CAE 331/513
Building Science
Fall 2013

Lecture 11: November 18, 2013
Finish energy estimation methods
Energy efficiency
Building diagnostic tools

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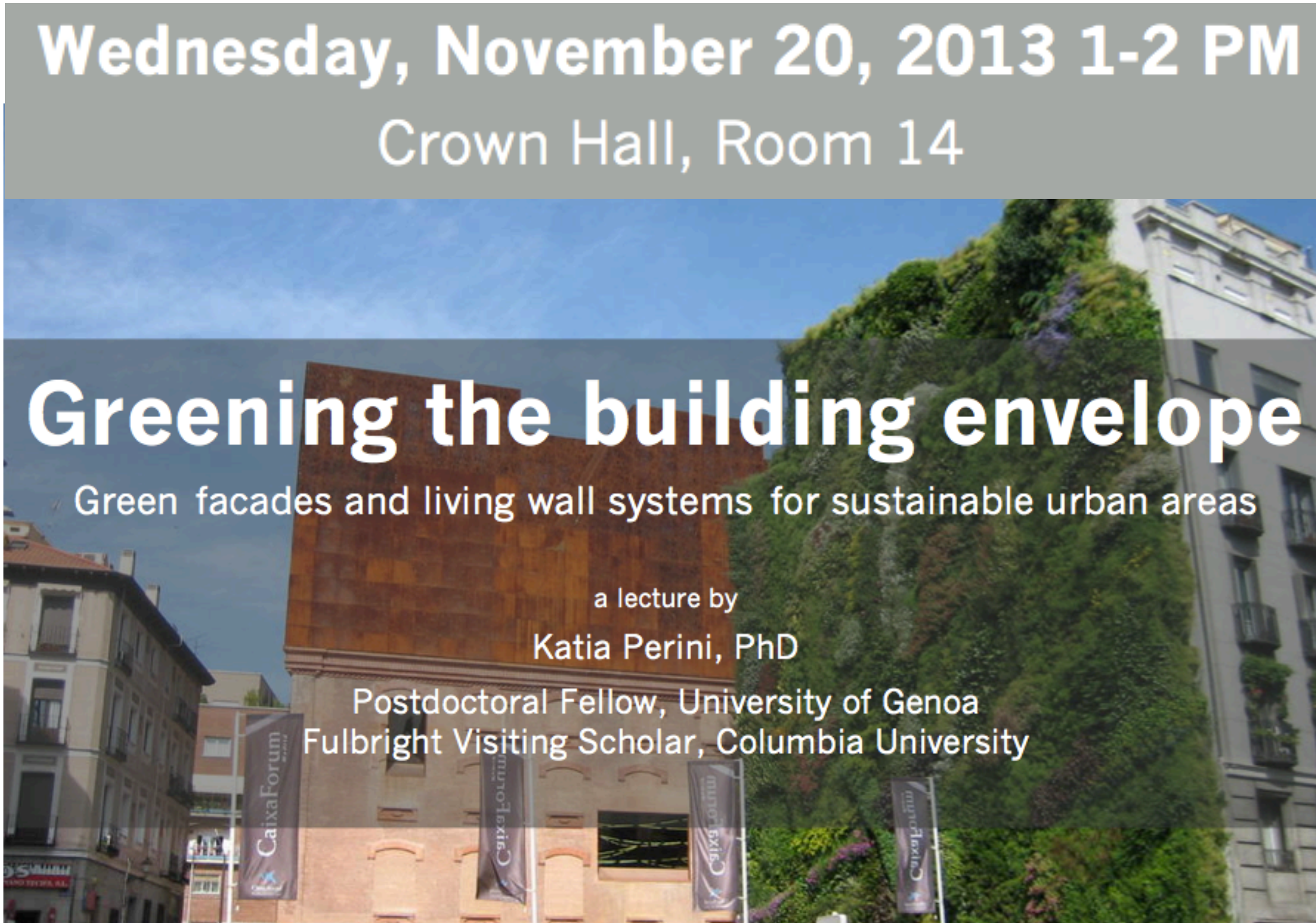
Last time

- Finished cooling loads
  - Heat balance method
- HVAC systems and equipment
- COP and equipment efficiency
- Time-varying energy calculations
- HW #6 assigned
  - Due today

Guest lecture this Wednesday



Today's objectives

- Finish energy estimation methods
- Fluid flows and pressure drops
- Better understand building energy consumption
- Energy efficiency in buildings
- Building diagnostic tools
- Course wrap-up

Next time

- Graduate students final projects due next week
  - 8 page paper single spaced
  - PDF emailed to me or uploaded to BB is fine

- Graduate student presentations next week
  - 12 student presentations
  - 10 minutes per presentation (2 minutes for questions)
    - Practice your presentations
    - **Don't go over** I will stop you at 10 minutes!

EER and SEER

- EER = energy efficiency ratio
  - Same as COP but in weird mixed units: $(\mathrm{Btu/hr})/\mathrm{W}$
  - Example from previous page:

$$COP = \frac{8.5\ [\mathrm{kW}]}{2.48\ [\mathrm{kW}]} = 3.43 \qquad EER = \frac{29.0\ [\mathrm{kBtu/hr}]}{2.48\ [\mathrm{kW}]} = 11.7$$

$$EER = COP \times 3.41$$

- SEER = seasonal energy efficiency ratio, units: $[\mathrm{Btu/Wh}]$
  - Cooling output during a typical cooling season divided by the total electric energy input during the same period
  - Represents expected performance over a range of conditions

$$EER \approx -0.02 \times SEER^2 + 1.12 \times SEER$$

Capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates

Table 4. Example Manufacturer EPT (Subset of Data Displayed)

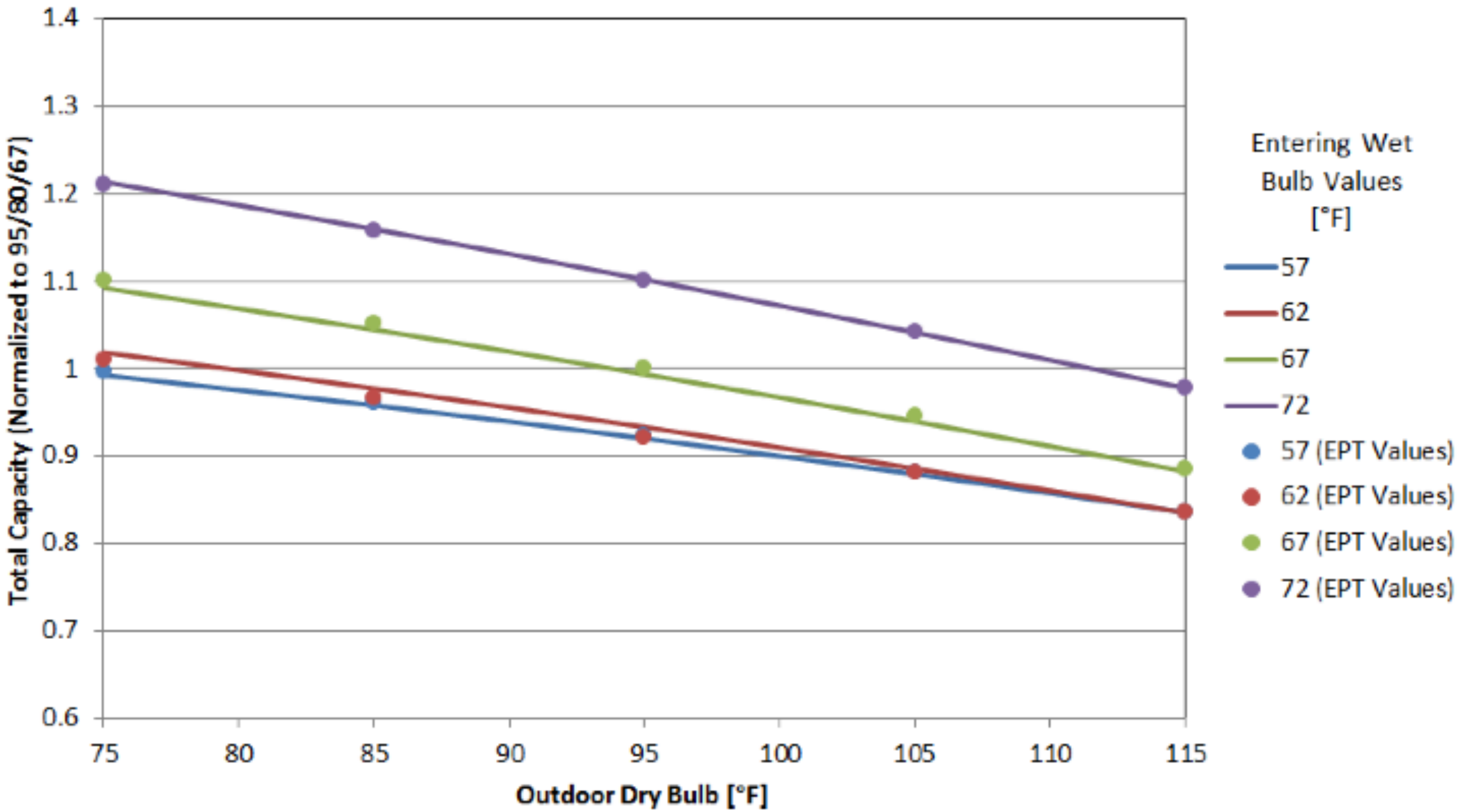
Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[1,2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]
875	72 (22)	34.32	17.27	1.96	31.24	16.13	2.44	29.59	15.54	2.71
	67 (19)	31.45	21.21	1.96	28.59	20.05	2.43	27.04	19.44	2.71
	63 (17)	29.35	20.58	1.96	26.66	19.40	2.43	25.19	18.78	2.70
	62 (17)	28.82	25.13	1.95	26.24	23.94	2.43	24.86	23.29	2.70
	57 (14)	28.00	28.00	1.95	25.89	25.89	2.43	24.74	24.74	2.70
1000	72 (22)	34.88	18.05	2.01	31.66	16.90	2.48	29.96	16.30	2.76
	67 (19)	31.98	22.49	2.01	29.00	21.31	2.48	27.40	20.68	2.75
	63 (17)	29.88	21.78	2.00	27.07	20.58	2.48	25.55	19.95	2.75
	62 (17)	29.44	26.90	2.00	26.81	26.81	2.48	25.62	25.62	2.75
	57 (14)	29.10	29.10	2.00	26.85	26.85	2.48	25.62	25.62	2.75
1125	72 (22)	35.27	18.78	2.06	17.61	17.61	2.53	30.22	17.07	2.81
	67 (19)	32.36	23.68	2.05	22.50	22.50	2.53	27.66	21.88	2.80
	63 (17)	30.25	22.90	2.05	21.70	21.70	2.52	25.82	21.07	2.80
	62 (17)	30.02	28.49	2.05	27.62	27.62	2.52	26.32	26.32	2.80
	57 (14)	29.99	29.99	2.05	27.62	27.62	2.52	26.32	26.32	2.80

[1] Total and sensible capacities are net capacities. Blower motor heat has been subtracted.

[2] Sensible capacities shown are based on 80°F (27°C) entering air at the indoor coil. For sensible capacities at other than 80°F (27°C), deduct 835 Btu/h (245 W) per 1000 cfm (480 L/S) of indoor coil air for each degree below 80°F (27°C), or add 835 Btu/h (245 W) per 1000 cfm (480 L/s) of indoor coil air per degree above 80°F (27°C).

[3] System kilowatt is the total of indoor and outdoor unit kilowatts.

Capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates



EER and SEER

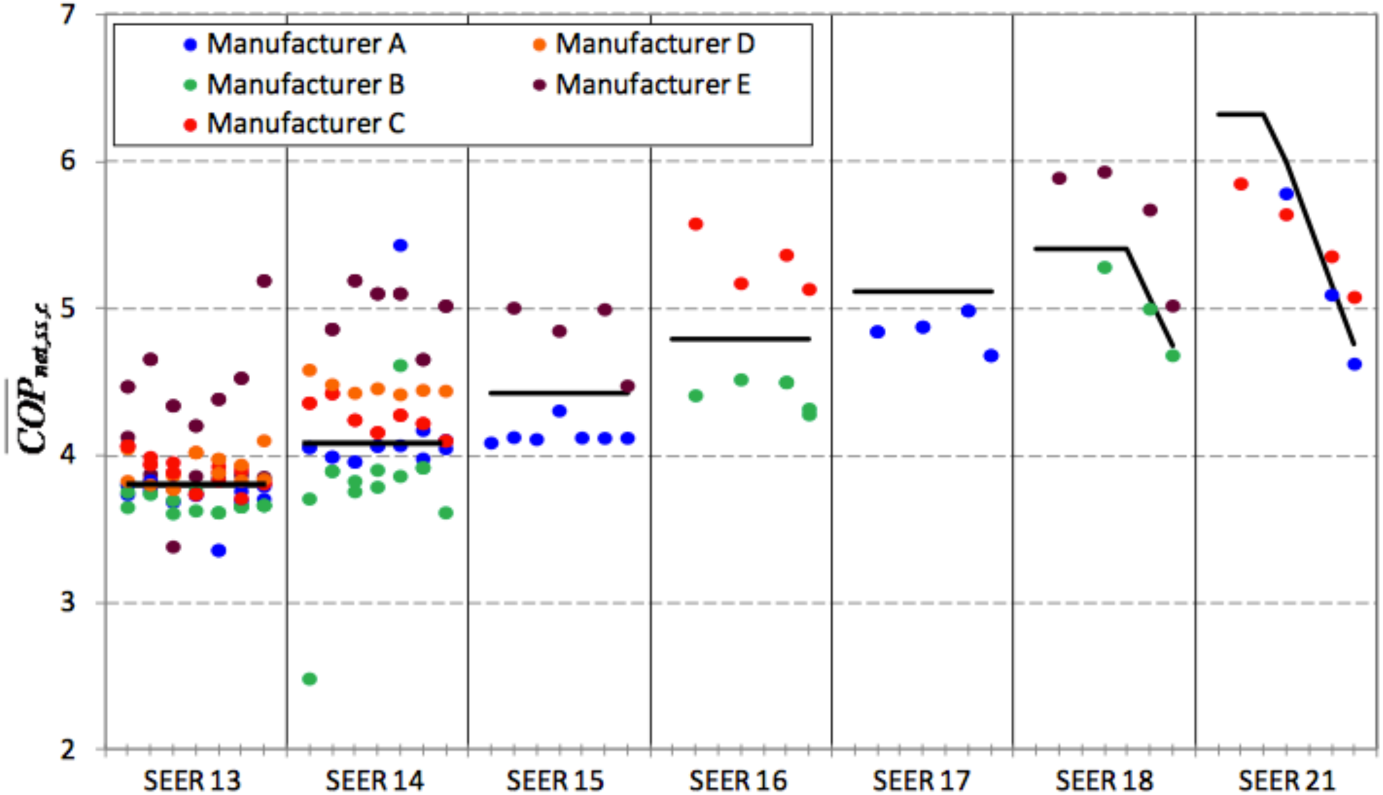


Figure 10. Simulation results for the AC library (shown in solid black lines) compared to individual AC units (individual capacities of 1.5, 2, 3, 4, and 5 tons shown in ascending order within SEER values)

- AC units must be 14 SEER (or 12.2 EER) beginning on January 1, 2015 if installed in southeastern region of the US

Using EER to estimate energy consumption

- If you know the load and you know the EER, you can estimate the instantaneous electric power draw required to meet the load:

$$\mathrm{P}_{elec} = \frac{Q_{cooling,load}}{COP}$$

- Multiply by the number of hours and sum over period of time and get energy consumption:

$$E = \sum \mathrm{P}_{elec}\,\Delta t$$

- Can break into bins if COP/EER changes with varying conditions

ENERGY ESTIMATION METHODS

Annual heating and cooling energy requirements

Simple energy estimation methods

- Two methods:
  - Degree-day methods (simplest)
    - Constant equipment efficiency
  - Bin methods
    - Accounts for varying efficiencies or indoor conditions

Degree-day method

- The simplest method of estimating energy use is the Degree-Day Method (DDM)

- The DDM makes uses the concept of the degree-day (DD) to estimate energy used for heating or cooling

- The method is better for estimating heating requirements than cooling requirements since solar gain is essentially ignored

- Works best where the efficiency of the HVAC equipment is constant

Degree-Day Methods

- The basic idea is that the energy use of a building is directly related to the temperature difference between outdoor and indoor air

- Heating equipment is assumed to run when the outdoor temperature drops below the "balance temperature"
  - The **balance temperature** is the outdoor air temperature at which the internal heat gains balance the heat loss to the outside
  - This is less than the interior temperature set point

- Cooling equipment is assumed to run when the outdoor temperature is above the balance temperature
  - The balance temperature might not be the same for heating and cooling because the interior temperature, interior heat gain, and building heat loss usually differ in summer and winter

Heating degree days and cooling degree days

- In many codes, standards, references and literature, you will see references to Heating Degree Days (HDD) or Cooling Degree Days (CDD)
  - Codes and ASHRAE Standard 90.1 make reference to HDD and CDD throughout

- HDD and CDD are design-days used to estimate the energy demand for heating and cooling using Degree-Day Methods

Calculating HDD and CDD

- A degree-day is the sum of the difference between the average outside temperature and a base temperature (often 65°F or 18°C) for a fixed time frame
  - Add up the product of time and temperature difference **below** the reference for heating (and the product of time and temperature difference **above** for cooling)
  - The most accurate estimates use minute-by-minute weather data

$$HDD_{REF} = \sum_i \frac{(T_{base} - T_{out})}{24\ \text{h}} \text{ when } T_{out} < T_{REF}$$

$$CDD_{REF} = \sum_i \frac{(T_{out} - T_{base})}{24\ \text{h}} \text{ when } T_{out} > T_{REF}$$

  - Units: “degree-days” = °F-days or °C-days
  - We can convert between HDD in °F to HDD in °C by multiplying by 5/9

Selecting a base temperature

- HDD_{65F} and CDD_{50F} are common HDD/CDD levels that are used regularly in industry, so you might use those regardless of your true base temperature
- If your building has a different base temperature, then you should immediately know that your estimates using DDM will not be accurate
- The best base temperature is the balance point temperature where internal gains balance the heat loss to outside

Finding the balance point temperature

- We find the balance point temperature by setting the heat gain/loss of the building to zero and solving for the outside temperature

$$Q_h \approx \left[(UA)_{total} + \dot{V}_{\inf} \rho C_p \right] \left(T_{in} - T_{out} \right)$$

at $T_{out} = T_{bal}, \;\; Q_h + Q_{int} = 0,$ so

$$T_{bal} = T_{in} - \frac{Q_{int}}{(UA)_{total} + \dot{V}_{\inf} \rho C_p}$$

Understanding balance point temperatures

$$T_{bal} = T_{in} - \frac{Q_{int}}{(UA)_{total} + \dot{V}_{\text{inf}}\rho C_p}$$

- As the insulation increases, T_{bal} drops
- As infiltration decreases, T_{bal} drops
- As internal gains increase, T_{bal} drops
- As a result, most modern buildings have a T_{bal} well below 65°F (usually closer to 55°F)

Balance point example

- A 10000 ft^3 building has an overall UA of 250 Btu/hr-°F, an infiltration rate of 0.7 ACH, and an internal gain of 5 kBtu/hr
- What is its balance point temperature?

Balance point example

- A 10000 ft^3 building has an overall UA of 250 Btu/hr-°F, an infiltration rate of 0.7 ACH, and an internal gain of 5 kBtu/hr

- What is its balance point temperature?

$$\dot{V}_{\text{inf}} = \left(ACH\right)V = \left(0.7\right)10000 = 7000\,\tfrac{\text{ft}^3}{\text{hr}}$$

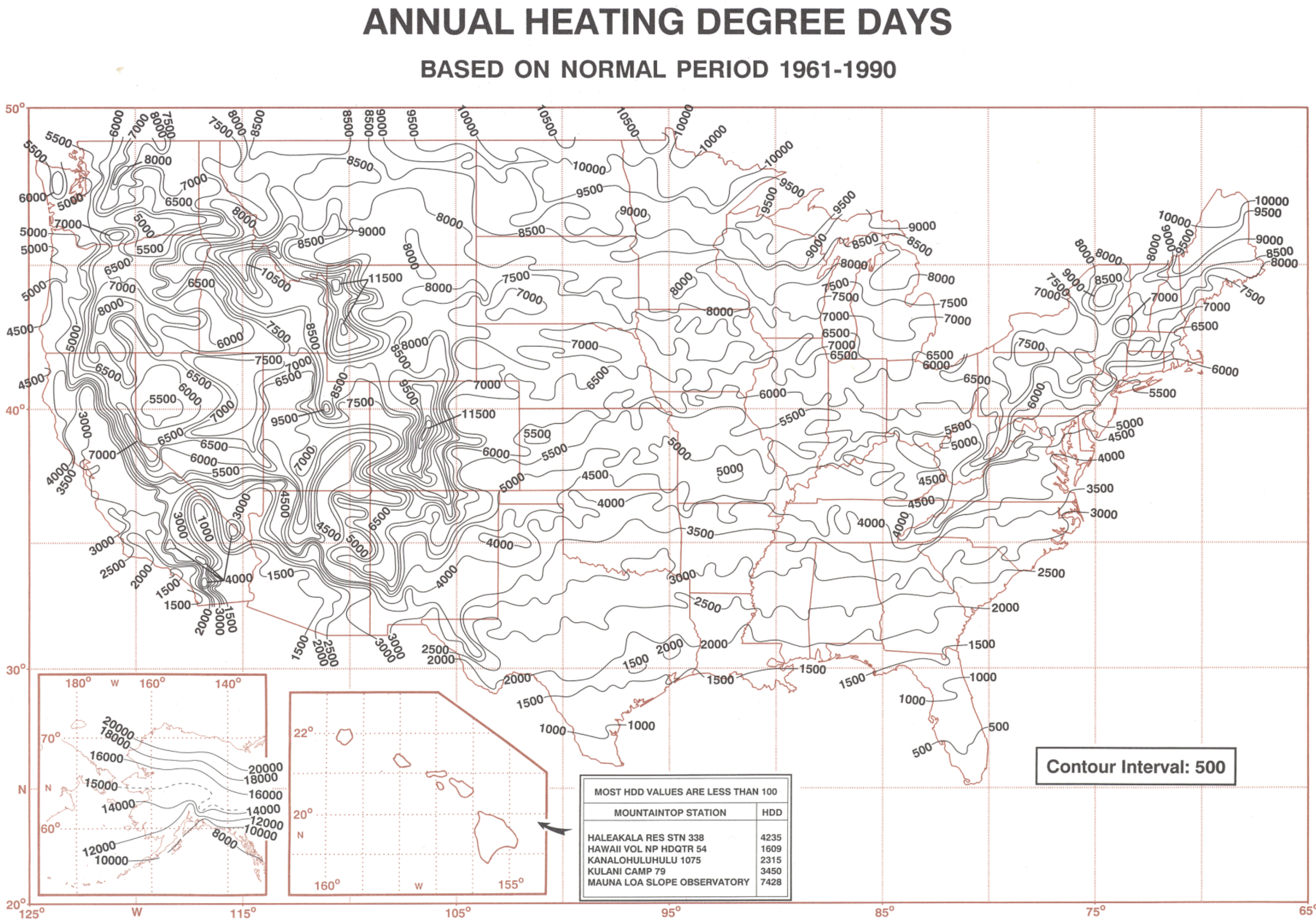
Assume $\rho \approx 0.075\,\tfrac{\text{lb}}{\text{ft}^3},\; C_p \approx 0.24\,\tfrac{\text{Btu}}{\text{lb°F}},\; T_{in} = 68$°F:

$$T_{bal} = 68 - \frac{5000}{250 + 7000(0.075)(.24)} = 68 - 13.3 = 54.7\text{°F}$$

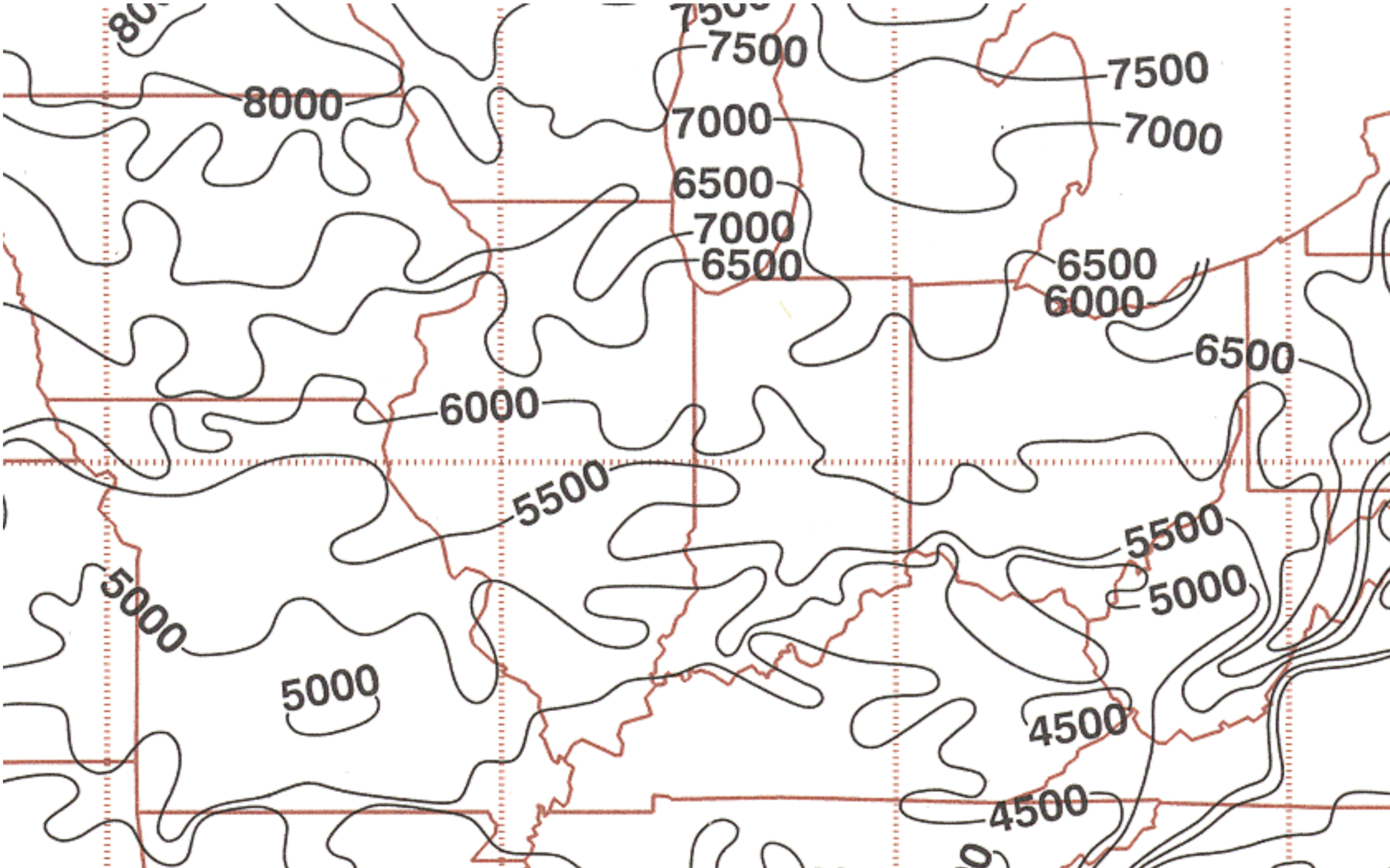
Online CDD/HDD calculators

- There are a number of online calculators that use TMY (typical meteorological year) data
  - http://www.degreedays.net/
  - http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/
  - http://pnwpest.org/cgi-bin/usmapmaker.pl

