

CAE 331/513

Building Science

Fall 2018



November 27, 2018

Energy estimation and design for efficiency

Built
Environment
Research

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*Advancing energy, environmental, and
sustainability research within the built environment*

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Last time

- Demonstrated Trane Trace 700 for load calculations
- HW 6 due today

BUILDING ENERGY SIMULATION

Building energy simulation

- The same methods for estimating peak heating and cooling loads (particularly the **heat balance method**) can also be used to develop **whole building annual energy simulations**
- Annual energy simulations use software to solve systems of equations (dozens, hundreds, or thousands) to predict hourly (or sub-hourly) energy use over the course of a Typical Meteorological Year (TMY)
 - All based on energy balances at surface nodes, interior nodes for materials, and indoor air nodes

Estimating energy use from load calculations

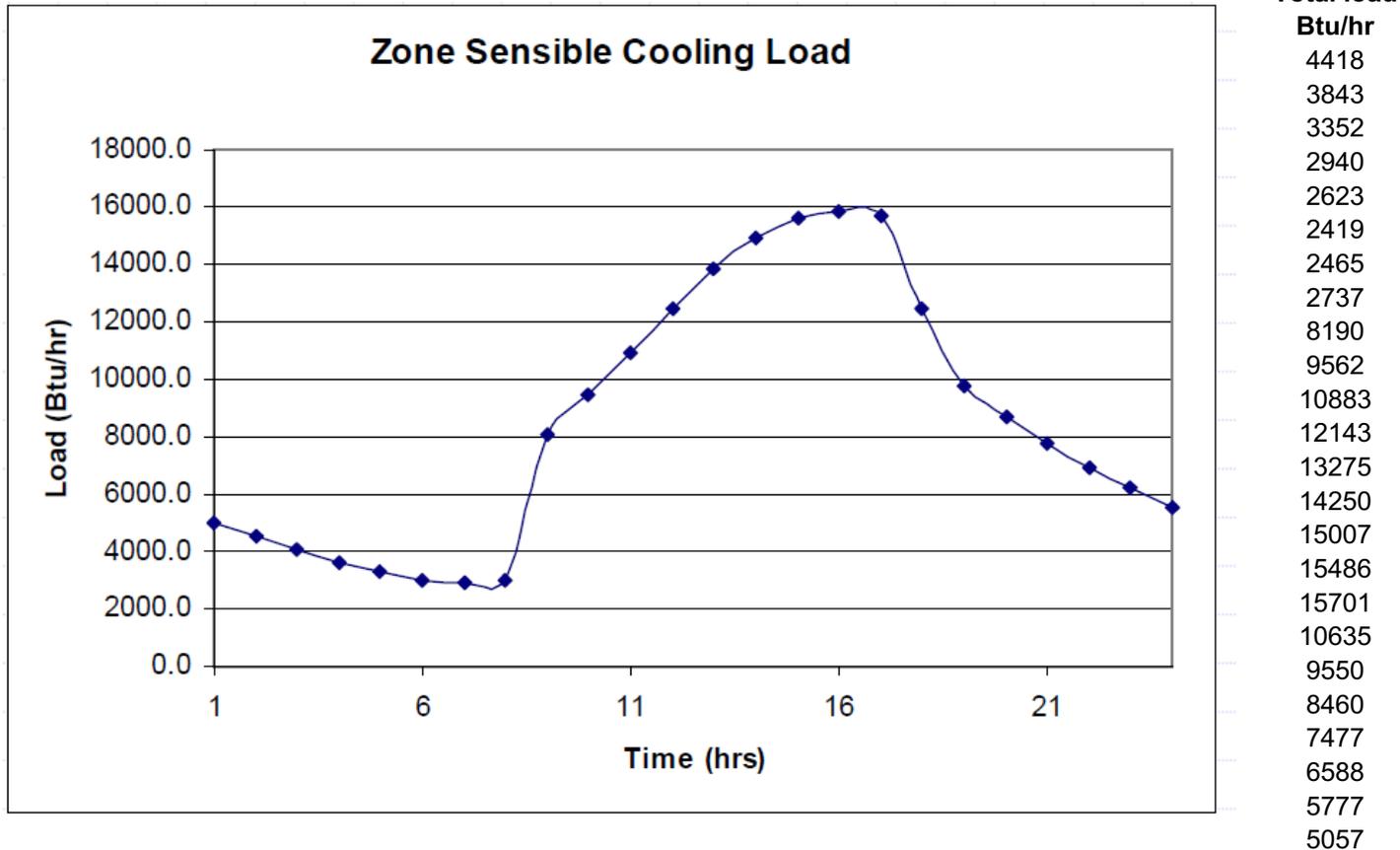
- Once we have estimated the hourly heating or cooling energy demand, we can fairly easily estimate energy use required for **heating** or **cooling** purposes
- If you know the hourly load (either for just a **peak day** or for the **whole year**), you can estimate the amount of energy required to meet that load by knowing the efficiency of the system (COP or EER)

$$P_{elec} = \frac{Q_{cooling,load}}{COP} \quad [W \text{ or } kW]$$

$$E = \sum P_{elec} \Delta t \quad [Wh \text{ or } kWh]$$

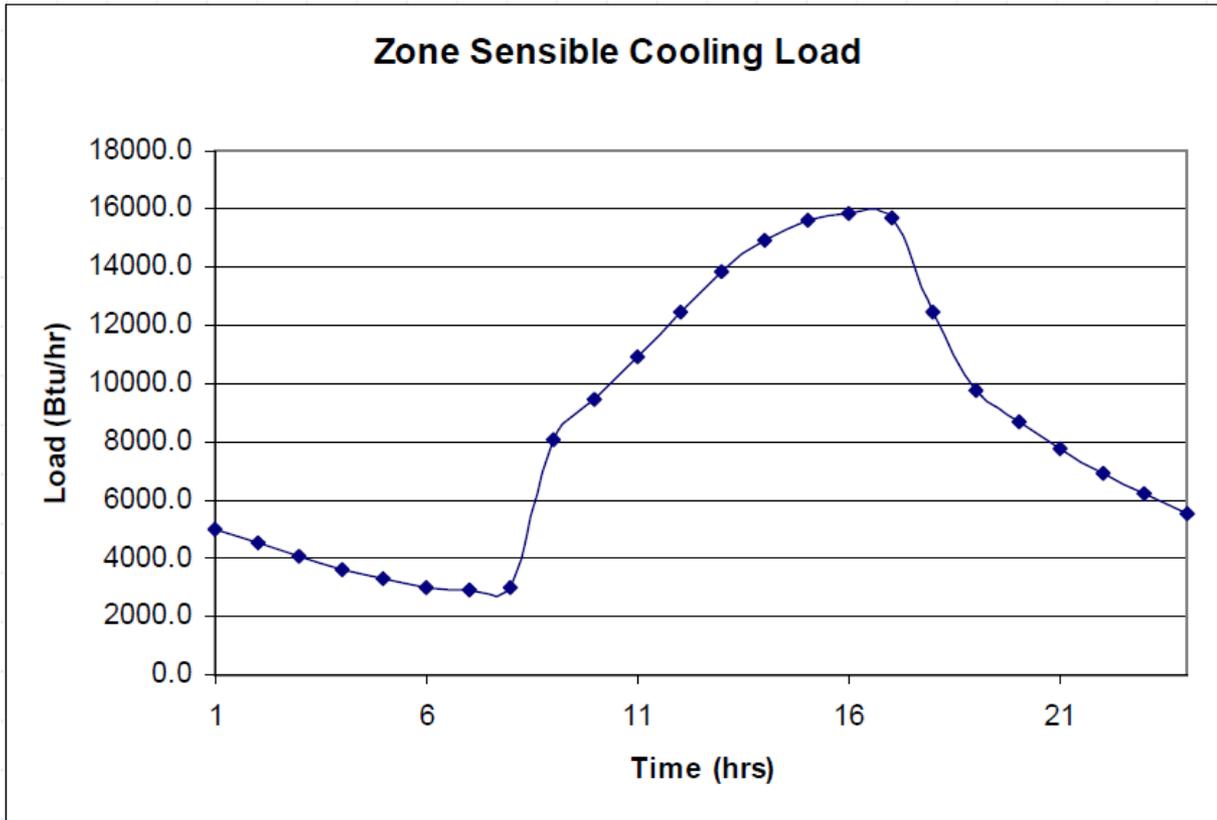
Estimating energy use from load calculations

Example for cooling energy:



Estimating energy use from load calculations

Example for cooling energy:



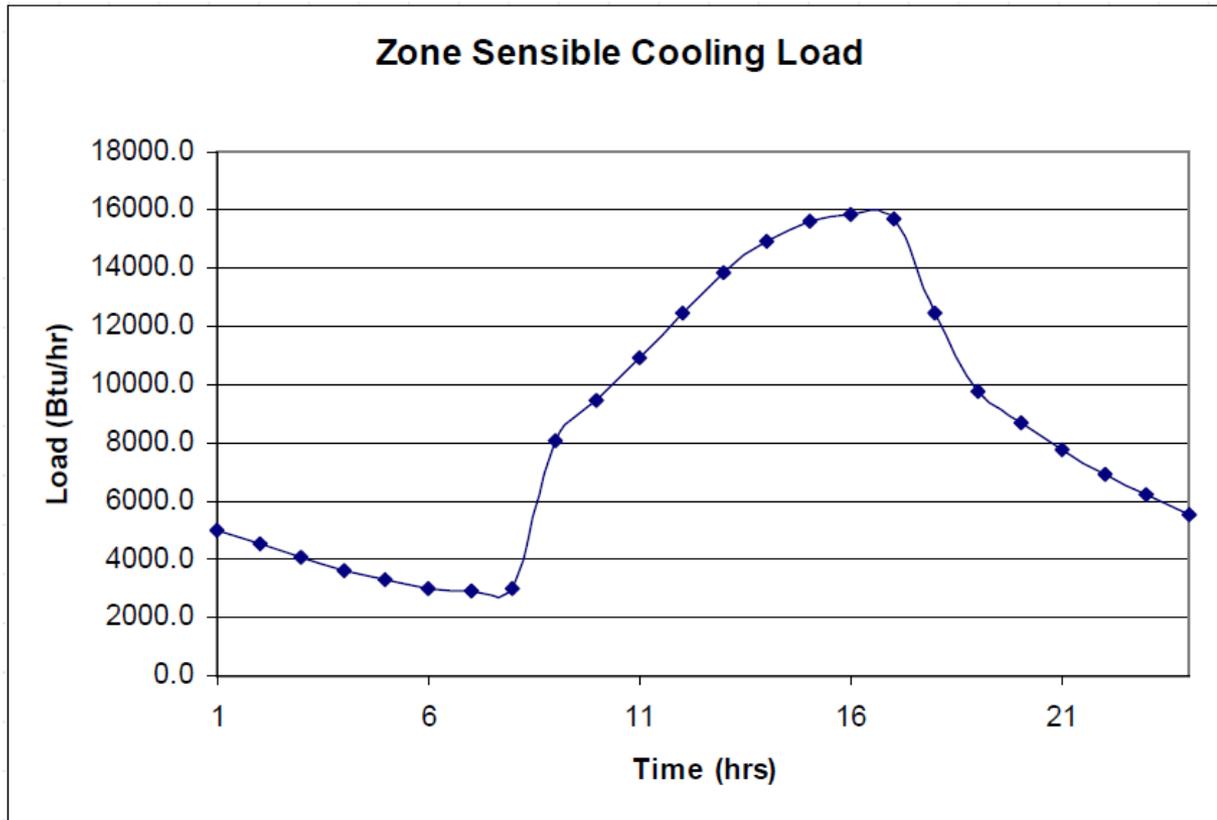
Total load Btu/hr	Power draw W
4418	432
3843	375
3352	327
2940	287
2623	256
2419	236
2465	241
2737	267
8190	800
9562	934
10883	1063
12143	1186
13275	1297
14250	1392
15007	1466
15486	1513
15701	1534
10635	1039
9550	933
8460	827
7477	730
6588	644
5777	564
5057	494

$$P_{elec}(t) = \frac{Q_{cooling,load}(t)}{EER}$$

COP 3.0
EER 10.24

Estimating energy use from load calculations

Example for cooling energy:



Total load Btu/hr	Power draw W	Energy kWh
4418	432	0.43
3843	375	0.38
3352	327	0.33
2940	287	0.29
2623	256	0.26
2419	236	0.24
2465	241	0.24
2737	267	0.27
8190	800	0.80
9562	934	0.93
10883	1063	1.06
12143	1186	1.19
13275	1297	1.30
14250	1392	1.39
15007	1466	1.47
15486	1513	1.51
15701	1534	1.53
10635	1039	1.04
9550	933	0.93
8460	827	0.83
7477	730	0.73
6588	644	0.64
5777	564	0.56
5057	494	0.49

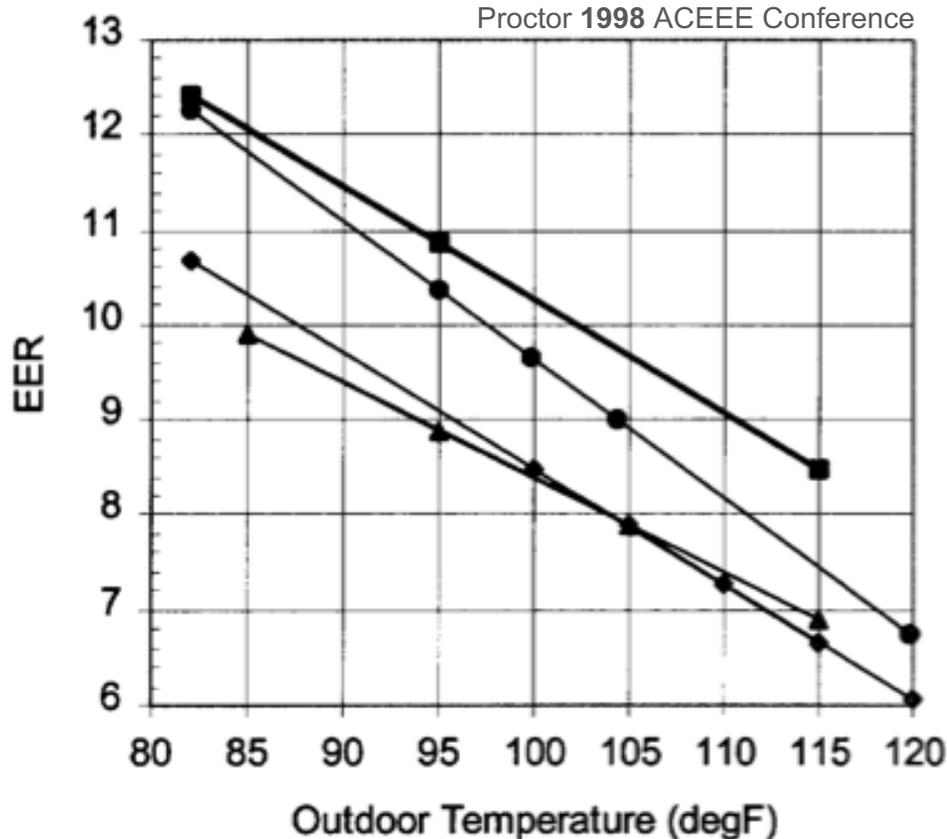
Energy used (kWh) 18.8
Energy price (\$/kWh) 0.11
Energy cost (\$) \$2.07

$$E = \sum P_{elec} \Delta t$$

*Note that COP will vary as a function of time and outdoor conditions

Estimating energy use from load calculations

- Accounting for varying COP/EER w/ T_{out}



$$P_{elec}(t) = \frac{Q_{cooling,load}(t)}{EER}$$

$$E = \sum P_{elec} \Delta t$$

Total load	Outdoor Temp	Varyin g EER	Power draw	Energy
Btu/hr	deg F	r/kW	W	kWh
4762	75.9	11.0	433	0.43
4324	75.0	11.1	390	0.39
3953	74.2	11.3	351	0.35
3641	73.7	11.4	319	0.32
3409	73.5	11.5	296	0.30
3274	73.9	11.4	287	0.29
3377	74.8	11.2	302	0.30
3694	76.5	11.0	336	0.34
9174	78.9	10.8	849	0.85
10538	81.6	10.5	1004	1.00
11805	84.8	10.2	1153	1.15
12962	87.7	10.0	1296	1.30
13950	90.0	9.7	1438	1.44
14753	91.4	9.5	1553	1.55
15325	92.0	9.3	1648	1.65
15625	91.4	9.5	1645	1.64
15682	90.2	9.7	1617	1.62
10495	88.1	10.0	1049	1.05
9335	85.7	10.3	906	0.91
8226	83.3	10.4	791	0.79
7283	81.3	10.5	694	0.69
6491	79.4	10.7	607	0.61
5816	77.9	10.9	534	0.53
5250	76.8	11.0	477	0.48

