

# **Faster Warming in U.S. Urban Areas and its Potential Effect on the Demand and Cost for Residential Heating and Cooling**

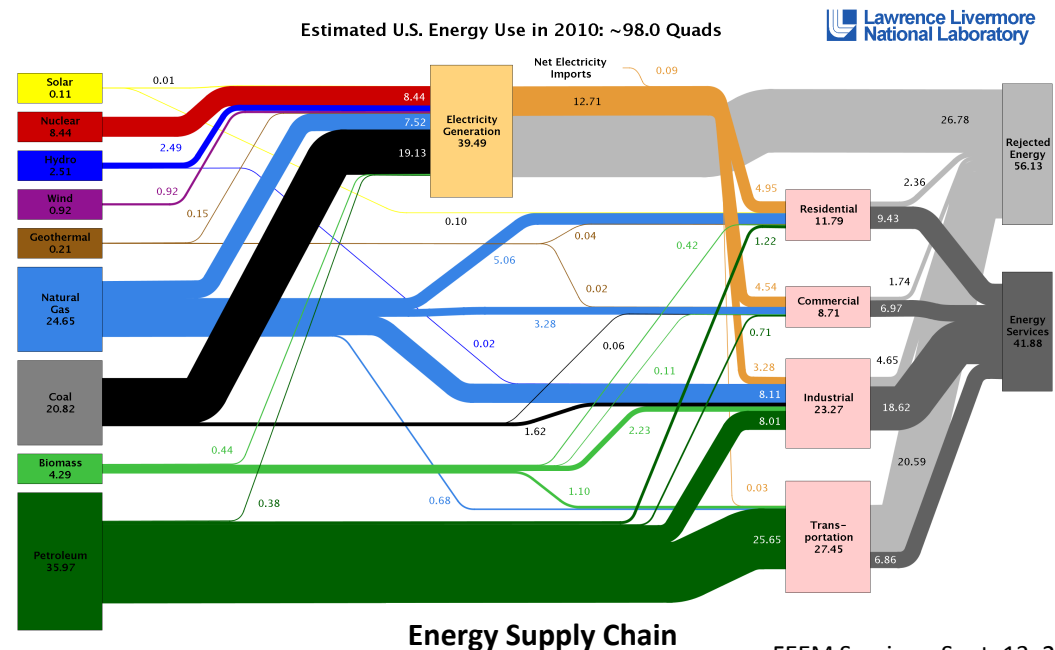
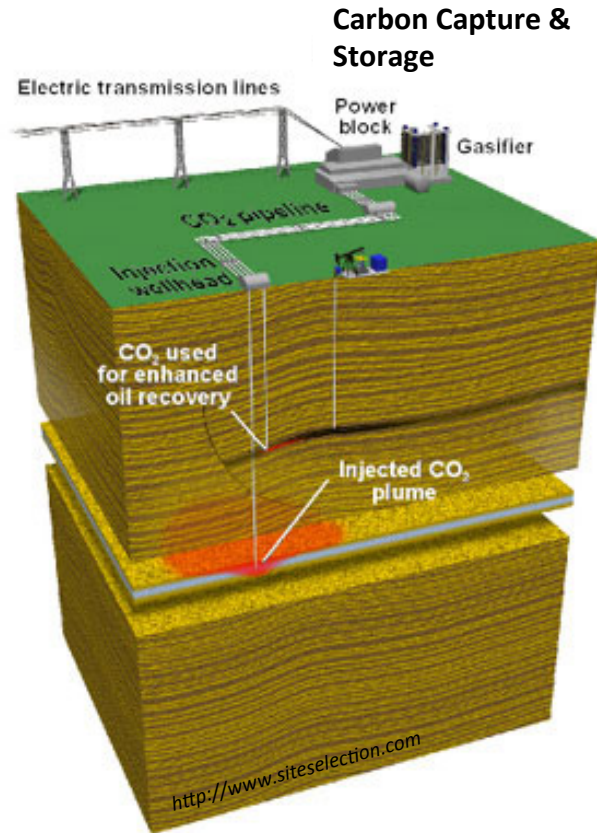


<http://www.panoramio.com>

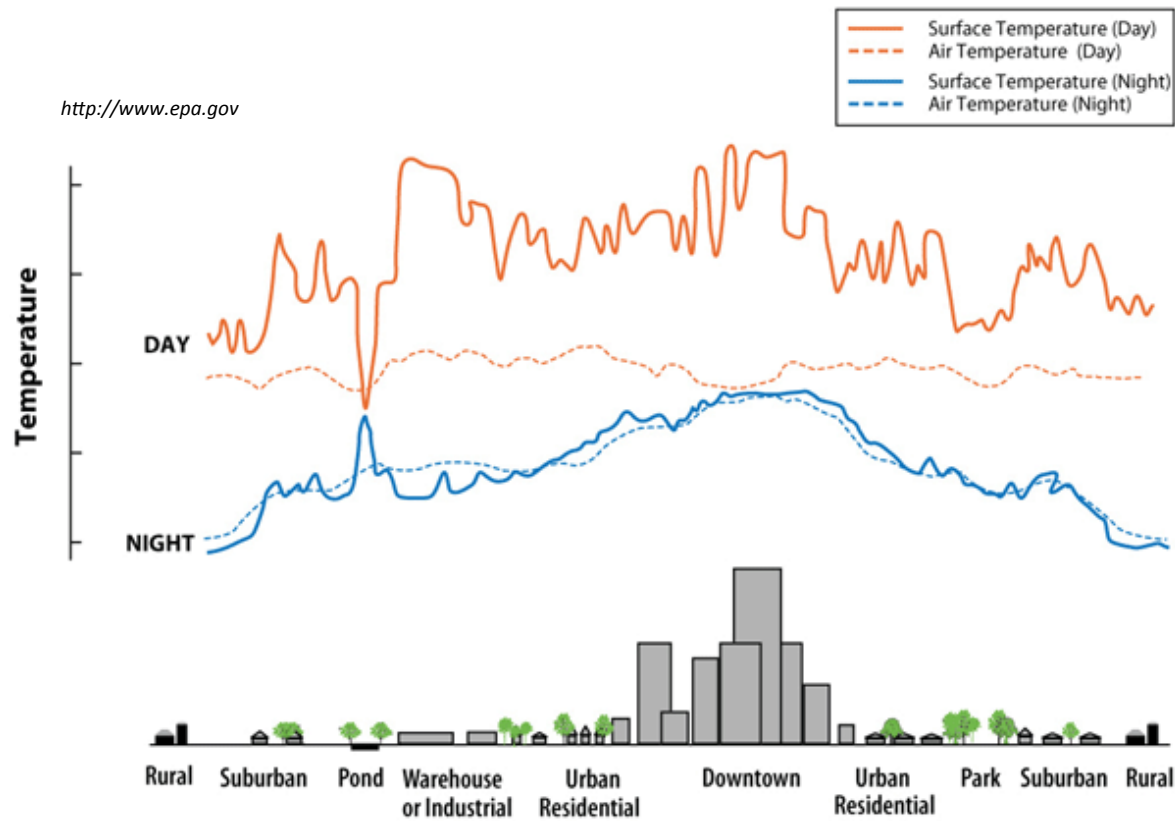
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Nicholas School of the Environment  
Duke University, Durham, NC 27708 USA

# My Research Interests

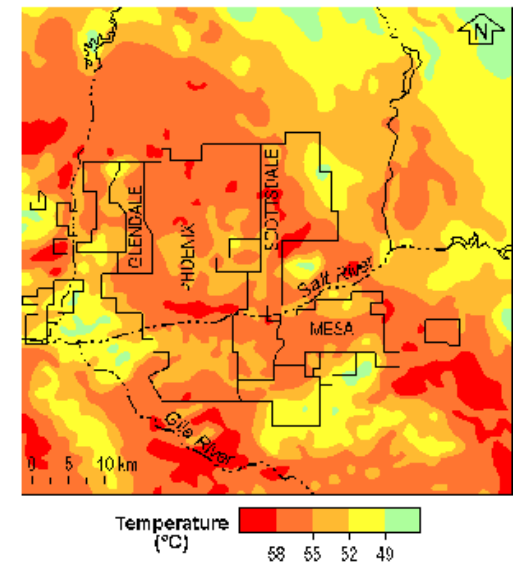
## Energy Storage & Integration of Renewable Energy into the Grid



