtu/Tree)
3000
2000
1000
0
-1000
-2000
-3000
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail
Average of Elec Savings (kBtu/Tree)
Average of Gas Savings (kBtu/Tree)
Average of Energy Savings (kBtu/Tree)

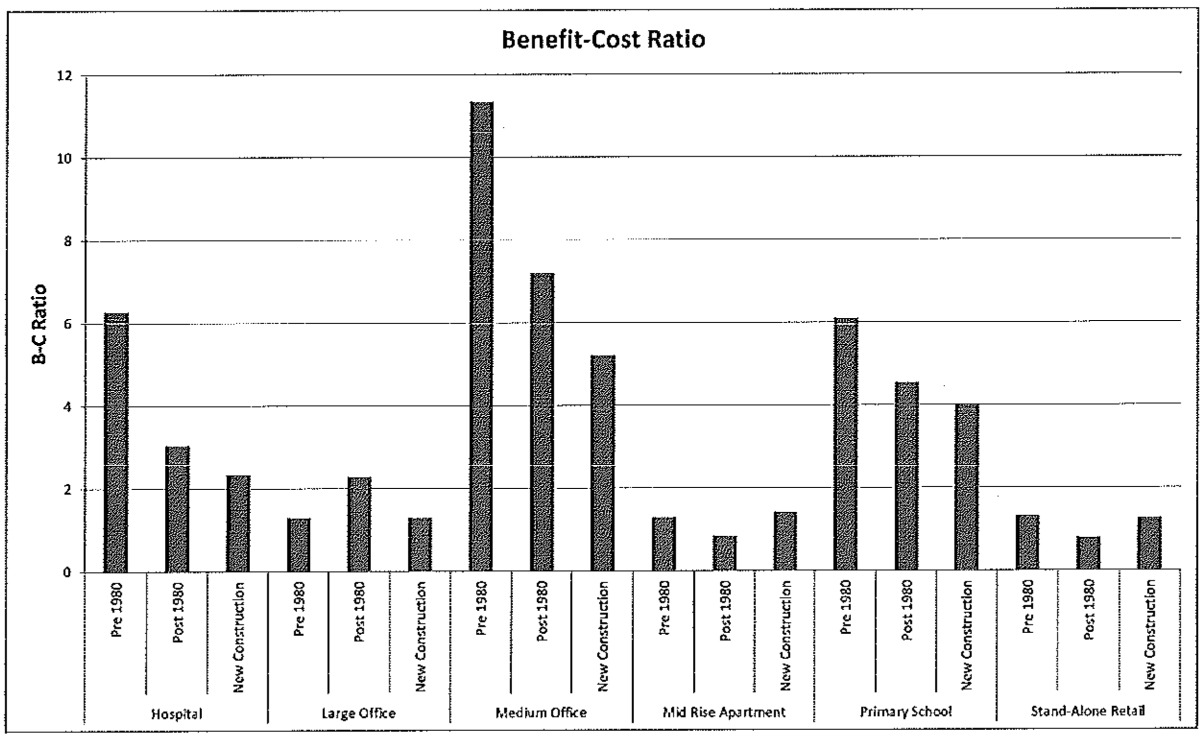
Measure CS-3


CO2 Emissions Reduction (per Tree)
CO2 Reduction (lb/Tree)
1200
1000
800
600
400
200
0
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail


Emissions Reduction (per Tree)
Emissions Reduction (lb/Tree)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail
Average of NOx Savings (lb/Tree)
Average of SOx Savings (lb/Tree)

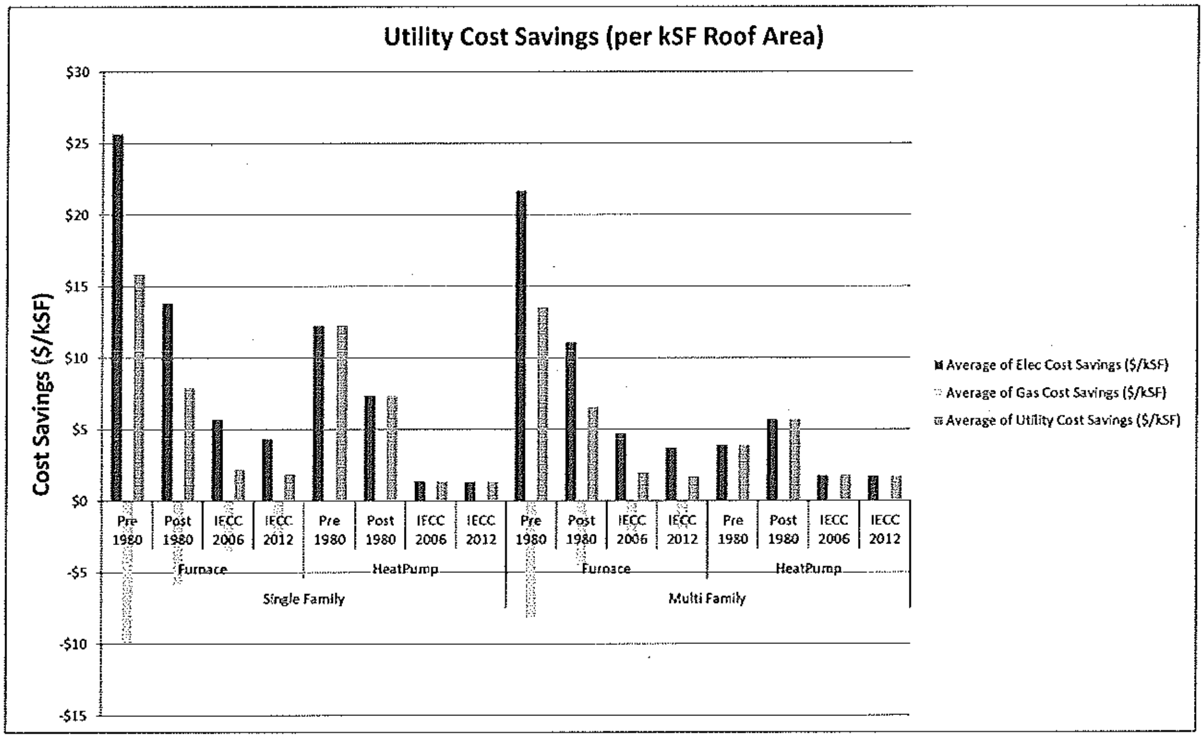
Measure CS-3


Simple Payback
SPB (Years)
35
30
25
20
15
10
5
0
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail

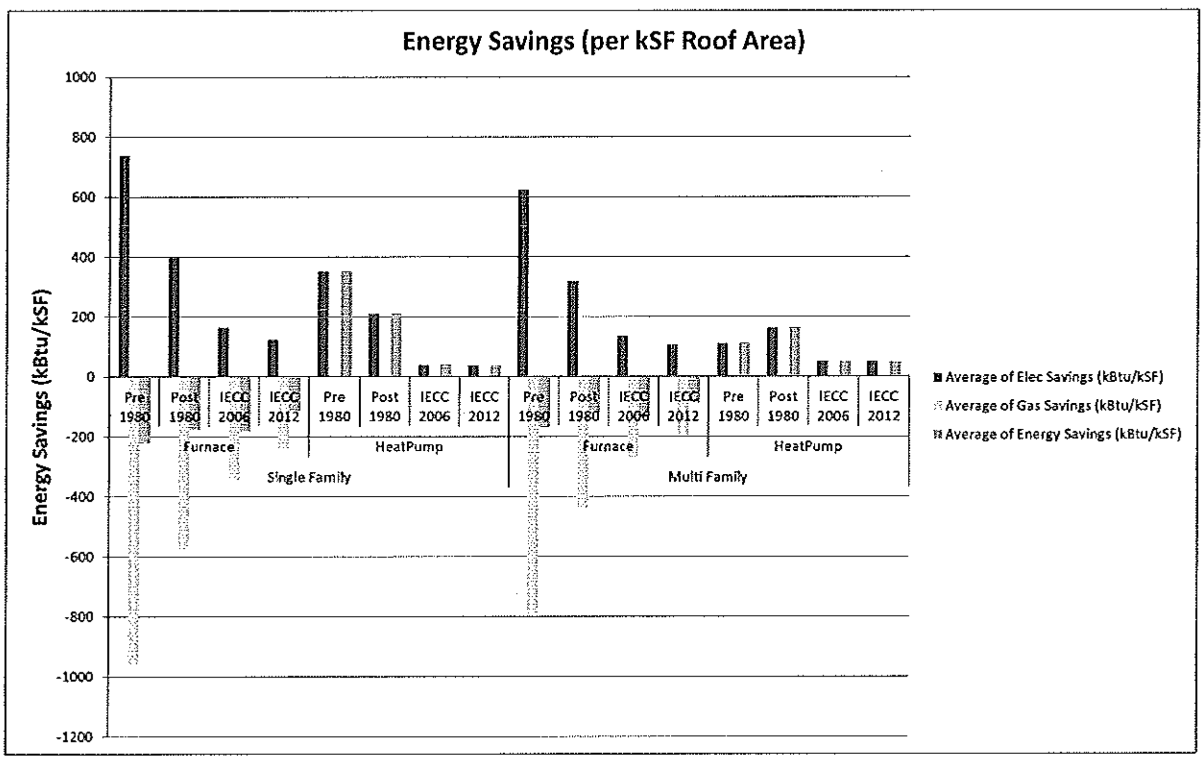

Benefit-Cost Ratio
B-C Ratio
12
10
8
6
4
2
0
Pre 1980
Post 1980
New Construction
Hospital
Large Office
Medium Office
Mid Rise Apartment
Primary School
Stand-Alone Retail

Appendix B: Residential Measure Results

Measure RR-1

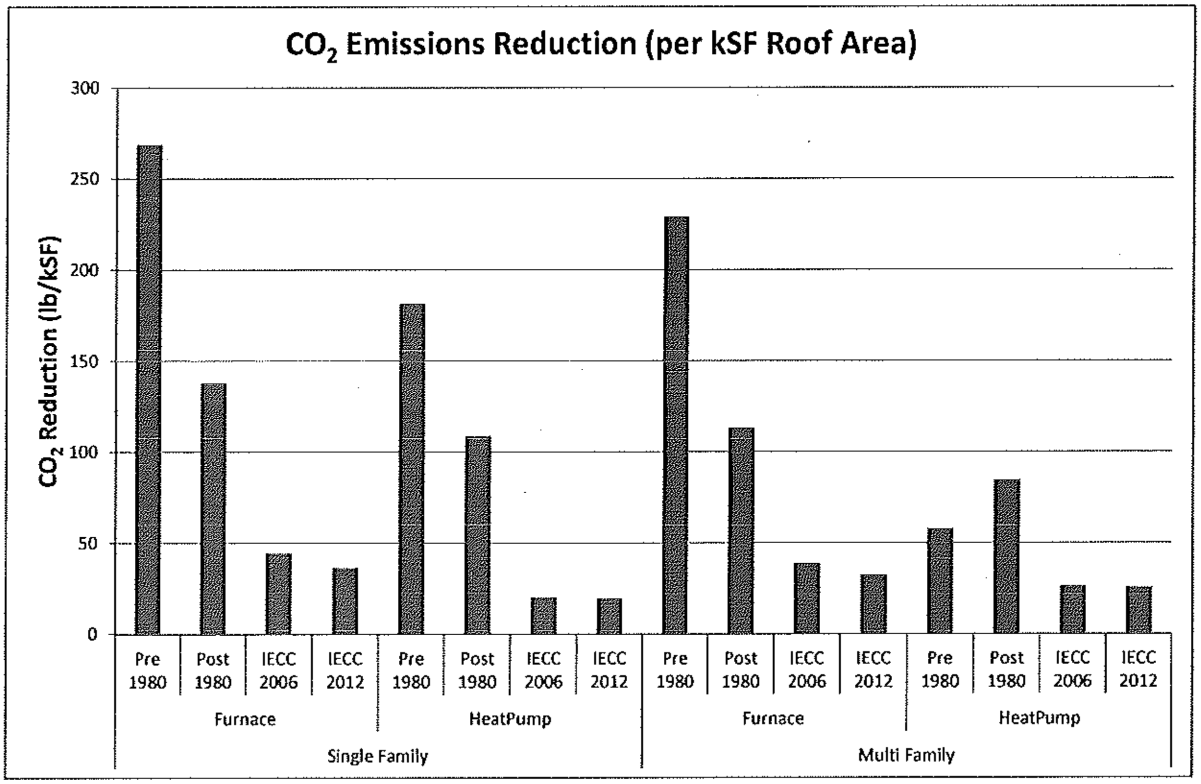


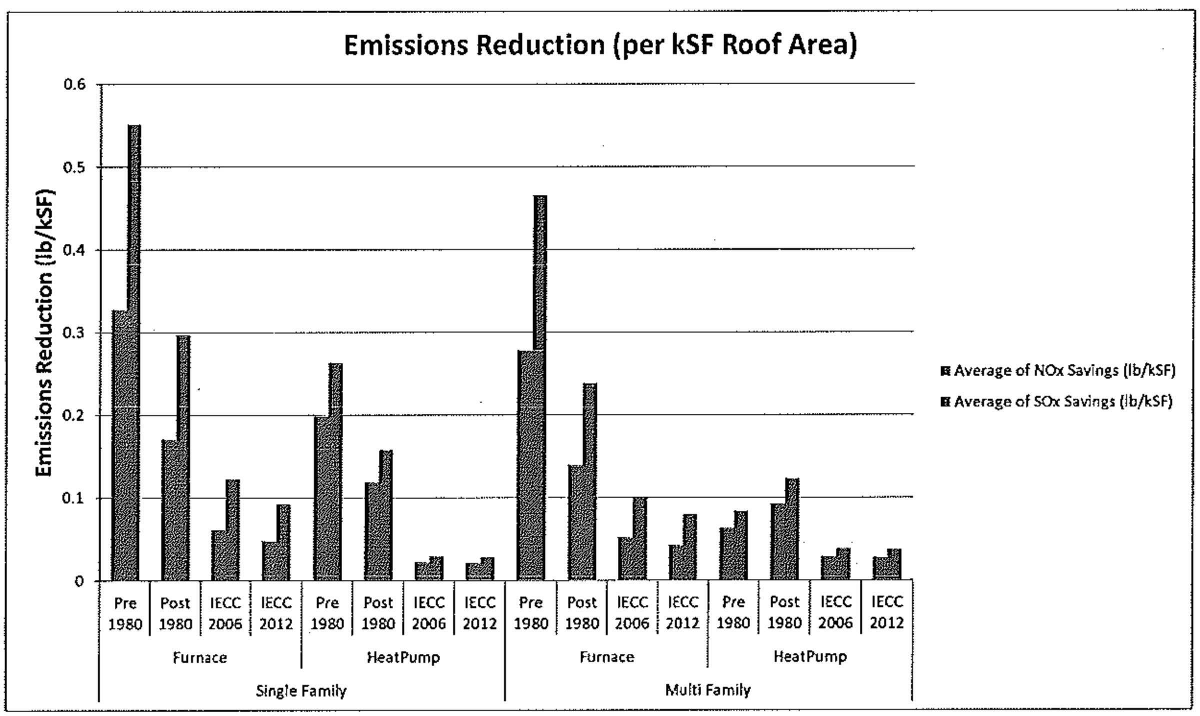
Utility Cost Savings (per kSF Roof Area)
Cost Savings ($/kSF)
$30
$25
$20
$15
$10
$5
$0
-$5
-$10
-$15
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Cost Savings ($/kSF)
Average of Gas Cost Savings ($/kSF)
Average of Utility Cost Savings ($/kSF)



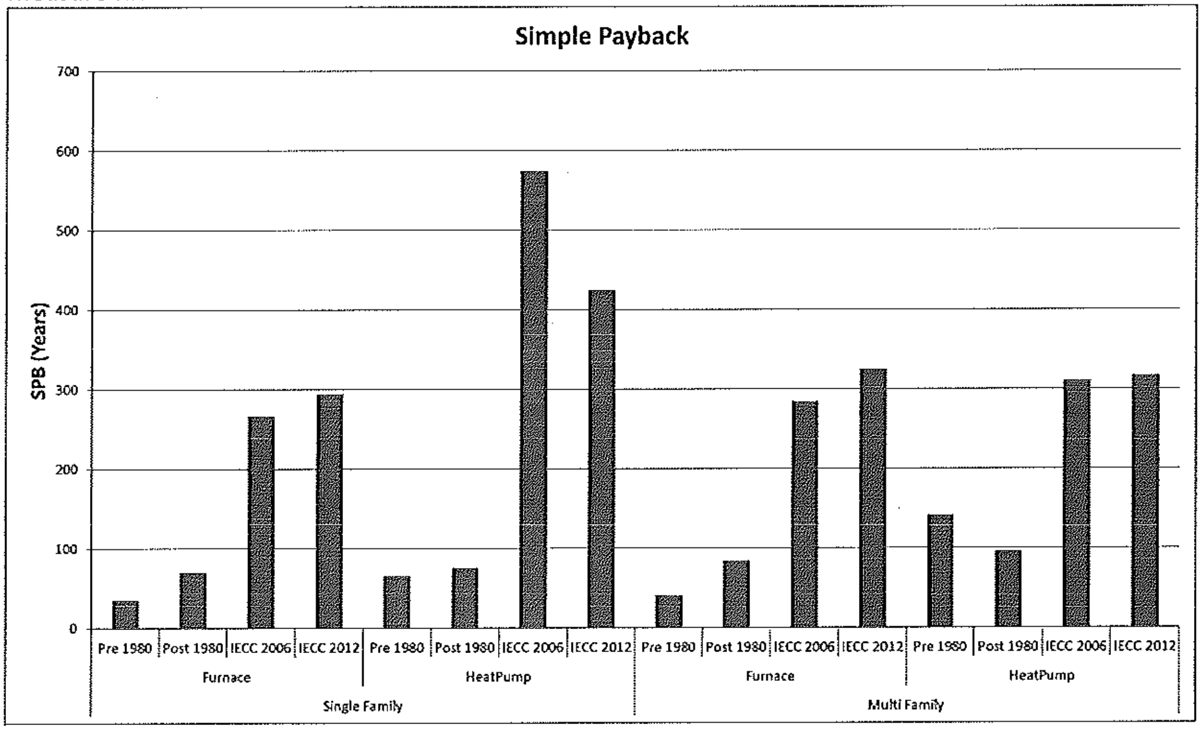
Energy Savings (per kSF Roof Area)
Energy Savings (kBtu/kSF)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Savings (kBtu/kSF)
Average of Gas Savings (kBtu/kSF)
Average of Energy Savings (kBtu/kSF)

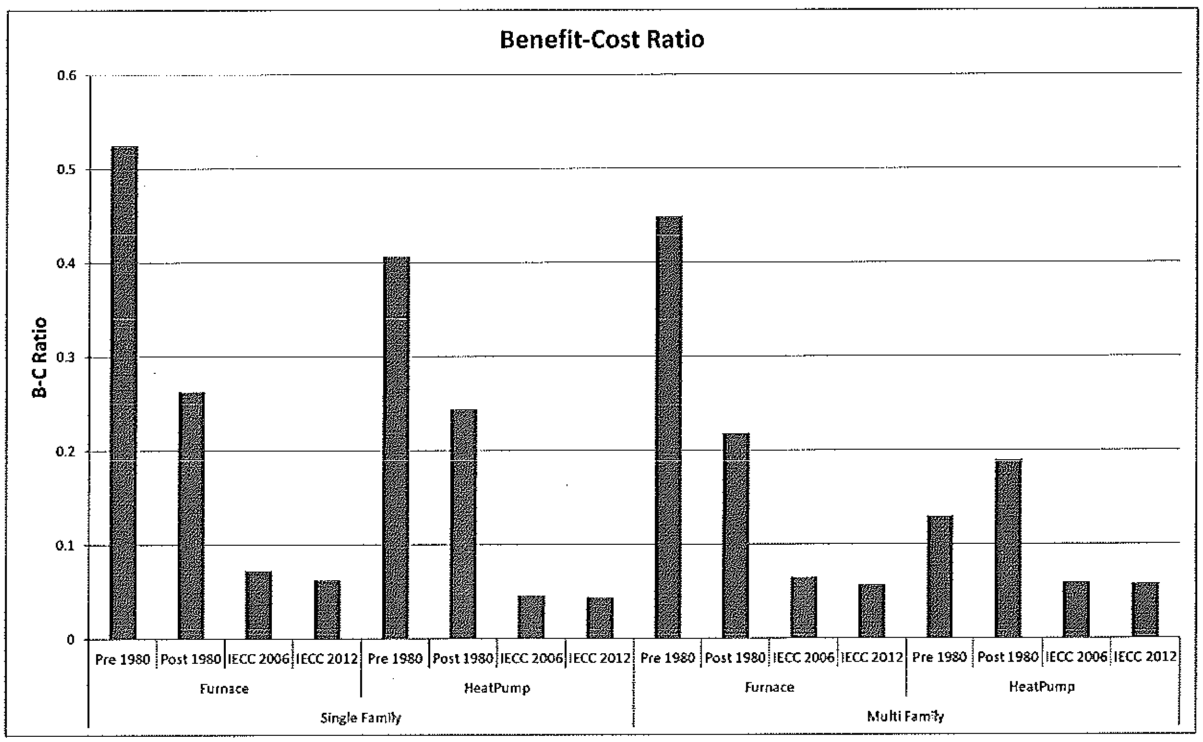
Measure RR-1


CO_2 Emissions Reduction (per kSF Roof Area)
CO_2 Reduction (lb/kSF)
300
250
200
150
100
50
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

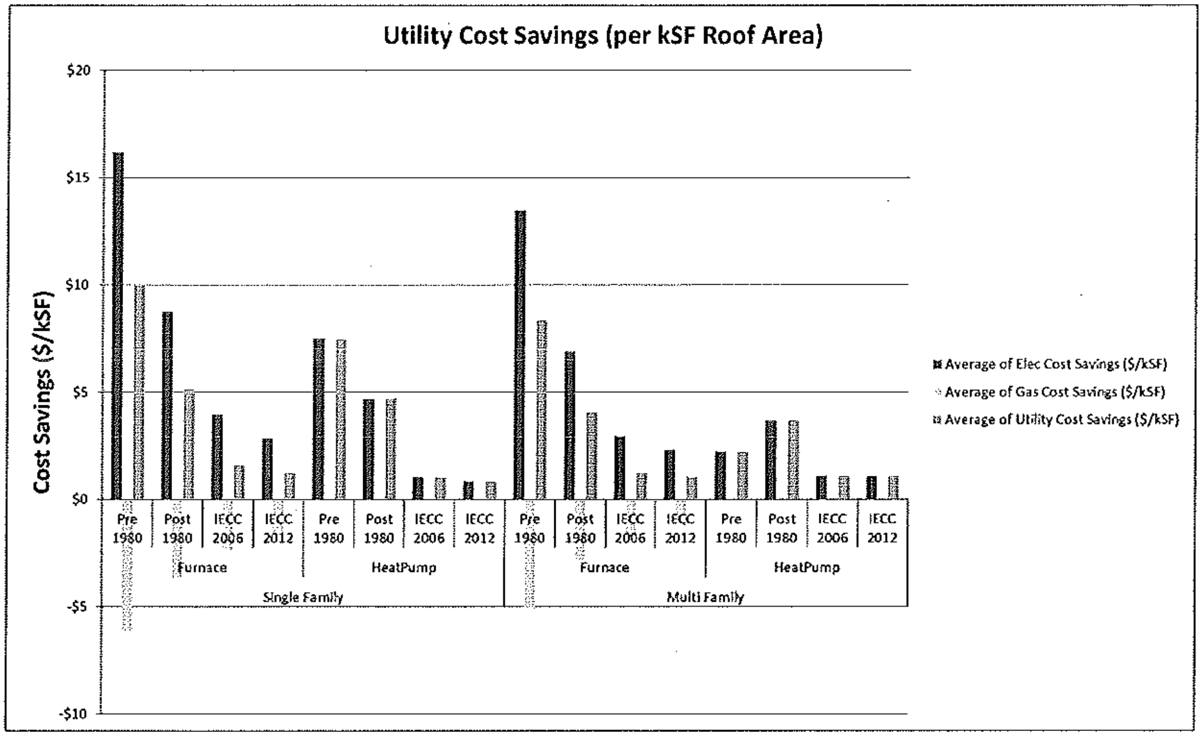

Emissions Reduction (per kSF Roof Area)
Emissions Reduction (lb/kSF)
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of NOx Savings (lb/kSF)
Average of SOx Savings (lb/kSF)

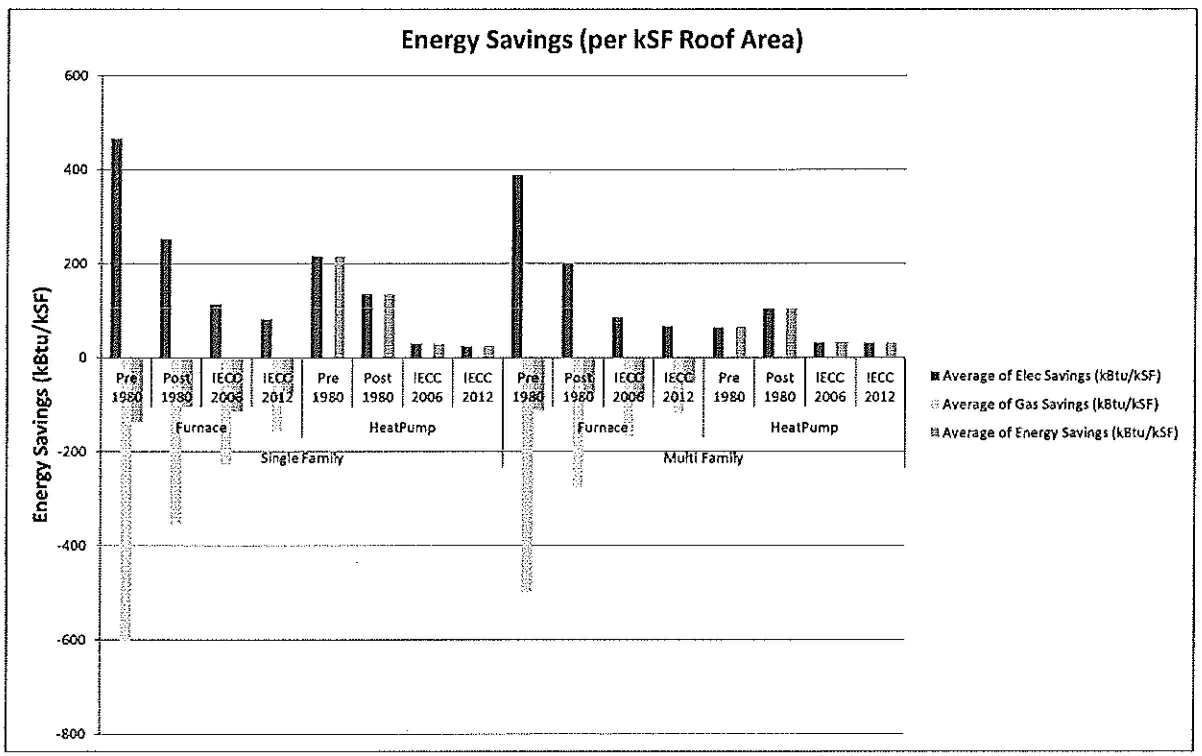
Measure RR-1


Simple Payback
SPB (Years)
700
600
500
400
300
200
100
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

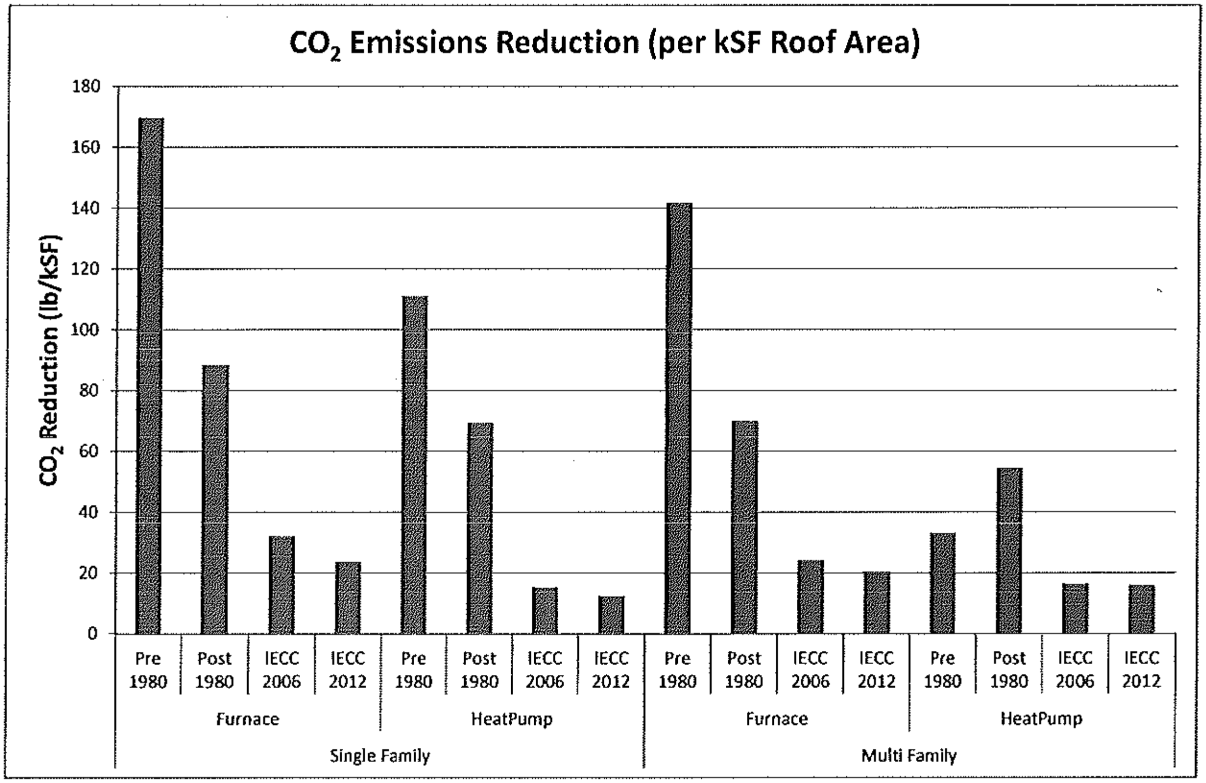

Benefit-Cost Ratio
B-C Ratio
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

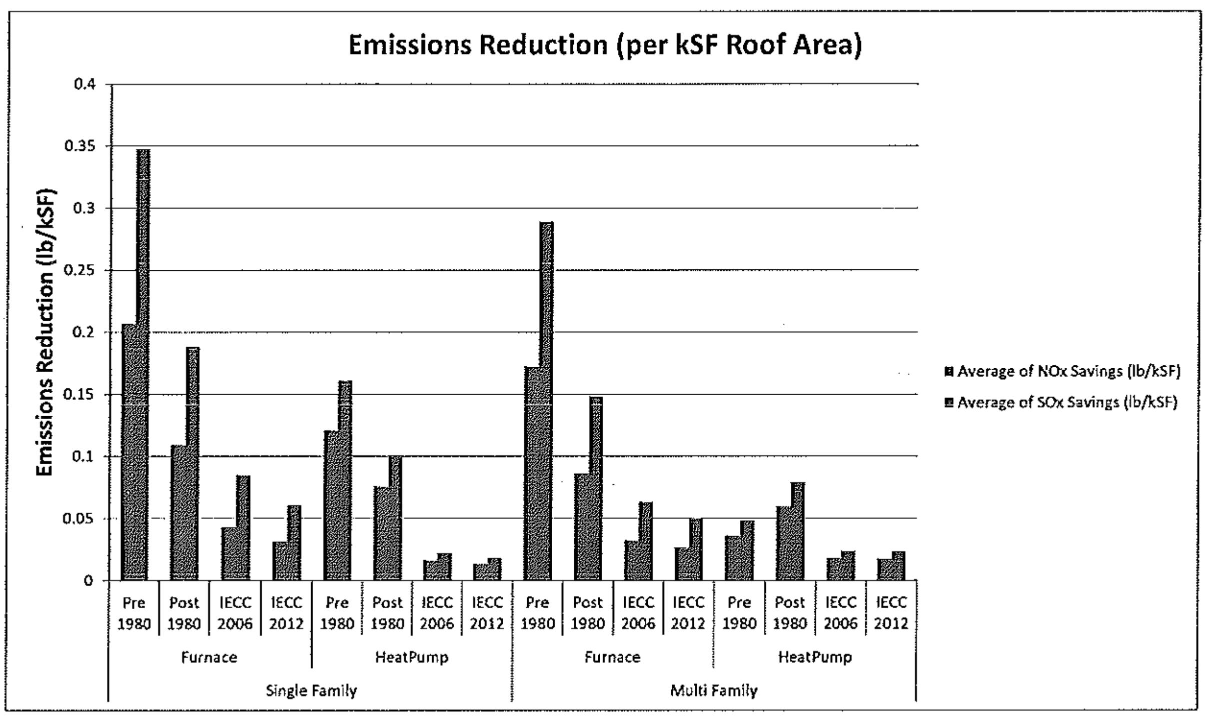
Measure RR-2


Utility Cost Savings (per kSF Roof Area)
Cost Savings ($/kSF)
$20
$15
$10
$5
$0
-$5
-$10
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Cost Savings ($/kSF)
Average of Gas Cost Savings ($/kSF)
Average of Utility Cost Savings ($/kSF)

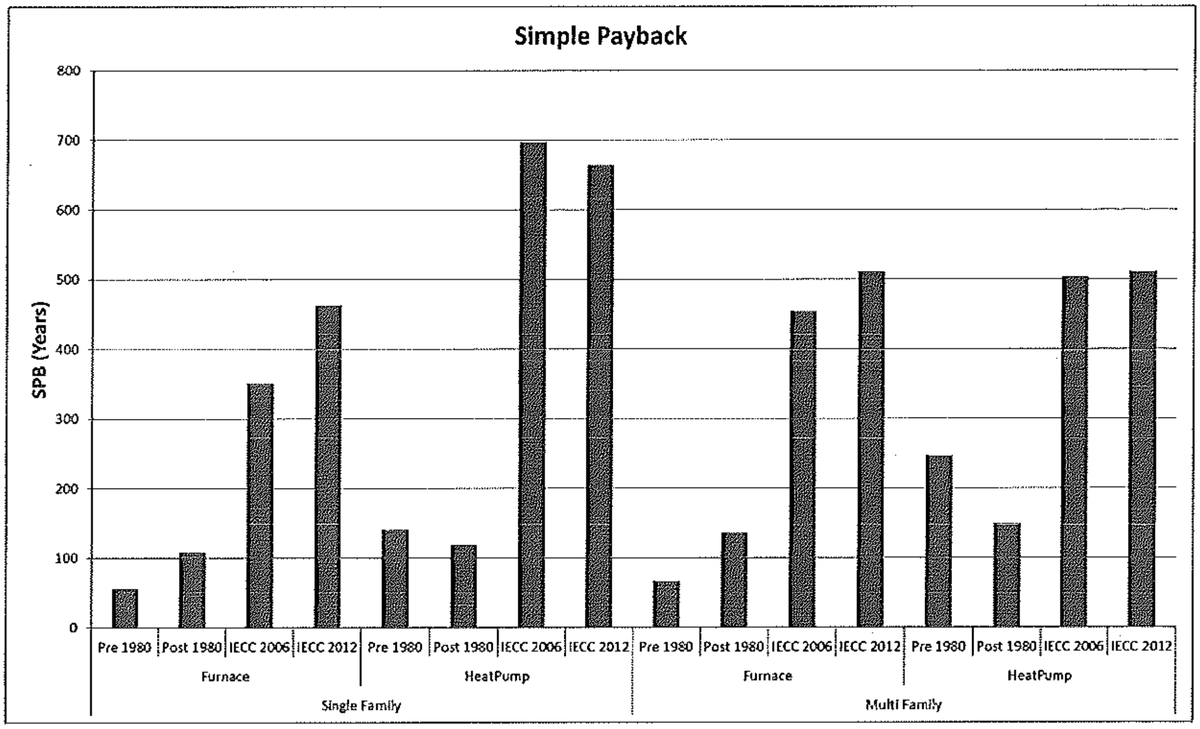

Energy Savings (per kSF Roof Area)
Energy Savings (kBtu/kSF)
600
400
200
0
-200
-400
-600
-800
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Savings (kBtu/kSF)
Average of Gas Savings (kBtu/kSF)
Average of Energy Savings (kBtu/kSF)

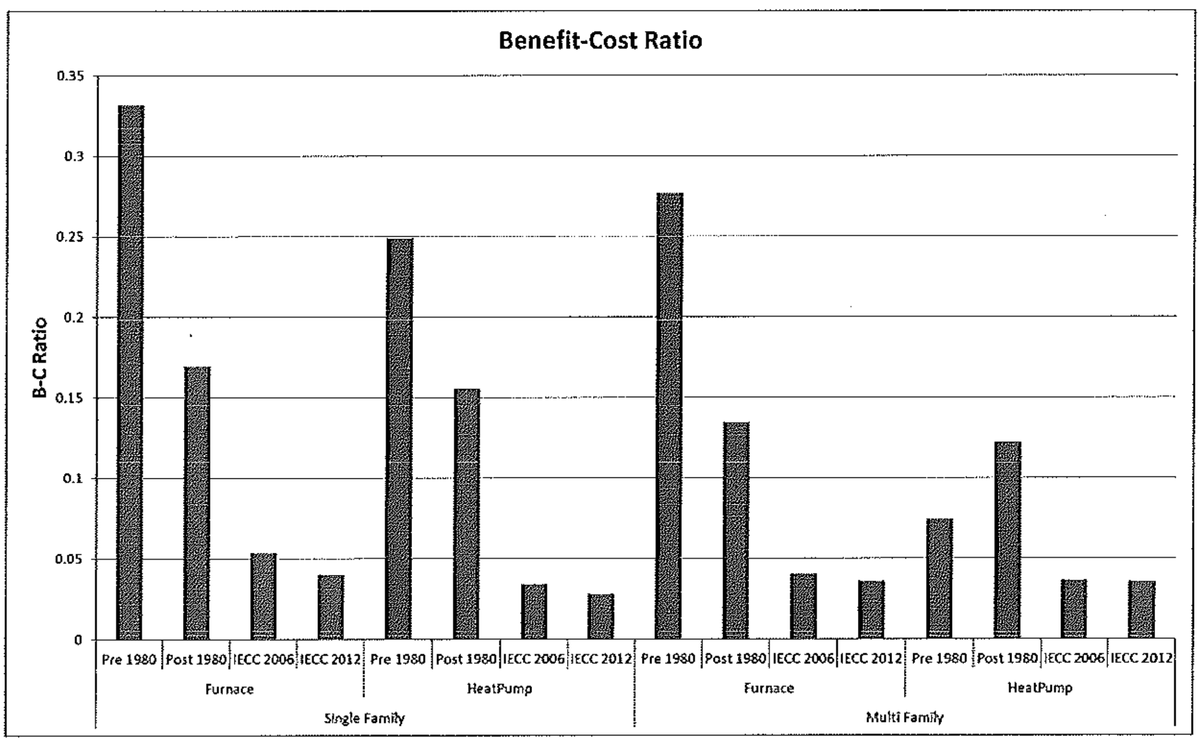
Measure RR-2


CO_2 Emissions Reduction (per kSF Roof Area)
CO_2 Reduction (lb/kSF)
180
160
140
120
100
80
60
40
20
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

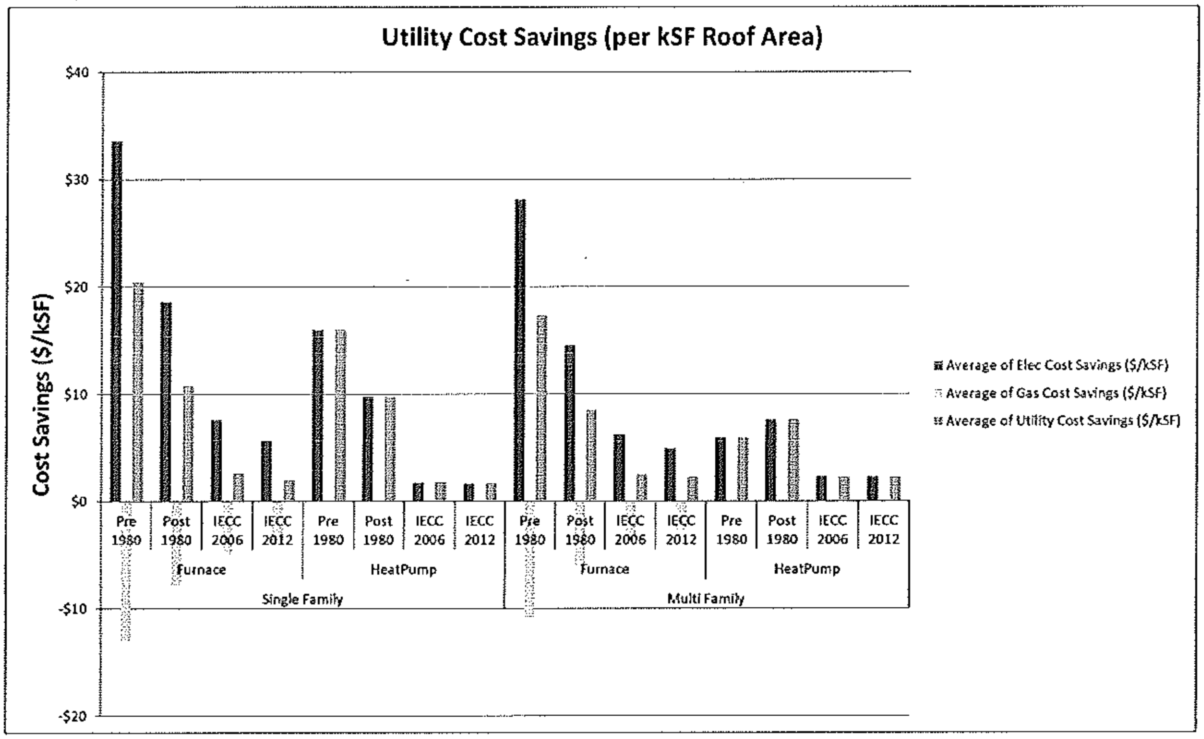

Emissions Reduction (per kSF Roof Area)
Emissions Reduction (lb/kSF)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Average of NOx Savings (lb/kSF)
Average of SOx Savings (lb/kSF)
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

Measure RR-2

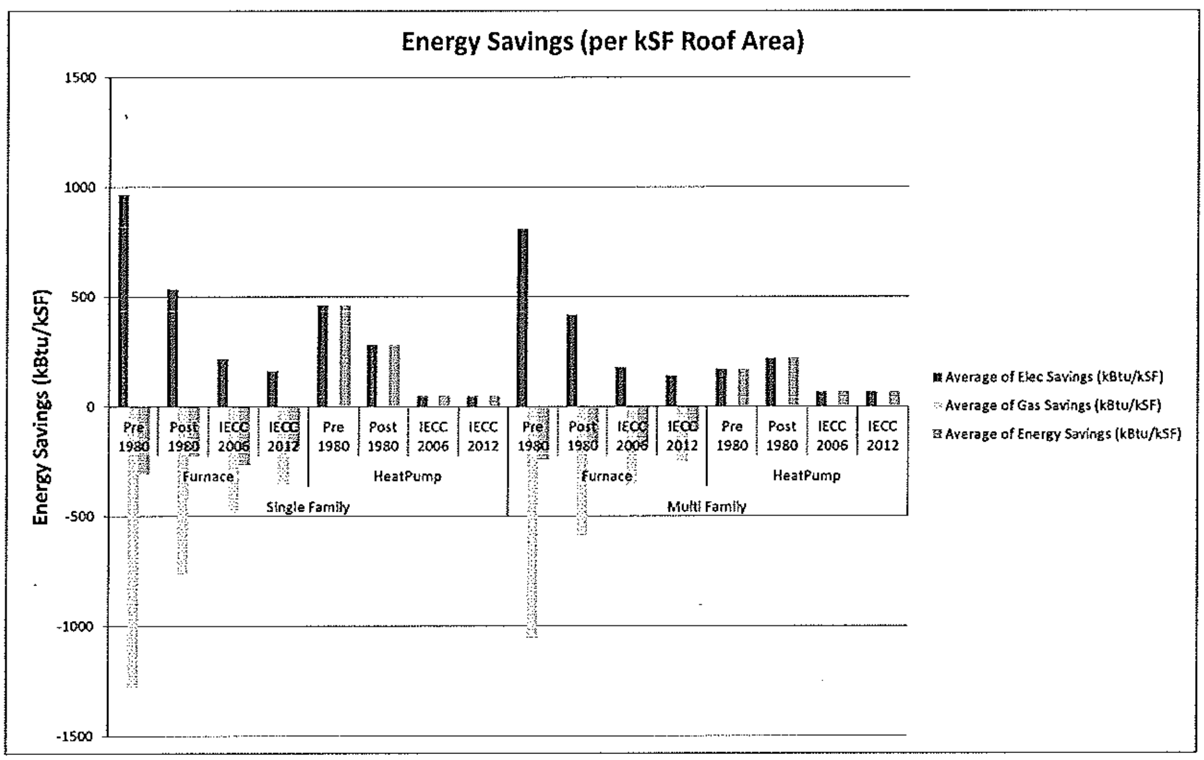

Simple Payback
SPB (Years)
800
700
600
500
400
300
200
100
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family


Benefit-Cost Ratio
B-C Ratio
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

Measure RR-3

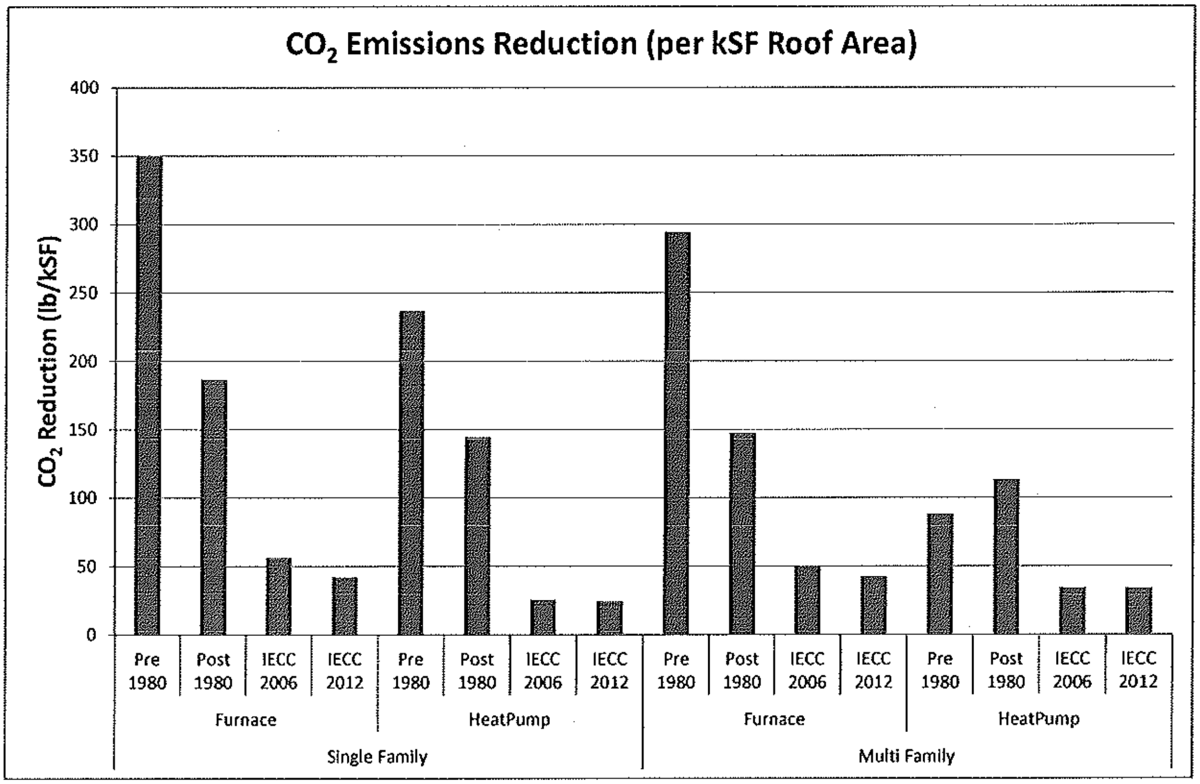


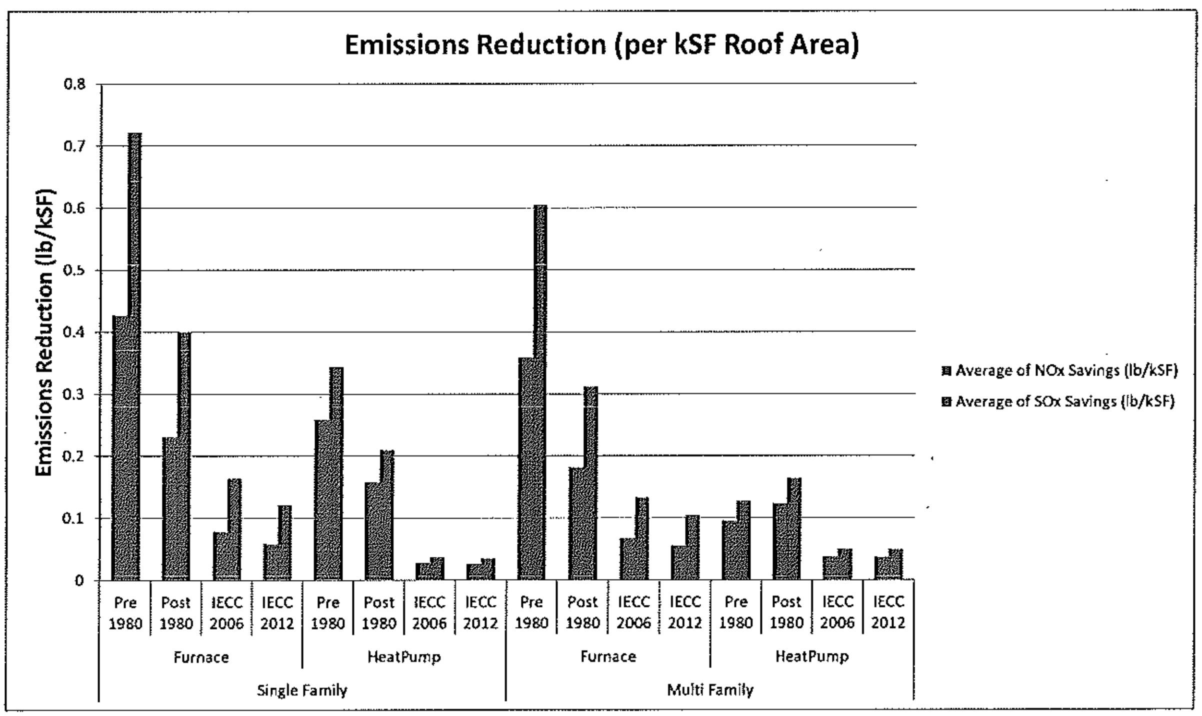
Utility Cost Savings (per kSF Roof Area)
Cost Savings ($/kSF)
$40
$30
$20
$10
$0
-$10
-$20
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Cost Savings ($/kSF)
Average of Gas Cost Savings ($/kSF)
Average of Utility Cost Savings ($/kSF)



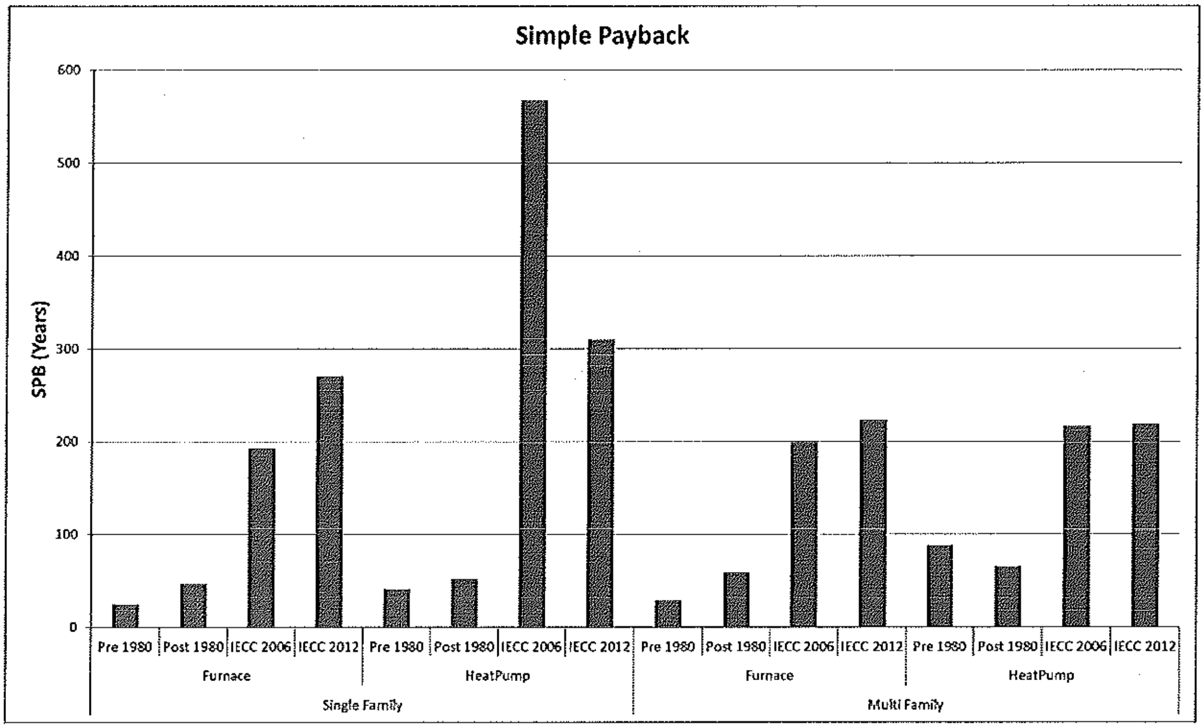
Energy Savings (per kSF Roof Area)
Energy Savings (kBtu/kSF)
1500
1000
500
0
-500
-1000
-1500
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Savings (kBtu/kSF)
Average of Gas Savings (kBtu/kSF)
Average of Energy Savings (kBtu/kSF)

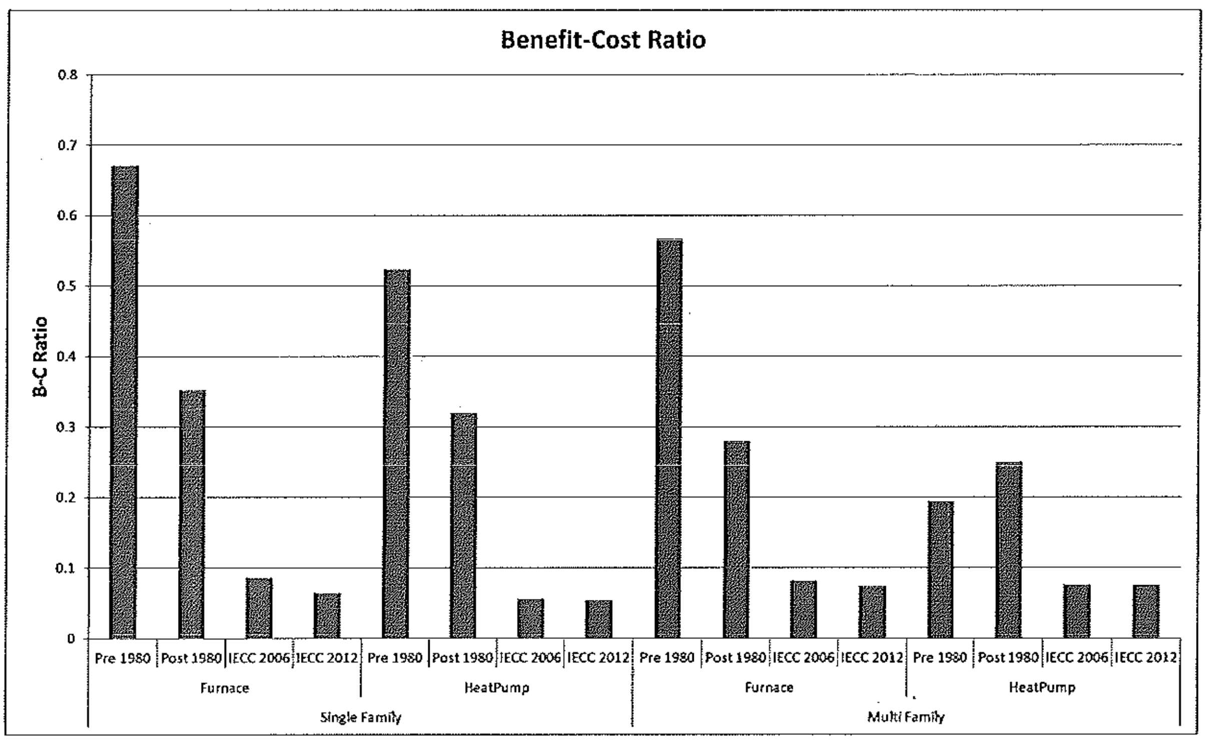
Measure RR-3


CO2 Emissions Reduction (per kSF Roof Area)
CO2 Reduction (lb/kSF)
400
350
300
250
200
150
100
50
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

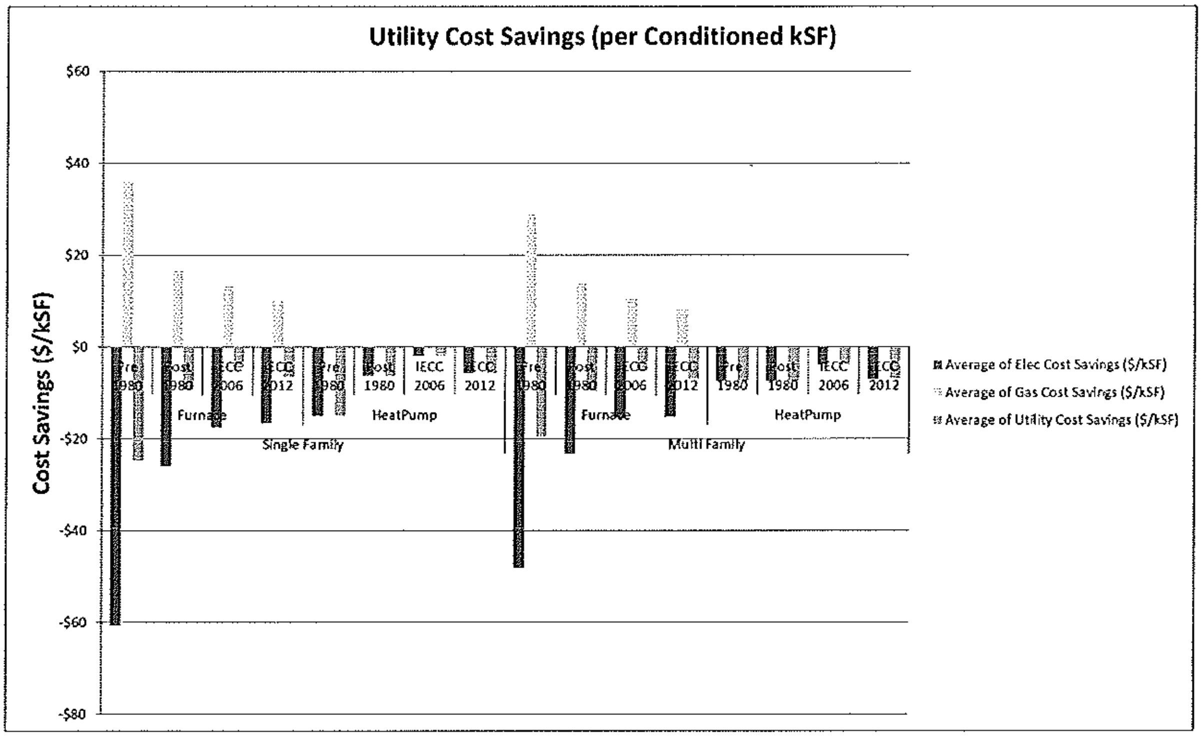

Emissions Reduction (per kSF Roof Area)
Emissions Reduction (lb/kSF)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of NOx Savings (lb/kSF)
Average of SOx Savings (lb/kSF)