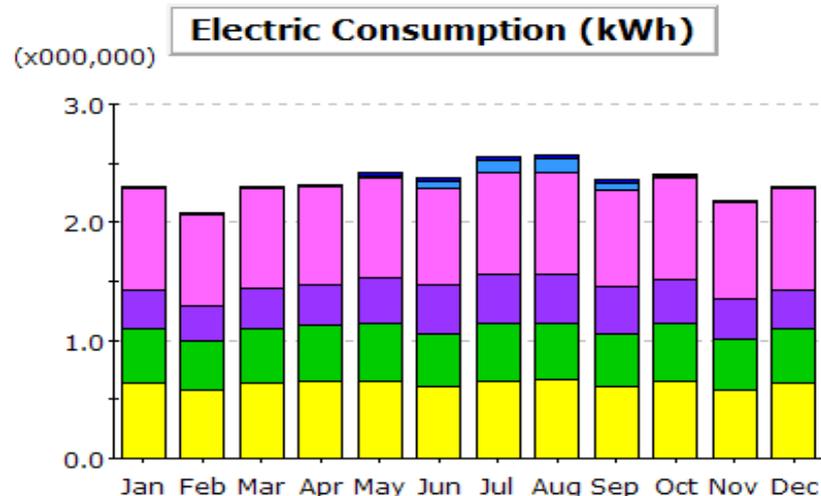
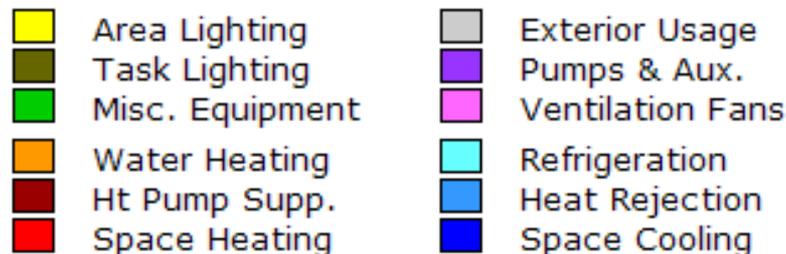
Energy used (kWh) 20.0
Energy price (\$/kWh) 0.11
Energy cost (\$) \$2.20

Whole building energy simulation

- We use the same equations for calculating peak cooling loads to write the total **building energy balance**
 - This forms the core of all building energy modeling programs
- We build a **system of equations** linking energy balances at a series of “nodes”
 - Each node has an equation accounting for all modes of heat transfer
 - Involves linking the nodes and predicting hourly indoor air temperatures (or HVAC loads) as the primary unknown
 - Also requires us to add interior heat gains
 - People, lights, equipment, etc.
 - Direct power draw + indirect heat gains
- Whole building energy simulation goes a few steps further:
 - Include HVAC system capacity & efficiency models to get HVAC energy
 - Gives us estimates of total energy use

Whole building energy simulation

- Takes into account:
 - External conditions (outdoor temperature, RH, W, solar radiation)
 - Building material properties (conductivity, U-values, R-values, SHGC, heat capacity, absorptivity, etc.)
 - HVAC system types, efficiencies, capacities, and controls
 - Building schedules (occupancy profiles, lighting profiles, thermostat settings, equipment profiles, etc.)
- Hourly (or sub-hourly) results are then used to sum over the entire year to estimate annual energy consumption



Whole building energy simulation

We can use software tools and knowledge of basic building physics and heat transfer equations to predict building energy use with *reasonable* accuracy

But be careful!!!

Never fool yourself into thinking your model will be exact

Building energy models are best used to understand design options and trade-offs (i.e., relative comparisons)

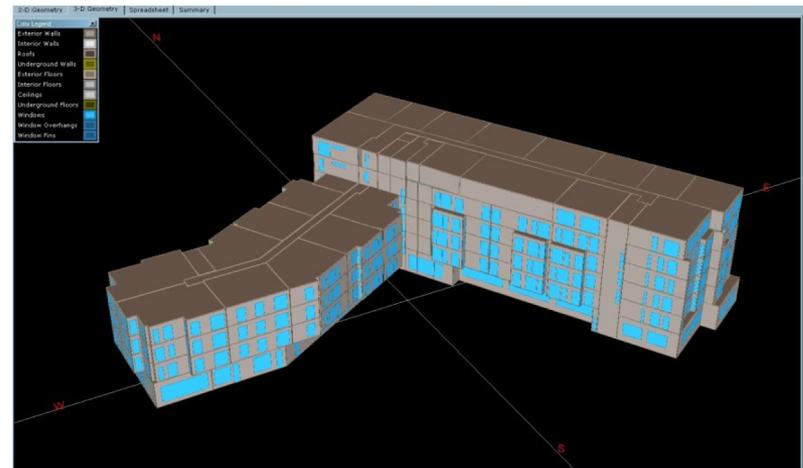
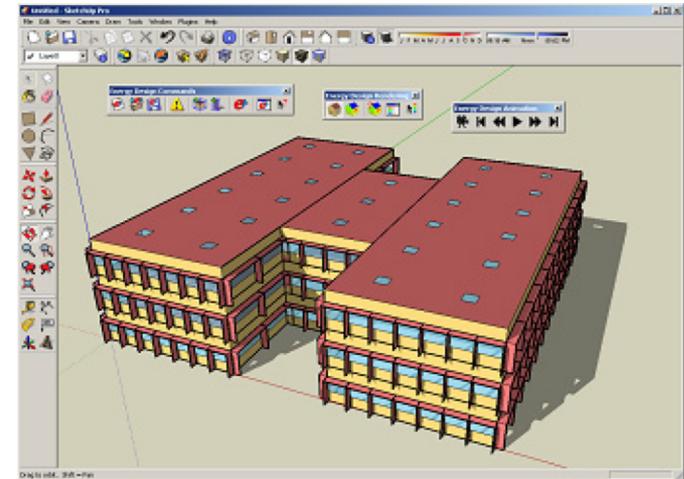
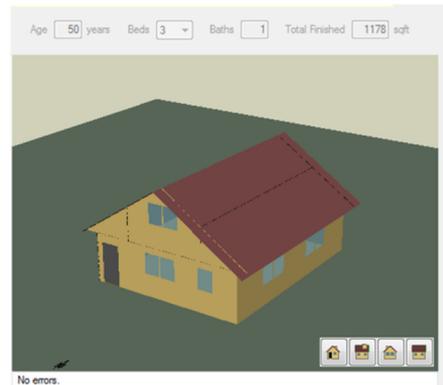
Building energy modeling

There are many software packages available (some are free)

Examples:

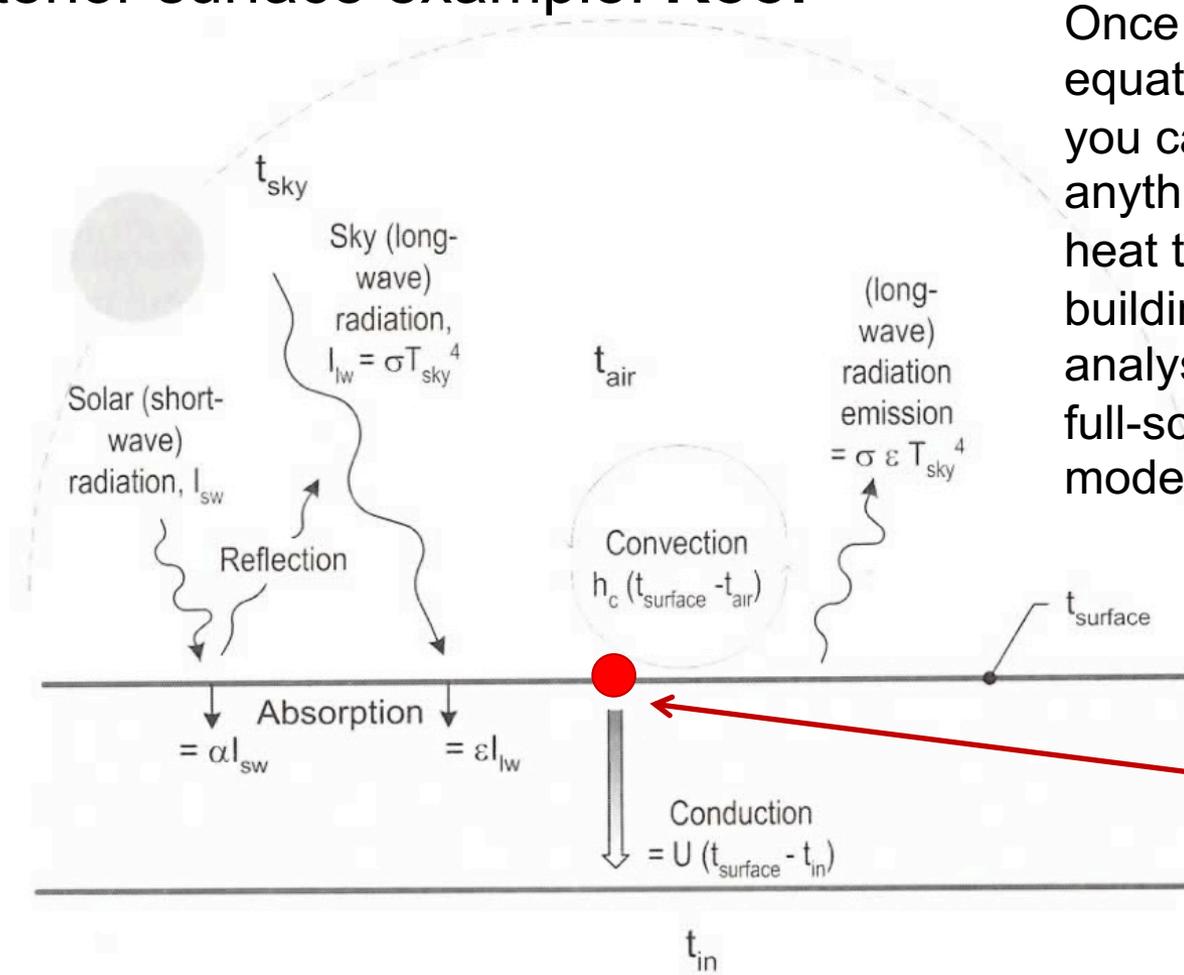
- EnergyPlus
 - OpenStudio
 - Simergy
 - BEopt
- eQUEST
- IES-VE
- TRNSYS
- Trane Trace
- Many others

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



Surface energy balance example

- Exterior surface example: **Roof**



Once you have this equation described, you can do just about anything regarding heat transfer in building enclosure analysis, leading into full-scale energy modeling

$$q_{solar} + q_{longwaveradiation} + q_{convection} - q_{conduction} = 0$$

Surface energy balance example

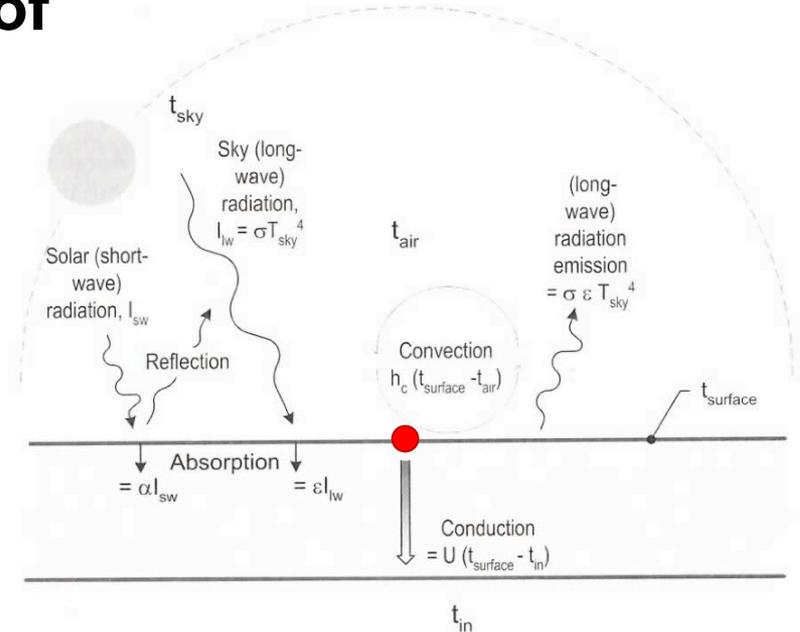
- Exterior surface example: **Roof**

$$\sum q = 0$$

We can use this equation to estimate indoor and outdoor surface temperatures

At steady state, net energy balance is zero

- Because of T^4 term, often requires iteration



Solar gain

$$\alpha I_{solar}$$

$$q_{sw,solar}$$

Surface-sky radiation

$$+\epsilon_{surface} \sigma F_{sky} (T_{sky}^4 - T_{surface}^4)$$

$$+q_{lw,surface-sky}$$

Convection on external wall

$$+h_{conv} (T_{air} - T_{surface})$$

$$+q_{convection}$$

Conduction through wall

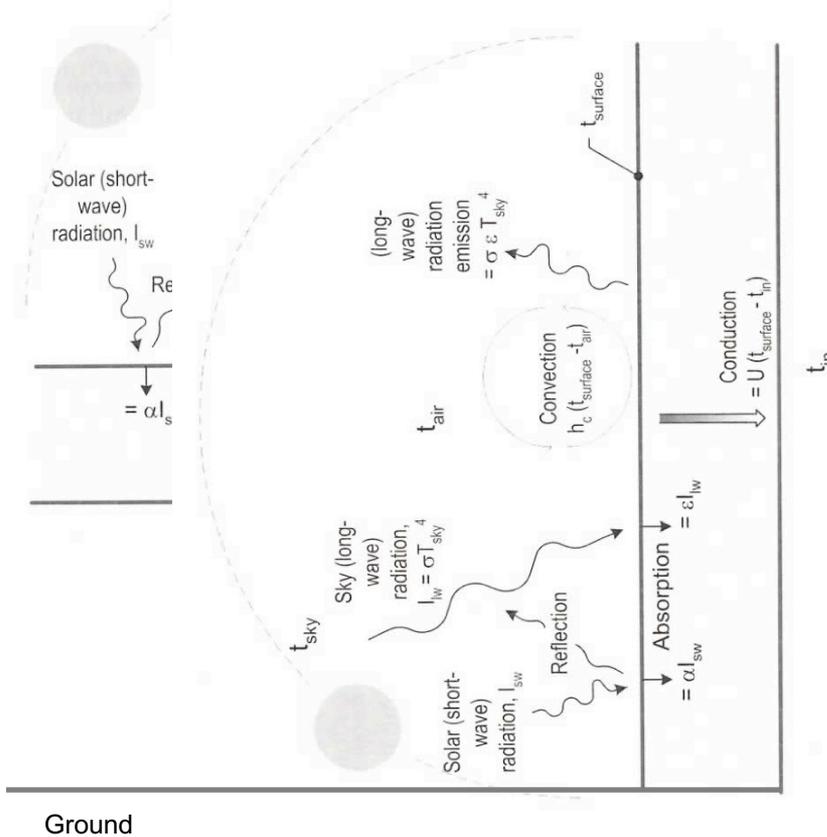
$$-U(T_{surface} - T_{surface,interior}) = 0$$