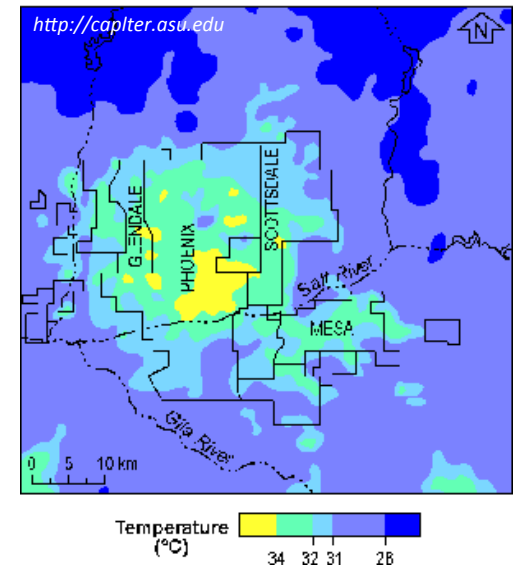
# The Urban Heat Island Effect



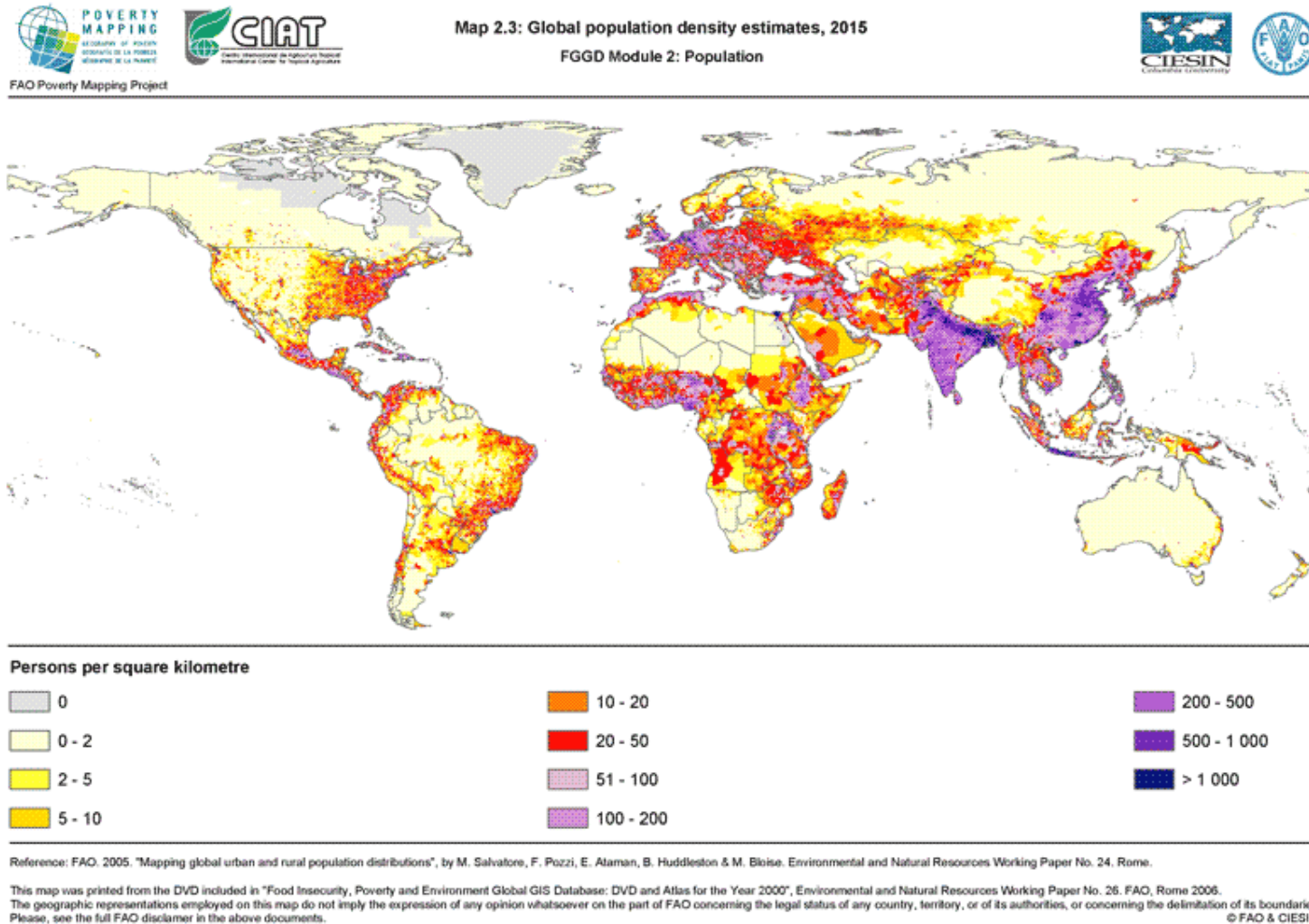
A. Day



B. Night

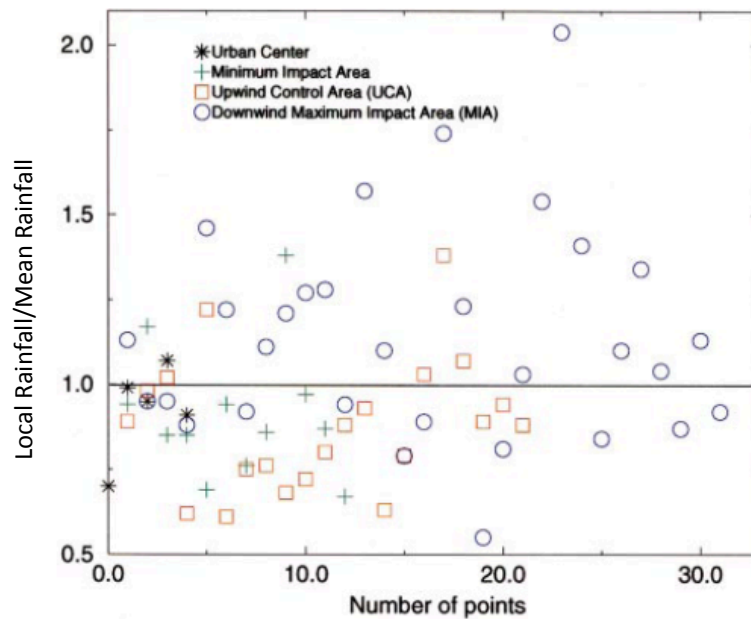


# Urbanization

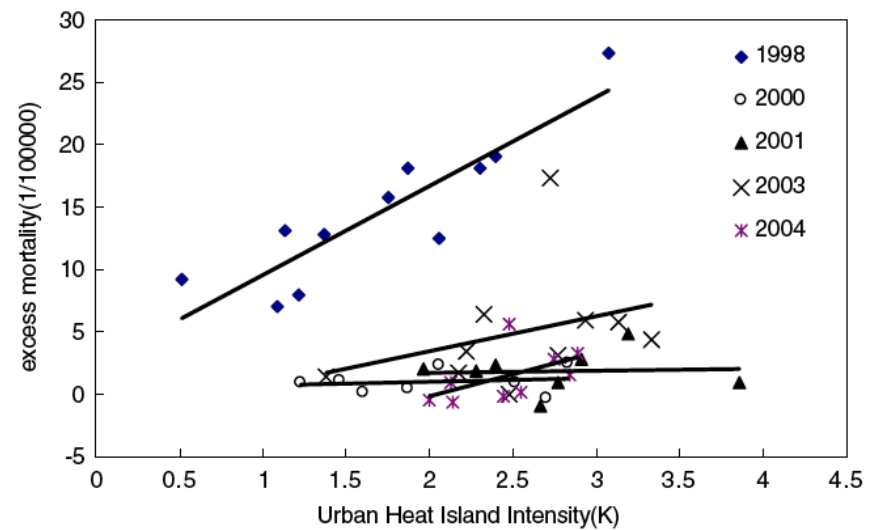




# Local Impacts on Local Climate and Health

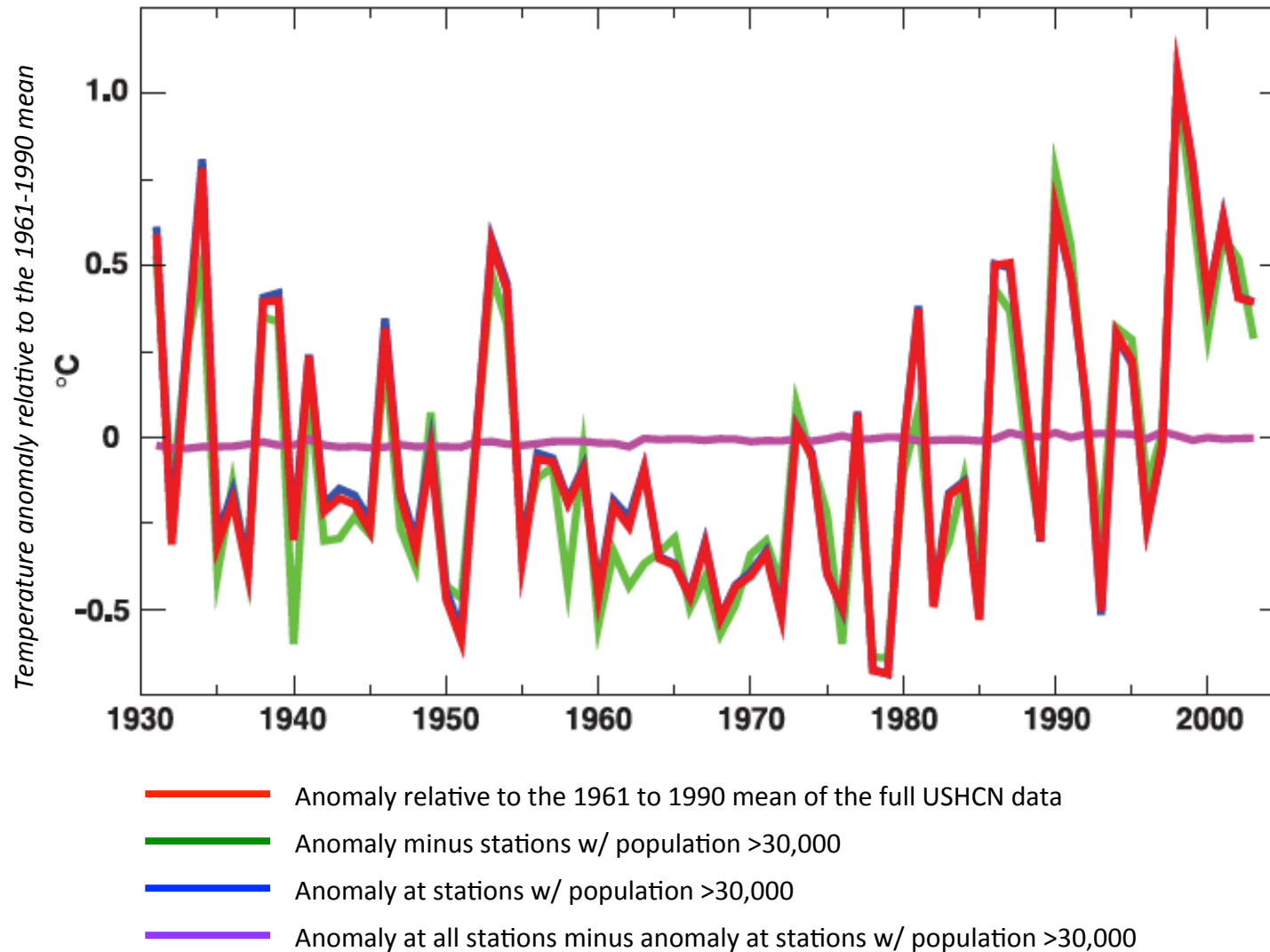


Shepherd, J., Pierce, H., and Negri, A. (2002). Rainfall modification by major urban areas: observations from spaceborne rain radar on the TRMM satellite. *Journal of Applied Meteorology*, 41, 689-701.