HDD_{65F} maps


ANNUAL HEATING DEGREE DAYS
BASED ON NORMAL PERIOD 1961-1990
Contour Interval: 500
MOST HDD VALUES ARE LESS THAN 100
MOUNTAINTOP STATION HDD
HALEAKALA RES STN 338 4235
HAWAII VOL NP HDQTR 54 1609
KANALOHULUHULU 1075 2315
KULANI CAMP 79 3450
MAUNA LOA SLOPE OBSERVATORY 7428

HDD_{65F} maps


8000
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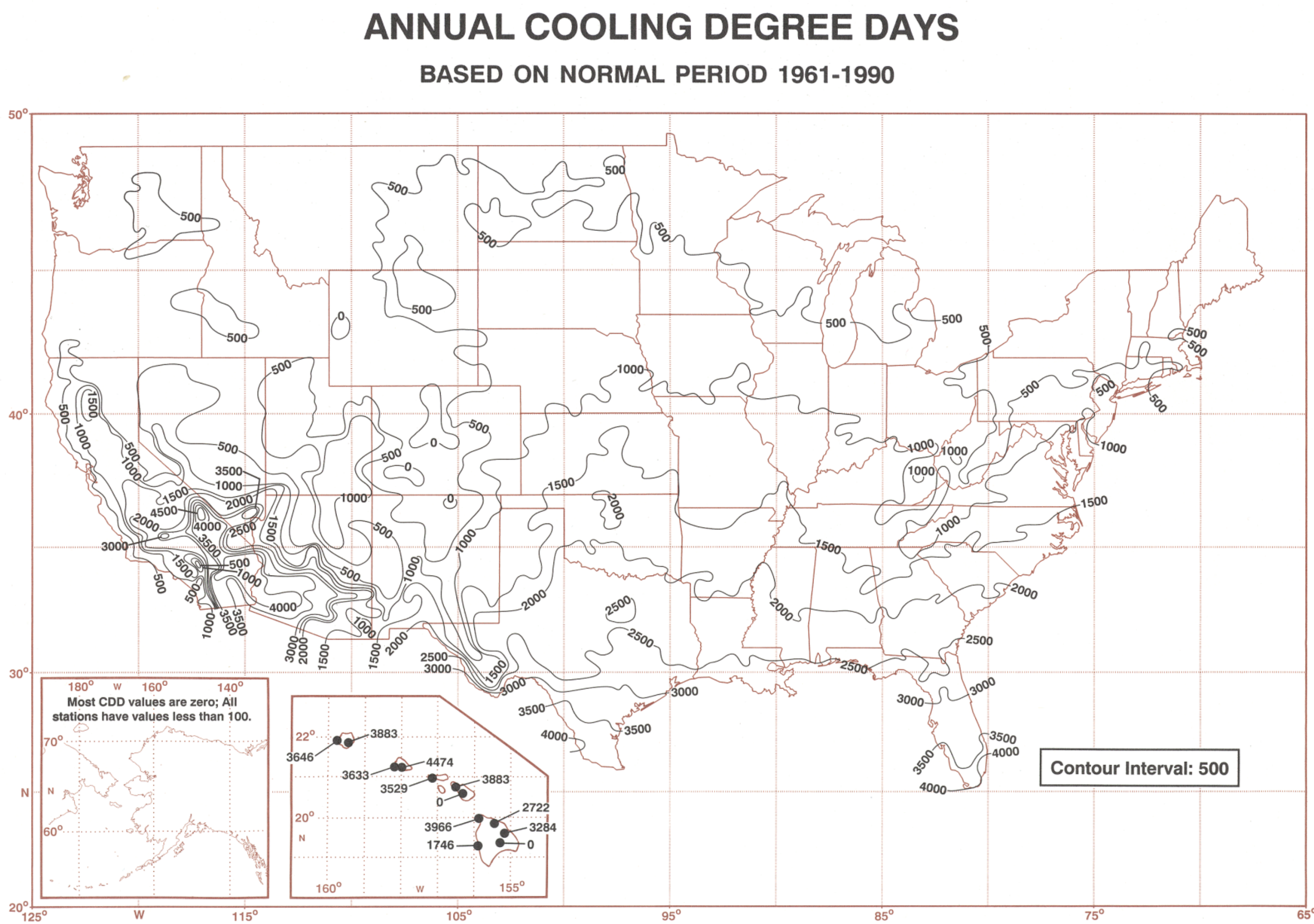
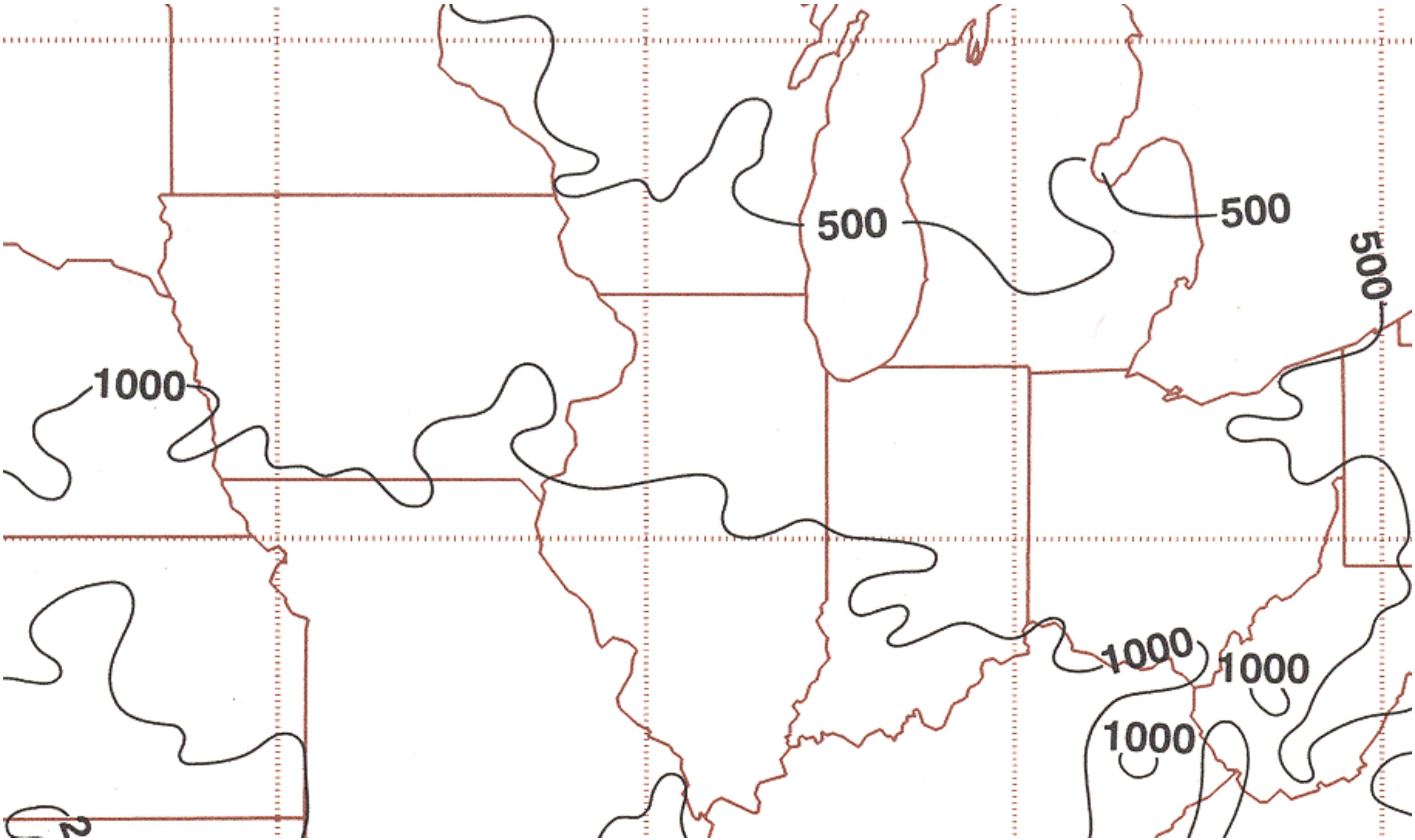
CDD$_{65F}$ maps


ANNUAL COOLING DEGREE DAYS
BASED ON NORMAL PERIOD 1961-1990
Most CDD values are zero; All stations have values less than 100.
Contour Interval: 500

CDD_{65F} maps



Chicago Area HDD/CDD (Fahrenheit)

- HDD65 = 6280 and CDD65 = 1115
- HDD60 = 5080 and CDD60 = 1740
- HDD55 = 4220 and CDD55 = 2500
- HDD50 = 3080 and CDD50 = 3400
- HDD45 = 2280 and CDD45 = 4420

- All units are in °F-days

Estimating energy use with HDD

- Now that we know how to get HDD, we can calculate the heating energy, E, required to keep the building heated

- Using hourly values:

$$E_{heating} = \frac{(UA)_{total}}{\eta} \int [T_{bal} - T_{out}(t)]\,dt \quad \text{when} \quad T_{out} < T_{bal}$$

Where η = heating system efficiency (-)

- Using HDD:

$$E_{heating} = \frac{(UA)_{total}}{\eta} HDD$$

*Convert HDD to degree-seconds

Estimating energy use with HDD

- Example problem 8.1
- Find the annual heating bill for a house in New York under the following conditions:
  - UA_{total} = 205 W/K
  - Heat gain = 569 W
  - T_{in} = 21.1 degrees C
  - Heating system is 75% efficient
  - Fuel prices is $8/GJ
  - HDD = 2800 K-days

1. Find balance temperature
2. Estimate energy requirements
3. Estimate costs

Estimating cooling energy use

- Estimates for cooling energy are not as accurate but we can still use them

$$E_{cooling} = \frac{(UA)_{total}}{COP} \int [T_{bal} - T_{out}(t)]\,dt \quad \text{when} \quad T_{out} > T_{bal}$$

$$E_{cooling} = \frac{(UA)_{total}}{COP} CDD$$

*Make sure time units align

Bin method

- The Bin Method is another variation of the degree-day method where we break down the year into temperature ranges or “bins” and compute the energy use in each of the bins
  - 5 degree temperature ranges are usually used

- In this method, we can easily account for:
  - Varying loads
  - Varying heating/cooling systems
  - Varying system efficiencies
    - This is especially important for air-conditioner units and heat pumps where the efficiency depends greatly on the temperature at which it is working

Bin method

- We need to find the number of hours (N_{bin}) that the outdoor temperature (t_o) is in a temperature bin

$$Q_{bin} = N_{bin}\frac{K_{tot}}{\eta_h}[t_{bal} - t_o]^{+}$$

Table 7 Sample Annual Bin Data

	Bin																				
Site	39/ 41	36/ 38	33/ 35	30/ 32	27/ 29	24/ 26	21/ 23	18/ 20	15/ 17	12/ 14	9/ 11	6/ 8	3/ 5	0/ 2	–3/ –1	–6/ –4	–9/ –7	–12/ –10	–15/ –13	–18/ –16	–21/ –19
Chicago, IL			74	176	431	512	960	660	591	780	510	770	686	1671	380	304	125	66	49	11	4
Dallas/Ft. Worth, TX	4	170	322	511	922	1100	1077	750	803	870	581	728	418	464	37	3					
Denver, CO			81	217	406	390	570	726	712	902	809	783	750	1467	446	216	106	85	52	44	8
Los Angeles, CA	4	10	9	16	56	194	1016	1874	2280	2208	843	227	23								
Miami, FL			14	648	2147	2581	1852	734	390	202	100	76	14	2							
Nashville, TN		4	82	366	717	756	1291	831	693	801	670	858	639	793	141	89	29				
Seattle, WA				10	88	139	330	497	898	1653	1392	1844	1127	715	40	26	1				

Bin method

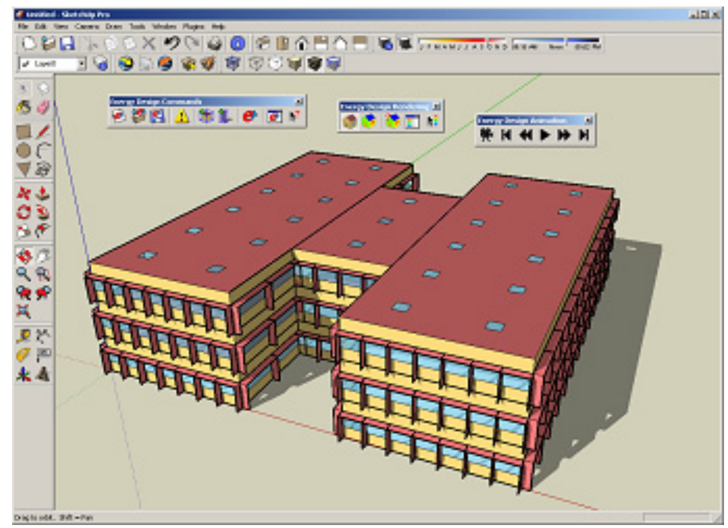
Table 8 Calculation of Annual Heating Energy Consumption for Example 4

Climate			House	Heat Pump							Supplemental		
A	B	C	D	E	F	G	H	I	J	K	L	M	N
Temp. Bin, °C	Temp. Diff., $t_{bal} - t_{bin}$	Weather Data Bin, h	Heat Loss Rate, kW	Heat Pump Integrated Heating Capacity, kW	Cycling Capacity Adjustment Factor[a]	Adjusted Heat Pump Capacity, kW[b]	Rated Electric Input, kW	Operating Time Fraction[c]	Heat Pump Supplied Heating, kWh[d]	Seasonal Heat Pump Electric Consumption, KWh[e]	Space Load, kWh[f]	Supplemental Heating Required, kWh[g]	Total Electric Energy Consumption, kWh[h]
16	1.8	693	0.70	12.80	0.764	9.78	3.74	0.072	488	187	485	—	187
13	4.8	801	1.87	12.01	0.789	9.48	3.63	0.197	1 496	573	1 497	—	573
10	7.8	670	3.04	11.22	0.818	9.18	3.52	0.331	2 036	781	2 037	—	781
7	10.8	858	4.21	9.80	0.857	8.40	3.40	0.501	3 611	1 462	3 612	—	1 462
4	13.8	639	5.38	8.49	0.908	7.71	3.18	0.698	3 439	1 418	3 438	—	1 418
1	16.8	793	6.55	7.98	0.955	7.62	3.10	0.860	5 196	2 114	5 195	—	2 114
–2	19.8	141	7.72	7.47	1.000	7.47	3.02	1.000	1 053	426	1 089	36	462
–5	22.8	89	8.89	6.95	1.000	6.95	2.93	1.000	618	261	791	173	434
–8	25.8	29	10.06	6.48	1.000	6.48	2.85	1.000	188	83	292	104	187
–11	28.8	0	11.23	5.69	1.000	—	—	—	—	—	—	—	—
								Totals:	18 125	7 305	18 436	313	7 618

[a]Cycling Capacity Adjustment Factor = 1 – $C_d(1 - x)$, where C_d = degradation coefficient (default = 0.25 unless part load factor is known) and x = building heat loss per unit capacity at temperature bin. Cycling capacity = 1 at the balance point and below. The cycling capacity adjustment factor should be 1.0 at all temperature bins if the manufacturer includes cycling effects in the heat pump capacity (Column E) and associated electrical input (Column H).
[b]Column G = Column E × Column F
[c]Operating Time Factor equals smaller of 1 or Column D/Column G
[d]Column J = Column I × Column G × Column C
[e]Column K = Column I × Column H × Column C
[f]Column L = Column C × Column D
[g]Column M = Column L – Column J
[h]Column N = Column K + Column M

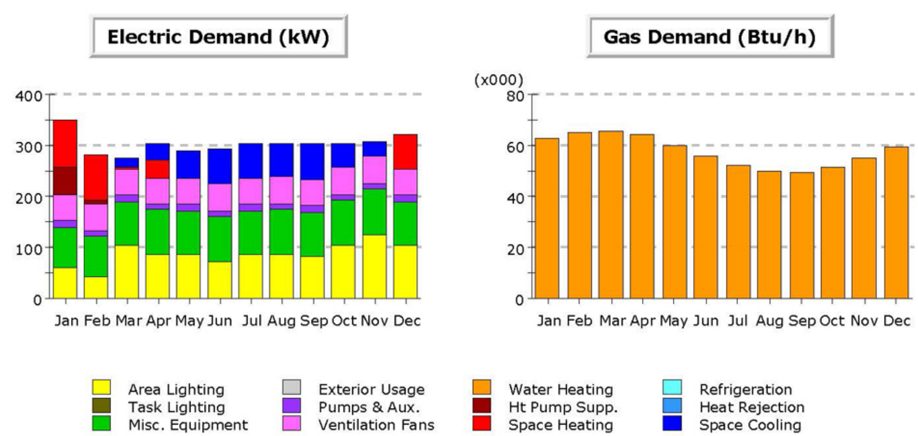
Annual energy estimation

- While these methods are good for rough estimates, it is best to perform whole building energy simulations using software to get better estimates



- EnergyPlus
- eQUEST
- IES-VE
- TRNSYS
- Many others

http://apps1.eere.energy.gov/buildings/tools_directory/subjects.cfm/pagename=subjects/pagename_menu=whole_building_analysis/pagename_submenu=energy_simulation



FLUID FLOWS

For distribution systems

Fluid flows in buildings

- We use liquids and gases to deliver heating or cooling energy in building mechanical systems
  - Water, refrigerants, and air
- We often need to understand fluid motion, pressure loses, and pressure rises by pumps and fans in order to size systems
  - And to understand how much power they draw and how well they perform when they are operating
- We can use the Bernoulli equation to describe fluid flows in HVAC systems:

$$\mathrm{p}_1 + \frac{1}{2}\rho_1 v_1^2 + \rho_1 g h_1 = \mathrm{p}_2 + \frac{1}{2}\rho_2 v_2^2 + \rho_2 g h_2 + K\frac{v^2}{2}$$

Static pressure

Velocity pressure

Pressure head

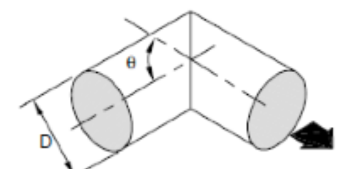
Friction

Pressure losses

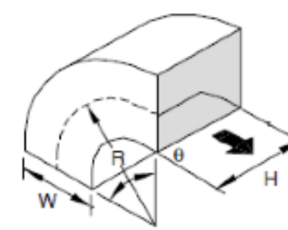
- We often need to find the pressure drop in pipes and ducts
- Most flows in HVAC systems are turbulent

$$\Delta p_{friction} = f\left(\frac{L}{D_h}\right)\left(\frac{1}{2}\rho v^2\right)$$

$$D_h = \frac{4A}{P} = \text{hydraulic diameter}$$

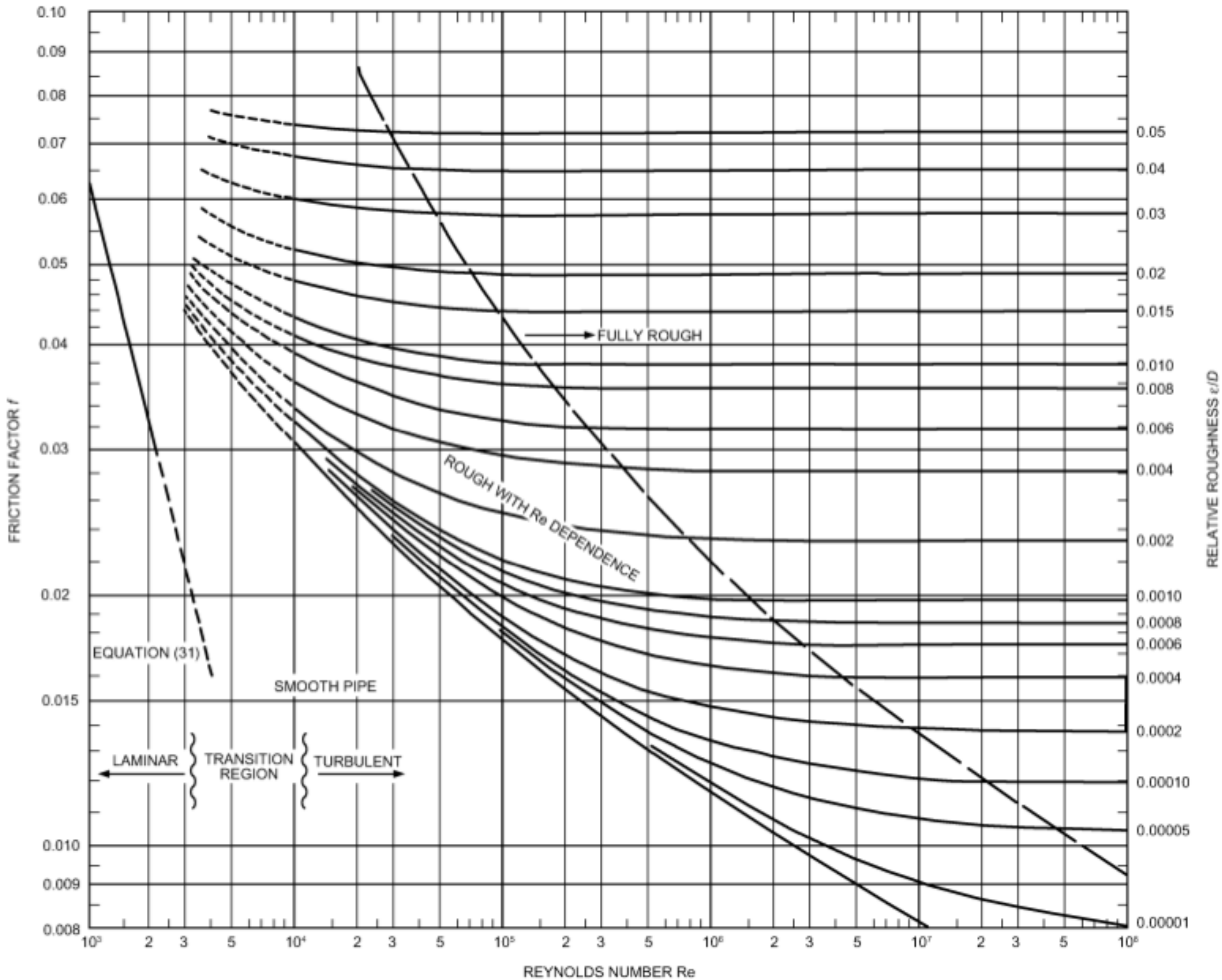


$$K = f\left(\frac{L}{D_h}\right)$$ In a straight pipe



$$K = f\left(\frac{L}{D_h} + \sum_{fittings} K_f\right)$$ In a straight pipe with fittings

Friction factor



$$\mathrm{Re} = \frac{VL}{\nu}$$

Reynolds number

- Reynolds number relates inertial forces to viscous forces:

$$\mathrm{Re} = \frac{VL}{\nu}$$

- Kinematic viscosity

$$\nu = \frac{\mu}{\rho} = 1.5 \times 10^{-5}\ \frac{\mathrm{m}^2}{\mathrm{s}}\ \text{(for air at T=25°C)}$$