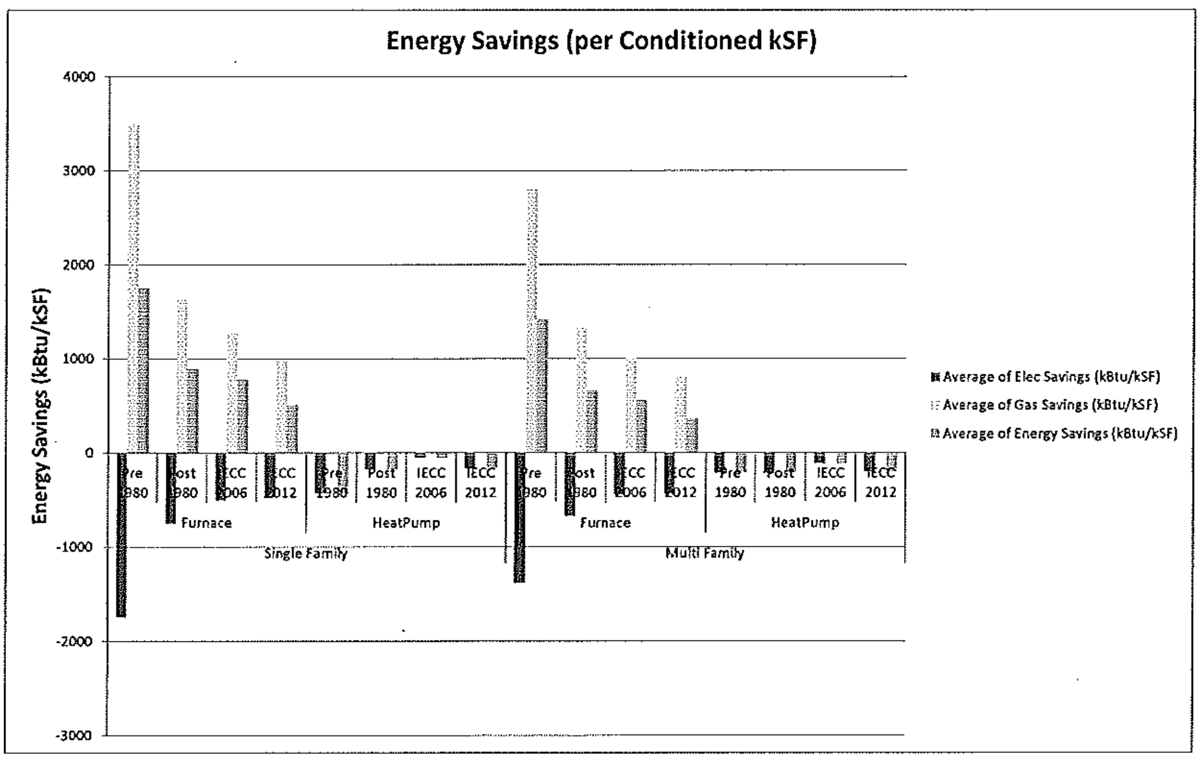
Measure RR-3


Simple Payback
SPB (Years)
600
500
400
300
200
100
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

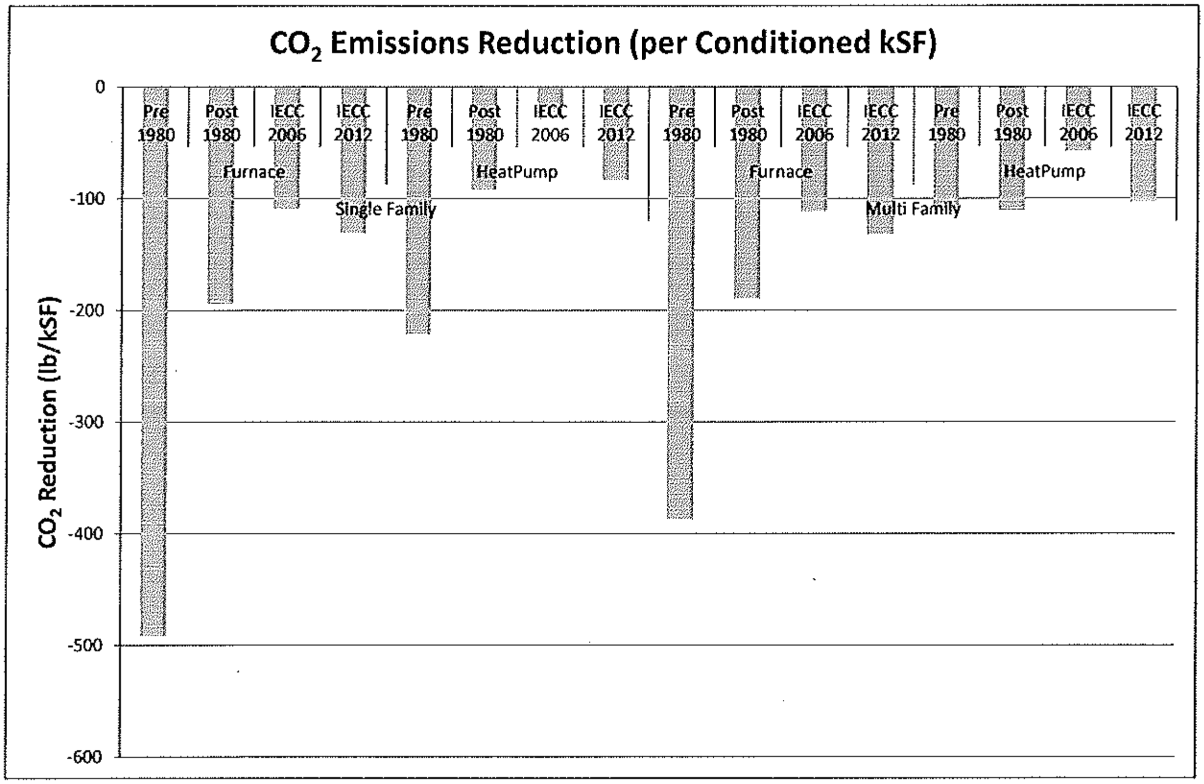

Benefit-Cost Ratio
B-C Ratio
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

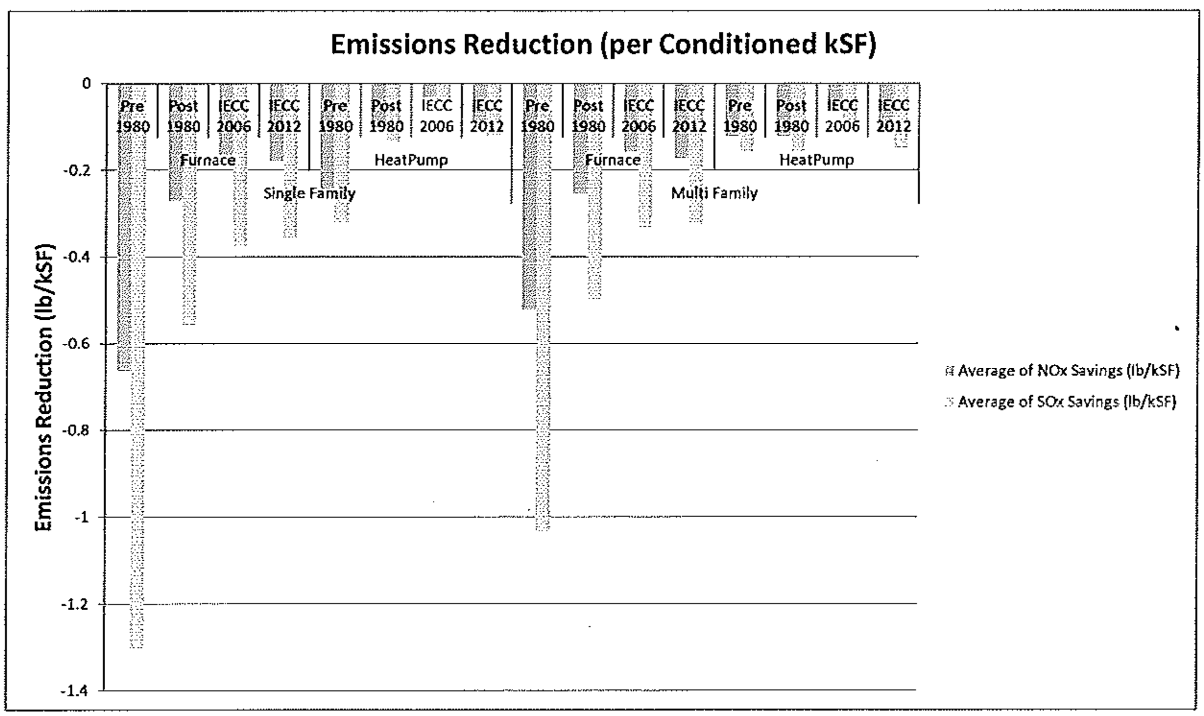
Measure RG-1


Utility Cost Savings (per Conditioned kSF)
Cost Savings ($/kSF)
$60
$40
$20
$0
-$20
-$40
-$60
-$80
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Cost Savings ($/kSF)
Average of Gas Cost Savings ($/kSF)
Average of Utility Cost Savings ($/kSF)

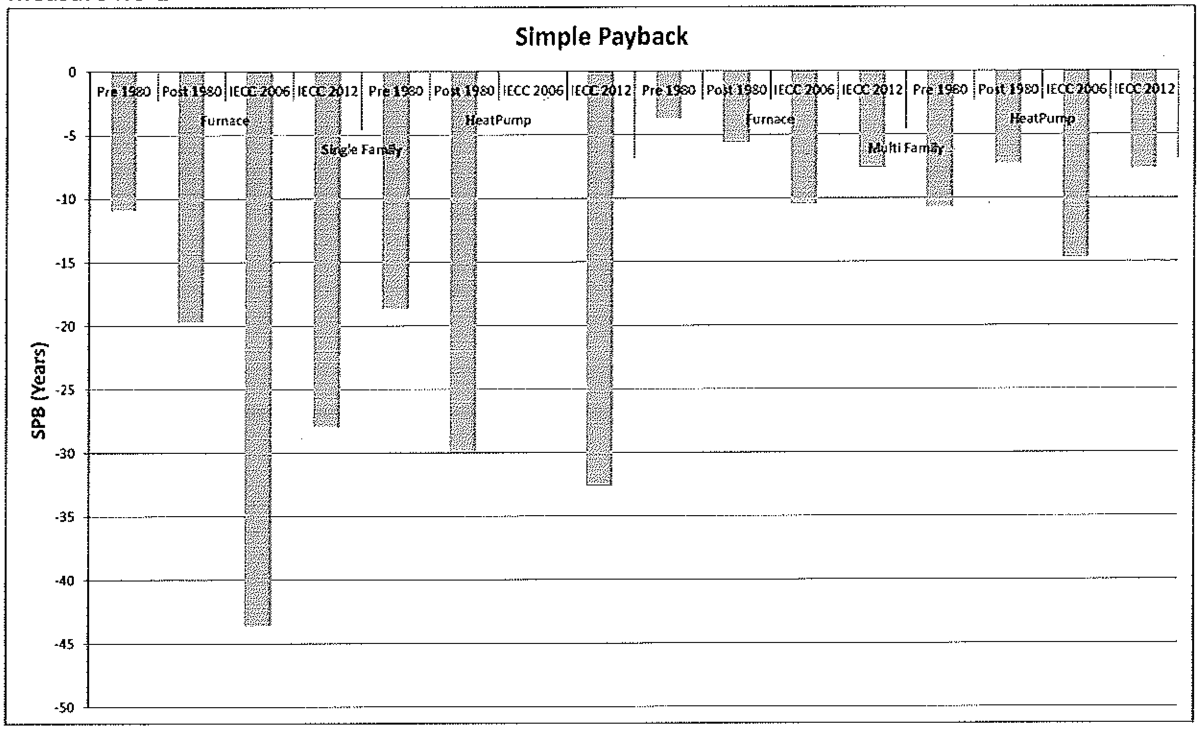

Energy Savings (per Conditioned kSF)
Energy Savings (kBtu/kSF)
4000
3000
2000
1000
0
-1000
-2000
-3000
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Savings (kBtu/kSF)
Average of Gas Savings (kBtu/kSF)
Average of Energy Savings (kBtu/kSF)

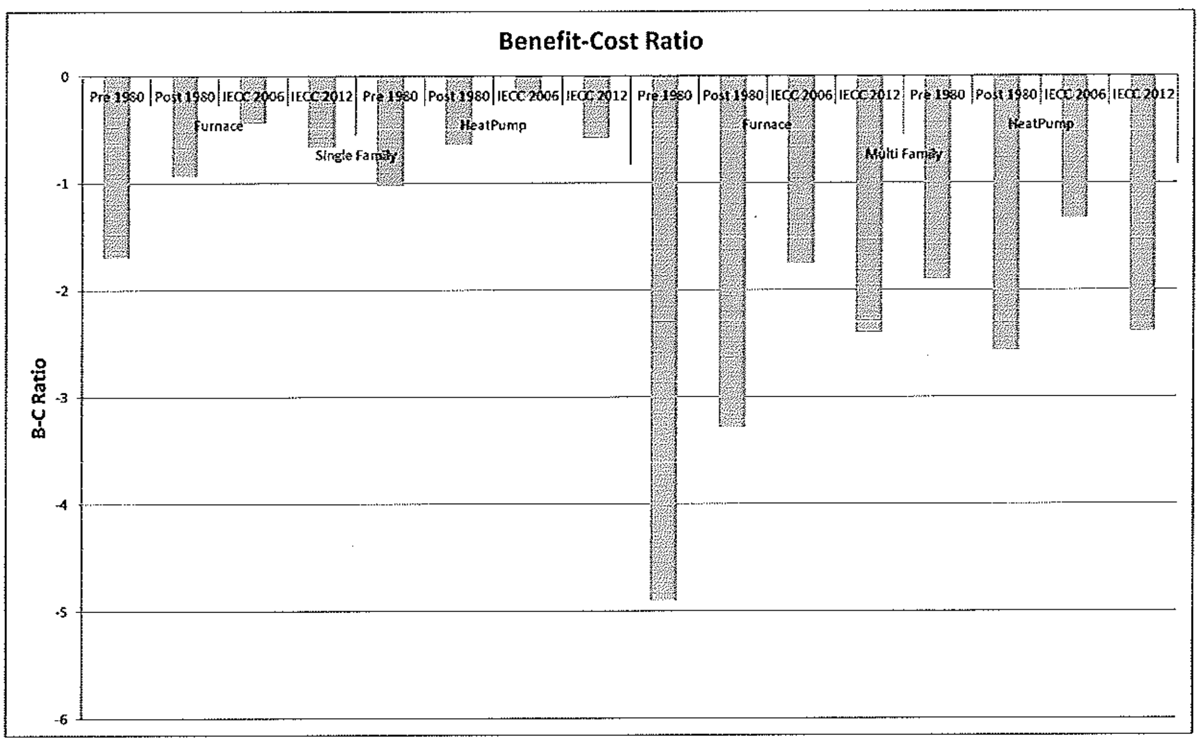
Measure RG-1


CO2 Emissions Reduction (per Conditioned kSF)
CO2 Reduction (lb/kSF)
0
-100
-200
-300
-400
-500
-600
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

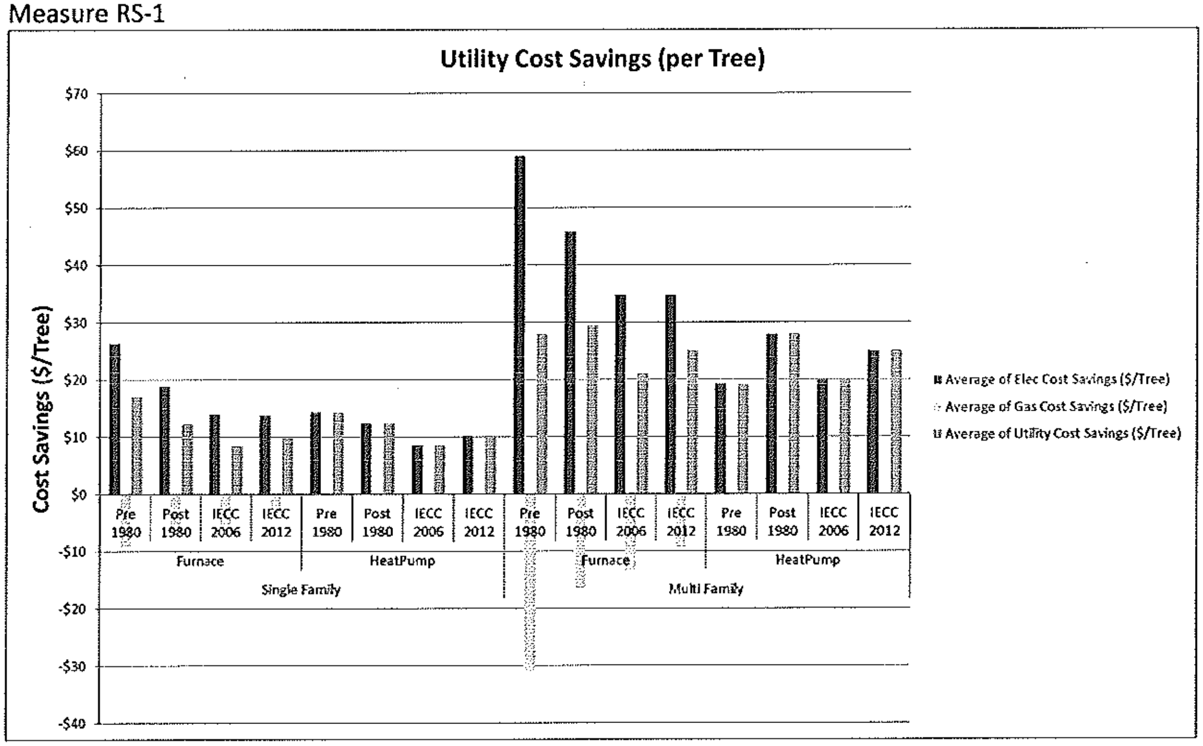

Emissions Reduction (per Conditioned kSF)
Emissions Reduction (lb/kSF)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of NOx Savings (lb/kSF)
Average of SOx Savings (lb/kSF)

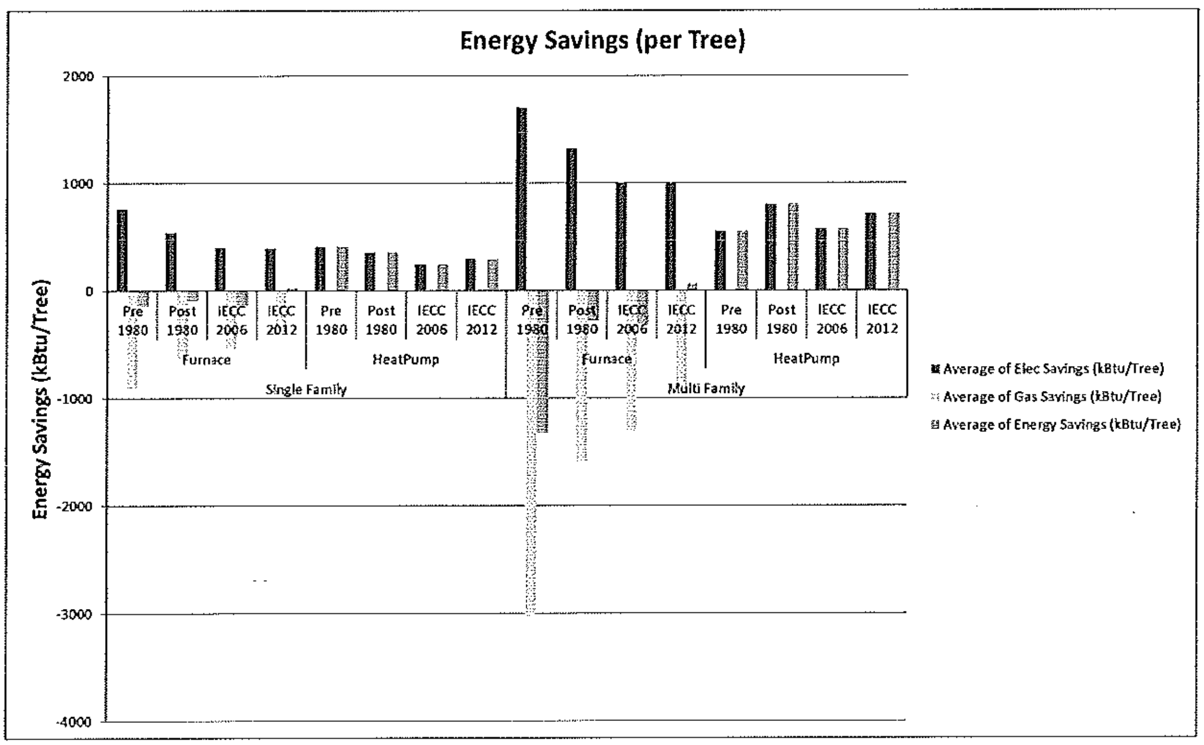
Measure RG-1


Simple Payback
SPB (Years)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

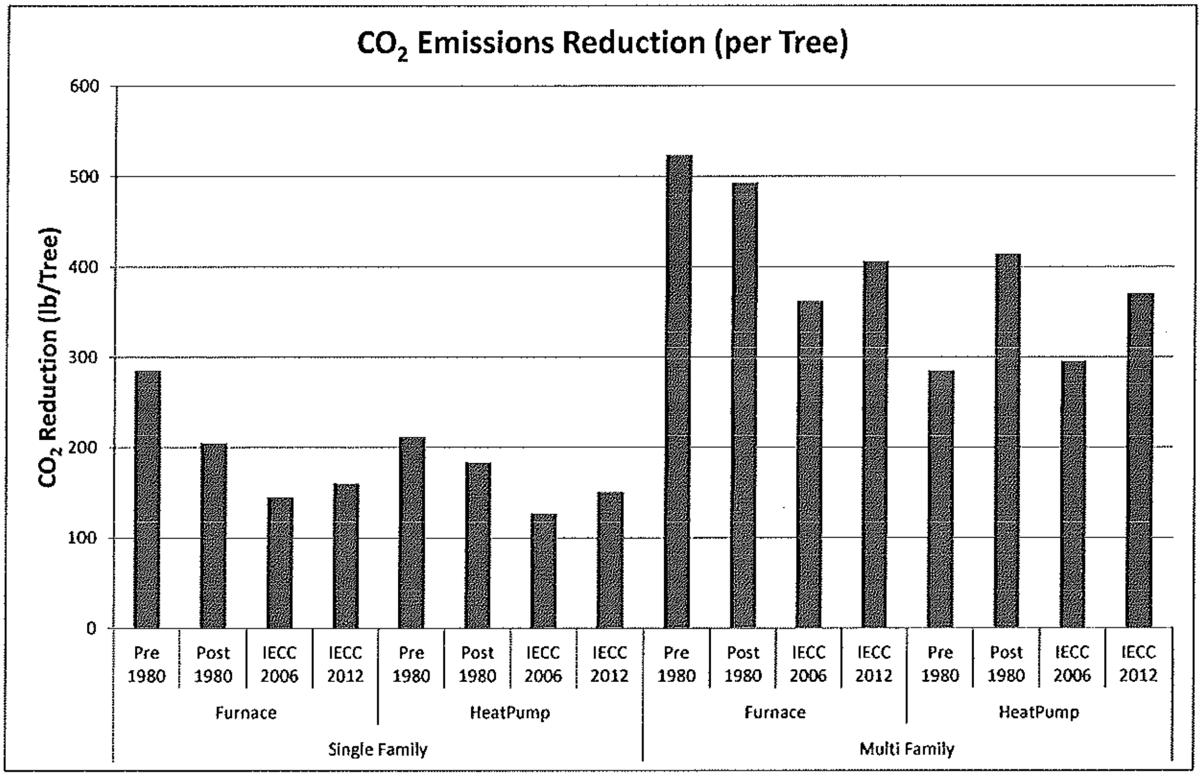

Benefit-Cost Ratio
B-C Ratio
0
-1
-2
-3
-4
-5
-6
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

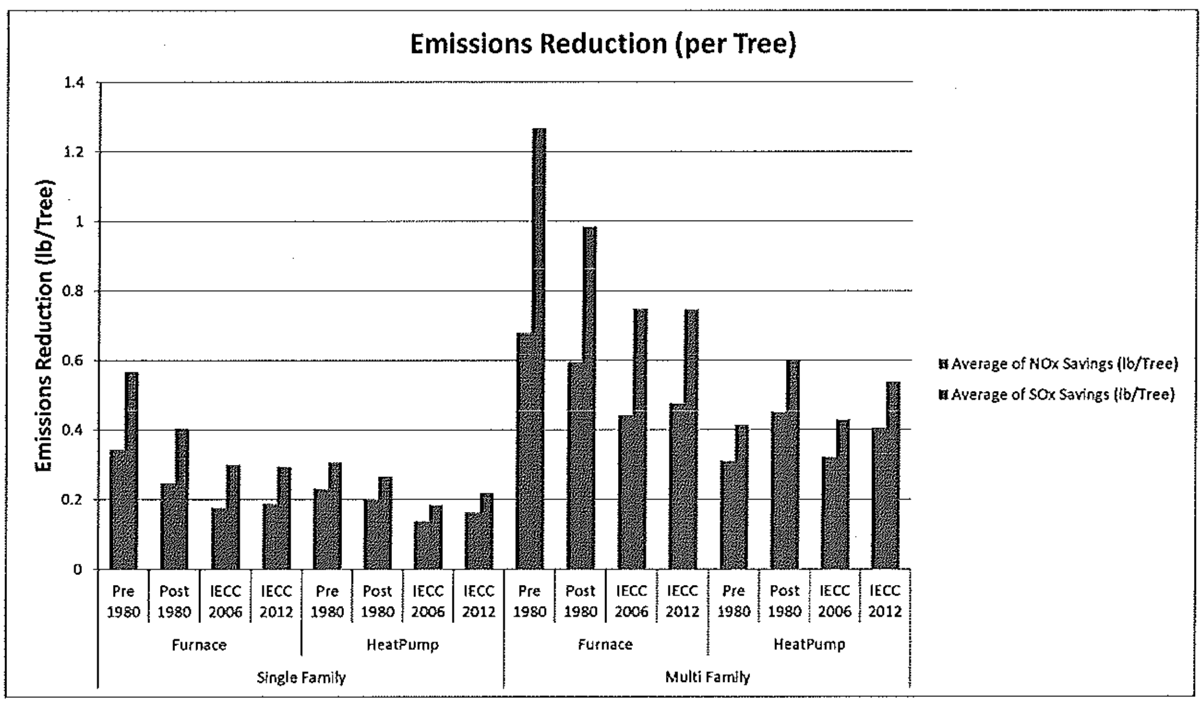
Measure RS-1


Utility Cost Savings (per Tree)
Cost Savings ($/Tree)
$70
$60
$50
$40
$30
$20
$10
$0
-$10
-$20
-$30
-$40
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Cost Savings ($/Tree)
Average of Gas Cost Savings ($/Tree)
Average of Utility Cost Savings ($/Tree)

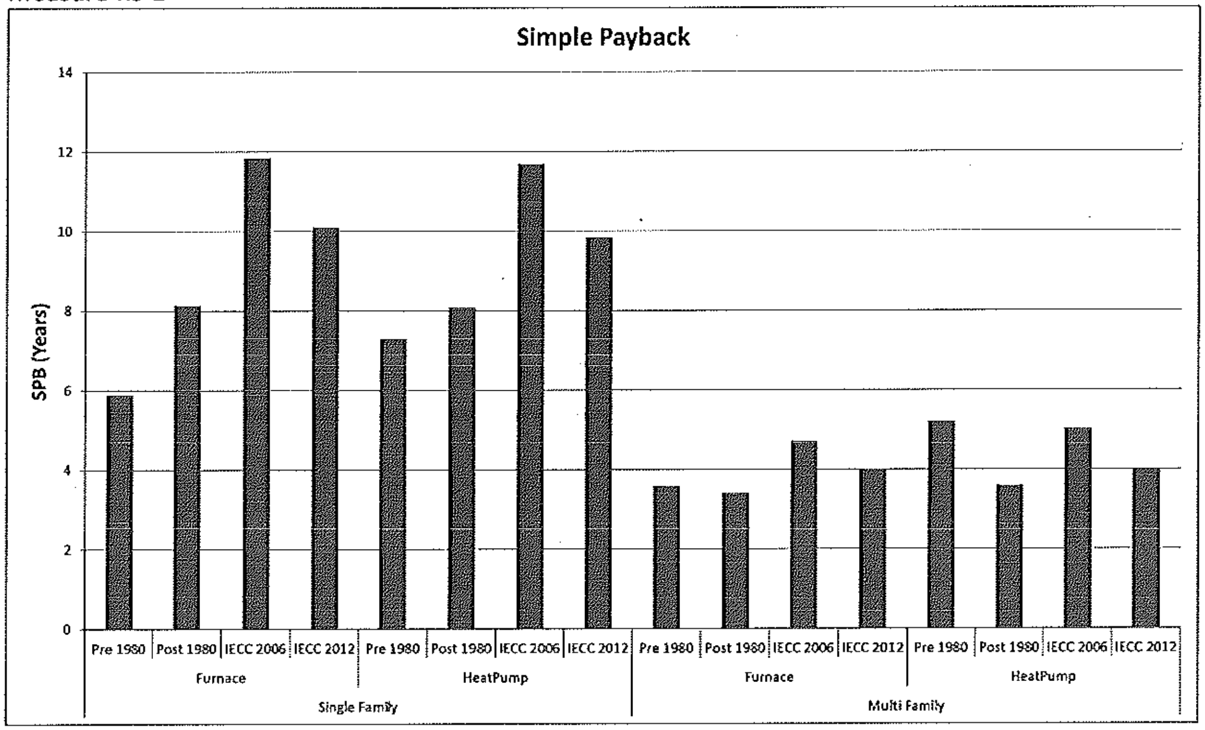

Energy Savings (per Tree)
Energy Savings (kBtu/Tree)
2000
1000
0
-1000
-2000
-3000
-4000
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Savings (kBtu/Tree)
Average of Gas Savings (kBtu/Tree)
Average of Energy Savings (kBtu/Tree)

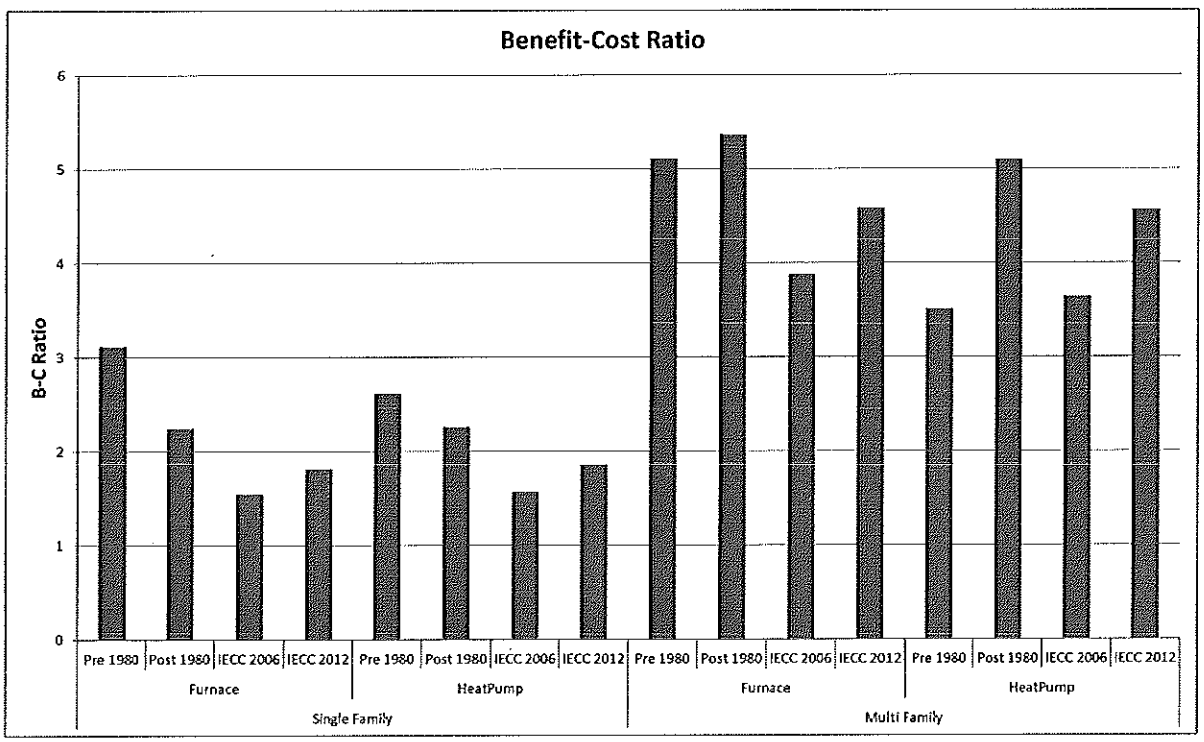
Measure RS-1


CO2 Emissions Reduction (per Tree)
CO2 Reduction (lb/Tree)
0
100
200
300
400
500
600
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

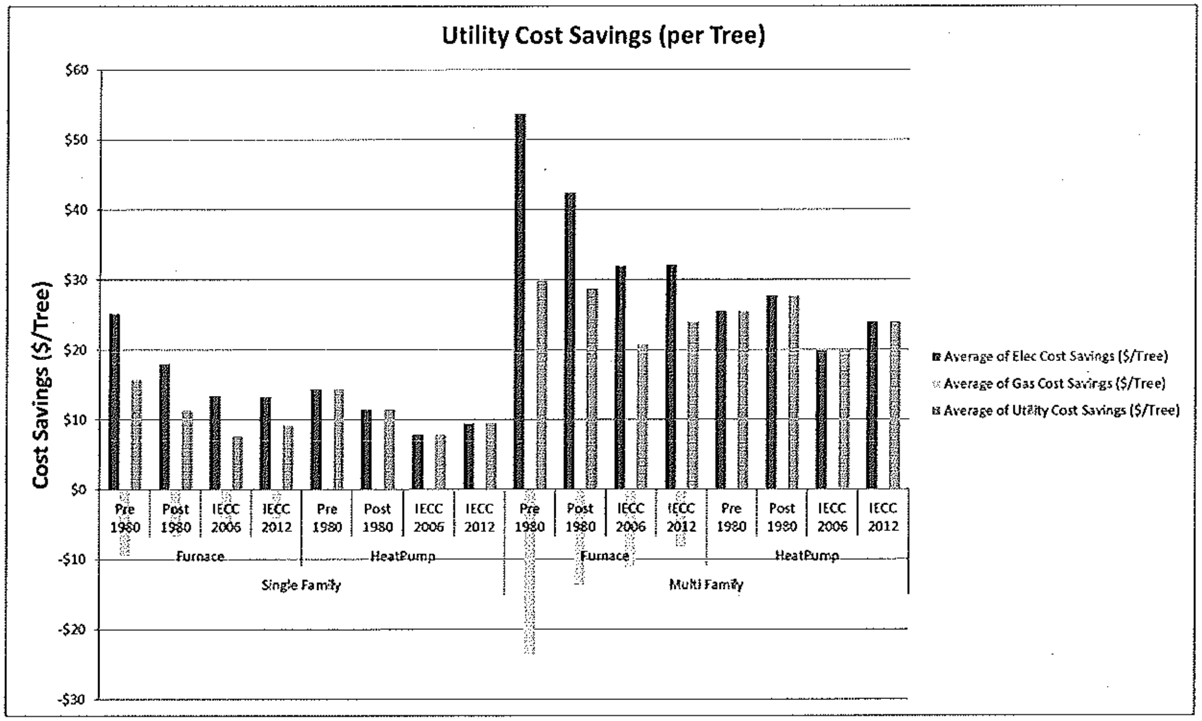

Emissions Reduction (per Tree)
Emissions Reduction (lb/Tree)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of NOx Savings (lb/Tree)
Average of SOx Savings (lb/Tree)

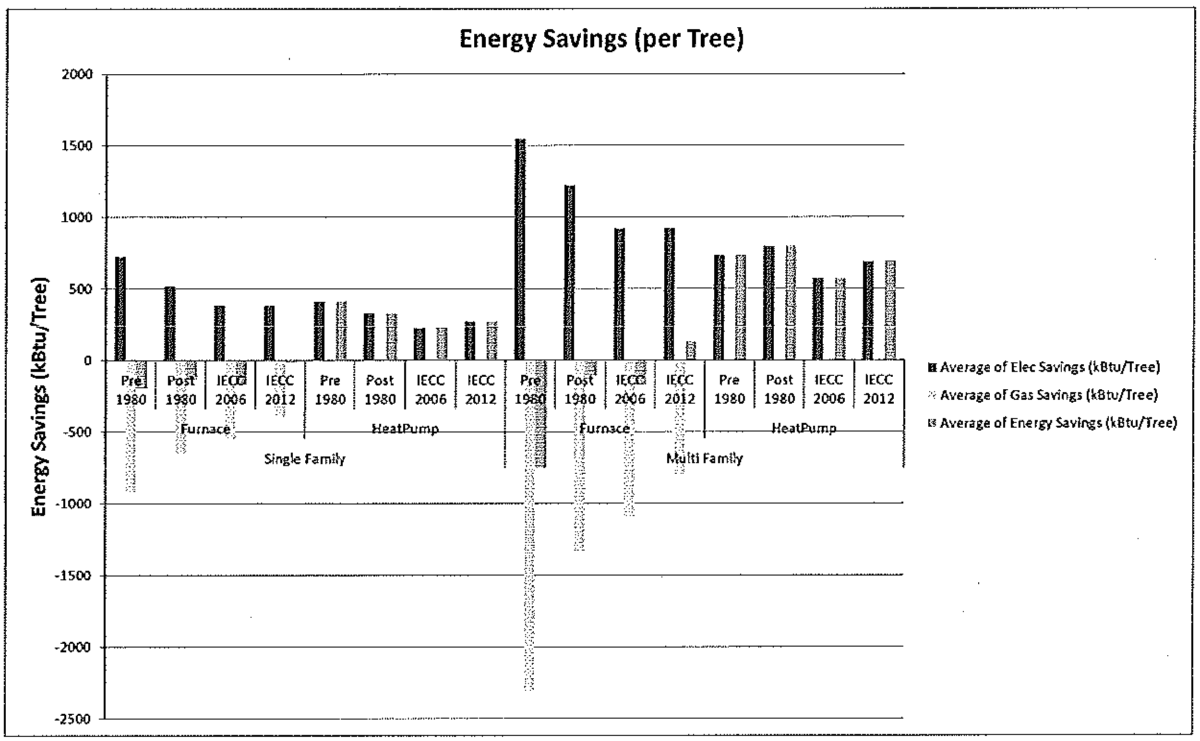
Measure RS-1


Simple Payback
SPB (Years)
14
12
10
8
6
4
2
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

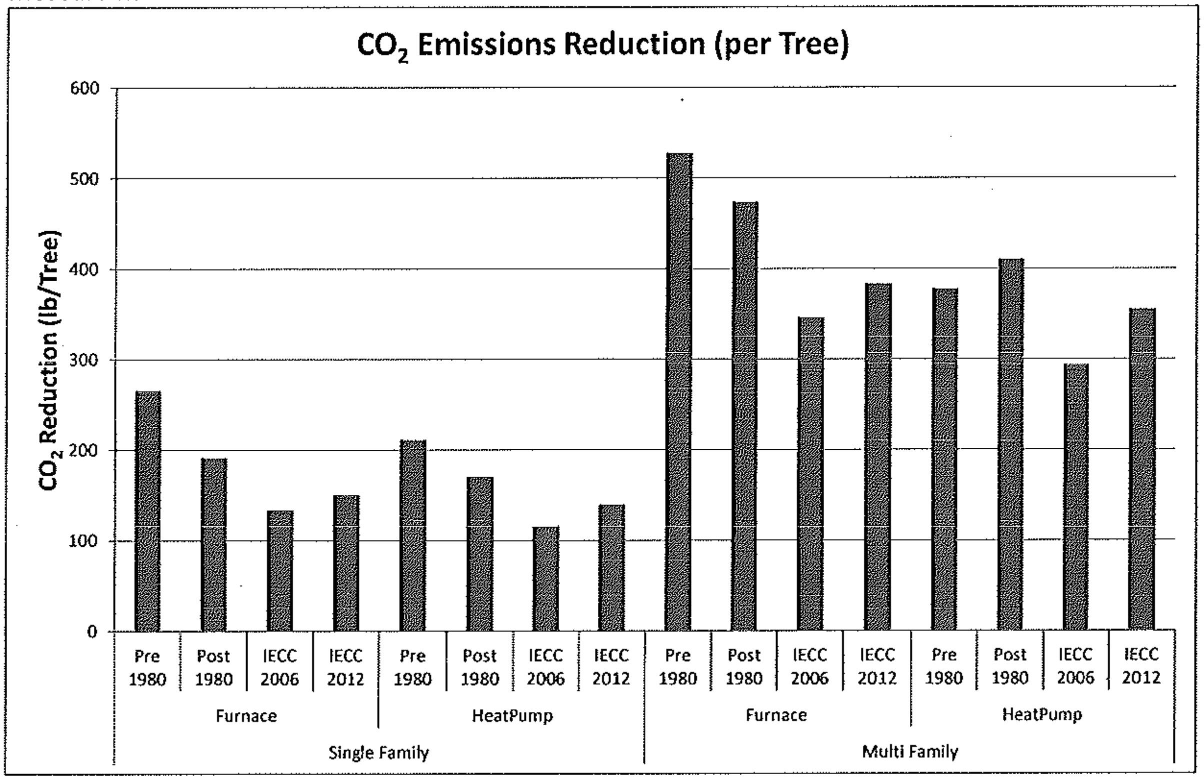

Benefit-Cost Ratio
B-C Ratio
6
5
4
3
2
1
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

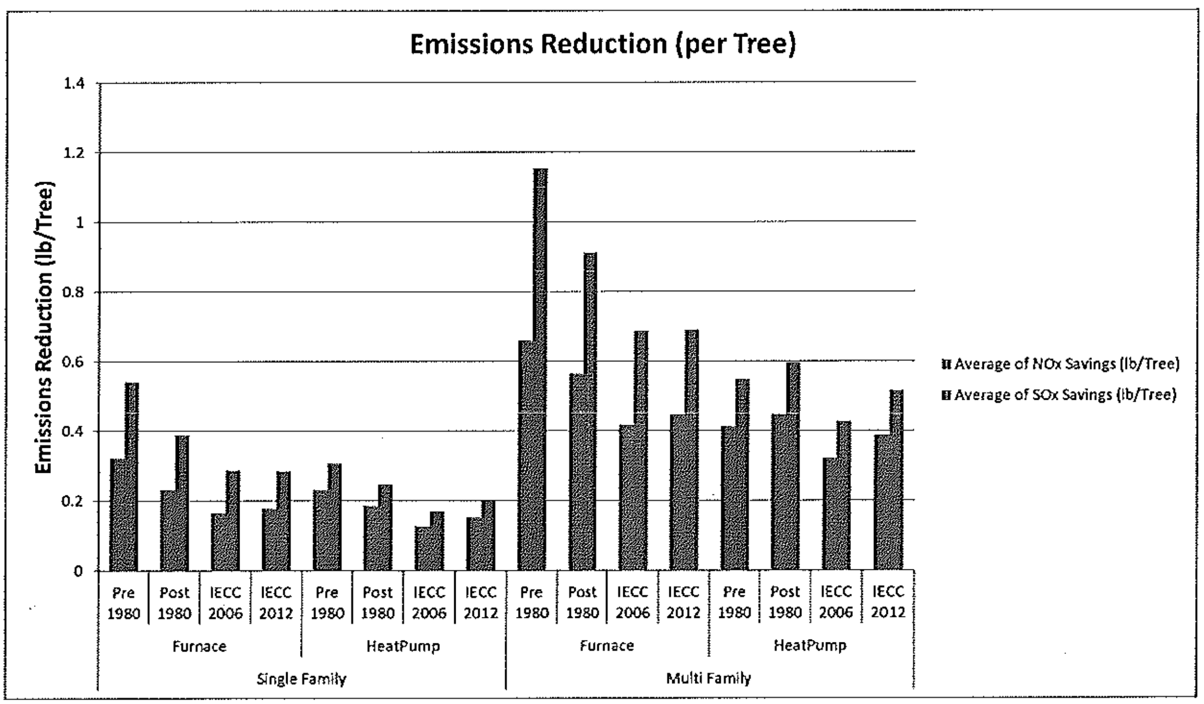
Measure RS-2


Utility Cost Savings (per Tree)
Cost Savings ($/Tree)
$60
$50
$40
$30
$20
$10
$0
-$10
-$20
-$30
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Cost Savings ($/Tree)
Average of Gas Cost Savings ($/Tree)
Average of Utility Cost Savings ($/Tree)

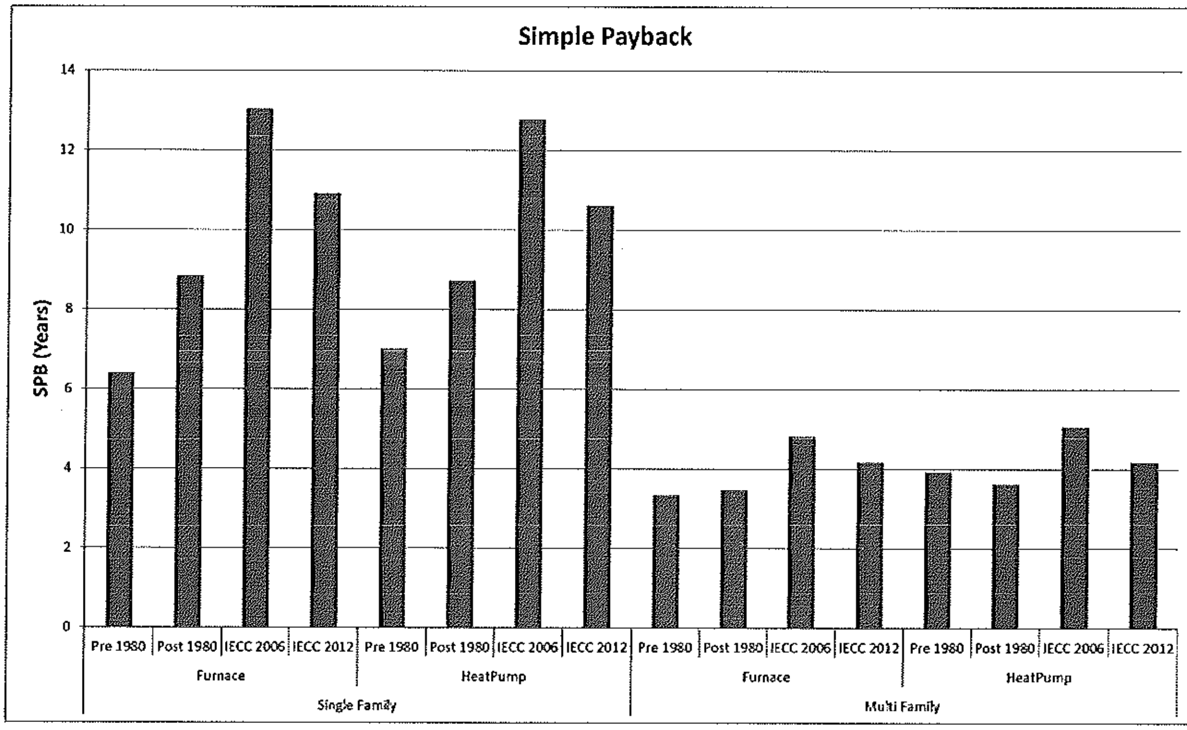

Energy Savings (per Tree)
Energy Savings (kBtu/Tree)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Savings (kBtu/Tree)
Average of Gas Savings (kBtu/Tree)
Average of Energy Savings (kBtu/Tree)

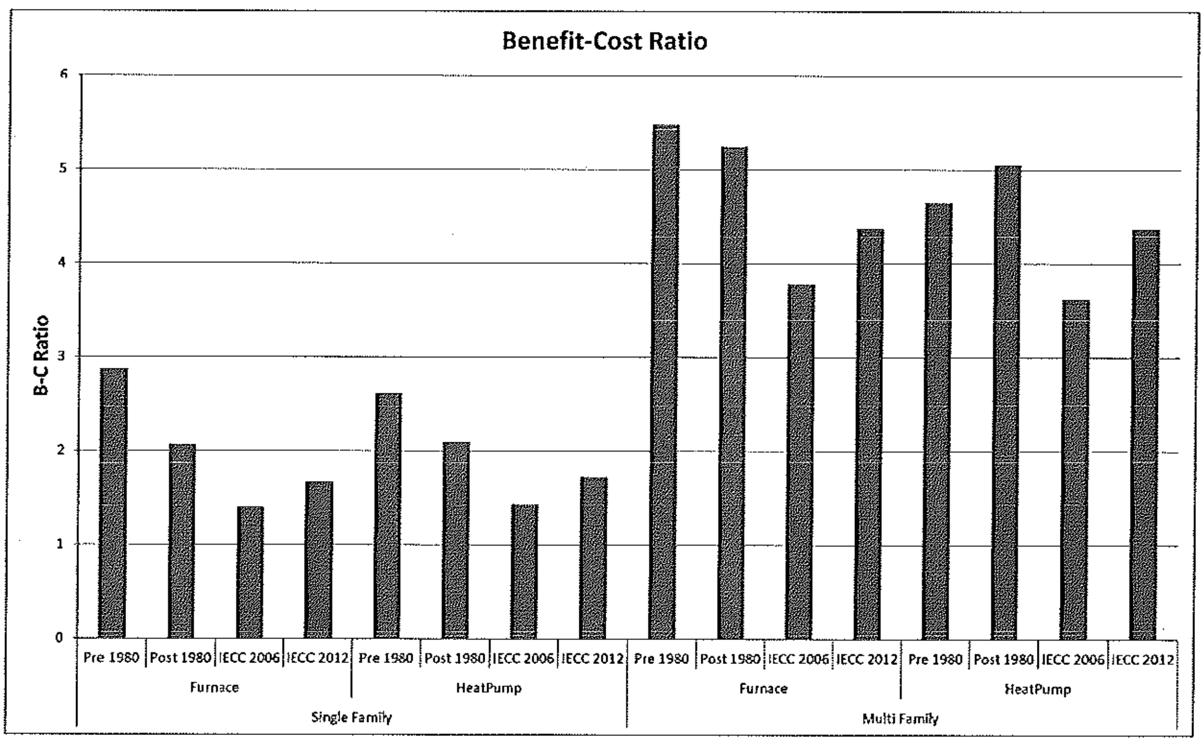
Measure RS-2


CO2 Emissions Reduction (per Tree)
CO2 Reduction (lb/Tree)
600
500
400
300
200
100
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

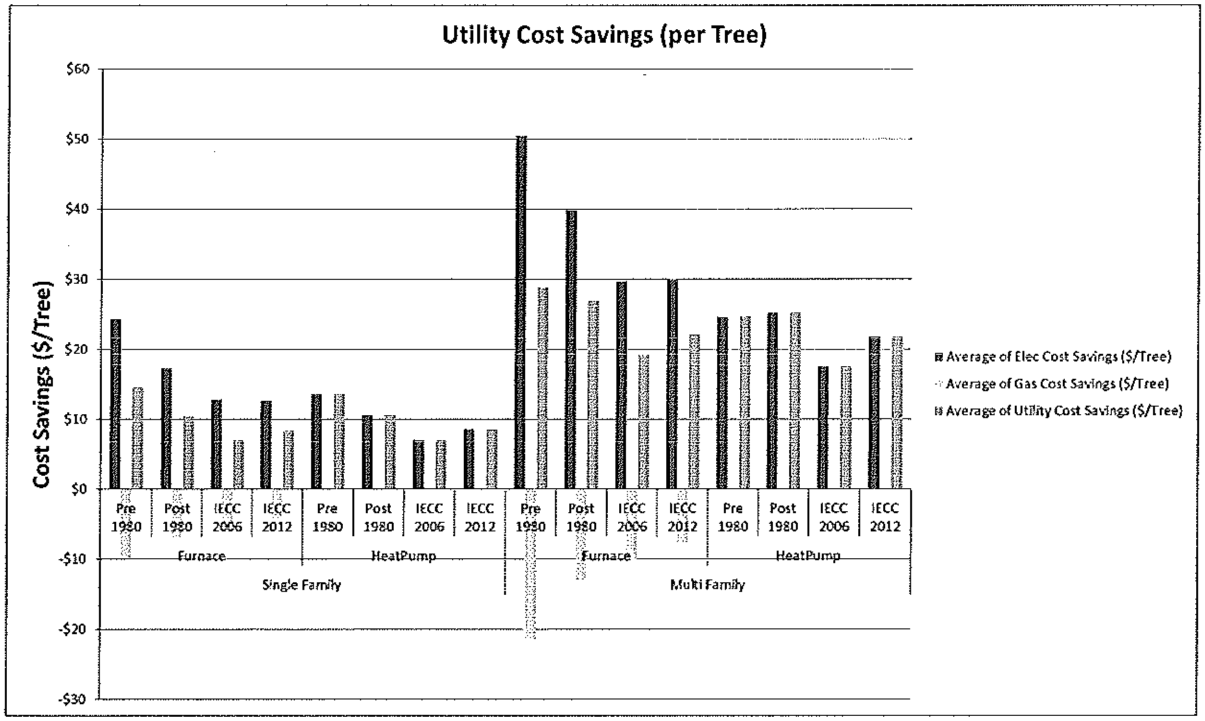

Emissions Reduction (per Tree)
Emissions Reduction (lb/Tree)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of NOx Savings (lb/Tree)
Average of SOx Savings (lb/Tree)

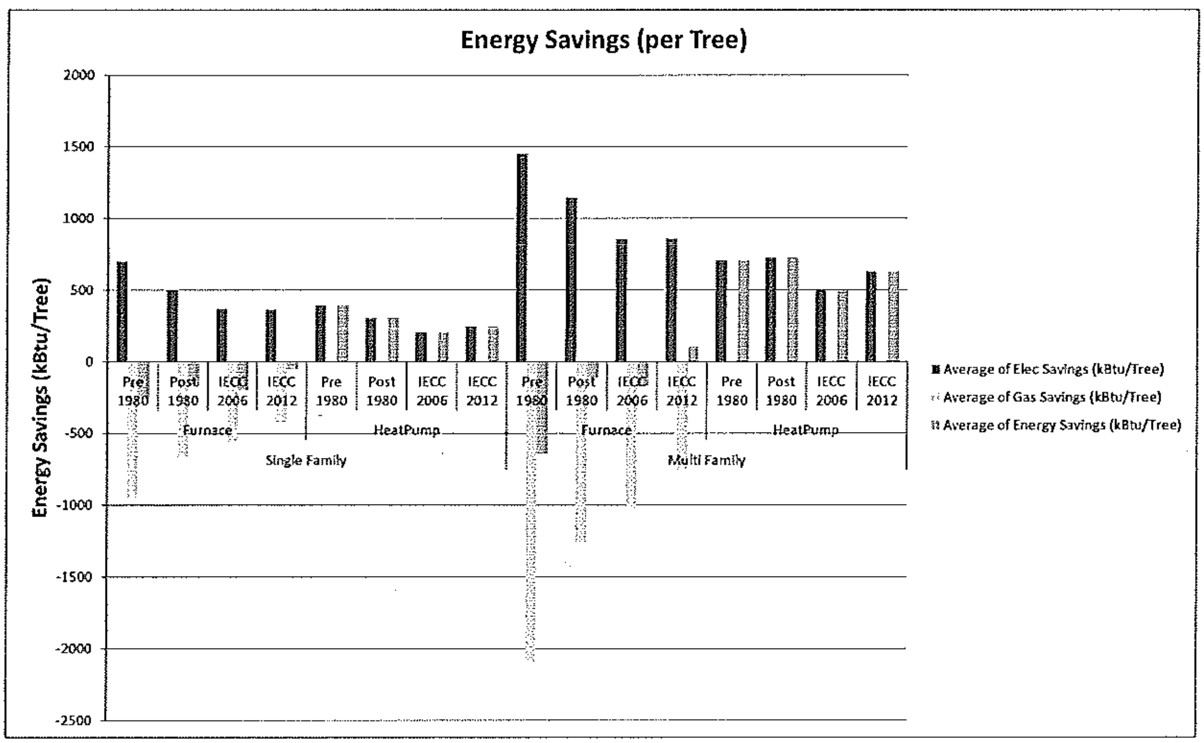
Measure RS-2


Simple Payback
SPB (Years)
0
2
4
6
8
10
12
14
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