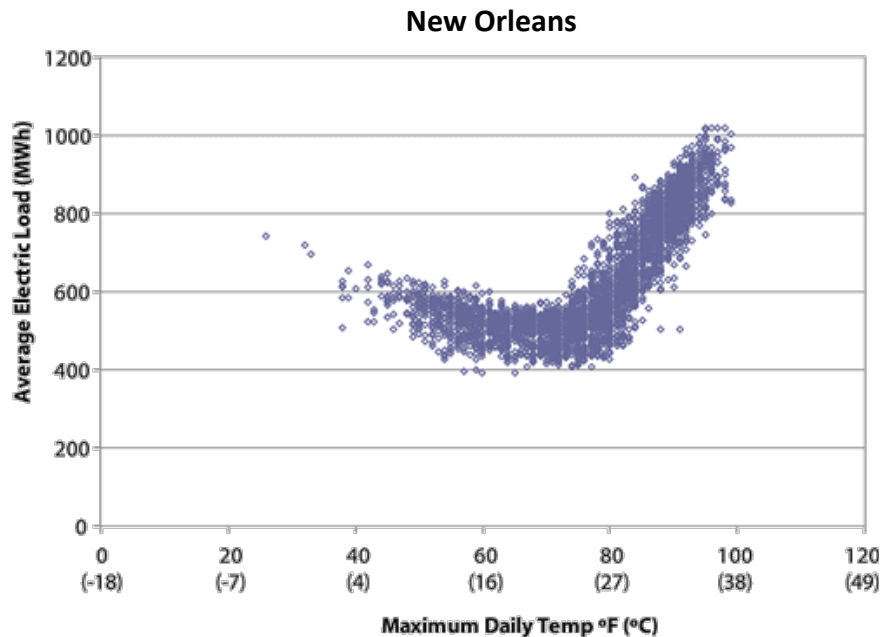
Tan et al., 2010, The urban heat island and its impact on heat waves and human health in Shanghai: *Int J Biometeorol.* 54(1):75-84.

# Global Impact on Climate Change...?



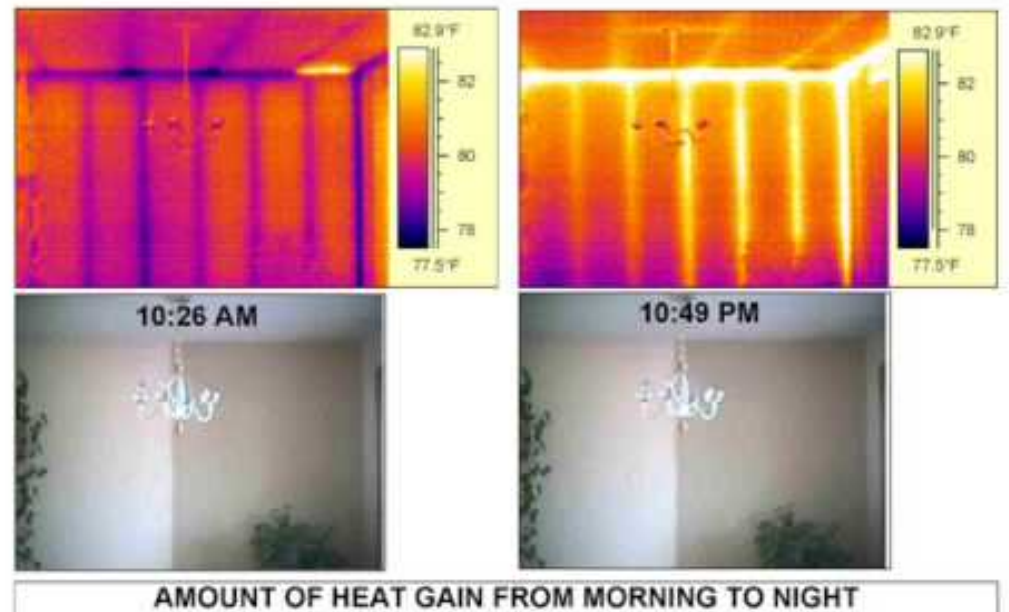
Peterson, Thomas C., Timothy W. Owen, 2005: Urban Heat Island Assessment: Metadata Are Important. *J. Climate*, **18**, 2637–2646.

# Impact of Heat on Residential Energy Use



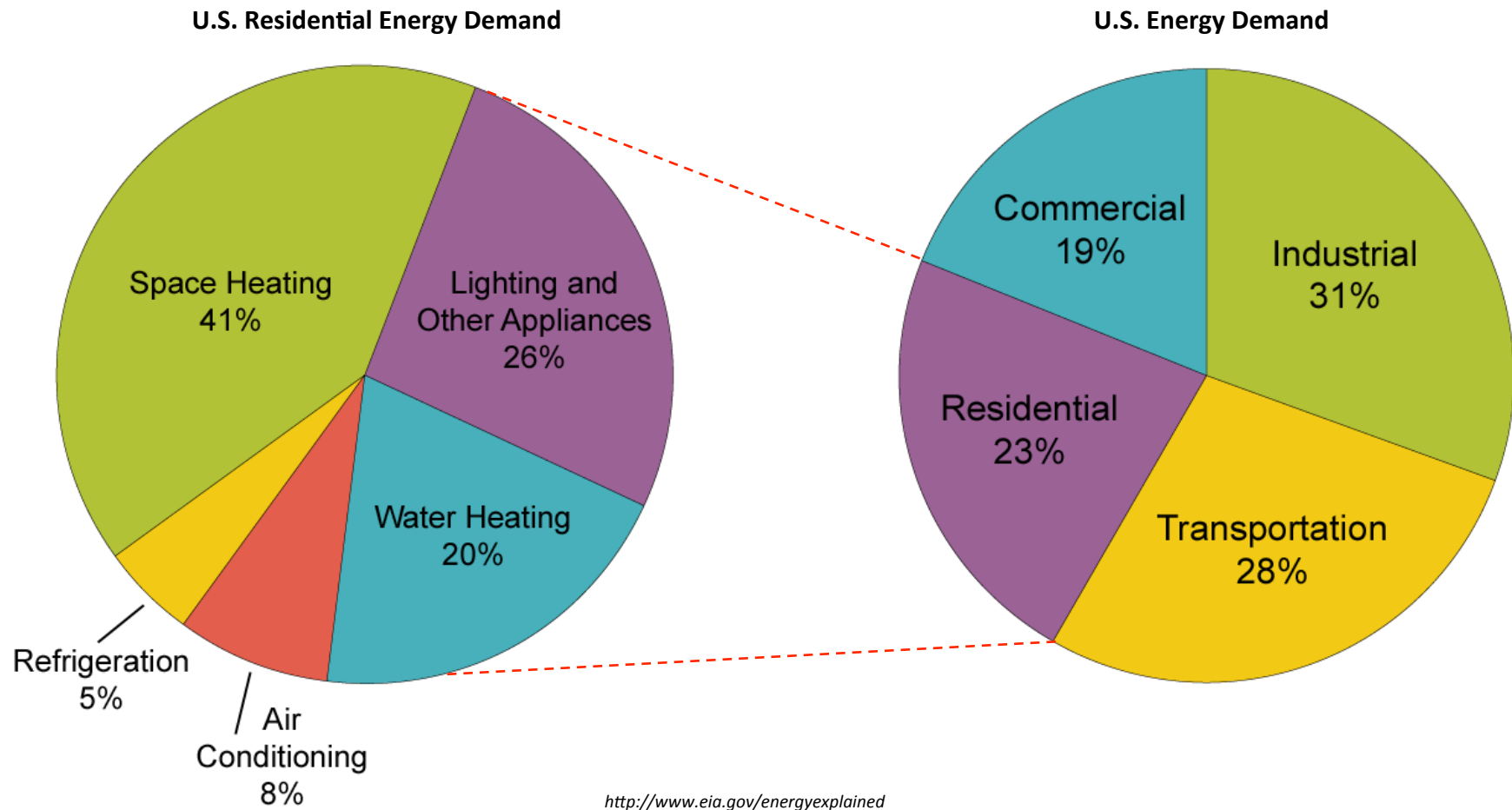
*Reducing Urban Heat Islands: Compendium of Strategies, U.S. EPA*