L = D_h in a pipe or duct

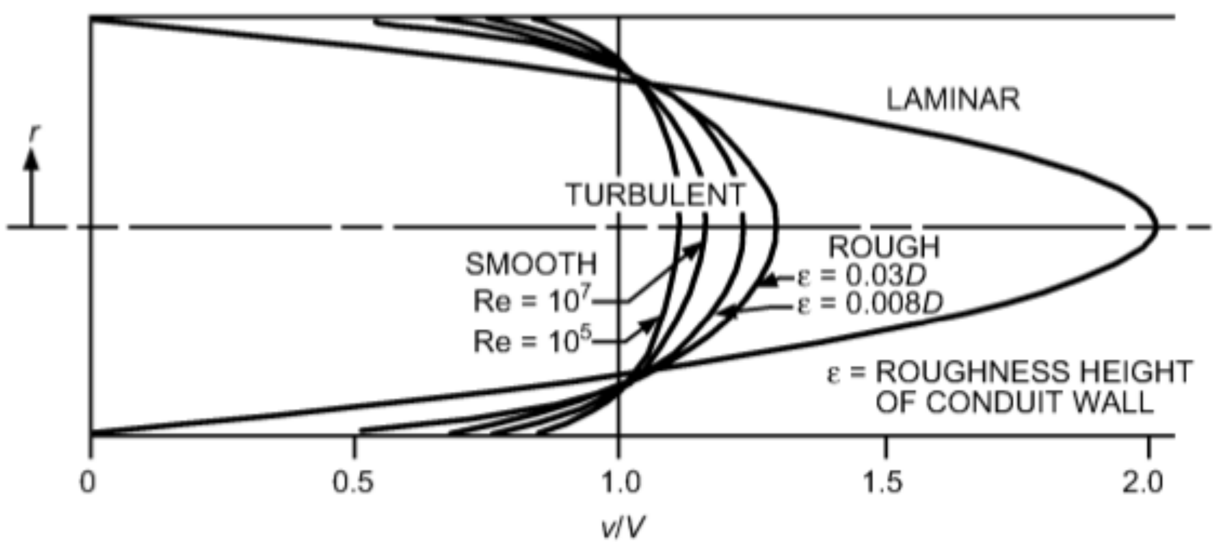
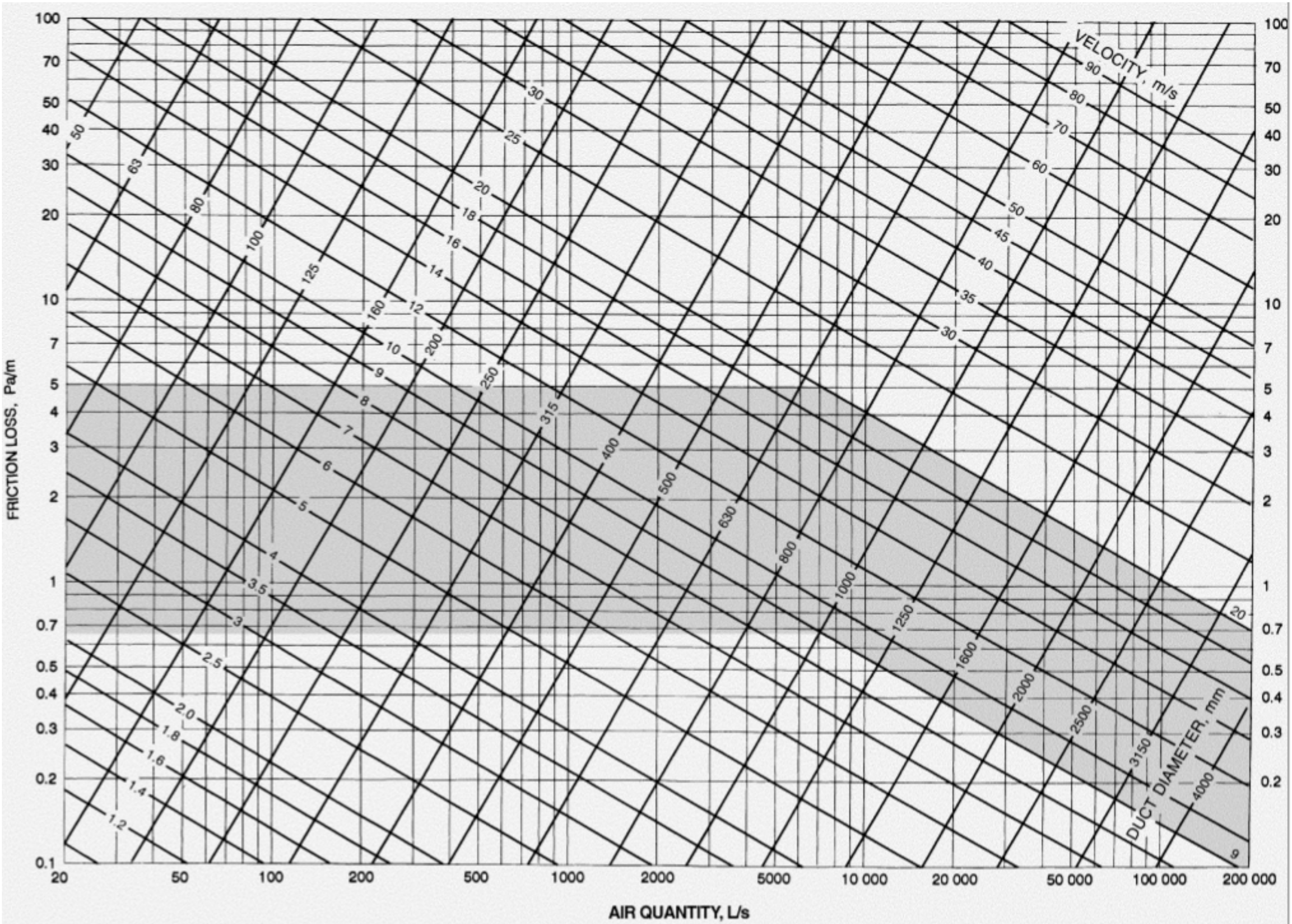
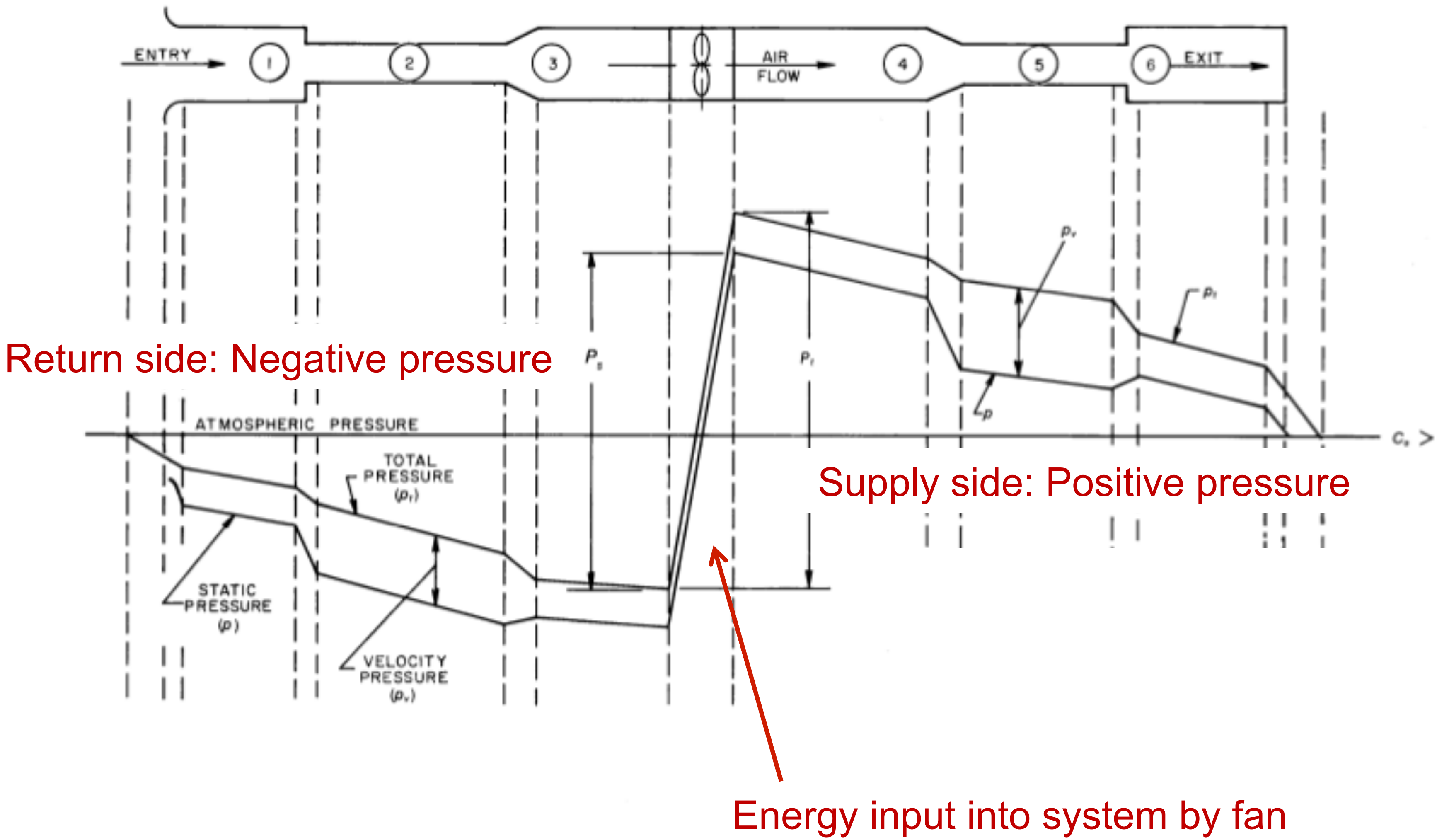


Fig. 4 Velocity Profiles of Flow in Pipes

Duct friction charts

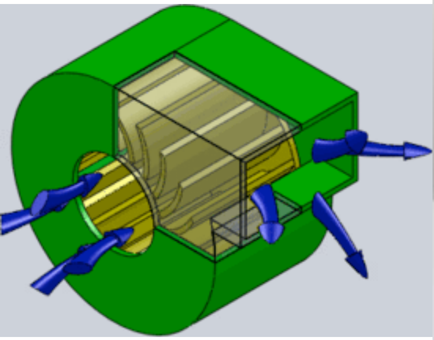


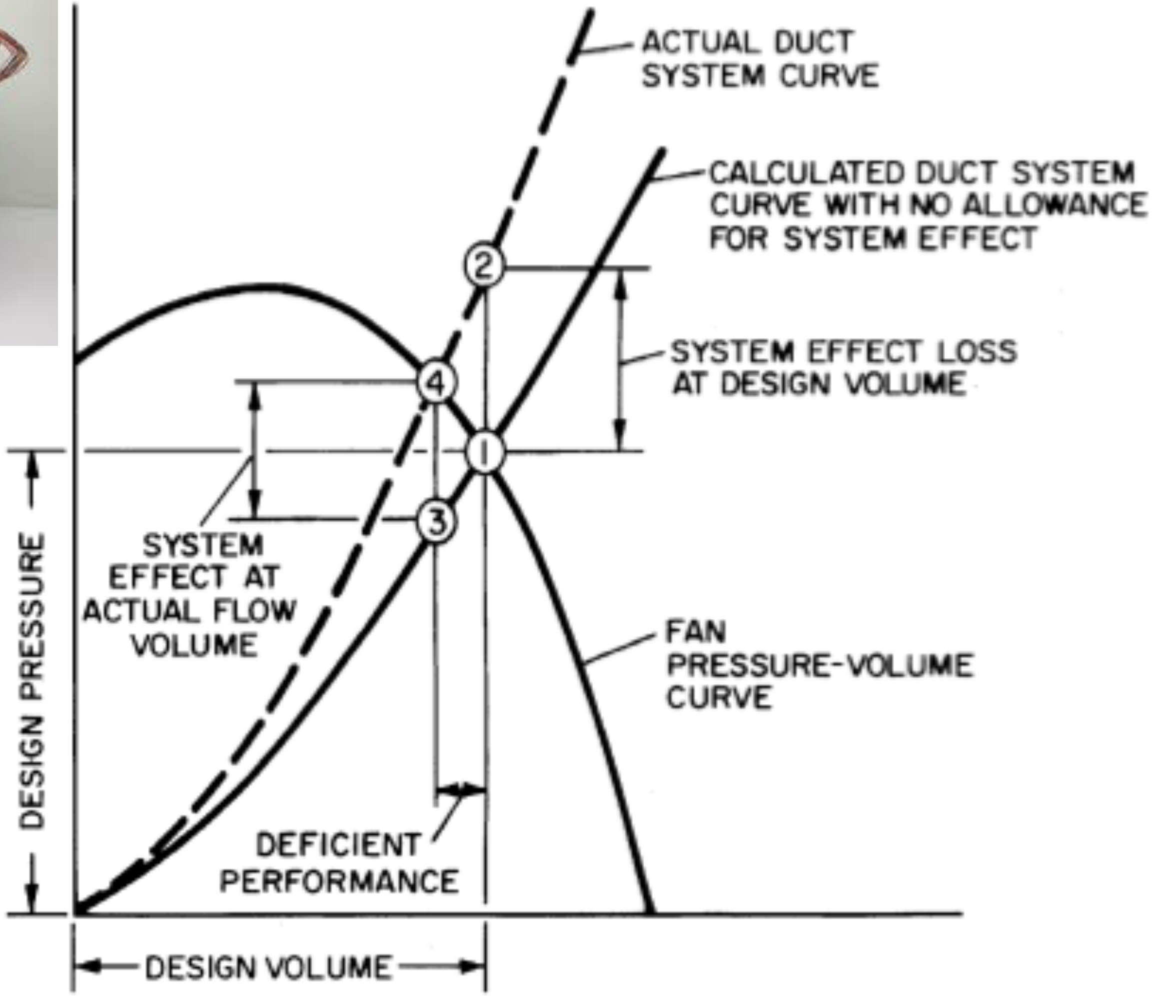
Pressure losses and gains in distribution systems



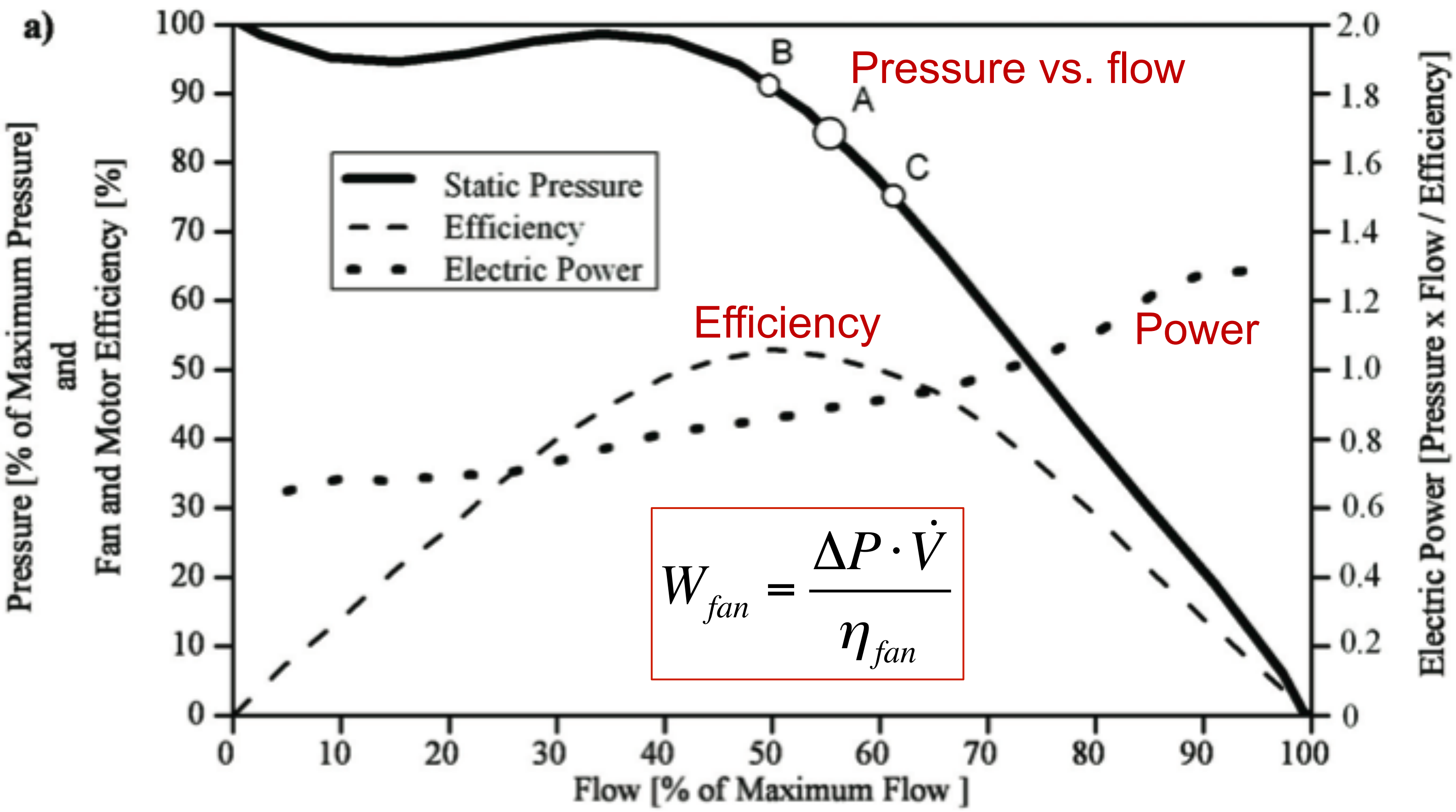
Fan and system pressures

- Fan curves and system curves



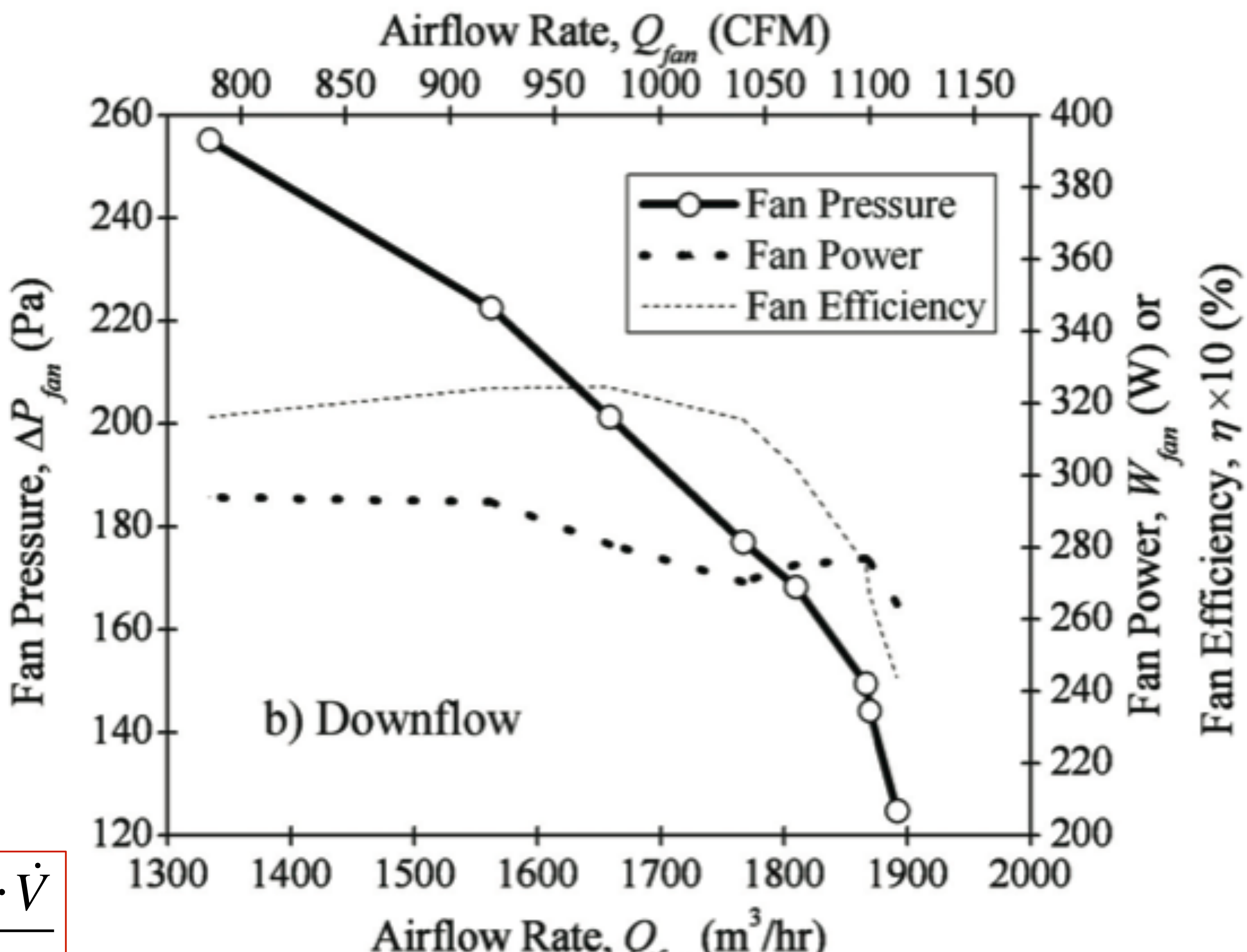


Fan and system curves: Ideal



$$W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}$$

Fan and system curves: Real



$$W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}$$

ENERGY EFFICIENCY IN BUILDINGS

Designing for efficiency

- We can’t change HDD and CDD, so what can we do?

- Reduce UA (including infiltration)
- Increase COP/efficiency of equipment
- Reduce internal loads and power draws
- Change thermostat settings (affect thermal comfort)
- Utilize passive solar and thermal mass

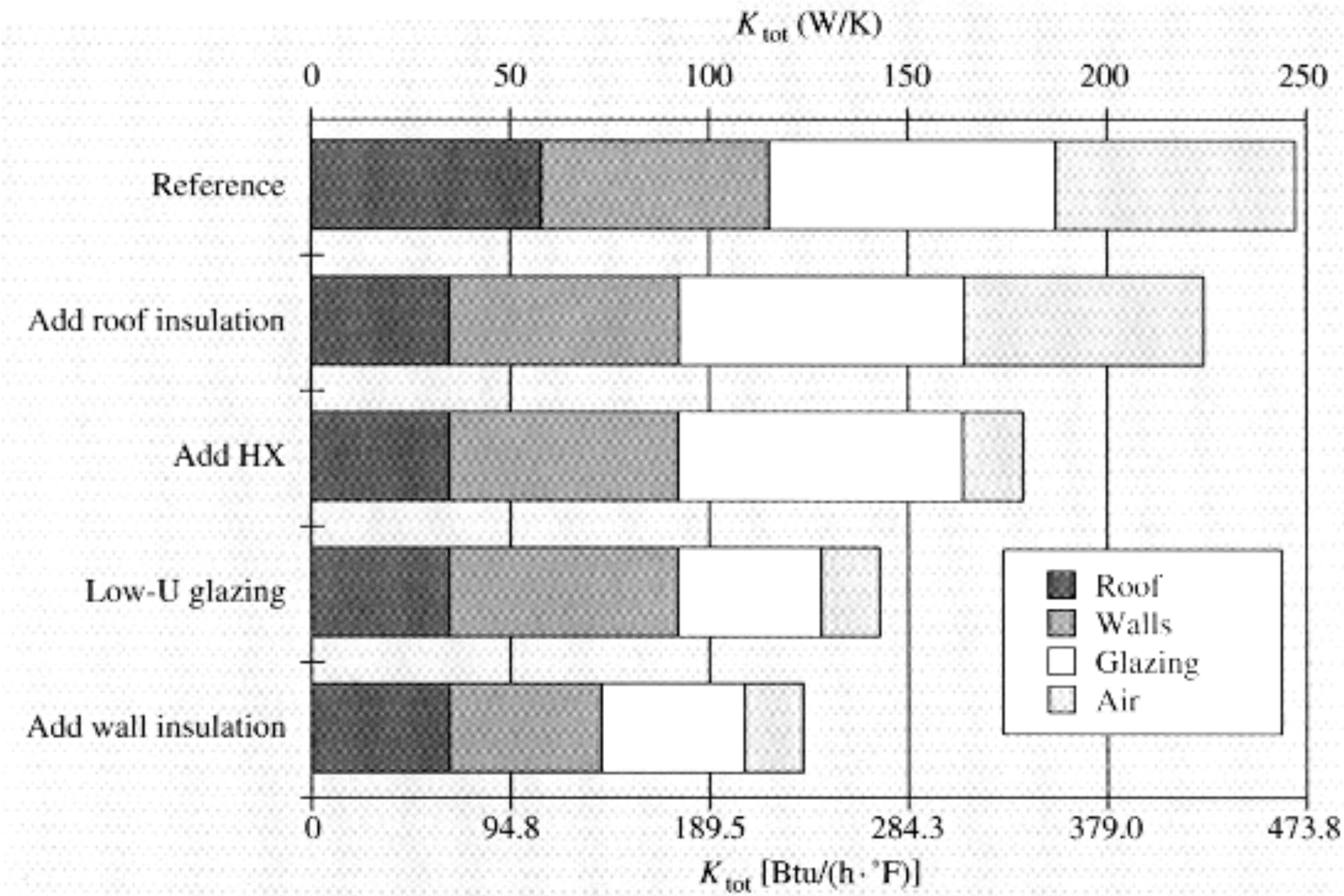
- Many guidelines and certifications exist:
  - RESNET HERS Ratings
  - PassiveHouse
  - LEED (follows ASHRAE)

Designing for efficiency

- ASHRAE Standards and Guidelines
  - Standard 90.1: Energy standard for buildings except low-rise residential buildings
  - Standard 90.2: Energy Efficient Design of Low-Rise Residential Buildings
  - Standard 189.1: Standard for the design of high-performance, green buildings
  - Advanced Energy Guidelines for 30% and 50% savings
- IECC: International Energy Conservation Code
  - From the International Code Council (ICC)
- IRC: International Residential Code