$$-q_{conduction} = 0$$

Surface energy balance example

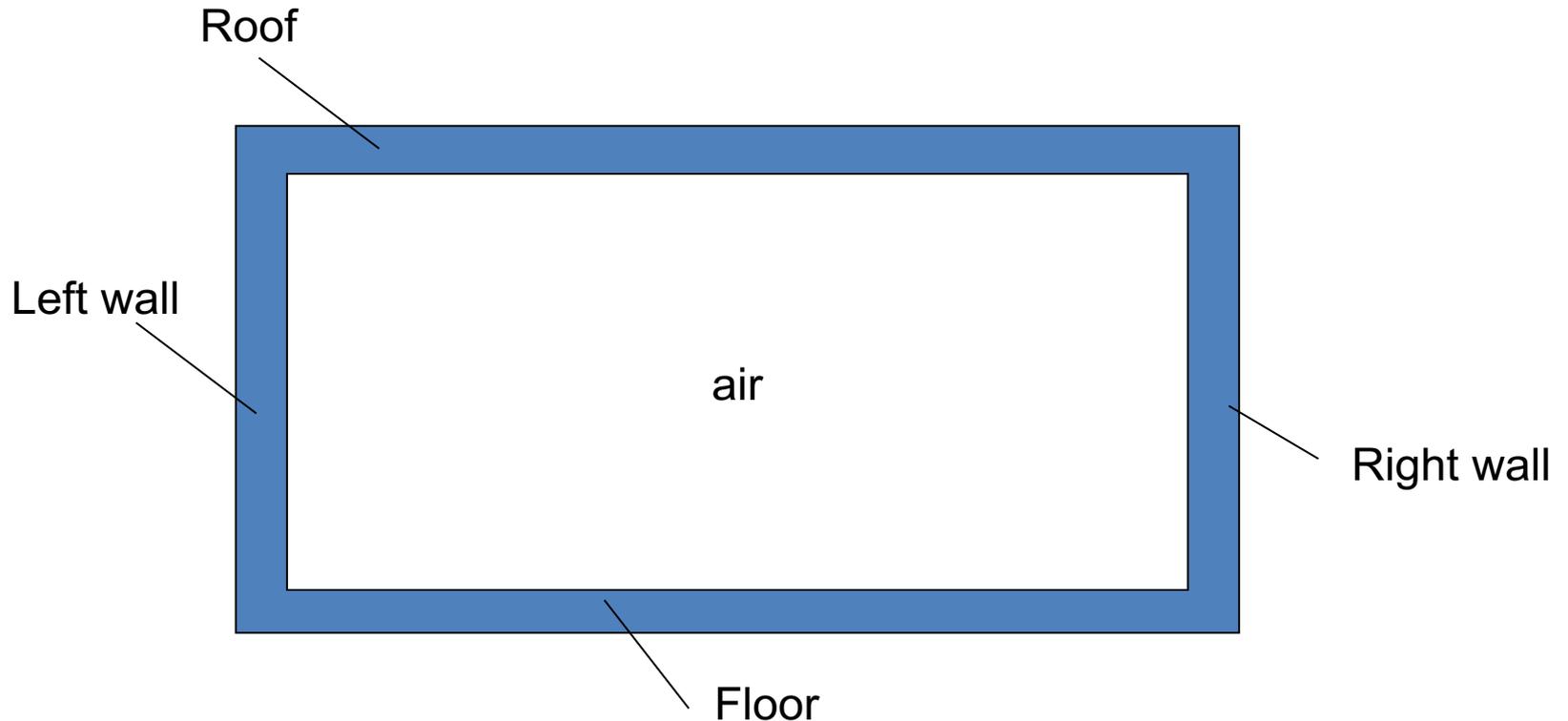
- Similarly, for a vertical surface:

$$q_{solar} + q_{lwr} + q_{conv} - q_{cond} = 0$$



$$\begin{aligned} & \alpha I_{solar} \\ & + \epsilon_{surface} \sigma F_{sky} (T_{sky}^4 - T_{surface}^4) \\ & + \epsilon_{surface} \sigma F_{ground} (T_{ground}^4 - T_{surface}^4) \\ & + h_{conv} (T_{air} - T_{surface}) \\ & - U (T_{surface} - T_{surface,interior}) = 0 \end{aligned}$$

Simplest 'box' model

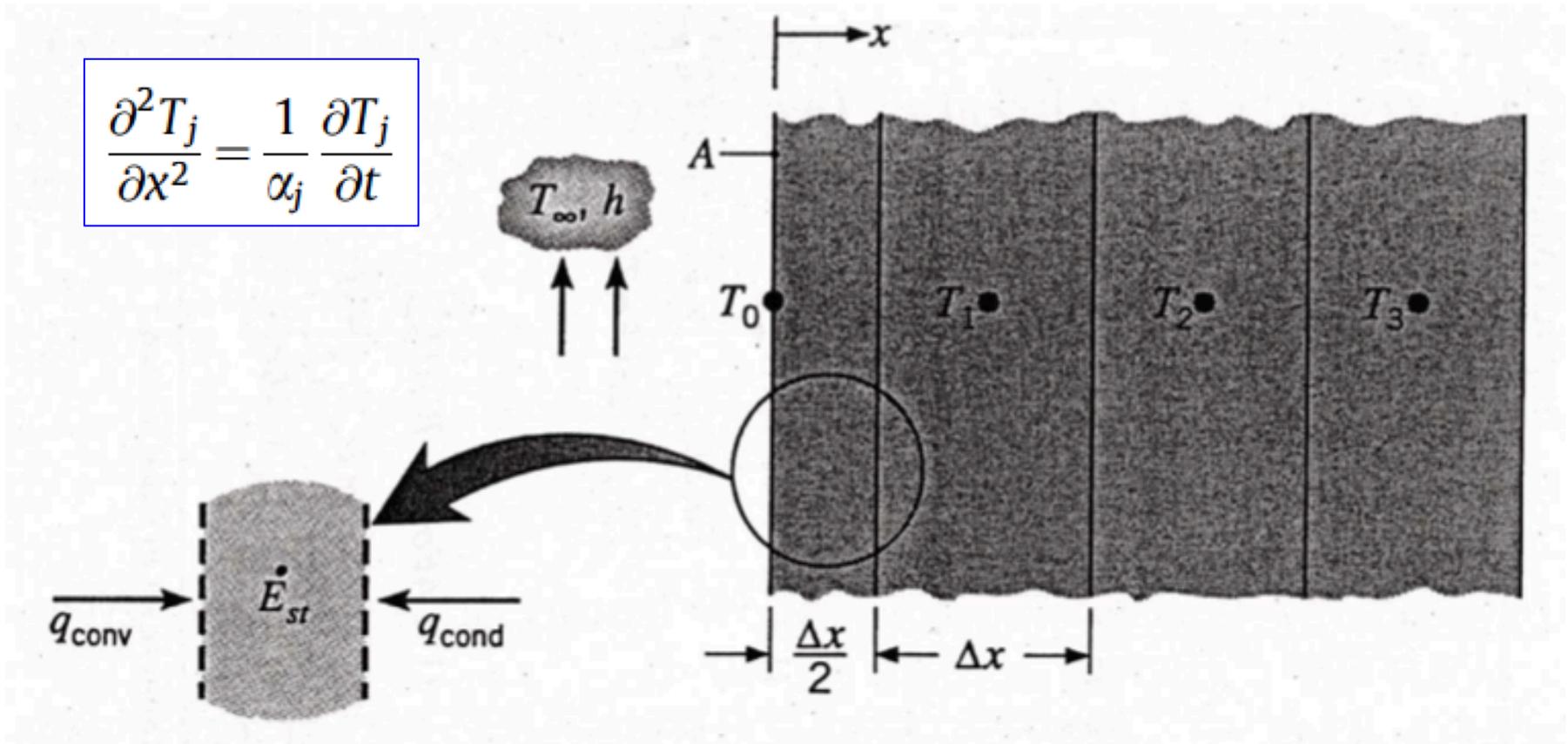


Elements are connected by:

- 1) Convection – air node
- 2) Radiation – surface nodes

Modeling thermal mass: Transient (unsteady) conduction

- Divide material assembly into multiple nodes



Modeling thermal mass: Lumped capacitance model

- Wall example: Exterior surface balance at T_1 changes

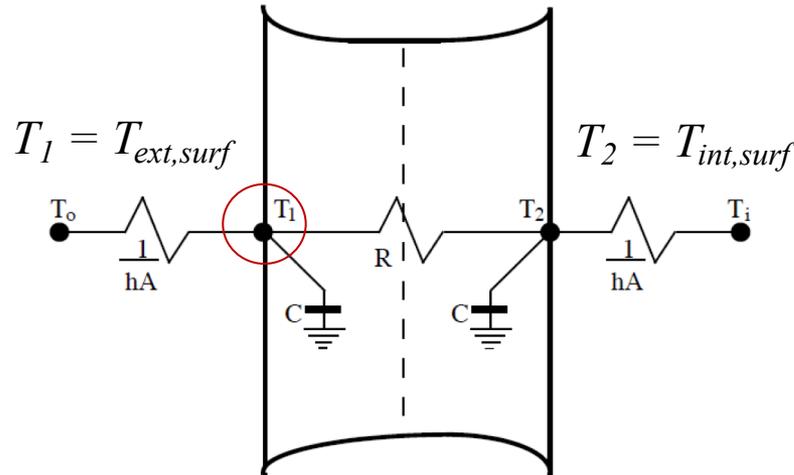


Figure 9. Two Node State Space Example.

From:

$$\begin{aligned}
 & q_{sw,solar} \\
 & + q_{lw,surface-sky} \\
 & + q_{lw,surface-ground} \\
 & + q_{convection} \\
 & - q_{conduction} = 0
 \end{aligned}$$

To:

$$\begin{aligned}
 & q_{sw,solar} \\
 & + q_{lw,surface-sky} \\
 & + q_{lw,surface-ground} \\
 & + q_{convection} \\
 & - q_{conduction} = \rho C_p \frac{L}{2} \frac{dT}{dt}
 \end{aligned}$$

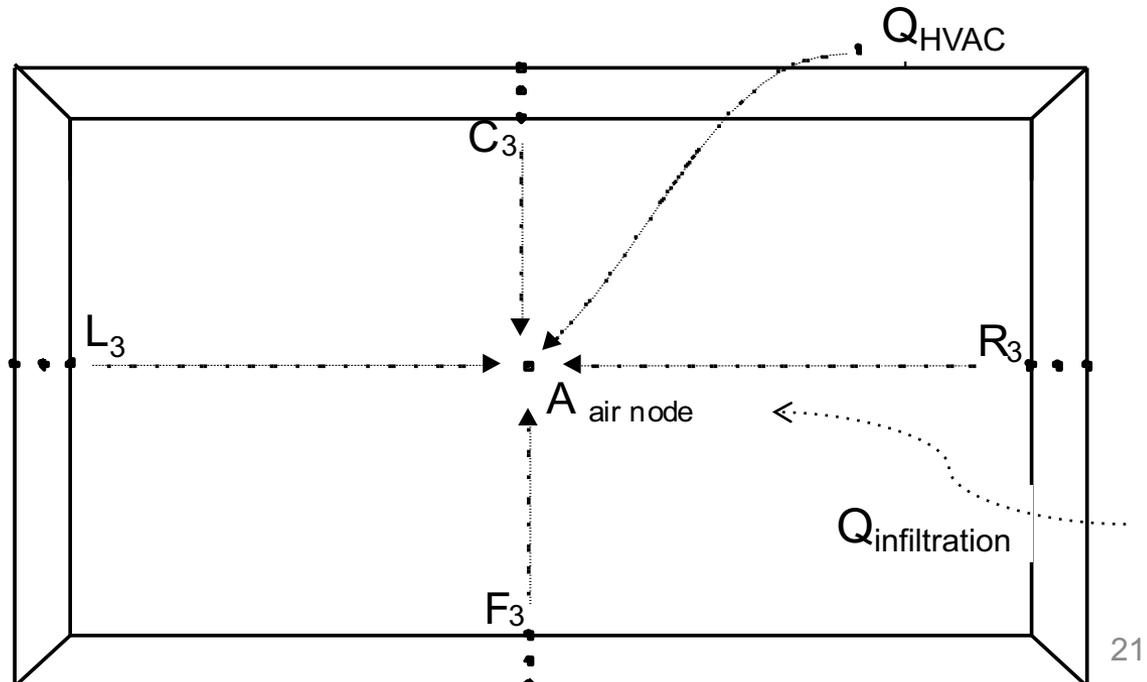
Unsteady energy balance for air node

- To get the impact on indoor air temperature (and close the system of equations)
 - Write an energy balance on the indoor air node
 - Air impacted directly only by convection (bulk and surface)