**Time Lapse Infrared Images of House Interior**



<http://www.youtube.com/watch?v=9AEgopYYmtI>

# Study Objective: Quantify Impact of UHI on US Residential Energy Demand





# Residential Energy Use & Temperature



Conductive Energy Loss through Walls, Floors & Ceilings = Area x  $U$  x  $\Delta$ Temperature x Time

$U$  = Thermal Conductance =  $1/R$ ;

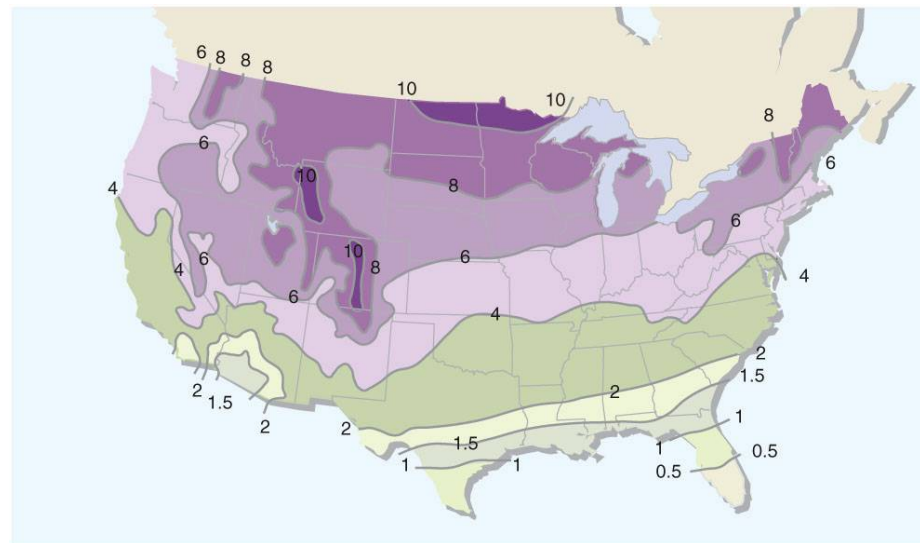
$R$  = Thermal Resistance

# Heating Degree Day (HDD) & Cooling Degree Day (CDD)

## $\Delta$ Temperature

Heating Degree Day (*HDD*) = 65°F – Mean Temp

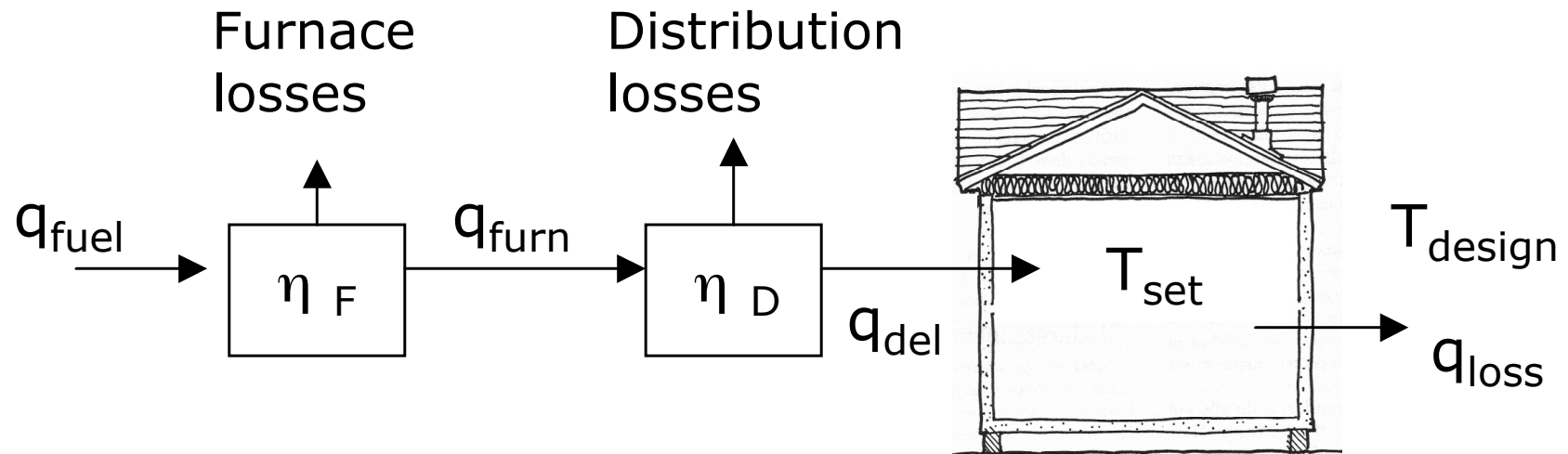
Cooling Degree Day (*CDD*) = Mean Temp – 65° F



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**Mean Annual Heating Degree Days over the US in thousands of °F**