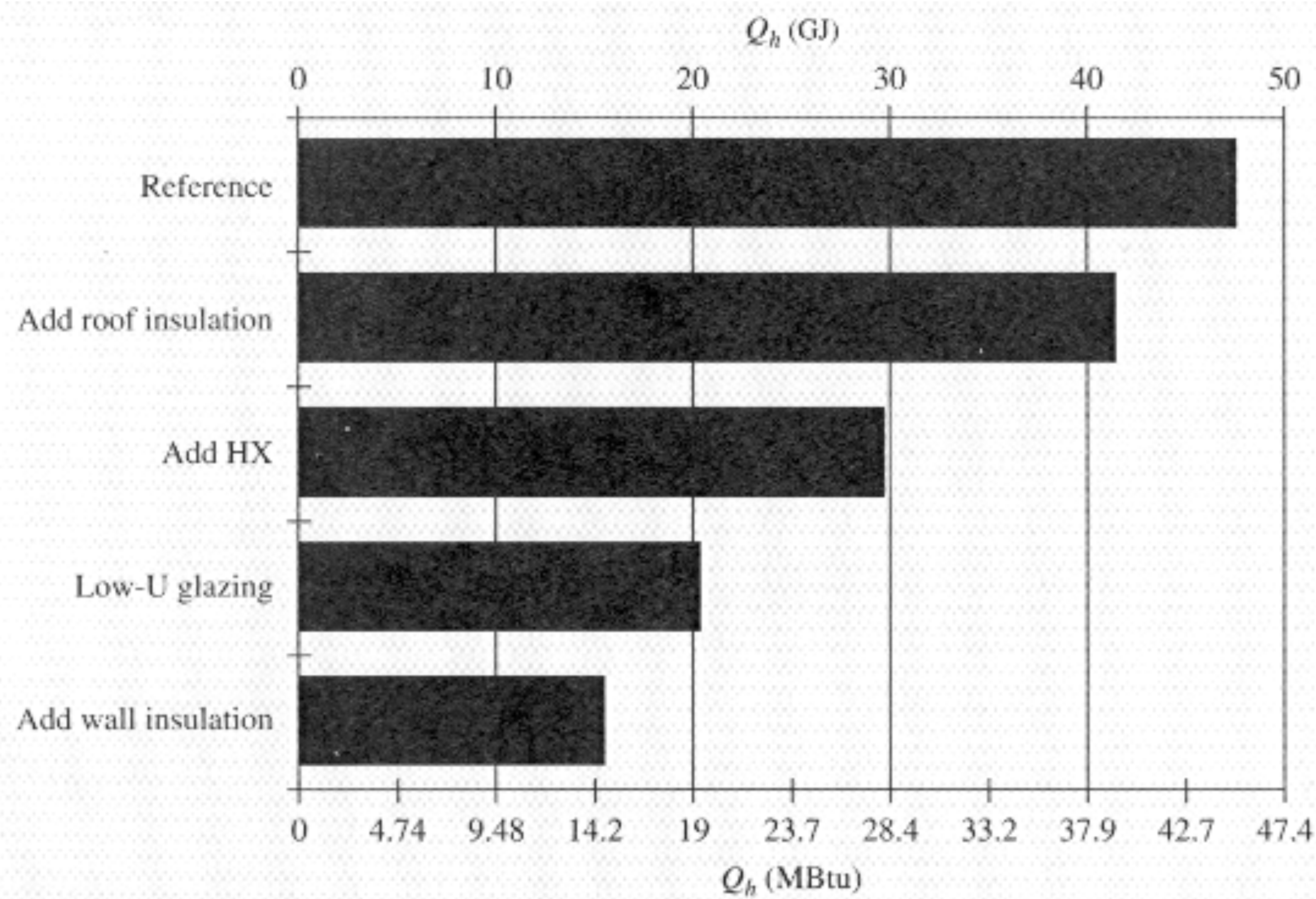
Design for efficiency

- Make changes to the envelope $(UA)_{total}$
  - Parametric changes early in the design phase



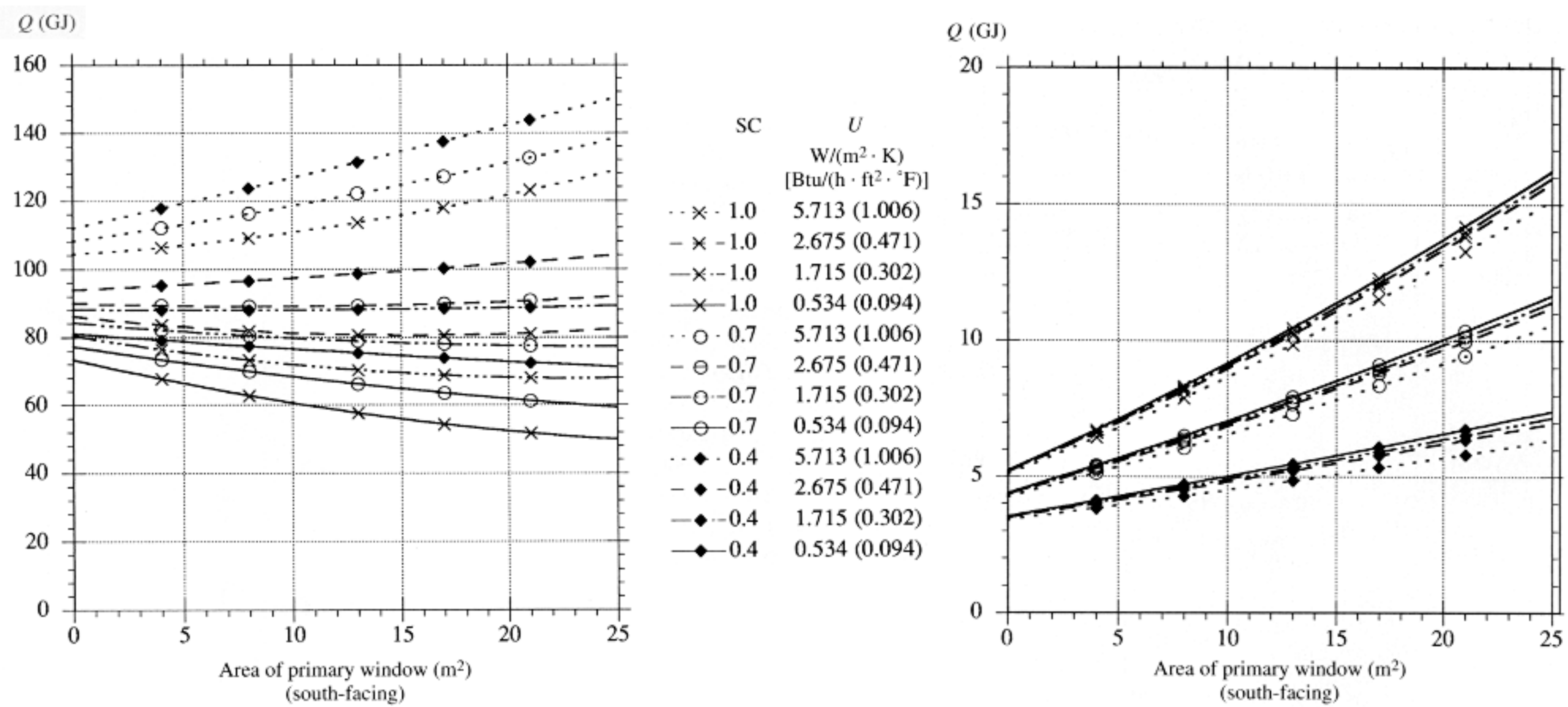
Design for efficiency

- Estimate impact of changes to the envelope $(UA)_{total}$
  - Parametric changes early in the design phase



Design for efficiency

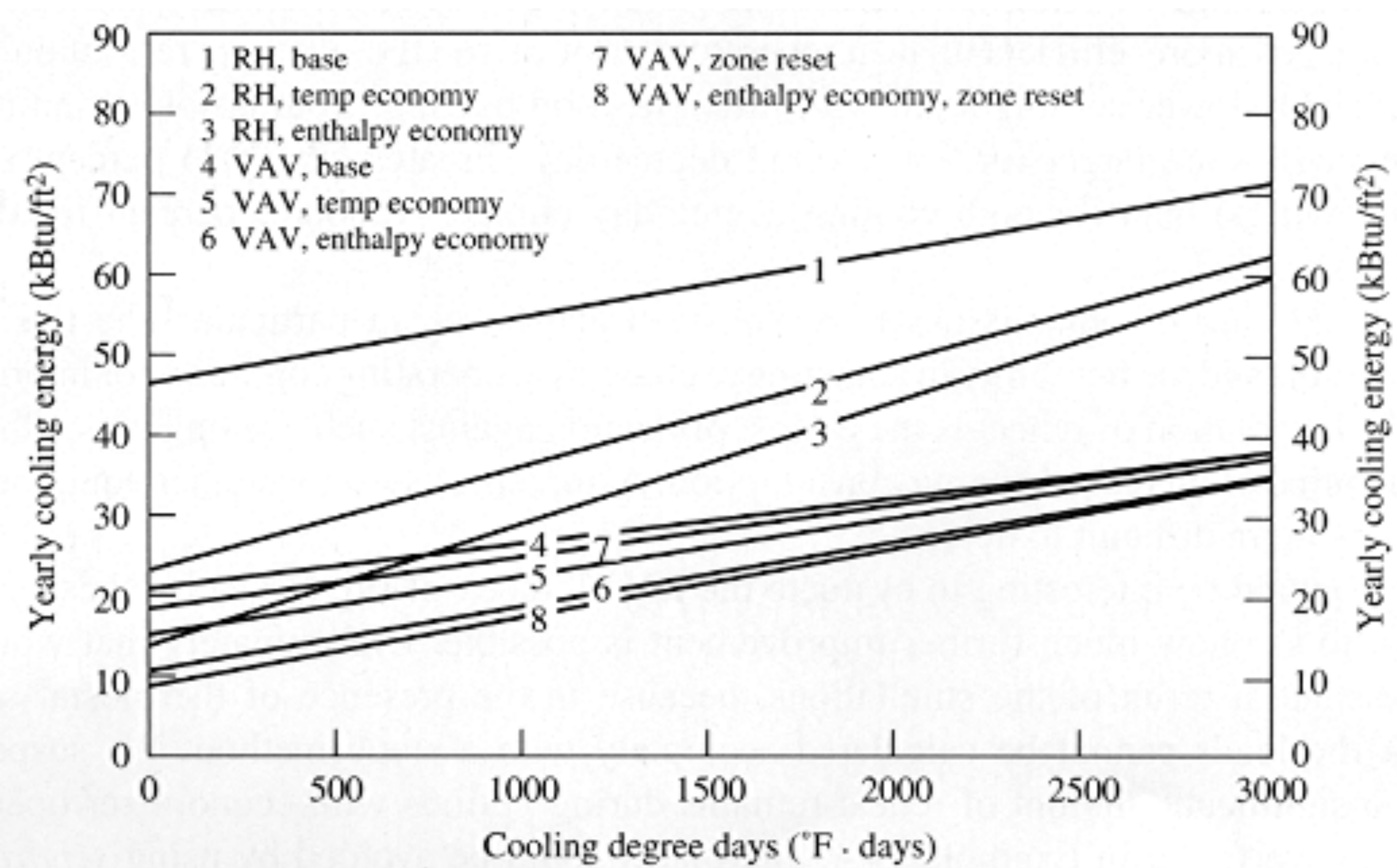
- Parametric studies: Window area, shading, and U-values

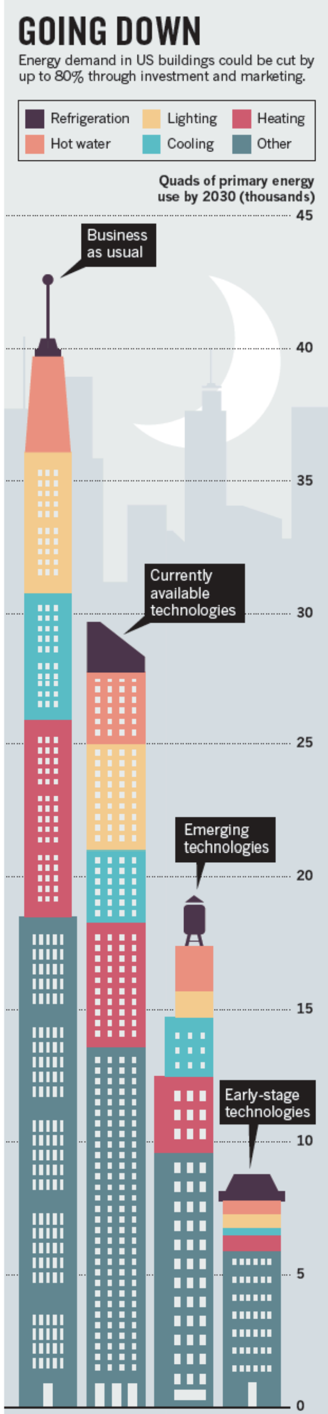


Heating **Cooling**

Design for efficiency

- Parametric studies: Changing HVAC type in an office





Paths toward *lower energy* buildings

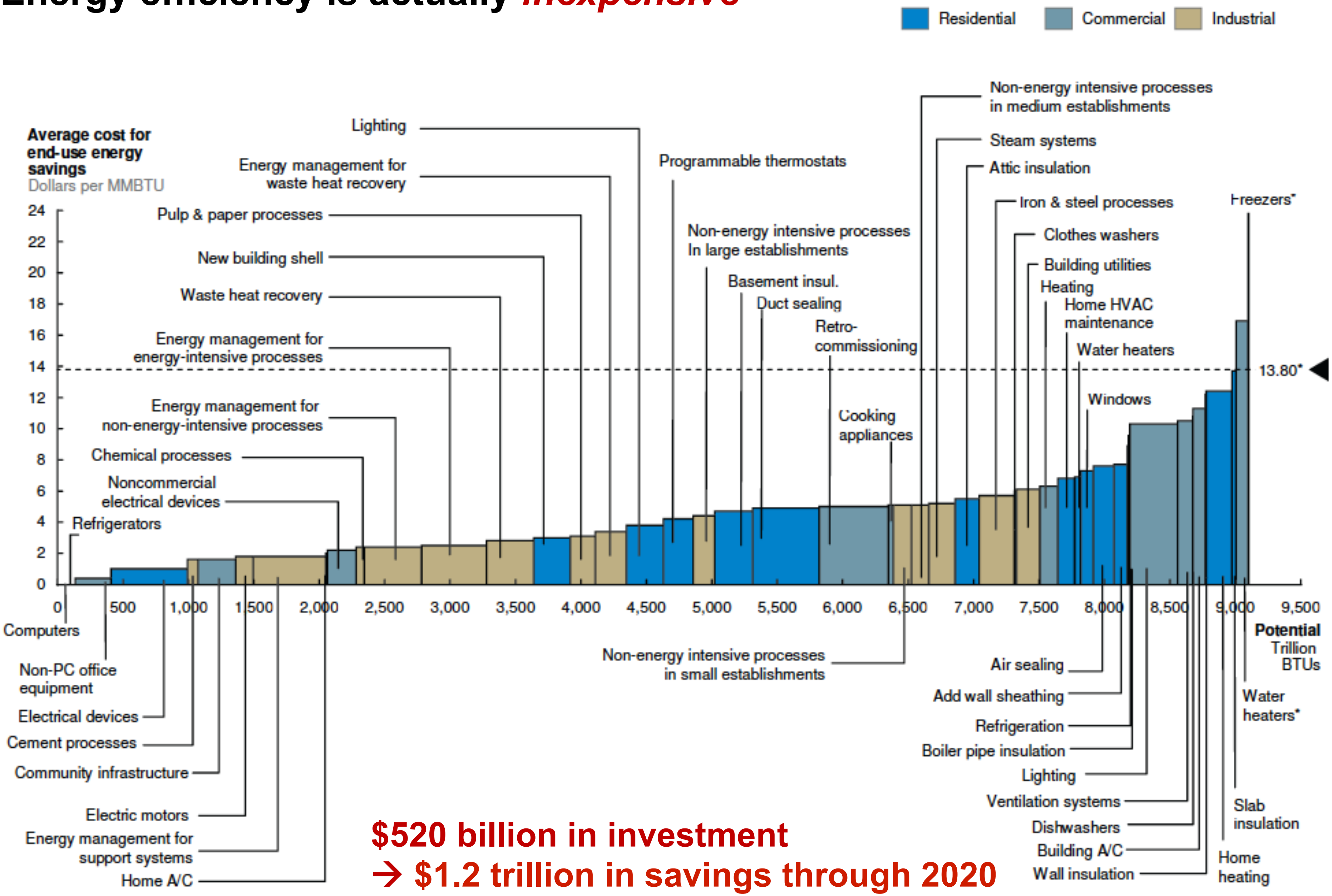
- Efficient building ***systems***
  - Mechanical systems
  - Mechanical driving forces
  - Controls and equipment

- ***Passive*** building design
  - Natural systems
  - Natural driving forces
  - Form and materials

"Energy demand in U.S. buildings could be cut by up to 80% through investment and marketing"

Farese, 2012, How to build a low-energy future. *Nature* 488:275-277

Energy efficiency is actually *inexpensive*



$520 billion in investment
→ $1.2 trillion in savings through 2020

McKinsey & Company, 2009 *Unlocking energy efficiency in the US economy*

Energy use profiles: Actual data

Research highlights from a large scale residential monitoring study in a hot climate

Danny S. Parker*

Florida Solar Energy Center, 1679 Clearlake Road, Cocoa, FL 32922, USA

ENERGY and BUILDINGS

- 204 residences in Florida measured electricity use at 15 minute intervals

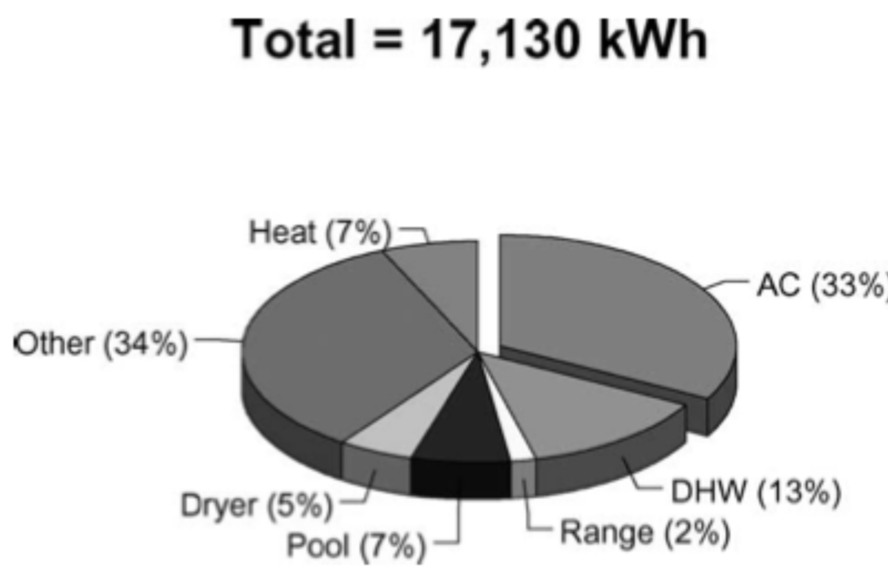
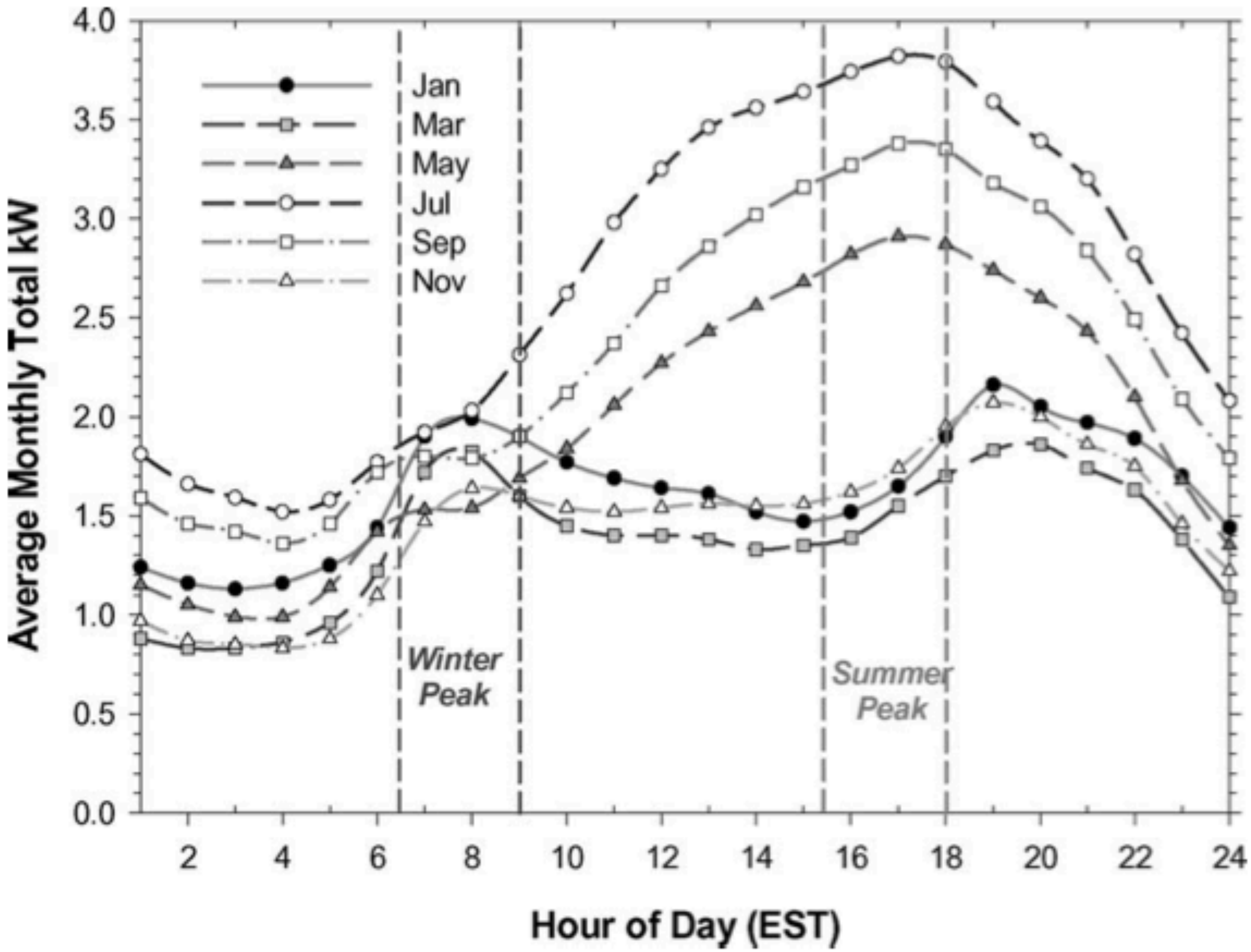


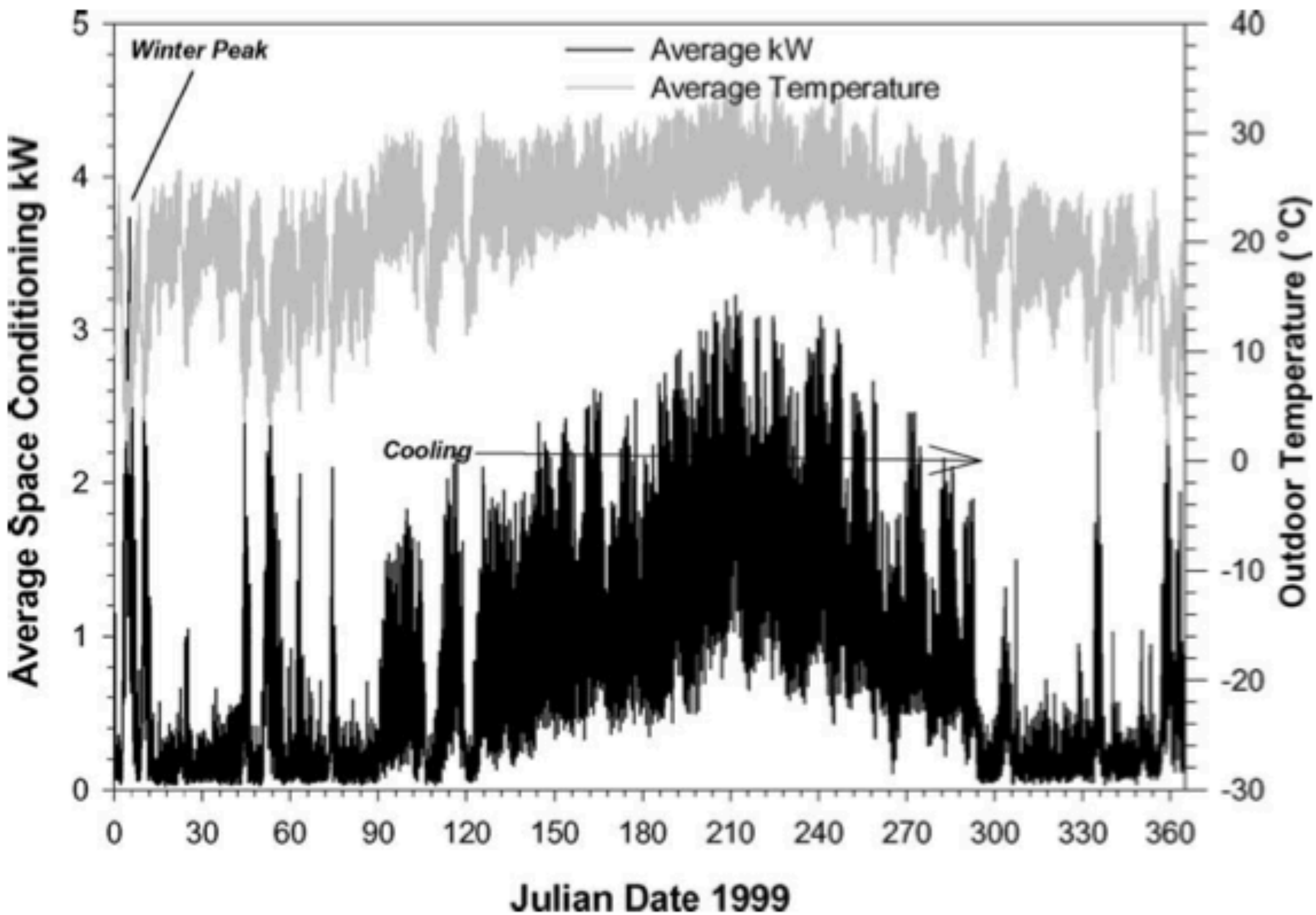
Fig. 1. Percentage of measured electricity consumption by end-use in pure sample (n = 171).