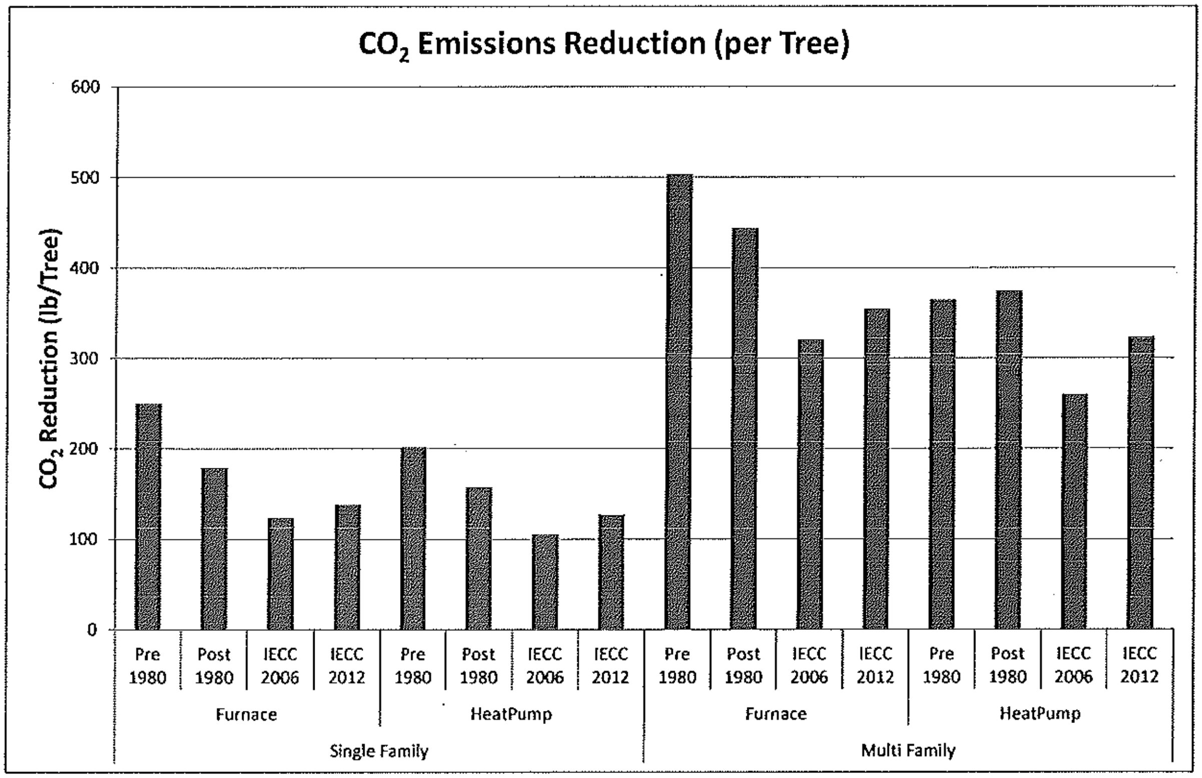

Benefit-Cost Ratio
B-C Ratio
0
1
2
3
4
5
6
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family

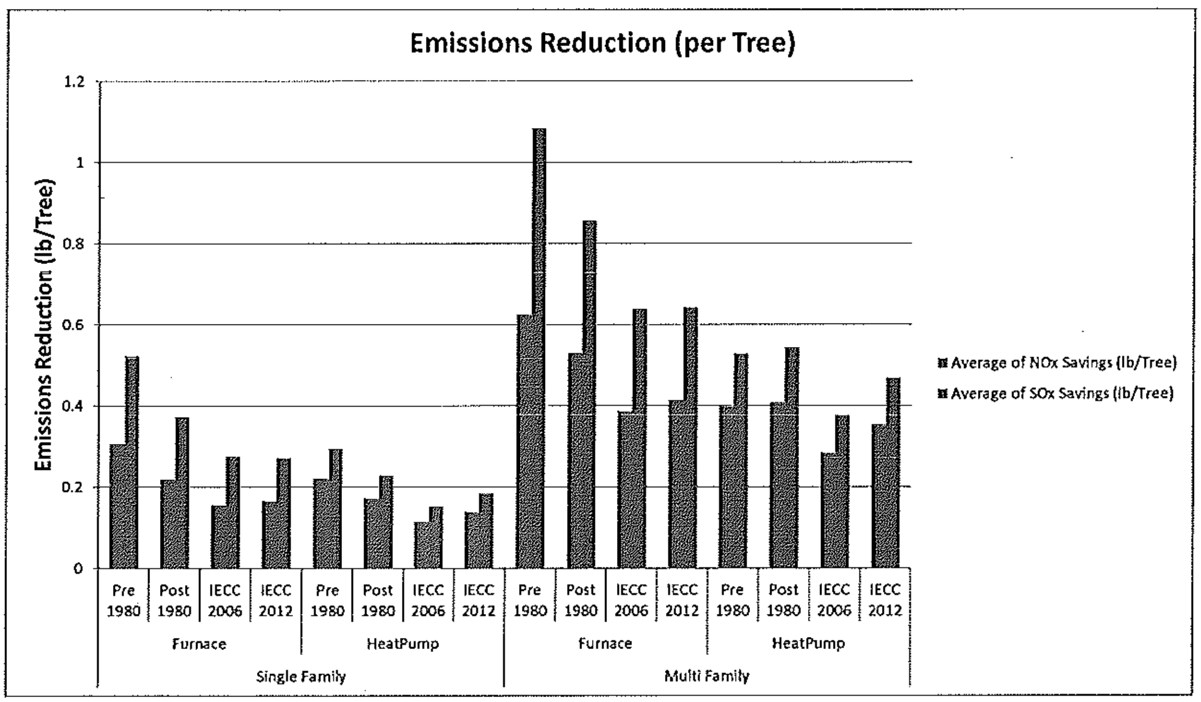
Measure RS-3


Utility Cost Savings (per Tree)
Cost Savings ($/Tree)
$60
$50
$40
$30
$20
$10
$0
-$10
-$20
-$30
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Cost Savings ($/Tree)
Average of Gas Cost Savings ($/Tree)
Average of Utility Cost Savings ($/Tree)

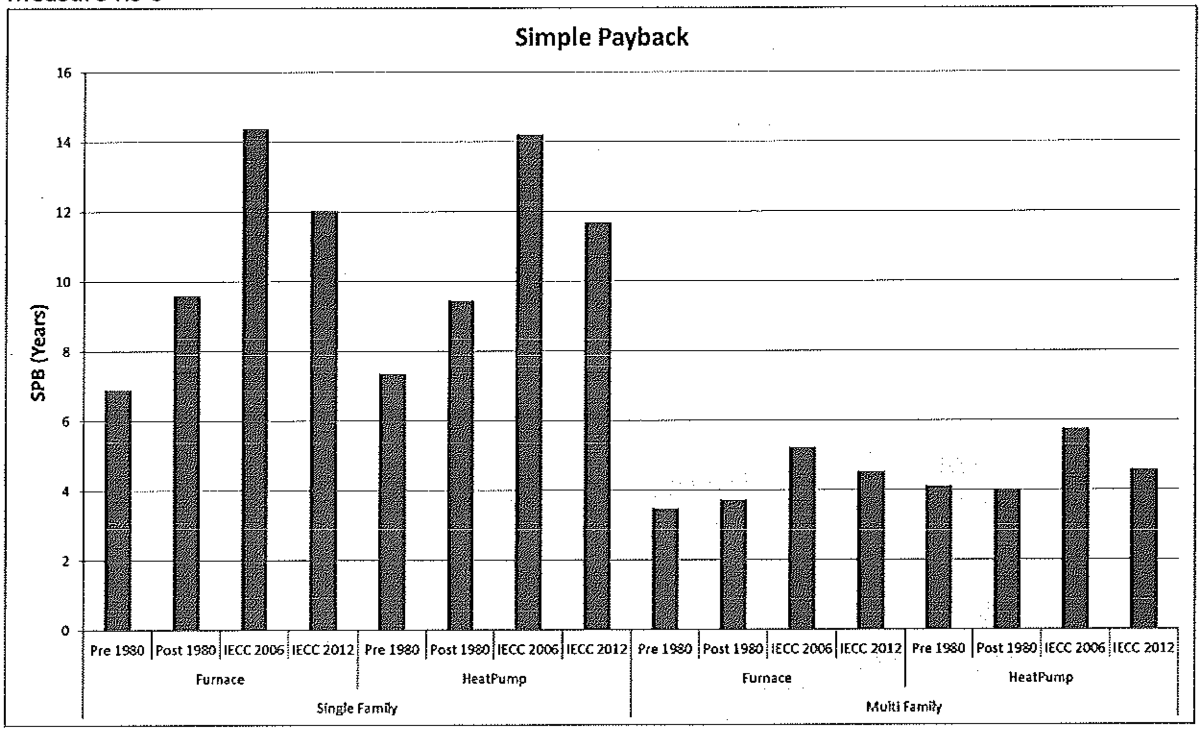

Energy Savings (per Tree)
Energy Savings (kBtu/Tree)
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of Elec Savings (kBtu/Tree)
Average of Gas Savings (kBtu/Tree)
Average of Energy Savings (kBtu/Tree)

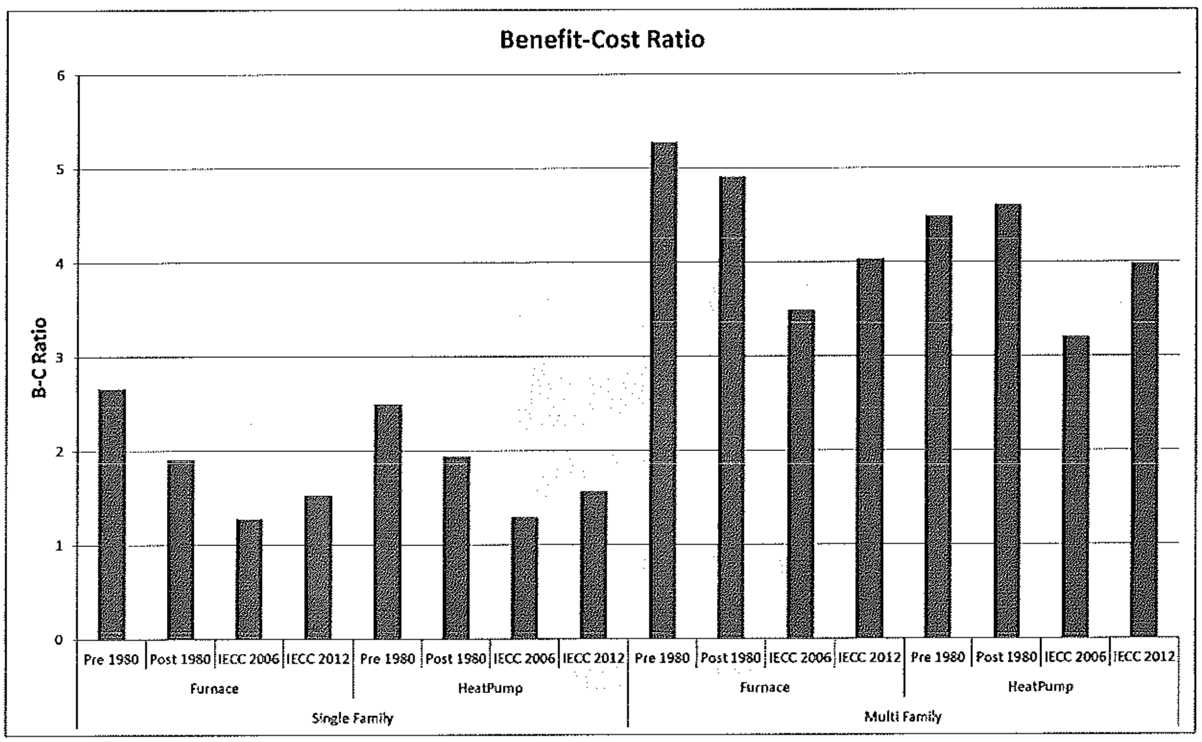
Measure RS-3


CO2 Emissions Reduction (per Tree)
CO2 Reduction (lb/Tree)
0
100
200
300
400
500
600
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family


Emissions Reduction (per Tree)
Emissions Reduction (lb/Tree)
0
0.2
0.4
0.6
0.8
1
1.2
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Single Family
Multi Family
Average of NOx Savings (lb/Tree)
Average of SOx Savings (lb/Tree)

Measure RS-3


Simple Payback
SPB (Years)
16
14
12
10
8
6
4
2
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Pre 1980
Post 1980
IECC 2006
IECC 2012
Pre 1980
Post 1980
IECC 2006
IECC 2012
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Furnace
HeatPump
Single Family
Multi Family

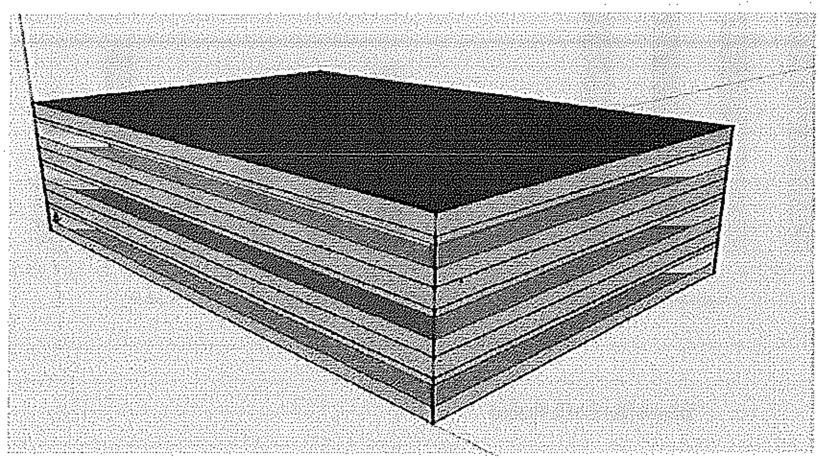

Benefit-Cost Ratio
B-C Ratio
6
5
4
3
2
1
0
Pre 1980
Post 1980
IECC 2006
IECC 2012
Pre 1980
Post 1980
IECC 2006
IECC 2012
Pre 1980
Post 1980
IECC 2006
IECC 2012
Pre 1980
Post 1980
IECC 2006
IECC 2012
Furnace
HeatPump
Furnace
HeatPump
Single Family
Multi Family

Appendix C: Commercial Prototype Buildings

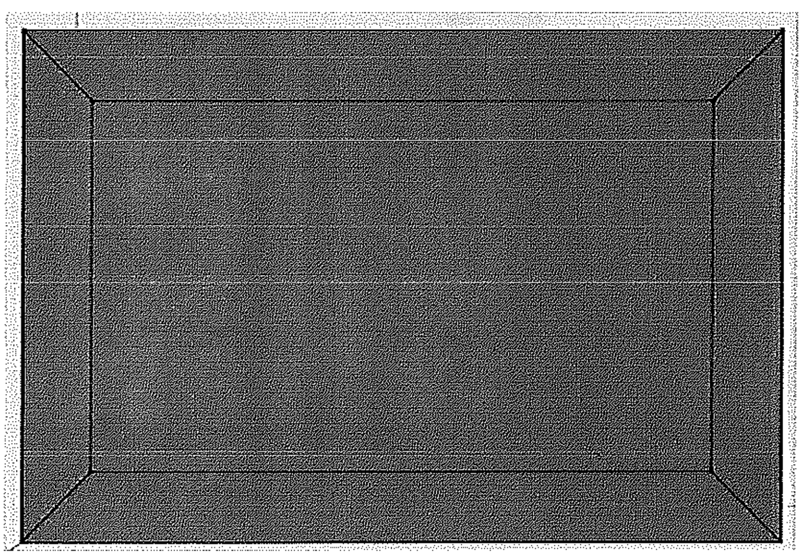
Medium Office

- 53,628 ft^2
- 3 floors
- 0.33 Window-to-Wall Ratio

Building Image



Typical Floor Plan



Space Types

Offices

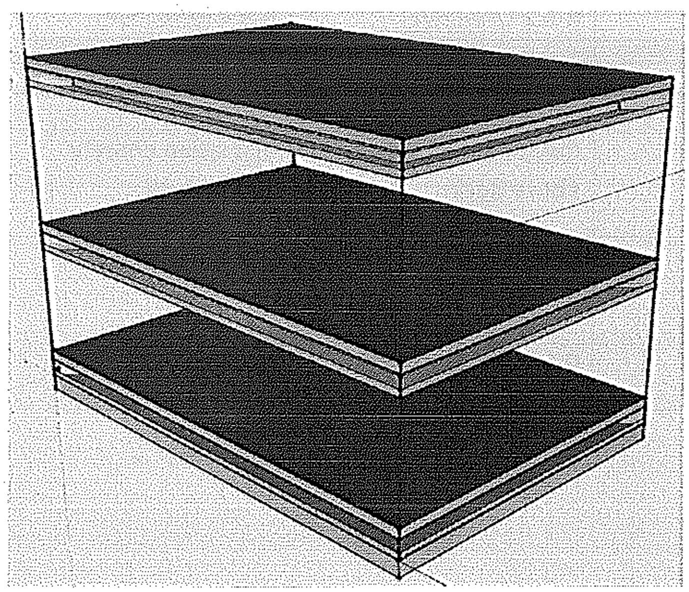
Construction Vintages

	Pre 1980	Post 1980	New Construction
Wall Construction	Steel frame	Steel frame	Steel frame
Wall Insulation	R-3.8 (effective) U-0.178 assembly	R-6.2 (effective) U-0.124 assembly	R-9.4 (effective) U-0.089 assembly
Roof Construction	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck
Window Assembly U-Value	1.22	0.59	0.57
Window SHGC	0.54	0.36	0.39

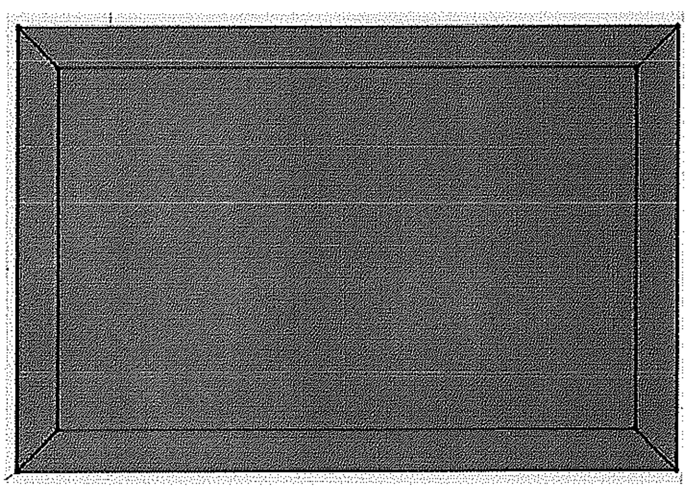
Large Office

- 498,588 ft^2
- 12 floors plus basement
  - Middle floor in image below has a multiplier of 10 to fill in the space between the bottom and top floors
- 0.38 Window-to-Wall Ratio

Building Image



Typical Floor Plan



Space Types

Offices

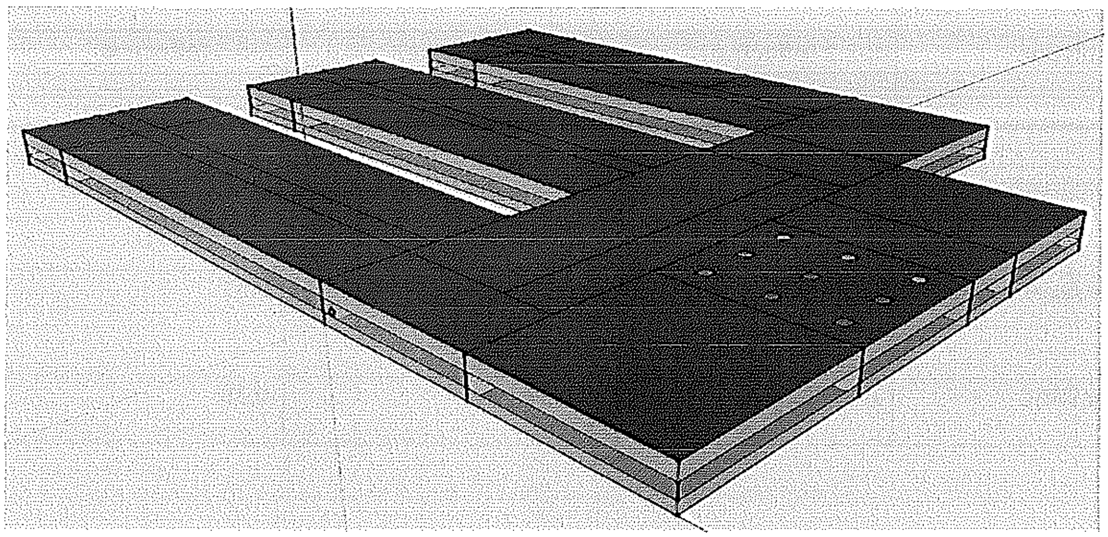
Construction Vintages

	Pre 1980	Post 1980	New Construction
Wall Construction	Mass	Mass	Mass
Wall Insulation	R-3.2 (effective) U-0.178 assembly	R-4.2 (effective) U-0.58 assembly	R-5.9 (effective) U-0.120 assembly
Roof Construction	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck
Window Assembly U-Value	1.22	0.59	0.57
Window SHGC	0.54	0.36	0.39

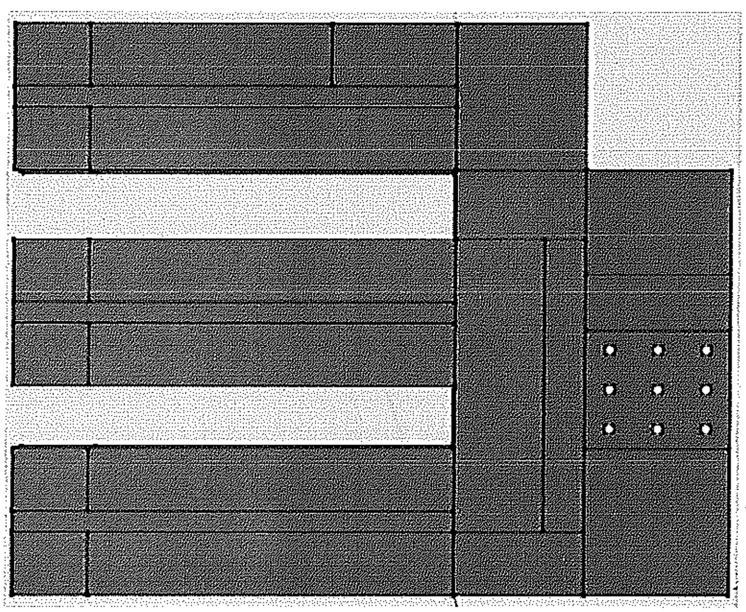
Primary School

- 73,960 ft²
- 1 floor
- 0.35 Window-to-Wall Ratio
- Secondary School is similar, but with 2 floors, and 210,887 ft²

Building Image



Typical Floor Plan



Space Types

Classrooms, cafeteria, restrooms, corridor, gym, kitchen, library, computer class, mechanical, offices, lobby

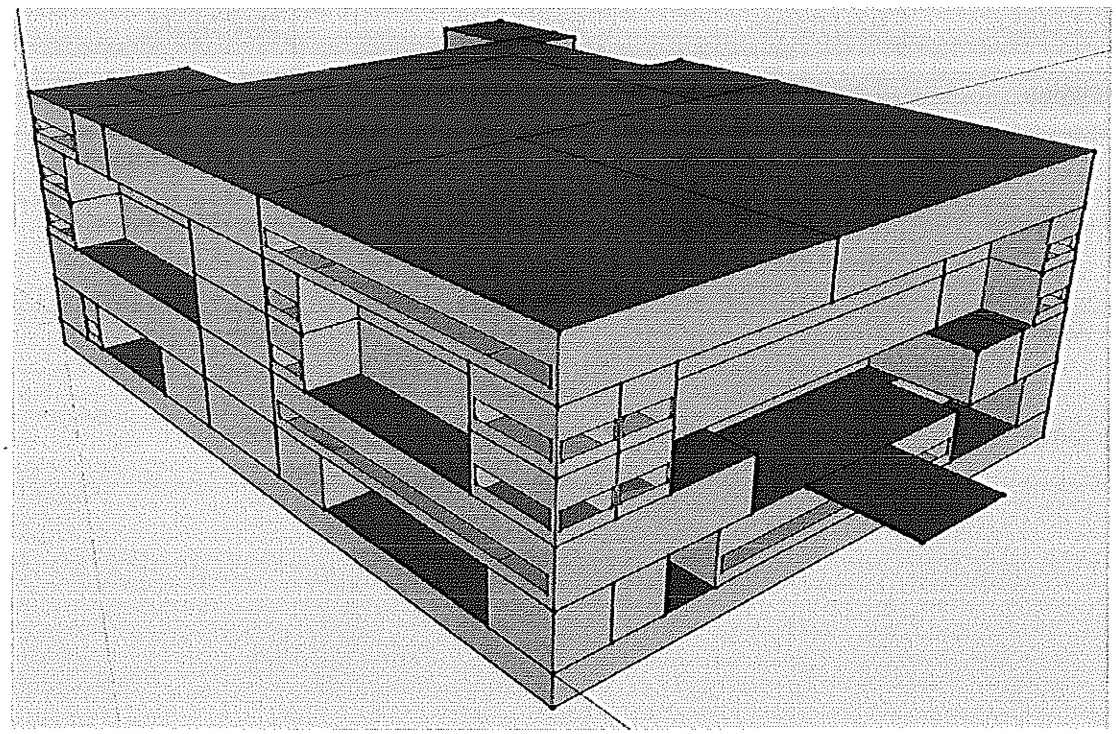
Construction Vintages

	Pre 1980	Post 1980	New Construction
Wall Construction	Steel frame	Steel frame	Steel frame
Wall Insulation	R-3.8 (effective) U-0.178 assembly	R-6.2 (effective) U-0.124 assembly	R-9.4 (effective) U-0.089 assembly
Roof Construction	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck
Window Assembly U-Value	1.22	0.59	0.57
Window SHGC	0.54	0.36	0.39

Hospital

- 241,351 ft^2
- 5 floors plus basement
    - Numerous rooms use multipliers, which fills in the blank spaces in the image below
- 0.15 Window-to-Wall Ratio

Building Image



Typical Floor Plan

- Varies by floor
- Patient floors and OR floors

Space Types

Basement, corridors, dining, kitchen, exam rooms, nurses stations, trauma rooms, triage, patient rooms, ICU, labs, lobby, offices, operating rooms, physical therapy, radiology

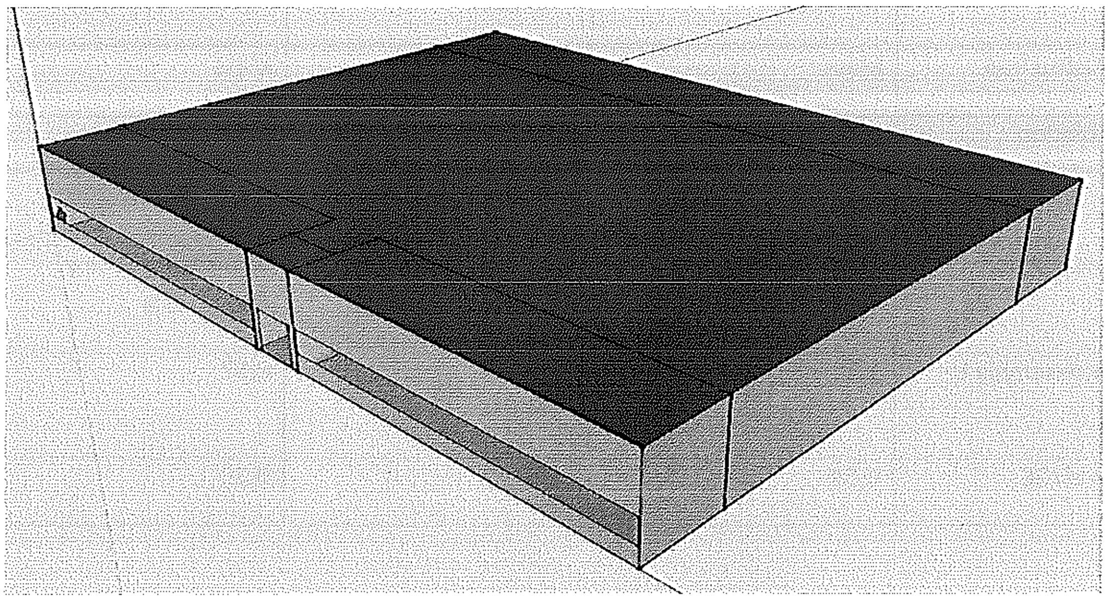
Construction Vintages

	Pre 1980	Post 1980	New Construction
Wall Construction	Mass	Mass	Mass
Wall Insulation	R-3.2 (effective) U-0.178 assembly	R-4.2 (effective) U-0.58 assembly	R-5.9 (effective) U-0.120 assembly
Roof Construction	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck
Window Assembly U-Value	1.22	0.59	0.57
Window SHGC	0.54	0.36	0.39

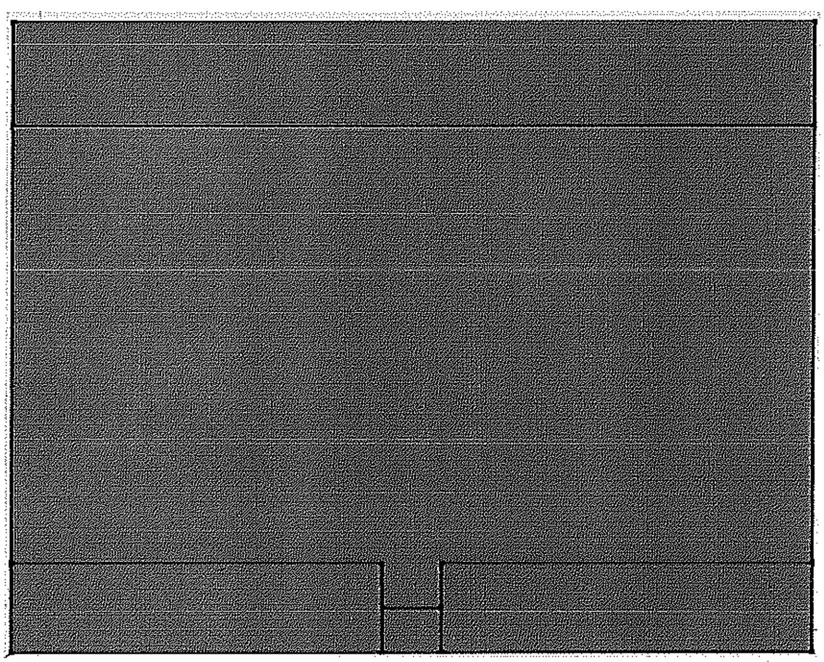
Stand-Alone Retail

- 24,962 ft^2
- 1 floor
- 0.07 Window-to-Wall Ratio

Building Image



Typical Floor Plan



Space Types

Retail, point of sale, front entry, back space

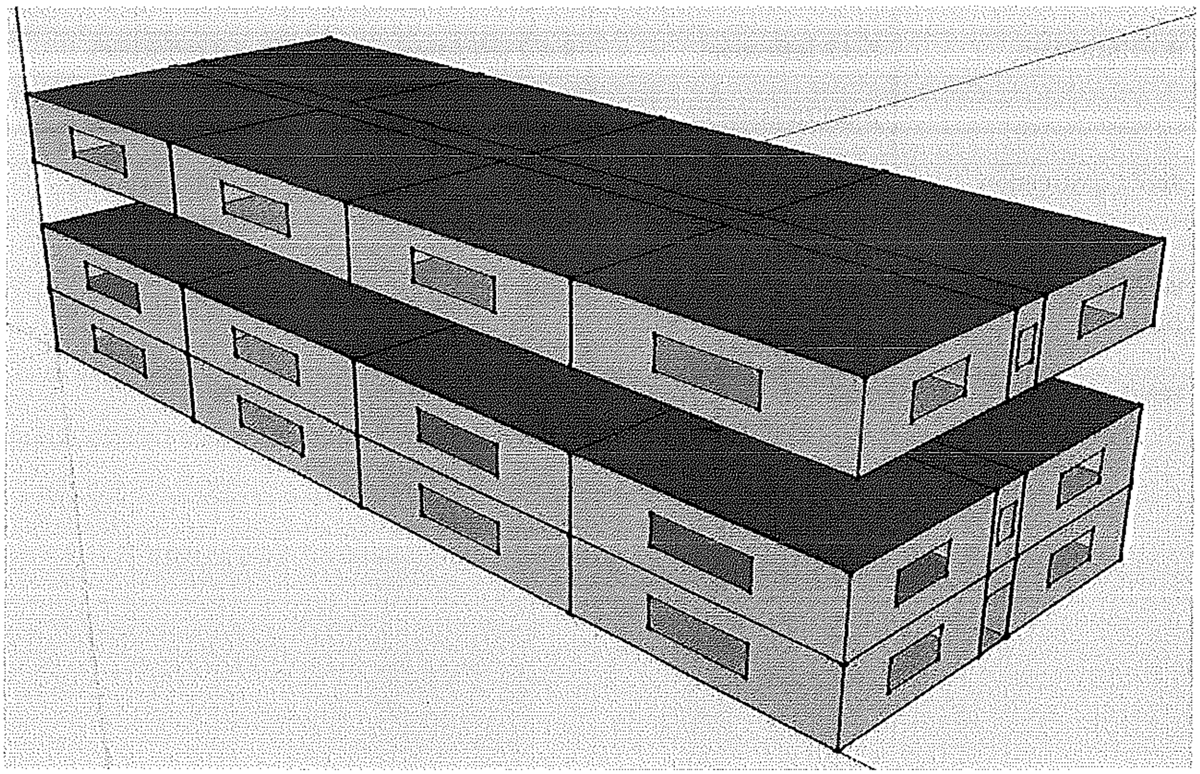
Construction Vintages

	Pre 1980	Post 1980	New Construction
Wall Construction	Steel frame	Mass	Mass
Wall Insulation	R-3.8 (effective) U-0.178 assembly	R-4.2 (effective) U-0.58 assembly	R-5.9 (effective) U-0.120 assembly
Roof Construction	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck
Window Assembly U-Value	1.22	0.59	0.57
Window SHGC	0.54	0.36	0.39

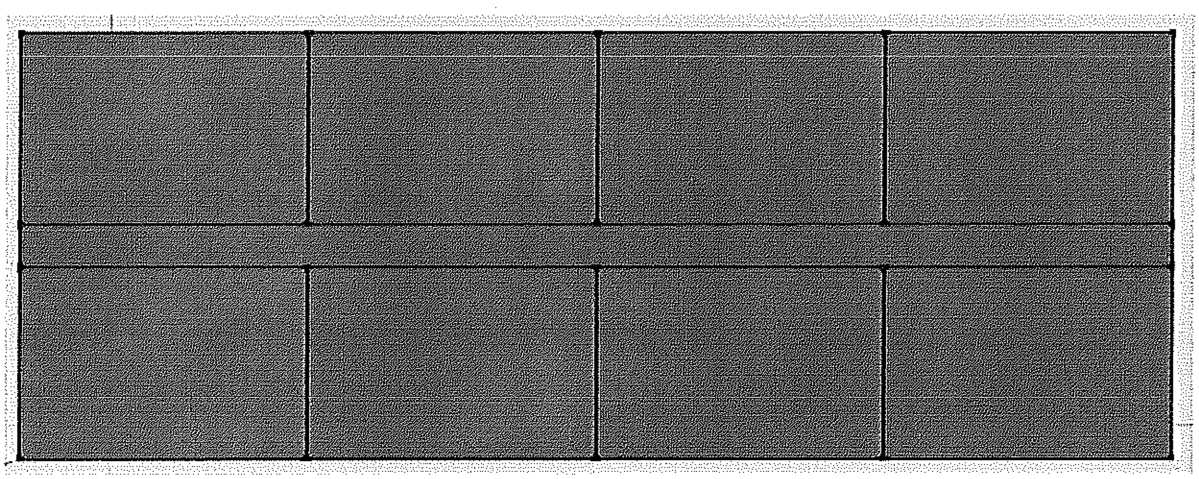
Mid Rise Apartment

- 33,740 ft^2
- 4 floors
    - Middle floor has a multiplier of 2
- 0.15 Window-to-Wall Ratio

Building Image



Typical Floor Plan



Space Types

Corridor, apartments, rental office

Construction Vintages

	Pre 1980	Post 1980	New Construction
Wall Construction	Steel frame	Steel frame	Steel frame
Wall Insulation	R-3.8 (effective) U-0.178 assembly	R-6.2 (effective) U-0.124 assembly	R-9.4 (effective) U-0.089 assembly
Roof Construction	Insulation entirely above deck	Insulation entirely above deck	Insulation entirely above deck
Window Assembly U-Value	1.22	0.59	0.57
Window SHGC	0.54	0.36	0.39

Miscellaneous

Additional inputs can be found in the following document:

http://www.nrel.gov/docs/fy11osti/46861.pdf

Changes to Energy Simulation Models from DOE Prototypes

All Models

- Changed design day data to match Kansas City, MO
- Changed water mains and ground temps to match Kansas City, MO
- Changed window construction methodology to provide more flexibility
- Changed Post 1980 Wall insulation to be between Pre 1980 and New Construction (average of two)
- Changed Pre 1980 Window properties to ASHRAE 90.1 Table A8.2 single pane clear properties
    - U-0.125
    - SHGC-0.82
    - VLT-0.76
- Changed Post 1980 Window properties to ASHRAE 90.1 Table A8.2 metal frame double pane tinted properties
    - U-0.90
    - SHGC-0.50
    - VLT-0.40

Medium Office

- Changed VAV reheat to hot water, added boiler, hot water reheat coils, and variable speed pump
- Changed system type to VAV RTU with HW reheat to be consistent with Post 1980 and New Construction models

Midrise Apartment

- Changed electric heating coils to gas heating coils

Primary School

- Added skylights to Pre 1980 and Post 1980 to be consistent with New Construction model

Stand-Alone Retail

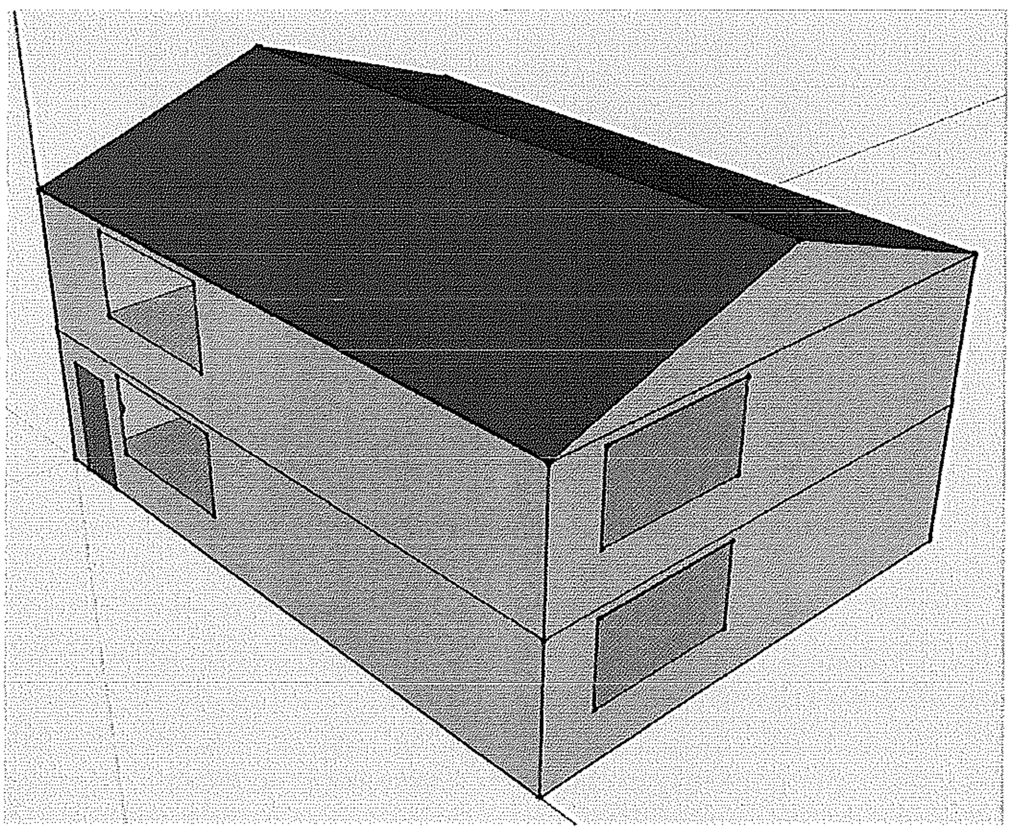
- Changed electric heating coils to gas heating coils
- Changed New Construction and Post 1980 wall construction to steel frame to be consistent with Pre 1980

Appendix D: Residential Prototype Buildings

Single Family

- 2,400 ft^2
- 2 floors plus attic
    - Option of on slab construction, heated basement, unheated basement, and crawlspace
    - Since the study focuses on roof material, site shading, and surrounding pavement/vegetation, the basement construction is not important. Slab is the easiest to change and run.
- 0.14 Window-to-Wall Ratio

Building Image



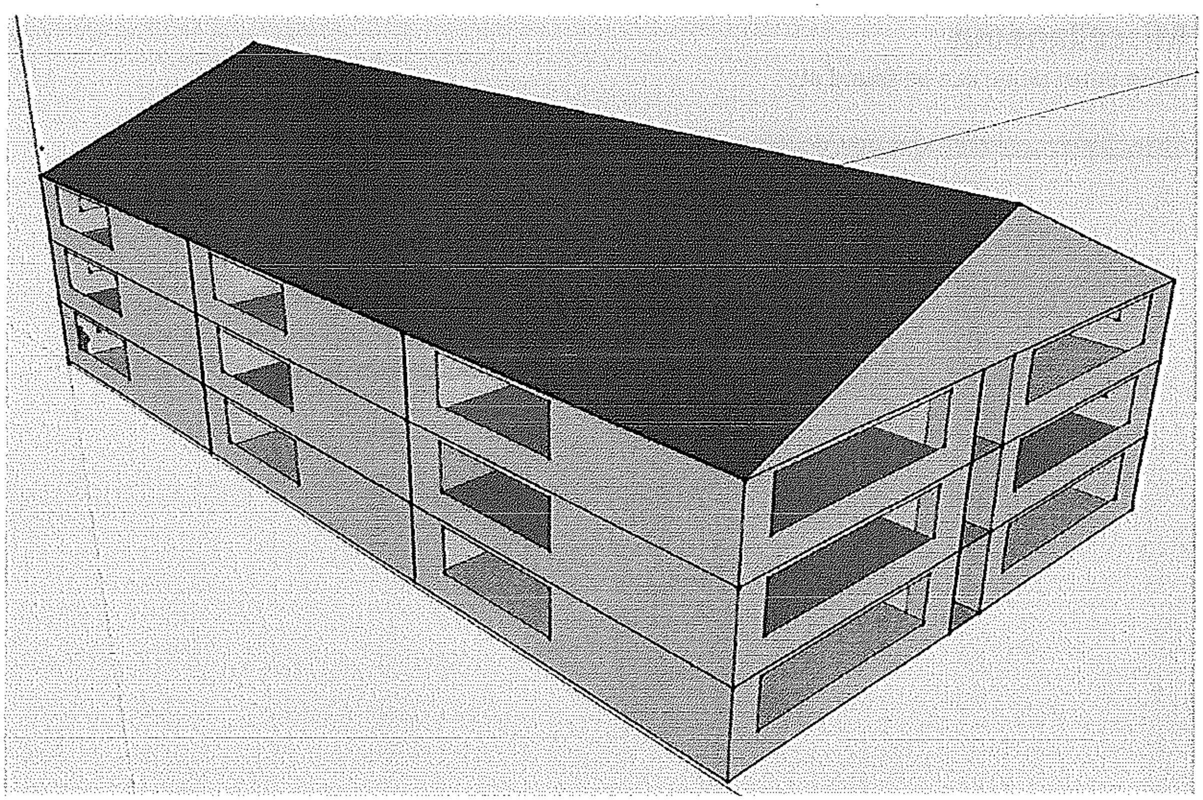
Construction Vintages

Component	Pre-1980	Post-1980	IECC 2006	IECC 2012
Wall Construction	Wood Frame	Wood Frame	Wood Frame	Wood Frame
Wall Insulation	none	R-11 batt	R-13 batt	R-13 batt + R-5 continuous
Roof Construction	Attic	Attic	Attic	Attic
Window Assembly U-Value	1.25	0.6	0.4	0.35
Window SHGC	0.82	0.59	0.59	0.4
Heating Efficiency				
Furnace (Thermal Efficiency, %)	75%	75%	78%	80%
Heat Pump (HSPF)	6.8	6.8	7.7	8.2
Cooling SEER	9	10	13	14

Multi Family

- 21,610 ft^2
- 3 floors plus attic
  - Option of on slab construction, heated basement, unheated basement, and crawlspace. Heated basement is not used for living space.
  - Since the study focuses on roof material, site shading, and surrounding pavement/vegetation, the basement construction is not important. Slab is the easiest to change and run.
- 18 living units
- 0.16 Window-to-Wall Ratio

Building Image



Construction Vintages

Component	Pre-1980	Post-1980	IECC 2006	IECC 2012
Wall Construction	Wood Frame	Wood Frame	Wood Frame	Wood Frame
Wall Insulation	none	R-11 batt	R-13 batt	R-13 batt + R-5 continuous
Roof Construction	Attic	Attic	Attic	Attic
Window Assembly U-Value	1.25	0.6	0.4	0.35
Window SHGC	0.82	0.59	0.59	0.4
Heating Efficiency				
Furnace (Thermal Efficiency, %)	75%	75%	78%	80%
Heat Pump (HSPF)	6.8	6.8	7.7	8.2
Cooling SEER	9	10	13	14

Miscellaneous

More information can be found at:

https://www.energycodes.gov/development/residential/iecc_models

Urban Heat Island Countermeasures to Cool the Kansas City Region

Ronnen Levinson, Ph.D.

Staff Scientist & Leader
Heat Island Group
Lawrence Berkeley National Laboratory
Berkeley, California, USA

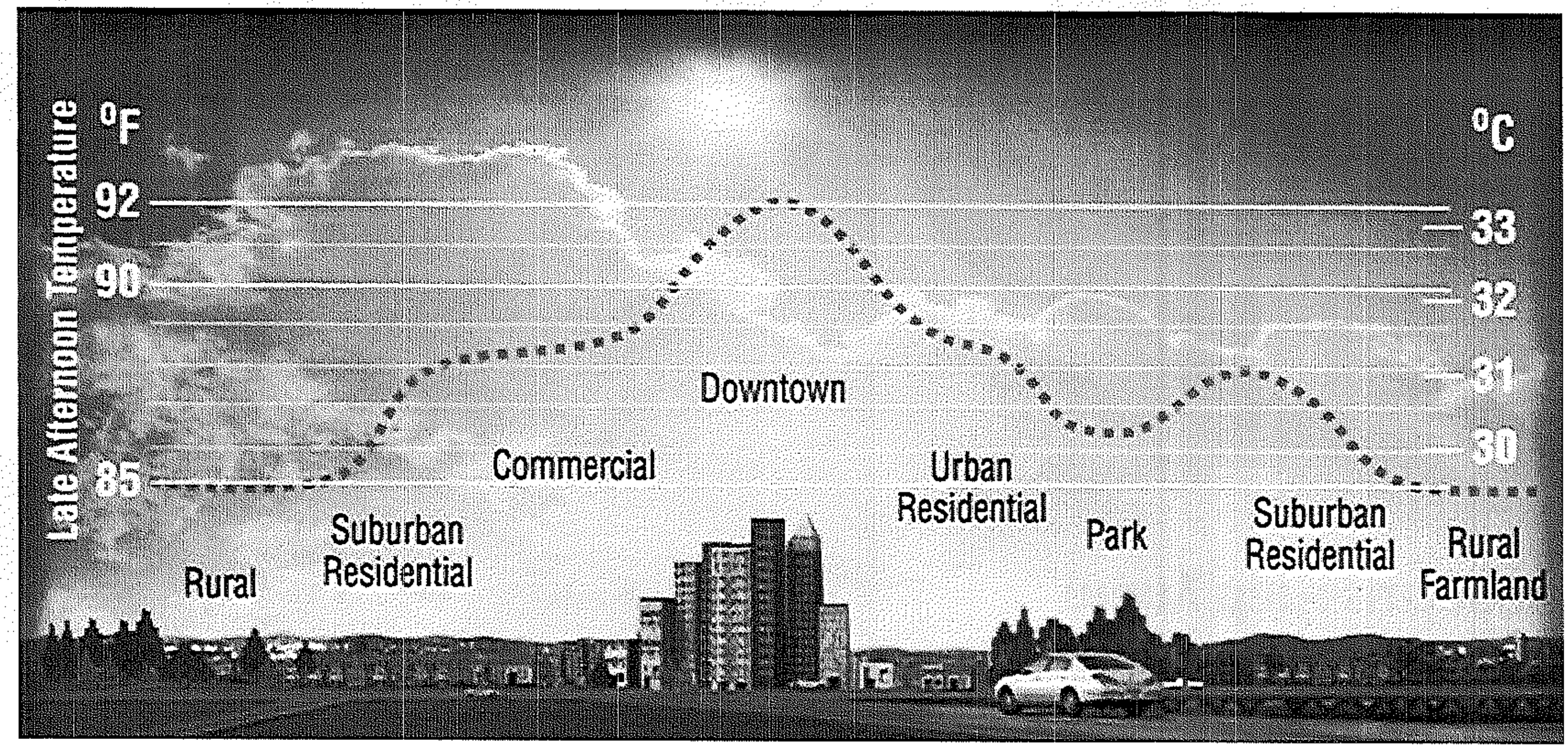
tel. +1 510-486-7494
RMLevinson@LBL.gov

Mid-America Regional Council Conference Center • Kansas City, MO • 2016-10-20

GM-12
1/38

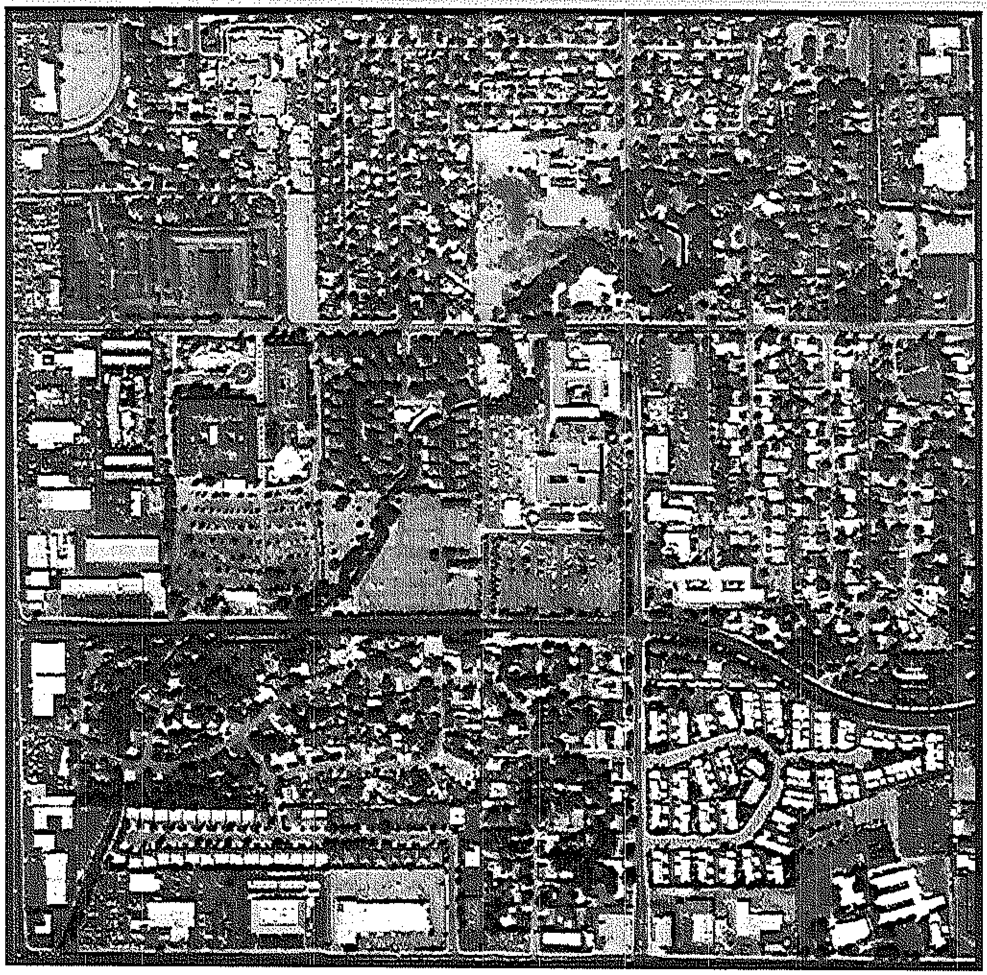
1. The Urban Heat Island

Hot town—summer in the city



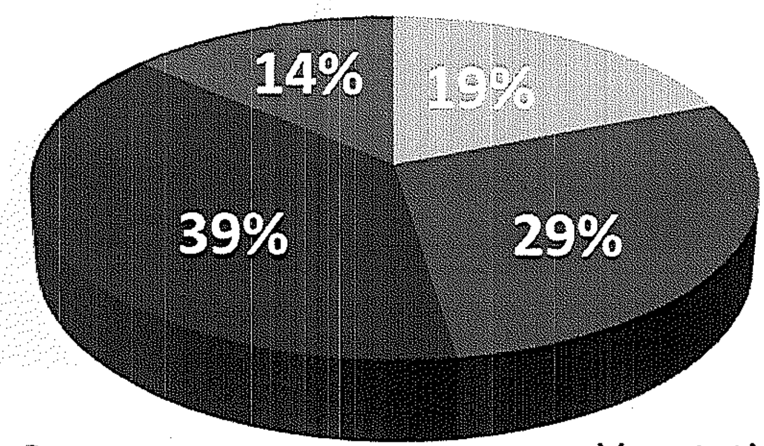
a summer urban heat island

What makes cities warm?

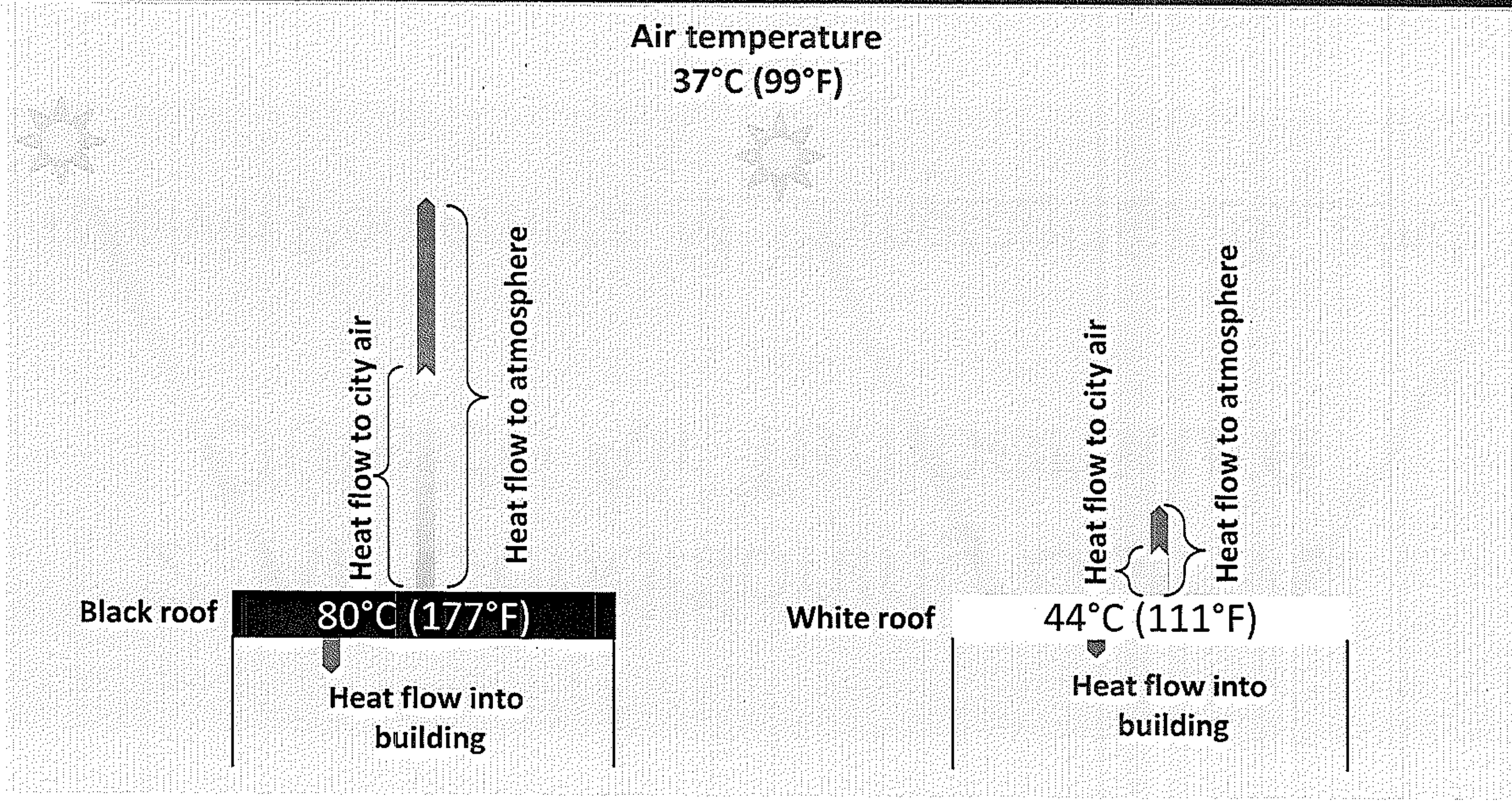


Sacramento, California (≈ 1 km^2)

One reason:
many dark surfaces.