# Modeling Heating (or Cooling) & Fuel Demand



## PRINCIPAL EQUATIONS

**Annual Heat Need** =  $24(h/d) \times UA_{\text{total}}(\text{BTU/h-}^\circ\text{F}) \times HDD(^\circ\text{F-d/y})$

**Annual Fuel Need** = Annual Heat Need / (Furnace Efficiency x Distribution Efficiency)

**Annual Fuel Cost** = Annual Fuel Need \* Fuel Cost

## PRINCIPAL INPUTS

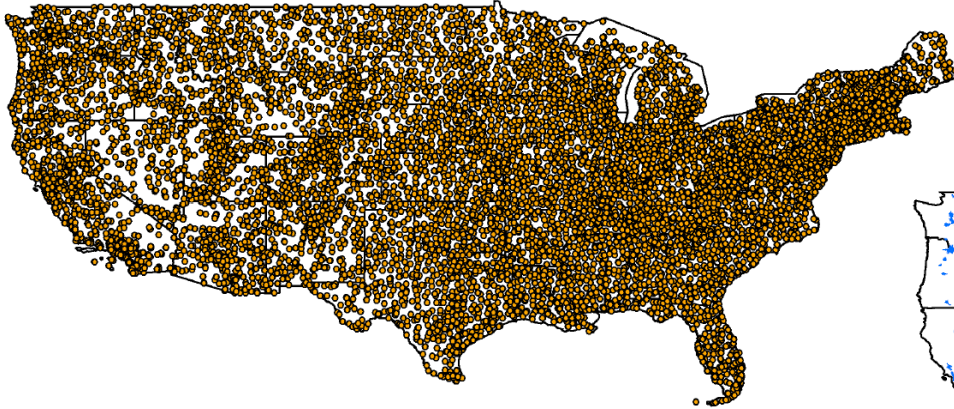
Urban vs. Rural Temperature Records

Home Insulation & HVAC Efficiencies

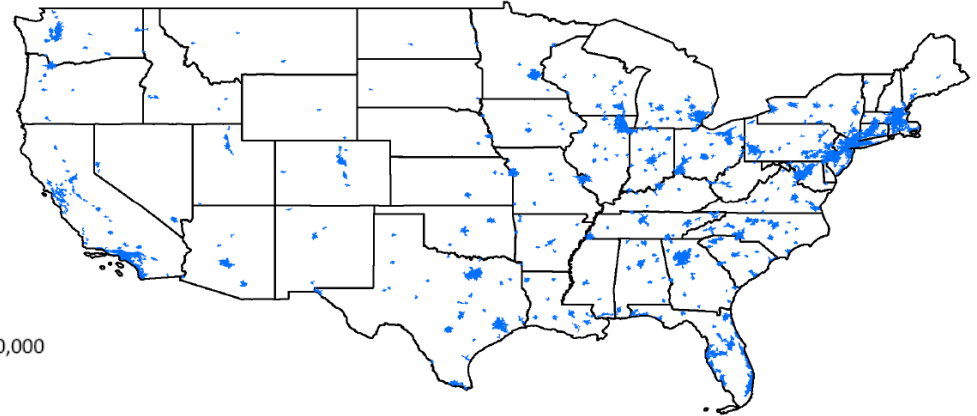
Home Areas & Fuel Costs

# Urban vs. Rural Temperature Records

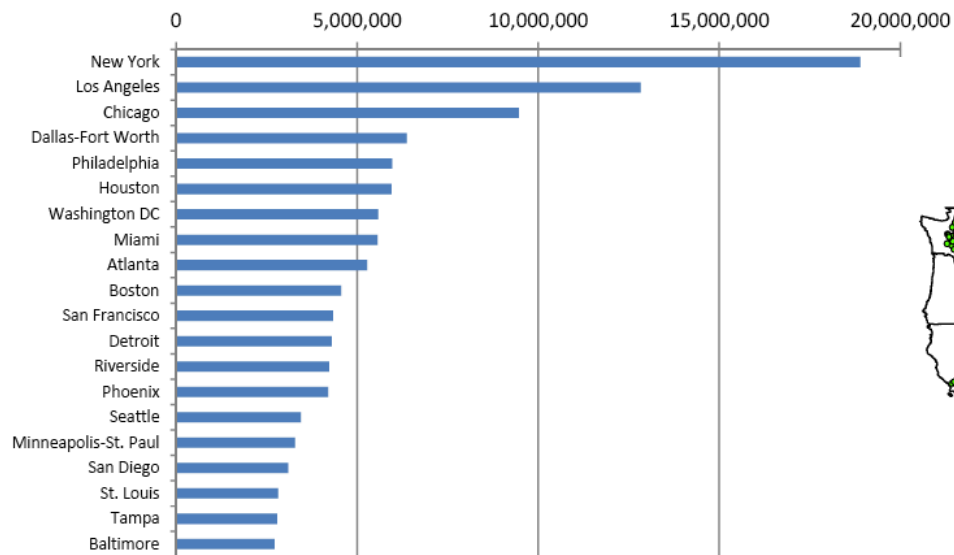
US GHCN Weather Station Data, 1960-2010



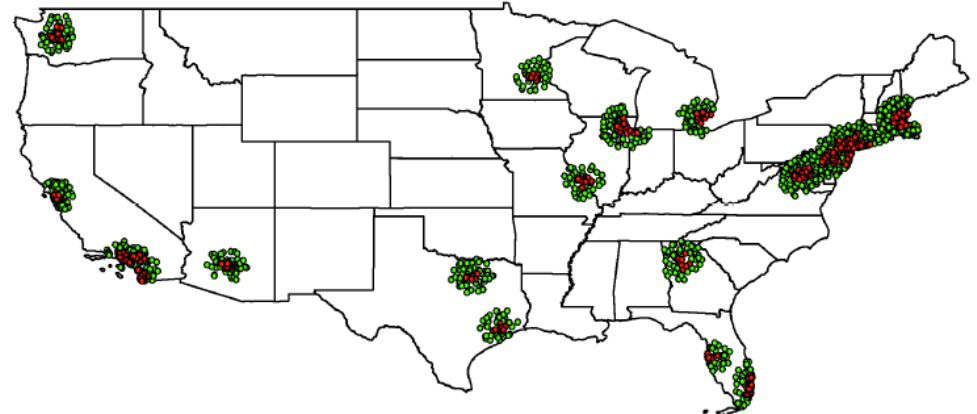
US 2010 Census Urbanized Areas



Top 20 U.S. Cities by 2010 Population

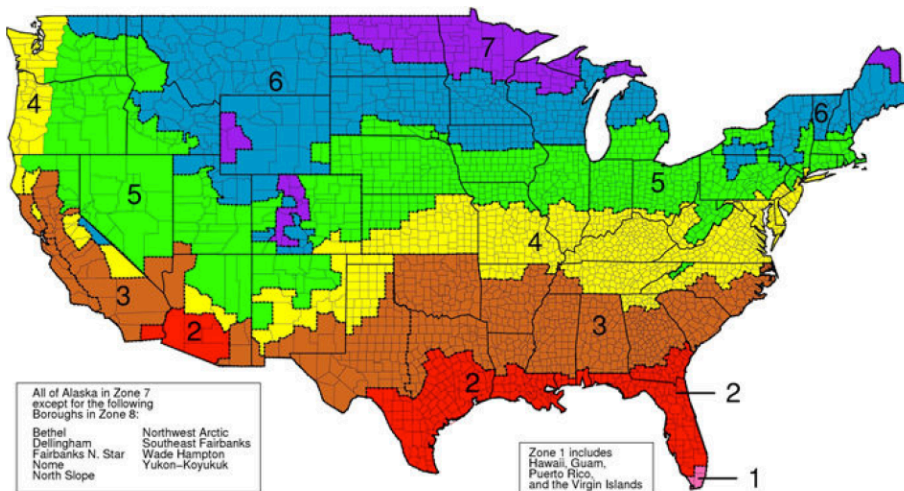


Urban & Rural Weather Stations, Top 20 US Cities



# Heating, Ventilation & Air Conditioning (HVAC) Inputs

US DOE Climate Zones



| R-Values of Space Components                 |              |              |              |
|----------------------------------------------|--------------|--------------|--------------|
| Components (Ceiling / Wall / Floor)          | Ceiling      | Wall         | Floor        |
| Exterior air film                            | 0.17         | 0.17         | 1.23         |
| Wood Bevel Siding                            | No siding    | 0.80         | No siding    |
| Air Space (between siding and sheathing)     | No air space | 0.94         | No air space |
| Air barrier/Sheathing/0.75" Plywood Subfloor | Climate Zone | Climate Zone | 0.93         |
| Cavity insulation (Fiberglass Batt)          | Climate Zone | Climate Zone | Climate Zone |
| 0.5" Drywall/Carpet + Rubber Pad flooring    | 0.45         | 0.45         | 3.31         |
| Interior Air Film                            | 0.61         | 0.68         | 0.92         |
| Single-Pane Glass Windows - R-Value          | No windows   | 0.91         | No Windows   |
| Square footage per window                    | No windows   | 15           | No Windows   |
| Total number of windows                      | No windows   | 4            | No Windows   |
| Total window area, ft <sup>2</sup>           | No windows   | 60           | No Windows   |
| Wooden Studs - R-Value                       | 4.38         | 4.38         | 4.38         |
| Board width, inches                          | 2            | 2            | 2            |
| Number of boards in stud                     | 1            | 1            | 1            |
| total individual stud width                  | 2            | 2            | 2            |
| Stud spacing, inches on-center               | 16           | 16           | 16           |
| Hollow Core Wooden Door, 1.75" - R-Value     | No Doors     | 2.17         | No Doors     |
| Square footage per door                      | No Doors     | 32           | No Doors     |
| Total number of doors                        | No Doors     | 2            | No Doors     |
| Total door area, ft <sup>2</sup>             | No Doors     | 64           | No Doors     |
| % Frame                                      | 12.50%       | 12.50%       | 12.50%       |
| % Cavity                                     | 87.50%       | 87.50%       | 87.50%       |

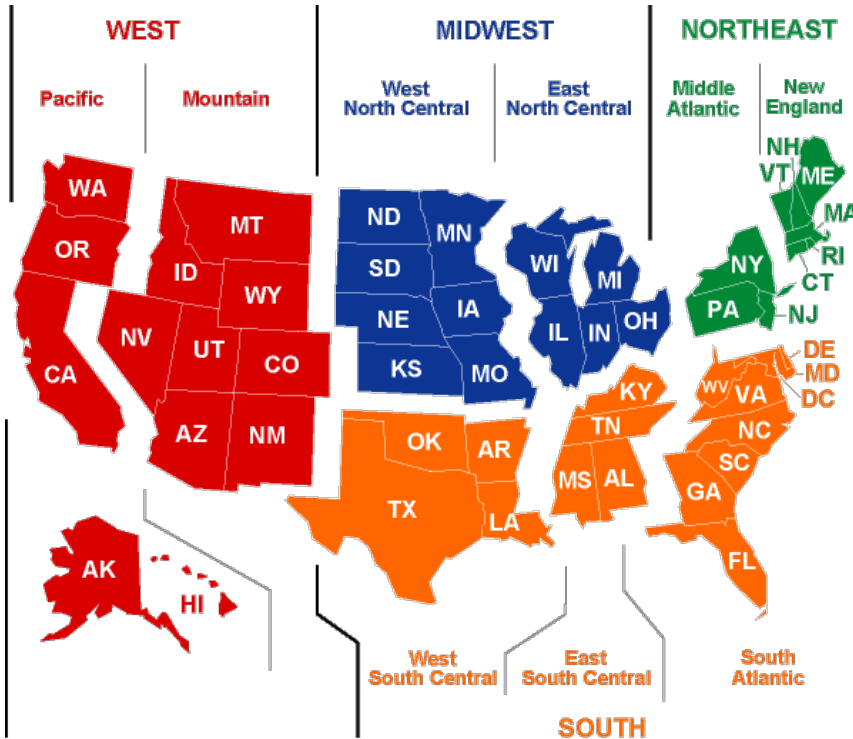
| FURNACE EFFICIENCY RANGE |                      |                 |
|--------------------------|----------------------|-----------------|
| Type                     | Minimum Federal AFUE | High Efficiency |
| Natural Gas              | 78%                  | 97%             |
| Electricity              | 97%                  | 97%             |
| Heating Oil              | 78%                  | 89%             |
| Wood*                    | 40%                  | 90%             |
| Propane                  | 78%                  | 97%             |

| AIR CONDITIONER EER RANGE |                |                 |
|---------------------------|----------------|-----------------|
| Type                      | Low Efficiency | High Efficiency |
| Central System            | 10             | 12              |
| Window Unit               | 8              | 10              |