Large scale residential energy monitoring: FL homes



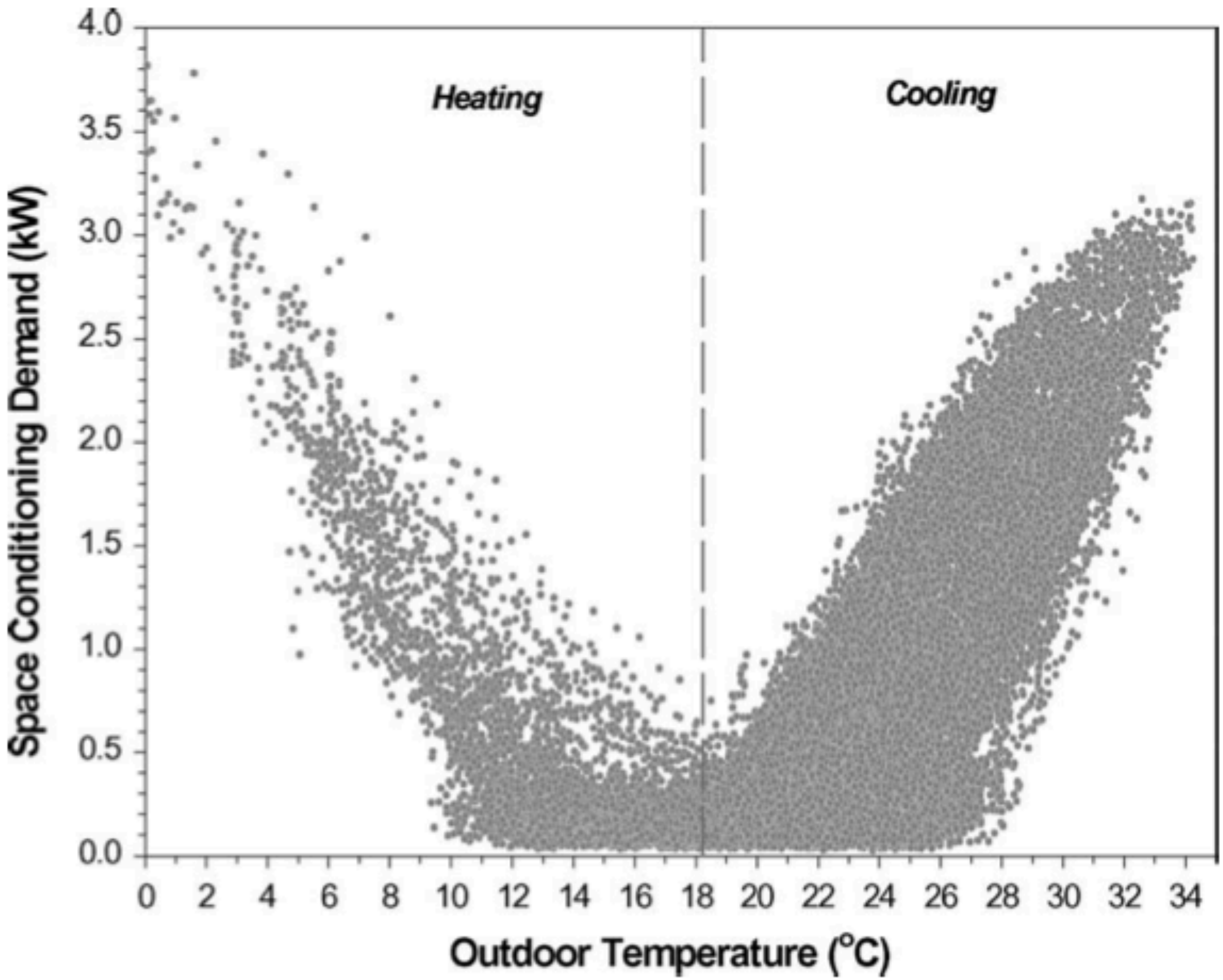
Parker **2003** *Energy and Buildings* 35:863-876

Large scale residential energy monitoring: FL homes



Parker **2003** *Energy and Buildings* 35:863-876

Large scale residential energy monitoring: FL homes



Parker **2003** *Energy and Buildings* 35:863-876

Large scale residential energy monitoring: FL homes

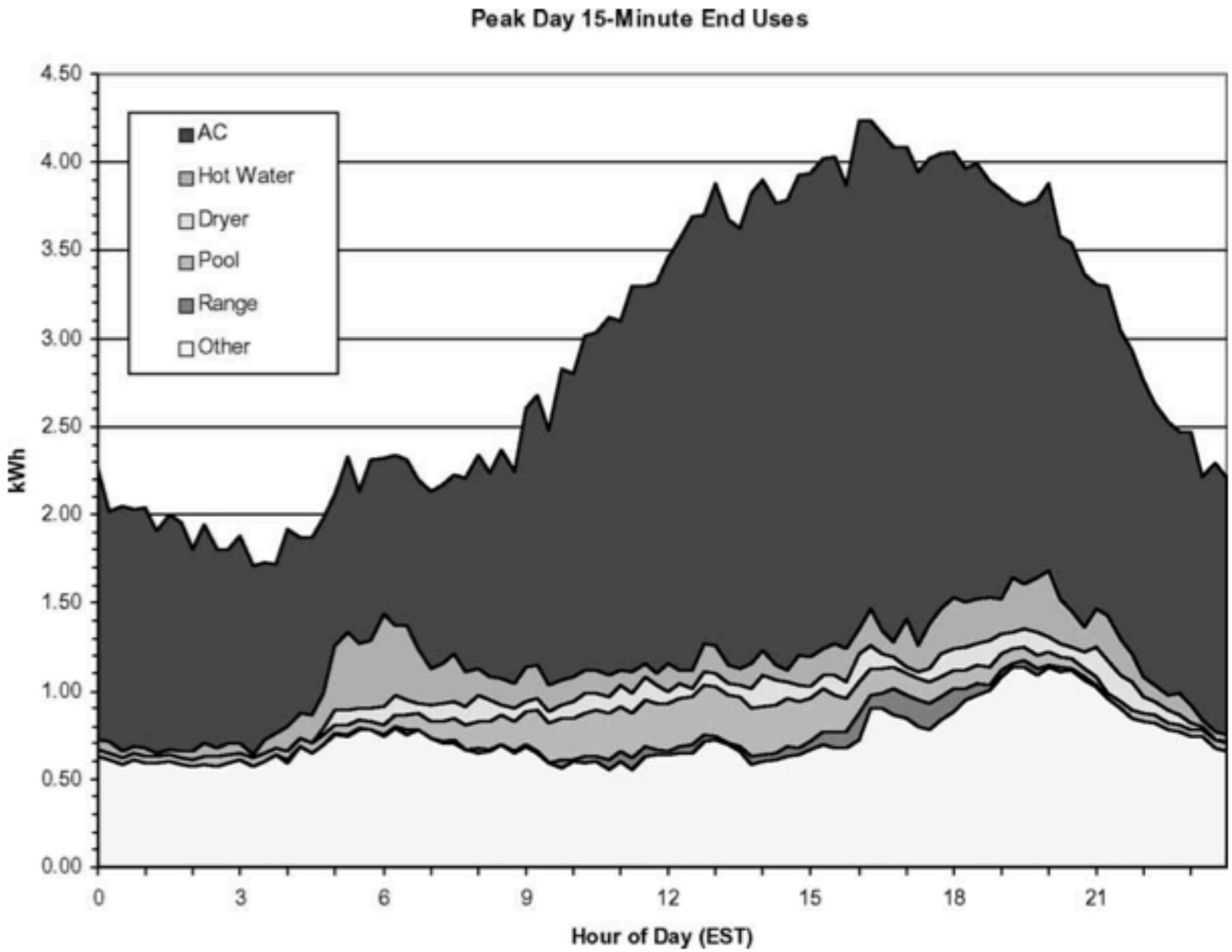


Fig. 8. End-use demand components on summer peak day (30 August 1999).

Parker **2003** *Energy and Buildings* 35:863-876

Large scale residential energy monitoring: FL homes

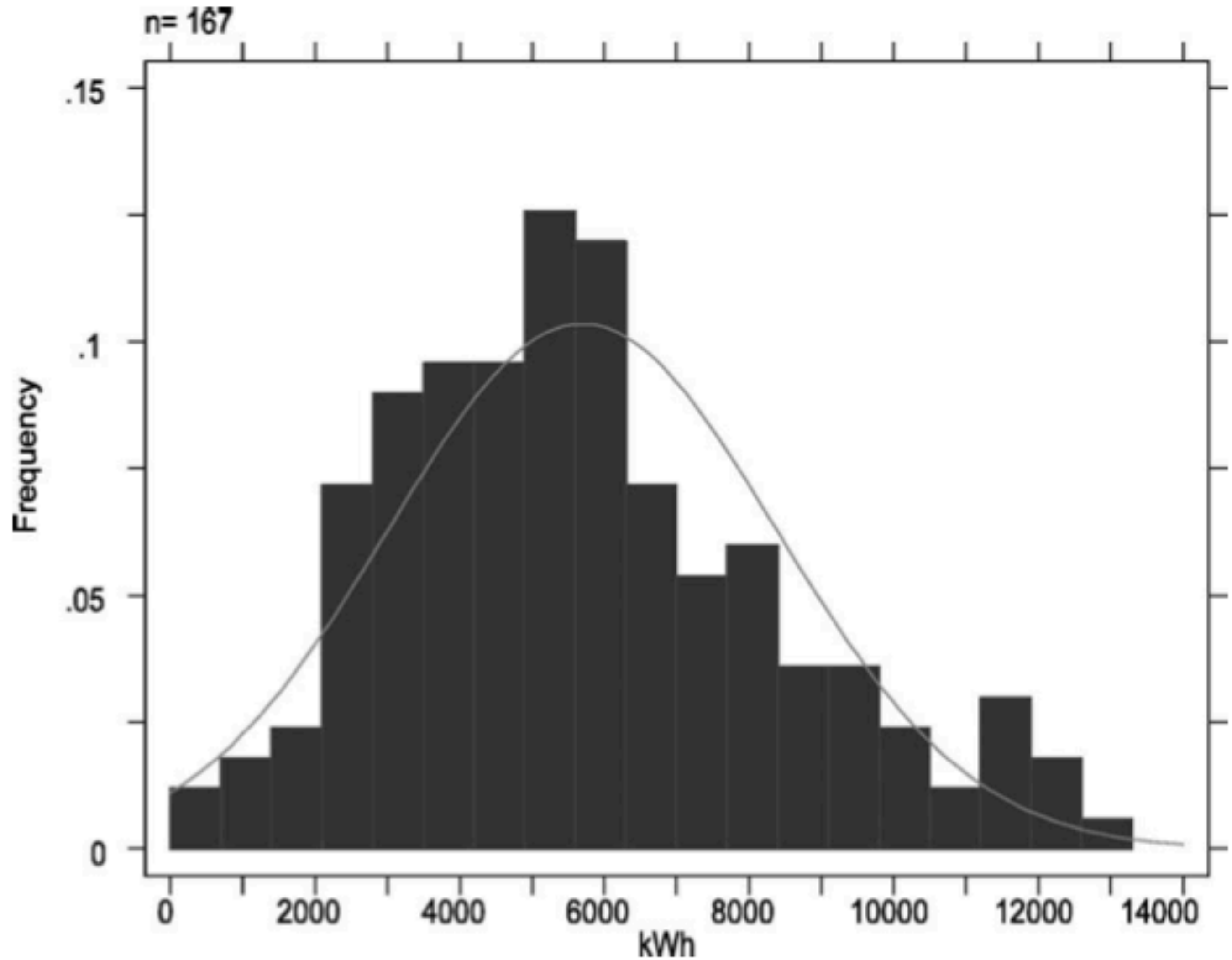
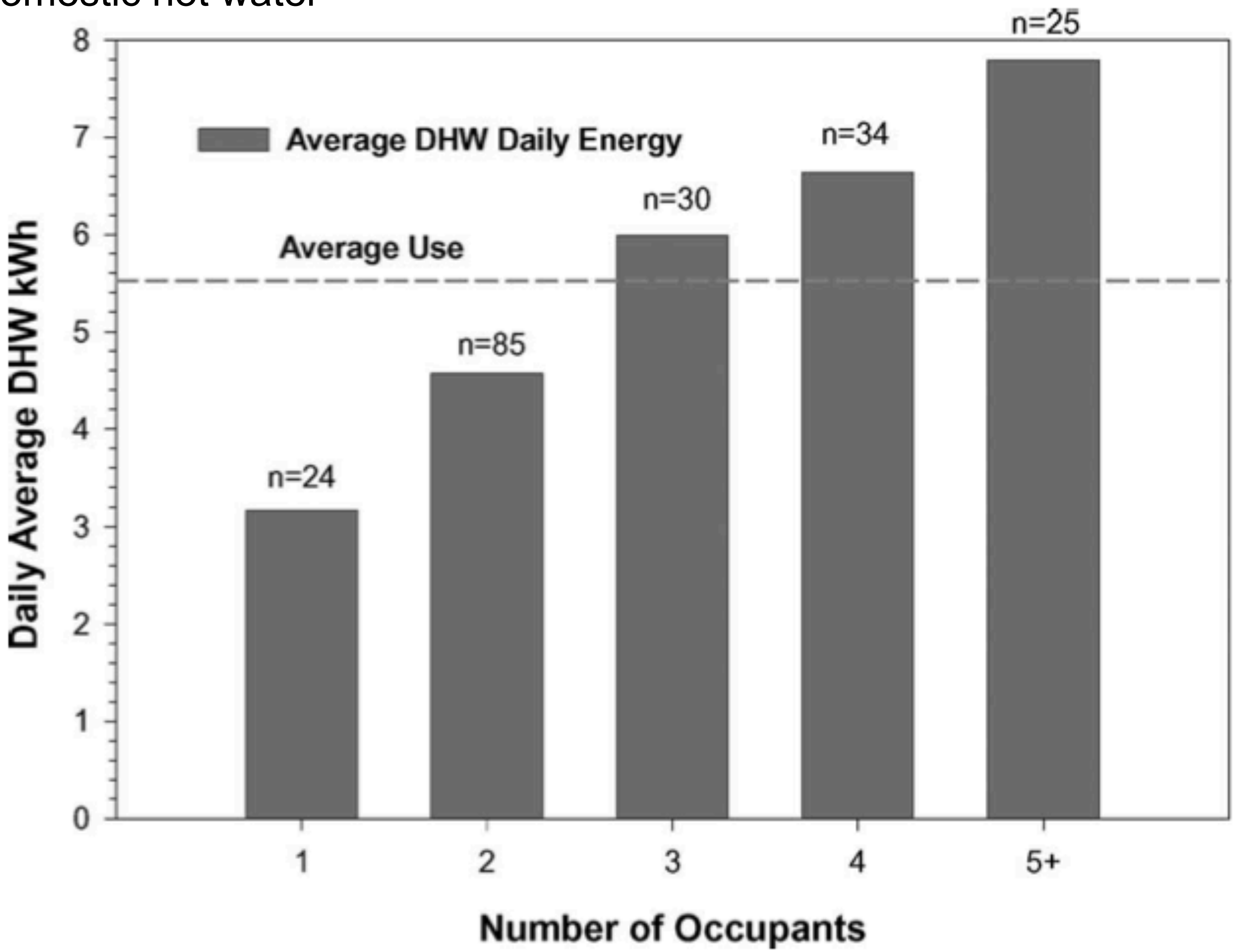


Fig. 9. Frequency distribution of measured cooling energy use. A normal curve is superimposed.

Parker **2003** *Energy and Buildings* 35:863-876

Large scale residential energy monitoring: FL homes

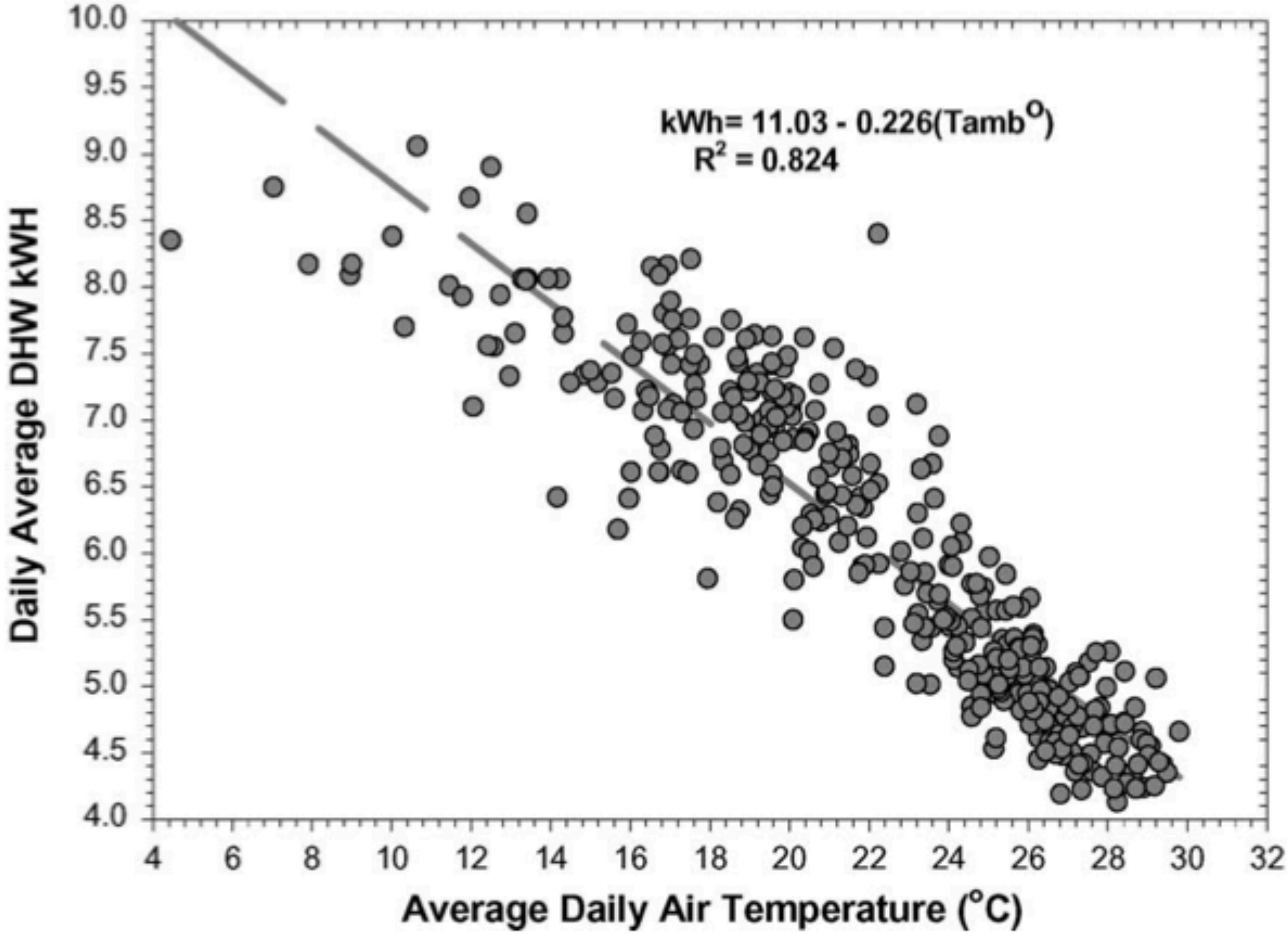
DHW = domestic hot water



Parker **2003** *Energy and Buildings* 35:863-876

Large scale residential energy monitoring: FL homes

DHW = domestic hot water



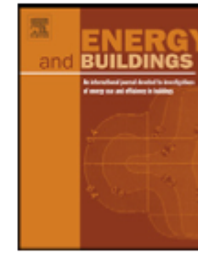
Parker **2003** *Energy and Buildings* 35:863-876

Very low-energy homes: Real data

Very low energy homes in the United States: Perspectives on performance from measured data

Danny S. Parker *

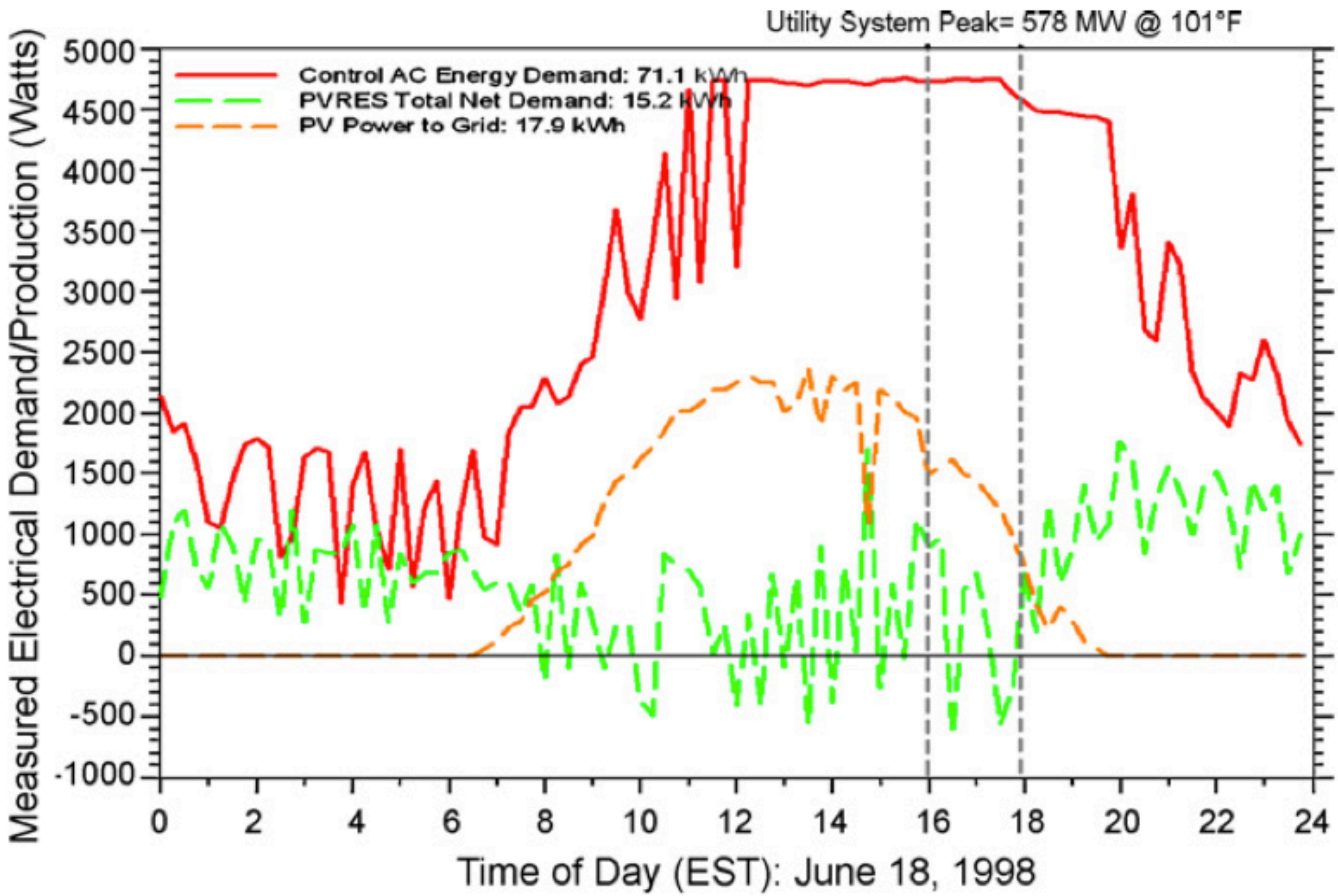
Florida Solar Energy Center, 1679 Clearlake Rd., Cocoa, FL 32922, USA



- Recent survey of very low energy homes (low UA, low infiltration, highly efficient equipment)
  - And net-zero-energy homes or (near) net-zero-energy homes
  - With solar PV providing electricity in addition to large savings from efficiency
  - Homes from all over the US