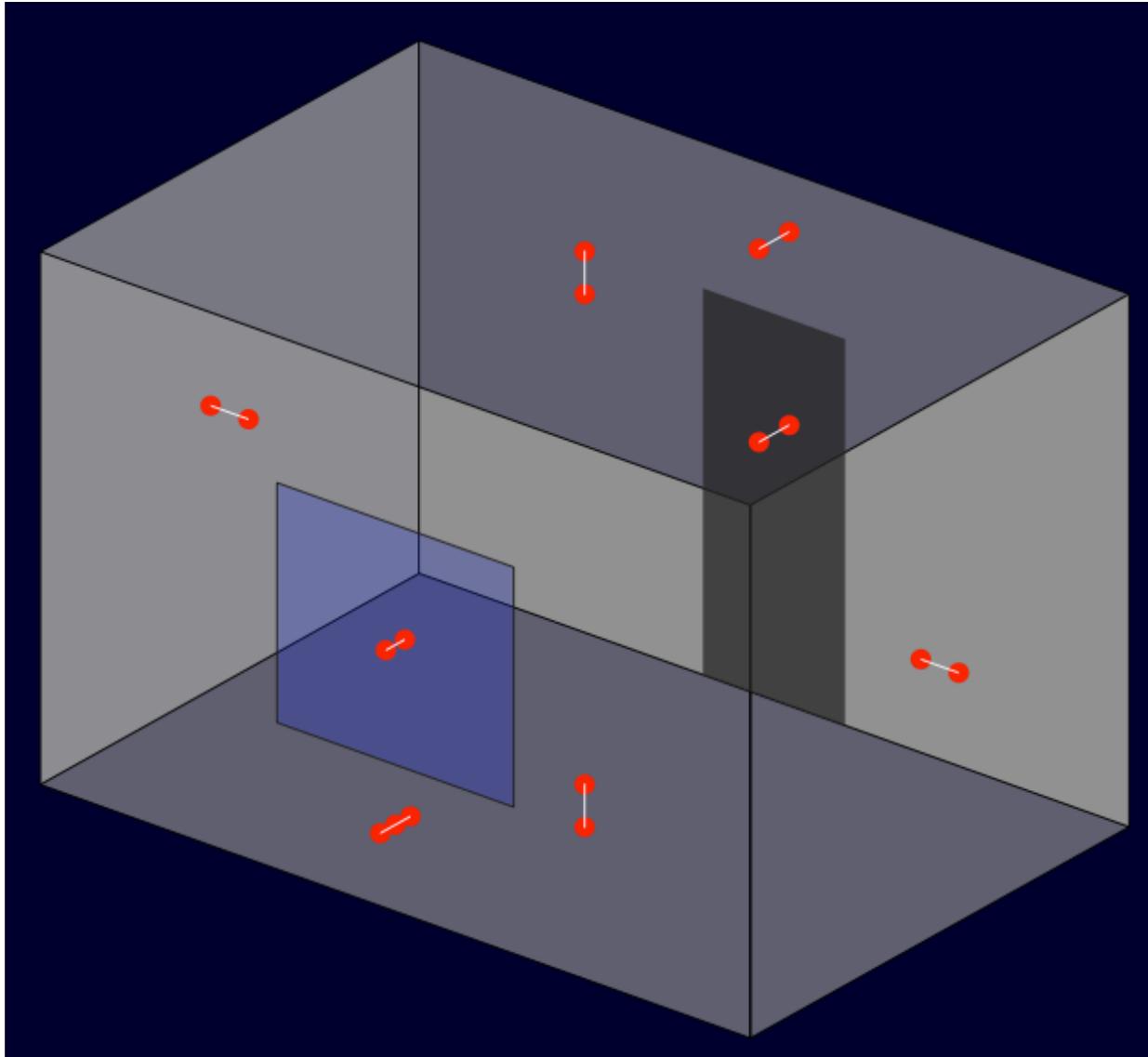
$$(V_{room} \rho_{air} c_{p,air}) \frac{dT_{air,in}}{dt} = \sum_{i=1}^n h_i A_i (T_{i,surf} - T_{air,in}) + \dot{m} c_p (T_{out} - T_{air,in}) + Q_{HVAC}$$

In plain English:

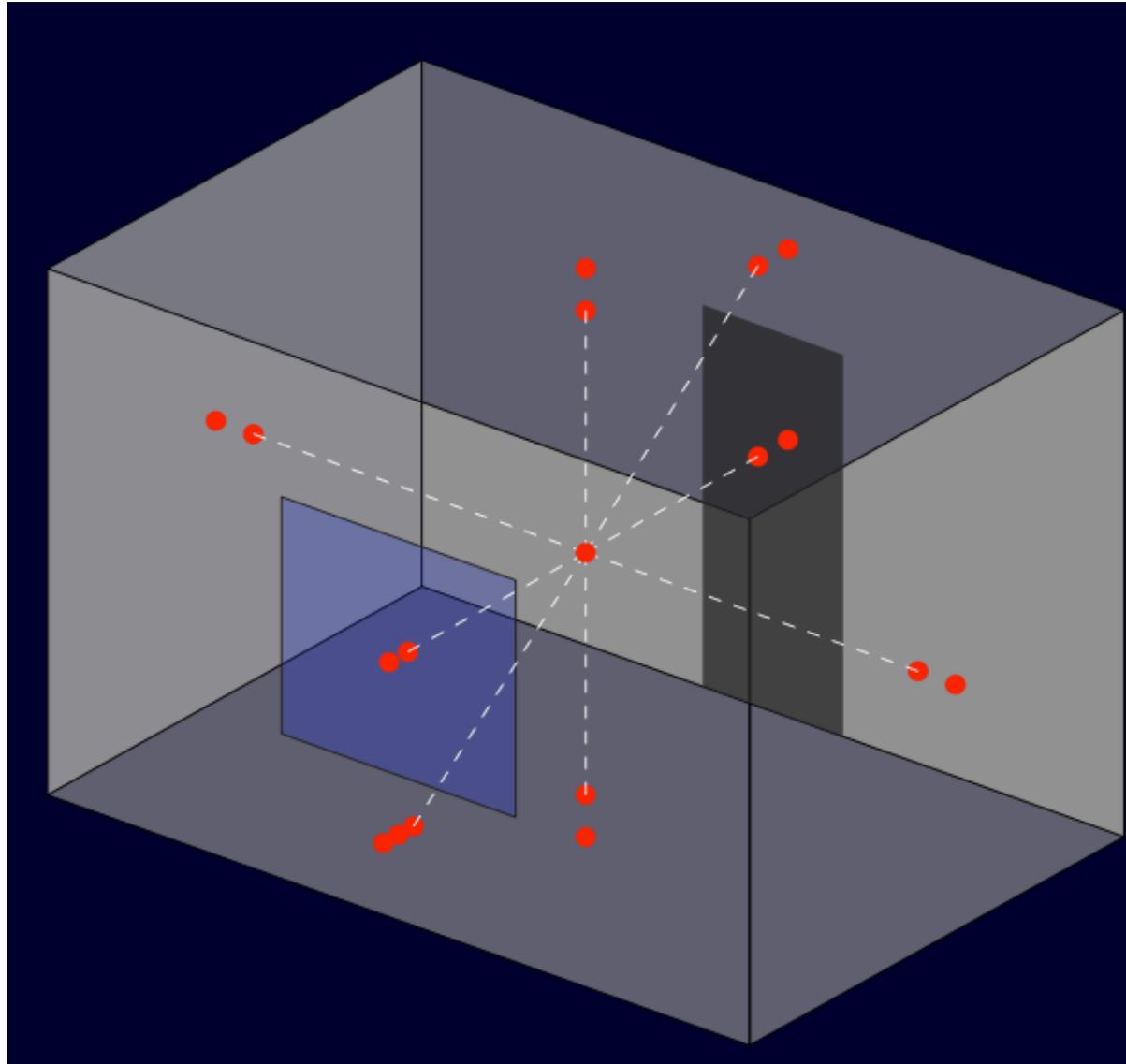
The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



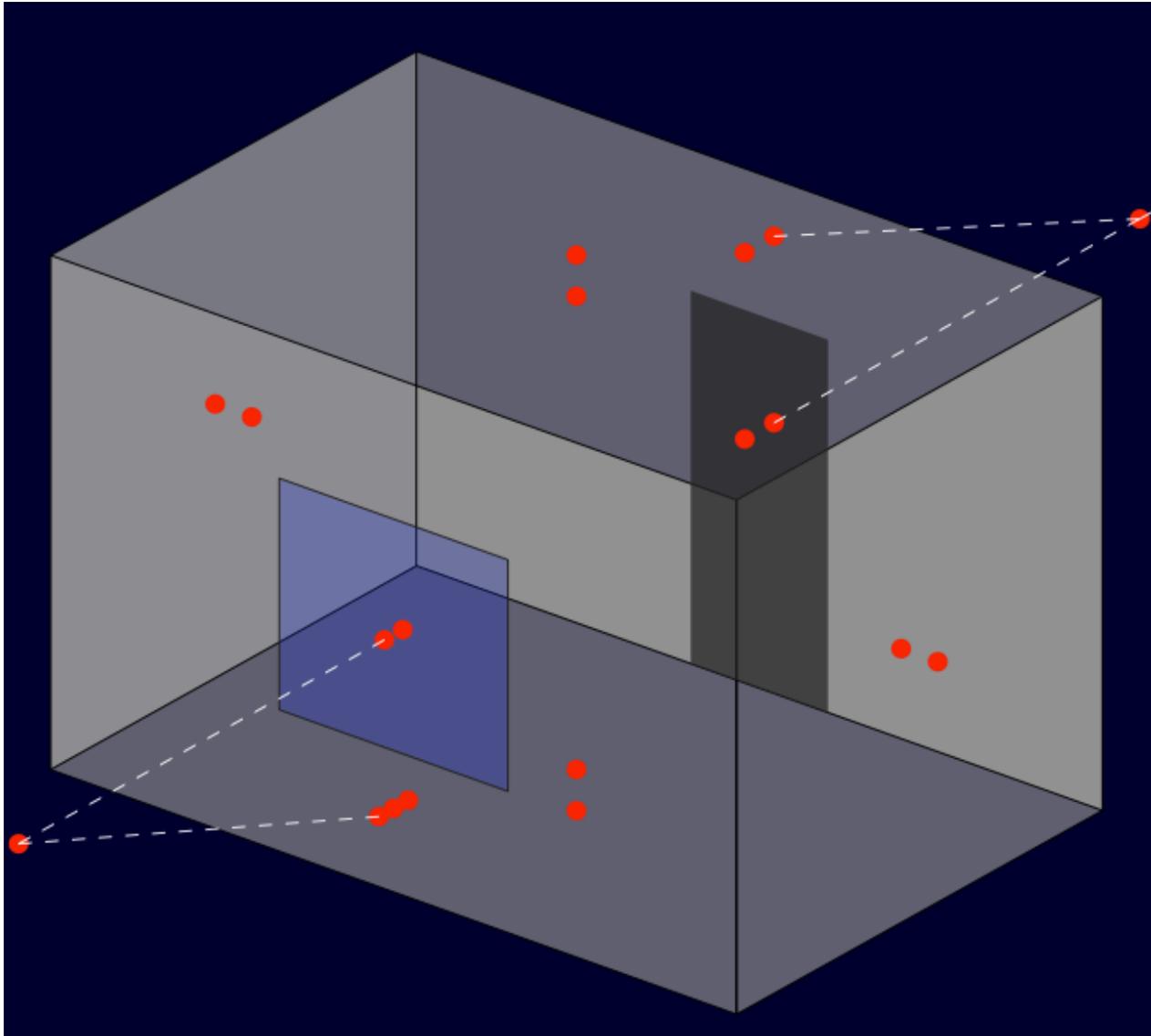
Simplest 'box' model: **Conduction** elements



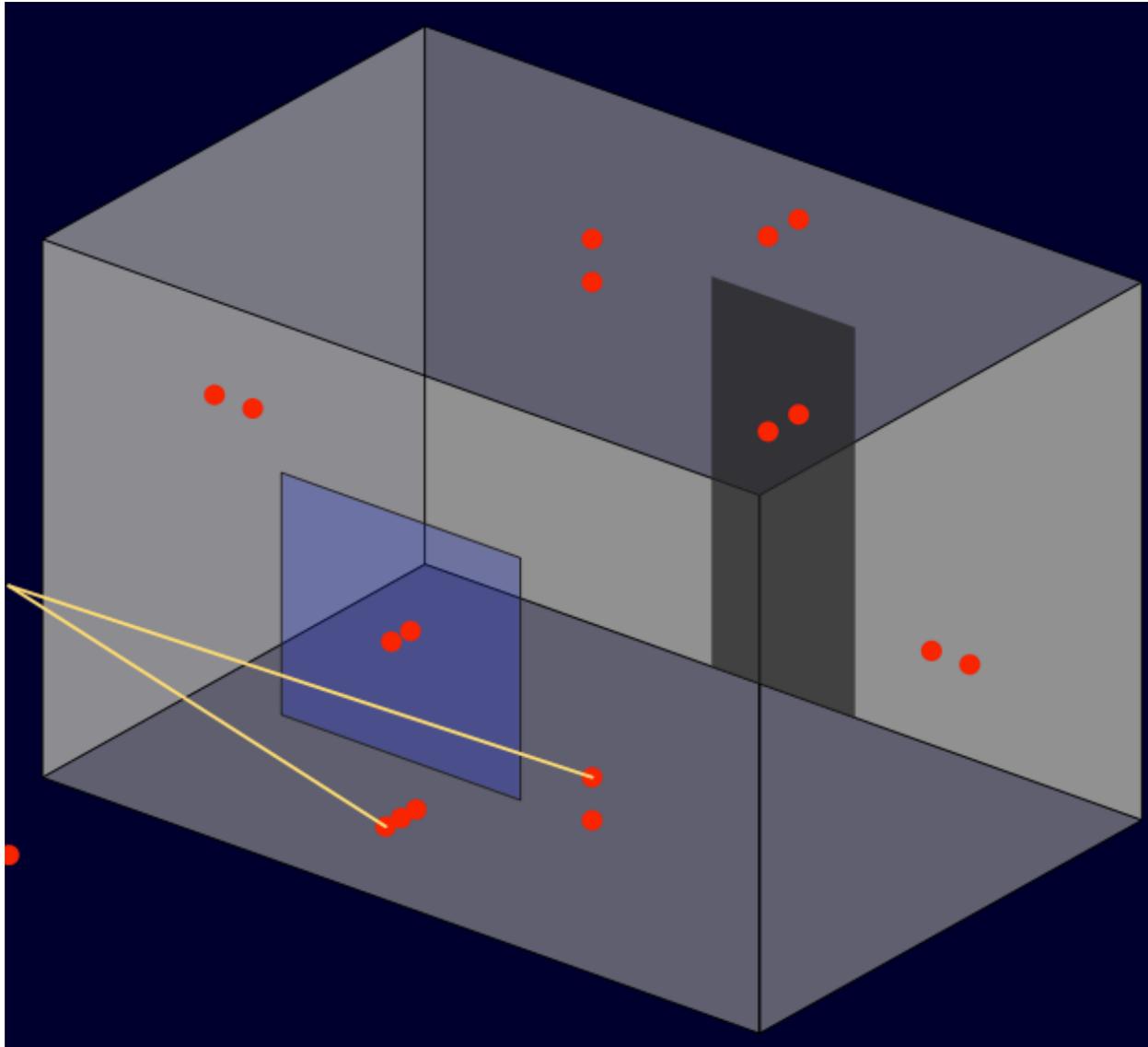
Simplest 'box' model: **Interior convection** elements