# Housing Size, Fuel Use & Fuel Costs

US Census Regions



| HOUSING SPACE AREA CHARACTERISTICS |                                    |                                                |                           |                                   |                                  |                                                       |
|------------------------------------|------------------------------------|------------------------------------------------|---------------------------|-----------------------------------|----------------------------------|-------------------------------------------------------|
| Census Division                    | number of housing units per region | average sq footage per region, ft <sup>2</sup> | one house side length, ft | area of one wall, ft <sup>2</sup> | total wall area, ft <sup>2</sup> | total wall area w/o windows or doors, ft <sup>2</sup> |
| New England                        | 5,500,000                          | 2,472                                          | 49.72                     | 596.63                            | 2,386.52                         | 2,262.52                                              |
| Middle Atlantic                    | 15,100,000                         | 2,284                                          | 47.79                     | 573.49                            | 2,293.98                         | 2,169.98                                              |
| East North Central                 | 17,700,000                         | 2,483                                          | 49.83                     | 597.96                            | 2,391.83                         | 2,267.83                                              |
| West North Central                 | 7,900,000                          | 2,281                                          | 47.76                     | 573.12                            | 2,292.47                         | 2,168.47                                              |
| South Atlantic                     | 21,700,000                         | 2,243                                          | 47.36                     | 568.32                            | 2,273.30                         | 2,149.30                                              |
| East South Central                 | 6,900,000                          | 2,137                                          | 46.23                     | 554.73                            | 2,218.93                         | 2,094.93                                              |
| West South Central                 | 12,100,000                         | 2,028                                          | 45.03                     | 540.40                            | 2,161.60                         | 2,037.60                                              |
| Mountain                           | 7,600,000                          | 1,951                                          | 44.17                     | 530.04                            | 2,120.17                         | 1,996.17                                              |
| Pacific                            | 16,600,000                         | 1,708                                          | 41.33                     | 495.94                            | 1,983.74                         | 1,859.74                                              |
| story height, ft                   | 12                                 |                                                |                           |                                   |                                  |                                                       |

| FUEL PRICES                        |         | Census Division |       |       |       |       |       |       |       |       |
|------------------------------------|---------|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Fuel                               | unit    | NE              | MA    | ENC   | WNC   | SA    | ESC   | WSC   | MTN   | PAC   |
| 2010 residential NG                | \$/Mcf  | 15.11           | 13.26 | 10.16 | 9.48  | 13.76 | 11.62 | 11.30 | 10.03 | 11.55 |
| 2010 residential electricity       | \$/kWh  | 0.162           | 0.158 | 0.114 | 0.096 | 0.110 | 0.096 | 0.107 | 0.105 | 0.123 |
| 2010 residential no. 2 heating oil | \$/gal  | 2.96            | 3.08  | 2.74  | NONE  | 3.01  | NONE  | NONE  | NONE  | NONE  |
| wood                               | \$/cord | 200             | 200   | 200   | 200   | 200   | 200   | 200   | 200   | 200   |
| wood pellets                       | \$/ton  | 250             | 250   | 250   | 250   | 250   | 250   | 250   | 250   | 250   |
| 2010 residential propane           | \$/gal  | 2.59            | 2.59  | 2.59  | 2.59  | 2.59  | 2.59  | 2.59  | 2.59  | 2.59  |

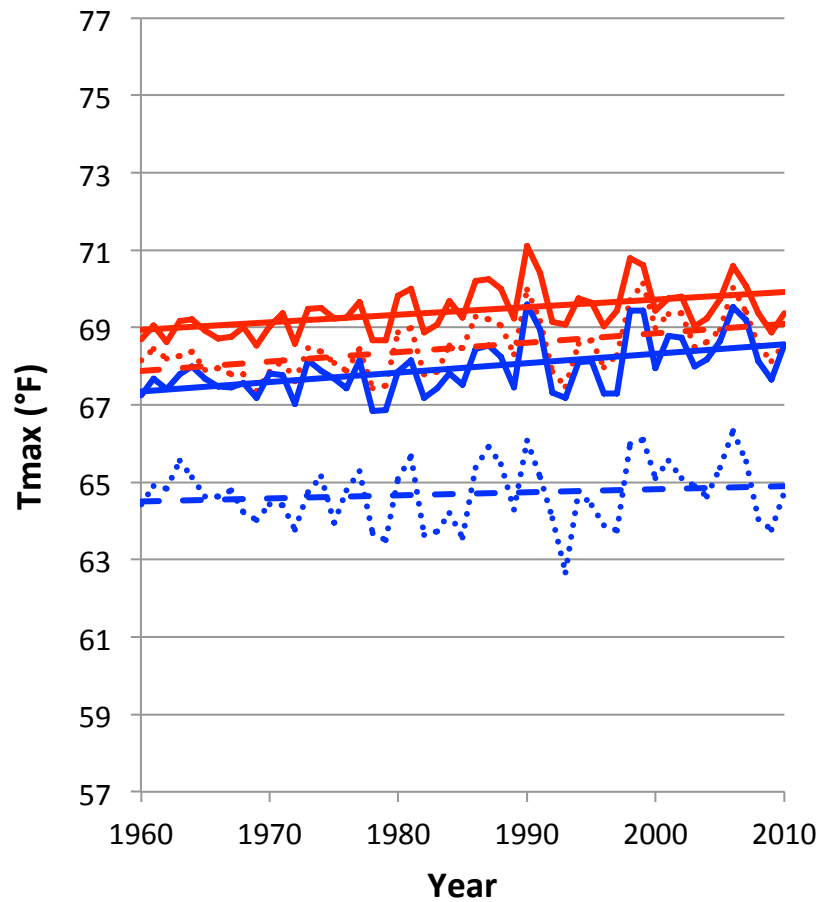
Fractional Use of Space Heating Fuels

| US Census Region | NE  | MA  | ENC | WNC | SA  | ESC | WSC | MTN | PAC |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Natural Gas, %   | 42% | 60% | 74% | 67% | 26% | 33% | 47% | 61% | 61% |
| Electricity, %   | 5%  | 9%  | 12% | 18% | 62% | 49% | 43% | 24% | 28% |
| Heating Oil, %   | 44% | 25% | 4%  | 0%  | 2%  | 0%  | 0%  | 0%  | 0%  |
| Wood, %          | 4%  | 2%  | 2%  | 4%  | 1%  | 3%  | 2%  | 4%  | 3%  |
| Propane, %       | 0%  | 2%  | 6%  | 10% | 5%  | 13% | 7%  | 8%  | 2%  |

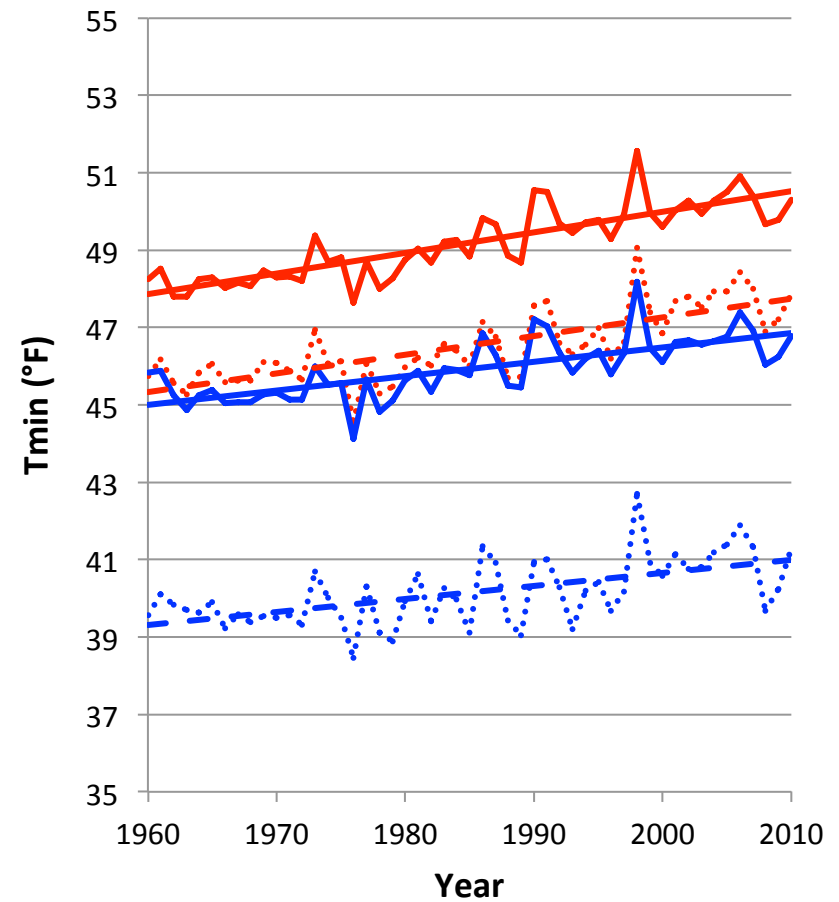
Fractional Use of A/C

| US Census Region        | NE  | MA  | ENC | WNC | SA  | ESC | WSC | MTN | PAC |
|-------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Do not have cooling, %  | 31% | 16% | 10% | 4%  | 4%  | 3%  | 2%  | 41% | 44% |
| Central system, %       | 15% | 34% | 64% | 76% | 81% | 75% | 77% | 51% | 39% |
| 1 wall unit, %          | 25% | 19% | 16% | 15% | 6%  | 12% | 7%  | 7%  | 14% |
| 2 wall units, %         | 20% | 21% | 8%  | 4%  | 5%  | 10% | 8%  | 0%  | 2%  |
| 3 or more wall units, % | 11% | 11% | 3%  | 0%  | 4%  | 3%  | 8%  | 0%  | 0%  |