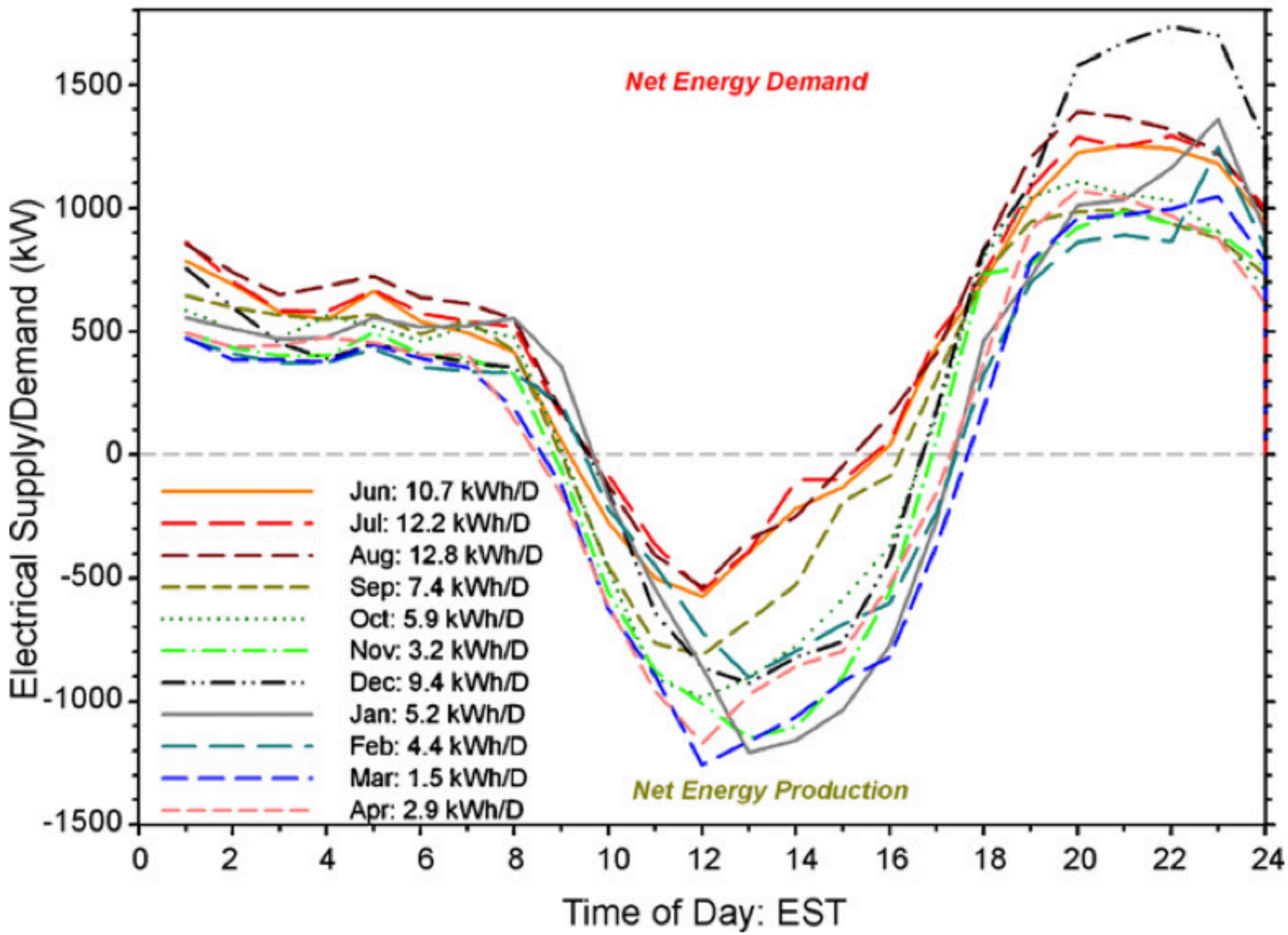
Parker **2009** *Energy and Buildings* 41:512-520

Large-scale monitoring of very low-energy homes



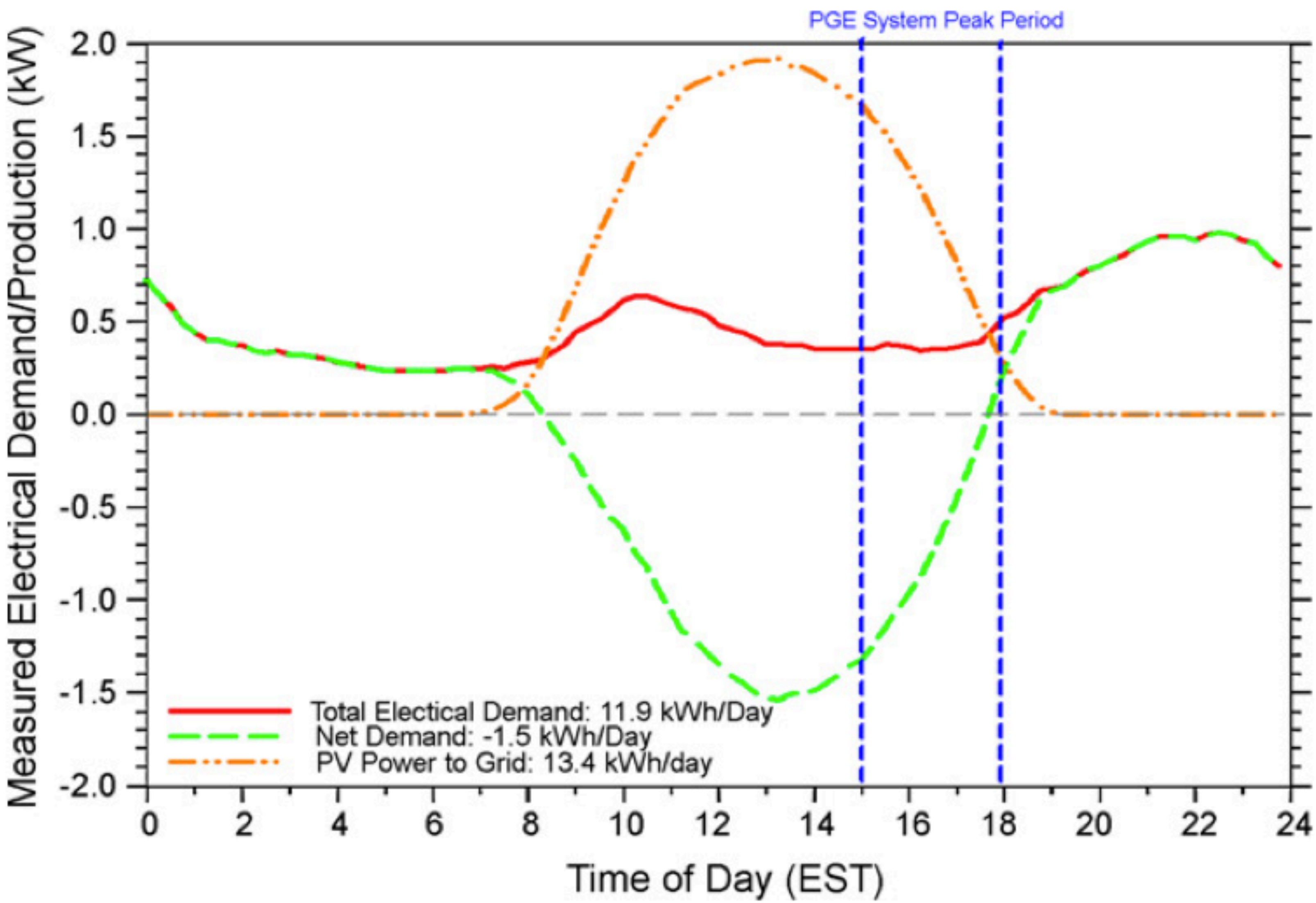
Parker **2009** *Energy and Buildings* 41:512-520

Large-scale monitoring of very low-energy homes



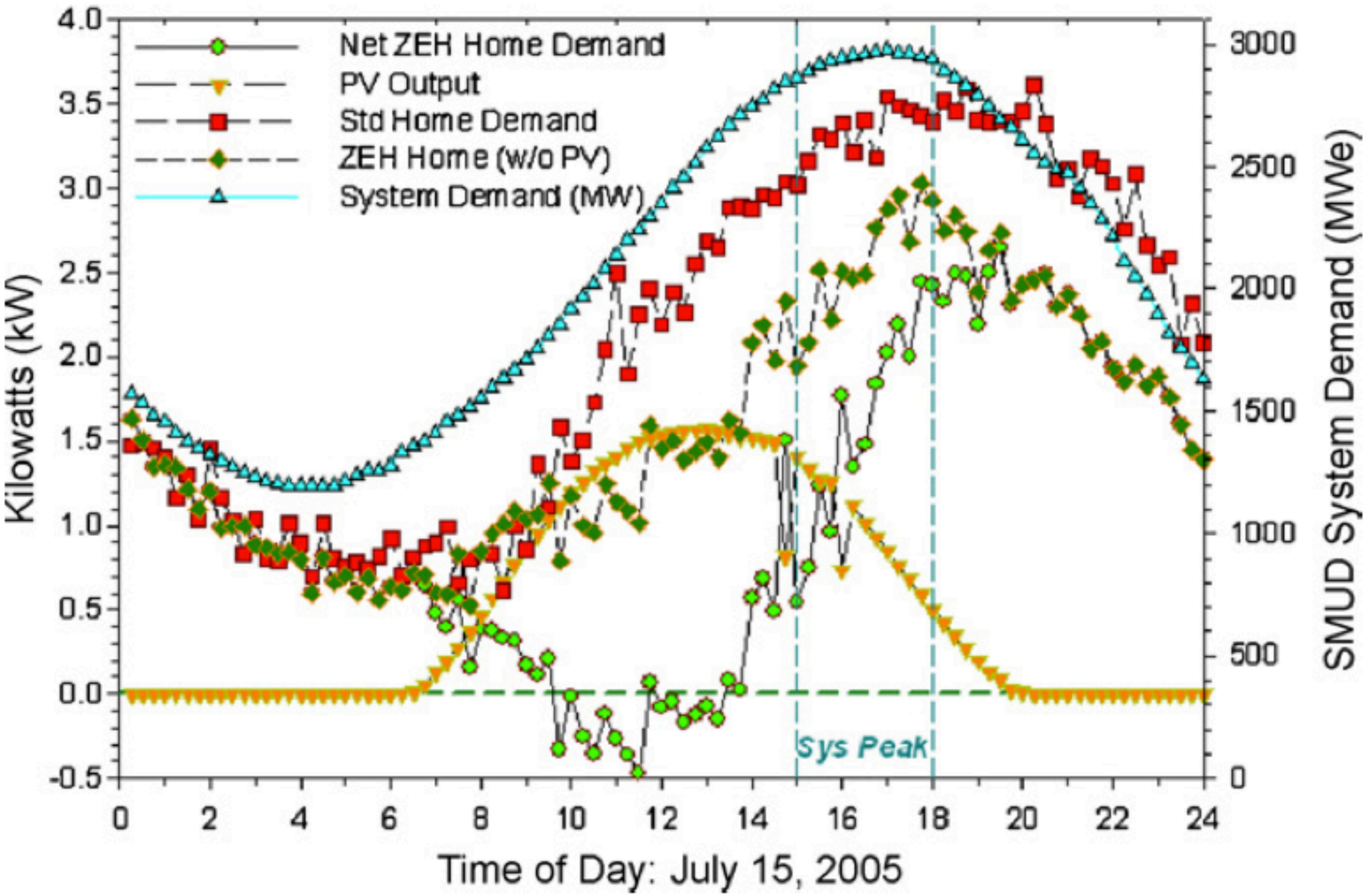
Parker **2009** *Energy and Buildings* 41:512-520

Large-scale monitoring of very low-energy homes



Parker **2009** *Energy and Buildings* 41:512-520

Large-scale monitoring of very low-energy homes



Parker **2009** *Energy and Buildings* 41:512-520

Large-scale monitoring of very low-energy homes

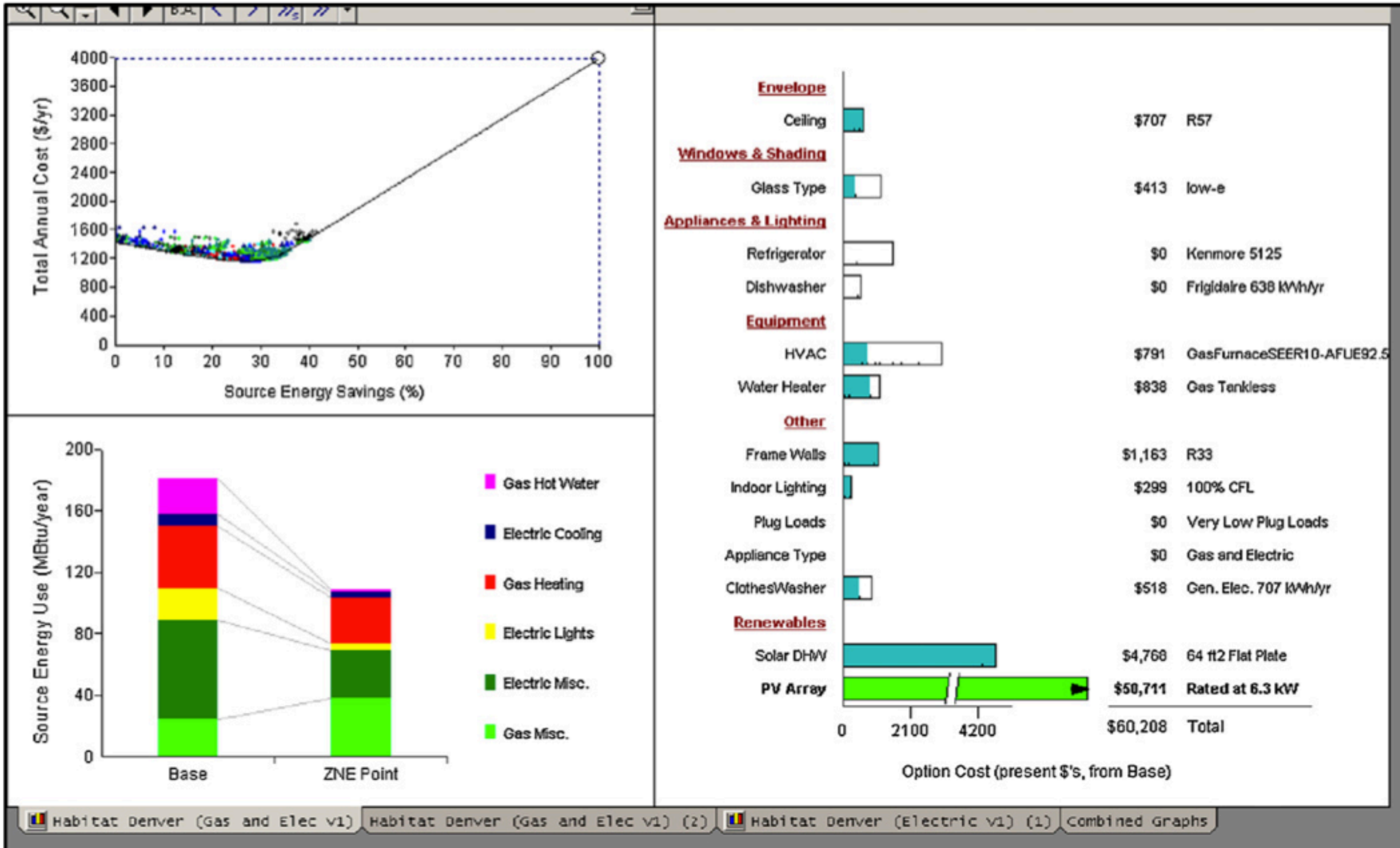


Fig. 9. Original analysis of Wheat Ridge ZEH using BEOpt software to evaluate a wide parameter field of competing options.

Parker **2009** *Energy and Buildings* 41:512-520

Large-scale monitoring of very low-energy homes

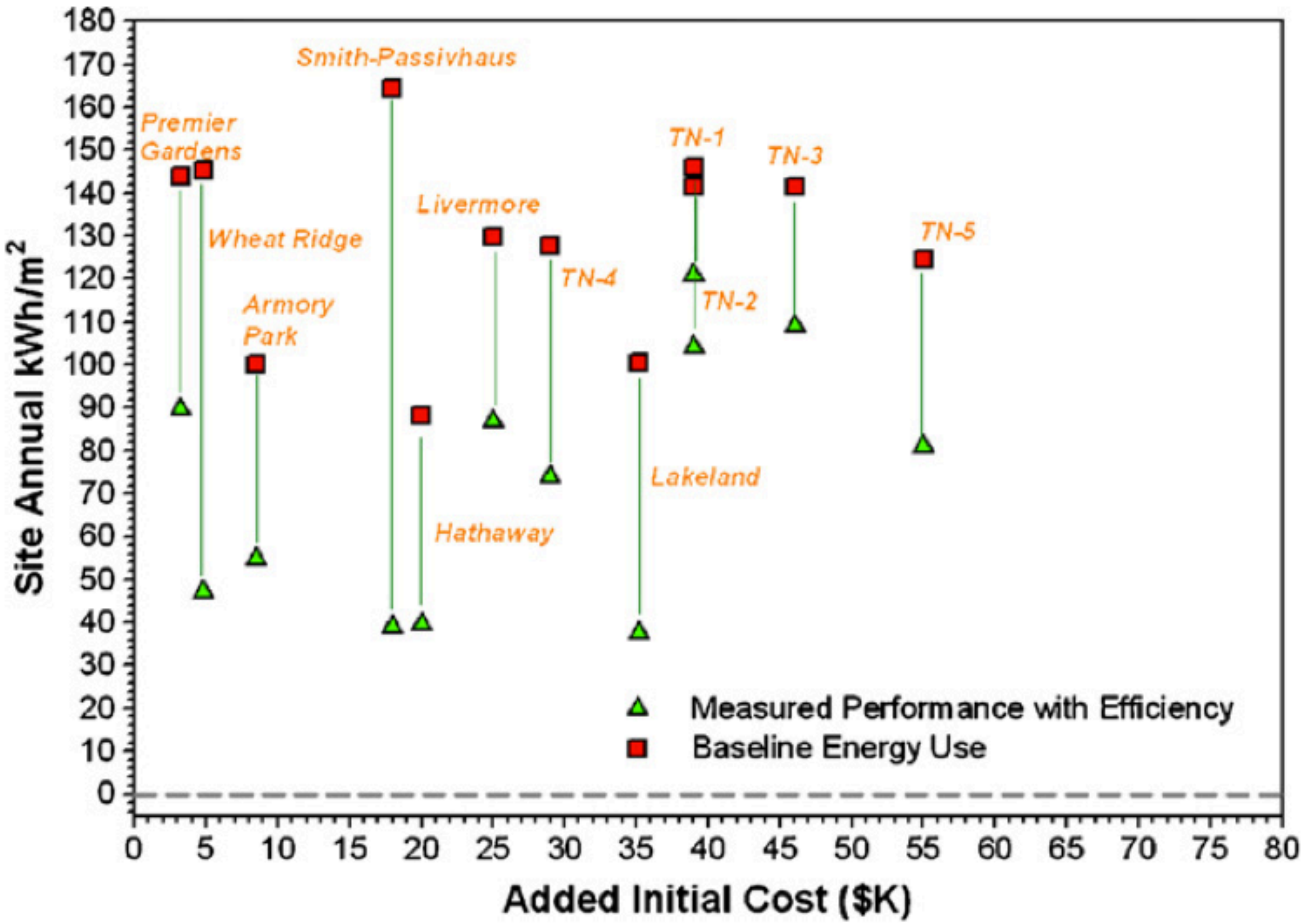


Fig. 10. Performance of efficiency measures in low energy homes.

Parker **2009** *Energy and Buildings* 41:512-520

Large-scale monitoring of very low-energy homes

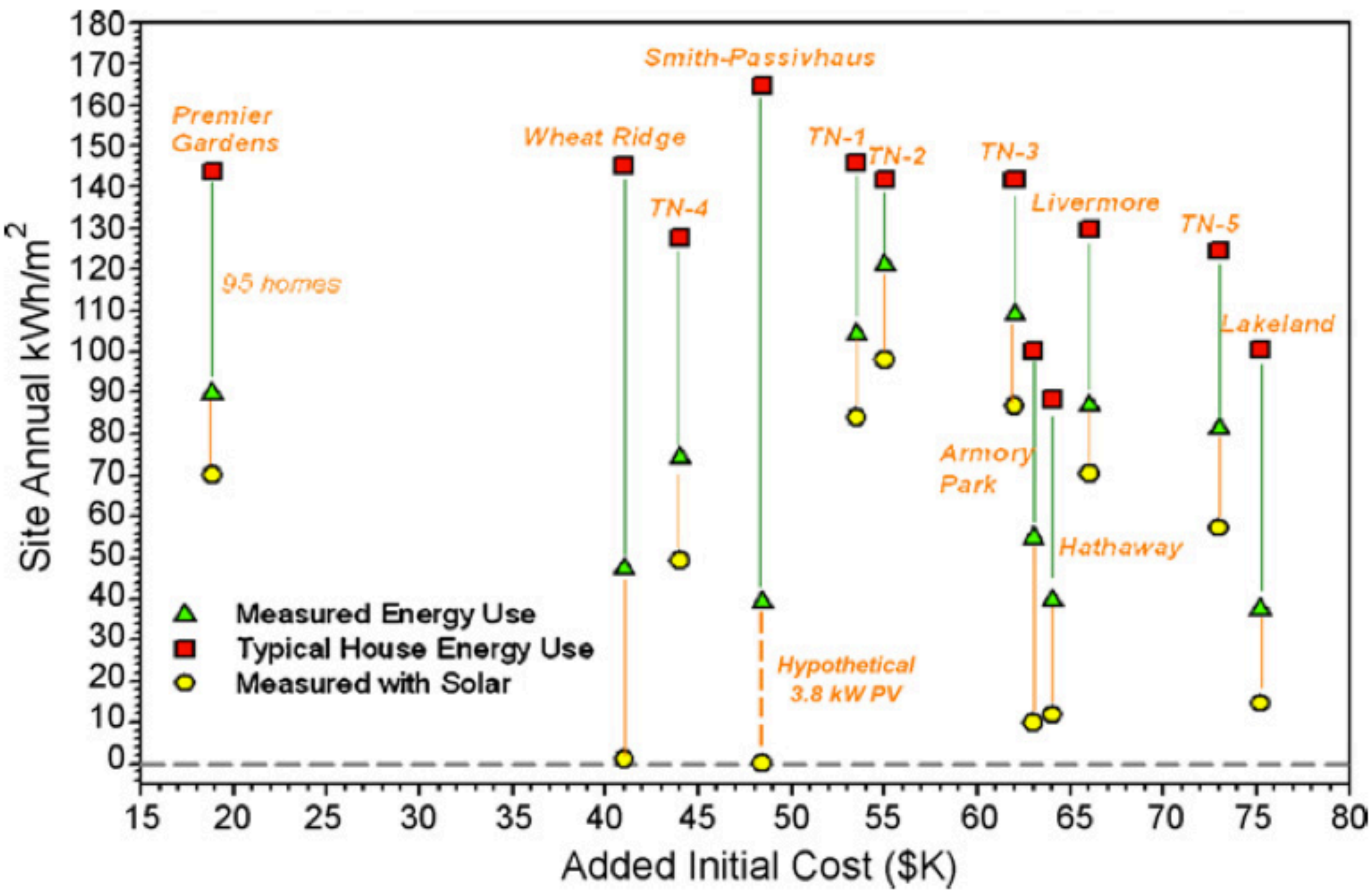
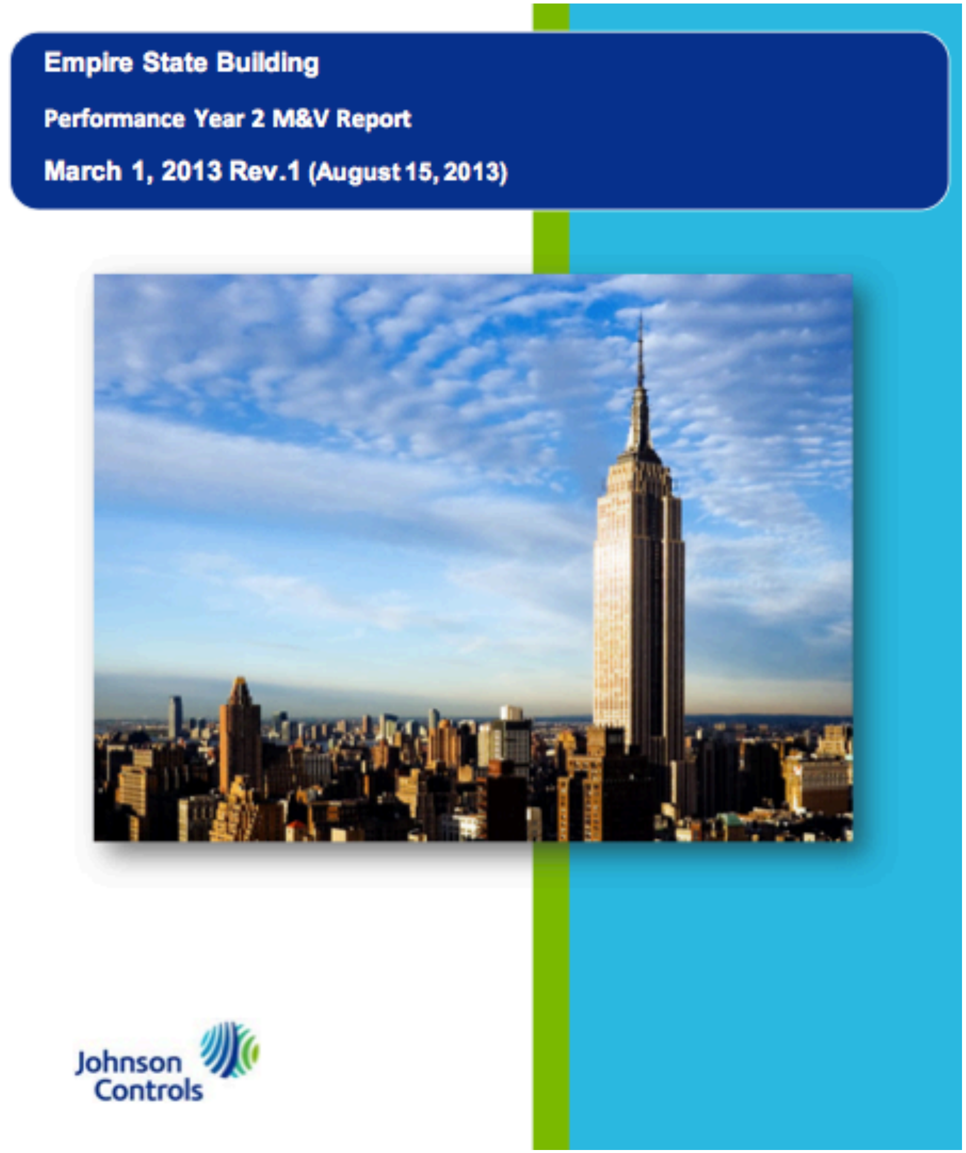


Fig. 11. Summary of energy performance of twelve advanced Zero Energy Homes around the United States.