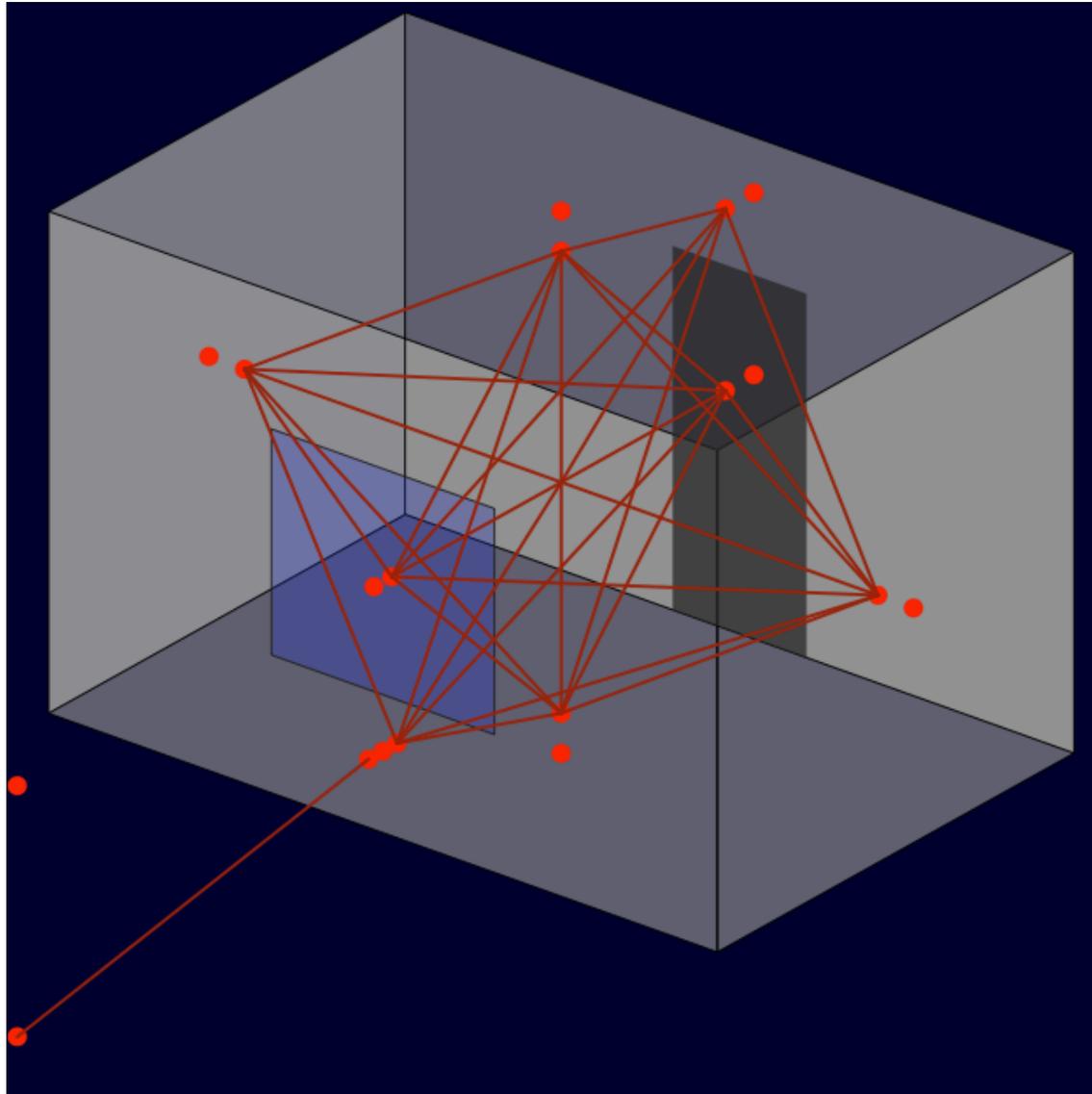
Simplest 'box' model: **Exterior convection** elements



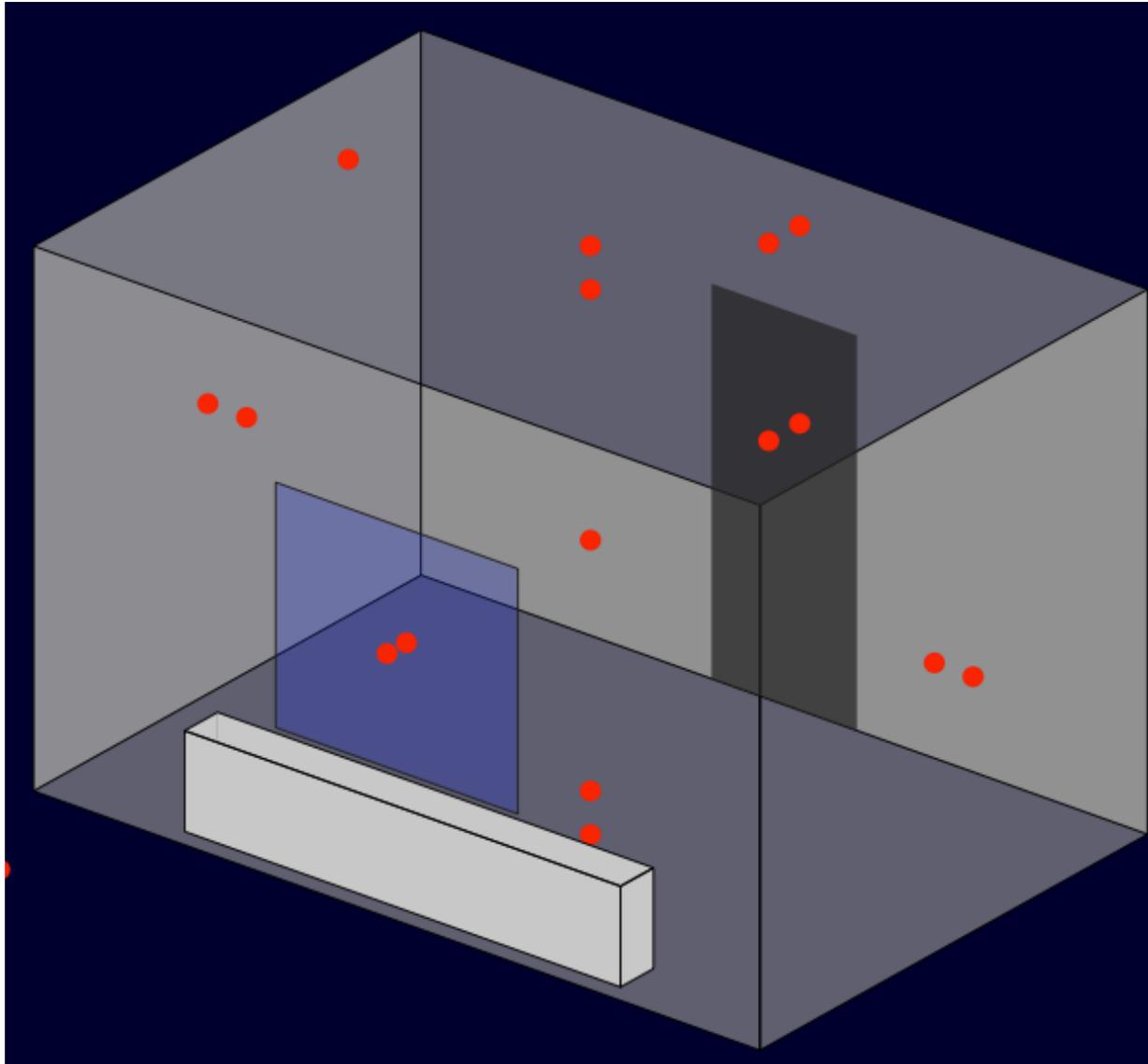
Simplest 'box' model: **Solar (direct + diffuse)**



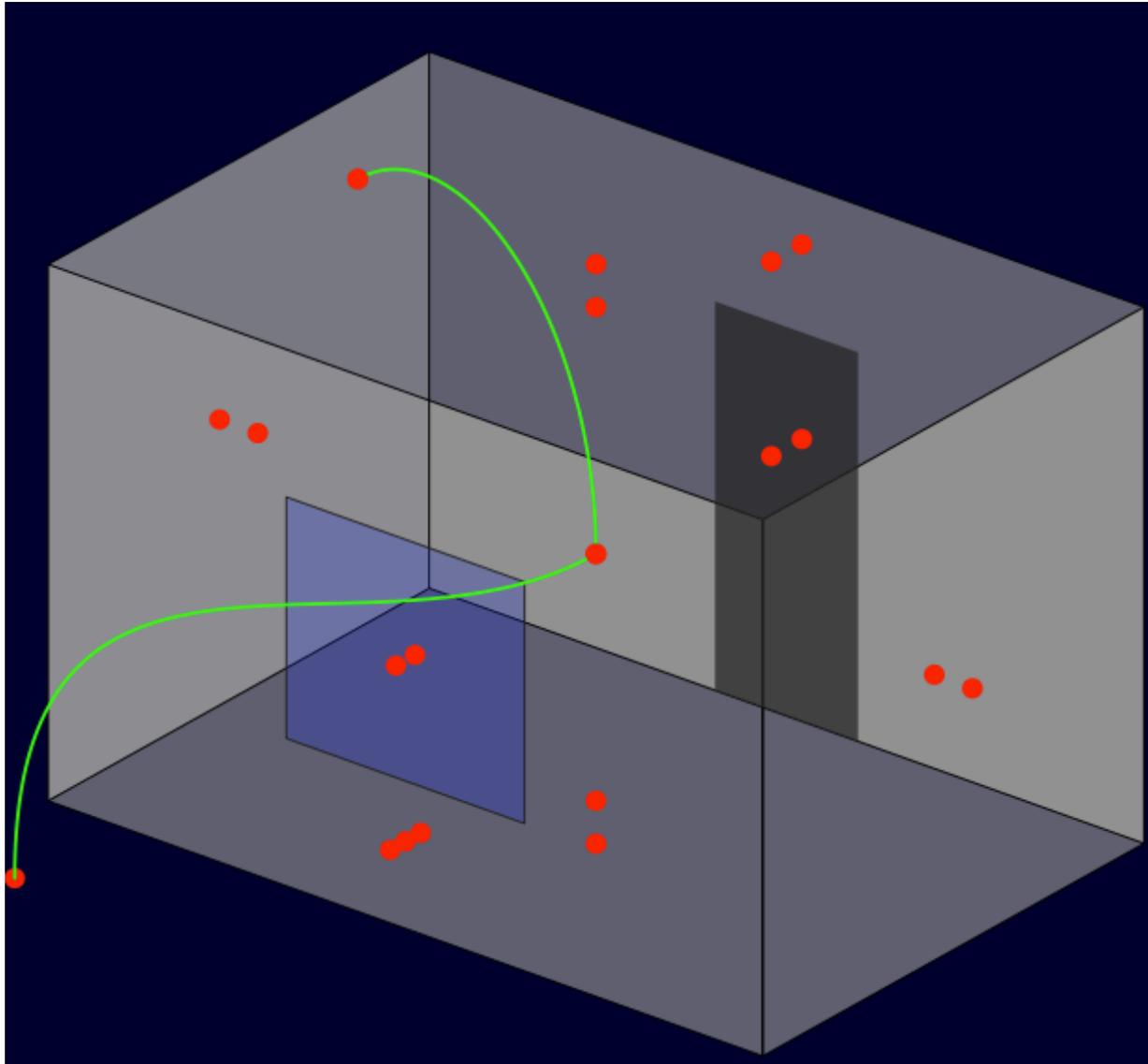
Simplest 'box' model: Long wave radiation elements



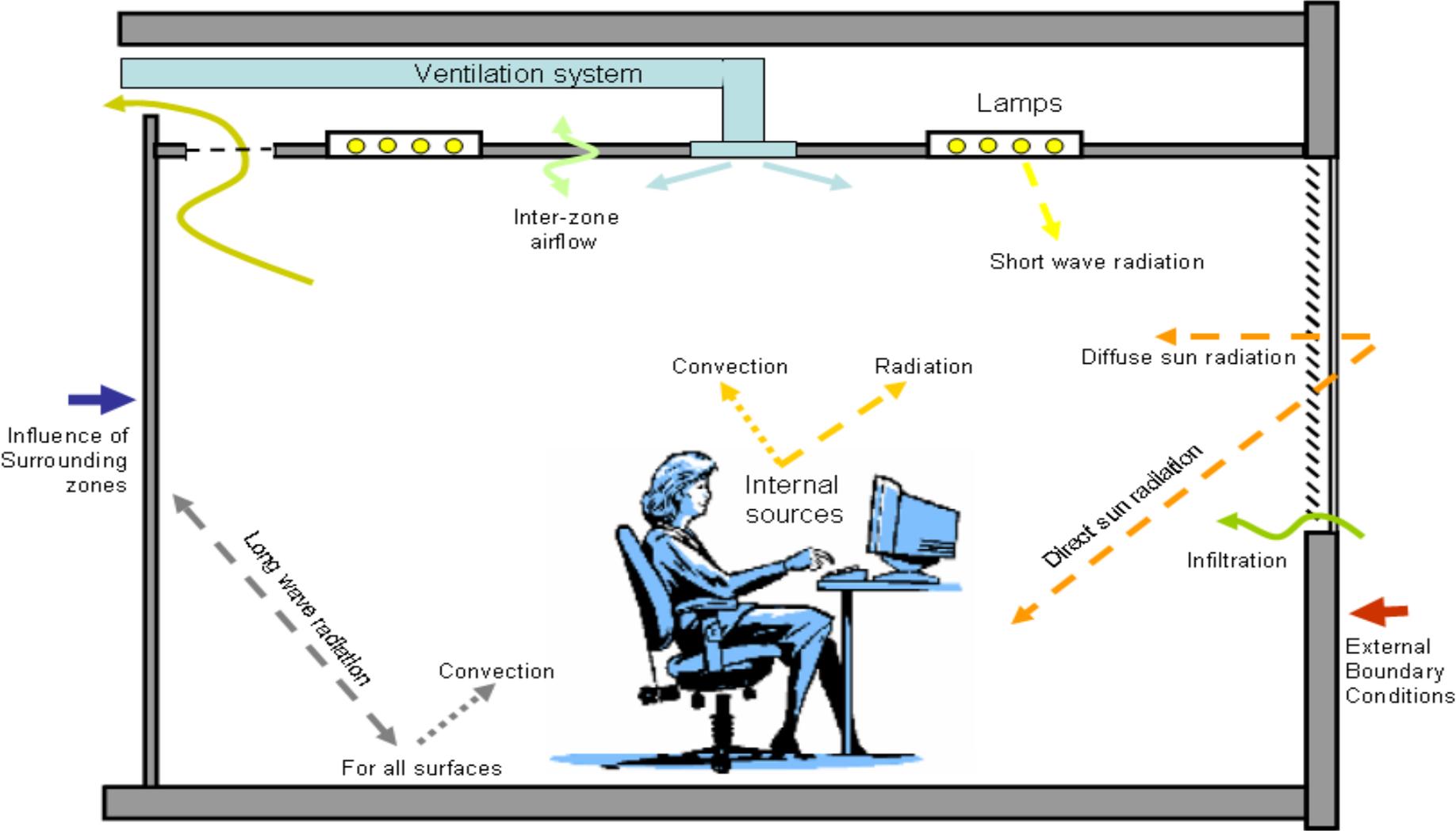
Simplest 'box' model: **Internal mass** (e.g., furniture)