## Results: Tmax & Tmin

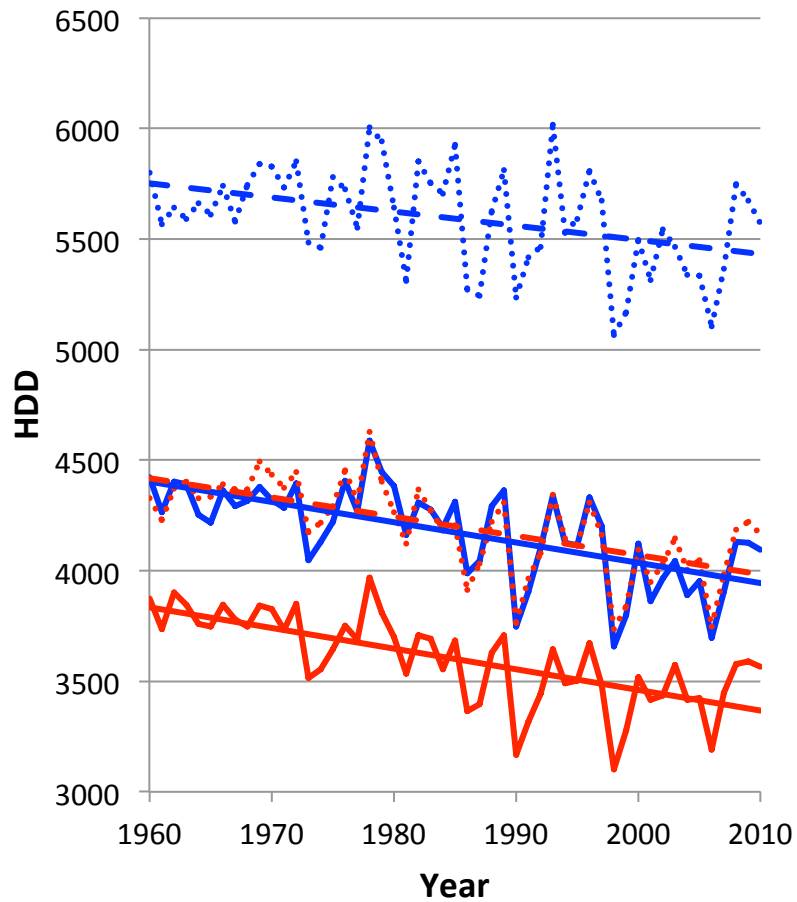


|     | Tmax           | $\Delta T_{\text{max}}/y$ | R2   |
|-----|----------------|---------------------------|------|
| —   | Top 20 Urban   | 0.02                      | 0.22 |
| ... | Top 20 Rural   | 0.02                      | 0.27 |
| —   | Lower 48 Urban | 0.02                      | 0.27 |
| ... | Lower 48 Rural | 0.01                      | 0.02 |

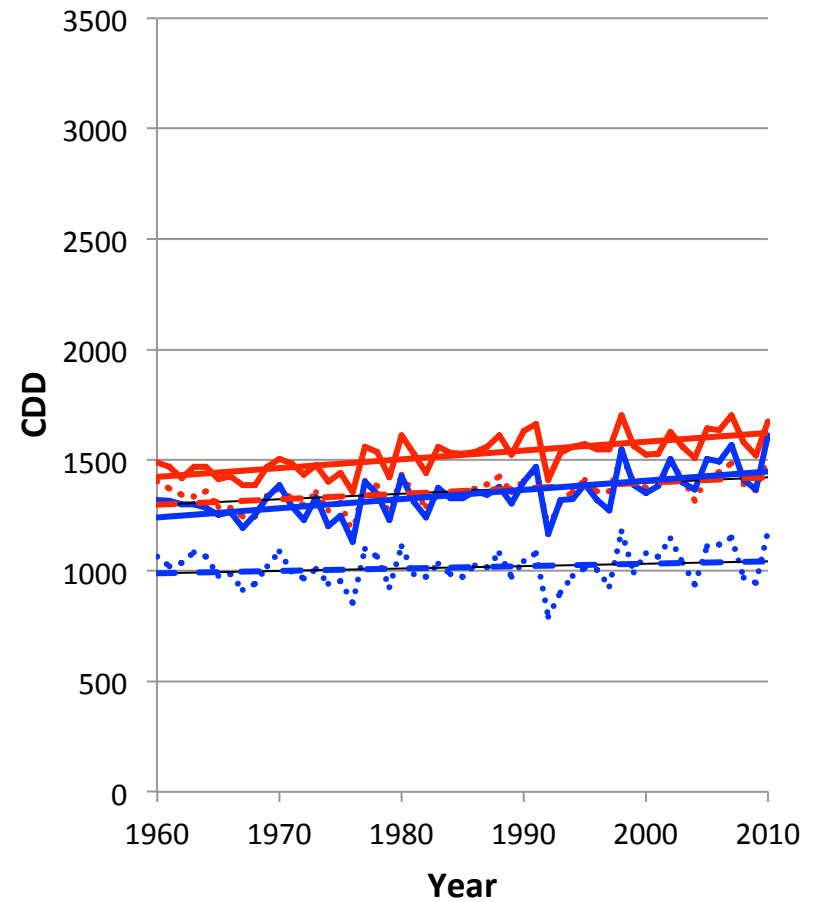


|     | Tmin           | $\Delta T_{\text{min}}/y$ | R2   |
|-----|----------------|---------------------------|------|
| —   | Top 20 Urban   | 0.05                      | 0.71 |
| ... | Top 20 Rural   | 0.04                      | 0.51 |
| —   | Lower 48 Urban | 0.05                      | 0.58 |
| ... | Lower 48 Rural | 0.03                      | 0.34 |

## Results: HDDs & CDDs



|     | HDD            | $\Delta\text{HDD}/\text{y}$ | R <sup>2</sup> |
|-----|----------------|-----------------------------|----------------|
| —   | Top 20 Urban   | -9.34                       | 0.49           |
| ... | Top 20 Rural   | -8.70                       | 0.42           |
| —   | Lower 48 Urban | -9.18                       | 0.42           |
| ... | Lower 48 Rural | -6.40                       | 0.17           |

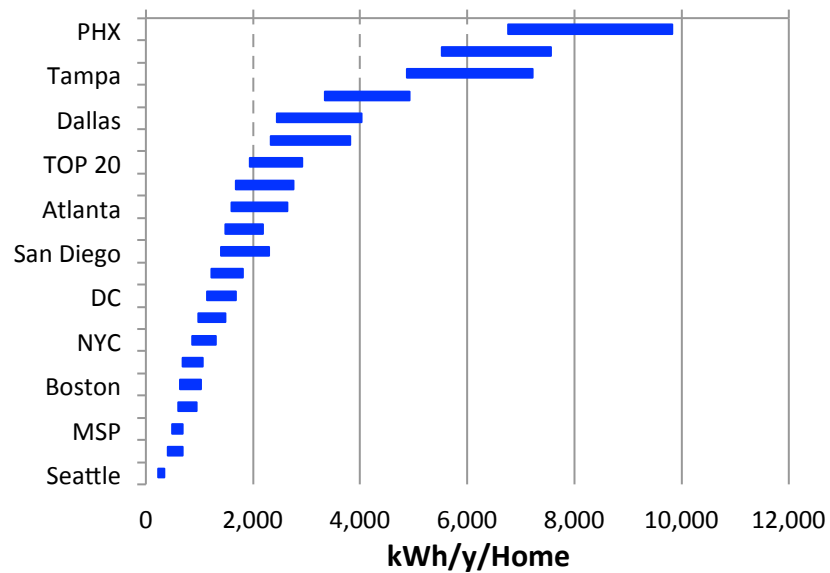


|     | CDD            | $\Delta\text{CDD}/\text{y}$ | R <sup>2</sup> |
|-----|----------------|-----------------------------|----------------|
| —   | Top 20 Urban   | 3.98                        | 0.49           |
| ... | Top 20 Rural   | 2.48                        | 0.26           |
| —   | Lower 48 Urban | 4.15                        | 0.38           |
| ... | Lower 48 Rural | 1.08                        | 0.04           |