Roofs with high solar reflectance cool our buildings, cities, and planet



2. Air Conditioning Use vs. Outside Air Temperature

(Melvin Pomerantz, M_Pomerantz@LBL.gov)

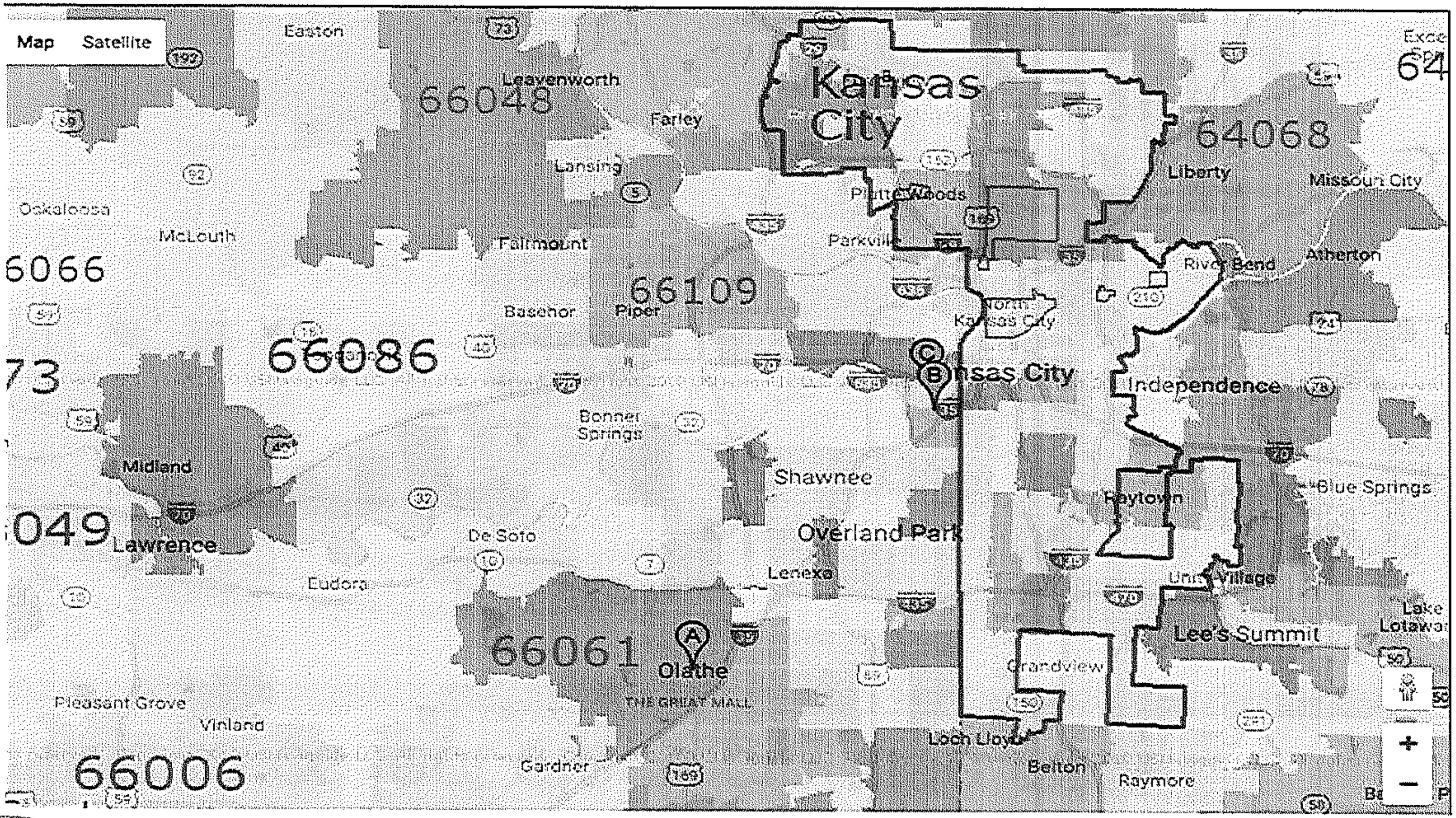
MARC and LBNL are working with local utilities to collect electricity use data

KCP&L®

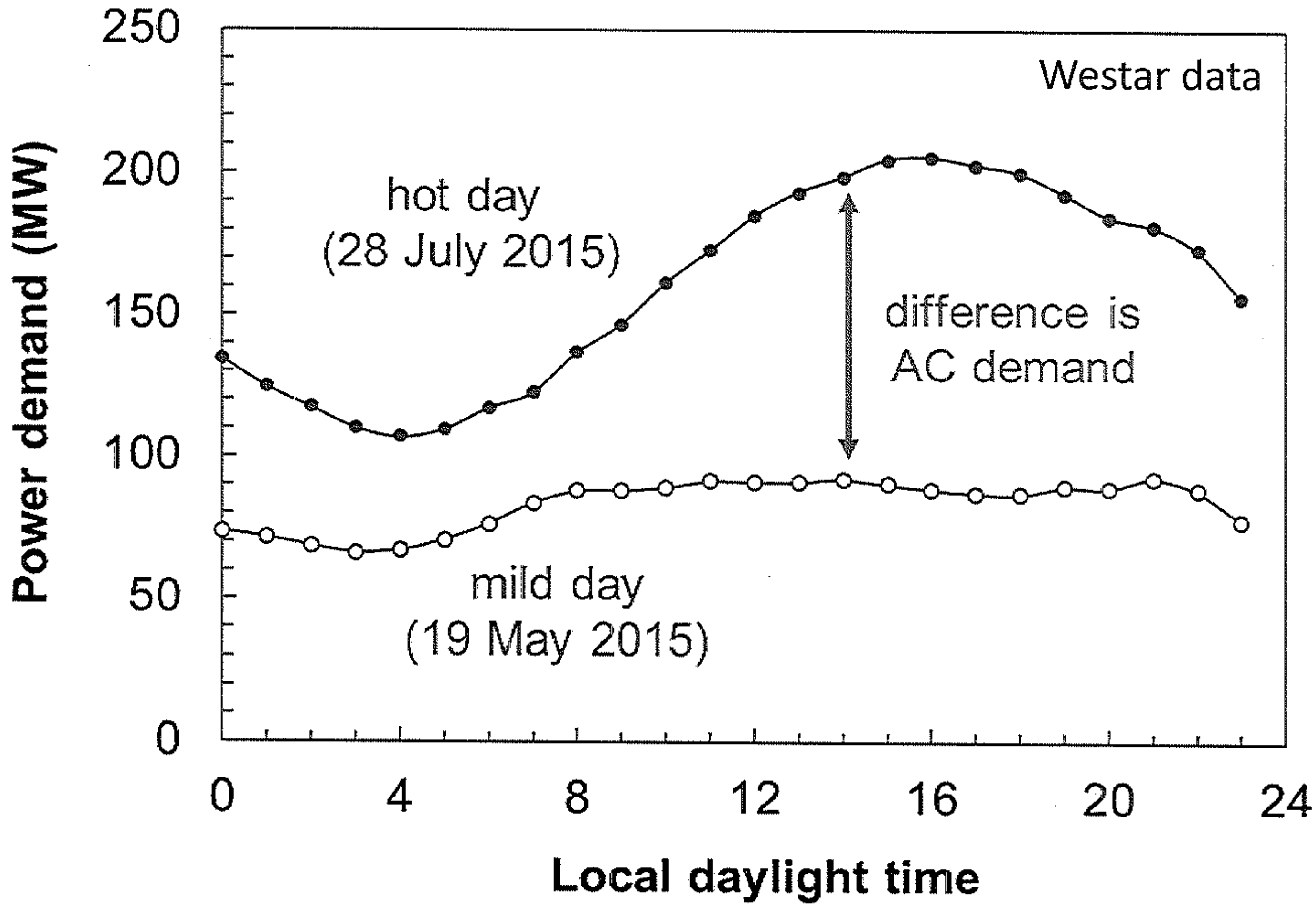
energizing *life*

Westar Energy®

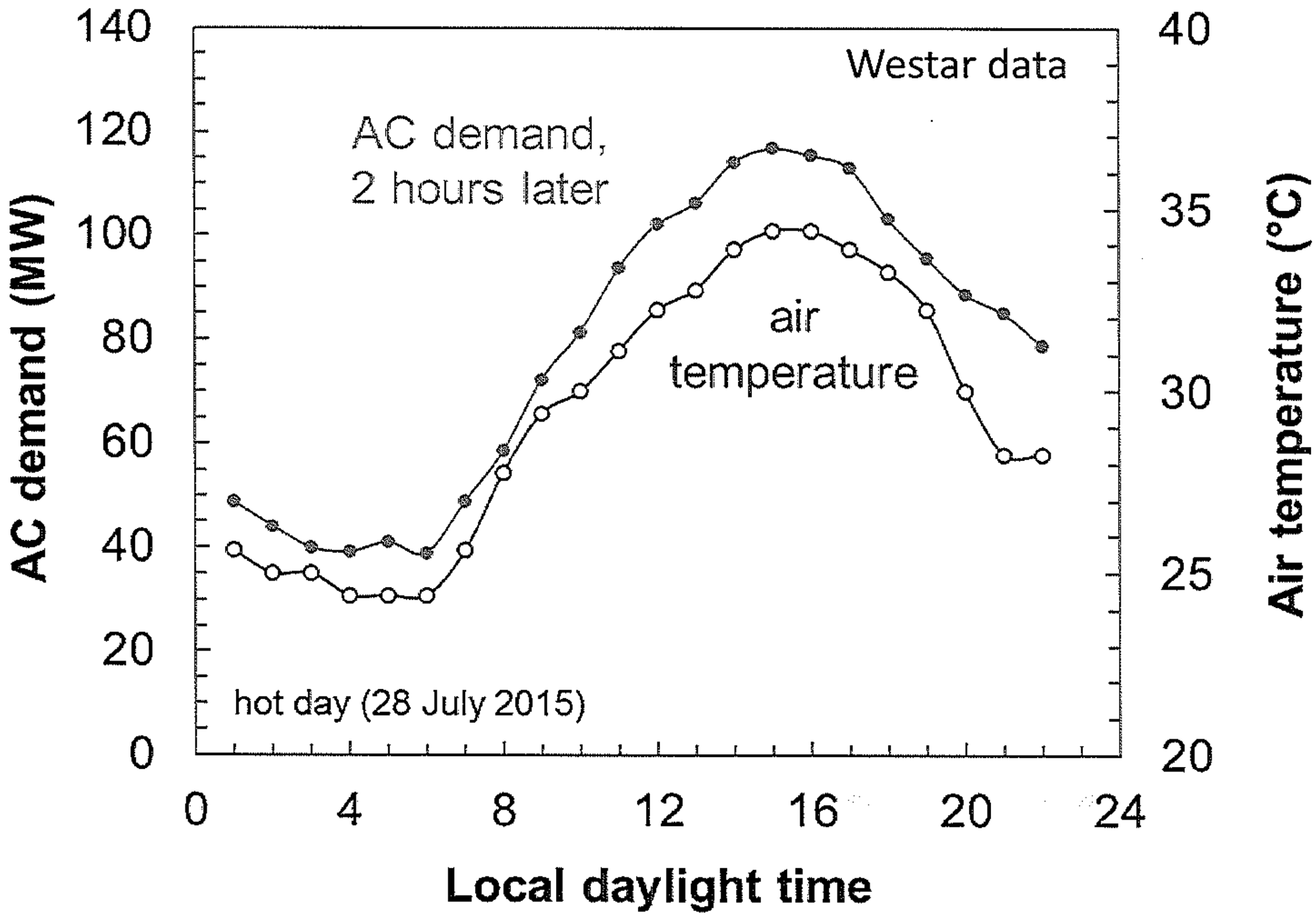
Example: Westar Energy shared hourly electrical demand for a few ZIP codes outside K.C.



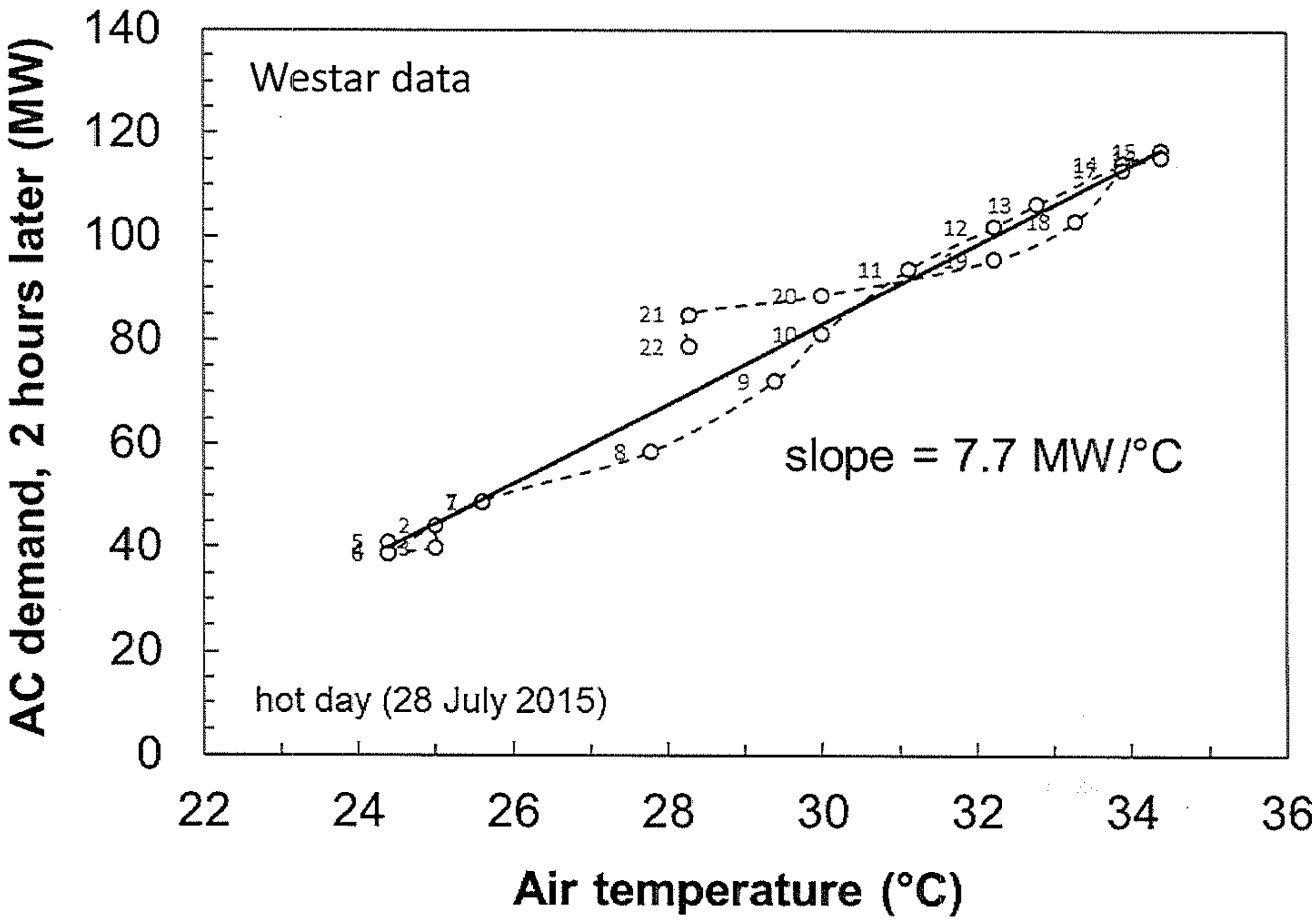
We compared power demands on hot/mild days equally spaced about summer solstice



AC power demand tracks outside air temperature with 2 hour lag



AC demand (2 hours later) scales almost linearly with outside air temperature



Energy and energy cost savings from air temperature reduction can be small

- Raising by 0.20 the albedo of all pavement (1/3 of urban area) in a California city would
  - lower outside air temperature by < 1 °C
  - save considerably less than 2 kWh of AC energy each year per m^2 of pavement modified
  - save < $2/$m^2$ of pavement modified over 10-year service life, assuming cooling-season time-of-use electricity price of $0.70/kWh
- **To be economical, savings must exceed cost**
  - pavements doubtful, roofs likely feasible
  - see Pomerantz et al. 2015, *Urban Climate*, http://dx.doi.org/10.1016/j.uclim.2015.05.007

3. Heat Island Countermeasures

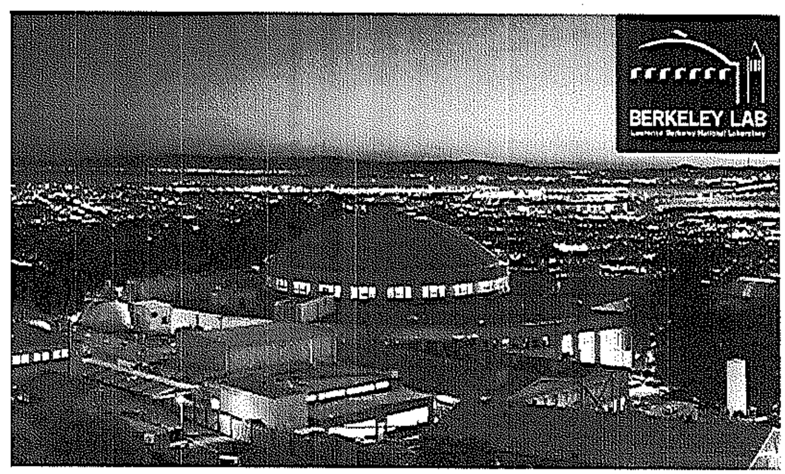
(Dev Millstein, DMillstein@LBL.gov)

MARC and LBNL will assess the K.C. region UHI and plan countermeasures

- The Mid-America Regional Council (MARC) is the regional and metropolitan planning organization serving the 119 local governments in the bi-state, 4,423-square mile Kansas City region.
- The Heat Island Group at Lawrence Berkeley National Laboratory (LBNL) seeks to cool buildings, cities, and the planet.

MARC

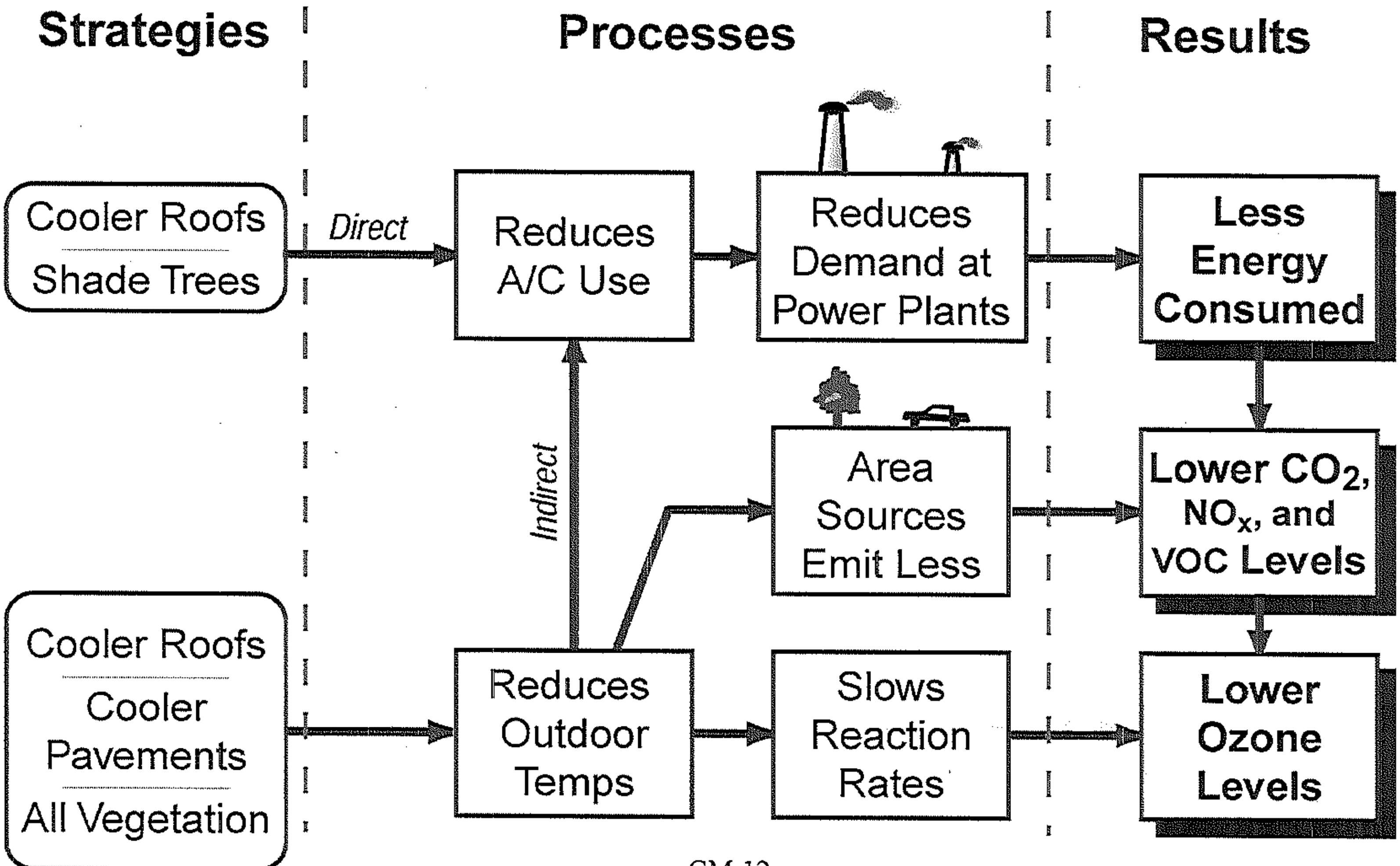
MID-AMERICA REGIONAL COUNCIL



Many strategies have been proposed to mitigate urban heat islands

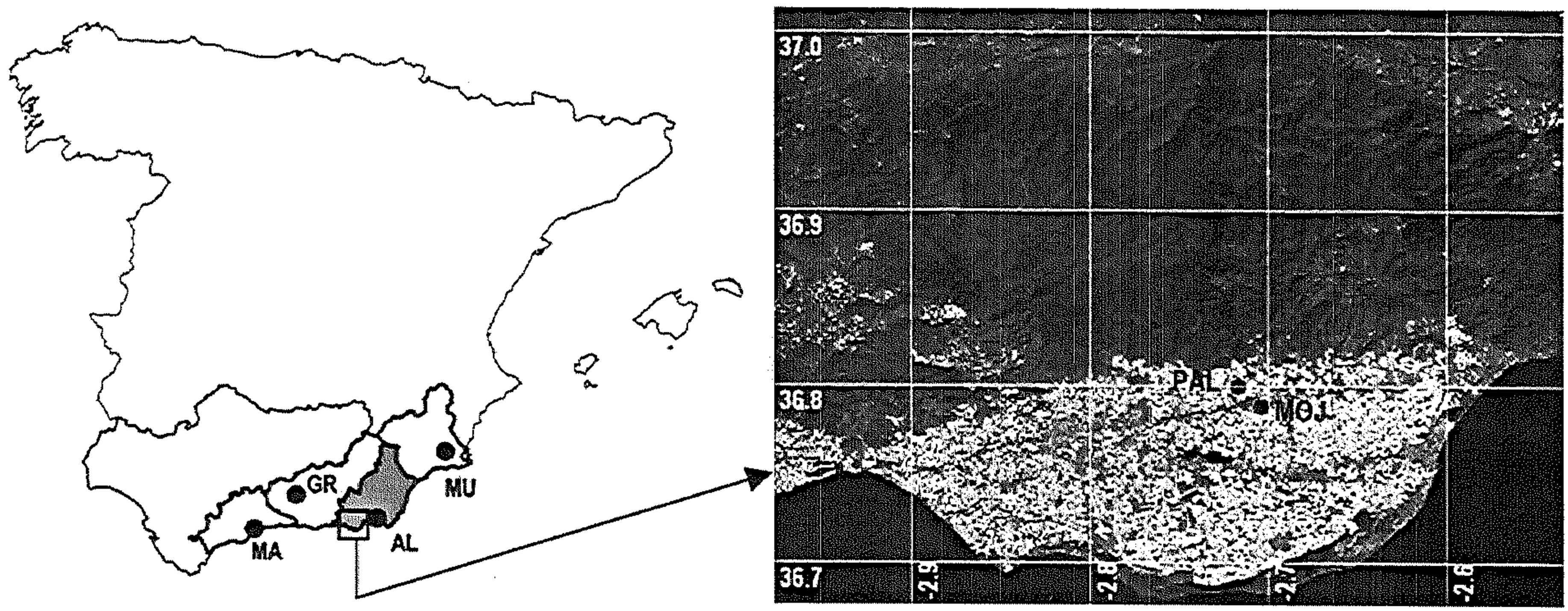
1. Increase the reflectance of roofs
2. Increase the reflectance of pavements
3. Increase the reflectance of walls
4. Install garden (“green”) roofs
5. Add trees or other plants at ground level
6. Reduce waste heat from human sources (“anthropogenic” heat)
7. Irrigate the city

Countermeasures can save energy, improve comfort, and boost air quality



- Observations and simulations indicate that reflective surfaces can cool cities.

Reflective roofs have been observed to cool outside air in Almeria, Spain

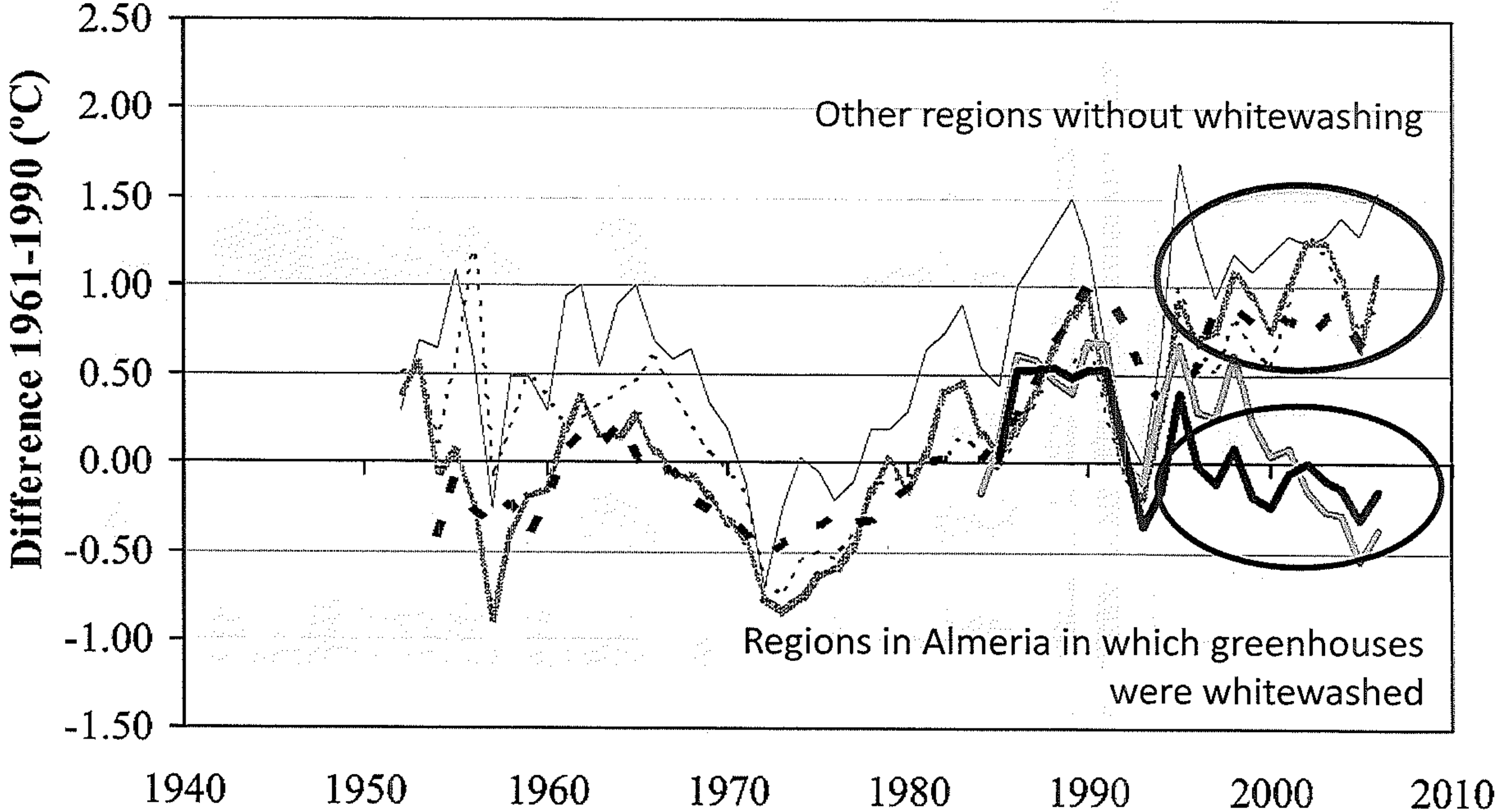


Farmers in Almeria started white-washing greenhouse roofs in summer to lower the temperature inside. These roofs can be seen by eye from the International Space Station!

Campra et al. 2008. *J. Geophys. Res. Atmos.*, http://dx.doi.org/10.1029/2008JD009912

Whitewashed roofs in Almeria, Spain

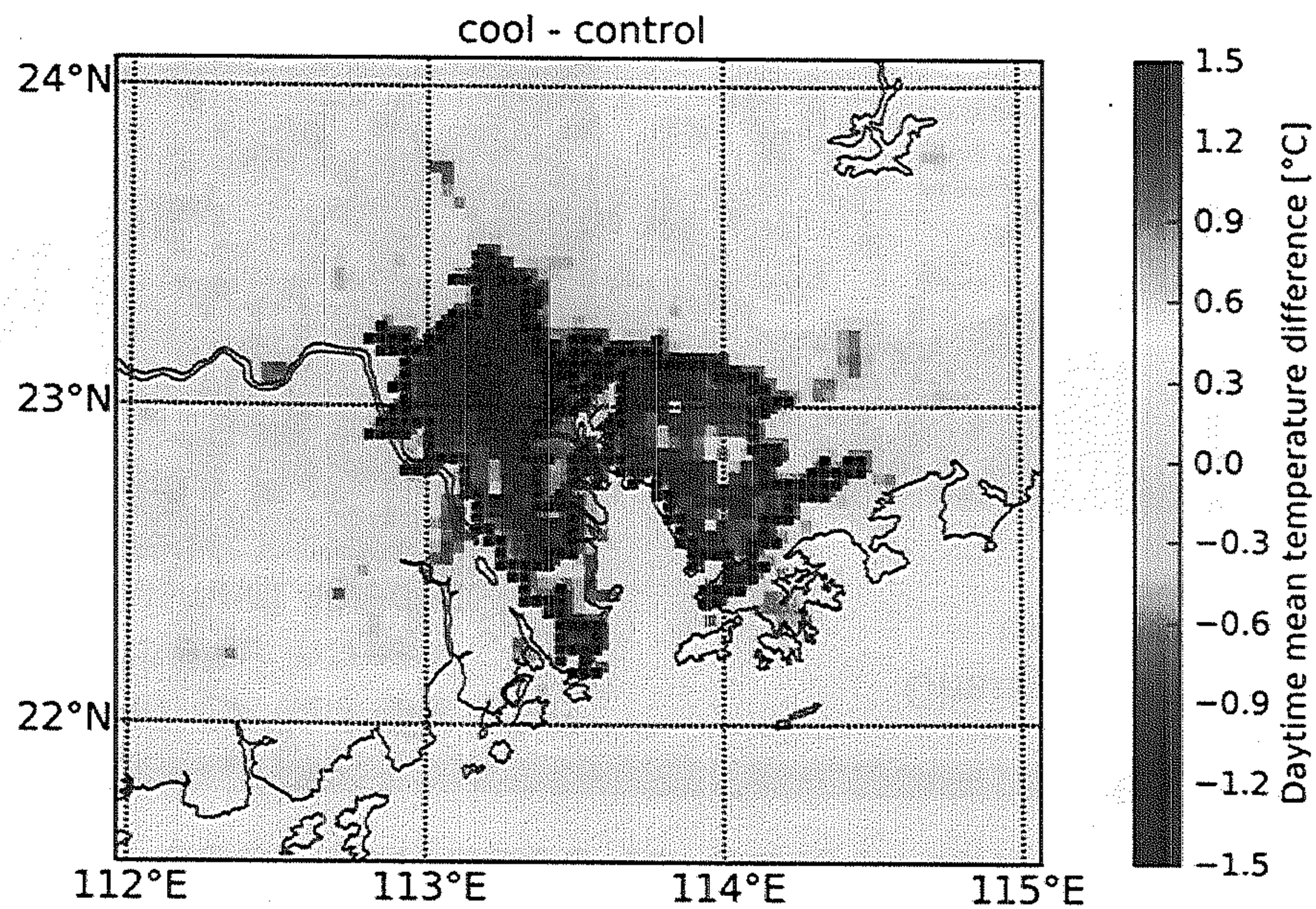
Measured outdoor air temperatures in Almeria fell as whitewashing peaked in the late 1990s



Campra et al. 2008. *J. Geophys. Res. Atmos.*, http://dx.doi.org/10.1029/2008JD009912

Modeling indicates widespread cool roofs could lower mid-day summer air temperatures in megacities by 1 °C

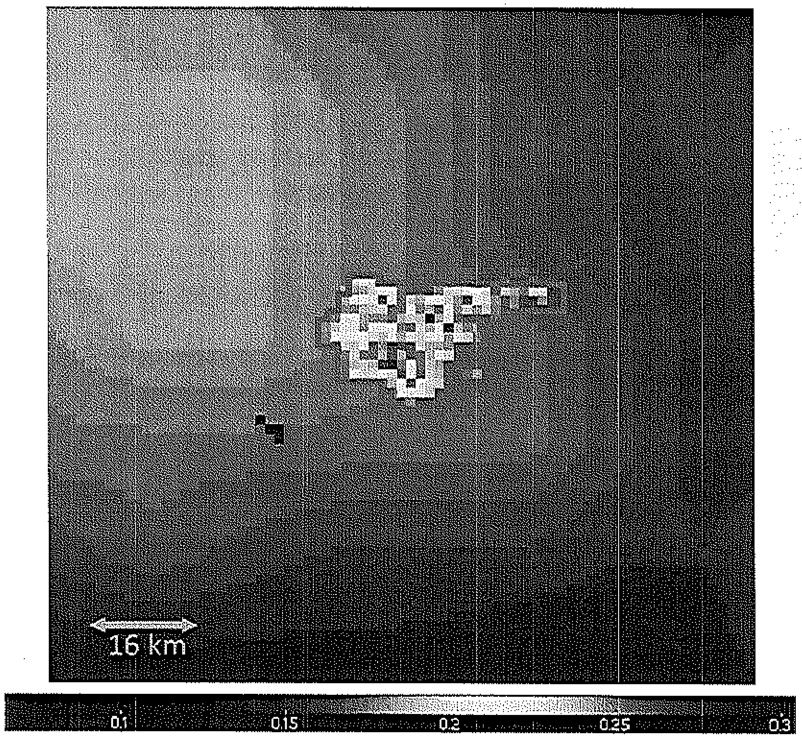
Daytime mean temperature change in Guangzhou, China (°C)



Cao et al. 2015. *Environmental Science and Technology*, http://dx.doi.org/10.1021/acs.est.5b04886

While even small cities can benefit, air must flow over a few km of cool surfaces to detect temperature change

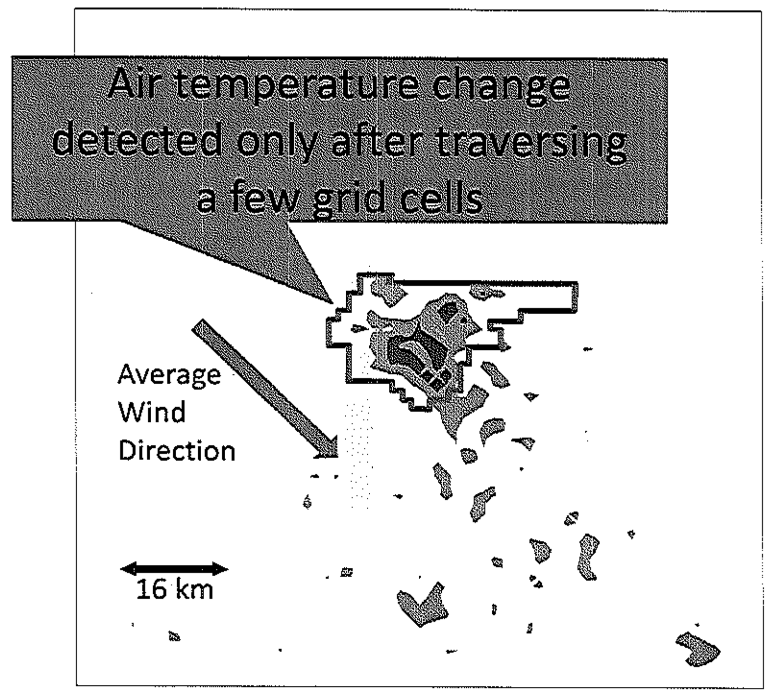
Bakersfield, CA was simulated before and after increasing roof & pavement albedos.



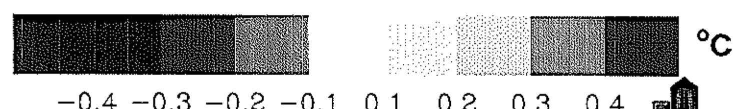
"Cool" case albedos

Albedos 0.60, 0.35, and 0.30 for flat roofs, sloped roofs, and pavements; maximum grid cell albedo increase ~0.15.

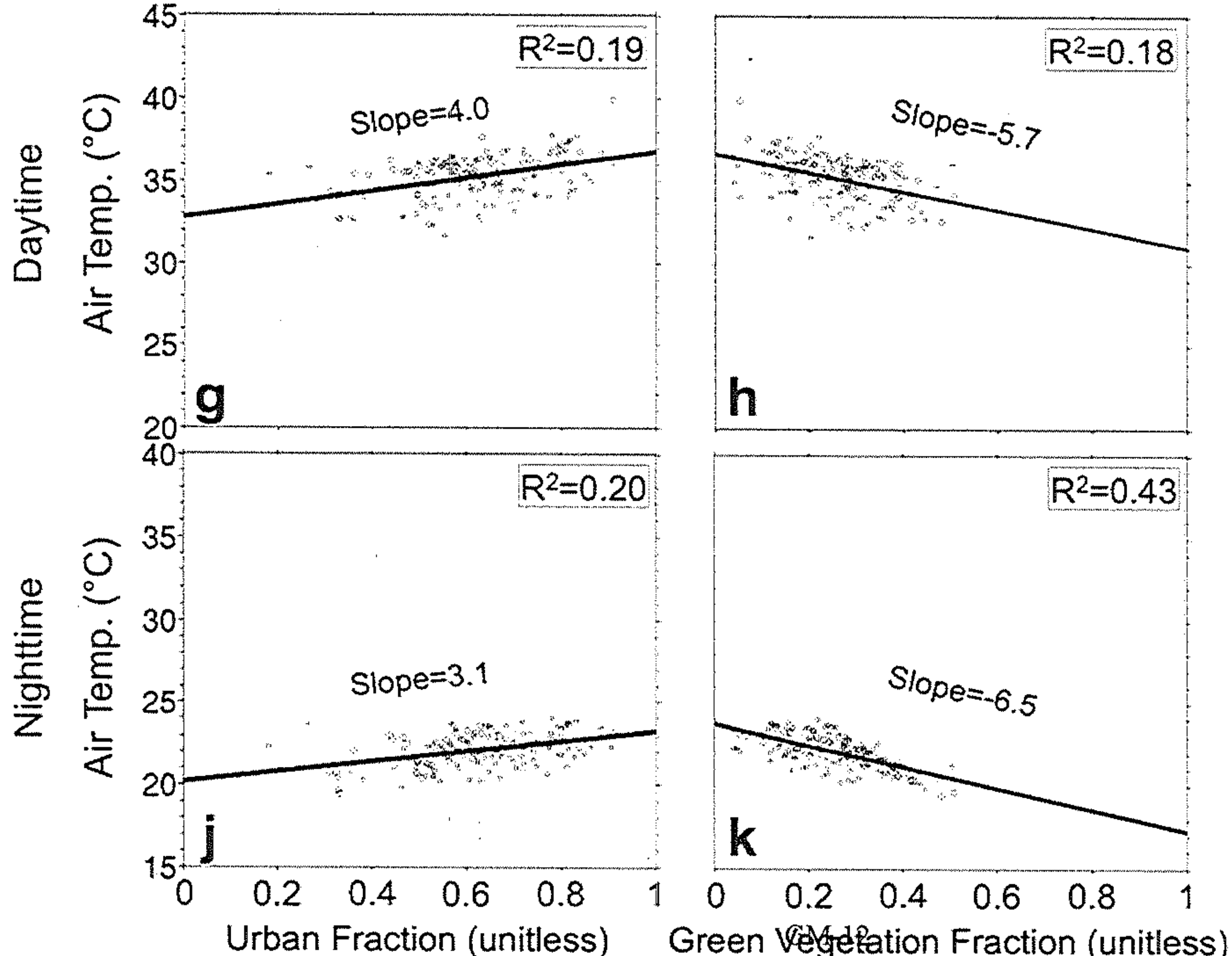
Change in 2 m air temperature on summer afternoon



Each grid cell is 1.3 km × 1.3 km



Modeling also supports increasing urban vegetation as a heat island countermeasure



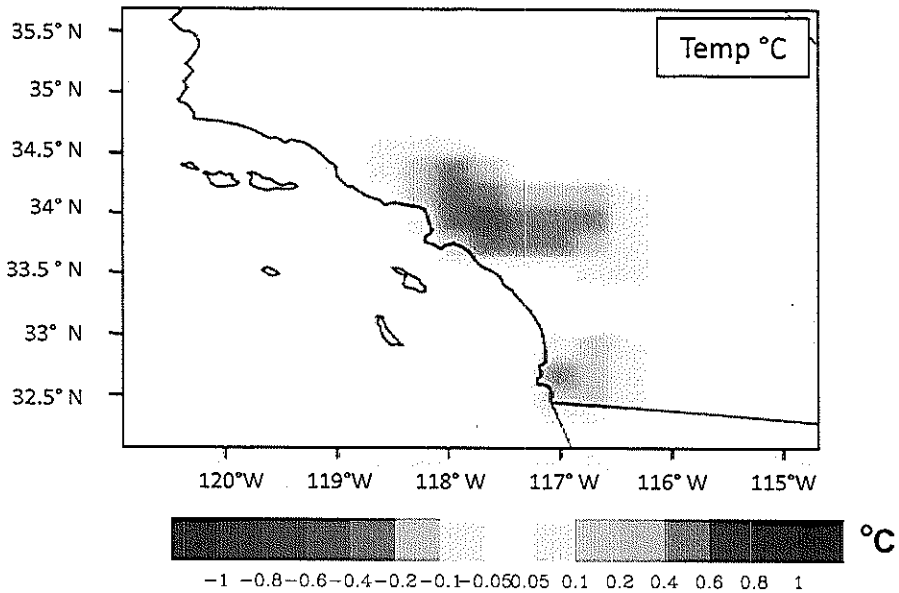
Los Angeles simulations correlated higher air temperature to increased urbanization and reduced vegetation.

Vahmani and Ban-Weiss. 2016. J. Geophys. Res. Atmos. http://dx.doi.org/doi:10.1002/2015JD023718

- But wait, there's more!

Cooling the air can slow formation of smog

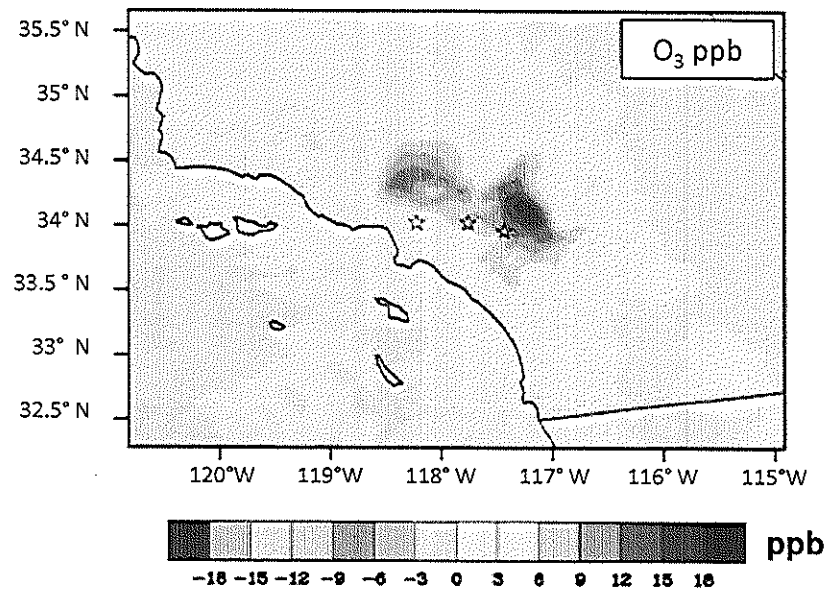
Modeled change in average summer afternoon air temperature from increasing the albedo of roofs (+0.25) and pavements (+0.15) in the Los Angeles basin



Grid cell albedo increase was 0.11 in downtown Los Angeles

Millstein & Menon 2011. *Env. Res. Let.*, http://dx.doi.org/doi:10.1088/1748-9326/6/3/034001

Modeled change in ozone concentration from increasing outdoor air temperature in southern California by about 2 °C



Millstein & Harley. 2009. *Atmos. Chem. Phys.* http://dx.doi.org/10.5194/acp-9-3745-2009

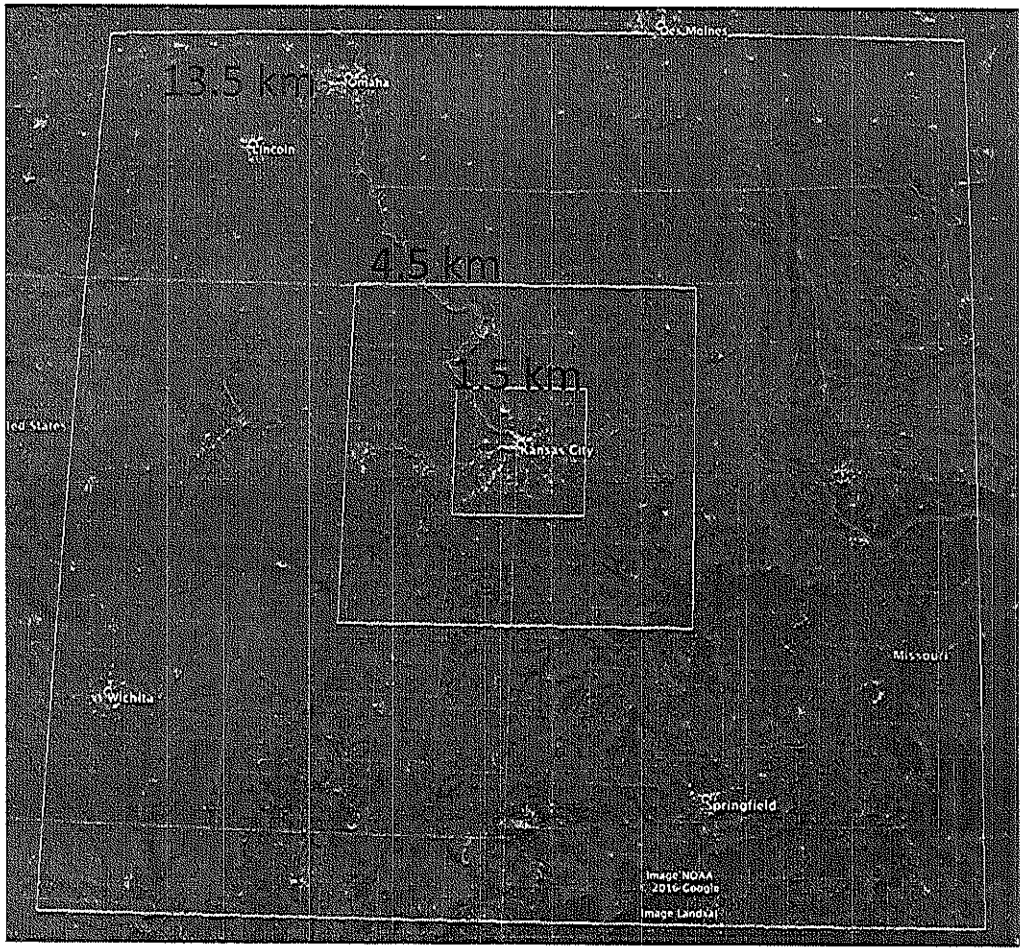
4. Preliminary Meteorological Modeling of the Kansas City Region

(Dev Millstein, DMillstein@LBL.gov)

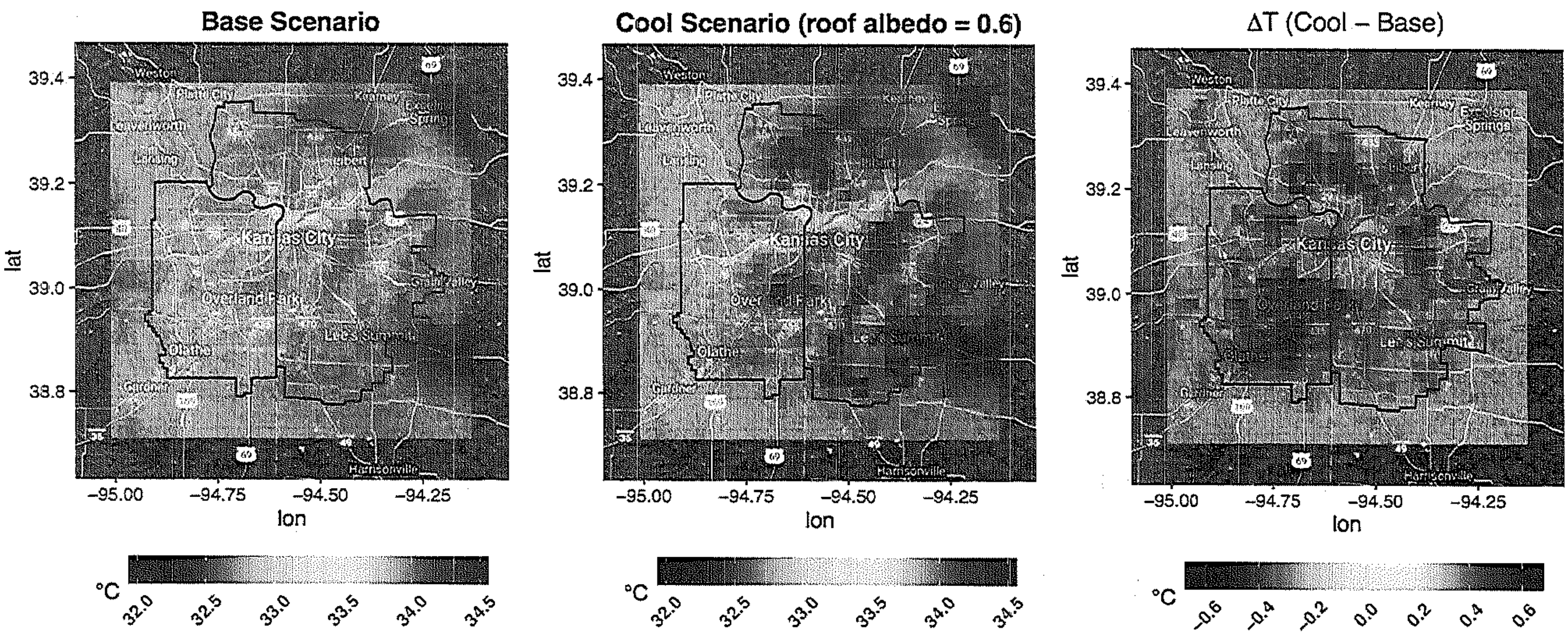
First simulations evaluated a cool roof strategy

- Compared cool-roof and base-case scenarios (roof albedo raised to 0.6 from 0.2)
- Details:
  - Calculated difference (cool - base) in near-surface air temperature at 2 pm LST
  - Jul + Aug (7 days per month), 2011 – 2015
    - Total of 70 days per scenario
  - Weather Research & Forecasting (WRF) v. 3.8
  - High resolution (1.5 km) for the inner domain

Modeling domain resolves the Kansas City area with 1.5 by 1.5 km grid cells



Cool roofs reduced average urban temperature by up to 0.4 °C



Results average the 70 days of simulations and assume all roofs are made cool.

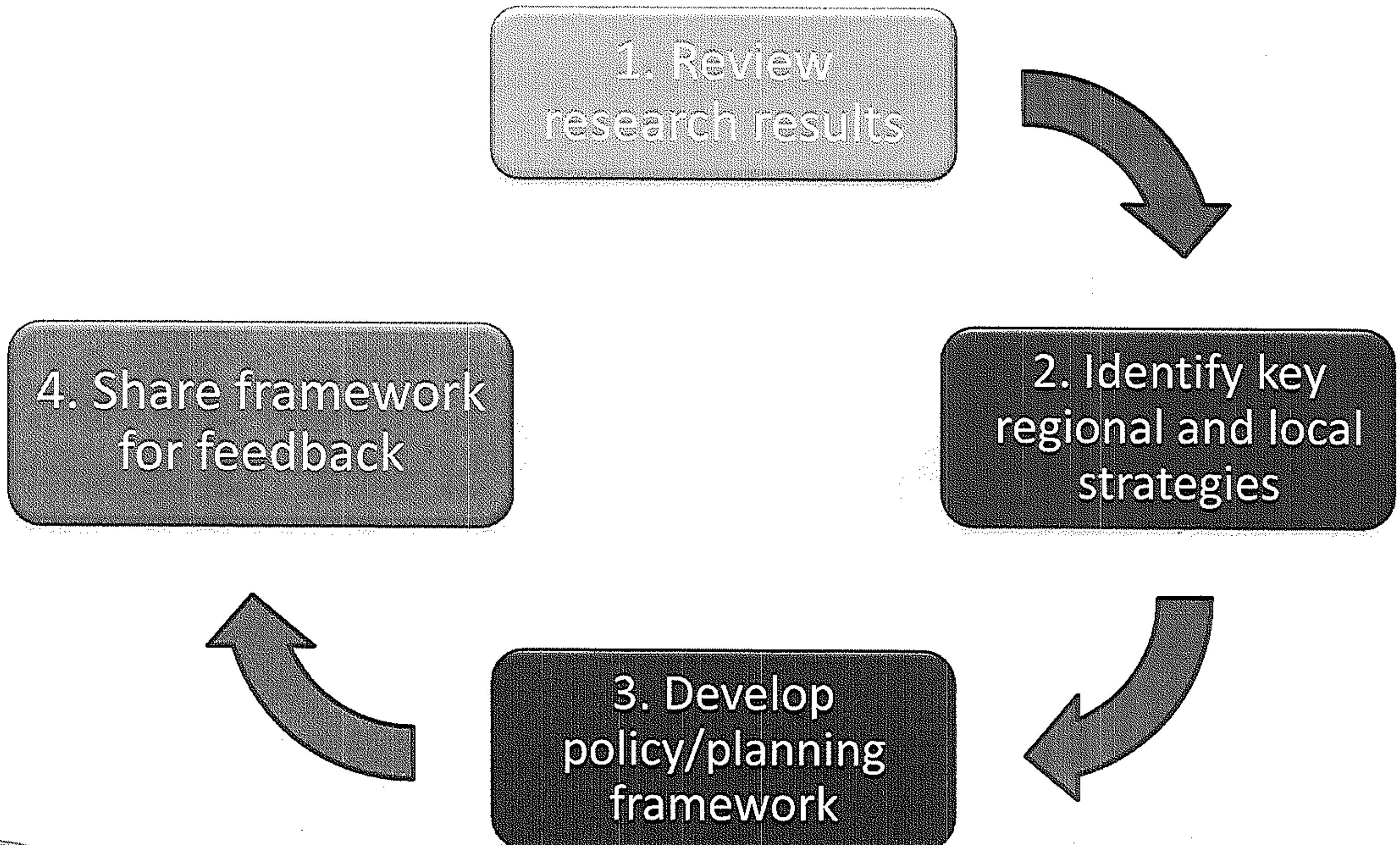
Other scenarios will be explored

- Planting shade trees or other vegetation
- Greater benefits during heat waves?