Simplest 'box' model: **Ventilation/infiltration** elements



Adding occupants, equipment, and lights

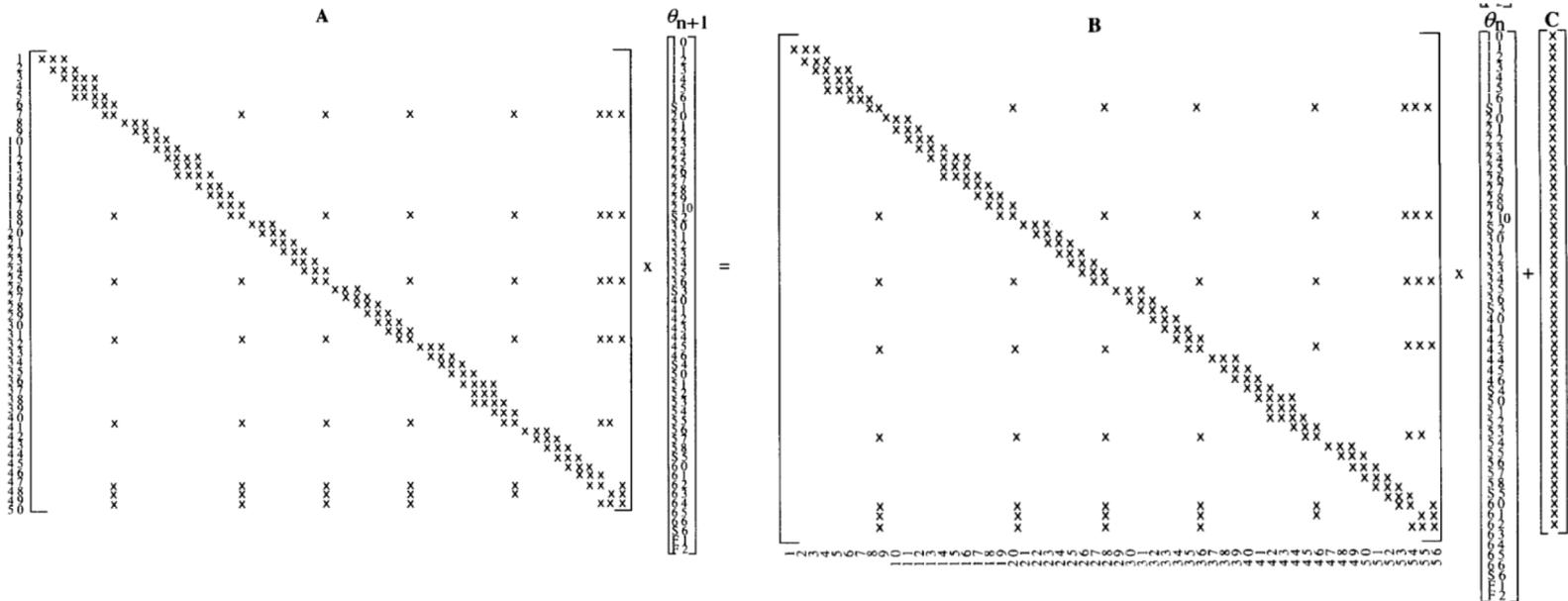


Solving the system of equations

In matrix notation, the system of equations can be expressed as

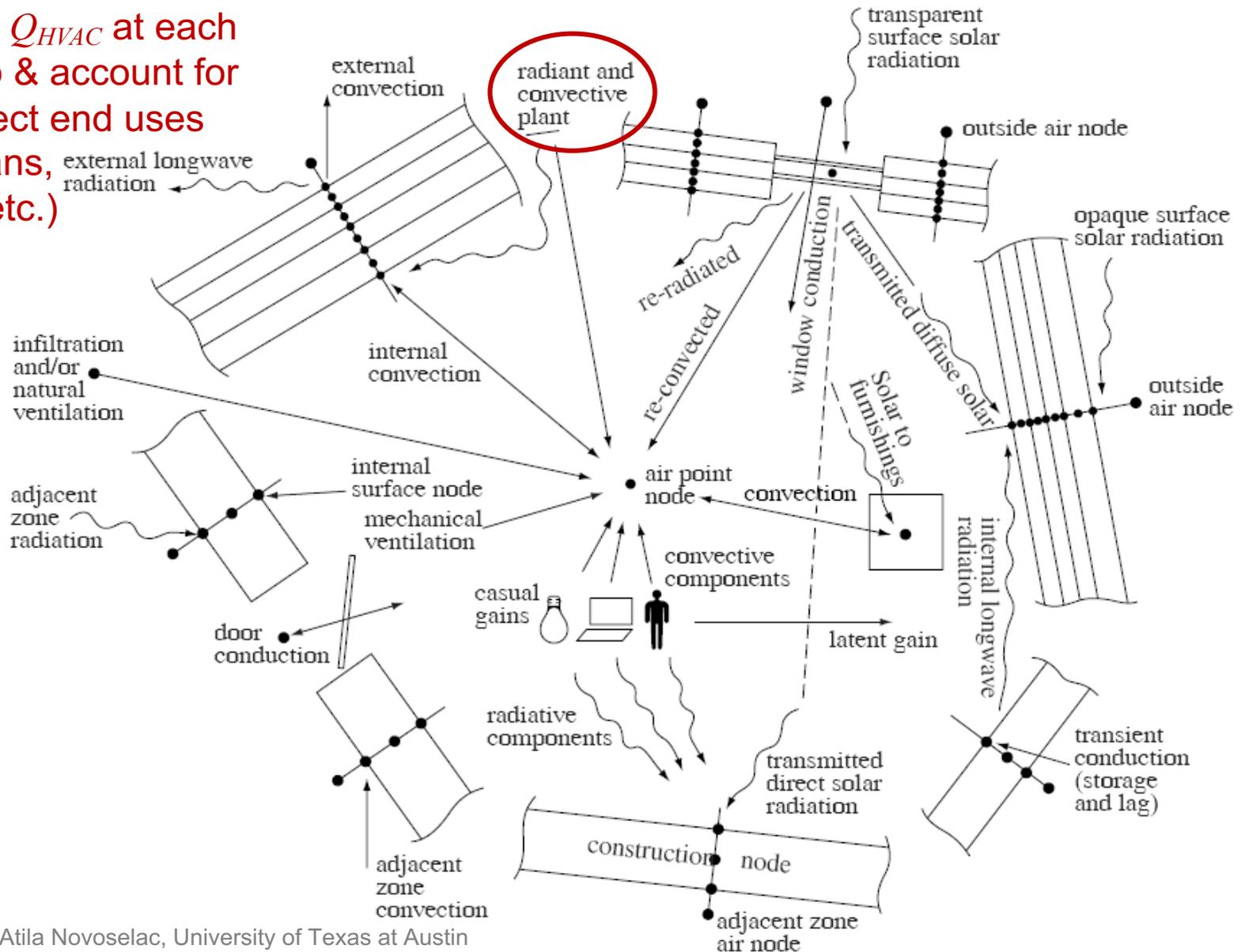
$$\mathbf{A}\theta_{n+1} = \mathbf{B}\theta_n + \mathbf{C} = \mathbf{Z} \quad (4.1)$$

where \mathbf{A} is a sparse matrix of future time-row coefficients of the nodal temperature or heat injection terms of the conservation equations, \mathbf{B} the corresponding matrix established at the present time-row, \mathbf{C} a column matrix of known boundary excitations relating to the present and future time-rows, θ a column matrix of nodal temperatures and heat injections, $n + 1$ refers to the future time-row, n the present time-row, and \mathbf{Z} is a column matrix. Initial conditions are given by $\theta(0) = \theta_0$.



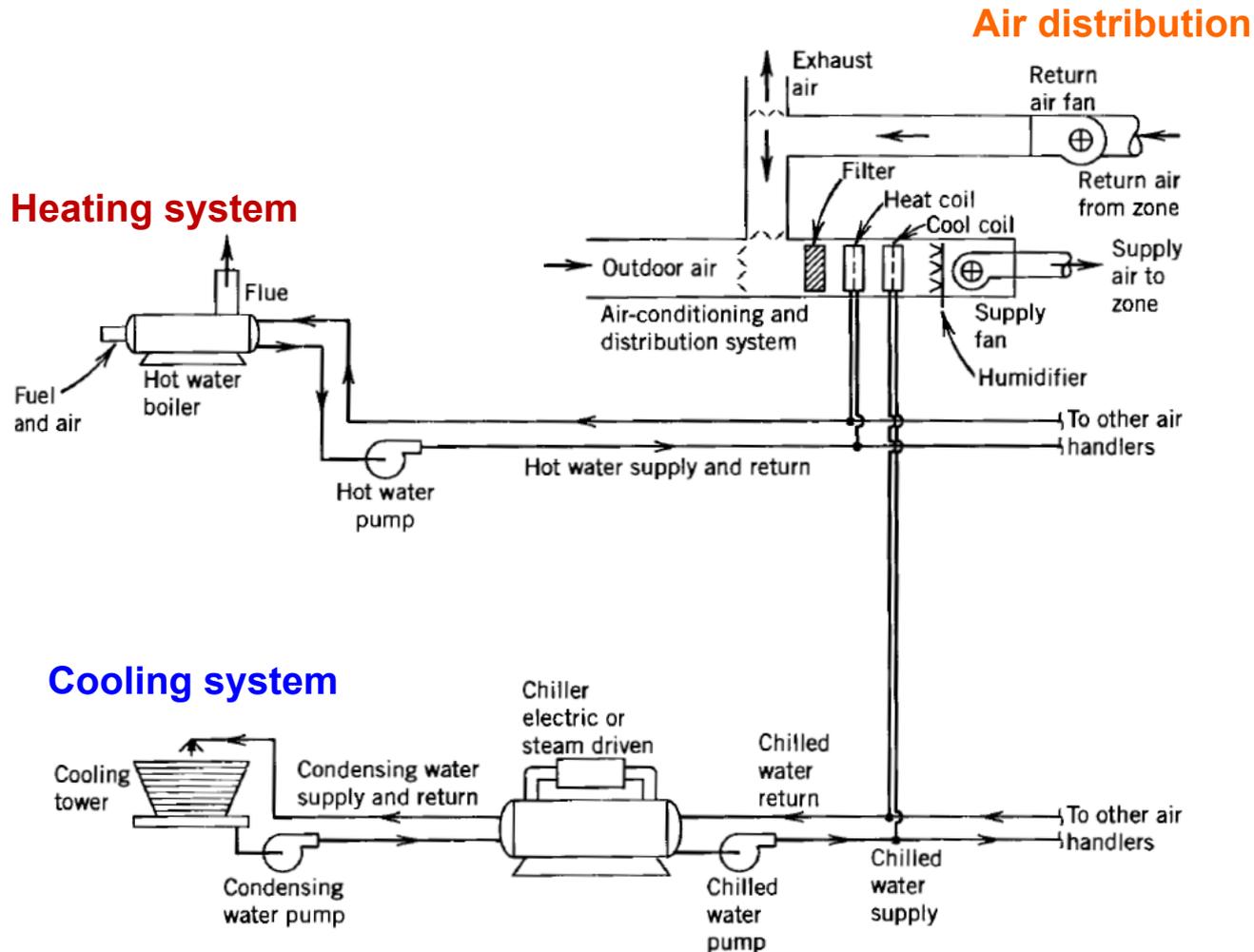
Whole building energy simulation

Solve for Q_{HVAC} at each time step & account for other direct end uses (lights, fans, pumps, etc.)



HVAC system models

- You also need to know some details of the HVAC systems to complete the energy modeling procedure



HVAC system models

- We don't have time to go into HVAC system models in detail
- Most programs utilize empirical models of operating HVAC system components
 - Chillers, boilers, direct expansion AC units, radiant cooling/heating systems
 - Fans are a bit simpler
- **Example model for a chiller:**

$$P = P_{NOMINAL} \cdot CAPFT \cdot EIRFT \cdot EIRFPL$$

CAPFT – Capacity as function of evaporator and condenser temperature

EIRFT – Energy Input Ratio as function of of condenser and evaporator temperature

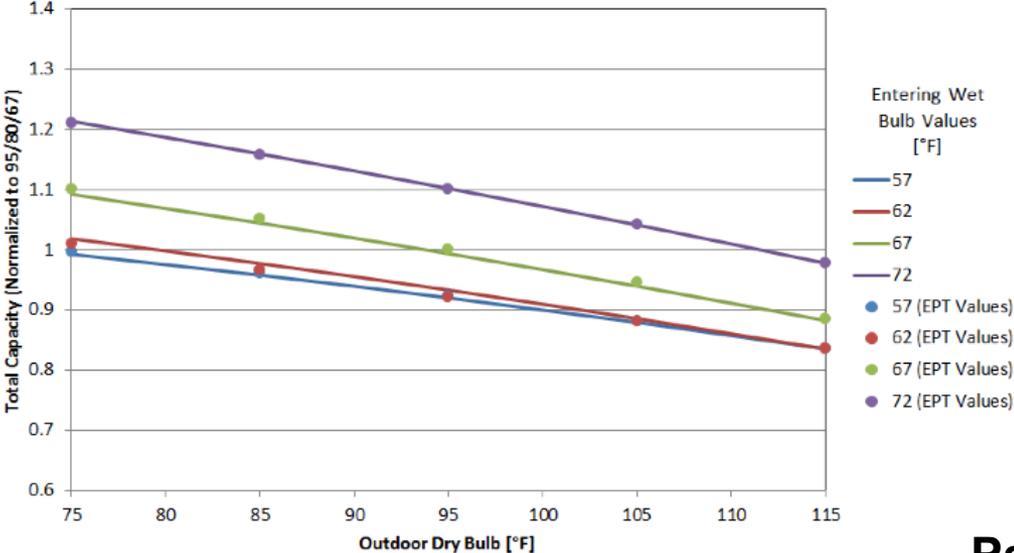
EIRFPLR – Energy Input Ratio as function of Part Load Ratio

PLR – Part Load Ratio

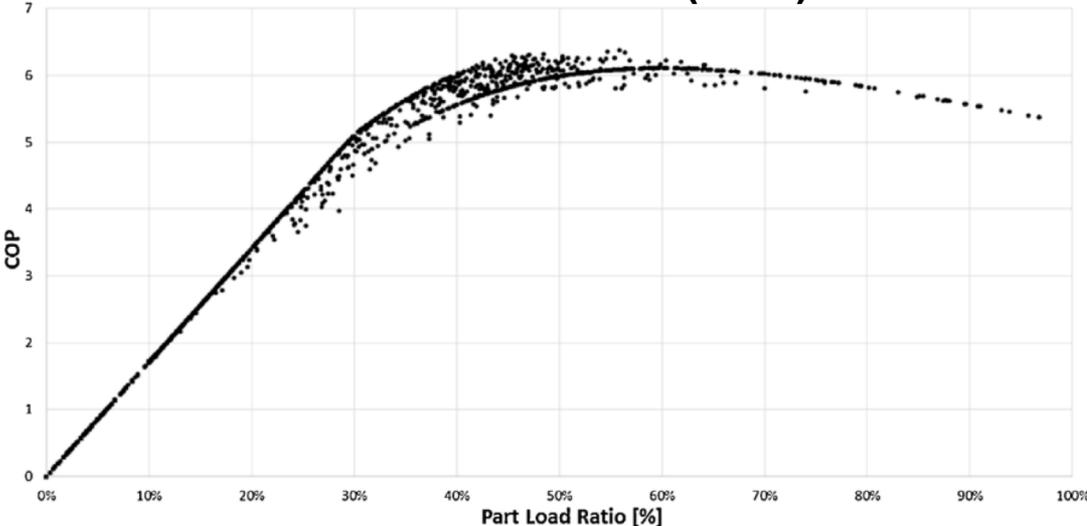
$$P_{elec} = \frac{Q_{cooling,load}}{COP}$$