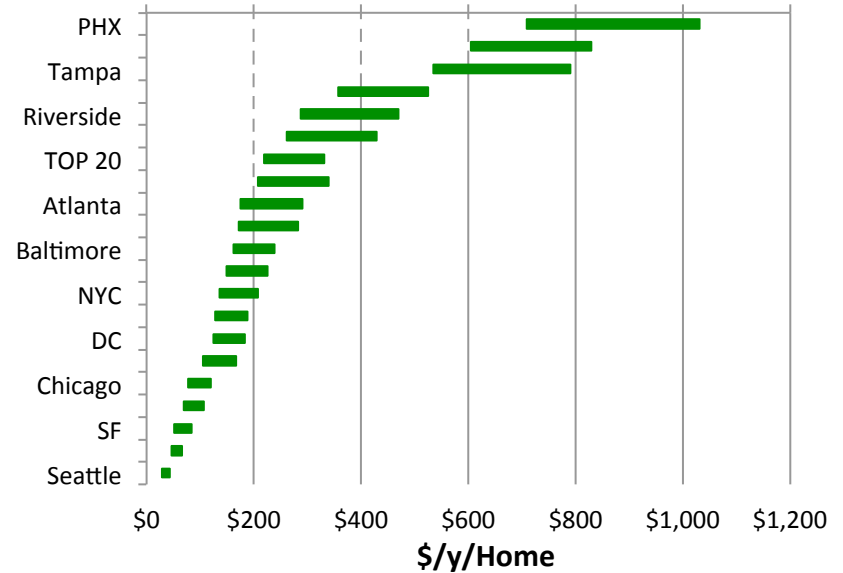
# Results: CDD Energy Use & Cost

*Range of Low to High Insulation/High HVAC Efficiency*

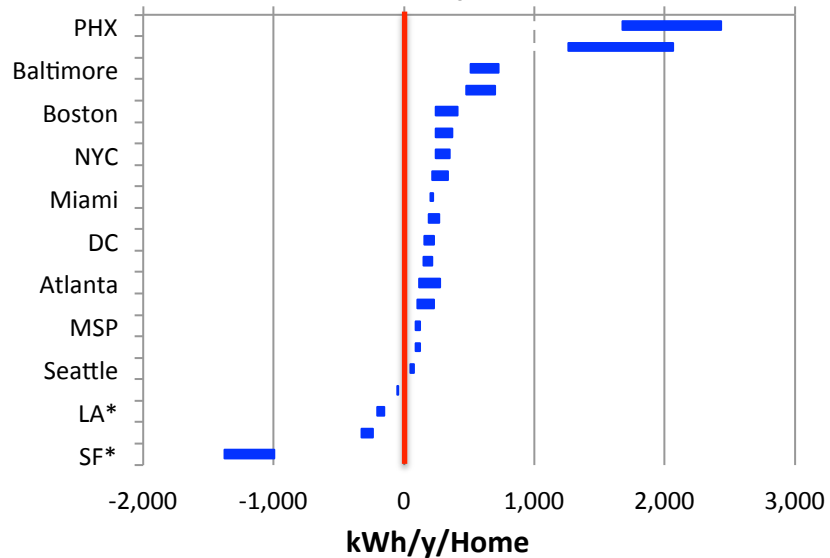
## A/C Demand



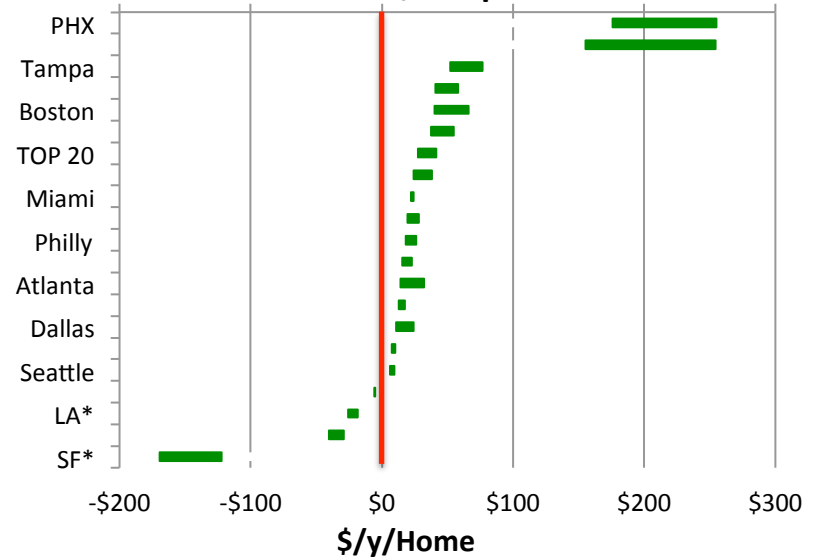
## A/C Expenditures



## Urban - Rural A/C Demand



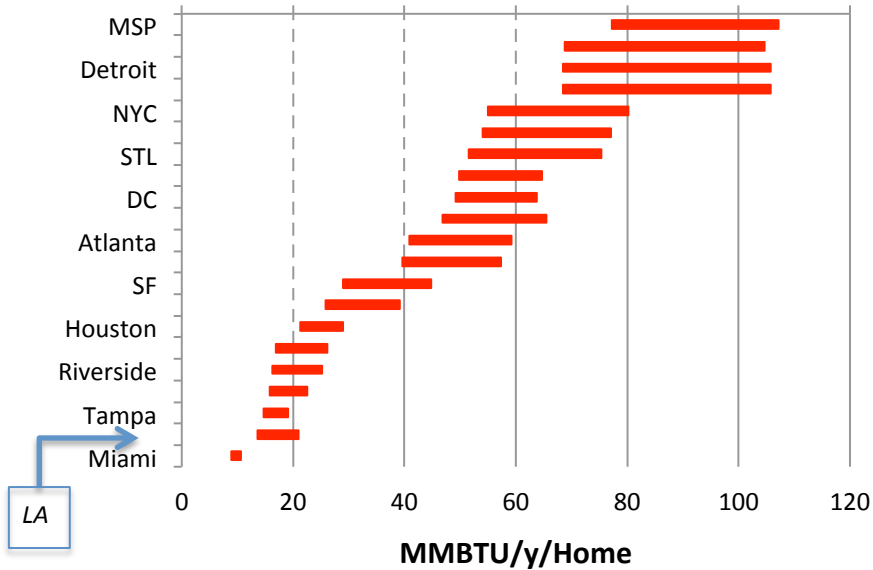
## Urban - Rural A/C Expenditures



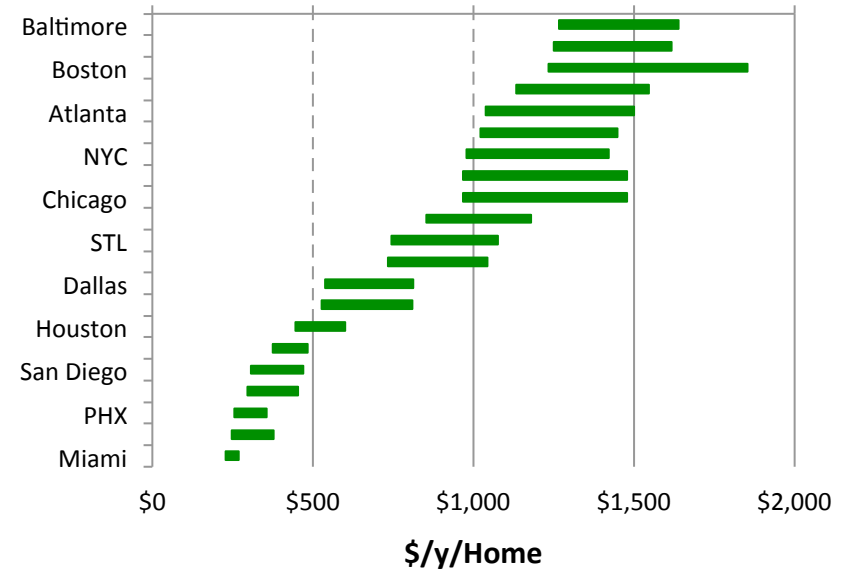
# Results: HDD Energy Use & Cost

*Range of Low to High Insulation/High HVAC Efficiency*

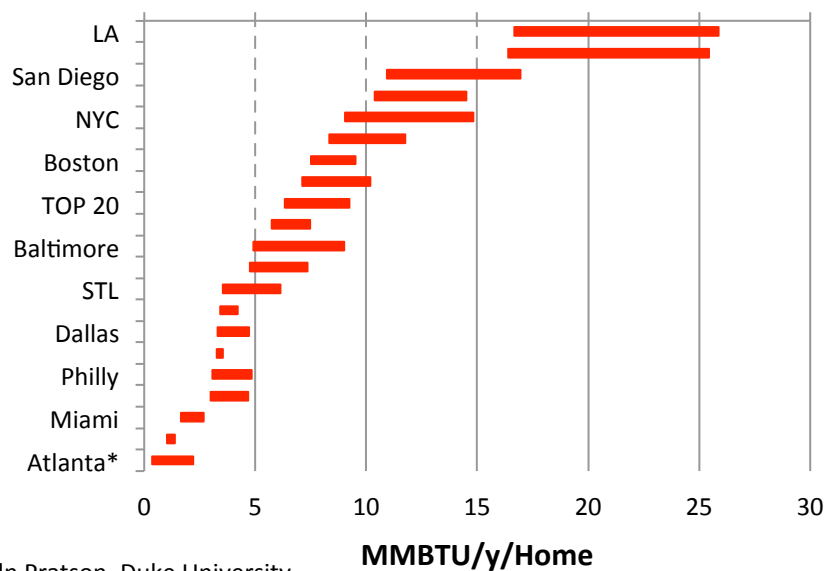
## Space Heating Demand



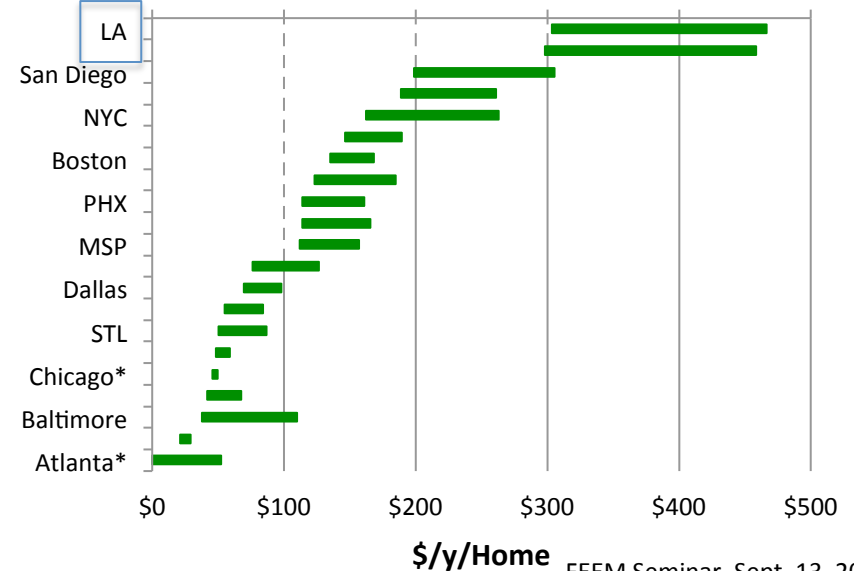
## Space Heating Expenditures



## Rural – Urban Heating Demand\*



## Rural – Urban Heating Expenditures\*





# Conclusions

1.  $T_{min}$  is rising at roughly twice the rate of  $T_{max}$ .
2. HDDs are declining 2-6 times faster than CCDs are rising.
3. Rates of change are  $\sim 1\%$  of absolute difference between Urban & Rural Temperatures, so UHI impact on energy use dominates over global warming impact.
4. UHI impact on energy use varies with city; from negligible to significant.
5. Reduction in urban energy use for heating  $\sim 3$  times the increase in urban energy use for cooling, leading to a net impact of reduced energy use by urban residences.
6. UHI impact on energy costs depends on factors governing fuel price as well as fuel demand.