5. Policy and Planning

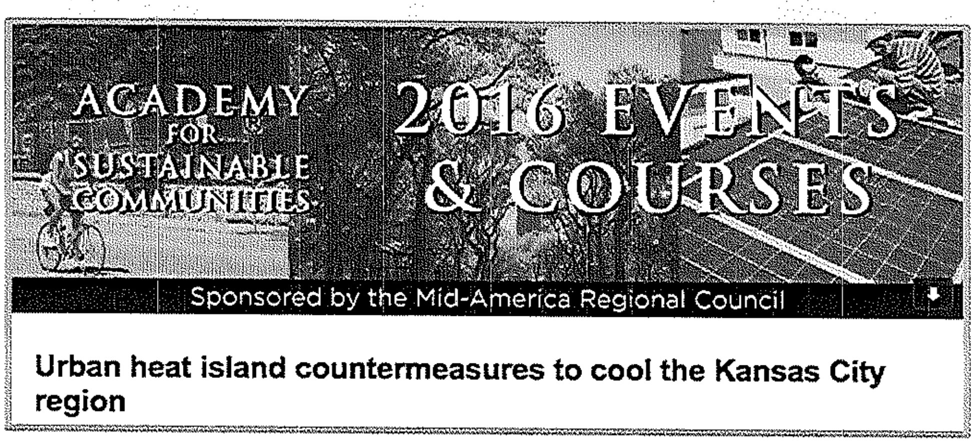
(Haley Gilbert, HEGilbert@LBL.gov)

MARC and LBNL will create policy/planning framework to support local UHI countermeasures

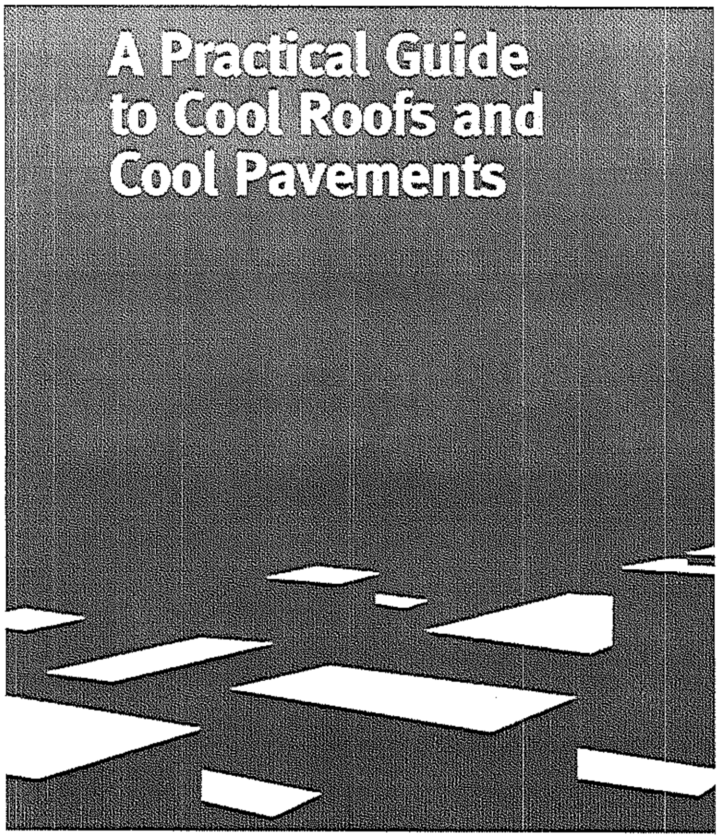


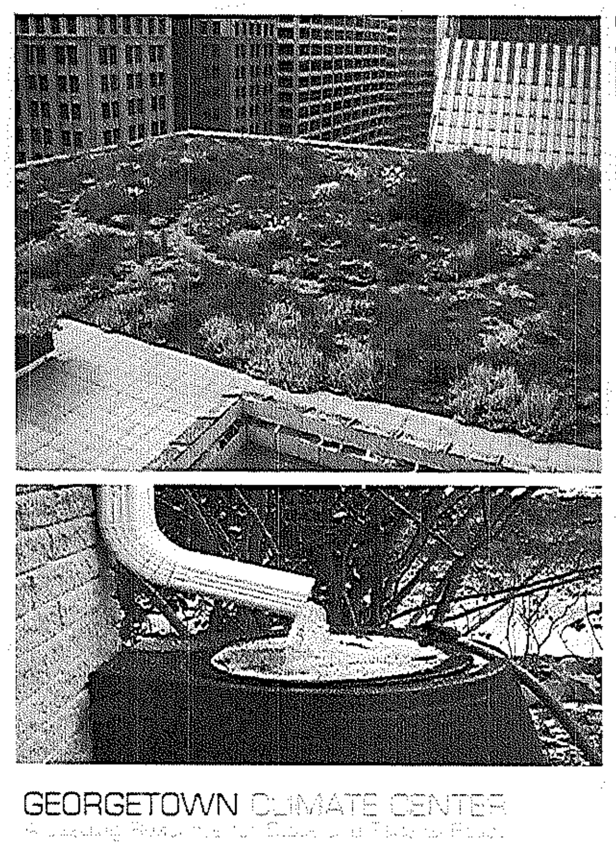
MARC and LBNL will facilitate local implementation of UHI countermeasures

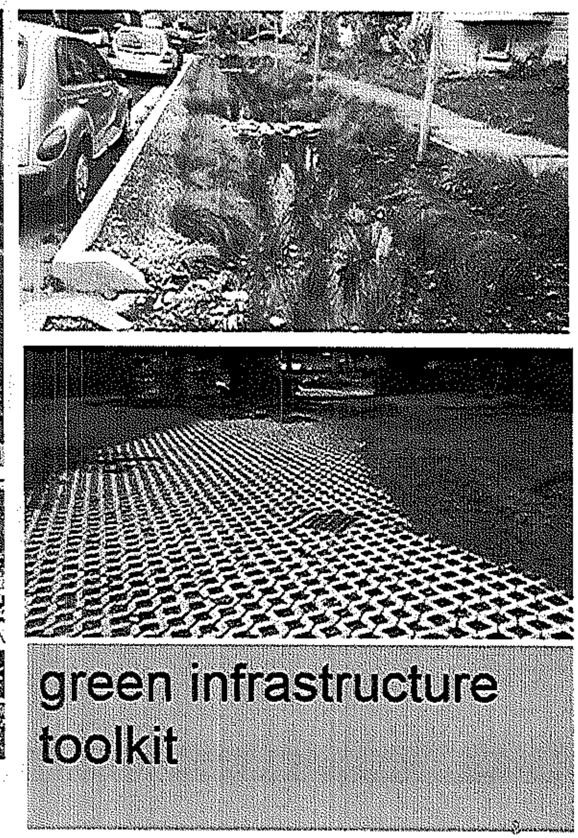
- Host webinars/workshops
- Organize a charrette (summer 2017)
- Present at conferences and publish to share project research and results



MARC and LBNL will develop guidance to support similar UHI research and policy efforts nationwide



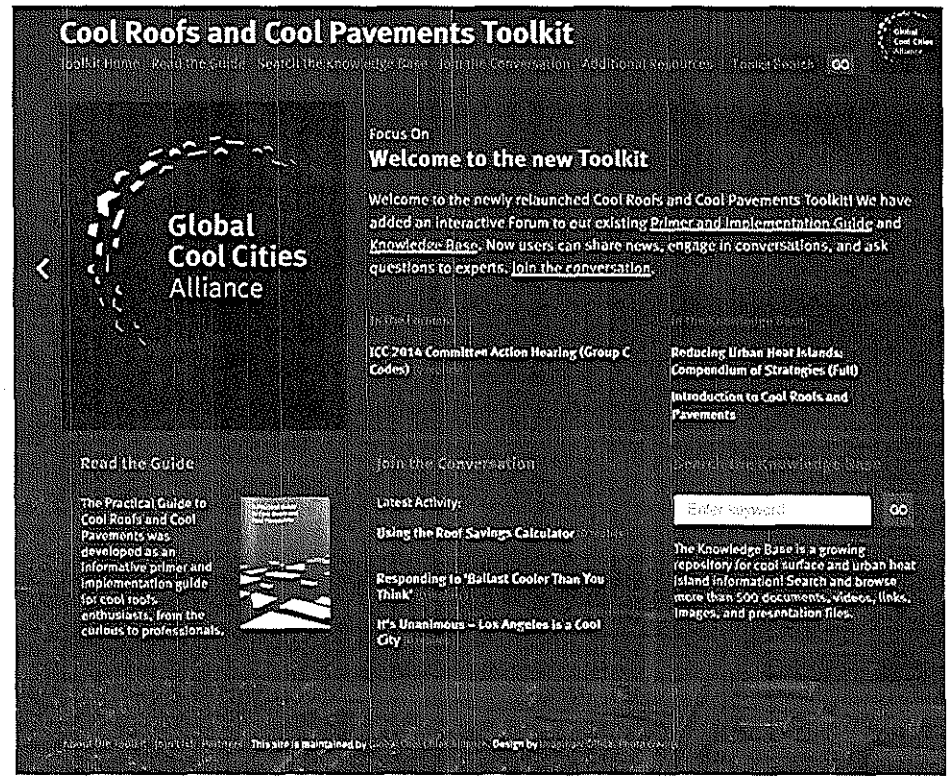




6. Good Stuff Online

Global Cool Cities Alliance offers UHI mitigation resources for officials, experts, and the public

- Science, costs, and benefits of cool surfaces
- Global best practices for program and policy implementation
- Sample materials and relevant organizations.
- A comprehensive "knowledge base"
- Networking Forum



CoolRoofToolkit.org

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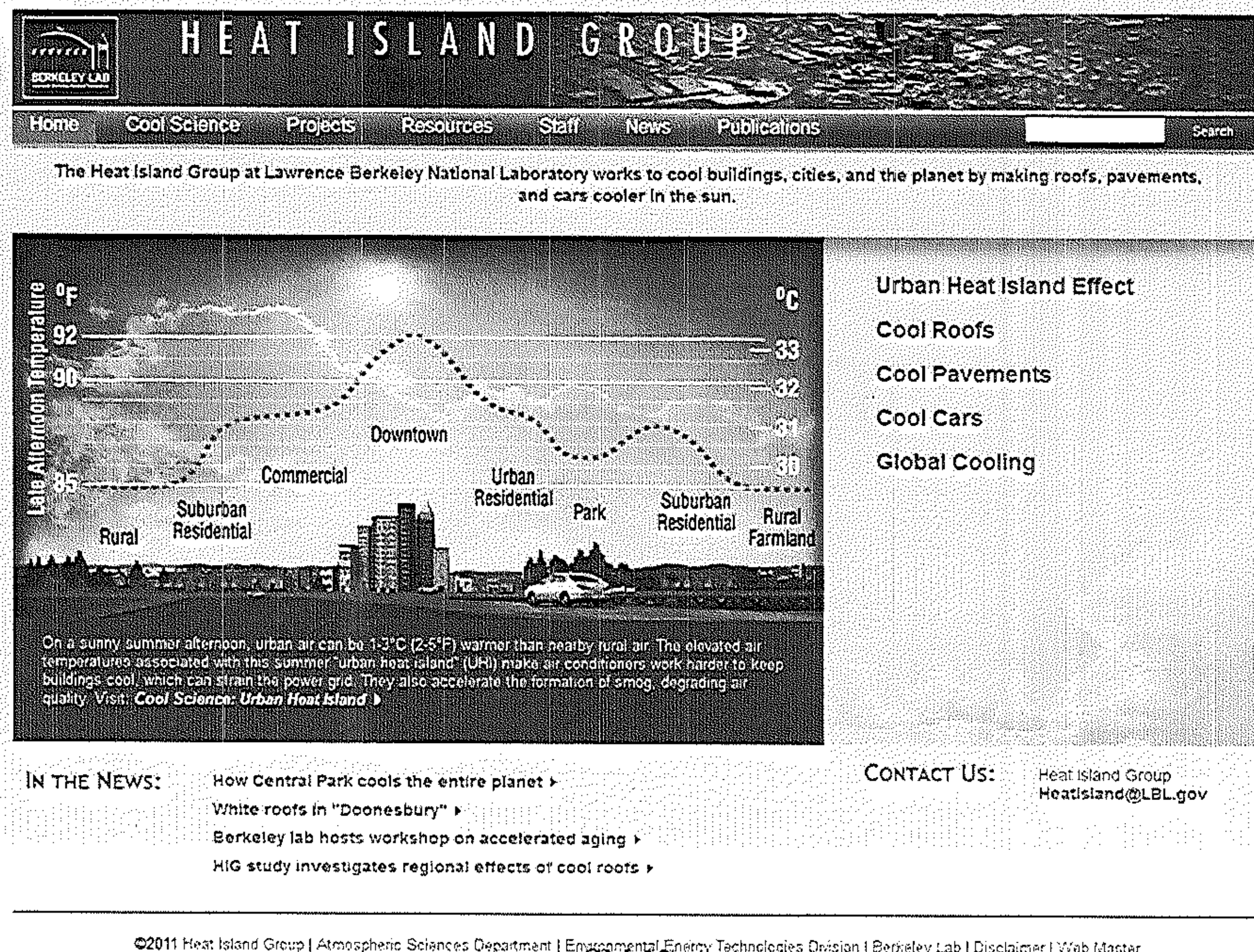
Heat Island Group website

HeatIsland.LBL.gov



Thank you!

Investigating Climate Impacts of Urbanization and the Potential for Cool Roofs to Mitigate Future Climate Change in Kansas City

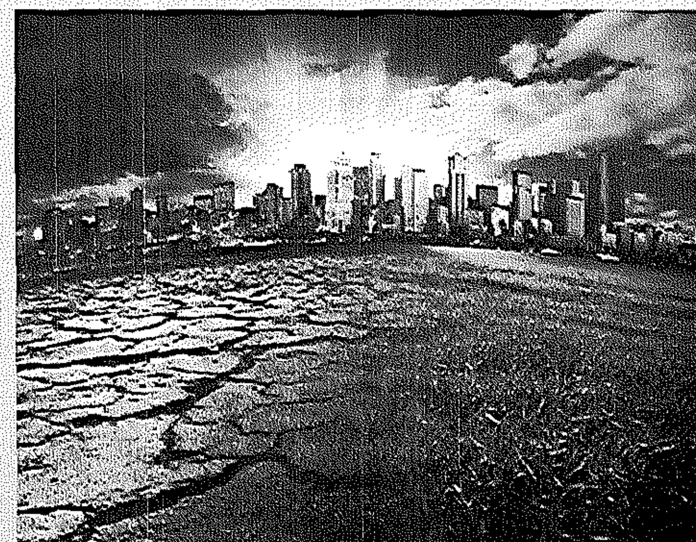
KYLE REED AND FENGPENG SUN, PhD

DEPARTMENT OF GEOSCIENCES

UNIVERSITY OF MISSOURI – KANSAS CITY

Goals of this study

- *To understand the* ***impacts land cover change*** *on regional climate by numerical simulations;*
- *To provide evidence for the* ***mitigation of urban heat island*** *through the implementation of cool roofs, which will benefit the local community by improving city's resilience to climate change.*

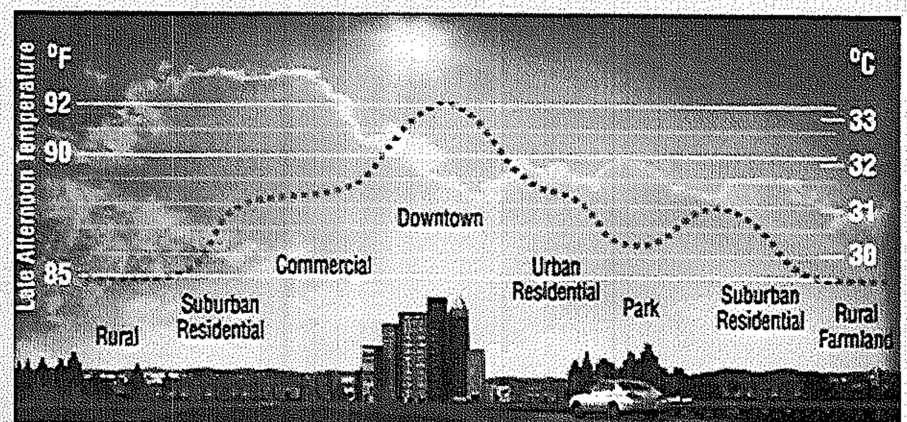


Presentation Outline

- **What is an urban heat island (UHI)?**
- Urban growth and the Kansas City metropolitan area
- Cool roofs
- High-resolution climate modeling to analyze Kansas City's UHI and its mitigation
- Summary

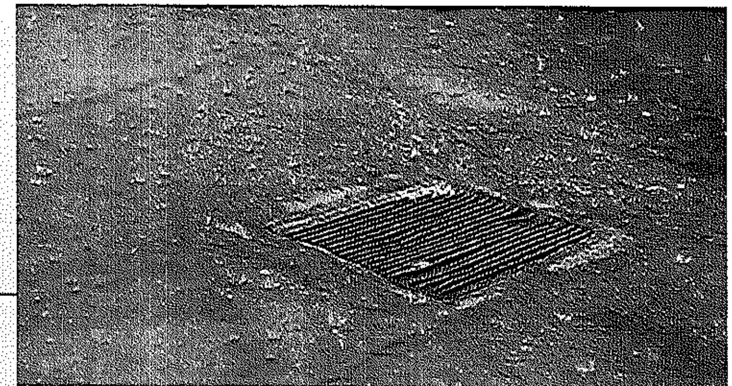
What is an Urban Heat Island?

- Phenomenon where the air temperature within a city is warmer than that of surrounding rural areas, especially at night
- Difference can be up to 12°C in the evening
- Most intense in the urban core due to density of infrastructure



What Causes UHIs?

- Multiple causes (UCAR 2017):
  - Less absorption of moisture by urban surfaces
  - Human activities
  - Buildings prevent mixing of air
  - Albedo of urban surfaces



Presentation Outline

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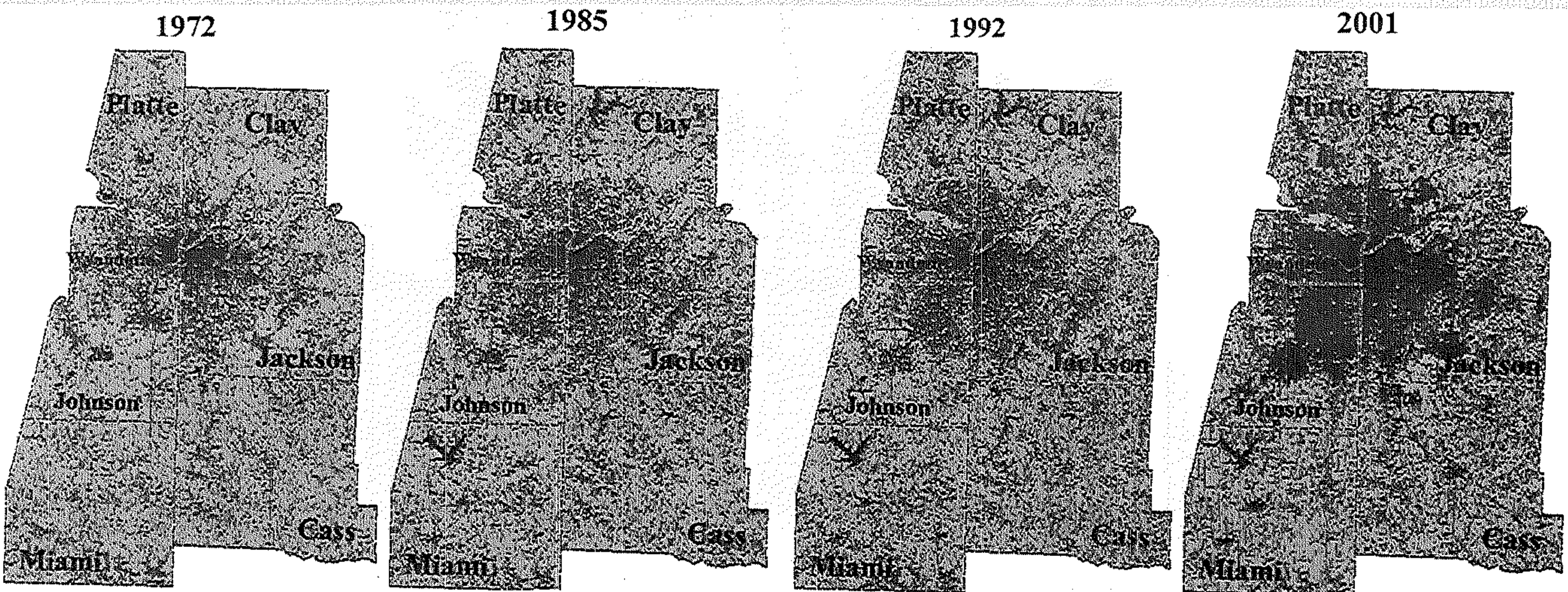
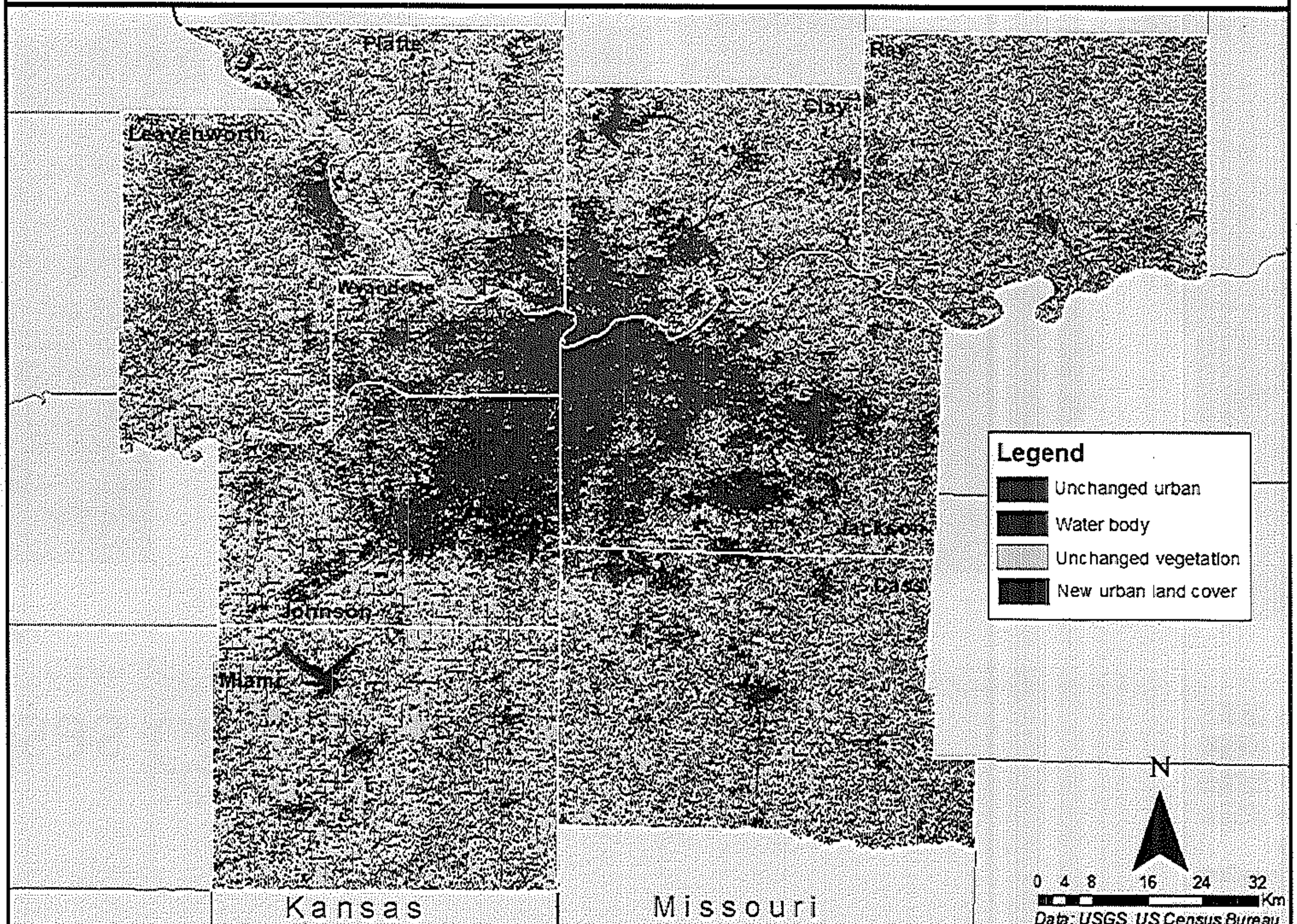
Kansas City Urban Growth

Legend
County Boundary
Non-forest Vegetation
Forestland
Built-up Area
Waterbody



(Ji et al., 2005)

Kansas City Metro Land Cover Change from 1990 to 2017 Using Landsat Imagery



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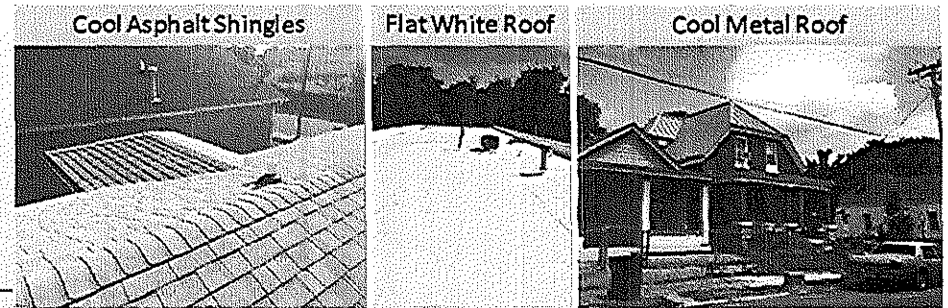
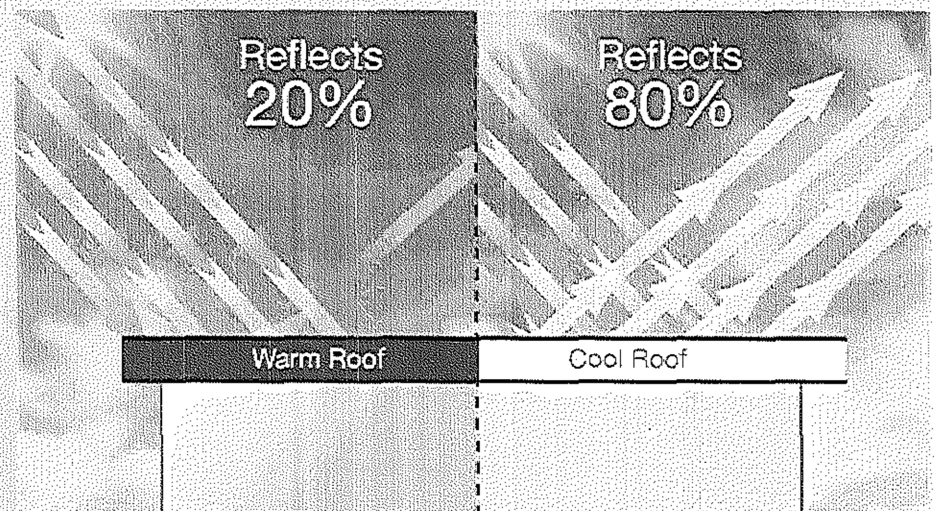
Cool Roofs



- Replaces conventional roofing materials with lighter-colored materials
- Greater reflection of solar radiation
- Advantages vs green roofs
  - Less costly
  - Less upkeep
  - Doesn't require additional structural support
- Disadvantage
  - Albedo decreases with debris
    - Can be restored with cleaning



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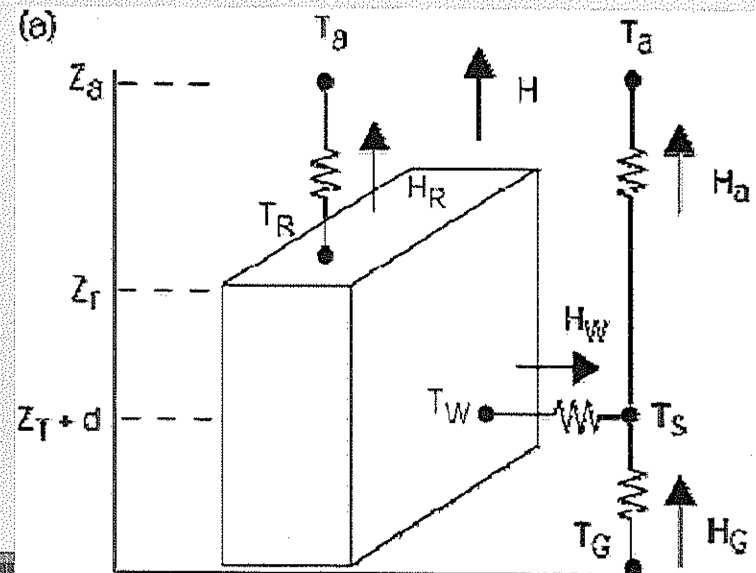
High-Resolution (1-km) Climate Model

- Weather Research and Forecasting (WRF) model
- Mesoscale numerical weather prediction system
- Coupled to an urban canopy model (UCM)
- Commonly used for researching UHI effect and cool roofs (Vahmani 2016, Sharma 2016, Li 2014, Jandaghian 2018)

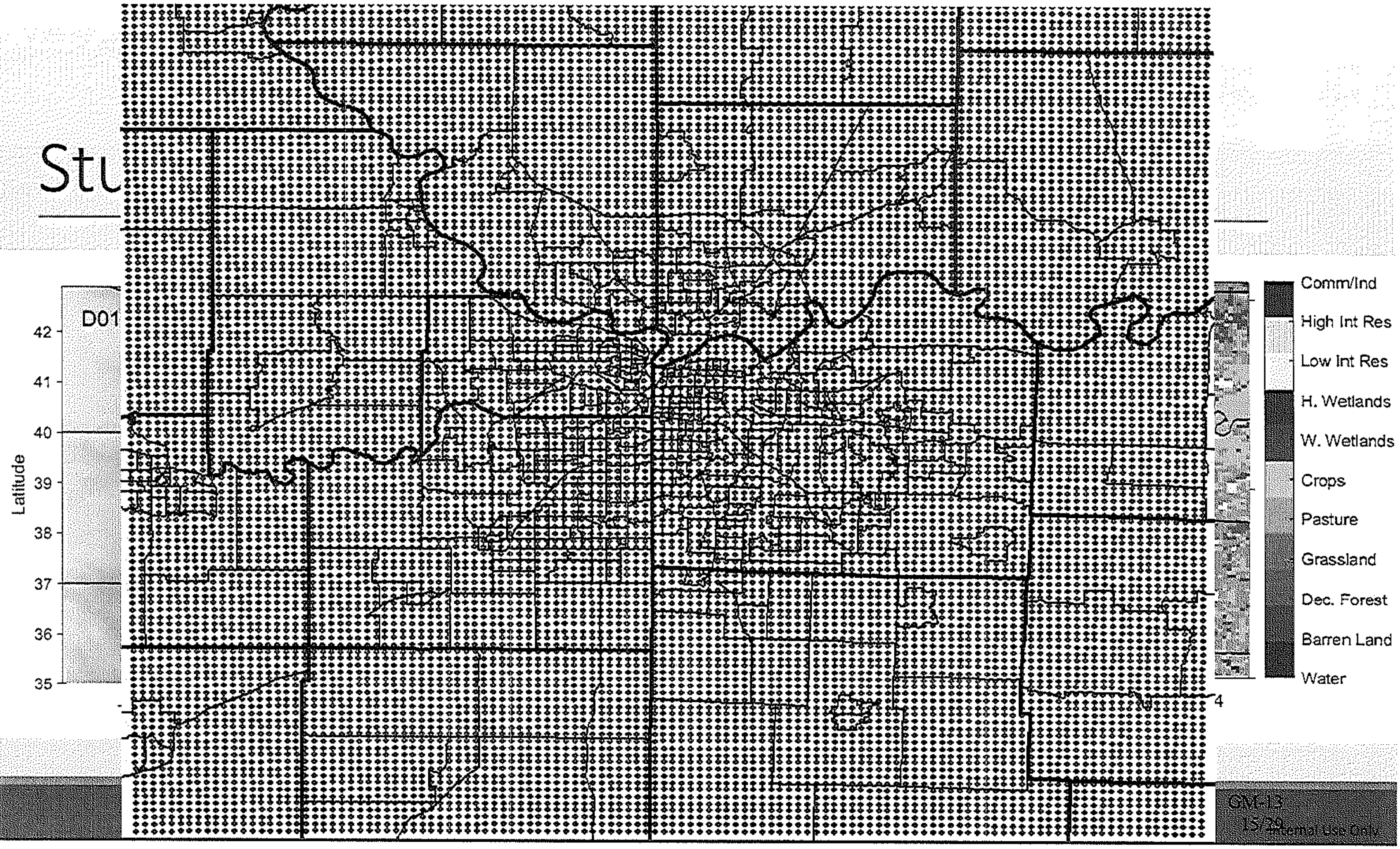


(Tewari 2007)

Part 1 – Sensitivity Simulations

Part 1 – Sensitivity Simulations

- Area of interest: Kansas City metropolitan area
- Time frame: July 17th – 26th, 2012
  - Maximum observed temperature: 40°C (104°F)
  - Average observed temperature: 31°C (88°F)
- Initial and boundary conditions
  - North American Regional Reanalysis (NARR)
- Land cover
  - Urban pixels: National Land Cover Database (NLCD) 2011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35
Latitude
Comm/Ind
High Int Res
Low Int Res
H. Wetlands
W. Wetlands
Crops
Pasture
Grassland
Dec. Forest
Barren Land
Water
4
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Internal Use Only

Part 1 - Results

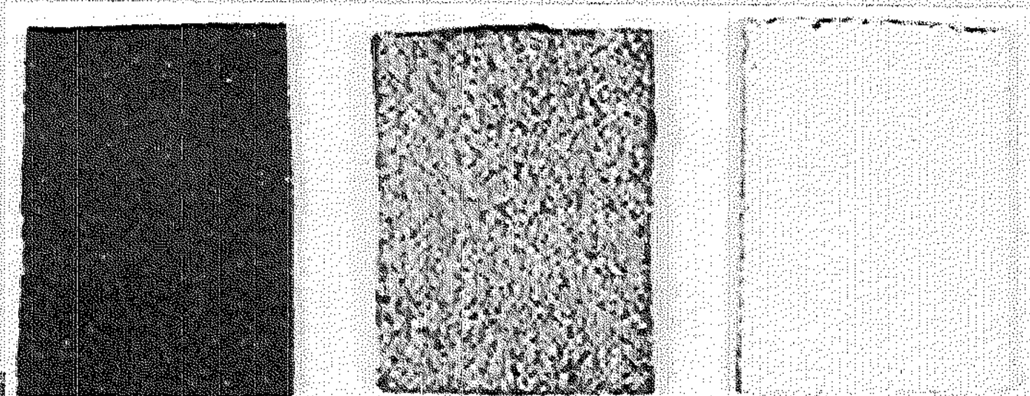
- Model performance assessed using root mean squared error, mean bias, and mean absolute error
  - Lower values = better performance
  - Combination of measurements is more accepted (Chai 2014)
- Compared to observation data from Charles B. Wheeler Downtown Airport

Parameterizations			Statistics		
PBL/Surface Layer	**LW**	**SW**	**RMSE (°C)**	**MB (°C)**	**MAE (°C)**
MYJ/Eta					
	RRTMG	RRTMG	2.29	0.88	1.78
	RRTM	Dudhia	2.19	0.60	1.74
	RRTM	Goddard	2.26	1.08	1.81
BouLac/MM5					
	RRTMG	RRTMG	2.49	1.86	2.07
	RRTM	Dudhia	2.39	1.67	1.95
	RRTM	Goddard	2.69	2.11	2.26
	RRTM	RRTMG	2.68	2.05	2.22
	CAM	RRTMG	2.10	1.04	1.66
	CAM	Dudhia	1.91	0.66	1.50
	GFDL	GFDL	2.91	2.34	2.43
ACM2/MM5					
	RRTMG	RRTMG	2.18	1.44	1.72
	RRTM	Dudhia	2.01	1.10	1.61
	CAM	CAM	2.07	0.66	1.65
MYNN2/MM5					
	RRTMG	RRTMG	1.96	0.94	1.53
→	RRTM	Dudhia	1.74	0.45	1.39
	CAM	RRTMG	2.05	0.05	1.69

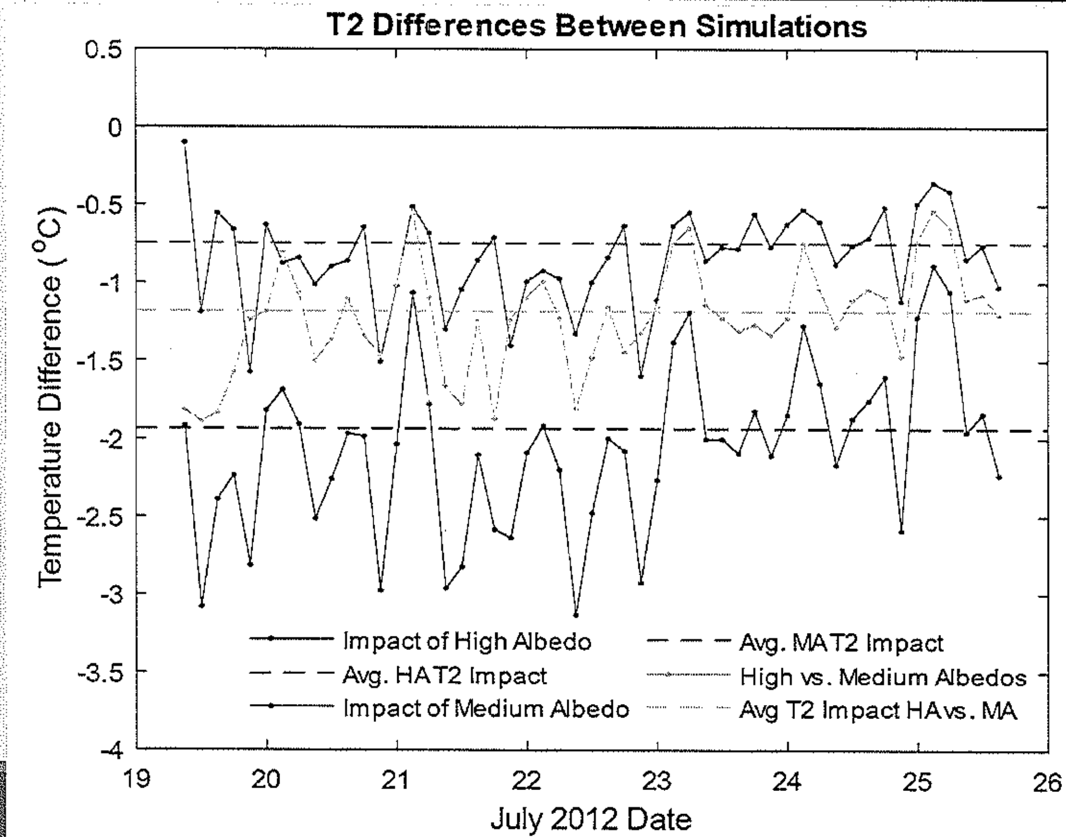
Part 2 - Short-Term Cool Surfaces Sensitivity Simulations

Part 2 - Short-Term Cool Surfaces Sensitivity Simulations

- Cool surfaces simulations were ran in addition to the normal albedo (0.2) simulations
  - Medium albedo (0.5)
  - High albedo (0.8)
- All simulations included the same 3 domains, land cover data, parameterizations, and forcing data
- Results were then compared

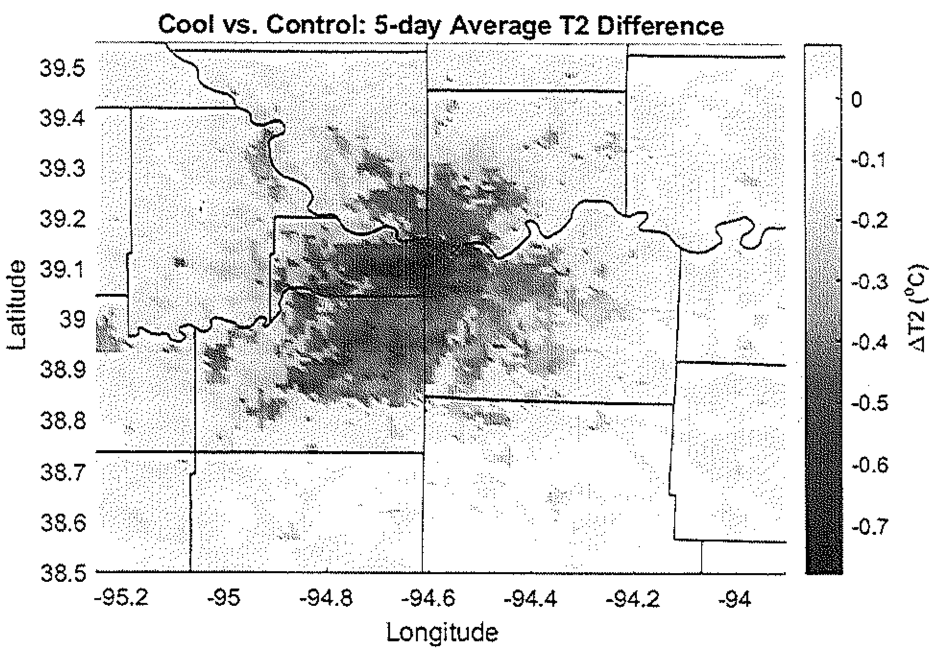


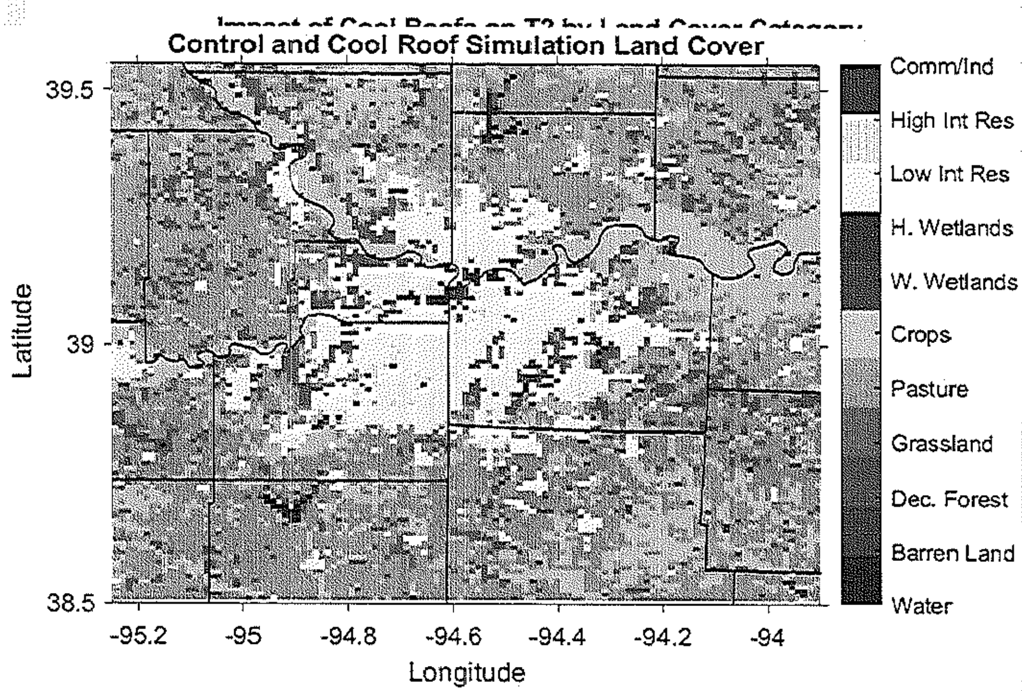
Part 2 - Results



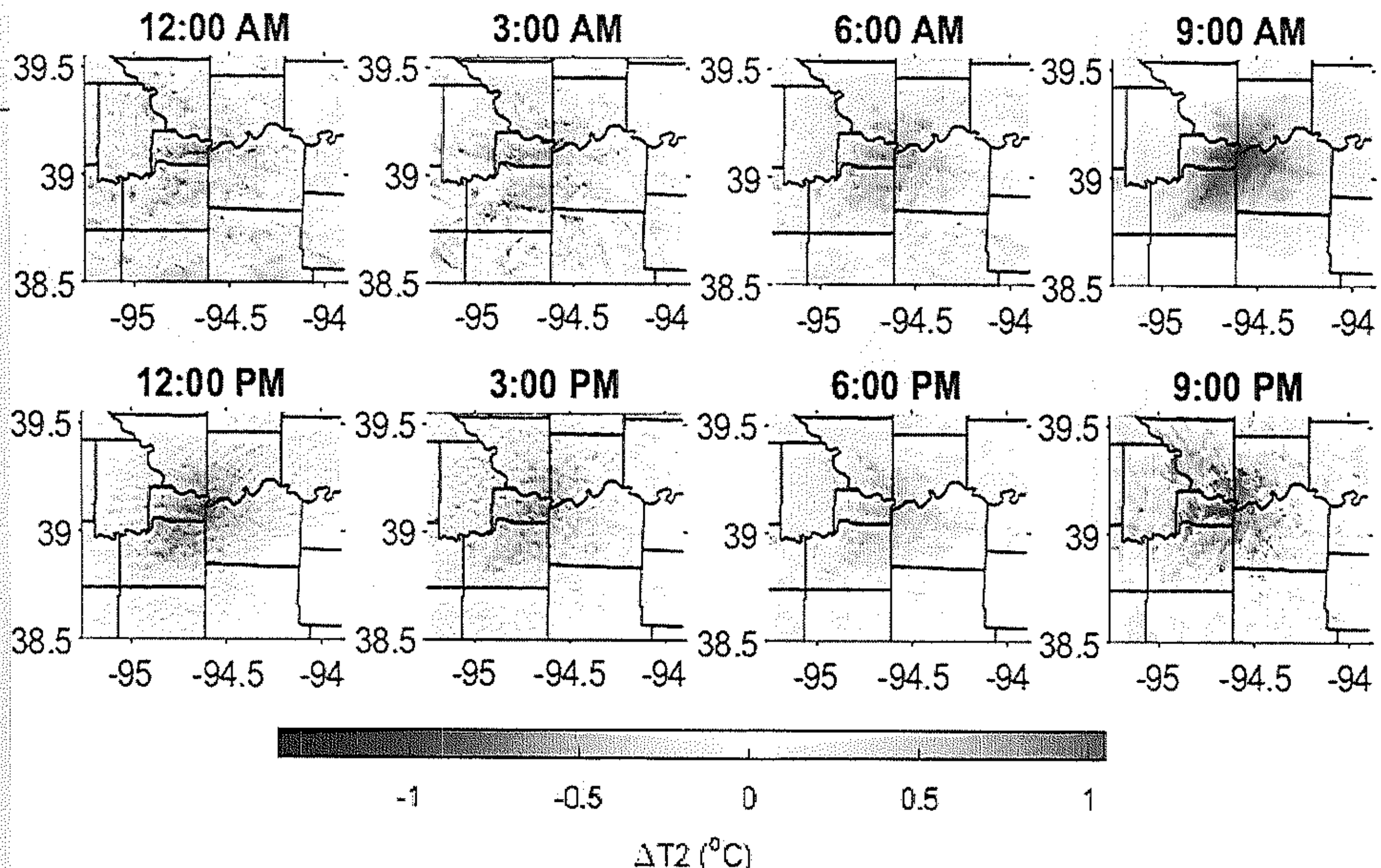
Part 3 – Cool Roof Simulation

Part 3 Results: 2-meter Air Temperature (T2)

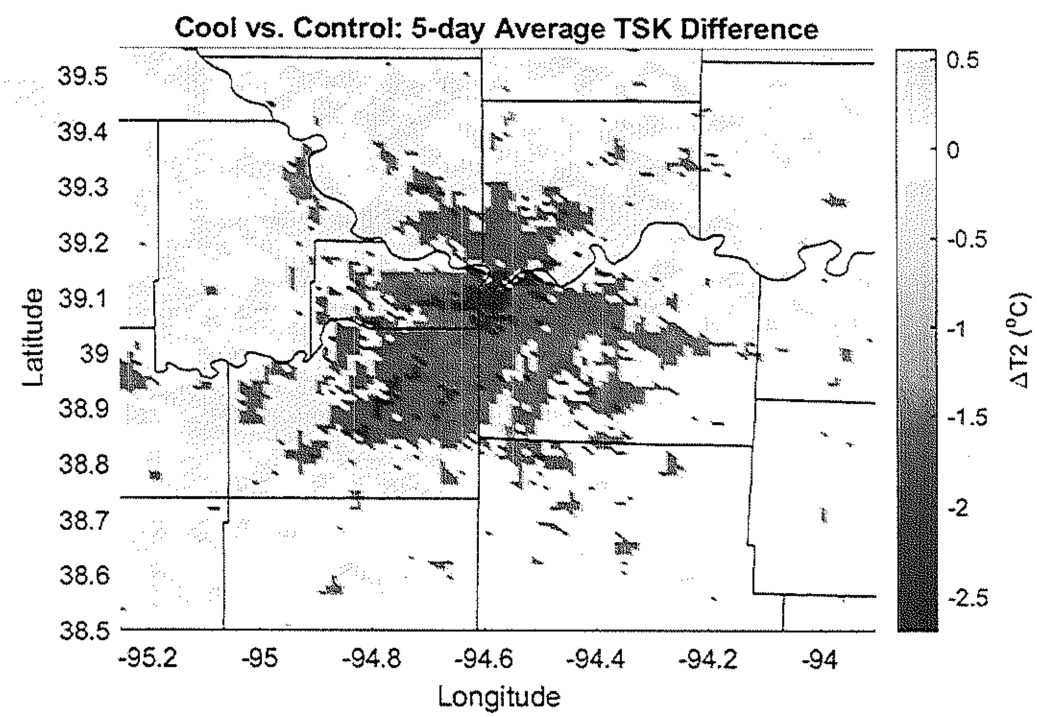




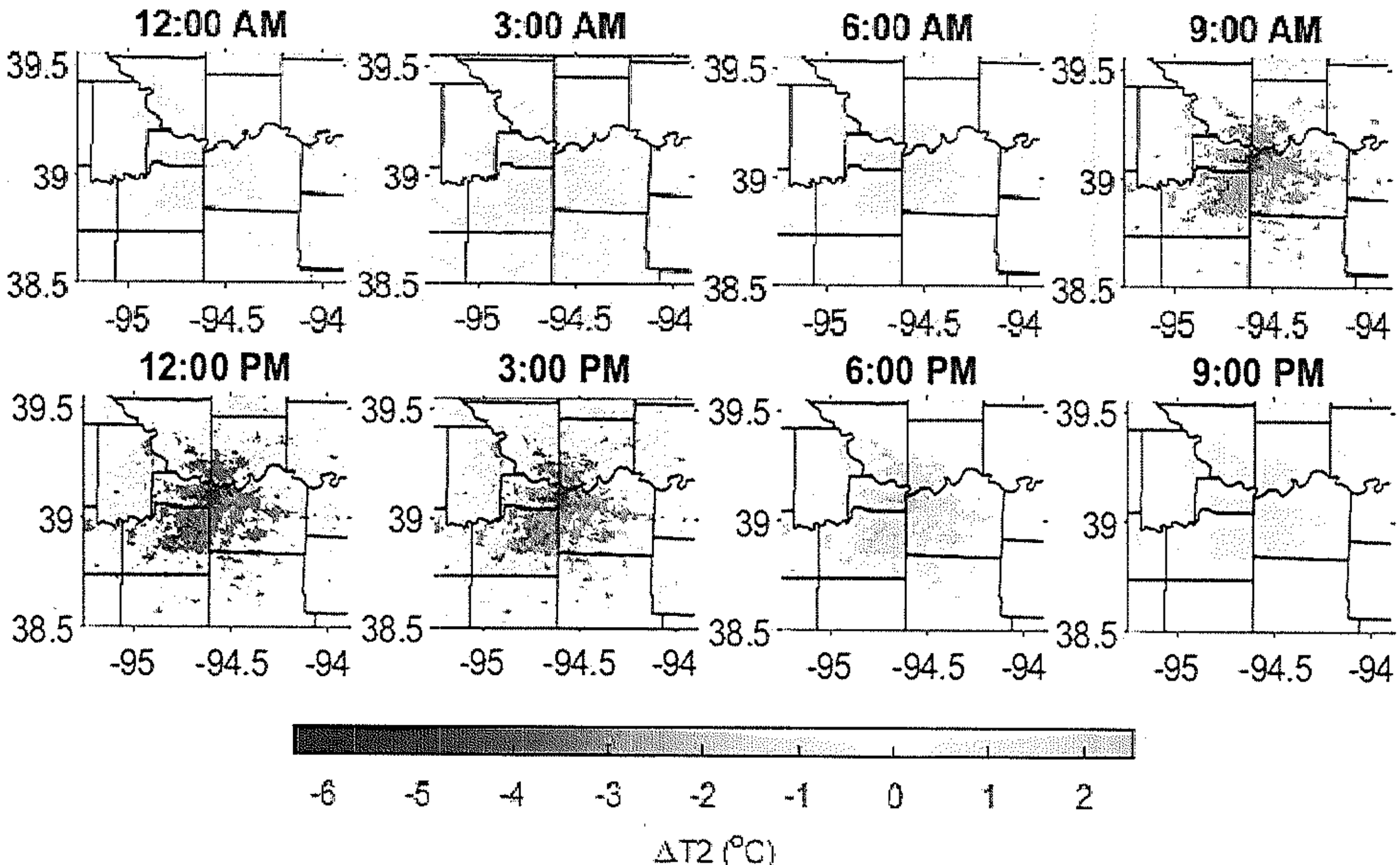
Impact of Cool Roofs on KC UHI T2



Part 3 Results: Skin Temperature

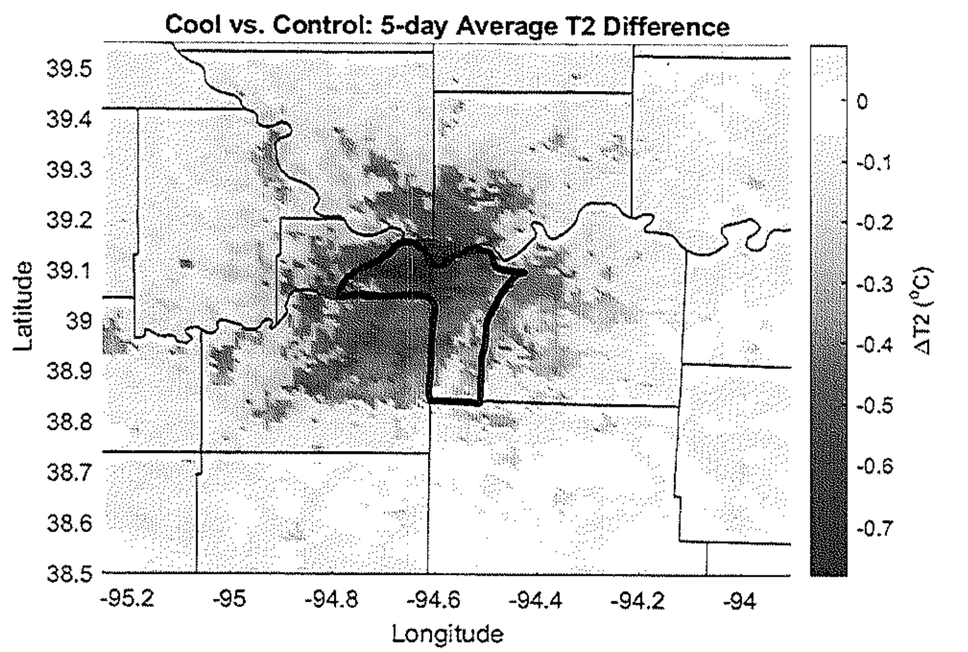


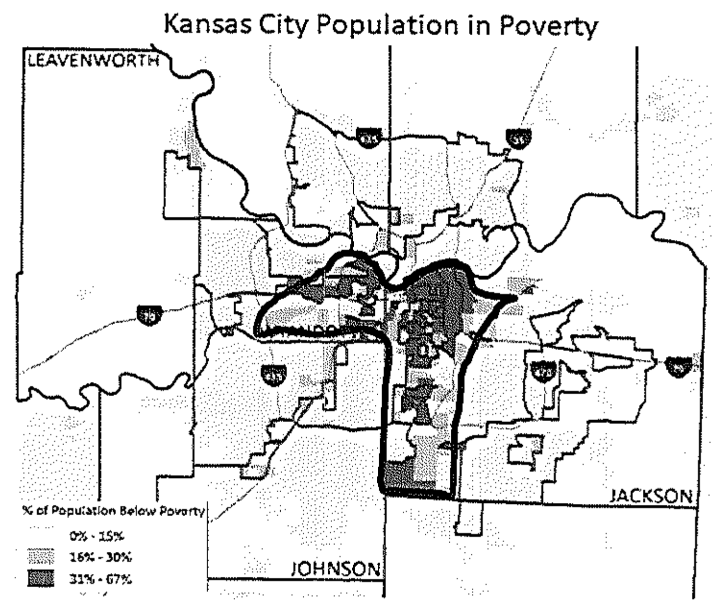
Impact of Cool Roofs on KC UHI TSK



Part 4 – Implications for socio-economic impacts

UHI Mitigation vs Poverty in Kansas City





(MARC 2014b)

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- What is an urban heat island (UHI)?
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Summary

- WRF was shown to reasonably simulate the diurnal 2-m air temperatures during the July 2012 heat wave in the Kansas City metro
- Impact of cool roofs on T2 was found to be -0.45°C (-0.81°F), averaged over the entire heat wave for all urban land cover
  - TSK reduced by -1.66°C (2.99°F)
- The highest intensity urban built-up area experienced the greatest reduction in T2

Next steps

- Short-Term
  - Look at socioeconomic impacts of cool roofs by collaborating with other researchers
  - Look at effect of green roofs on the UHI effect
  - Investigate the effect of UHI mitigation on human thermal comfort using a biometeorological index
- Long-Term
  - Compare the present-day and end-of-century UHI effect and the impact of cool roofs

UHI Collaborative Meeting II

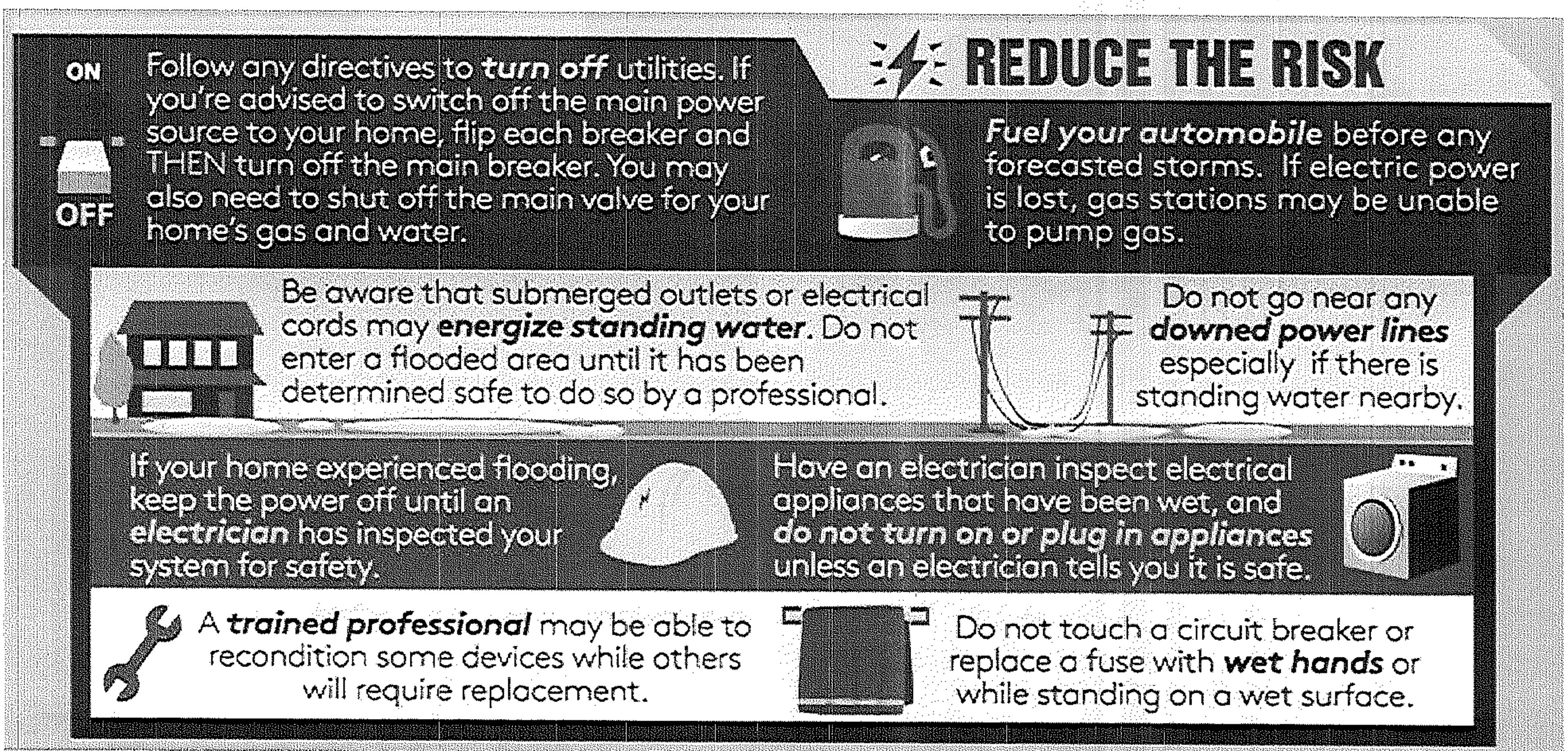
June 25, 2019

KCP&L
energizing *life*

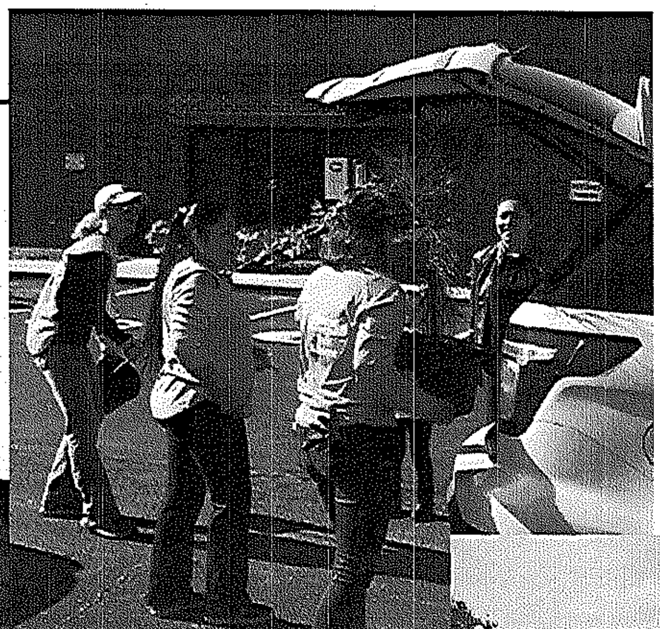
Meeting Agenda

- Introductions
- Safety Tip
- Urban Tree Canopy
  (BTG, Arbor Day Foundation & KCP&L)
- Global Cool Cities Alliance – Kurt Shickman
- UMKC – Dr. Sun Fengpeng & Kyle Reed
- Discussion and Questions
- Wrap-up

Safety Tip: Water and Electricity



Urban Tree Canopy – Event 1 Update



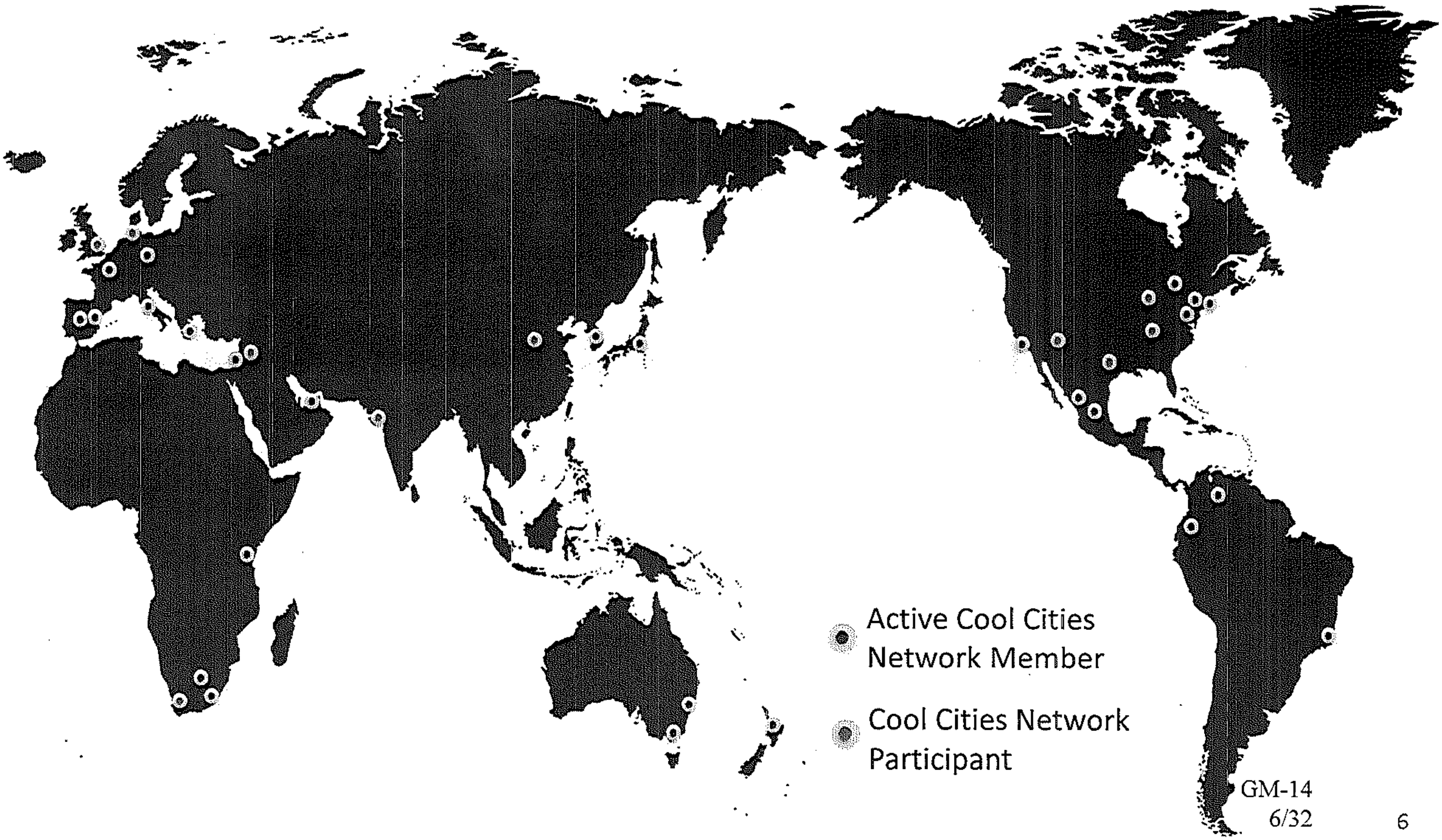
What Cities are Doing to Cool Off

Presentation to the Kansas City UHI Collaborative

Kurt Shickman

June 25, 2019

Cool Cities Network Members



GM-14
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A selection of GCCA initiatives

Global Cool Cities ALLIANCE

Quantifying the value of cool roofs.