HVAC system models

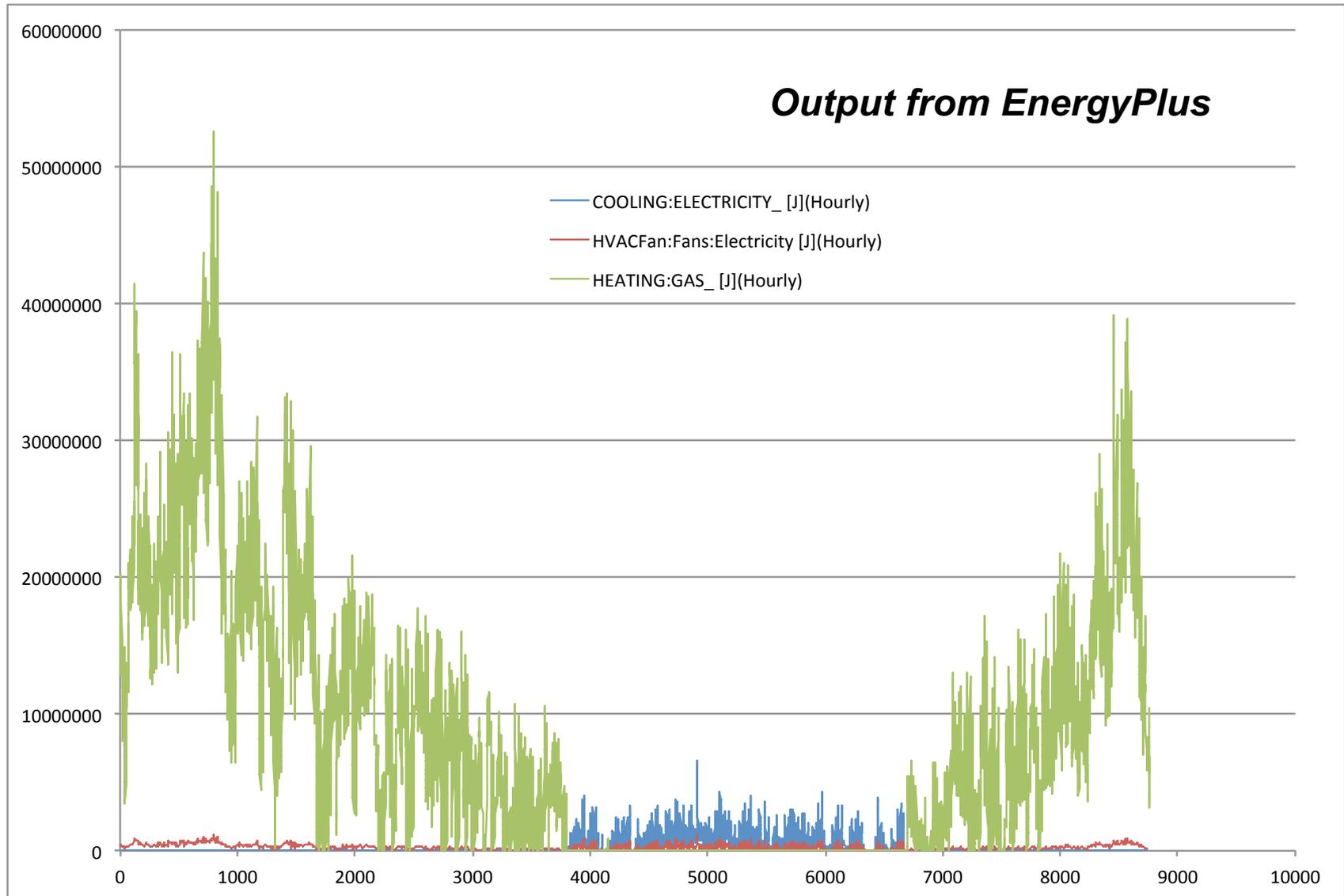
Outdoor conditions



Part load ratio (PLR)



Building energy simulation results: Example home in Chicago



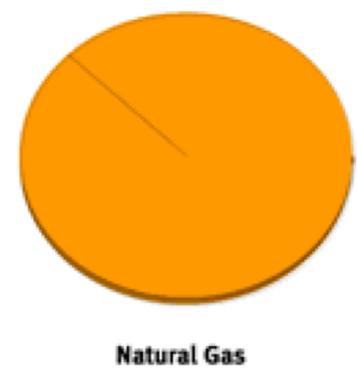
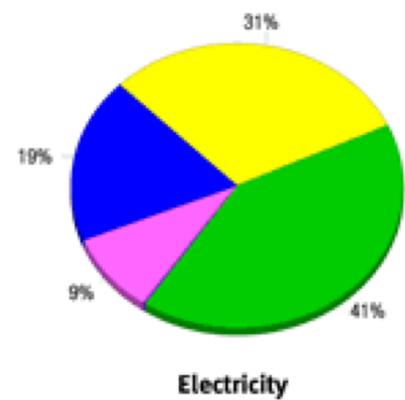
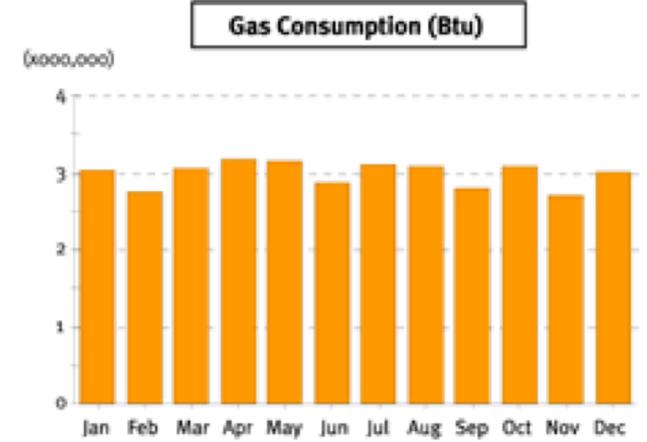
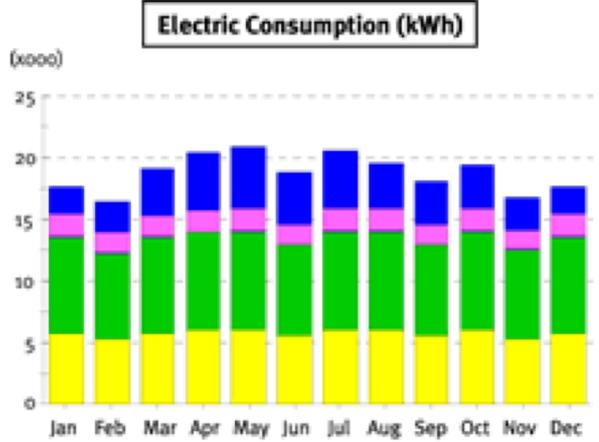
Building energy simulation results: Example home in Chicago

Annual summary	Electric	Gas
Total J	29270600548	90956293121
Total kWh	8131	
Total MMBTU		86.2
\$/unit	\$0.10	\$8.00
Annual energy cost	\$813	\$690

~\$1500 in annual energy costs in this home

- Once we've established a baseline, we can make design and system changes to predict the impacts on energy, costs, and environmental pollution

Annual energy simulation results (eQUEST)



Important input parameters for energy simulation

- Meteorological data (TMY, AMY)
 - Temperature, wind speed, solar radiation, cloud cover
- Envelope heat transfer properties
- Radiation and convection models
 - Internal and external
- Windows and shading
- Air infiltration models
- Conduction to the ground
- HVAC system and control models
- Conduction (and storage) solution method
 - Finite difference (explicit, implicit)
 - Response function techniques (simpler, less accurate)
- Time steps
 - Too short and calculations take forever
 - Too long and solutions diverge

DESIGNING FOR ENERGY EFFICIENCY

Energy use intensity (EUI)

- Energy use intensity (EUI) = energy use per floor area
 - kBTU/ft² (MJ/m²)

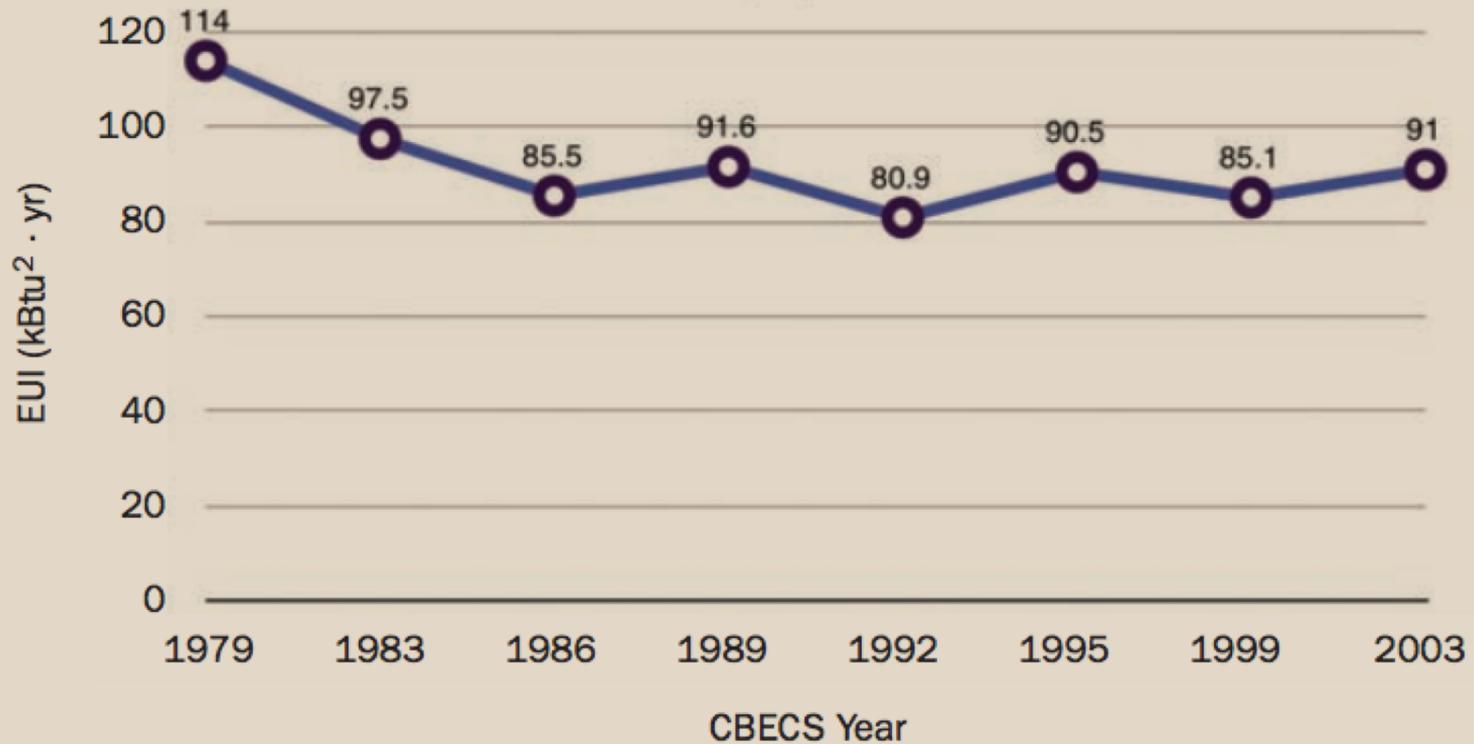
$$\frac{\text{Annual Building Energy Use}}{\text{Building Area}} = \text{EUI}$$

(kBtus or MJ) / (ft² or m²)

- Can be calculated on a source (primary) or site (secondary) energy basis
- Has EUI been increasing or decreasing in the U.S.?

Energy use intensity (EUI)

FIGURE 2 U.S. COMMERCIAL BUILDING TOTAL SITE ENERGY INTENSITY TREND



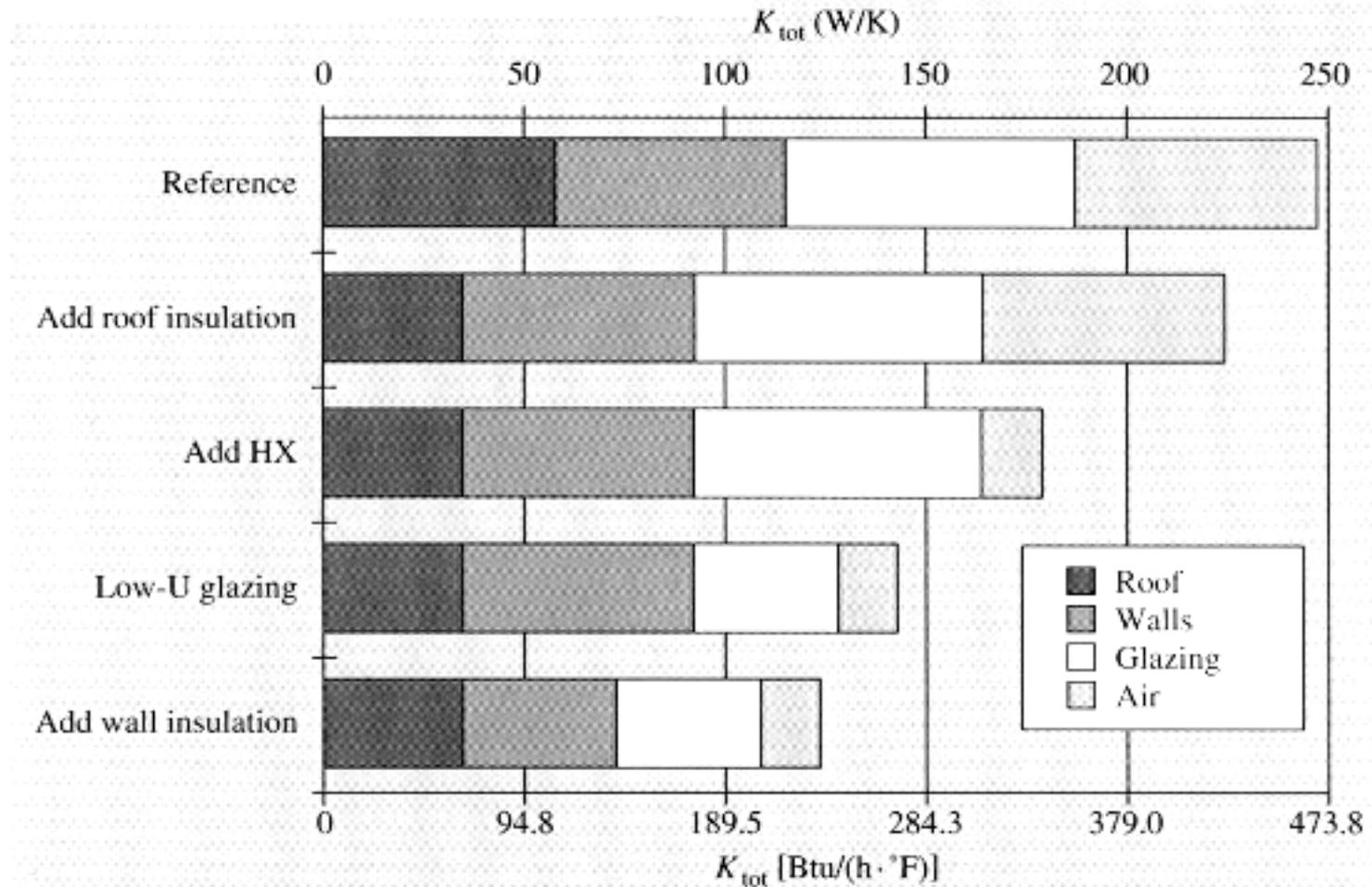
Energy Information Administration
Commercial Buildings Energy Consumption Survey