Parker **2009** *Energy and Buildings* 41:512-520

Energy savings in commercial buildings

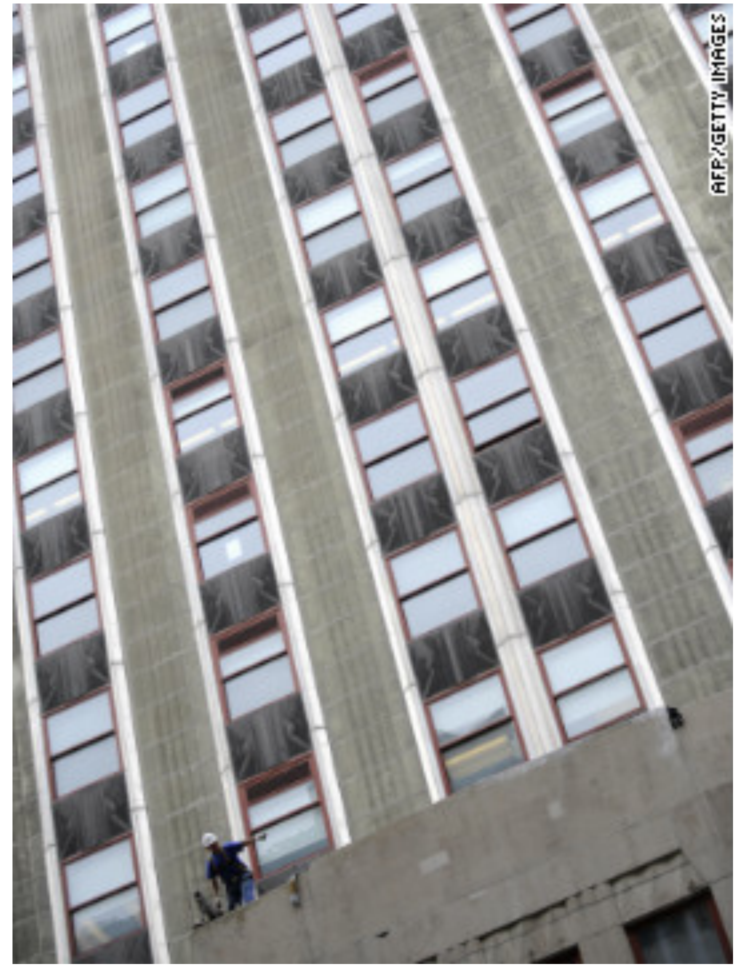
- Empire State Building
- New York, NY
- Implemented 5 energy conservation measures (ECMs) in 2011
  - Window retrofit
  - Radiator insulation and steam traps
  - Building automation system
  - Chiller retrofit
  - Tenant energy management
- Collected data and compared modeled savings versus measured



Energy savings in the Empire State Building

Window retrofits

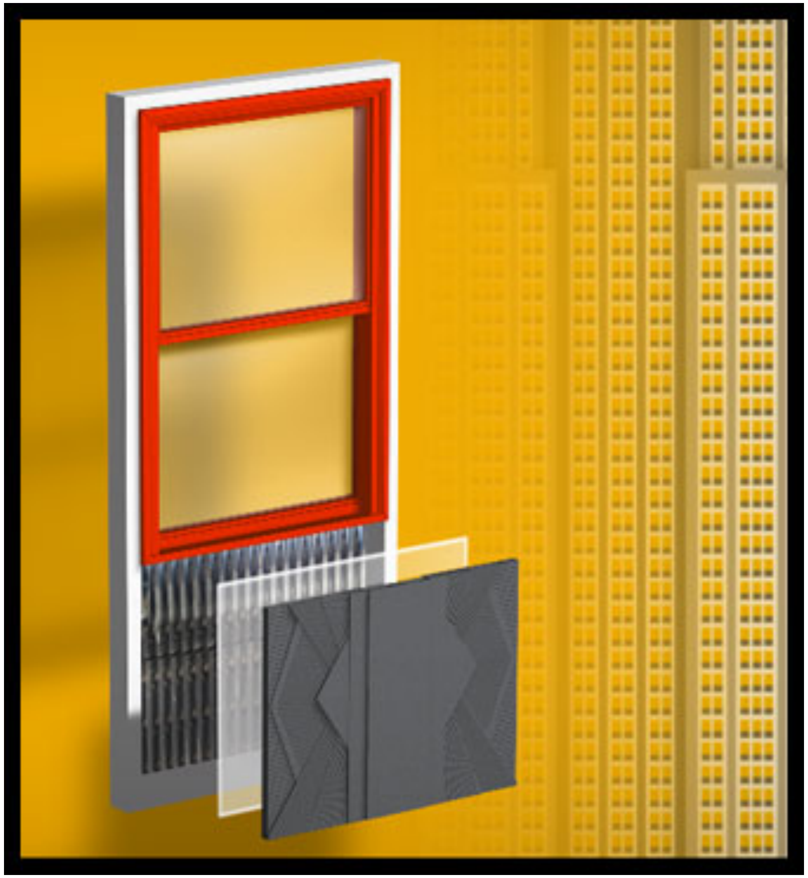
- Upgraded over 6500 double-hung insulated glazing units
- Original windows:
  - U-value = 0.58 Btu/hr-ft^2-°F
  - SHGC = 0.65
- New windows (krypton + argon):
  - U-value = 0.37 Btu/hr-ft^2-°F on north wall and 0.38 on S-E-W walls
  - SHGC = 0.45 on north wall and 0.33 on S-E-W walls

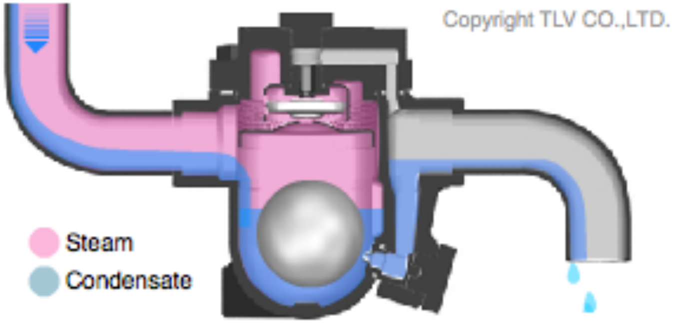


Energy savings in the Empire State Building

Radiator system

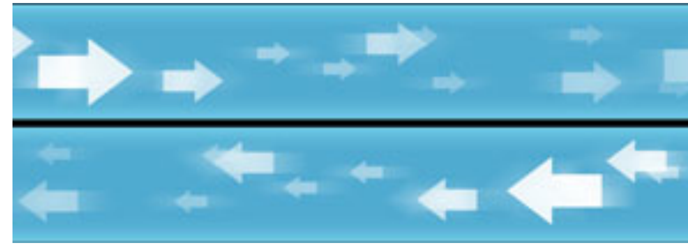
- Added insulated reflective barriers *behind* radiator units and in front of walls on the perimeter of the building
- Original insulation:
  - U-value = 0.21 Btu/hr-ft^2-°F
- New insulation:
  - U-value = 0.12 Btu/hr-ft^2-°F
- Also upgraded control system and added “steam traps”



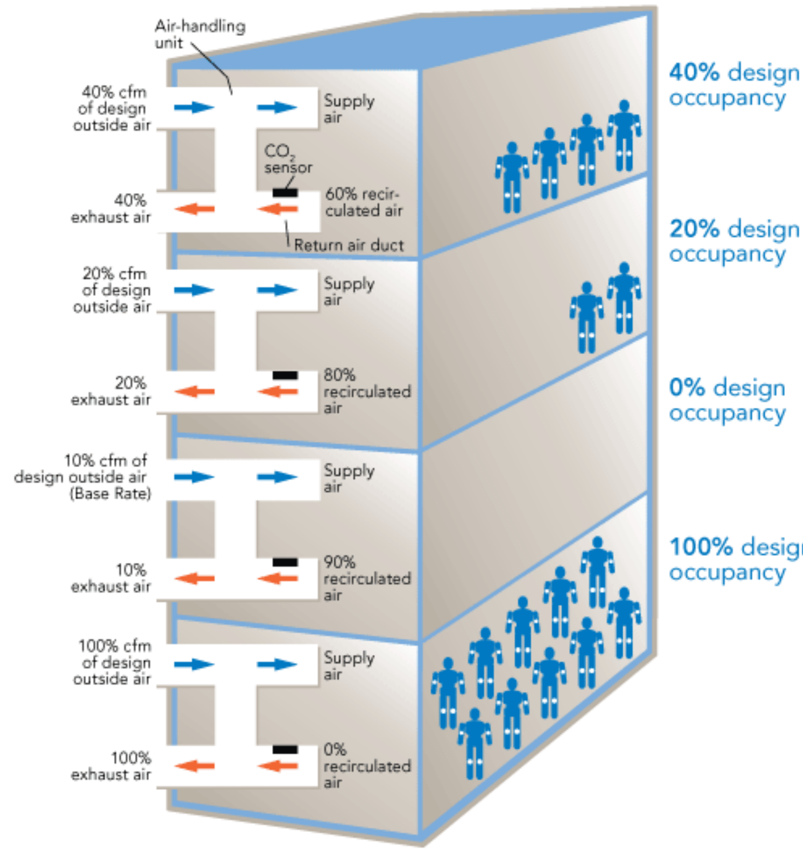


Energy savings in the Empire State Building

Building automation system (BAS)



- Reduced overall outdoor air intake by using “demand controlled ventilation” (DCV) and modulating dampers
  - Uses CO_2 to measure occupancy



- Original BAS:
  - No controls, OA = from 0.25 cm/ft^2
- New BAS:
  - Keep OA low until CO_2 in return air = 800 ppm and better controls for OA economizer
  - New OA = from 0.12 cm/ft^2

Energy savings in the Empire State Building

Chiller plant retrofit

- Replaced compressors with variable speed drives (VSDs) and replaced evaporator and condenser tubes
- Increased chilled water supply T
- Valve changes and VSD automation
- Cooling tower fan switched to automated VSD

Energy savings in the Empire State Building

Tenant energy management portal

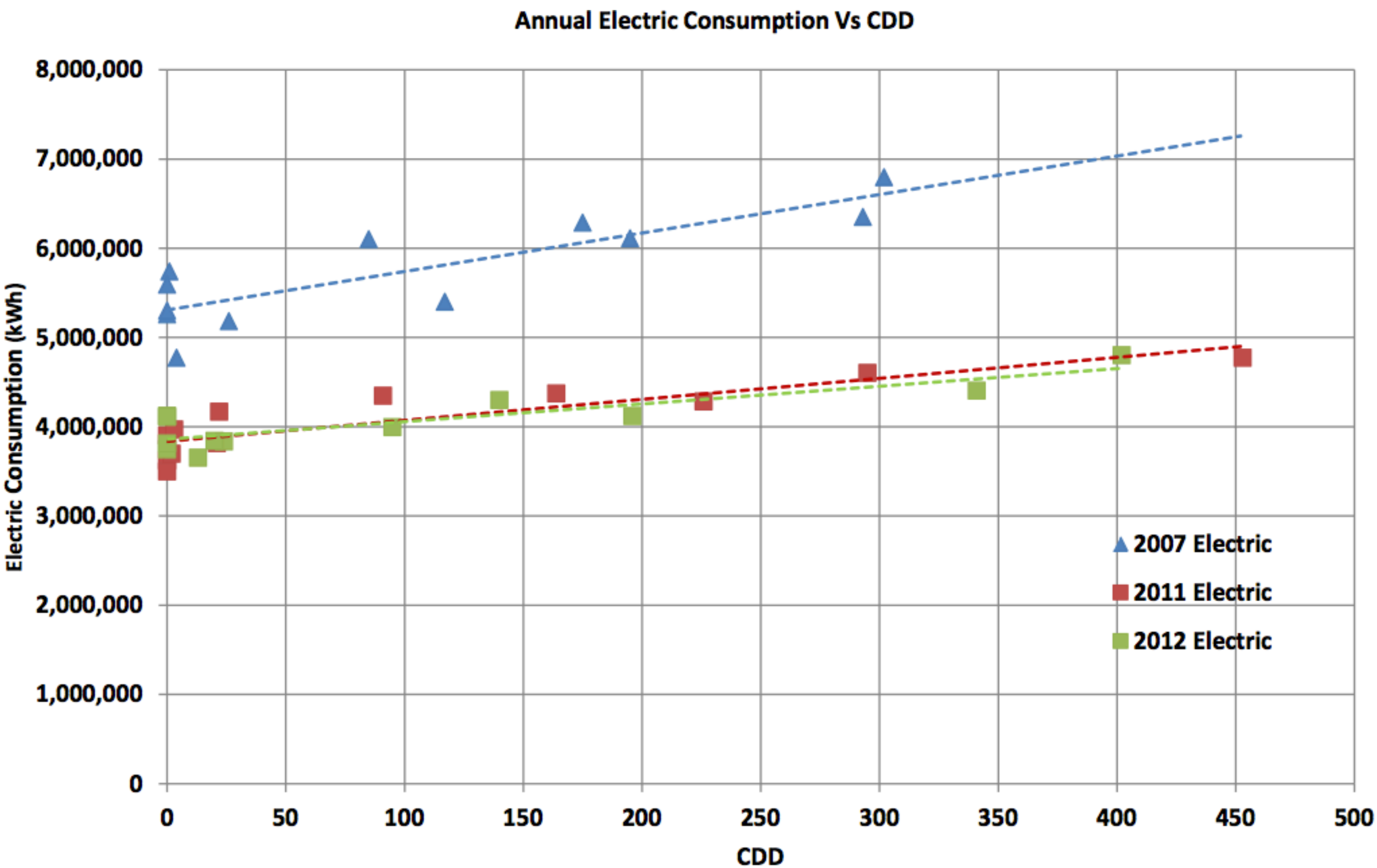
- Gave tenants a digital dashboard displaying energy use and endorsing energy efficient practices
  - Lighting, thermostat settings, etc.

Predicted cost and savings in the Empire State Building

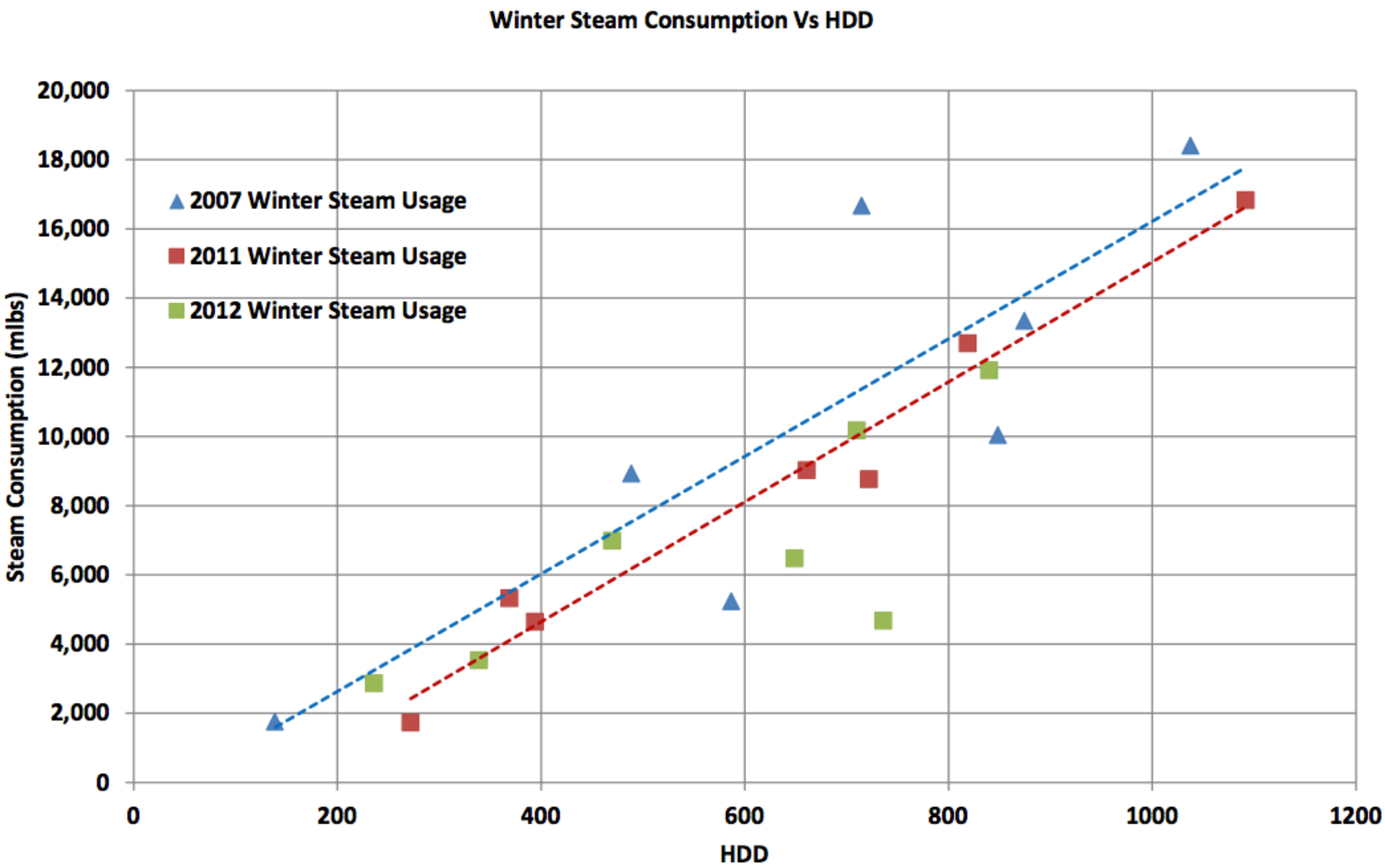
Project Description	*Projected Capital Cost*	*2008 Capital Budget*	*Incremental Cost*	*EstimatedAnnual Energy Savings**
Windows	$4.5m	$455k	$4m	$410k
Radiative Barrier	$2.7m	$0	$2.7m	$190k
DDC Controls	$7.6m	$2m	$5.6m	$741k
Demand Control Vent	Inc. above	$0	Inc. above	$117k
Chiller Plant Retrofit	$5.1m	$22.4m	-$17.3m	$675k
VAV AHUs	$47.2m	$44.8m	$2.4m	$702k
Tenant Day/Lighting/Plugs	$24.5m	$16.1m	$8.4m	$941k
Tenant Energy Mgmt.	$365k	$0	$365k	$396k
Power Generation (optional)	$15m	$7.8m	$7m	$320k
TOTAL (ex. Power Gen)	$106.9m	$93.7m	$13.2m	$4.4m

Invested a total of ~$13 million in energy retrofits while undergoing a $107 million planned retrofit

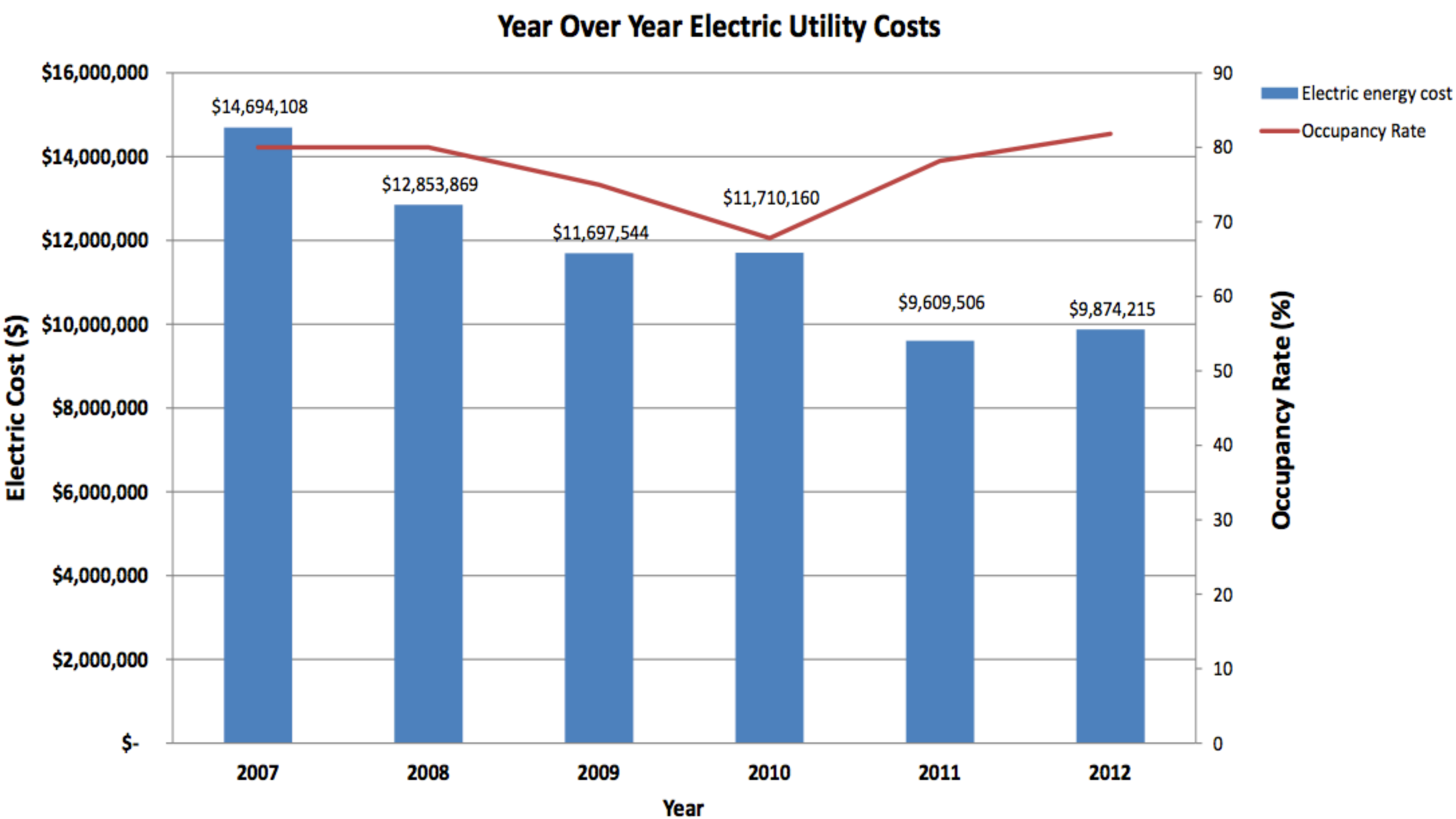
Measured performance in the Empire State Building



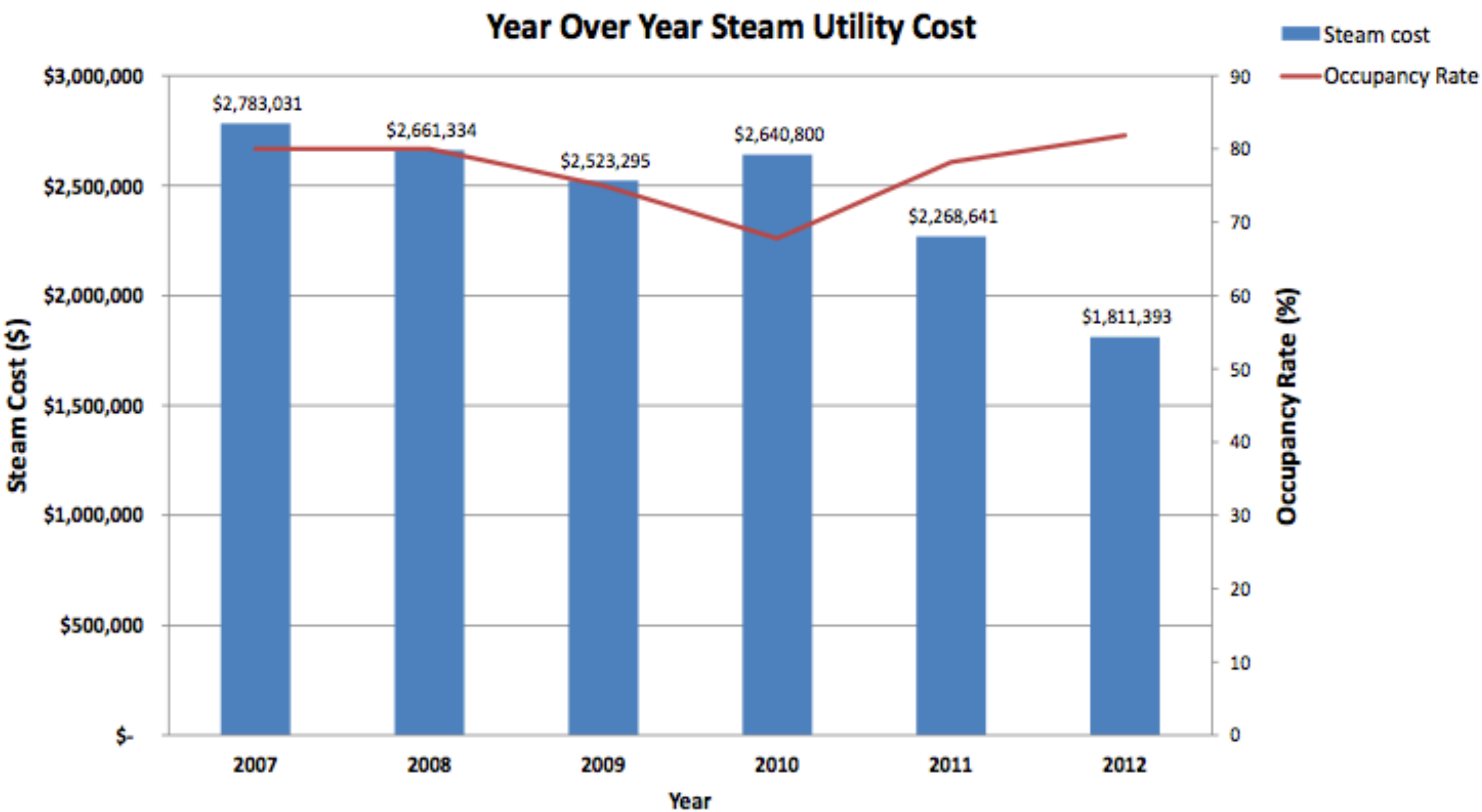
Measured performance in the Empire State Building