Up to 20% energy savings, on average

Reduced heat wave deaths from small increases in reflectivity and vegetation

2-4°C indoor air temperature reductions

Equivalent of taking 50% of all vehicles off the road for 20 years

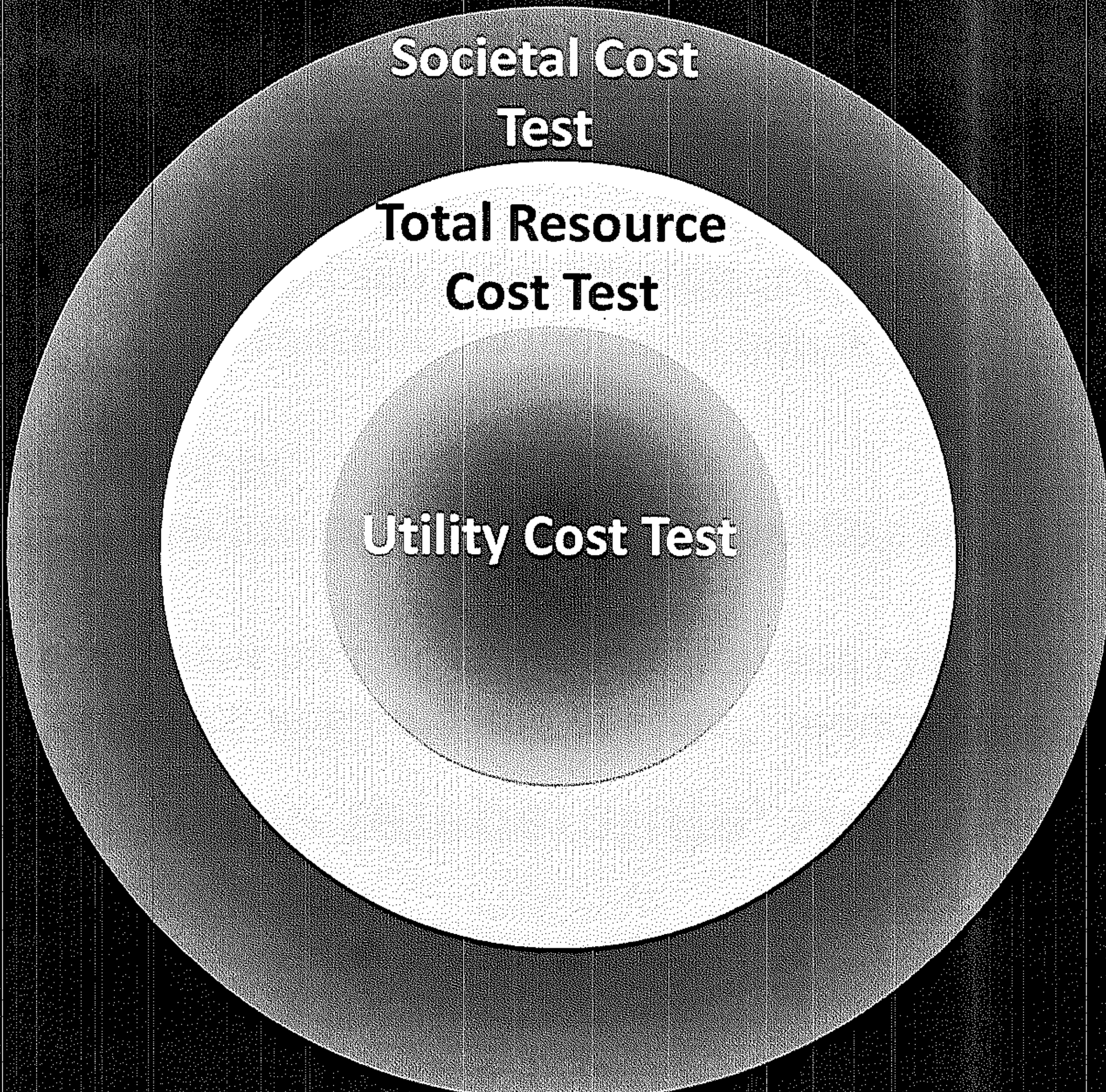
Reduced ER visits, less direct and indirect heat health challenges

Peak demand reductions, improved transmission efficiency

Efficiency gains and lower temperatures reduce ozone

Cool surfaces deliver benefits worth 12x their cost

Cooling benefits to utilities



1. Avoided energy cost
2. Peak demand reduction
3. Grid reliability
4. Lower energy trans/distro costs

5. Energy price suppression
6. Low-income impacts

7. Water impacts
8. Air quality impacts
9. Health
10. Other

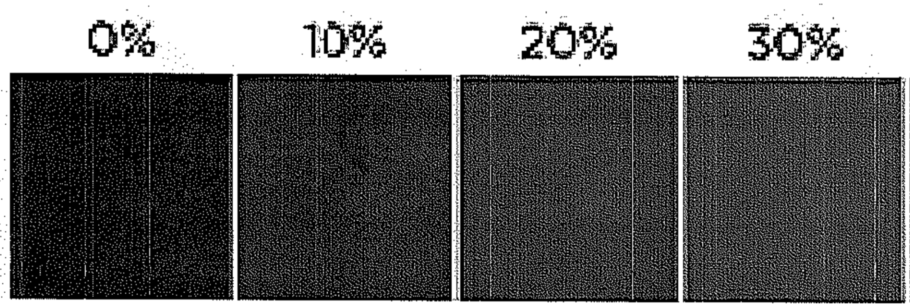
Global Cool Cities ALLIANCE

Lower the temperature, save lives

Cool roofs, implemented at scale*, reduced average temperatures during heat waves by **1.5C** in both Boston and Chicago.

Equivalent to cancelling 70% of Chicago's average UHI and all of Boston's average UHI.

Modeled reductions in mortality during heat waves of **8 – 9%** in Boston and **3 – 10%** in Chicago – the equivalent of saving up to 300 lives over the next decade.



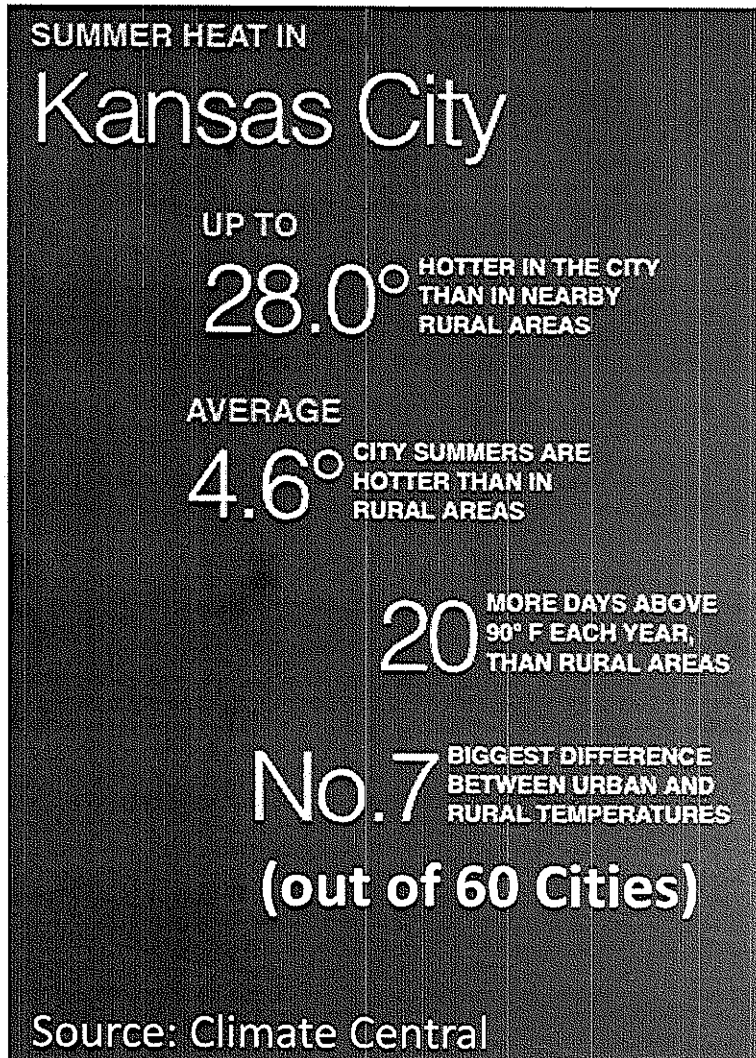
***At scale = an increase in avg. roof SR of 0.25**

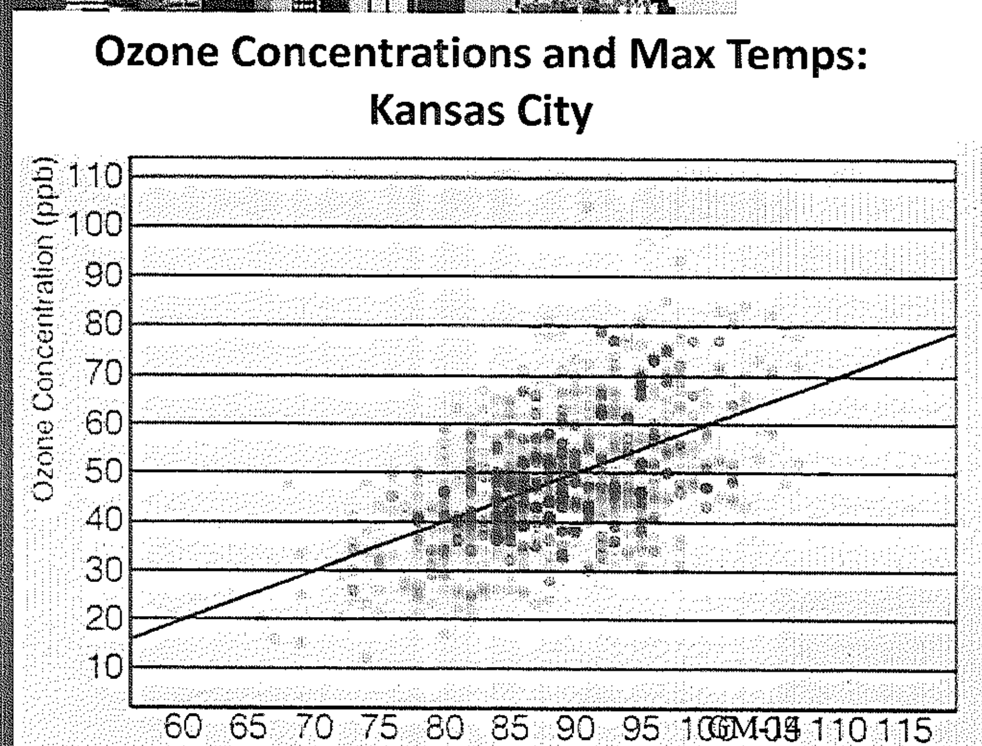
IN PRESS – ASTM International Ninth Symposium on Roofing Research and Standards Development

Laurence Kalkstein,[1] Frank Klink,[2] Kurt Shickman,[3] Sarah Schneider,[4] Mischa Egolf,[4] and David Sailor[5]

The Potential Impact of Cool Roof Technologies Upon Heat Wave Meteorology and Human Health in Boston and Chicago

Heat is a serious challenge for Kansas City





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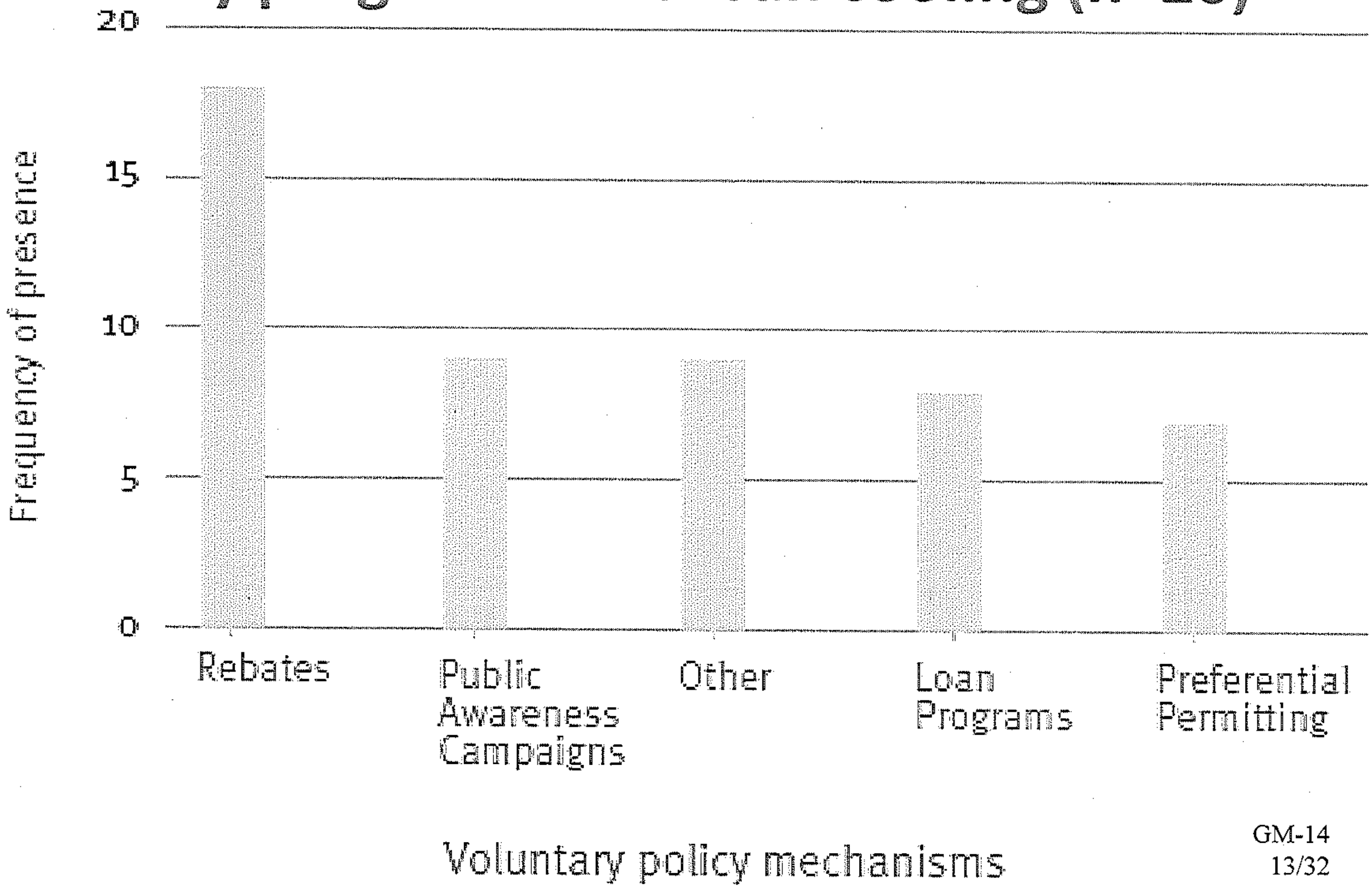
Global Cool Cities ALLIANCE

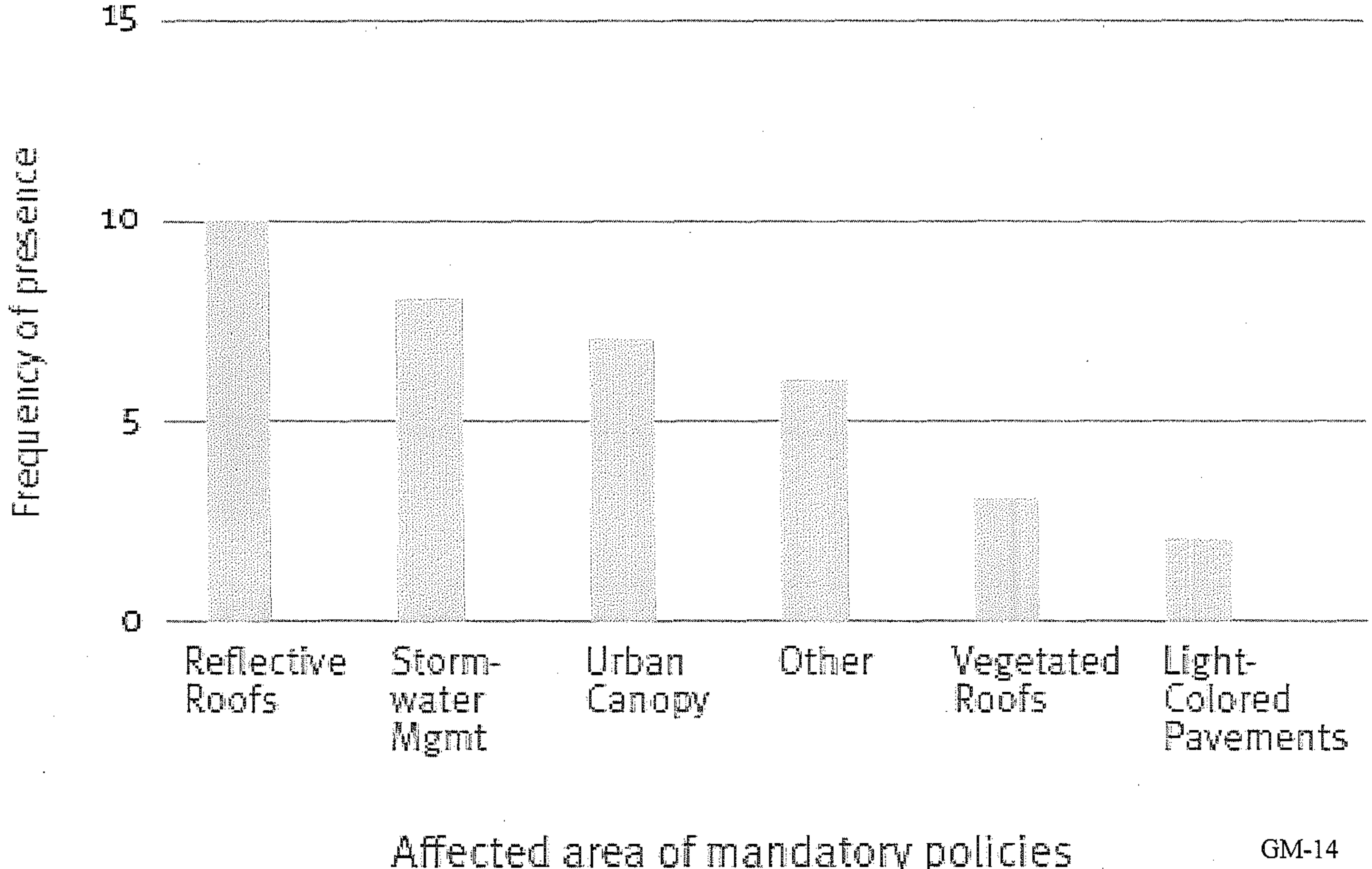
How are cities implementing urban cooling?

A few examples...

Voluntary programs for urban cooling (n=26)



Requirements supporting urban cooling (n=26)



GM-14
14/32

Cool roof requirements in the U.S.

1999 → 2019

ASHRAE 90.1, 1999
- credit

IECC 2003
- allows compliance via ASHRAE

California Title 24 2001 - credit

Florida State 2001 – credit

City of Chicago 2001 - requirement

California Title 24 2005 - requirement

Washington, DC 2008 – green code

Houston 2008

Dallas 2008

Miami 2009

ASHRAE 90.1, 2010
- requirement, with exemptions

Florida 2010

Philadelphia 2010

IECC 2012
- requirement

New York City 2012

Phoenix 2013

Los Angeles 2013

Washington, DC 2013

ASHRAE 189.1 2019
- expanded requirement

Denver 2019

Global Cool Cities ALLIANCE

Rebates and financing for cool roofs

St. Louis:

Set the PACE St. Louis. *Financing for low-sloped roofs with 0.65 SR, or steep-sloped roofs with 0.25 SR.*

Toronto:

Eco-Roof Incentive. *Eligible green roof projects receive $75 per sq meter. Cool roof projects receive $2-$5 per sq meter.*

Washington DC: leading by example

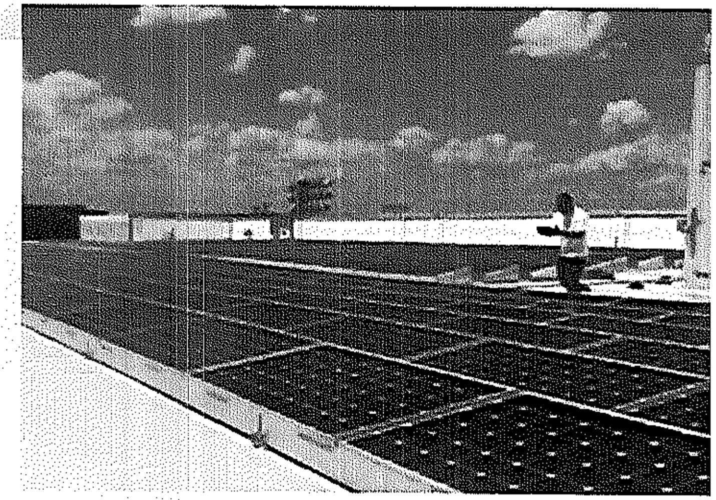
Comprehensive CBA

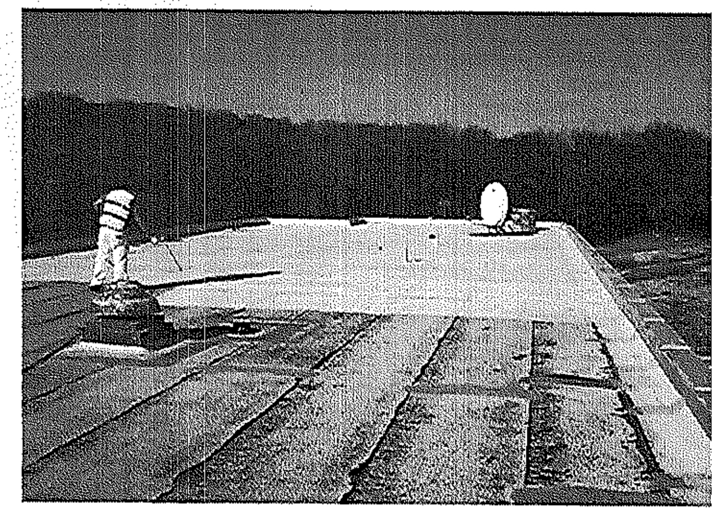
Evaluate → Plan → Implement

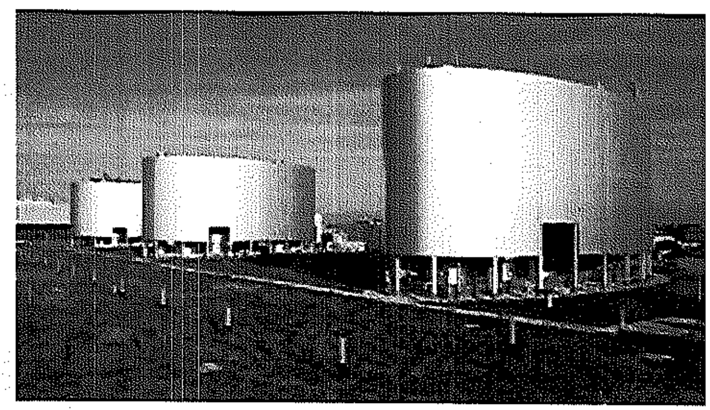
Evaluate	Plan	Implement
Roof Condition Score	Prioritization	Total: 11M ft^2 low-slope
Remaining Roof Life	Capital Planning	As of Feb 2016: 167,000m^2 Reflective 35,000m^2 Green 12MW Solar
Economics		

Net Economic Benefit (over 40 Years) of Sustainable Municipal Roofs in Washington DC (~11M ft^2)

Comparison to Standard Dark Roofs	Reflective Roof	Vegetated Roof	Standard Roof with Solar PV (PPA)
Costs	$5,580,000	$203,000,000	$0
Benefits	$52,100,000	$528,000,000	$294,000,000
Net Total	$46,500,000	$335,000,000	$294,000,000
Internal Rate of Return	58%	11%`	N/A
Simple Payback	2 years	11 years	N/A
Benefit to Cost Ratio	6.62	2.65	N/A
Net Present Value per m^2	$46.07	$401.08	$908.90

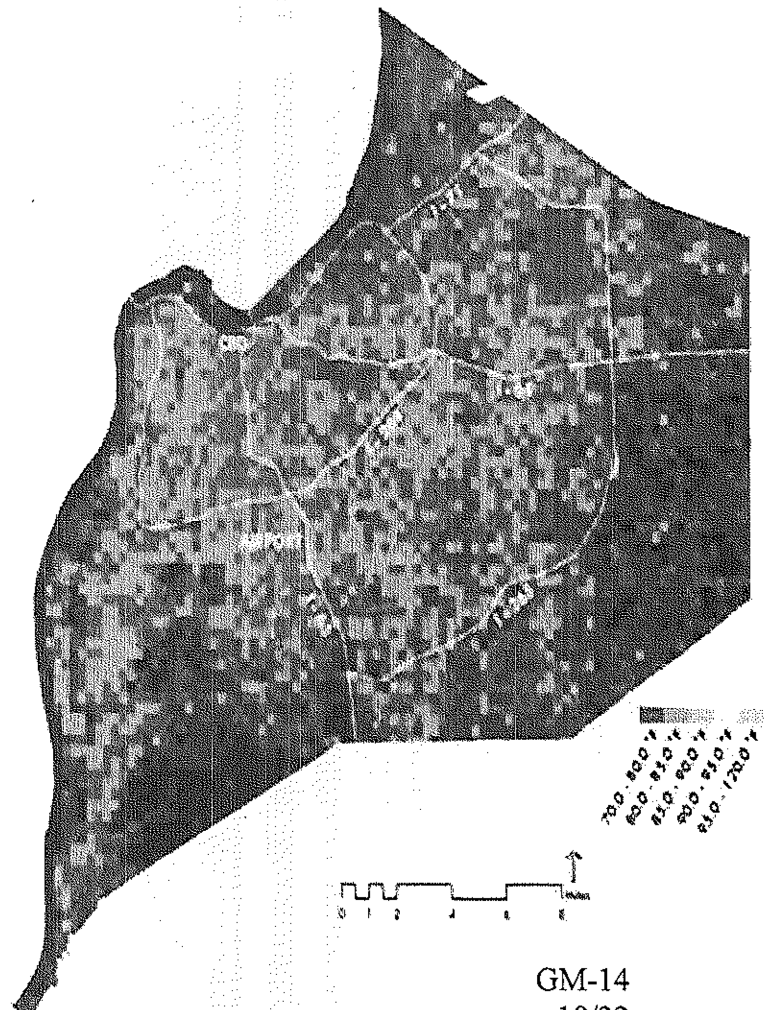






Louisville: Impact research to target implementation

- 2-year technical study to assess urban warming and mitigation impacts at a resolution of 500m.
- 8 months of public workshops and policy development
- Targeted rebates for cool and green roofs based on high heat vulnerability.



Global Cool Cities Alliance

San Antonio: "Under 1 Roof"

City program to replaces steep slope roofs with lighter shingles on homes of income-qualified residents

Expanded from a $200,000 pilot to a program with a 2019 budget of $4.25M ($1M from philanthropic sources).

Attic temps down 23F with average annual energy savings of $1200 per house.

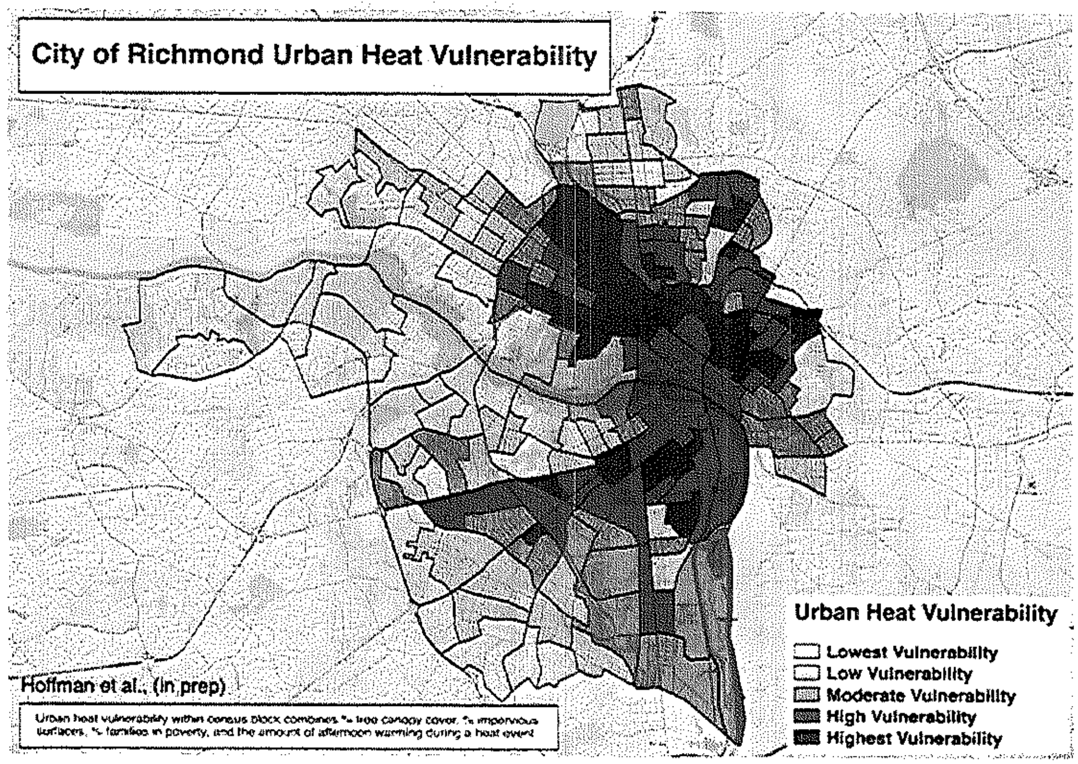
Source: CPS Energy

Global Cool Cities ALLIANCE

Richmond: citizen science & community engagement

- Richmond Urban Heat Island Collective – public/community/scientific partnership.

- Throwing Shade in RVA - An initiative of the Science Museum of Virginia and Groundworks.
  - Citizen science
  - Effective youth engagement through hands-on science



Global Cool Cities ALLIANCE

Reflections from "Smart Surfaces" Interviews

Interviews with:

Boulder, CO
Las Cruces, NM
Los Angeles County, CA
Louisville, KY
Newark, NJ
Reno, NV
Richmond, VA
Tempe, AZ
Washington, DC

1. How do "smart surfaces" currently fit into your city's strategy, planning, and implementation efforts?
2. What have been the key challenges to progress on heat mitigation?
3. What would be a useful set of resources/activities to reduce those challenges?

Reflections from "Smart Surfaces" Interviews

1. Progress on urban cooling is opportunistic, not systemic. There are no "Departments of Heat"

2. Heat is rarely a driving policy force but is often buried in other goals.

3. Cities want help avoiding the echo chamber. Cities want to grow the cohort of people in various agencies that understand and incorporate heat into their planning, targets, and budgets (particularly public works, capital planning/procurement, emergency services, and health).

4. Nearly every city interviewed described how valuable academic/scientific partnerships were for both data and analysis they can provide but also the credibility.

Global Cool Cities Alliance

New Tool Preview

Evaluating the solar reflectance of urban surfaces in Kansas City

WORLD RESOURCES INSTITUTE ROSS CENTER

Cities are seeking a way to meaningfully measure progress on heat mitigation

There is currently no cost-effective, easily repeatable way to measure urban surface changes.

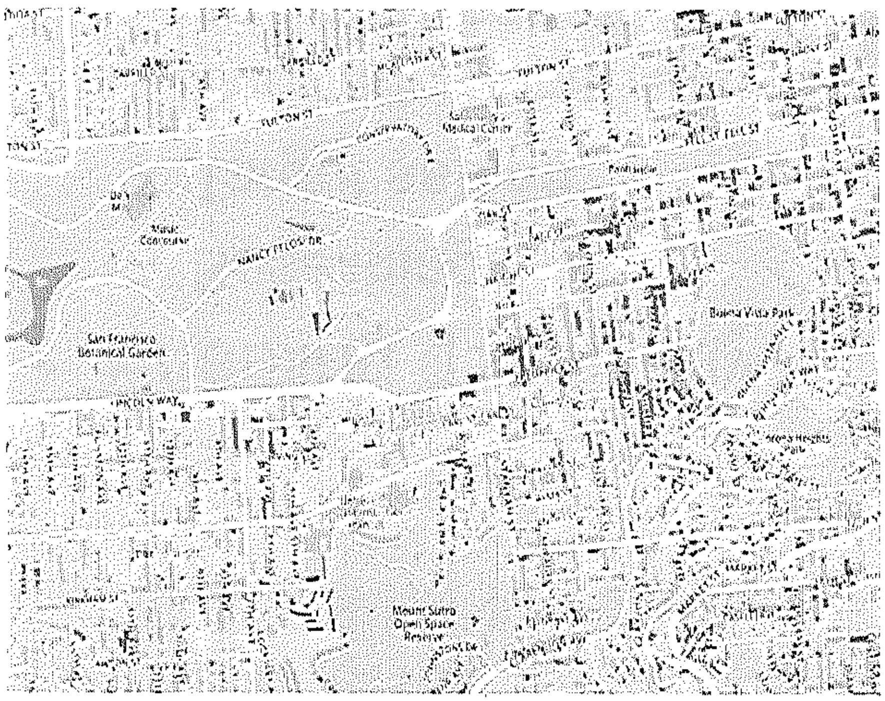
The lack of concrete measurability slows the adoption of urban heat mitigation policies, despite the clear need.

Cities are seeking a scientifically sound way to target heat policy to maximize the effectiveness of limited budgets.

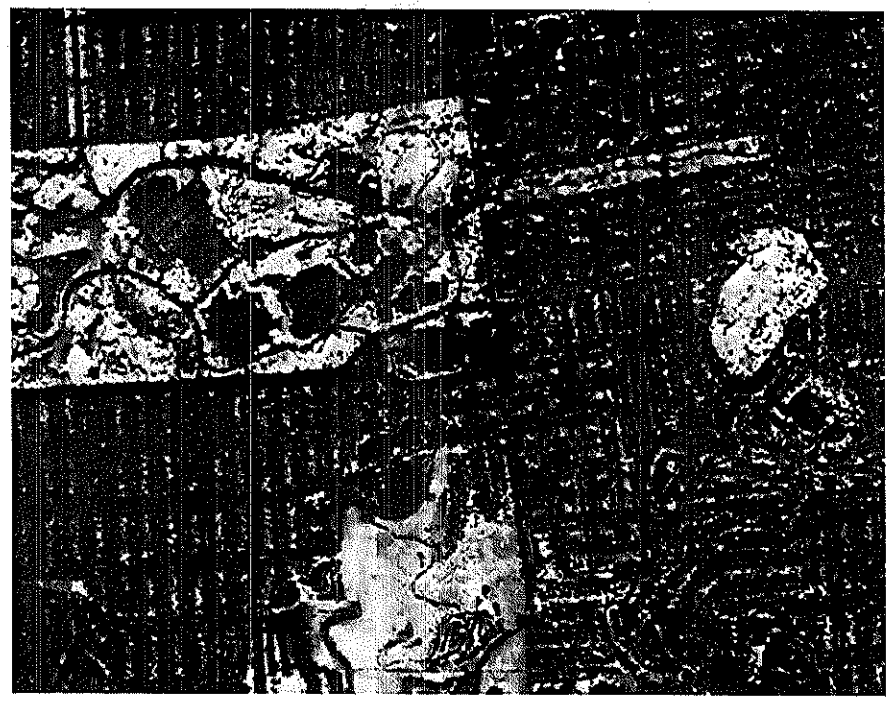
The First Globally scalable AI methods to quantify Surface reflectivity & Tree Canopy

- High spatial-resolution data on top 2 urban heat mitigation measures – reflectivity and trees
- Resulting datasets both already available for California at ≤ 1m resolution
- Data not previously applied together
- In principle, both methods globally scalable at low cost (pending imagery access and training data)

"Albedo Map" – LBNL/USC



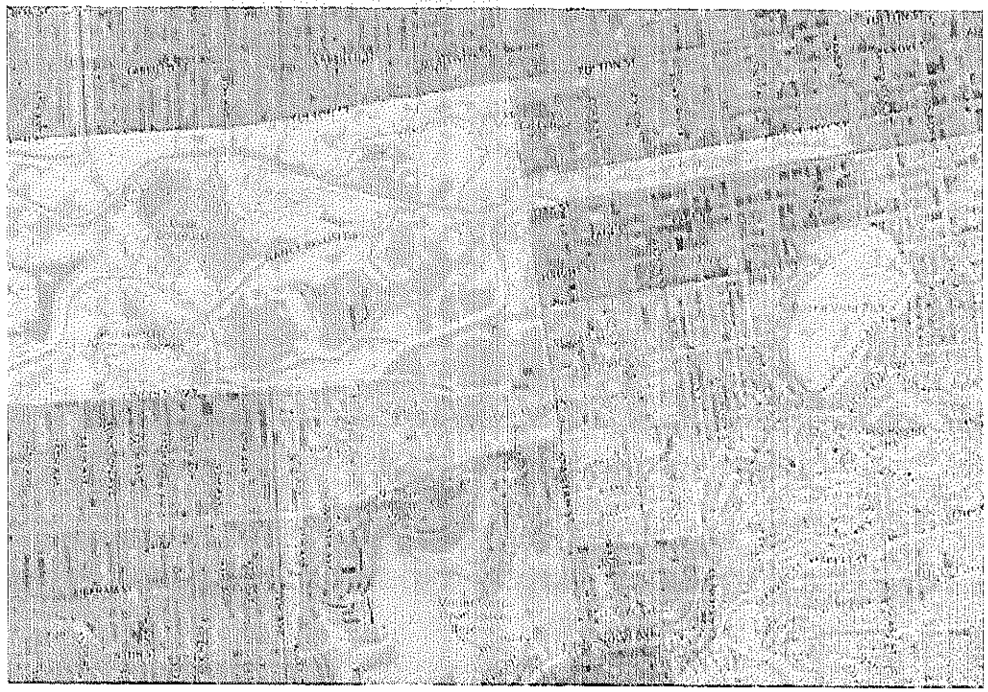
"DL Trees" – Descartes Labs



Golden Gate Park and surrounding neighborhoods, San Francisco

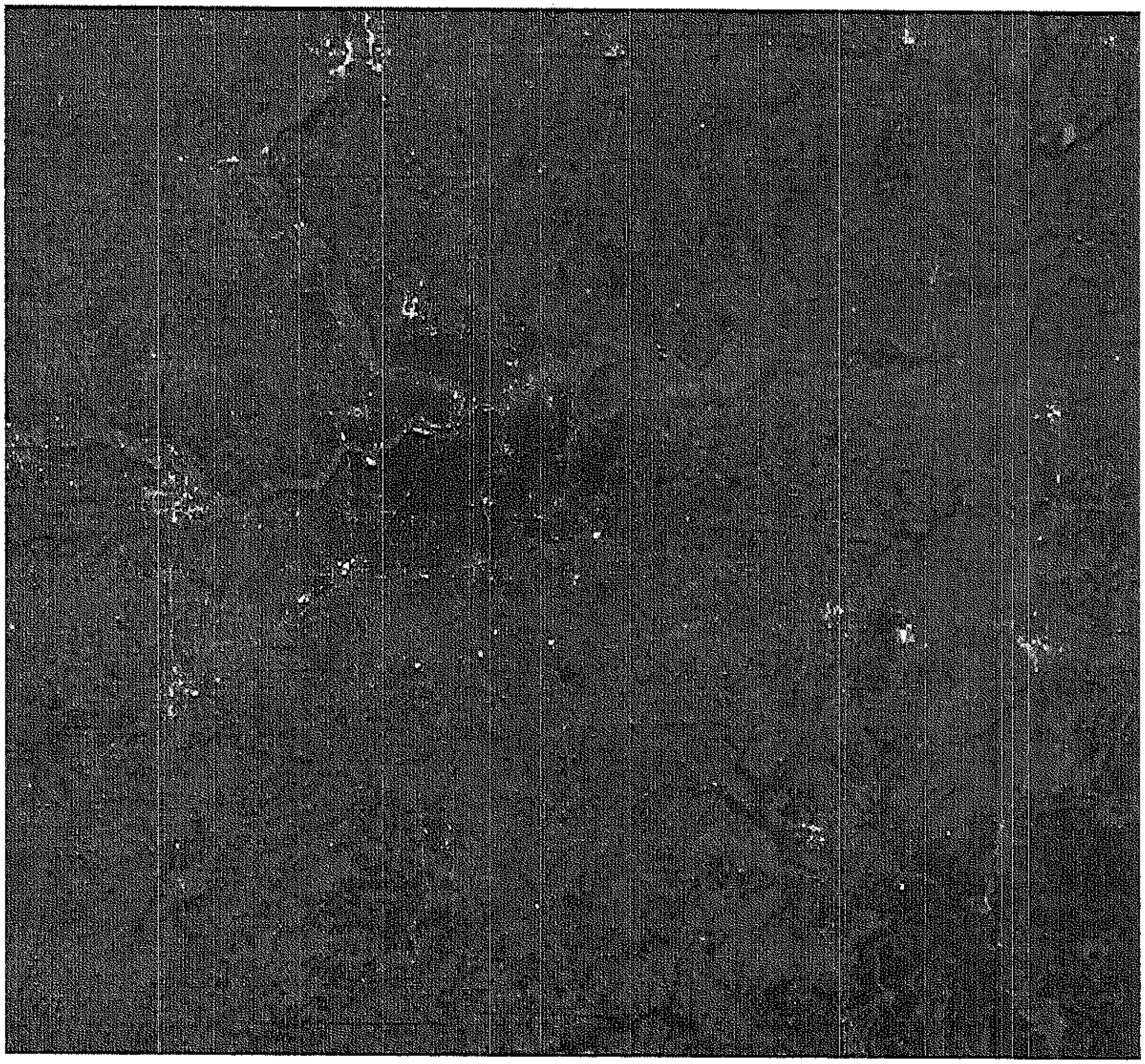
A Transformational improvement in Data-Driven URBAN Heat Mitigation

- Enabling quantitative:
  - Baselining
  - Target setting
  - Scenario planning and cost-benefit analysis
  - Geographic targeting
  - Progress measurement



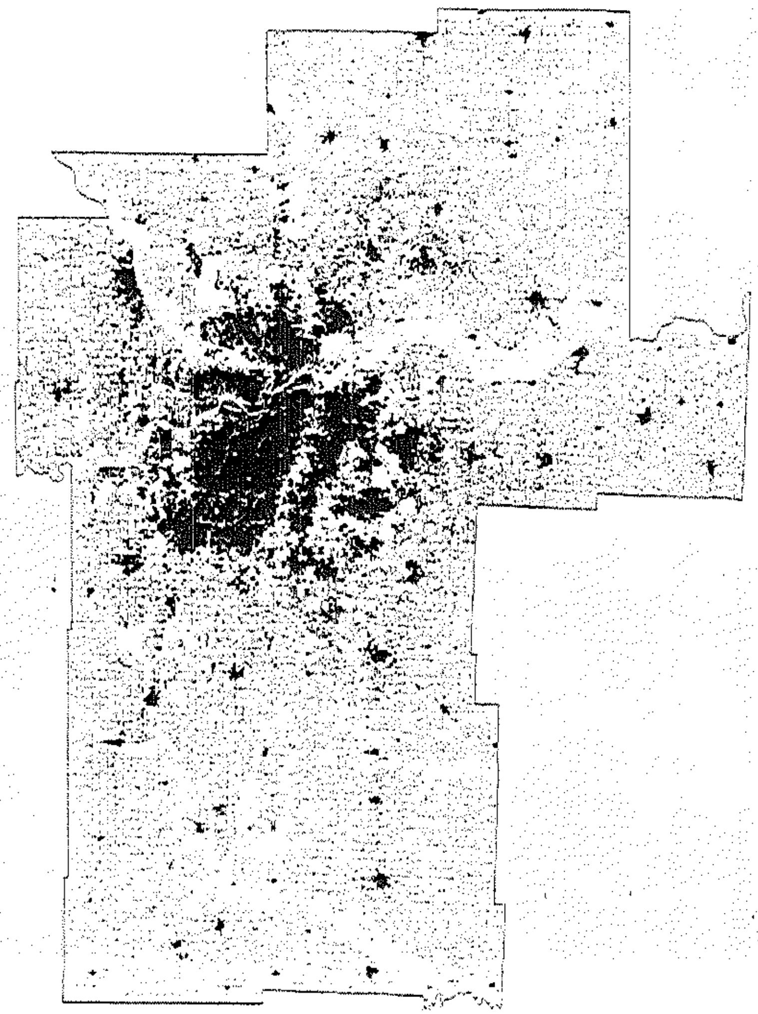
Hypothetical tool mock-up: overlay of trees, reflectivity and social vulnerability index (SVI). Darker areas are more vulnerable to heat.

Kansas City Metro Building Footprints



Source: Google Maps, US Census, Microsoft Building Footprints

Kansas City Metro Building Footprints



Source: US Census, Microsoft Building Footprints

WORLD RESOURCES INSTITUTE

every Roof in Kansas City Metro Area & its estimated Reflectivity

every Street in Los Angeles & its estimated Reflectivity

Global Cool Cities ALLIANCE

Thank You!

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UMKC

UNIVERSITY OF MISSOURI-KANSAS CITY

Dr. Sun Fengpeng & Kyle Reed

Highly Solar Reflective "Cool" Roofs in Kansas City

The Effects of Excess Heat and Urban Cooling Strategies

Rising urban temperatures have broad and serious negative implications for nearly every aspect of urban life. This section captures some of the main negative effects of excess heat on cities including on:

- human health outcomes,
- resiliency of health,
- transportation, and energy systems,
- air and water quality,
- crime,
- equity, and
- economic prosperity.

By reducing urban heat and its negative effects, cool roofs and walls (among other cooling strategies) will produce quantifiable benefits to the same set of factors listed above. The body of existing scientific and observational research allows us to establish an approximate range of temperature impact from each solution. However, it is impossible to offer a specific answer to this question as each solution's effect will vary based on building characteristics, urban environment, land cover, and meteorological and geographical conditions. Combinations of solutions that might be highly effective in a temperate, humid climate may have little to no positive effect in a desert climate, for example.

A comprehensive review of studies evaluating the cooling ability of solar reflective and vegetated surfaces found that, if deployed at a city-scale, such strategies would substantially reduce urban air temperatures. The consensus of studies was that average ambient temperatures could be reduced by 0.3°C per 0.10 increase in solar reflectance across a city. Peak ambient temperature decreases by up to 0.9°C per each 0.10 increase in solar reflectance. Air temperature reductions possible with city scale green roof deployment ranged from 0.3°C to 3°C. Street tree deployment at scale would have a similar cooling effect of between 0.4°C and 3°C, with the greatest cooling effect occurring within 30 meters of the tree.

There are many societal benefits of adopting strategies to cool down urban temperatures. Some of these are economically quantifiable (e.g., human health, air quality, productivity) and others remain challenging to quantify (e.g., school performance, tourism effect) or primarily qualitative in nature (e.g., quality of life). Since these are societal benefits, they are often hidden from the building owner and may not factor into their buying decisions. Policymakers should consider these quantitative and qualitative benefits when considering incentives and regulatory actions. The positive effects of urban cooling are noted below in each subsection, with a focus on those benefits that are quantified by existing research.

Reflective infrastructure

The concept of creating cooler structures using a surface's ability to reflect sunlight and to efficiently emit absorbed heat dates back to ancient Sumerian and Egyptian construction. Every opaque urban surface (e.g., roofs, walls, pavements) reflects some incoming sunlight and absorbs the rest, turning it into heat. Some of this solar heat contributes to the heat island effect. Reflecting solar radiation into the sky, ideally through the atmosphere and into space, can reduce the amount of solar heat gain in cities. The effectiveness of so-called "cool surfaces" is measured by the fraction of solar radiation they reflect versus the fraction that they absorb and convert into heat (measured by solar reflectance or SR). Cool surfaces are also measured by how efficiently and quickly they shed heat. A surface absorbing solar radiation becomes hotter and releases some of that heat by conduction, convection, and radiation (measured by thermal emittance or TE). A cool urban surface is both highly reflective and highly thermally emissive to minimize the amount of solar radiation converted into heat and to maximize the amount of heat that is lost by the surface. However, solar reflectance is the predominant factor in determining whether a surface is cool. Figure 1 illustrates how sunlight is managed by different colored surfaces and the implications for building and community heat gain.

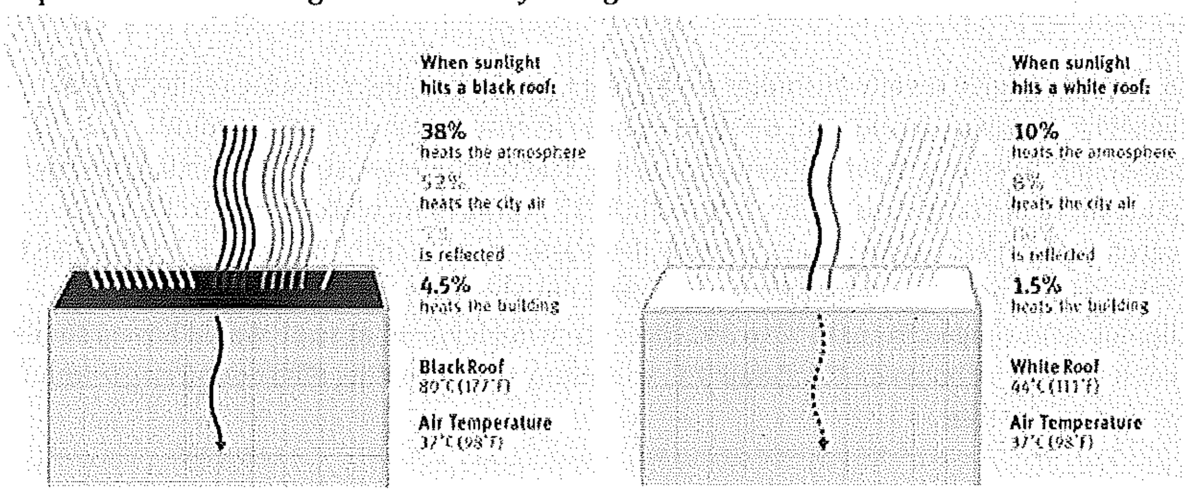


Figure 1 How solar energy interacts with dark and highly-reflective urban surfaces. Source: Lawrence Berkeley National Laboratory

Cool roofs

Measure	**Cool Roofs**
Cooling method	Cools by reducing the amount of solar energy absorbed by a building's roof
Benefits	· Net energy savings · Improved indoor thermal comfort · Air temperature reductions (at scale) · Global cooling
Considerations (effect)	· Net energy savings reduced by increased heating energy demand in very cold climates (minor) · Loss of some surface reflectivity over time (minor) · Potential for moisture build-up in cold climates (minor)
Economics	Cool roof installations generate a net economic benefit in all but the coldest climates. First costs for flat cool roofs are comparable to dark roofs. Slight first cost premium for steep slope cool roofs.
Applicable use cases	Cool roofs are globally applicable to all building types.
General Recommendation	Cool roofs should be encouraged/required as the minimum building standard.

Roofs typically make up 25% to 30% of an average city's urban surfaces[MB1]. Roofs may be either steep-sloped or nearly flat. There are a wide variety of highly reflective roofing products available today. As Figure 8 demonstrates, [MB2] there are now cool options for nearly every type of roof.

Roof Type	Life Expectancy (years)	Roof Slope	Non-Cool Roof Options	Non-Cool Roof Solar Reflectance	Cool Roof Options	Cool Roof Solar Reflectance
Asphalt Shingle	15 to 30	steep-sloped	black or dark brown with conventional pigments	0.05–0.15	"white" (actually light gray) or cool color shingle	0.25
Built-Up Roof	10 to 30	low sloped	with dark gravel	0.10–0.15	with white gravel	0.30–0.50
			with aluminum coating**	0.25–0.60	white smooth coating	0.75–0.85
Clay Tile	50+	steep sloped	dark color with conventional pigments	0.20	terracotta (unglazed red tile)	0.40
					color with cool pigments	0.40–0.60
					white	0.70
Concrete Tile	30 to 50+	steep-sloped	dark color with conventional pigments	0.05–0.35	color with cool pigments	0.40–0.50
					white	0.70
Liquid Applied Coating	5 to 20	low- or steep-sloped	smooth black	0.05	smooth white	0.70–0.85
Metal Roof (Uncoated corrugated metal is typically less durable than coated metal)	20 to 50+	low- or steep-sloped	unpainted, corrugated**	0.30–0.50	white painted	0.55–0.70
			dark, painted corrugated	0.05–0.10	color with cool pigments	0.40–0.70
Modified Bitumen	10 to 20	low sloped	with mineral surface capsheet (SBS, APP)	0.10–0.20	white coating over a mineral surface (SBS, APP)	0.60–0.75
Single-Ply Membrane	10 to 20	low sloped	black (polyvinyl chloride (PVC) or ethylene propylene diene monomer rubber (EPDM))	0.05	white (PVC or EPDM)	0.70–0.80
					color with cool pigments	0.40–0.60
Wood Shake	15 to 30	steep sloped	painted dark color with conventional pigments	0.35–0.50	bare	0.40–0.55

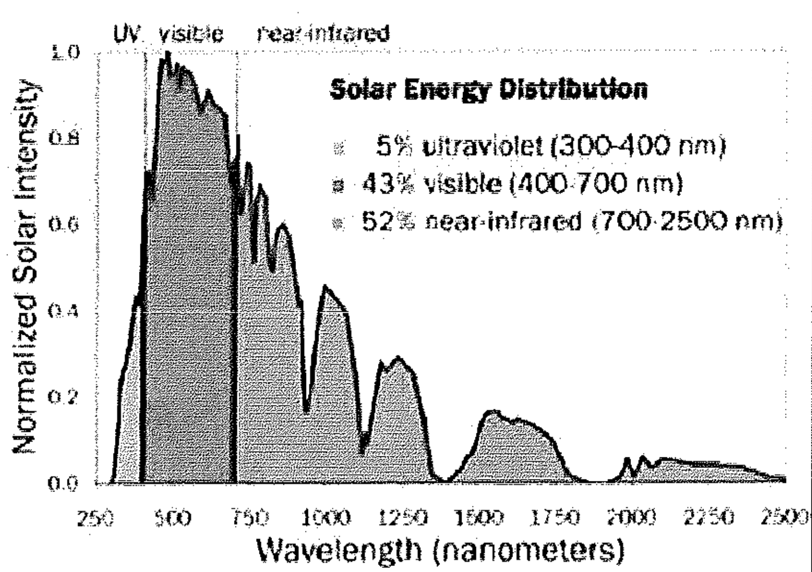
Figure 2 Common roof material options and their cool alternatives. Source: U.S. Department of Energy and Global Cool Cities Alliance

Most changes to roof solar reflectance will occur when making a decision to install a new roof or a replacement roof. At these times, it is much easier to design for and choose a cool option. There are also options to use coatings to increase the solar reflectance of an existing, functional roof. Coatings are typically applied to a functional roof to waterproof it or to extend its useful life. Table 3 highlights the coating options currently available and their strengths and weaknesses.

Coating	Strengths	Weaknesses
Acrylic	• Cost-effective • Good balance of cost to performance • UV resistant • Easy to apply	• Thickness loss with weathering • Applied and cure only above 10°C (day and night temp) • Poor in ponding water conditions
Elastomeric	• "Rubber" acrylic, but thicker and more flexible • Good for waterproofing	• Long cure in humid conditions • Applied and cure only above 10°C (day and night temp)
Polyurethane (aromatic base, aliphaltic top)	• Stays clean longer than most options • Durable and traffic resistant • Better with ponding water than acrylic	• More expensive than acrylic. • Noxious, potentially toxic gassing at application
Silicone	• Very durable and long lasting (25+ years) • Good in humid conditions and ponding water • Mold resistant	• Will remain dirty without rain/ washing • Cannot recoat over existing silicone • More expensive

Figure 3 Coating types and their characteristics

Cool surfaces are commonly created by lightening their color to reflect more solar energy in the visible spectrum (e.g., a white roof rather than a dark roof). However, slightly less than 50% of solar energy is contained in the visible spectrum.[i] The vast majority of the remaining solar energy is in the near infrared spectrum that is invisible to the naked eye (Figure 4). Certain technologies known as cool colors take advantage of that fact to allow colored surfaces (i.e., red, green, blue, grey) to be more highly reflective than traditional methods would allow.



Cool colors are most often used on steep-sloped roofs, where the roof's aesthetics is more noticeable. Cool colored roofing products are available for conventional roofing materials such as tile, asphalt shingle, and steel. Figure 5 shows some examples of highly solar reflective color options.

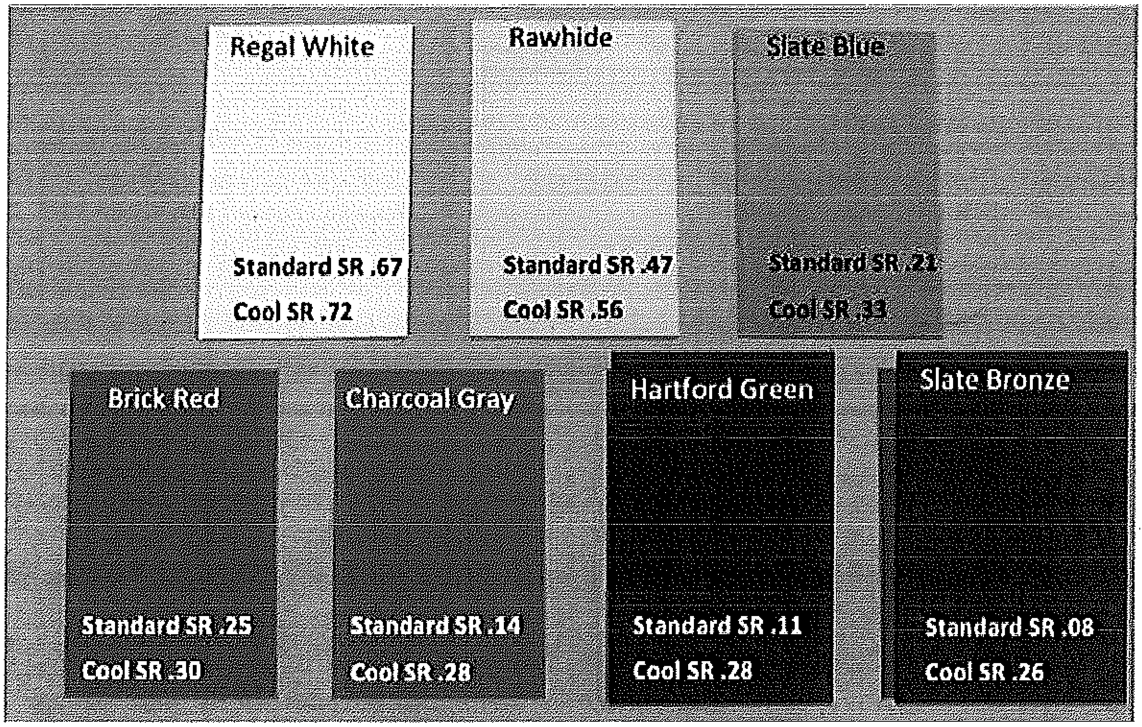
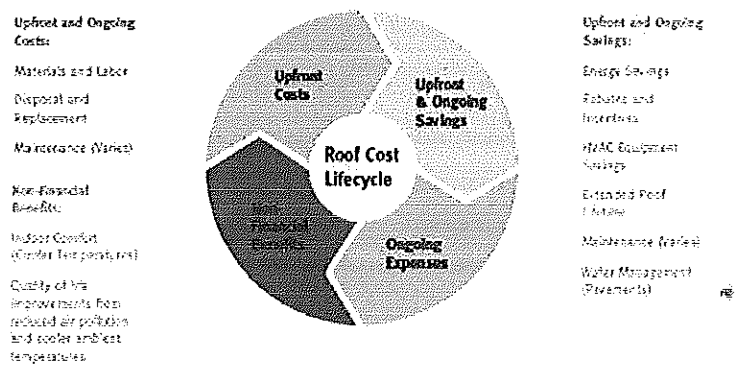


Figure 5 Some cool reflective color options.

Cool roof economics

First cost premiums will vary, but highly reflective roof options are generally cost-competitive with traditional roofs.[MB4] The simple economic paybacks[1] of choosing highly reflective roof options range between 0 and 6 years based on building energy savings alone. The labor required to install cool roofs is about the same as for non-cool roofs. Other factors to consider when evaluating cost-effectiveness include changes in expected life of the roof, expected maintenance (i.e., regular roof inspections, repairs, or washing), roof material disposal, and replacement costs. For example, coating a functioning roof may have a high upfront cost but payback in energy savings, lengthened roof life, and other benefits. Figure 6 (above) illustrates some of the lifetime costs and benefits to consider when evaluating cool roofing installations.

To minimize cost premiums, the best time to install cool roofs is when a new roof will be installed or an existing roof needs to be replaced anyway. Repairs to an existing functional roof, especially when waterproofing, are also a cost-effective time to shift to a highly solar reflective roof.



Built-Up Roof	Mineral aggregate embedded in flood coat	Light-colored aggregate, like marble chips, gray slag	0.00
	Asphaltic emulsion	Field-applied coating on top of emulsion	0.80–1.50
	Mineral surfaced cap sheet	White mineral granules	0.50
Metal	Unpainted metal	May already be cool	0.00
		Factory-applied white paint	0.20
	Painted metal	Cool-colored paint	0.00–1.00
Modified Bitumen	Mineral surface cap sheet	Factory-applied coating, white mineral granules	0.50
	Gravel surface in bitumen	Light colored gravel	0.00
	Metallic foil	May already be cool	0.00
		Field-applied coating	0.80–1.50
	Asphalt coating	Field applied coating on top of asphaltic coating	0.80–1.50
Shingles	Mineral granules	White granules	0.00
		Cool colored granules	0.35–0.75
Sprayed Polyurethane Foam	Liquid applied coating	Most coatings are already cool to protect the foam	0.00
	Aggregate	Light colored aggregate	0.00
Thermoplastic Membranes	White, colored, or dark surface	Choose a white or light colored surface	0.00
Thermoset Membranes	Dark membrane, not ballasted (adhered or mechanically attached)	Cool EPDM formulation	0.20–0.45
		Factory cool ply or coating on dark EPDM	0.50
Tiles	Non reflective colors	Clay, slate (naturally cool)	0.00
		Cool colored coatings	0.00

Price Premiums for Cool Roofs on New Roofs

Roof Materials	Typical Non-Cool Surface	Cool Alternative	Price Premium (US$ per ft²)
Built-Up Roof	Mineral aggregate embedded in flood coat	Light-colored aggregate, like marble chips, gray slag	0.00
	Asphaltic emulsion	Field-applied coating on top of emulsion	0.85–1.50
	Mineral surfaced cap sheet	White mineral granules	0.50
Metal	Unpainted metal	May already be cool	0.00
		Factory-applied white paint	0.20
	Painted metal	Cool colored paint	0.00–0.10
Modified Bitumen	Mineral surface cap sheet	Factory-applied coating, white mineral granules	0.50
	Gravel surface in bitumen	Light colored gravel	0.00
	Metallic foil	May already be cool	0.00
		Field applied coating	0.60–1.50
	Asphalt coating	Field-applied coating on top of asphaltic coating	0.60–1.50
Shingles	Mineral granules	White granules	0.00
		Cool-colored granules	0.35–0.75
Sprayed Polyurethane foam	Liquid applied coating	Most coatings are already cool to protect the foam	0.00
	Aggregate	Light colored aggregate	0.00
Thermoplastic Membranes	White, colored, or dark surface	Choose a white or light colored surface	0.00
Thermoset Membranes	Dark membrane, not ballasted (adhered or mechanically attached)	Cool EPDM formulation	0.10–0.15
		Factory cool ply or coating on dark EPDM	0.50
Tiles	Non reflective colors	Clay, slate (naturally cool)	0.00
		Cool colored coatings	0.00

Figure 13 shows approximate cost premiums for cool products by roofing type in the U.S.. Prices are similar in other mature markets but please note that these costs will vary greatly in developing countries..

Cool roofs: Issues to consider

Winter heating penalty – Cool roofs may increase demand for building heating in the winter. With the exception of extremely cold/polar climates, the additional energy for heating demand in winter is more than offset by the cooling energy savings in the summer. A number of factors minimize the "winter heating penalty" of cool roofs in many cases.

- The sun is generally at a lower angle in winter months than it is in summer months, which means that solar radiation is less intense during the winter.

- In some areas, snow cover during the winter makes the underlying roof color irrelevant because it prevents sunlight from reaching the roof surface.
- Heating loads and expenditures are typically more pronounced in evenings and are not aligned with the daytime benefit of a darker roof in winter.
- Many commercial buildings have a high volume-to-surface-area ratio, so heat losses in winter are often fully offset by interior heat sources from human bodies, electric lighting, and office equipment. Occupancy patterns in some commercial buildings may be such that space cooling is used year-round and therefore reducing solar heat gain contributes to building energy savings year-round.

Changes in solar reflectance over time - The solar reflectance of roofs declines as they age, weather, and become soiled (i.e., a combination of accumulated soot, dust, salt, and, in some climates, mold and moss growth). Lowered solar reflectance performance reduces a roof's ability to reflect sunlight and increases the potential for heat transfer into buildings. The reduction in solar reflectance due to weathering and aging will vary based on the composition of the accumulated soil and precipitation patterns that help to wash the roof. In general, though, a roof may lose approximately 25% of its initial solar reflectance over the first 3 years after installation, with minimal additional loss in solar reflectance afterwards. Cool roof products have improved solar reflectance longevity by making products resistant to water (hydrophobic) and biological growth. Roofs may also be periodically washed to restore their solar reflectivity.

Condensation - Moisture from indoor air can condense within roof structures/systems. If allowed to accumulate over years, moisture could damage those materials and negatively affect the roof's durability and service life. In consistently hot and dry climates, there is little risk of moisture buildup. In winter months in cooler climates, all roof structures will develop some moisture that will then dry out in warmer summer months. This "self-drying principle" is a long-standing roof design feature. Without proper design and installation, both dark and cool roofs can accumulate moisture in colder climates. Highly solar reflective roofs maintain lower temperatures than dark roofs and will typically take longer to dry out over the course of an annual cycle than a dark roof. In all but the coldest climates, though, the cool roofs reach the same level of dryness as a dark roof over the course of a year.[xxxviii]

Effects of insulation – Both roof solar reflectance and insulation in the roof structure reduce heat flow into a building. The similarity in their effect on heat flows has, in some cases, led to policies that allowed increased surface solar reflectance to be traded off for lower insulation levels. Indeed, some building codes allow for a reduction in insulation levels when a solar reflective surface is installed. Recent research finds that insulation and surface reflectance are complementary, not substitute, solutions for building efficiency and comfort. Building heat flows during summertime are driven by roof surface color and heat flows during winter are correlated to insulation level.[xxxix]

Cool walls

Measure	Cool Walls
Cooling method	Cools by reducing the amount of solar energy absorbed by a building's walls.
Benefits	• Energy savings • Improved indoor thermal comfort • Air temperature reductions (at scale)
Considerations (effect)	• Increased solar energy reflected into neighboring buildings (minor) • Pedestrian thermal comfort (minor) • Aesthetics (minor)
Economics	Choosing lighter colored coatings will be cost neutral to dark color options. Dark colors that increase solar reflectance have some cost premiums, particularly in developing markets.
Applicable use cases	Cool walls are globally applicable to all building types. Additional analysis on effect recommended when buildings are close to each other and unshaded.
General Recommendation	Cool walls should be encouraged as the minimum building standard.

Cool walls are very similar to cool roofs but applied to vertical building surfaces. There are many cool-wall products available commercially and they tend to stay clean and reflective over time.[xxxx]

Cool walls mitigate urban heat islands like cool roofs. Simulations predict that increasing wall solar reflectance throughout Los Angeles County by 0.40[1] would lower daily average outside air temperature in the "urban canyon" between buildings by about 0.2 °C in July (a hot summer period). This is comparable to about 84% of the air temperature reduction provided by the same countywide increase in roof albedo.[xxxxi]

Cool wall economics

As with highly solar reflective roofs, there are cool alternatives for most wall material types, including metal cladding, vinyl siding and exterior paint. Based on the limited evidence currently available on cool wall products, color does not appear to affect price. Some advanced cool color technology does carry a cost premium, however. An estimate of cost premiums for dark, cool colors over traditional dark colors for California found substituting them for conventional dark paint colors would yield a median cost premium per liter of about $4, with a range between $0.50 to $16. Cool walls generate economic value by improving building energy efficiency. In warm United States climates, cool walls lowered annual energy costs by up to to $\$1.1/m^2$ in single-family homes, up to $\$1.8/m^2$ in medium offices, and up to $\$3.7/m^2$ in stand-alone retail stores.[2] Energy cost savings would be more substantial in markets with higher energy costs.[xxxxii]

Cool walls: Things to Consider

Increased reflectance into neighboring buildings Cool walls reflect more sunlight between urban surfaces than dark walls, potentially leading to increased heat transfer. This effect may increase cooling load, decrease heating load, and reduce the need for artificial lighting in nearby buildings. The size of the effect will vary based on the solar reflectance of wall surfaces (both the wall reflecting the sunlight and the wall absorbing it) and the view factor between them. View factor is explained in the Urban Geometry section below.

Pedestrian thermal comfort. Walls are made more reflective to reduce building solar heat gain, but cool walls also affect the thermal environment of pedestrians by (a) increasing the solar radiation striking nearby pedestrians; (b) decreasing longwave (thermal infrared) radiation incident on the pedestrian; and (c) lowering the outside air temperature. The magnitude of these often opposing effects on pedestrians can be quantified by human comfort models, but research indicates that that the pedestrian thermal comfort change induced by raising wall solar reflectance is small.[xxxxiii]

Aesthetics. Because walls are highly visible, color choices will often be based on aesthetic preference over other benefits.

Laying a Solid Foundation for Cool City Policy

Awareness of excess heat as a critical resiliency challenge for cities is growing. Fortunately, the methods for cooling cities are well known and increasingly available across the globe. There are many examples of progress and good practice on urban heat mitigation—several of which are included as case studies in this handbook.

Still, implementing heat mitigation strategies presents unique challenges for city practitioners that has resulted in slower progress than the urgency of the heat problem dictates. The biggest obstacle to implementing urban heat mitigation measures is that there is no single entity within the city responsible for heat. Many different municipal departments may be affected by heat including agencies responsible for health, public works, water and electric utilities, parks, capital and budget planning, emergency response, building and zoning codes, and sustainability/resiliency strategy. Each department may address those challenges without looking beyond their own programs, resources, or budgets.

A systems approach to developing and implementing urban cooling policy and programs matches the uniquely cross-cutting nature of challenges and opportunities posed by excess urban heat. Integrating efforts across departments and agencies allows for community scale action with a mix of solutions optimized to mitigate heat. A systems approach requires a great deal more coordination and communication to be successful than an opportunistic, department by department, approach. Cities will also need inputs from relevant stakeholders such as academic institutions, the private sector, and local NGOs.[MB1]

Though it requires a significant commitment of time and effort to pursue, a systems approach to urban cooling is helpful to encourage coordinated planning for multiple hazards. Integrated hazard planning can uncover opportunities for heat mitigation strategies to serve multiple benefits, such as siting green infrastructure in areas prone to stormwater challenges. There are a number of steps cities can take to foster a systems approach to heat. These steps can be taken in any order, but each is an important part of developing popular, measurable, and successful urban cooling programs.

Identify existing local priorities and characterize how heat mitigation efforts could aid in achieving them. This exercise helps reframe the issue of heat in the context of existing issues that have stronger political influence and awareness within municipal government and the public at large. The effort to identify local priorities also helps to build communication and collaboration between government agencies. Often, city officials that deal most directly with excess heat have few resources and wield advisory power only. Though they take time to develop, a cohort of representatives from various agencies that understand and are willing to incorporate heat into their planning, targets, and budgets can drive substantial progress.

Evaluate existing city policies, programs, partnerships or research that could support or advance heat mitigation implementation and better understand the local potential of urban cooling strategies. This might include existing academic partnerships, major upcoming land developments, and building codes.

Singapore has also experienced a 1.1° C increase in temperature since 1972.[i] This warming is amplified by the urban heat island effect that can increase temperatures in urban zones by as much as 7° C as compared to nearby non-urban zones.[ii]

Measure the many aspects of urban cooling initiatives to track progress. Identify successes and areas for improvement and raising awareness within the community and beyond. Evaluate how existing policies that indirectly affect heat mitigation are measured and determine whether those metrics are relevant for tracking urban cooling. Identify new metrics that highlight the physical changes brought by successful urban cooling strategies (e.g., neighborhood air temperature reductions, vegetated cover changes over time, surface solar reflectance changes over time) as well as more "people-oriented" metrics that highlight the human effect of cooler cities (e.g., reduced emergency room visits, reduced mortality, improved air quality). The first step is establishing a baseline of data and performance for each metric. Cities should also identify resources needed to monitor changes in each metric over time (e.g., a network of weather monitors or reporting requirements for hospitals). Chart XX summarizes the types of data that are useful to collect.

	Data to Collect
Roofs and Walls	· Estimates of the percentage of surface area covered by roofs. · Total roof area by building type (e.g, commercial, residential, institutional, and municipal buildings) and roof type (e.g., flat and steep-sloped) · Characteristics of common building types including building height and window to wall ratios. · Existing building codes for roofs, walls, and insulation requirements · Estimated roof life of locally available products · Market share of local roof types and materials

Weather	• Average solar insolation (the amount of solar radiation energy received on a given surface in a given time, usually given in watts per meter squared) • Wind speeds and direction • Seasonal, annual, and peak rainfall • Maximum and minimum daily temperatures, cooling degree days, heating degree days, or average temperature by day for several years • Air quality • Frequency and intensity of extreme heat or extreme rain events.

Build local support and relevant stakeholders outside of municipal government. Engaging the local ecosystem of non-government actors such as community organizations, developers, contractors, hospitals, and foundations will bring important insight into policy development and program implementation. Early engagement also improves acceptance of new programs and makes it easier to raise public awareness. Promoting academic or scientific partnerships for cooler cities is of particular value. Technical partners significantly bolster the ability of municipal governments to gather and analyze data to understand where they are hot, where vulnerable populations live, and what combination of mitigation strategies perform best in a local context. Beyond helping to prioritize action on heat, this information is important for tracking progress and effects over time.

There is also a need to engage and coordinate with other levels of government. In some cities, new urban areas are outside municipal control but nevertheless have an effect on heat in areas that are under their control. Additionally, decisions on some policy options that support urban cooling, such as building codes, may be outside of municipal control and require collaborative effort to change.

Activity	Questions to Ask	Actions

Identify existing priorities	· Are urban cooling strategies a part of existing plans, codes, laws, regulations, or incentives? · To what extent have cool city materials been widely deployed in your region? · Are there any high-profile local examples?	· Identify existing climate, sustainability, or resiliency plans for your city/state/region. · Research existing building and energy codes, stormwater programs, and incentives. · Review existing aerial and satellite imagery to determine areas of excess surface heat, heat vulnerable populations, and penetration of cool city solutions.
Evaluate existing activities and potential	· Is there existing local research on heat mitigation and what institution produced it? · What types of buildings and pavements are common in your city? · What types of green spaces or parks exist? · What are the climate and weather characteristics? · What is the market availability of cool city solutions today?	· Identify weather and air quality data files as well as building construction and pavement characteristics. · Work with utilities/grid operators to secure energy use and pricing data and compare to temperature data. · Engage local contractors, distributors, and manufacturers to determine availability of heat mitigation measures. · Develop the economic case for cool surfaces.

Build local support and capacity	· How can cool city champions and stakeholders be identified and organized? · What are the relevant funding opportunities? · What existing resources and networks are available for technical support, training, and good practices? · What policies are within municipal control and which require other levels of government to pursue?	· Find supporters and attract funding. · Identify technical resources locally and globally. · Join or leverage existing memberships in city/regional organizations. · Develop local training and education programs[KS5] [DB6].

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[1] An increase of 0.4 is roughly equivalent to changing from a black surface to a medium gray surface.
[2] Based on energy costs for Florida (warm, humid climate) and New Mexico (warm, desert climate). Residential electricity costs during the analysis period were between $0.12 and $0.13/kWh in both states. Commercial electricity costs were between $0.09 and $0.10/kWh.

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[1] Payback is defined as the amount of time it takes for benefits to equal costs

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[1] The effect of urban cooling strategies on human health is substantial but is decreasing as the use of electrical space cooling to keep buildings comfortable is increasing (though the effect on energy use has increased for the same reason).
[2] In this case, this is the payoff, in U.S. dollars, for $1 invested in each cooling strategy scenario.

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The Potential Impact of Cool Roof Technologies Upon Heat Wave Meteorology and Human Health in Boston and Chicago

ABSTRACT

Heat is the greatest weather-related killer in Boston and Chicago, as well as other large urban areas. Our goal is to determine whether increasing urban solar reflectance, through the use of reflective roof products, would lessen the intensity of extreme heat events and save lives during such events. We use a synoptic climatological approach that places days into air mass categories encompassing a wide variety of individual weather metrics including air temperature and dew point. The dry tropical (DT) and moist tropical plus (MT+) air masses are the most oppressive and deadliest. We identify and perform an air mass classification for four actual heat events in Boston and Chicago to determine whether a 0.15 and a 0.25 increase in roof surface reflectance would alter weather conditions during heat waves. These reflectance modifications are achievable in cities adopting reasonable urban heat mitigation strategies. For Boston and Chicago, reflective roofs reduce temperatures and dew points enough to generate actual changes in air mass type from DT and MT+ to more benign air masses that are not harmful to human health. In Boston, using the 0.25 reflectance increase, our modeling indicates that twelve lives would be saved during the four extreme heat events. For Chicago, we find that 42 lives would be saved using the same reflectance increase. Considering that ten to 15 such heat events could occur over a decade, we suggest that the use of reflective roofing products could potentially save hundreds of lives per decade during excessive heat events in each city.

Keywords

Urban heating, solar reflectance, cool roofs, air mass category, synoptic climatological approach, heat-related mortality

Introduction

Urban warming is a critical challenge that negatively impacts human health, quality of life, energy use, air quality, social equity, and economic prosperity. More than eight out of ten Americans currently live in an urbanized area [1] and, on average, urban spaces are heating up at twice the global rate [2]. The Fourth National Climate Assessment estimates with high confidence that urban heat islands in the United States lead to daytime temperatures that are 0.5° to 4°C higher and nighttime temperatures that are 1° to 2.5°C higher in urban areas than in rural ones, with wider differences in humid regions, larger cities, and areas with higher population density [3].

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The impact of excessive heat on human health cannot be underestimated. In many large urban centers in the United States, heat is the leading weather-related killer, greatly outstripping hurricanes, tornadoes, lightning, and blizzards [4]. It is estimated that approximately 1,500 heat-related deaths occur in the United States during an average summer, though the number is highly variable from year-to-year and can sometimes exceed 5,000 deaths [5].

The goal of our study is to quantify how increasing urban reflectance through the use of reflective roofing products would lessen the intensity of extreme heat events (EHE) and save lives in Chicago and Boston. Chicago and Boston were selected due to the vulnerability of these cities to negative health outcomes during EHEs, despite being widely considered "cool climate" cities. It is often not the intensity of the heat, but the variability of the summer weather that renders an urban area most vulnerable to excessive heat. We hypothesize that a reduction in temperature and Apparent Temperature[6] (AT) will cause a possible change in air mass type and a reduction in excess mortality.

Although EHEs are rare in Chicago and Boston, their presence often leads to a rapid increase in mortality since the urban structure of these cities is ill-equipped to allow for internal cooling of living space. Brick row homes and apartment buildings with traditional dark-colored asphaltic, slate, or tile roofing products, few windows, and often without air conditioning are perfect examples of structures that are not designed for EHEs. Conversely, hotter cities, such as Phoenix and Miami, often demonstrate low vulnerability to negative heat/health outcomes because these cities are always very hot in the summer; the low summer weather variability suggests that the population is behaviorally-adapted to excessive heat.

Literature Review

IMPACTS OF URBAN HEAT, COOL CITY STRATEGIES, AND URBAN HEAT MITIGATION

Heaviside et al. [7] provides a detailed review of the current research related to urban heat and health. Excess heat can lead to dehydration, heat exhaustion, and heat stroke but these conditions are only a small portion of the health challenges caused by heat. Heat has a more hidden impact by aggravating existing medical conditions such as diabetes, respiratory disease, kidney disease, and heart disease [8].

Stone et al. [9] estimates changes in heat-related deaths up to the year 2050 resulting from changes in vegetative cover and surface reflectance in Atlanta, Philadelphia, and Phoenix and finds that a combination of vegetation and reflectance enhancement could offset projected heat mortality increases by 40 to 99%.

THE RELATIONSHIP BETWEEN REFLECTIVITY AND TEMPERATURE

Santamouris' [10] comprehensive review on urban heating finds that when a global increase of the city's reflectivity is considered, the expected mean decrease of the average ambient temperature is close to 0.3°C per 0.1 increase in reflectivity,[7] while the corresponding average decrease of the peak ambient

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[6] Apparent Temperature (AT) is defined as the temperature equivalent perceived by humans, caused by the combined effects of air temperature, dewpoint, and wind speed [6].

[7] Reflectivity is measured on a scale of 0 to 1. A surface with a reflectance of 0 absorbs all the incoming solar energy, while a surface reflectance of 0.5 means that the surface reflects 50% of the solar energy that contacts it while absorbing the other 50%.

temperature is close to 0.9°C. Many studies demonstrate that cool roofs reduce 2-meter (roughly head height from ground) urban temperatures by increasing the reflectance of incoming solar radiation [11].

There are also real-world examples of regional cooling resulting from higher reflectivity. Campra [12] compares weather station data in the Almeria region of Spain to similar surrounding regions. Almeria has a unique tradition of whitewashing its greenhouses, and thus, reflects more sunlight than neighboring regions. Over the 20-year study, researchers find that Almeria has cooled 0.8°C compared to the surrounding regions.

SYNOPTIC CLIMATOLOGICAL APPROACH

Synoptic climatological approaches have been utilized extensively within a large variety of heat/health studies [13]. The approach classifies days into one of a number of discrete "air mass" types that traverse a given area and provide unique weather characteristics to that area. Humans respond to an entire suite of weather variables that impact the individual simultaneously; the synoptic climatological approach is a more accurate way to evaluate human response to extreme weather, rather than analyzing temperature, humidity, and other meteorological variables separately. The holistic approach that a synoptic evaluation provides allows the researcher to pinpoint "offensive" conditions that lead to unusual human response, such as heat-related mortality [14].

Our research uses the "spatial synoptic classification" (SSC) [15] which incorporates observations of temperature, dewpoint, pressure, wind, and cloud cover four times daily for a particular location via a hybrid manual/automatic classification scheme, and classifies the days into an air mass type (Table 1) [16]. Two of these air masses, dry tropical (DT) and moist tropical plus (MT+) have been determined in many studies to be associated with statistically significantly higher mortality rates, particularly during the summer months [17].

Table 1. Summary of air mass type abbreviations and descriptions. Bold items indicate air mass types with statistically significantly higher mortality rates.

SSC Air Mass Type Abbreviation	Air Mass Type Description
DP	Dry Polar: cool, dry air mass
DM	Dry Moderate: comfortable and seasonally warm
DT	**Dry Tropical: hot, dry, and very oppressive**
MP	Moist Polar: cool and moist, overcast
MM	Moist Moderate: warmer than MP but still wet and overcast
MT	Moist Tropical: typical summer air mass, warm and humid
MT+, MT++	**Moist Tropical Plus: excessively hot and humid; oppressive**
TR	Transition between different air masses; frontal boundary

The SSC approach has been successfully employed within heat/health warning systems [18], climate change studies [19], and most recently in determining the impacts of changes in urban structure on cooling densely-populated cities [20]. This recent use of the SSC has suggested that, by utilizing highly-reflective materials on roofs and pavement and by incorporating more tree canopy within the urban area, we can actually change the character of some DT and MT+ days during intense heat waves to something less likely to produce negative health outcomes.

Methodology

DEVELOPING HEAT-HEALTH RELATIONSHIPS

We first determined the historical relationships between weather and heat-related mortality for each city. Our previous research has shown that each city reacts differently to heat in terms of the magnitude of negative health outcomes [16]. Cities vary considerably in terms of urban structure, demographics, and climate, all of which play a role in determining their vulnerability to heat/health issues. Thus, separate evaluations were developed for Boston and Chicago to determine their heat-related mortality vulnerabilities.

Heat-related mortality has generally been associated with the occurrence of the warmest air masses, MT+, MT++, and DT. As moist tropical air masses are fairly common in the summer across much of the mid-latitudes, the MT+ and MT++ subsets have been developed to describe more intense versions of the air mass.

As populations in different cities have different levels of acclimatization, the SSC categories are useful in that the mean conditions associated with the different weather types vary from place to place. Thus, an MT+ day in Chicago is very different from an MT+ day in New Orleans.

Using the SSC, daily air mass types have been determined for over 300 cities in the United States since 1948 (see [21]). For Boston and Chicago, the meteorological data utilized to determine air mass types were taken from Logan International Airport and O'Hare International Airport, respectively. Both locations provide the detailed hourly meteorological data necessary to develop our SSC analysis. Although Logan is located adjacent to a large water body, there is no problem using such data for air mass identification. Air masses are macro-scale phenomena, which suggests that, if an MT+ is located over Boston, it is located over the entire urban area. Thus, the more micro-meteorological events that might impact a coastal location have little impact on overall air mass delineation.

Daily mortality data were obtained from the National Center for Health Statistics, which included information on the cause, place (county), date of death, age, and race [22]. These data were extracted for summer only (May 1 through September 30) for Chicago and Boston for the years 1985 – 2010. Total daily mortality across the cities' standard metropolitan statistical area were summed for each day and then standardized to account for demographic changes in the population characteristics during the period (see [23]). The mortality for each day is expressed as a variation above or below a standardized baseline.

After standardization, mean anomalous daily mortality[8] was calculated for each air mass type. In both Chicago and Boston the DT, MT+, and MT++ air masses were associated with the greatest increase in mortality over baseline levels. However, not all days within these air masses demonstrate elevated mortality, so a stepwise linear regression was developed for each city to determine which variables accounted for this mortality variation. The independent variables used in our analysis were meteorological (e.g., morning and afternoon temperature, dew point, wind speed, and cloud cover), persistence-oriented,[9] and seasonal (time of season).[10] This statistical procedure resulted in an algorithm for each city

[8] Mean anomalous daily mortality is the number of deaths above what would normally by expected on that day.
[9] How many consecutive days of the air mass are occurring within the EHE.
[10] June EHEs have shown to be more deadly than similar EHEs in September.

containing statistically significant independent variables. It was utilized to estimate mortality during particular EHEs both in reality and under modeled simulations.

Upon the establishment of heat/health algorithms, we then selected four important EHEs for each city based on their character and seasonality. Since EHEs are physically different, some being very humid and others being excessively dry, we chose different types of events, from the most extreme to somewhat common. Finally, we wanted EHEs from different times in the season, including early and late season events. This is important because late season EHEs frequently exhibit lower excess mortality than early season counterparts with the same magnitude of oppressive weather [24].

After the EHEs were selected for each city, they were evaluated in terms of baseline meteorology and a determination of the air mass present. Using the algorithms described above for each city, we estimated the daily excess mortality attributed to heat for each day within the EHEs. This resulted in an established baseline from which to determine how the modeling of each city, based upon increased urban reflectance, would impact the meteorology, air mass type, and associated daily excess mortality for each of the newly-modeled EHEs.

ESTIMATING EFFECTS OF HIGH REFLECTANCE MITIGATION SCENARIOS ON LOCAL METEOROLOGY

Once relationships between local meteorology and heat-mortality were established for each city, we used mesoscale meteorological modeling to estimate the effects of various heat-mitigation strategies (e.g., increasing urban reflectance) on the diurnal course of ambient air temperature and dewpoint temperature.

We used the Weather Research and Forecasting (WRF) model, version 3.8.1, for regional (mesoscale) atmospheric simulation of urban environments (see [25]). We modeled each urban area using four nested grids with resolutions ranging from 27 kilometers (km) for the outermost grid down to 1 km for the innermost grid. The outermost domain typically had an extent of 1,500 to 2,000 km in both the North-South and East-West directions. Each of the nested domains included approximately 100 grid cells in each direction. Simulations for each city used a time step (for the outer domain) of one minute. To ensure appropriate model spin-up, the simulation of the outermost domains was run for a seven-day period, at which time the finer domains were initiated for an additional four-day period.

~~***Figure 1. Domain configurations for (a) Boston and (b) Chicago, each showing four nested domains.***~~

Baseline simulations for each city and each EHE were simulated and validated against data from a local National Weather Service weather station for the same period of time. The validated baseline models were then modified to represent different scenarios of reflectance modification (REFL1 and REFL2). These test cases were simulated by modifying the reflectance of individual urban facets (roofs and roads) for each of the three categories of urban development. Roofs and roads for the baseline simulations were assigned a reflectance value of 0.15. The REFL1 case represented an overall reflectance increase by 0.15 (to 0.30), while the REFL2 case corresponded to an overall 0.25 increase in reflectance (to 0.40). These increases in reflectance were implemented in the model through modifications of roof and road surface reflectance across low, medium, and high intensity categories of urbanized land cover.

The low, medium, and high intensity development categories used in the modeling are based on fraction of impervious surface as defined in the National Land Cover Database (NLCD) as described in Homer et al. [26]. Low intensity urban land cover corresponds to areas with a mix of constructed materials and vegetation, with impervious surfaces accounting for 20 to 49% of total cover (typically single-family housing units). The medium intensity urban land cover includes areas with 50 to 79% impervious surface cover (typically higher density housing). The high intensity classification is for areas with 80 to 100% impervious cover (typically commercial and industrial areas). This overall increase in modeled urban reflectance was accomplished by increasing road reflectance to 0.30, which is reasonably obtained through a variety of currently-available paving techniques.[11] The reflectance of rooftops was modified such that the overall urban surface reflectance (accounting for fraction of urban areas covered by roofs and paving) would be either 0.30 or 0.40, for cases REFL1 and REFL2, respectively.

The REFL1 and REFL2 scenarios were selected to model the sensitivity of the composite urban reflectance of cool roof solar reflectance, roughly mimicking the current span in aged solar reflectance values for cool roofing products that meet California's Title 24, Part 6; CALGreen (Title 24, Part 11); or ENERGY STAR® requirements.

At the completion of each simulation (for each EHE and for each simulation case), hourly data from the finest model grid domain were exported for urban grid cells using a specialized script. The hourly values of air temperature and dewpoint temperature perturbations were then provided for input to the previously developed heat/health relationships to estimate the effects of the projected changes on heat-related mortality.

The results of the REFL1 and REFL2 modeling are compared to the baseline values to determine how these increases in reflectance have altered the meteorology, air mass character, and associated excess heat-related mortality. Based on our hypothesis, we expect a reduction in temperature and AT, a possible change in air mass type from more to less oppressive, and a reduction in excess mortality. These values have rarely been quantified, which will hopefully provide value as to how reflective materials can influence meteorology and negative health outcomes during EHEs.

Results and Discussion

MORTALITY ALGORITHM DEVELOPMENT

For each city we determined which air mass types are most likely to produce heat-related mortality (Table 2). The DT, MT, and MT+ days all show the greatest increases in daily mortality totals, and in some cases, these can exceed six extra deaths per day. The other air masses (e.g., DP, DM, and MP) show mortality deviations below baseline values. When the oppressive air masses occur earlier in the summer season they show a higher disparity than later in the summer season; this is a typical result that we find in many mid-latitude cities.

Table 2. Mean daily variations in mortality around the standardized baseline for each air mass type in each summer month in Boston. Bold numbers indicate ~~higher positive~~ disparities greater than 5.0 ~~darker green numbers are higher negative disparities~~.

[11] The solar reflectance of concrete is typically 0.25 to 0.30.

	Dry Moderate (DM)	Dry Polar (DP)	Dry Tropical (DT)	Moist Moderate (MM)	Moist Polar (MP)	Moist Tropical (MT)	Transition (TR)	Moist Tropical + (MT+)
May	-1.3	-1.1	4.9	-2.2	-2.7	3.7	-1.5	**5.9**
June	-0.4	-1.8	**6.6**	-1.5	-2.3	3.0	-0.4	**6.2**
July	-1.5	-1.7	**7.8**	-0.6	-3.8	3.3	1.1	**5.7**
August	-1.4	-1.8	**5.4**	-1.8	-3.8	1.6	0.6	3.5
September	-1.9	-3.8	0.1	-1.6	-2.3	1.9	-2.7	3.2

In addition, consecutive days of the oppressive DT and MT+ air masses show increasingly higher positive deviations (Table 3). By the seventh consecutive day, average daily mortality is over five times higher than on the first day of oppressive air mass intrusion.

Table 3. Mean daily variations in mortality during consecutive day runs of DT and MT+ air masses in Boston.

Day in Sequence	Excess Deaths
1	2.9
2	5.2
3	7.3
4	9.7
5	11.7
6	13.9
7	16.2

After isolating the days with DT, MT+, and MT++ air masses during the period of record, we can develop an algorithm that estimates positive mortality disparities on each oppressive air mass day using a stepwise linear regression approach. The algorithm developed for Boston is shown in Eq 1.

$$M = -1.36 + 2.243\,DIS + 0.154\,AT17 - 0.011JD\#(1)$$

Where:

M = excess daily mortality during oppressive air mass days,

DIS = day in sequence,

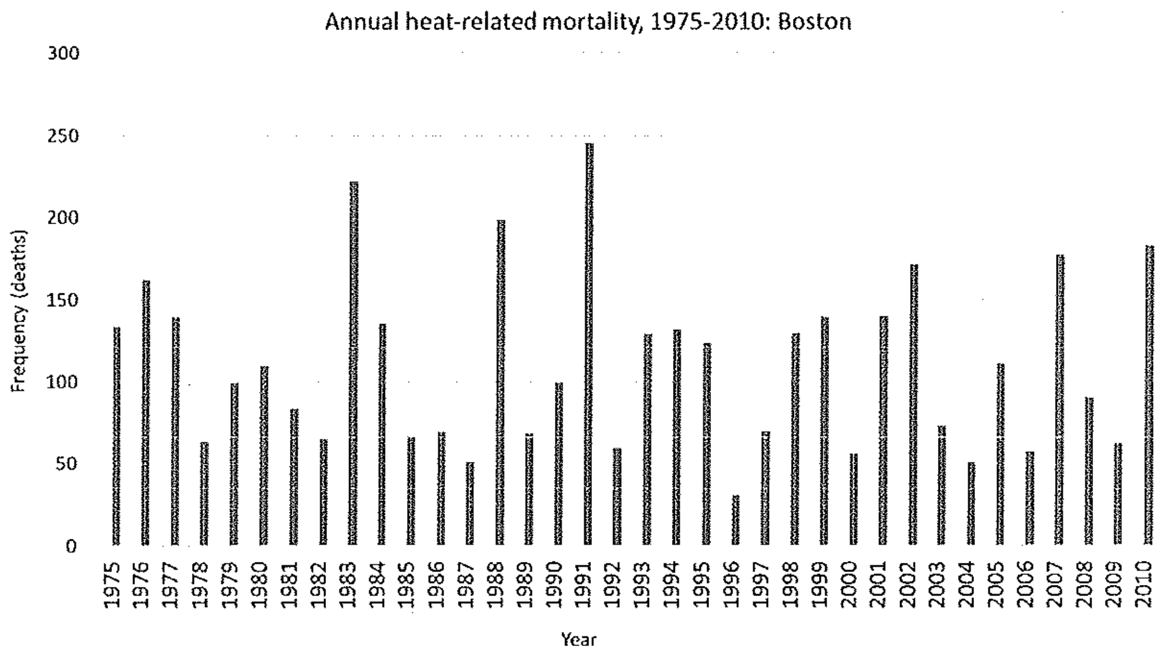
AT17 = the AT at 5PM (°C), and

JD = Julian date, where May 1 is 1, May 2 is 2, June 1 is 32, and so on.

The JD variable is inversely related to M and indicates that, as the season wears on, the same intensity EHE will cause lesser mortality. This is not an uncommon result in our research (see [16]) since the population acclimatizes to the heat as the summer progresses, and there is a "mortality harvesting" component, where early season heat deaths result in a lesser number of susceptible individuals available to die later in the season.

Thus, each oppressive air mass day has an estimated excess mortality that is largely attributed to heat-related causes. These can be added for each summer season to determine the estimated heat-related death totals annually (see Figure 1). These values vary considerably from one summer season to the next, and are dependent upon the number of oppressive air mass days, the length of consecutive day EHEs, and AT. Some years have fewer than 50 seasonal deaths, while others can exceed 200.

Figure 1. Total estimated heat-related mortality for each summer season in Boston using the developed algorithm.



A similar analysis for Chicago produced the algorithm displayed in Eq 2.

$$M = -26.74 + 4.62\ DIS + 0.777\ AT16\#(2)$$

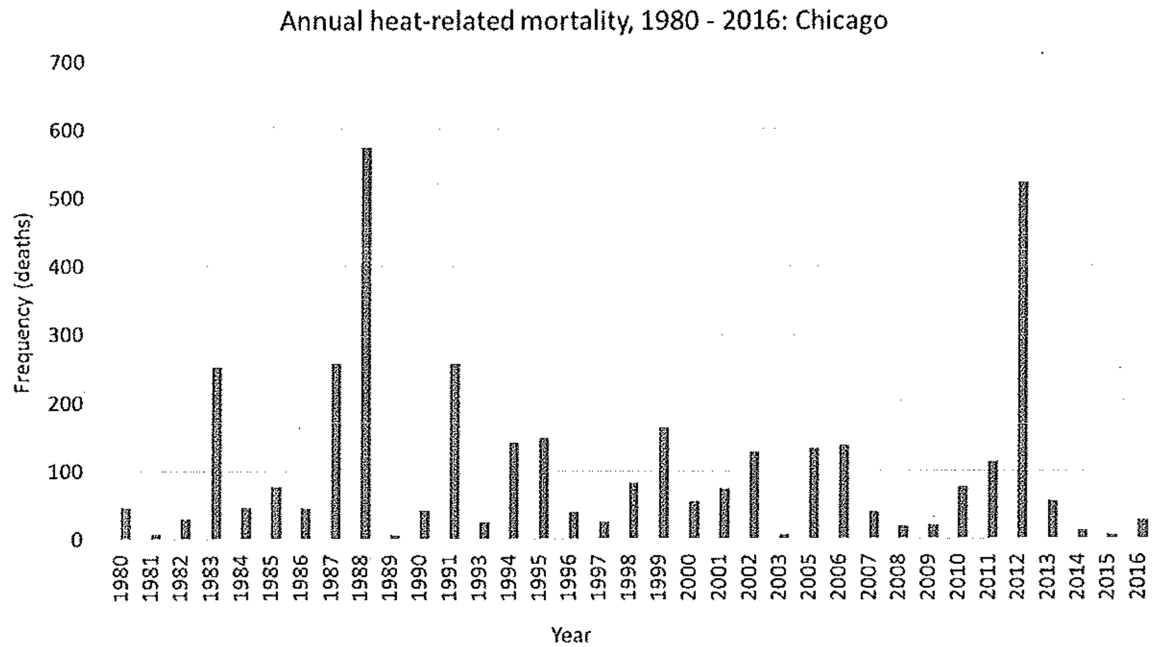
Where:

DIS = day in sequence, and

AT16 = the AT at 4PM (°C).

Much like Boston, we can estimate seasonal excess or heat-related mortality for Chicago (Figure 22).

Figure 2. Total estimated heat-related mortality for each summer season in Chicago using the developed algorithm.



During typical summers Chicago's seasonal heat-related mortality is higher than Boston's; it averages slightly over 100 deaths per summer with a very high standard deviation. However, during extreme years (1988 and 2012), Chicago totals far exceed any that are estimated for Boston. Thus, on an inter-seasonal basis, variations in Chicago heat-related mortality are even more variable than those in Boston.

The Chicago mortality estimates returned a relatively low number of deaths during the 1995 EHE, the worst in the city's recorded history. During that singular event in mid-July of 1995, it is estimated that 800 people perished from the heat [27]. Our model significantly underestimated that total. We will discuss the reasons for this later in the paper.

BOSTON SIMULATION RESULTS

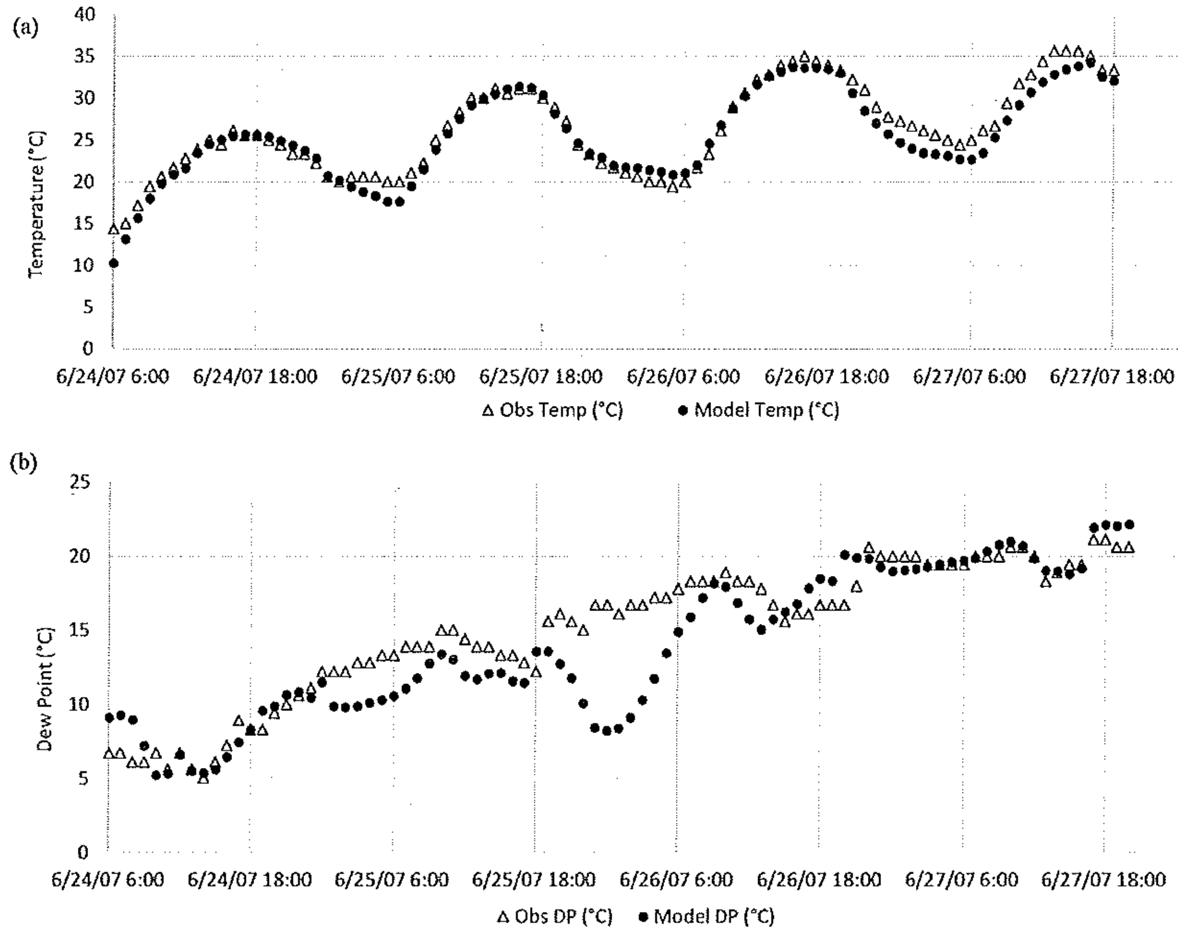
For the Boston simulations, we selected these four EHEs for evaluation: July 19-23, 1994; July 16-18, 1999; August 12-18, 2002; and June 25-28, 2007 (see Table 4). The selection was predicated upon finding meteorologically different types of EHEs to determine whether responses to our reflective roof scenarios were similar or different across events. For example, the July 1994 event is hot, humid, and dominated by MT days. The July 1999 event was hot and dry with all DT days. The August 2002 and June 2007 events were mixtures of hot and dry and hot and humid days. For the June 2007 event we wanted to observe potential differences in this early season EHE.

Table 4. Daily maximum, minimum, and dewpoint temperatures for the four Boston EHEs.

Date	Temperature, Max, °C	Temperature, Min, °C	Average Dewpoint, °C	Air Mass Category
1994-07-19	31.67	20.00	20.00	MT
1994-07-20	33.90	22.78	21.11	MT
1994-07-21	35.56	23.89	22.78	MT++
1994-07-22	33.90	23.89	22.22	MT+
1994-07-23	32.78	22.22	21.67	MT
1999-07-16	35.00	21.11	17.78	DT
1999-07-17	36.67	23.89	20.56	DT
1999-07-18	36.11	22.78	20.00	DT
2002-08-12	32.22	21.11	18.89	MT
2002-08-13	36.11	22.78	19.44	DT
2002-08-14	37.78	25.00	19.44	DT
2002-08-15	33.90	22.78	20.56	MT+
2002-08-16	33.90	25.00	22.22	MT++
2002-08-17	35.56	25.56	17.78	DT
2002-08-18	35.00	22.22	20.00	DT
2007-06-25	31.67	18.33	13.89	DT
2007-06-26	35.00	19.44	17.78	DT
2007-06-27	35.56	24.44	20.00	MT++
2007-06-28	33.33	24.44	20.00	MT+

Our baseline simulation was developed for the June 2007 EHE to determine if the modeled baseline simulation closely duplicates reality. We gathered the necessary airport meteorological data (Logan Airport, a first order meteorological station), extracted the simulation output (for Logan), and compared the model output with observed data for the June 2007 EHE (see Figure 3). The root mean square error for air temperature and dewpoint estimates are 2°C and 2.4°C, respectively. The comparison graphs show how well the control simulation duplicates reality, with one exception of a few hours overnight on June 25, 2007.

Figure 3. Comparison of model-predicted (a) temperature and (b) dew point with observations for the control simulation for Boston, June 25 – 28, 2007.



The simulations for the June 2007 EHE exemplify the results that we uncovered for the four EHEs (Table 5). The modeling demonstrates a significant cooling, particularly during daytime hours. Not surprisingly, the magnitude of cooling is greatest for the REFL2 scenario, where urban reflectance was increased by 0.25. In some cases, cooling approaches and even exceeds 1.5°C using the REFL2 scenario, and is greater than 0.6°C under the REFL1 scenario. The decreases under the REFL2 scenario are quite important, as this magnitude of cooling is sometimes sufficient to prevent some deaths from heat-related causes.

Table 5. Six-hourly data output (air temperature and dewpoint temperature) for REFL1 and REFL2 scenarios for the June 2007 EHE in Boston. Data correspond to the grid cell containing Logan Airport. <u>Italicized items indicate values above baseline. Items in bold and shaded gray indicate 1.00° C or greater below or above baseline.</u>

Local Time	Baseline Temperature, °C	Base Dew Point, °C	REFL1 Temperature, °C	REFL1 Dew Point, °C	REFL2 Temperature, °C	REFL2 Dew Point, °C
6/24/07 at 5:00	9.65	9.03	9.65	9.03	9.64	9.03
6/24/07 at 11:00	20.86	5.31	20.36	*5.62*	**19.81**	*6.02*
6/24/07 at 17:00	25.63	7.43	25.26	7.14	24.91	7.01
6/24/07 at 23:00	22.84	10.47	22.34	10.53	**21.36**	***11.47***
6/25/07 at 5:00	17.67	10.32	17.13	10.18	**16.57**	*9.86*
6/25/07 at 11:00	27.56	13.06	26.96	*13.33*	**26.33**	*13.84*
6/25/07 at 17:00	31.28	11.46	30.56	***13.23***	**29.99**	***13.12***
6/25/07 at 23:00	22.93	8.4	22.83	*9.23*	22.33	***10.02***
6/26/07 at 5:00	20.87	13.46	20.84	13.28	20.66	13.19
6/26/07 at 11:00	30.33	16.86	**29.33**	***17.98***	**28.52**	***18.11***
6/26/07 at 17:00	33.67	17.84	33.29	17.28	32.86	17.22
6/26/07 at 23:00	25.71	19.26	25.51	*19.56*	25.39	19.28
6/27/07 at 5:00	22.74	19.59	22.43	19.60	22.37	19.59
6/27/07 at 11:00	30.73	20.7	29.91	*21.00*	**29.16**	*21.44*
6/27/07 at 17:00	32.54	21.93	31.95	*22.2*	**31.41**	*22.21*

~~**Figure 4. Hourly plots of temperature (a) and dewpoint (b) between the baseline (which represents reality) and REFL1 and REFL2 scenarios for Boston, June 24 – 27, 2007. Positive values indicate lower simulation values than the baseline (thus, a modeled reduction in values); negative values indicate higher simulation values than the baseline.**~~

Dewpoint temperatures do not show the systematic reduction we see with air temperature. In some cases, there are modest to moderate increases in dewpoint temperature, sometimes exceeding 1°C. This is related to the vertical motion of air (ventilation) during very hot conditions. If temperatures near the surface are reduced, ventilation is inhibited; even a small reduction in vertical motion can lead to the accumulation of more humid air near the surface resulting from evapotranspiration from vegetation, emissions from vehicles, and other sources of moisture. We have seen this occurrence consistently in our previous evaluations (e.g., [20]). Nevertheless, even with modestly rising dewpoint temperatures, AT is less at virtually all of the times, even in those unusual circumstances when dewpoint temperature increases at the same rate that the air temperature decreases. For example, on June 26 at 11AM, the AT for the baseline temperature/dewpoint combination of 30.33°C/16.86°C is 31°C. For the REFL2 scenario, the AT for a temperature/dewpoint combination of 28.52°C/18.11°C is only 29°C. Thus, the increased dewpoint has much less of an impact on AT than does a corresponding temperature decrease.

A summary of all four EHEs shows consistency among the events (see Table 6), although some important differences are noted. Afternoon (5PM) AT declines are greater for the REFL2 scenario as compared to REFL1; the difference can sometimes exceed 3°C, as is the case on August 13, 2002. In addition, there are occasions when the air mass actually changes. For example, during the June 2007 EHE, the first day of that EHE was originally a DT day, and because of AT reductions, it was altered to a much less oppressive DM day under the REFL1 scenario, and to a typical and more comfortable MT day under the REFL2 scenario.

Table 6. A summary of results for all four evaluated EHEs in Boston. **Boxes shaded in light gray represent air mass changes.**

	Baseline			REFL1			REFL2		
EHE #1	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
June 25, 2007	26.6	DT	3	26.2	DM	0.7	25.9	MT	0.7
June 26, 2007	31.7	DT	6.1	31.3	DT	3.8	30.5	DT	3.6
June 27, 2007	31.5	MT+	8.3	31.2	MT+	6	30.6	MT+	5.9
June 28, 2007	29.8	MT+	10.2	29.6	MT+	8	29.4	MT+	7.9
			27.6			**18.5**			**18.1**
EHE #2	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
August 13, 2002	33.6	DT	6.3	32.5	MT+	6.1	30	MT+	4.8
August 14, 2002	36.4	DT	9	36.1	DT	8.9	35.9	DT	8.9
August 15, 2002	31.4	MT+	11.2	31.1	MT+	11.2	30.8	MT+	11.1
August 16, 2002	32.7	MT+	13.4	32.2	MT+	13.4	31.7	MT+	13.4
			39.9			**39.6**			**38.2**
EHE #3	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 19, 1999	30.1	MT	3.8	29.9	MT	3.8	29.7	MT	3.7
July 20, 1999	30.3	MT	3.8	29.4	MT	3.8	28.5	MT	3.7
July 21, 1999	33.9	MT+	6.6	33.5	MT+	6.5	32.9	MT+	6.5
July 22, 1999	32.2	MT+	8.8	31.8	MT+	8.8	31.5	MT+	8.7
July 23, 1999	21.3	MT	4.3	20.7	MT	4.3	20.4	MT	4.2
			27.3			**27.2**			**26.8**
EHE #4	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 16, 1999	31.7	DT	6.3	31.4	DT	6.3	31.1	DT	6.2
July 17, 1999	35.3	DT	9.1	35	MT+	9.1	34.5	MT+	9
July 18, 1999	33.8	DT	11.3	33.8	MT+	11.3	33.4	MT+	11.2
			26.7			**26.7**			**26.4**
TOTAL EXCESS MORTALITY			**121.5**			**112**			**109.5**
TOTAL PERCENT REDUCTIONS						**8%**			**10%**

There were three other daily air mass changes noted in the four evaluated Boston EHEs: one during the August 2002 EHE and two others during the July 1999 EHE. In all of these cases, DT days were altered to almost equally-oppressive MT+ days. This is a possibility on days when there are temperature reductions and dewpoint temperature increases — something that was not uncommon in the EHEs evaluated for Boston. Thus, these modifications generally resulted in minor decreases in mortality.