Measured performance in the Empire State Building



Measured performance in the Empire State Building



Measured performance in the Empire State Building

- Investments of a total of ~$13 million is saving ~$2.5 million annually
  - Predicted to save more than this
  - Still a 20% rate of return with payback period around only 5 years

- Lessons: **Energy efficiency pays**

- For building science, we now understand enough fundamental concepts to drive lower-energy buildings
  - Basic building physics
  - HVAC loads
  - Internal gains
  - HVAC equipment efficiency

Words of caution: Energy, IAQ, and health

Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools

M. J. Mendell, E. A. Eliseeva,
M. M. Davies, M. Spears,
A. Lobscheid, W. J. Fisk,
M. G. Apte

Elementary school student absences were shown to be lower in classrooms with higher outdoor air ventilation rates in a recent study in California

Increasing outdoor air ventilation will increase costs in most climates

However, in California, increasing classroom ventilation rates to the State standard is estimated to decrease student absences for illness by 3.4% (increasing state funding to schools by $33 million annually) at a cost of only $4 million

Mendell et al., 2013, *Indoor Air*, just accepted

BUILDING DIAGNOSTIC TOOLS

Important building diagnostic tools

Air Temperature/RH and light levels

Data logging

Surface temperatures

CO_2

Electric power

Heat flux meters

IR camera

Solar radiation

Important building diagnostic tools

Blower door
(envelope air leakage)

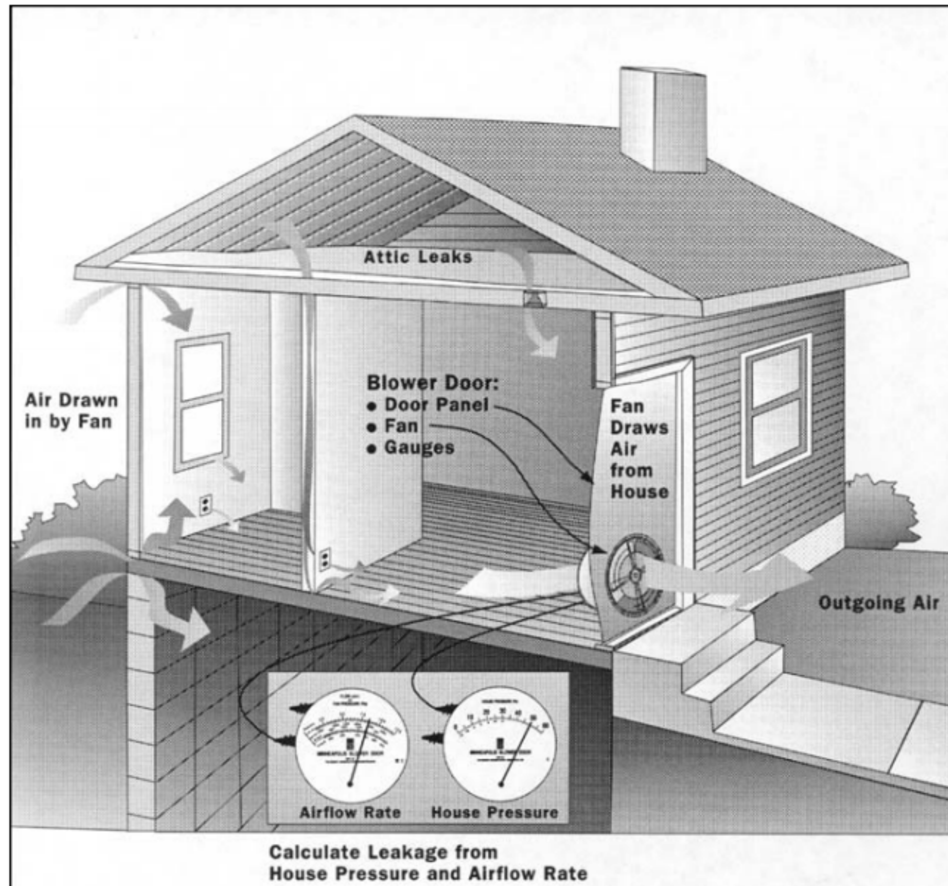
Duct blaster
(duct leakage)

Pressure

TrueFlow
(HVAC airflow rates)

Blower doors: theory of operation

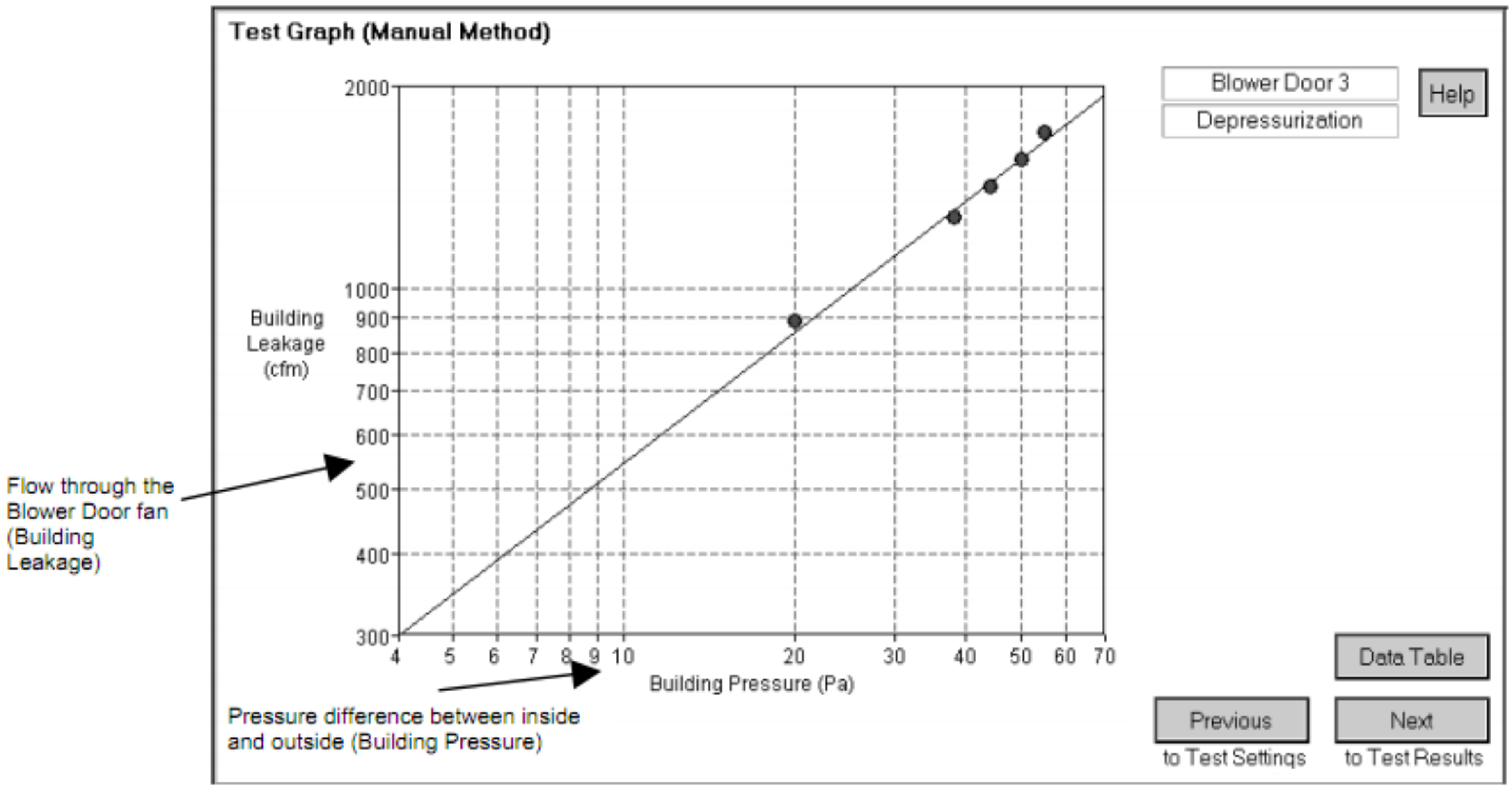
- Used to measure air-tightness in buildings worldwide



Source: Energy Conservatory Blower Door Manual

Blower doors: theory of operation

- Record flow through blower door (and thus through leaks) at each measured I/O pressure difference



Blower doors: theory of operation

- Perform test across a range of pressures and flows
- Develop relationship:

$$Q = C\Delta\mathrm{P}^{\mathrm{n}}$$

- To solve for C & n from measurements of Q and ΔP,
  - Log transform equation:

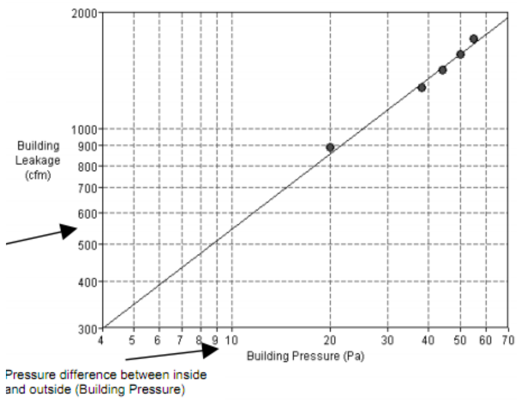
$$\ln Q = \ln C + n \ln \Delta\mathrm{P}$$

$$Y \;=\; b \;+\; mx$$

Slope = n

Intercept = lnC, therefore C = $\exp^{\text{intercept}}$

Blower door tests: resulting parameters



$$Q = C\Delta P^{n}$$

Airflow ($m^3\ s^{-1}$)

Leakage Coefficient ($m^3\ s^{-1}\ Pa^{-n}$)

I/O Pressure Difference (Pa)

Leakage Exponent (dimensionless)

$$ELA = C\Delta P_{ref}^{n-0.5}\sqrt{\frac{\rho}{2}}$$

Estimated Leakage Area (cm^2)

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

Normalized Leakage, NL (dimensionless)

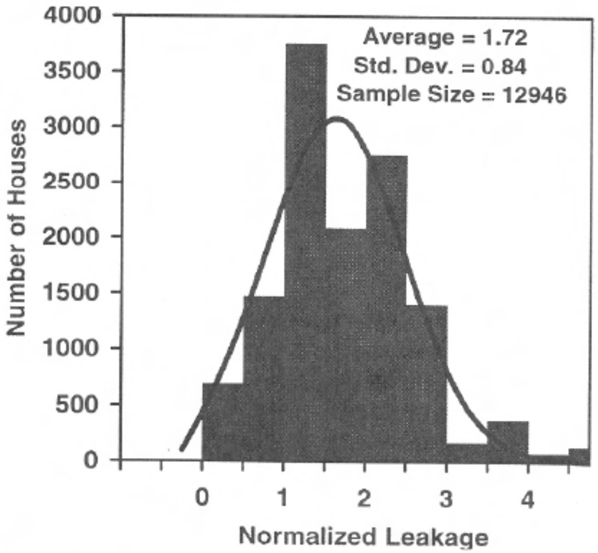
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$

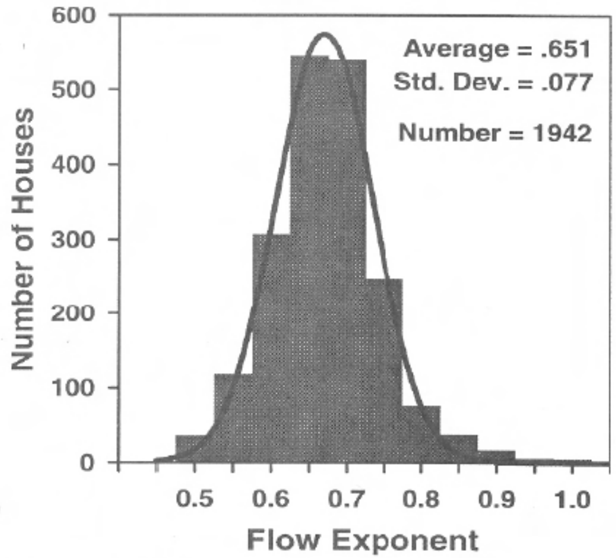
Air Changes per Hour @ 50 Pa (hr^{-1})

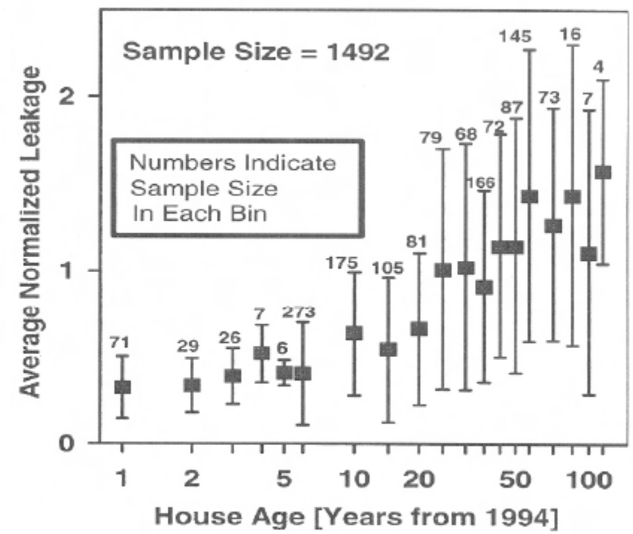
Source: ASTM E 779 and ASHRAE Standard 119

Blower door results: US homes

- From a big database of blower door tests





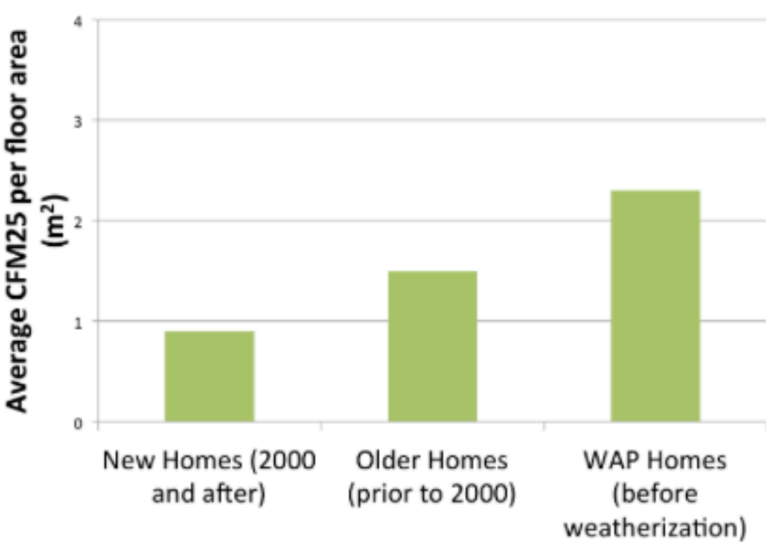


	Mean	Std Dev.	Number of Houses
Year Built	1965	24.2	1492
Floor Area [m^2]	156.4	66.7	12946
Normalized Leakage	1.72	0.84	12946
ACH_{50}	29.7	14.5	12902
Exponent	0.649	0.084	2224

Sherman and Dickerhoff 1998 *ASHRAE Transactions*

Duct blaster duct leakage tests

Total duct leakage



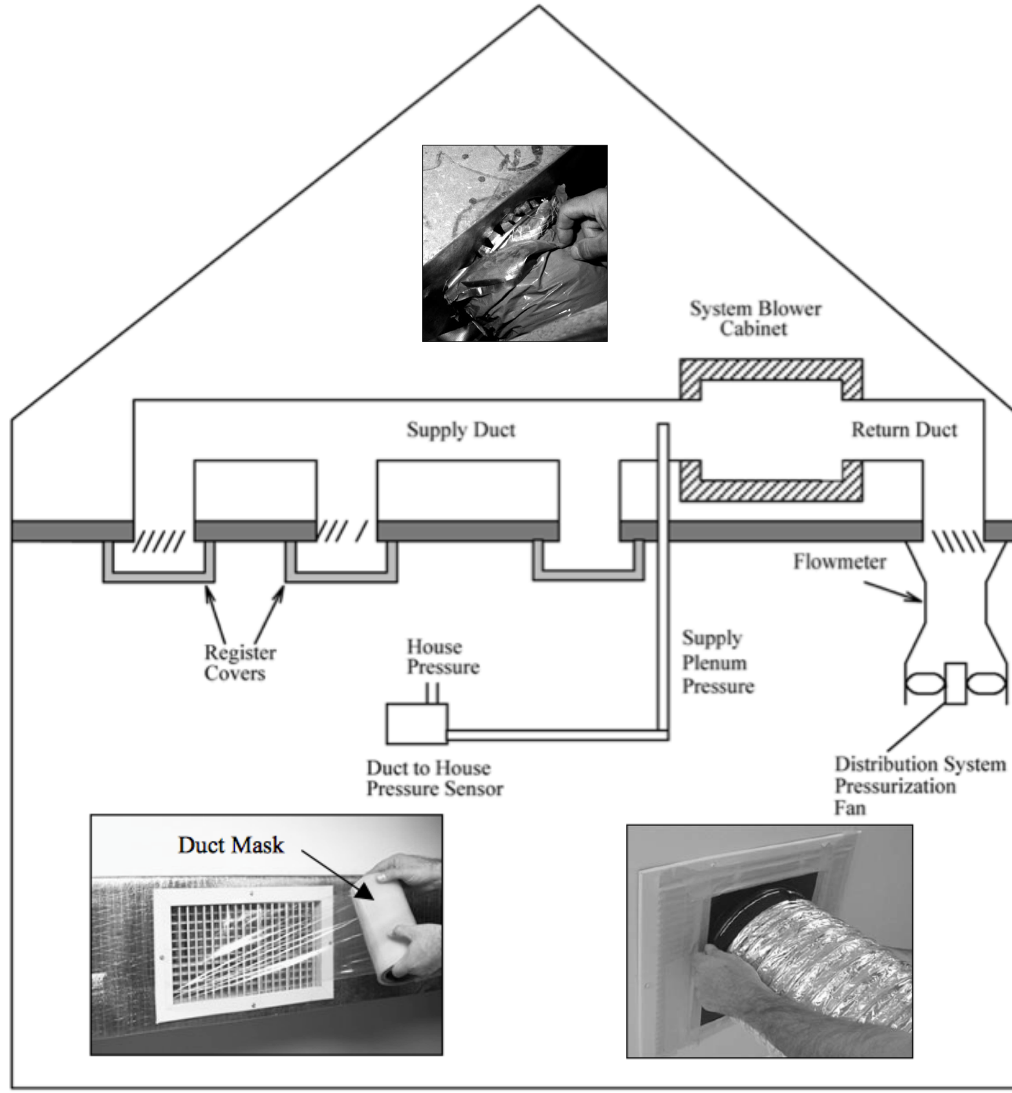


FIG. 2 Schematic of Method C—Distribution System Pressurization Test

Duct blaster duct leakage tests

Supply duct leakage to the exterior

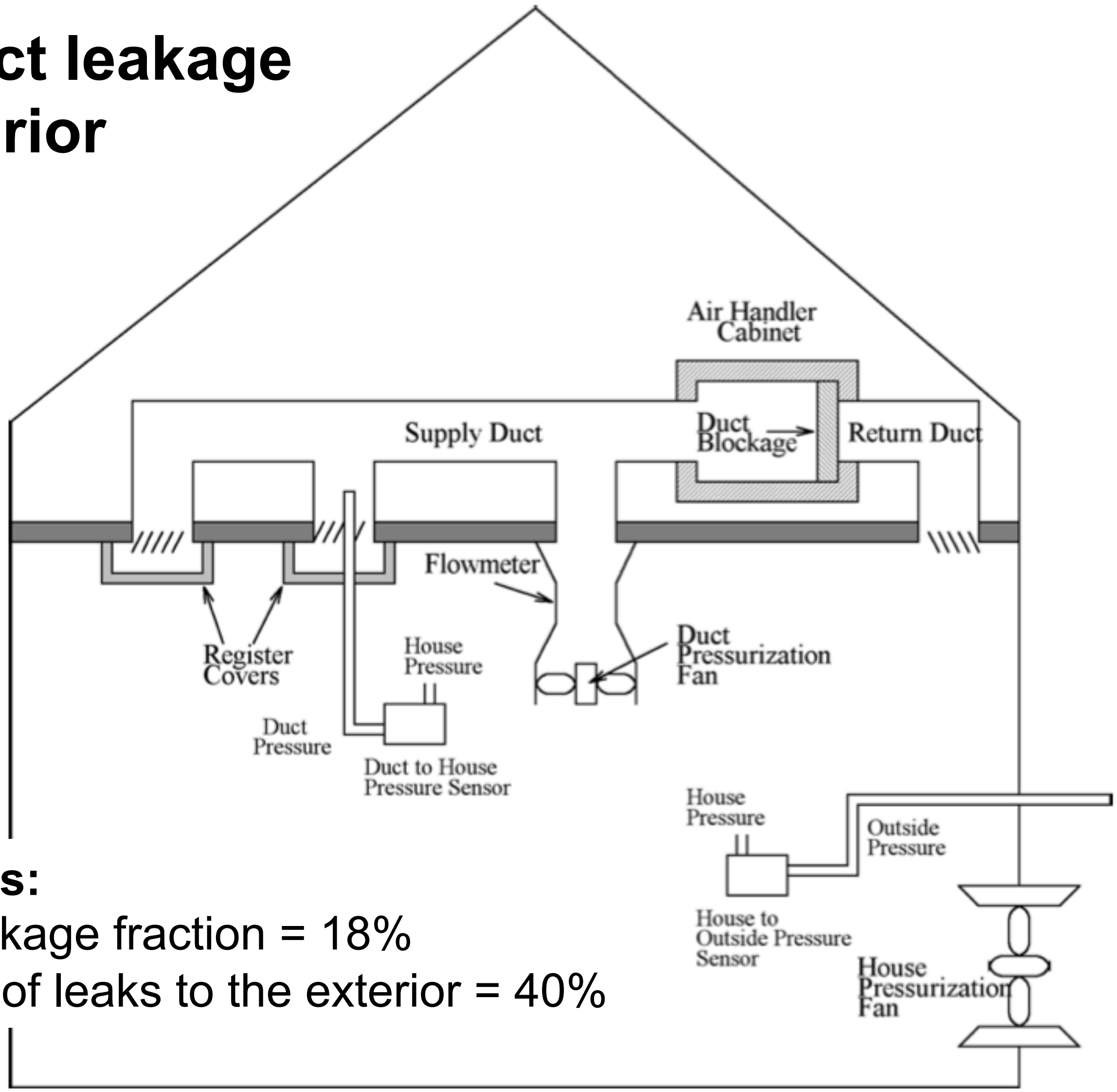
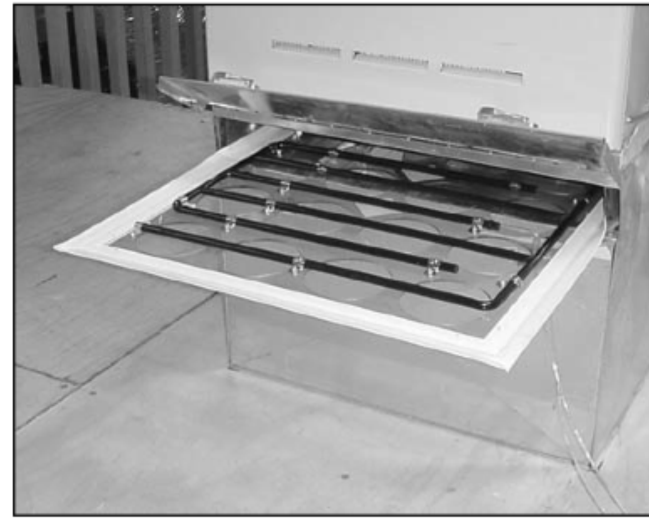
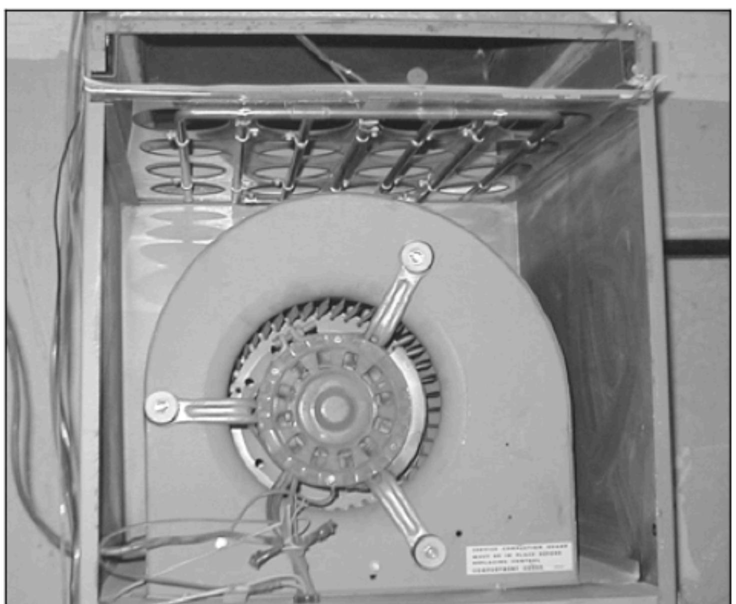


FIG. 1 Schematic of Method B—Distribution System and Building Pressurization Test (for Supply Leakage)

In US residences:
Average duct leakage fraction = 18%
Average fraction of leaks to the exterior = 40%

TrueFlow airflow measurements





Next class period

- Final project presentations from graduate students

- Final exam the following Monday