The reduction of excess mortality is noted in all four EHEs, although the largest drop occurred in the June 2007 event when estimated mortality for the baseline was almost 28 deaths as compared to 18 deaths for the REFL2 scenario. The other three events demonstrated more modest declines of about 1 or 2 deaths. For the June 2007 event, the large decline is partially attributed to the change in the day in sequence (DIS) variable. Since the first day changed from an oppressive air mass to a non-oppressive one for both REFL scenarios, that set the DIS counter back one full day for both scenarios, resulting in more significant mortality reductions.

Total baseline mortality for the evaluated events was about 122 deaths. This was reduced to 112 for the REFL1 scenario and 109 for the REFL2 scenario, which represents an 8.1% reduction for the former and a 9.2% reduction for the latter. The twelve saved lives for the events under the REFL2 conditions may not initially seem impressive, but assuming that the number of EHEs similar to these over a 30-year period can exceed 40 or 50 events (about one to two per year on average), a total of 150 to 200 lives can be saved during this period if REFL2 conditions are achieved. This is not an insignificant number, considering that there are much larger potential decreases in emergency room visits and ambulance calls, which were not evaluated here.

CHICAGO SIMULATION RESULTS

Much like the Boston analysis, the four EHEs selected for the Chicago simulations were individually unique (see Table 7). For example, the early August 1988 event was a mixture of DT and MT+ days, while the event in mid-August was pure MT+. Since we were trying to determine how a more typical EHE might respond under the REFL scenarios, the mid-August 1988 event was not viewed as particularly extreme. The July 1995 event was the most historic in Chicago history; hundreds of people died during this heat wave. As with the July 1995 event, the July 2012 event was also very hot, but dewpoint temperatures were generally lower than the unprecedented 1995 EHE, and thus, mortality totals were lower.

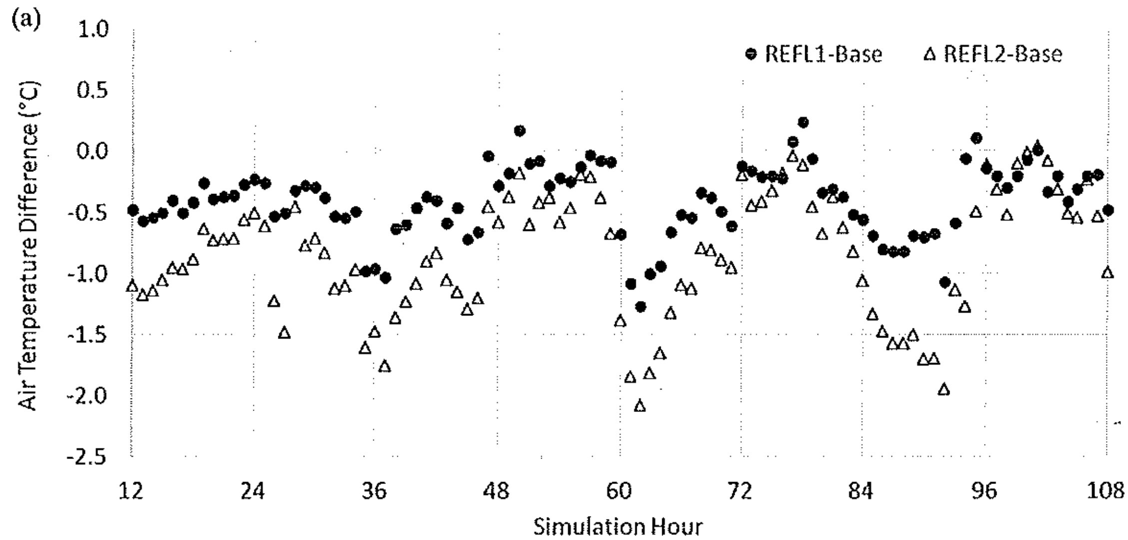
Table 7. Daily maximum, minimum, and dewpoint temperatures for the four Chicago EHEs.

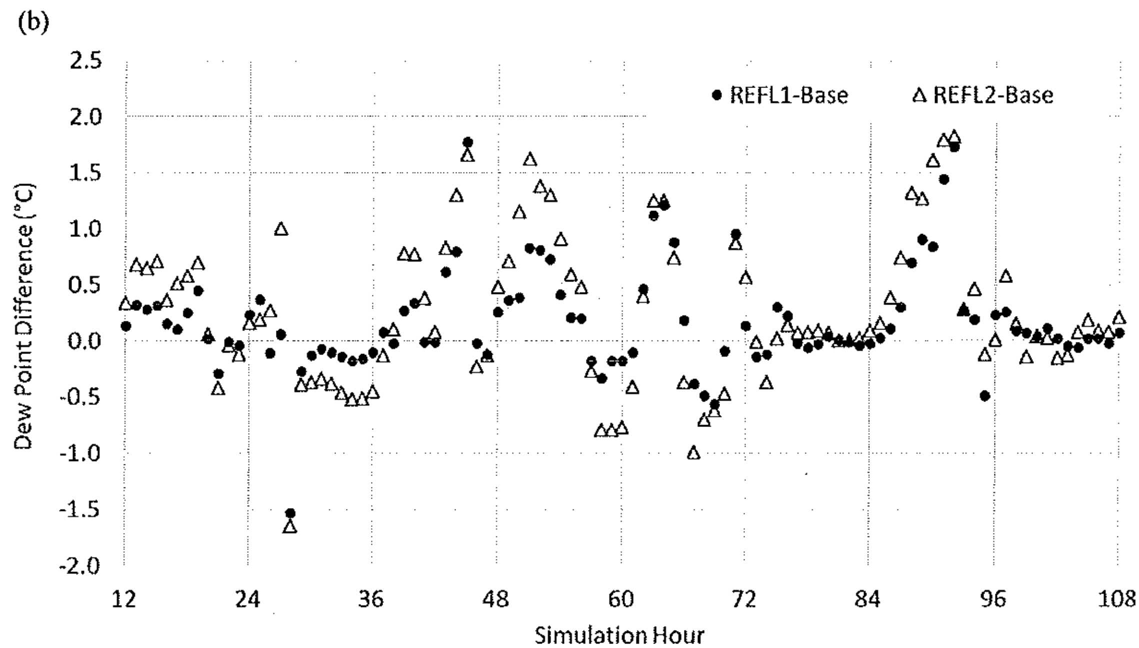
Date	Temperature, Max, °C	Temperature, Min, °C	Average Dewpoint, °C	Air Mass Category
1988-08-01	37.78	25.56	22.22	DT
1988-08-02	37.22	26.67	22.22	DT
1988-08-03	35.56	26.67	21.67	MT+
1988-08-04	35.56	25.56	22.22	MT+
1988-08-05	30.56	18.89	20.00	MT+
1988-08-11	33.33	22.22	22.78	MT+
1988-08-12	33.33	23.89	22.22	MT+
1988-08-13	32.22	25.00	22.78	MT+
1988-08-14	32.78	23.89	23.89	MT+
1988-08-15	33.89	23.89	21.67	MT+
1988-08-16	36.67	23.33	22.78	MT+
1995-07-12	35.56	22.78	21.11	DT
1995-07-13	39.44	27.22	25.00	MT++
1995-07-14	37.78	28.33	25.00	MT++
1995-07-15	36.11	23.89	22.22	MT++
2012-07-02	36.11	22.22	20.56	DT
2012-07-03	38.33	25.00	19.44	DT
2012-07-04	38.33	26.11	20.56	DT
2012-07-05	39.44	26.67	20.56	MT+
2012-07-06	39.44	28.33	21.67	DT

~~**Figure 5. Interannual frequency of DT and MT+ days in Chicago: 1960-2016.**~~

The August 1 - 5, 1988 simulations for REFL1 and REFL2 show temperature daytime reductions similar to those found in the Boston results, averaging from 1.5°C to over 2°C (Figure 4). The pattern is quite regular from one day to the next. The magnitude of these peaks under the REFL2 scenario are much higher than REFL1. Much like the Boston scenarios, there are both decreases and increases in dewpoint temperature, although the number of dewpoint decreases seem greater in Chicago than in Boston. In addition, the dewpoint departures from the baseline are generally smaller than the temperature departures, and they are much less cyclical. The other EHEs behaved rather similarly to the August simulations illustrated here, and dewpoint variations were approximately one third those for temperature.

Figure 4. ~~**Hourly plots of temperature (a) and dewpoint (b) between the baseline (which represents reality) and REFL1 and REFL2 scenarios for Chicago, August 1-5, 1988. Positive values indicate lower simulation values than the baseline (thus, a modeled reduction in values); negative values indicate higher simulation values than the baseline.**~~ **Plots of simulated air temperature (a) and dewpoint temperature (b) differences between the baseline (which represents reality) and REFL1 and REFL2 scenarios for Chicago, for the August 1-5, 1988 (108 hour long) heat wave episode. Negative values indicate lower values for the mitigation cases relative to the baseline (thus, a modeled reduction in values).**





~~**Figure 5. The magnitude of temperature reductions in the Chicago area under the REFL2 scenario, August 1, 1988, at 11AM (a) and 3PM (b). Arrows indicate prevailing windspeed and direction.**~~

The air mass change/mortality results for Chicago were more robust than those uncovered for Boston (see Table 8). Eight days demonstrated changes in air mass for the REFL2 scenario; five days showed changes for REFL1. Some of those changes were from the very oppressive DT to the slightly less oppressive MT+, but a few were from an oppressive air mass to a non-oppressive one. For example, during the August 5, 1988 EHE, MT+ was altered to a much less dangerous DM air mass, with an associated large drop in mortality.

Table 8. A summary of results for all four evaluated EHEs in Chicago. Boxes shaded in light gray represent air mass changes.

	Baseline			REFL1			REFL2		
EHE #1	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
August 1, 1988	39.7	DT	8.7	39.4	MT+	8.5	39.0	MT+	8.2
August 2, 1988	39.6	DT	13.3	39.3	MT+	13	39.1	MT+	12.9
August 3, 1988	37.3	MT+	16.1	37.0	MT+	15.9	36.4	MT+	15.4
August 4, 1988	36.2	MT+	19.9	35.8	MT+	19.6	35.5	MT+	19.3
August 5, 1988	29.3	MT+	19.1	28.7	MT+	18.7	28.1	DM	9
			77.1			**75.7**			**64.8**
EHE #2	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
August 11, 1988	35.6	MT+	5.5	35.1	MT+	5.2	34.8	MT+	4.9
August 12, 1988	35.2	MT+	9.9	34.6	MT+	9.4	34.1	MT+	9
August 13, 1988	31.8	MT+	11.8	31.5	MT+	11.6	31.1	MT+	11.3
August 14, 1988	35.3	MT+	19.2	34.9	MT+	18.9	34.2	MT+	18.3
August 15, 1988	33.0	MT+	22	32.2	MT+	21.4	31.3	MT	11.4
August 16, 1988	37.1	MT+	29.8	36.7	MT+	29.5	36.2	MT+	19.9
			98.2			**96**			**74.8**
EHE #3	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 12, 1995	36.0	DT	5.9	35.5	MT+	5.5	34.9	MT+	5
July 13, 1995	41.2	MT++	14.5	41.2	MT++	14.5	40.6	MT++	14
July 14, 1995	39.6	MT++	17.9	39.9	MT++	18.1	39.6	MT++	17.9
July 15, 1995	35.6	MT++	19.4	35.3	MT+	19.2	34.8	MT+	18.8
			57.7			**57.3**			**55.7**
EHE #4	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 2, 2012	35.4	DT	5.4	35.4	DT	5.4	34.9	MT+	5
July 3, 2012	34.5	DT	9.3	33.7	MT+	8.7	33.6	MT+	8.6
July 4, 2012	36.7	DT	15.6	36.4	DT	15.4	36.0	DT	15.1
July 5, 2012	29.5	MT+	14.7	28.6	MT+	14	28.6	MT+	14
July 16, 2012	39.7	DT	27.2	40.9	DT	28.1	38.8	DT	26.5
			72.2			**71.6**			**69.2**
TOTAL EXCESS MORTALITY			**305.2**			**300.6**			**264.5**

TOTAL PERCENT REDUCTIONS	**2%**	**13%**

The two August 1988 events showed dramatic drops in excess mortality, particularly under the REFL2 scenario. For example, the early August EHE had an estimated 77 excess deaths under baseline conditions, and this was reduced to about 65 deaths using REFL2 criteria, representing a 16% drop in excess mortality and 12 lives saved. The mid-August MT+ dominated event yielded even better results. One day was shifted to a non-offensive MT air mass; in all, we estimated approximately 24 saved lives, from 98 under baseline conditions to 74 using the REFL2 scenario.

The other two EHEs, including the very dangerous July 1995 EHE, did not demonstrate dramatic drops. The July 2012 REFL2 scenario showed only a 4% drop in mortality from the baseline, or three lives saved. Two days demonstrated air mass changes, but they were from DT to a nearly-as-oppressive MT+. Although the magnitude of the cooling was similar to the two 1988 EHEs, we have found that the dry, hot events often do not demonstrate the life-savings benefits that are gained during hot, humid events. We will explain reasons for this shortly.

Our biggest surprise was the lack of lower mortality response in the most extreme event (July 1995). A problem is immediately apparent: of the four EHEs evaluated here, the estimated number of deaths was lowest for the July 1995 event even though it is well-documented that this was the worst heat wave in recent Chicago history in terms of lives lost. Additionally, our modeling indicates only a 3% decrease in mortality under the REFL2 scenario, which translates to two lives saved.

Excluding the July 1995 EHE, the three remaining EHEs were estimated to have killed about 250 individuals. Chicago averages about one or two of these magnitude events annually, as the majority of years has at least ten DT and MT+ days per summer. Based upon our modeling, the REFL2 scenario would have saved 39 lives during these three events, a 16% reduction in heat-related mortality. If, on average, we can expect a 16% reduction in heat-related deaths during a typical Chicago EHE, this would amount to 150 to 300 lives saved in a decade based upon the number of these events that typically occur.

DISCUSSION

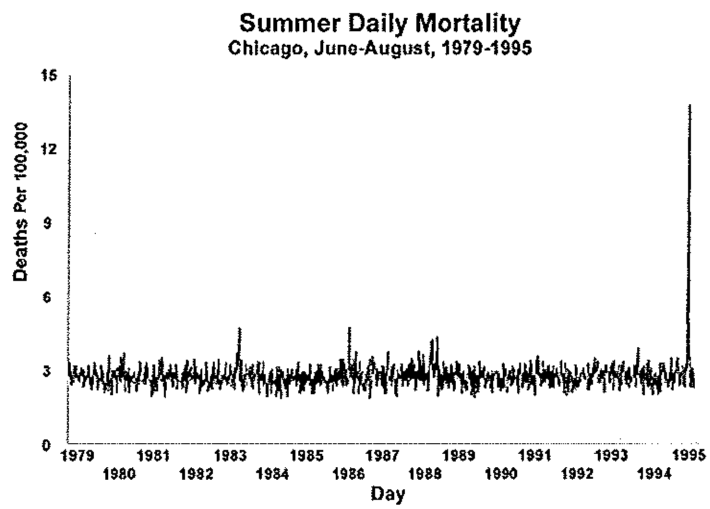
All the EHEs demonstrated cooler temperatures and decreases in mortality under the higher reflectance scenarios. Although the EHEs generally showed similar reductions in temperature under the various REFL scenarios, the REFL2 scenario demonstrated about a two to three times greater reduction than REFL1, and the magnitude of lives saved varied considerably.

We offer two suggestions as to why some EHEs performed better than others. The first involves whether the EHE was hot and humid or hot and dry. In general, the hot and humid events showed more drastic drops in mortality than the hot and dry events, particularly in Chicago. We believe this is because most of the DT days, when cooled by 1°C to 2°C, will change to an MT+ air mass, which is still oppressive and responsible for heat-related mortality. Dewpoint temperatures do not drop as much as air temperatures on most days, and sometimes even increase. Thus, a cooler DT day with a similar dewpoint temperature will switch to an MT+ if there is an air mass change on that day. This leads to minimal reduction in excess mortality on those days, thereby diminishing the health benefits of the increased reflectance. Our best results are often obtained during MT+ dominated EHEs, since air mass changes are never to the oppressive DT, but rather to the much more benign and common MT air mass, or occasionally to a common DM air mass, as was the case on August 5, 1988.

Second, we suggest that the most severe EHE, the Chicago July 1995 event, is not handled well by our models because this EHE is an incredible outlier. ~~Table 9 demonstrates that~~ The temperature reductions during that event were similar to the other EHEs we evaluated. Most of the REFL1 reductions were between 0.5°C to 1.0°C, while most of the REFL2 reductions were 1°C or greater. Most of the reductions were in the late morning or afternoon, much like the other EHEs we evaluated. In addition, the July 1995 EHE was largely a very hot and humid event, which we have indicated should respond in a better fashion in terms of lives saved. So why did this EHE not respond like the others if the temperature reductions were somewhat similar? ~~***Table 9. Temperature reductions during the July 1995 EHE in Chicago. Numbers in orange indicate reductions of greater than 1.5°C and pink numbers show reductions of greater than 2°C.***~~

One reason for this unexpected response relates to the outlier nature of the July 1995 event in terms of lives lost. When evaluating the raw mortality data for Chicago, it is clear that the July 1995 EHE is truly remarkable for the number of lives lost (Figure 5). The average daily summer death rate in Chicago is 3 per 100,000, but on two days during the EHE of July 1995 that number approached 14 per 100,000. The two August 1988 EHEs are also seen in Figure 5; those EHEs, along with any others that stand out, were much smaller in magnitude.

Figure 5. Number of daily all-cause deaths per 100,000 in Chicago: June through August, 1975 – 1995.



When developing our Chicago mortality algorithm for DT and MT+ days, all of the daily mortality totals for these oppressive air masses were included as dependent variables. Although those atypical July 1995 days were included, they had less impact on the algorithm than the dozens of DT and MT+ days that typically had 3.5 to 5 deaths per 100,000. Thus, considering the linear nature of the stepwise multiple regression that we employed, the few highly extreme days of July 1995 had much less impact upon the algorithm than they had in terms of real-life impact. As a result, the Chicago algorithm greatly underestimated the number of excess deaths for those July days in 1995 when the EHE was most extreme. That explains the 57 baseline excess deaths that the algorithm estimated for the July 1995 EHE, which is more than an order of magnitude below the number of actual excess deaths. It also partially explains why there was such a comparatively small drop in mortality using the same algorithm for the REFL1 and

REFL2 scenarios. In short, based on the way our study was modeled we could not properly handle an event such as the July 1995 EHE in Chicago.

An obvious question is why the July 1995 event was, in reality, so anomalous. The weather data do not fully explain why this EHE was so much worse than the others in terms of actual excess mortality. Table 6 above, which compares ATs for all the events, shows that there was a day during the 1995 event that exceeded a 41°C AT, and another day that exceeded 39.5°C. Those are exceedingly hot days, but the August 1 – 5, 1988 EHE had two days that exceeded 39.5°C (although no days during this event exceeded 40°C). The pertinent observation here is that the 1995 EHE was not much worse in terms of AT than the early August 1988 event, but the mortality rate was greater by fivefold. How can that be explained? The non-linear nature of the impact of AT on mortality is one partial explanation; a 1°C or 2°C increase in AT has a considerably greater effect when temperatures are approaching 40°C than when they are 30°C – 35°C . However, our main hypothesis relates to the *timing* of the July 1995 EHE. Figure 55 indictates that there were EHEs in 1983 and 1986 which preceeded the two events we evaluated in August of 1988. The data show there were virtually no excessive heat deaths from the period between 1988 and the EHE of July 1995. Therefore, we believe that the number of vulnerable individuals accumulated during that relatively meteorologically-benign seven-year period led to a highly inflated total for July 1995. Several EHEs in the early and mid-1980s, as seen in Figure 55, killed some of the heat-vulnerable people, leaving less to die during the two August 1988 EHEs.

With the exception of the July 1995 event, we believe our model is a valid approach to evaluate both the meteorological and health impacts of high reflectance solutions to address urban heating.

Conclusion

The goal of this research was to quantify how increasing urban reflectance through the use of reflective roof products can lessen the intensity of EHEs and save lives during such events. We employed an air mass-based synoptic climatological approach to define EHEs in terms of "oppressive air masses," which historically have been associated with excess mortality during EHEs. We also attempted to determine if some days might actually switch to a less oppressive air mass if the reduction in heat was sufficiently large.

The following are our major findings:

- Based on the unique algorithms we developed for each city, we estimate that in an average summer about 70 people die from heat-related causes in Boston and slightly over 100 die in Chicago.
- The algorithms are more reliable for the typical heat events and underestimate mortality significantly for the most extreme event (e.g., July 1995 EHE in Chicago).
- For Boston, the modeling typically demonstrates a significant cooling, particularly during daytime hours. The magnitude of cooling is greatest for the REFL2 scenario, where urban reflectance was increased by 0.25. In some cases, cooling approaches, and even exceeds, 1.5°C using the REFL2 scenario, and is greater than 0.6°C under the REFL1 scenario. Chicago simulations produce similar but slightly larger cooling values, with some exceeding 2°C.

- Dewpoint temperatures show more irregular fluctuations than air temperature for both cities, including some increases under the cooling scenarios. Decreases in dewpoint under the scenarios are more prevalent in Chicago than in Boston.
- All the evaluated EHEs for both cities show reductions in excess heat-related mortality, although the magnitude of the reduction is highly variable from one heat event to the next. For Boston, the average reduction in mortality for all the EHEs using the REFL1 scenario is 8.1%, and is 9.2% for REFL2. This translates to about 12 saved lives for the four events under REFL2 conditions. For Chicago, the REFL2 scenario leads to an average reduction in mortality of over 10%, with one event showing a 24% decline.
- The modeling does a poor job of identifying lives saved during the most intense EHE (July 1995) in Chicago. Since that EHE was an outlier, it should not be assigned to the same mortality-estimating algorithm as the other three EHEs. Nevertheless, the results for the other EHEs in Chicago were intuitive, and we estimate that under the REFL2 scenario 39 lives would have been saved. This could translate to approximately 200-300 saved lives a year during a decade's worth of EHEs in Chicago.
- The model projects larger numbers of saved lives occurring during hot and humid heat events for both cities as compared to hot and dry events.
- We suggest that more extensive use of reflective roofs in these two major cities would contribute significantly to saving numerous lives from heat during oppressive weather days.

There are several avenues that should be pursued to improve and expand upon the results of this study. The first would be a means to handle the most excessive of heat events, such as the Chicago July 1995 EHE. We concluded that this event was not evaluated properly when lumped together with the other three Chicago EHEs, since excess deaths were close to an order of magnitude higher during the 1995 EHE. We believe that a lack of severe heat for several years prior to the 1995 EHE partially contributed to its extreme mortality response, since it was only slightly hotter and more oppressive than the 1988 and 2012 events in terms of meteorology. There were obviously other factors at play as well, which need to be identified precisely.

The scope of our work was limited to heat-related mortality only; we did not evaluate morbidity, such as emergency room visits and ambulance calls. There is now increasing research on emergency room admissions and ambulance calls during EHEs (e.g., [28]), and there is no doubt that a study like this can be expanded to include morbidity, which is more widespread during EHEs than mortality. In addition, this study did not attempt to evaluate the potential impacts of human-induced climate change, and it is feasible to expect that more intense utilization of reflective technologies will help mitigate or delay these negative meteorological impacts upon human health.

We hope to expand our work in Boston and Chicago to evaluate more directly the impacts of cool technologies upon the suburban ring, which continues to become more densely populated in both of these urban areas. Thus, an even more comprehensive evaluation of the benefits of reflective roofing materials and other cool cities solutions is a longer-term goal growing out of this evaluation.

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Capturing the true value of trees, cool roofs, and other urban heat island mitigation strategies for utilities

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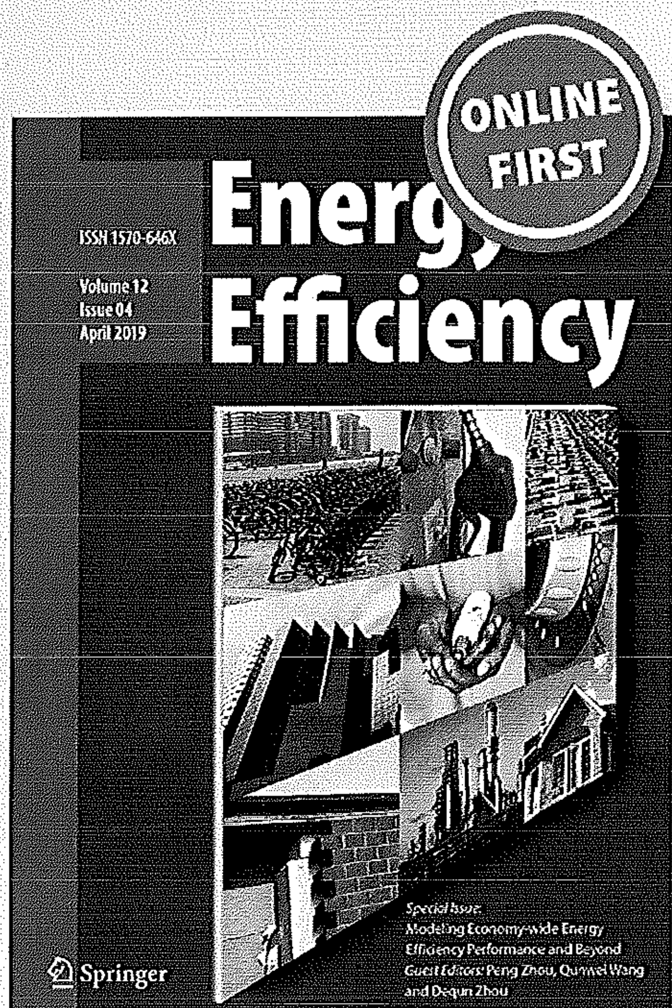

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ORIGINAL ARTICLE

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Capturing the true value of trees, cool roofs, and other urban heat island mitigation strategies for utilities

Kurt Shickman · Martha Rogers

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Abstract A growing body of research values the broad benefits of cooling down cities, such as improved energy efficiency, worker productivity, air quality, health, and equity, at hundreds of millions or even billions of dollars to a single city. However, widespread adoption of urban heat mitigation programs, such as urban greening and reflective surfaces, has been slower than their economic potential suggests it should be. One possible cause for this lag is a lack of robust engagement from important stakeholders like utilities that could fund and implement heat mitigation strategies. This paper highlights the benefits of urban heat mitigation and demonstrates how these benefits fit into private utility programs' standard cost–benefit tests. This paper serves as an introduction on how to include the wide suite of benefits that urban heat mitigation programs provide in cost–benefit tests and concludes with program design guidance.

Keywords Cool roofs · Utilities · Trees · Vegetation · Urban heat island

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Introduction

Rising urban heat is a critical challenge that negatively affects energy use, air quality, quality of life, economic prosperity, and social equity, to name a few. Nearly nine out of ten Americans live in an urbanized area (UNDP 2008) and, on average, urban spaces are heating up at twice the global rate (McCarthy et al. 2010). In the USA, the Fourth National Climate Assessment estimates, with high confidence, that urban heat islands lead to daytime air temperatures 0.9–7.2 °F (0.5–4.0 °C) higher and nighttime air temperatures 1.8–4.5 °F (1.0–2.5 °C) higher in urban areas compared to rural areas, with wider differences in humid regions, larger cities, and areas with higher population density (Wuebbles et al. 2017). The effects of this air temperature disparity will increase as cities grow; by 2050, nearly 70% of the world's population is expected to live in cities, up from 50% in 2007 (UNDP 2008). A recent study of 1700 cities finds that unchecked urban heat will impose a nearly 6% "tax" on the economic output of the median city by 2100 (Estrada et al. 2017).

Energy providers are faced with the challenge of meeting rising energy demand that is partly caused by this warming world. Akbari (2005) shows that electricity demand for cooling increases 1.5 to 2.0% for every 1 °F (0.6 °C) increase in air temperature, starting from 68 to 77 °F (20 to 25 °C). Similarly, Santamouris et al. (2015) finds that every 1 °F (0.6 °C) of temperature increase is associated with 0.25 to 2.5% increase in peak electricity demand. These results hold up when considering electricity demand in a single city; Fig. 1 plots

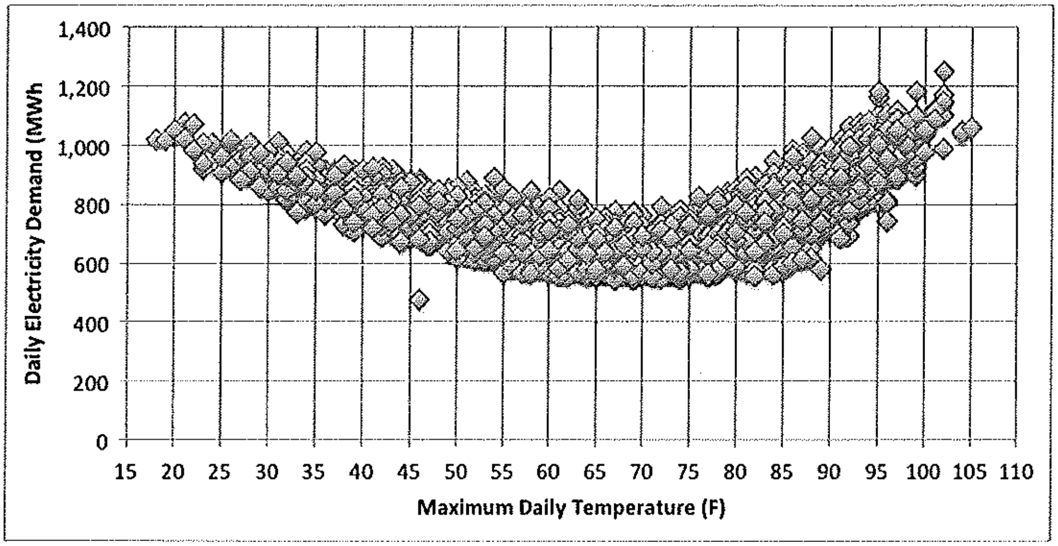

Fig. 1 Max daily temperature versus daily electricity demand for Washington, DC (2009–2017). A day with maximum daily temperatures of 85F and 95F will increase electricity demand by 27% and 55%, respectively. Source: Weather Underground, PJM Interconnection

electricity demand in Washington, DC, against the maximum temperature every day for 6 years (2009–2016). Demand for electricity climbs rapidly above 75 °F (24 °C). When the maximum temperature is 85 °F (29 °C), the city requires 27% more electricity, on average, than on 75 °F (24 °C) days. At 95 °F (35 °C), demand has spiked by nearly 55% over the 75 °F (24 °C) baseline. The graph's shape looks very similar to plots from other cities with high penetrations of air conditioning.

As urban heat islands get more intense in the coming decades, electricity demand in cities will grow which will affect electricity costs and system efficiency. Kolokotroni's (Kolokotroni et al. 2012) study of London's urban heat island suggests that cooling costs in the city could rise as much as 30% by 2050. Bartos et al. (2016) finds that by mid-century (2040–2060), increases in ambient air temperature may reduce average summertime transmission line efficiency by 1.9–5.8% relative to the 1990–2010 reference period. Peak per-capita summertime loads may rise by 4.2–15% on average due to increases in ambient air temperature. Consequently, cost-effective strategies to mitigate urban heat are critical for meeting future energy needs.

This paper focuses on the deployment of highly reflective surfaces and "urban greening" to reduce urban heat, approaches we collectively dub "cool city strategies." Cool, reflective, materials on roofs, walls, and pavements facilitate urban temperature reductions by reflecting a greater degree of solar energy away from surfaces and minimizing heat gain compared to a traditional dark surface. Urban greening, through forestry, green roofs, and other plant-based strategies, cools via evapotranspiration and by increasing shade cover.

How much cooler could our cities become with cool city strategies?

Santamouris (2014) provides a comprehensive review on cool city strategies and finds that when an overall increase in a city's surface solar reflectance is considered, the expected mean decrease of the average ambient temperature is close to 0.5 °F (0.3 °C) per 0.1 increase in solar reflectance,[1] while the corresponding average decrease of the peak ambient temperature is close to 1.6 °F (0.9 °C). Cool roofs also reduce air temperatures at a height 2-m above the surface (or roughly head height at 6.5 ft) by increasing the reflection of incoming solar radiation. Li et al. (2014) shows that green roofs with relatively abundant moisture cooled 2-m height ambient air temperatures by up to 6 °F (3.5 °C) over the Baltimore, Maryland–Washington, DC metropolitan area,

[1] Solar reflectance is measured on a scale of 0 to 1. A surface with a 0 solar reflectance rating would absorb all solar energy. A surface with 0.5 solar reflectance would reflect 50% of the solar energy that contacts it and absorb the other 50%.

and a cool roof with a solar reflectance of 0.7 reduced 2-m height ambient air temperatures by 5 °F (3 °C).

More broadly, higher solar reflectance may lead to regional air temperature reductions. Campra (2011) compares weather station data in the Almeria region of Spain to similar surrounding climatic regions. Almeria has a unique tradition of whitewashing its greenhouses and thus reflects more sunlight than neighboring regions. Over the 20 years in the study, researchers find that average air temperatures in Almeria have cooled 0.7 °F (0.4 °C) compared to an increase of 0.6 °F (0.3 °C) in the surrounding regions lacking whitewashed greenhouses.

Urban greening affects local air temperatures via transpirational cooling and shading. Transpirational cooling refers to the process by which trees cool the surrounding air as they transpire, e.g., when trees convert water from a liquid to a vapor. Shading refers to a tree's ability to block the sun's rays from striking and heating impervious surfaces, such as sidewalks. McDonald et al. (2014, p. 29) review 17 studies and show that street trees can cool surrounding areas anywhere from 0.7 °F (0.4 °C) to 5.4 °F (3.0 °C). Gromke et al. (2015) finds that tree-lined avenues in Arnhem, the Netherlands, lower the mean temperature by 0.7 °F (0.4 °C) with a maximum temperature reduction of 2.9 °F (1.6 °C). Ma and Pitman (2018) shows that, in combination, green roofs and cool roofs can reduce 2-m ambient air temperatures by 5–7 °F (3–4 °C) depending on the building characteristics, urban environment, and meteorological and geographical conditions.

Why focus on utilities?

Utilities are already implementing energy efficiency programs as a means of reducing peak energy demands, energy use, and lowering emissions. For example, in 2007, Minnesota passed the Next Generation Energy Act requiring electric utilities to invest 1.5% of their in-state revenue in efficiency savings for households and businesses. Taking the broader case of energy efficiency programs, utility spending on electric efficiency programs grew from $1.6 billion in 2006 to $6.3 billion by 2015, a nearly 300% increase in just 9 years (Berg et al. 2018). These utility expenditures have borne fruit, with projections that efficiency could save as much as a third of the US electrical service demand by 2030 with continued policy implementation or the equivalent of 487 power plants of capacity (Molina et al. 2016).

Cool city strategies are effective strategies to mitigate urban heat and reduce energy demand. To date, however, their implementation has not been rooted in a scalable process that effectively conveys the costs and benefits of these strategies. Utility funding of heat resiliency has been hampered by split incentives, the fact that heat policy has not been a priority for city officials, and, until recently, a relative lack of research into quantifying the co-benefits of heat mitigation for utilities and society as a whole. While cool roofs are incorporated into some programs as a prescriptive approach or a whole-building performance approach, a broad use of cost–benefit tests on cool city strategies has yet to be implemented by utilities. This lack of consideration has led to cool city strategies being undervalued in the market and assigned a lower priority than many other energy efficiency programs.

A similar utility commitment to cool city strategies as utilities make to other energy efficiency programs could unlock large co-benefits in energy demand, air quality, social equity, health, and economic prosperity. While there are examples of utility programs that support cool city strategies, such as Los Angeles' cool roof incentive program, these programs are limited. Thus, there is a need to better articulate the effects of cool city strategies in the context of utility program cost tests to promote their broader adoption in renewable energy and climate change goals. This paper summarizes quantifiable benefits of cool city strategies and evaluates how these effects would fit into some common utility cost test models.

Utility cost tests are a regulated methodology for determining whether a particular program is cost-effective and appropriate for the utility to implement. Each utility cost test prioritizes a different stakeholder's perspective and what key question they are seeking to answer. These differing considerations affect the breadth of costs and benefits included in each test. We focus on three utility cost tests: the utility cost test (UCT), the total resource cost test (TRC), and the societal cost test (SCT).[2] Table 1 summarizes these three tests, and their use across the USA (NESP 2017) provides a

[2] In this paper, we omit a specific discussion of two other standard cost–benefit tests: the participant cost test and the ratepayer impact measure test. These two tests represent the perspectives of the program participants and non-participants, respectively, which are both included in the total resource cost. Thus, the relevant benefits and costs for these two tests will be discussed in relation to the total resource cost test.

Table 1 Utility cost tests covered in this paper. Source: Woolf et al. 2012, p. 14; National Action Plan for Energy Efficiency 2008, Table 2-2; and Woolf et al. 2017

Test	States using (primary)	Perspective	Benefits covered in this paper
Utility cost test (UCT)	28 (5)	Utility provider	(1) Avoided energy costs, (2) peak demand reduction, (3) increased grid reliability/lower transmission and distribution costs
Total resource cost (TRC)	36 (29)	Program and non-program participants	Above plus (1) energy/capacity price suppression, (2) participant non-energy benefits and effects on low-income communities
Societal cost test (SCT)	17 (6)	Society	Above plus (1) water effects, (2) air quality, (3) health, and (4) other

comprehensive explanation of how utilities typically evaluate energy efficiency investments via cost-effectiveness testing.

The costs and benefits associated with energy efficiency programs will be most narrowly drawn in the UCT and most expansive in the SCT. This paper focuses on the benefits that are unique to cool city strategies as an energy efficiency program. We have omitted discussion of the costs and benefits of cool city strategies that would be a part of cost tests for other utility energy efficiency programs, including program administrative and incentive costs, participant and third-party contributions, energy and water bill savings, and reduced energy-generation emissions from lower energy use.

Utility cost test

The UCT determines whether a program adds to or reduces the private utility's cost to operate its system, including both variable and fixed costs. Variable costs refer to the operations and maintenance costs incurred for the transmission of each kilowatt hour of electricity to a home or business. Fixed costs, or capacity costs, relate to investments in the generation capacity of the entire electric grid. Cool city strategies reduce both variable costs—by decreasing the amount of electricity being delivered in the system—and capacity costs—by avoiding the need to invest in new generation capacity.

Avoided energy costs

Avoided energy costs are the most straightforward benefit of cool city strategies as they directly result from their ability to reduce the ambient air temperature. Pomerantz et al. (2015) finds that increasing solar reflectance of urban surfaces would reduce energy demand by an average of 2 kWh per modified meter squared. Taking the example from Washington, DC, above, each 1 °F (0.5 °C) temperature reduction above 77 °F (25 °C) reduces the need to produce 19,000 MWh of energy. Studies indicate that cool roofs reduce annual cooling energy use by up to 20% (Haberl and Cho 2004). In some cooler parts of the USA, a portion of the cooling energy savings is offset by increases in winter heating energy requirements. Most studies, however, find that this so-called winter heating penalty is minimal, even in the coldest climates (Hosseini and Akbari 2016).

An early study showed that a single 25-ft tall tree can reduce a household's annual heating and cooling costs from 8 to 12% (McPherson and Rowntree 1993). A more recent review on the subject showed that street trees can reduce annual energy costs anywhere from \$2.16 per tree per year to \$64 per tree per year, depending on local climatic conditions (Mullaney et al. 2015). In addition to providing transpirational cooling and shading, urban greening may reduce building energy needs by buffering ambient wind speeds, which will be especially pronounced in the winter months (Akbari 2002).

Peak demand reductions

The electric grid must be designed to meet electricity demand 24-h a day, particularly at times of peak demand, which varies by both the time of day and the season. Daily demand for electricity tends to peak during the day in business areas and during the evening hours in residential areas. Seasonally, in most regions,

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electricity demand peaks during the summer months when households and business run their air conditioning units. Average daily demand for electricity in the summer typically begins to rise in the early afternoon and peaks in the late afternoon or evening. Cool city strategies are particularly good at reducing summer peak demand because their energy reduction benefits occur when the sun is strongest and temperatures are highest. Peak demand reductions from cool city strategies average 1.6 °F (0.9 °C) and can help utilities avoid electrical transmission and distribution costs by avoiding heat-related line losses (Santamouris 2014). Pomerantz (2018) estimates that increase in roof and road solar reflectance would reduce maximum peak power demand by up to 7%.

Hoff (2014) evaluates cool roofs' ability to deliver energy cost savings by reducing peak demand charges for commercial and industrial customers. Figure 2 summarizes Hoff's (2014) energy cost savings analysis by climate zone, which can lead to significant savings for commercial, industrial, institutional, and, in some cases, residential buildings across the USA. Demand charges are typically based on the maximum energy demanded (measured in kilowatts) in a given time period, rather than on the total amount of power demanded (measured in kilowatt hours). For some customers, the peak charge can be 50% or more of the total bill. Hoff notes that despite the energy cost savings across the USA the economic effect of reduced peak energy usage is often omitted from cost–benefit calculations.

While the peak demand reductions of cool city strategies are largest during the periods of greatest cooling demand, they are not "dispatchable" in the same way as other demand response programs. Because some utilities do not count demand response unless its timing can be controlled, there is a chance that this substantial benefit of cool city strategies is not being counted.

ASHRAE Climate Zone	Annual Net Peak Energy Cost Savings	
	Low Range	High Range
1	$1,640	$3,040
2	$1,340	$2,250
3	$1,270	$1,870
4	$950	$1,490
5	$800	$1,220
6	$620	$1,150
7-9	$280	$880

Fig. 2 Net peak energy savings (cooling energy savings less increases in heating energy demand) by climate zone (20,000 ft^2 building). Source: Energy Information Agency and Hoff 2014

Increased grid reliability, lower transmission, and distribution costs

Cool city strategies can improve the efficiency of certain types of generation. High ambient air temperatures lower atmospheric pressures and oxygen concentrations and reduce the fuel efficiency of natural gas, oil, and nuclear electricity generation assets (Rademaekers et al. 2011). Transmission and distribution systems, like generation facilities, lose efficiency in high temperatures; as metal electrical resistance increases, electric flow decreases due to lower hanging transmission lines and other factors (Ward 2013). The transformers' capacity declines 1% for every 1.8 °F (1 °C) increase in air temperature and in copper lines for every 1.8 °F (1 °C) increase in air temperature the resistance increases 0.4%. Overall, network losses increase 1% for every 5.4 °F (3 °C) increase in air temperature; these increases occur in systems that already have initial losses of 8% (Rademaekers et al. 2011). Dr. Ray Klump highlights these unique challenges of heat on the electric grid in his article, "Why Does Hot Weather Cause Power Outages" (Lewis University 2013): "In other words, there are some rather nasty feedback mechanisms that take place that cause the grid a lot of stress when we all turn our air conditioners on. Power system operators traditionally have had a very limited number of controls to counteract these bad behaviors."

Total resource cost test

The TRC is primarily interested in determining how a program adds to or reduces costs for utility customers—both program participants and non-participants. The benefits of cool city strategies applicable to the UCT are also considered in the TRC. Regulators using the TRC could also consider several additional benefits when evaluating cool city strategies, such as price suppression and positive effects on program participants and low-income customers.

Energy/capacity price suppression

In jurisdictions with competitive wholesale energy and/or capacity markets, prices will be a function of the magnitude of demand. Thus, increased investment in energy efficiency resources benefits all consumers through its dampening of demand for electricity, which will reduce market clearing prices (at least to some extent and for some period of time). Conversely, extreme heat can push wholesale energy prices far above normal levels. For example, an August 2011 heat wave in Texas produced day-ahead, on-peak wholesale power prices in the Electric Reliability Council of Texas (the wholesale market operator for most of the State) that were five to six times higher than prices in the previous five Augusts (U.S. Energy Information Agency (EIA) 2011).

Participant non-energy benefits and effects on low-income communities

The TRC may also value some non-energy benefits such as water quality or health improvements that accrue to program participants. These non-energy benefits are discussed in more detail in"Societal cost test."

Cool city strategies reduce energy use that can strengthen the finances of middle- and lower-income households (whose energy bills can be 10% to over 50% of their monthly expenses) and help utilities reduce credit and collection costs (Drehobl and Ross 2016; and Chandler 2016). Improving building comfort and efficiency also has significant effects on middle- to low-income families and communities of color. Jesdale et al. (2013) show that low-income, minority communities tend to experience the worst effects of heat due to a lack of vegetation, old housing stock, and other factors. Reducing these costs is a non-trivial way to improve the economics of the most vulnerable families.

Societal cost test

The SCT considers the broadest set of effects of cool city strategies. Regulators using the SCT to evaluate cool city strategies could include all of the effects described above, as well as a number of other substantial societal benefits that are highlighted below.

Water quantity and water quality effects

Urban greening efforts reduce stormwater runoff in cities. Stormwater from cities often contains harmful pollutants, such as nitrogen and phosphorus from fertilizers and pet and yard waste, which can then be directly discharged into nearby surface water. Trees not only draw water from the soil for photosynthesis but will also absorb other harmful pollutants from the soil and intercept rainfall, causing less rain to hit the ground. Armson et al. (2013) find that trees can reduce runoff from asphalt by as much as 62%.

Air quality effects

Cool city strategies positively impact air quality in three key ways. First, the energy efficiency benefits of cool city strategies directly reduce pollutants emitted from power plants in many parts of the country. Levinson and Akbari (2010) details this benefit down to a zip code level for the USA.

Second, reduced ambient air temperature lowers the likelihood that smog and ozone will form. There is a very clear link between heat and smog formation, so lowering air temperatures can go a long way to reducing the formation of smog (Kenwood 2014). The relationship between heat and smog formation is not linear. Similar to energy use, there is a threshold air temperature, often between 75 and 80 °F (24 °C and 27 °C) that triggers smog formation. That means that every small reduction in air temperature, especially on warmer days, can have a significant impact on air quality. Ozone pollution is a major contributing factor to respiratory illness. The World Health Organization (2018) predicts ozone pollution will be the third leading cause of death by 2030. Traditionally, air quality improvement efforts have focused on reducing the emission of those precursor chemicals, but turning down urban air temperatures would also play an important role.

Third, urban greening removes particulate matter from the atmosphere through a process known as dry deposition. Dry deposition is when the particulate matter deposits itself on the tree's surface, where most of it becomes incorporated into leaf wax or cuticle, and is thus removed from the air. Nowak et al. (2013) surveys ten cities in the USA and finds that, in some cities, trees currently remove as much as 64 t of fine particulate matter measuring less than 2.5 μm in diameter ($PM_{2.5}$) a year. More broadly, a review of seven different scientific studies by The Nature Conservancy found that urban trees reduce nearby concentrations of $PM_{2.5}$ anywhere from 9 to 50% with the largest effects within 30 m of the tree (McDonald et al. 2014, p. 29).

Health effects

Cool city strategies improve health outcomes via improved air quality and improved water quality. The SCT values beneficial health effects that accrue to society at large—including individuals participating in a utility program and those that are not participating. Reducing urban heat can have a wide variety of benefits to health, including reduced heat stress and improved outcomes for people suffering from diseases of the heart, lungs, kidney, or diabetes (Martin Perera et al. 2012). Most importantly, cool city strategies can substantially reduce deaths during extreme heat days. Kalkstein et al. (2013) finds that a 0.1 increase in urban surface solar reflectance could reduce the number of deaths during heat events by an average of 6%. Similarly, he finds that a 10% increase in vegetative cover to the city yields and, on average, a 7% reduction in mortality during heat events.

A number of programs have demonstrated that reflective surfaces can reduce indoor air temperatures. In Philadelphia, the Energy Coordinating Agency upgraded rowhomes with a white roof coating and taught residents the proper use of window fans. They find air temperature reductions from these upgrades in the upstairs rooms of 5 °F (2.7 °C) (Kim 2006).

As noted in the previous section, urban greening efforts reduce the concentrations of particulate matter in the atmosphere, which lowers the risk of cardiovascular and heart disease. Fine particulate matter, measuring less than 2.5 μm in diameter (e.g., $PM_{2.5}$), is the most harmful as their small size allows them to lodge deep inside the lungs. In a survey of nearly 1600 cities, the World Health Organization (2018) finds that only 12% of the urban population lives in areas that are below recommended $PM_{2.5}$ levels. Over 700,000 premature deaths globally each year are attributed to exposure to $PM_{2.5}$ (The World Health Organization 2018). Anderson et al. (2012) review the literature from the last 30 years on the health effects of $PM_{2.5}$ and conclude that the particles have a "consistent and significant" effect on human health, most prominently through their link to cardiovascular disease, that results in a "large global public health burden" (p. 172). McDonald et al. (2014, p. 29) estimates that tree planting could reduce $PM_{2.5}$-related deaths by as much as 8%, not considering potential reductions in other cardiovascular diseases.

Limiting the scope of health effects to avoided deaths, cool city strategies have the potential to generate large monetary savings; the U.S. Environmental Protection Agency (EPA) (n.d.) values a statistical life at $9.2 million (2016 USD) to measure mortality risk reductions in its own cost–benefit analyses. For example, Mills and Kalkstein (2009) evaluate Philadelphia's urban heat mitigation plan and find that reduced mortality from extreme heat would be valued between $0.74 billion and $1.69 billion ($2006).

Other benefits

Urban heat, if left unchecked, will increase the cost of climate change for cities by 260% by 2100. Estrada et al. (2017) study 1700 cities and find that local climate change and urban heat will cost the median city approximately 5.6% of their gross domestic product (GDP)—a price tag measured in hundreds of billions or even trillions of dollars globally.

Even at moderate levels of deployment, cool city strategies can deliver energy savings, peak electricity demand reductions, improvements to health and air quality, and other benefits accruing from installations that are worth billions of dollars to local economies. Increasing the solar reflectance of just 20% of a city's roofs and half of its pavements could save up to 12 times what they cost to install and maintain and reduce air temperatures by about 1.5 °F (0.8 °C) (Estrada et al. 2017). For the average city, such an outcome would generate over a $1 billion in net economic benefits and is a very realistic target if existing cool city strategies best practices are adopted.

The improvements in air quality resulting from reductions in urban air temperatures that are possible from moderate deployment of cool city strategies also have a substantial economic benefit. Akbari (2005) summarizes some of the economic impact studies of reduced health care costs and improved productivity that result from reducing air temperatures in cities. McDonald et al. (2014) points to similarly substantial economic benefits from improved air quality. One analysis finds that converting a 1 ft^2 of dark roof to a reflective surface would generate $2.67 ($29.02 per m^2) of economic benefit,

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just from reduced particulate and ozone concentrations (Kats and Glassbrook 2016). Overall, Kats and Glassbrook (2016) find a cool roof delivers over $5 a square foot ($54 per square meter) in net benefits. Kardan et al. (2015) finds that people that live in areas with higher densities of trees have higher health perceptions; the addition of ten trees on a city block can improve an individual's health perception in a way that is comparable to a $10,000 increase in annual income.

Other effects of heat on utilities

This paper focuses on making the case for customer-focused programs to reduce excess heat through the lenses of various cost-effectiveness tests. This section looks at some additional reasons why utility efforts to mitigate excess heat would make sense.

Improving accuracy of capital planning

Heat mitigation efforts may be viewed as part of a bigger strategy to reduce utility capital investment requirements. Changes in local climates, particularly rapid heating, will dramatically impact demand for energy in the future. Globally, the demand for air conditioning will require a multi-trillion dollar investment in new generation that will equal the installed capacity of the USA, Europe, and India combined (Organization of Economic Cooperation and Development (OECD) and International Energy Agency 2018). There is increasing understanding that the climate prevalent historically will likely not reflect the climates of the future and that "back-casting" for demand predictions will systematically underestimate the energy needs of the future. As efficiency programs have long demonstrated, it is less expensive to not produce a kilowatt-hour than to produce one.

Reduced utility business risk

Beyond the grid resilience effects noted in the program section above, heat mitigation programs can benefit utility efforts to reduce wildfires and effects of planned and unplanned outages on customers and potentially reduce utility liability risks from wildfires. In 2018, the State of California determined that electric power and distribution lines, conductors, and power poles caused 12 wildfires in Northern California in 2017 (California Department of Forestry and Fire Protection 2018). Williams et al. (2015) showed that nighttime increases in surface temperature, driven, in part, by urbanization, were associated with increased cloud height and a reduction in fog occurrences in the Los Angeles area. Reduced cloud cover has been associated with increased risk of wildfires in the same area (Williams et al. 2018).

Reduced credit risk

A number of the effects of excess urban heat included in the cost-effectiveness tests could also have an impact on the credit risk of the utility itself. On the balance sheet, excess heat puts transmission and distribution infrastructure at greater risk of failure that could result in impaired assets for the utility. The burdens of financing new generation to meet cooling energy demand may have negative effects on borrowing capacity and increase liabilities. The broader negative economic impact of unchecked urban heat will limit willingness and ability of customers to support future rate increases. If utilities have a harder time securing timely rate increases to fund the necessary generation capacity needed to meet unchecked urban heat, it could leave them in a challenging performance dilemma. Investor organizations such as the Institutional Investors Group on Climate Change and the Investor Network on Climate Risk have called on utilities to undertake "stress tests" to assess how their portfolio and practices will contribute to limiting global temperature increases to under 2 °C in order to manage carbon asset risk. Programs contributing to urban heat mitigation could contribute to a utility's performance on such a stress test (Investor Network on Climate Risk 2016). Implementing even marginal steps to reduce the need for climate regulation will be a valuable mitigation effort. Taken together, these factors could weigh negatively on risk assessments by credit rating agencies and have substantial effects on the viability of utilities.

High level recommendations

Rebate programs

Rebates can help defray the cost premium that still exists for certain types of cool roof options over traditional ones (primarily in asphalt shingle markets). While rebates have been paid out of general municipal funds in some places (e.g., Louisville, Toronto), they have been funded out of utility funds in others (e.g., Los Angeles Department of Water and Power, Pacific Gas and Electric, Sacramento Municipal Utility District, Progress Energy Florida, Public Service Enterprise Group Long Island). The Cool Roof Rating Council website has gathered an even larger number of municipal and state government programs that subsidize cool roofs as part of broader residential and commercial energy performance programs (Cool Roof Rating Council n.d.).

Tree planting and maintenance programs

To date, a number of public utilities have adopted shade tree programs. The oldest and the largest of these programs is the Sacramento Shade Tree Program, commonly referred to as Sacramento Shade, which began in 1990. To date, Sacramento Shade has planted over half a million trees throughout Sacramento County. Sacramento Shade continues to run today; current Sacramento Municipal Utility District (SMUD) customers are eligible for up to ten free shade trees for their property (SMUD 2018). Ko et al. (2015) analyzed 22 years of tree survival, tree growth, and energy savings related to the program. The authors found that Sacramento Shade had a 22-year post-planting tree survival rate of 42% and that annual energy savings related to the program were 107 kWh per property and 80 kWh per tree. Since 1990, other utilities have followed suit and adopted their own shade tree programs, such as Salt River Project (AZ), Cedar Falls Utilities (IA), Tacoma Public Utilities (WA), Burbank Water and Power (CA), Columbia Water & Light (MO), and Riverside Public Utilities (CA).[3] To date, there are far fewer examples of shade tree programs being adopted by private utilities which is, in part, a sign of reluctance to incorporate trees into cost–benefit analyses.

Customer outreach and awareness

Roofing decisions are infrequent and, particularly for residential customers, informed solely by the contractor doing the work. Utilities have unique access to customers in the form of the monthly bill that could be leveraged to message cool roofing options. Utilities may also message cool roofing as part of a number of efficiency improvements that can help building owners reduce monthly costs or to qualify for whole building energy performance incentive programs. There is a similar opportunity related to trees. In order for trees to be most effective at reducing energy costs, the appropriate tree must be selected and it must be planted in the appropriate place. For example, one needs to ensure that the mature height of tree is enough to provide adequate shade and that the tree is placed in the best location for residential shading. To help overcome these challenges, many of the public utility shade tree programs require participating households to receive a home visit from a trained arborist or forester who helps them choose the appropriate location for the tree. In Burbank, CA, participating households are charged $90 if they do not plant their shade tree in the pre-determined site (Burbank Water and Power 2019, see footnote 3). Mailed coupons can also make it easy for households to participate in a shade tree program. In Cedar Falls, IA, residential customers are only required to ask the retailer for the "Cedar Falls TREES Plant-A-Tree" discount when purchasing a tree from a participating retailer (Cedar Falls Utilities 2019, see footnote 3). In all cities, engaging households so that they understand the importance of shade trees, and how to best care for their shade trees, is critical to the success of the program.

Participating in inter-agency collaborations

A number of cities, including Los Angeles, New York, Louisville, and Washington, DC, have established multi-agency platforms for evaluating and acting on the challenge of excess heat. These efforts are organized in a variety of different ways, ranging from informal working groups to official technical advisory groups. Utilities have an important role to play in the process by providing energy data, access to customer communications channels, and implementation options.

[3] Examples are based on a review of utility websites. See: Salt River Project: https://www.srpnet.com/energy/rebates/shadeTrees.aspx; Cedar Falls Utilities: https://www.cfu.net/save-energy/shade-tree-discounts/; Tacoma Public Utilities: https://www.mytpu.org/save-energy-money/shade-tree-program.htm; Burbank Water and Power: https://www.burbankwaterandpower.com/incentives-for-residents/shade-tree-program; Columbia Water and Light: http://www.columbiapowerpartners.com/residential/residential-tree-power/; and Riverside Public Utilities: https://www.riversideca.gov/utilities/pdf/NewsLetter/2016/March-2016-Back-of-Bil.pdf. Last accessed March 4, 2019.

Conclusion

Cool city strategies offer energy efficiency improvements with a broad and substantial set of additional co-benefits but, currently, are not widely implemented through private utility programs. In addition to the benefits of reduced energy use, cool city strategies deliver societal benefits such as health improvements, air and water quality improvements, and enhanced resiliency to climate change. This paper highlights the direct and measurable benefits unique to cool city strategies as an energy efficiency program, such as base and peak energy demand reductions, energy price suppression, and utility system resiliency, and layers on additional utility-relevant benefits to health, air and water quality, stormwater management, and equity. Taken together, the benefits of cool city strategies present a significant economic opportunity for utilities and their customers. Future work to refine designs for cool city utility programs with this body of research in mind is a priority next step.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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