Designing for efficiency

- We can't change outdoor conditions (e.g., temperature, solar radiation, or HDD and CDD)
 - So what can we do to reduce energy consumption?
- Reduce UA (including infiltration contribution, $\rho C_p \dot{V}$)
- Increase COP/efficiency of equipment
- Reduce internal loads and electrical power draws
- Change thermostat settings (affects thermal comfort)
- Utilize passive solar and thermal mass to shift loads
- The earlier in the design phase that we do this, the better

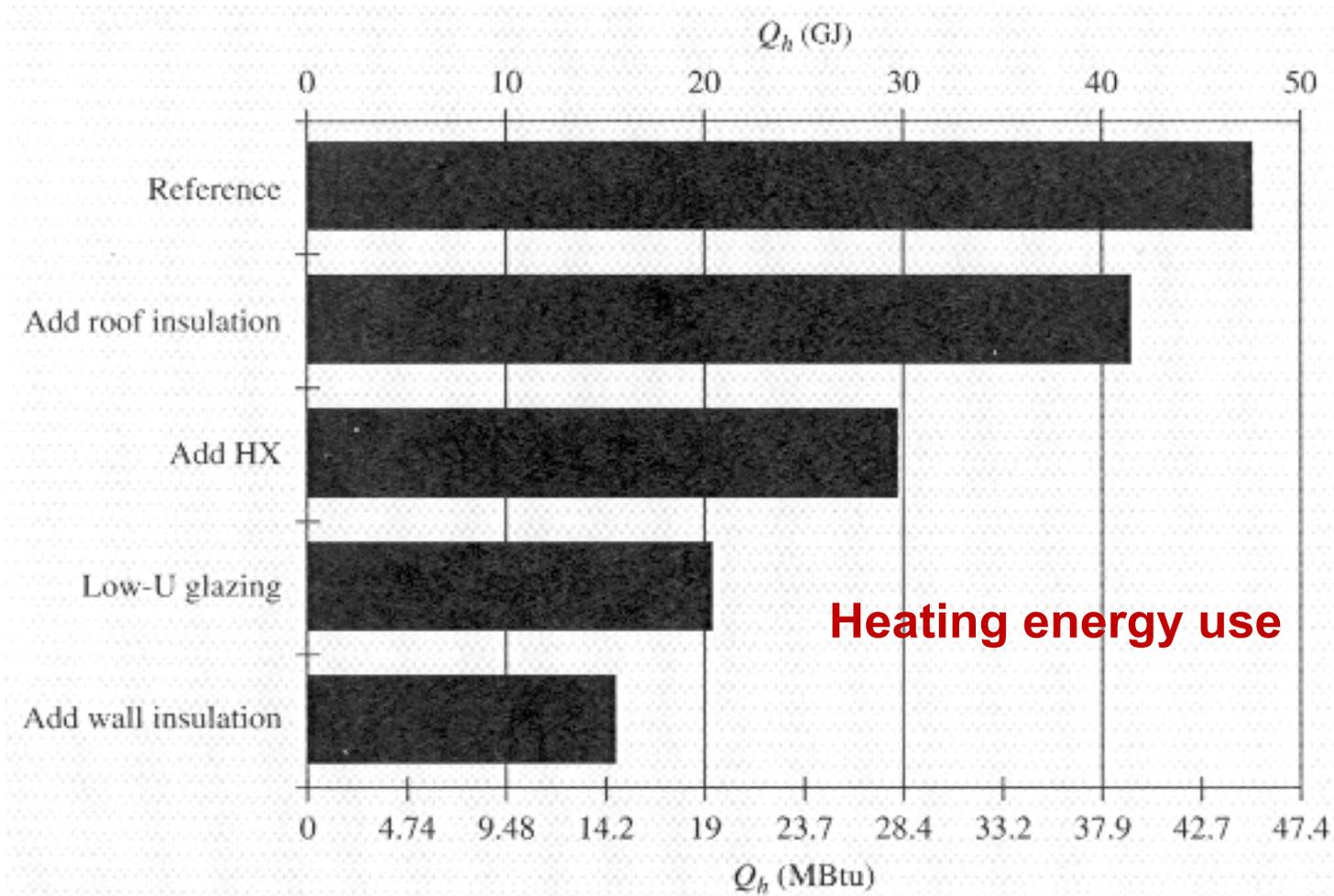
Parametric changes early in design phase

- We can make changes to the envelope $(UA)_{total}$



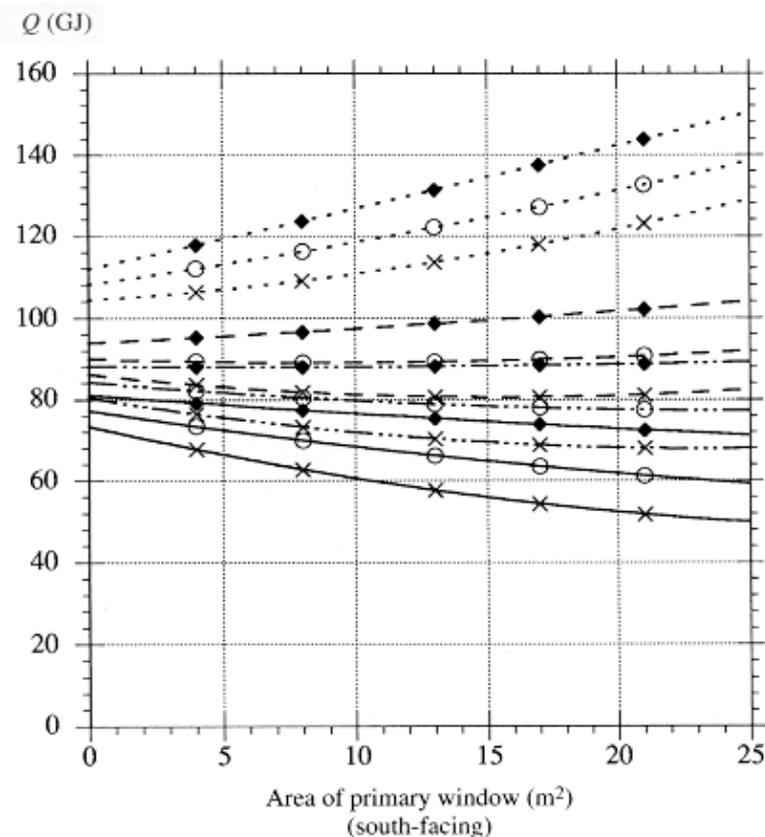
Parametric changes early in design phase

- We can estimate impact of changes to the envelope $(UA)_{total}$

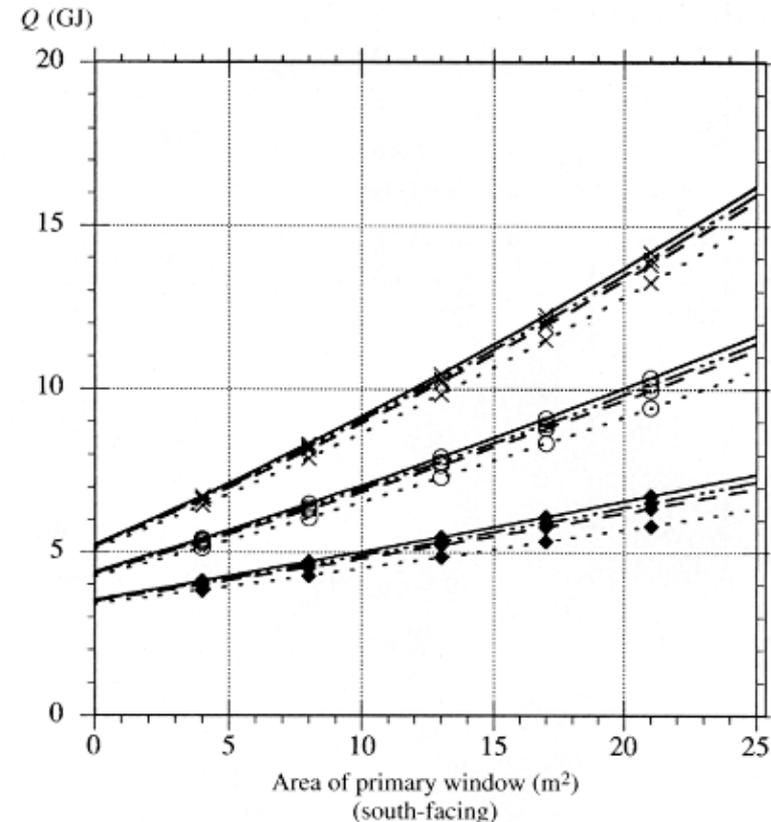


Parametric changes early in design phase

- We can adjust window areas, shading, and U-values, but they may have competing effects on heating/cooling energy



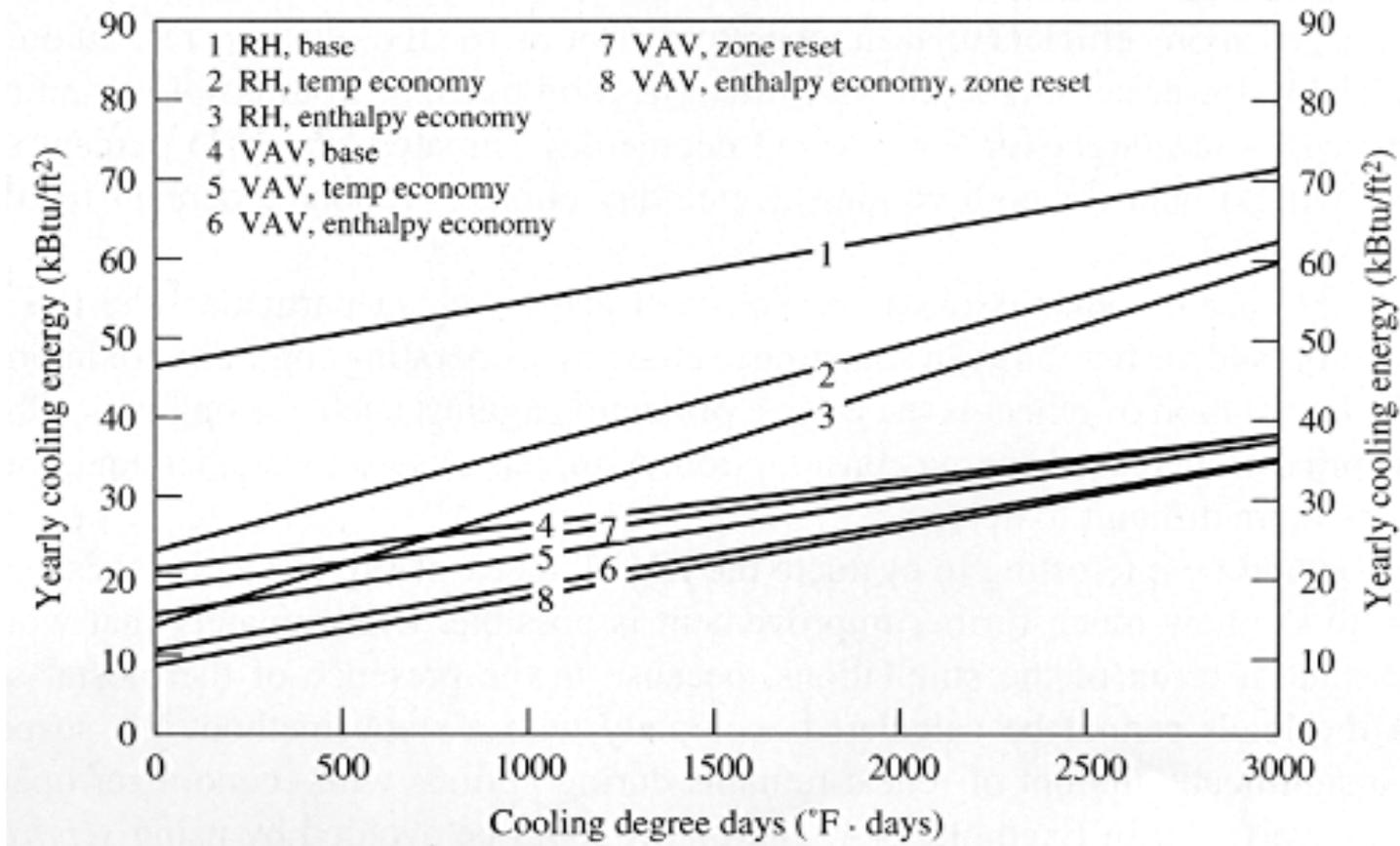
Heating



Cooling

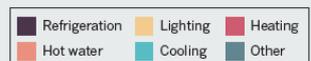
Parametric changes early in design phase

- We can change HVAC types (example in an office)

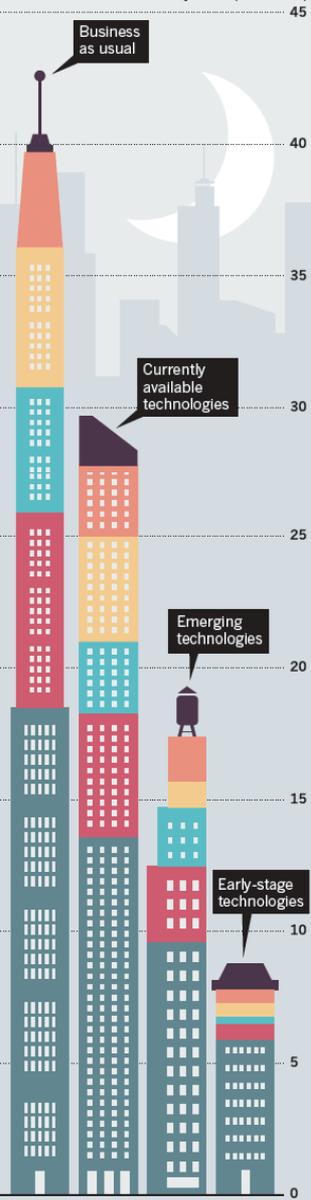


GOING DOWN

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



Quads of primary energy use by 2030 (thousands)

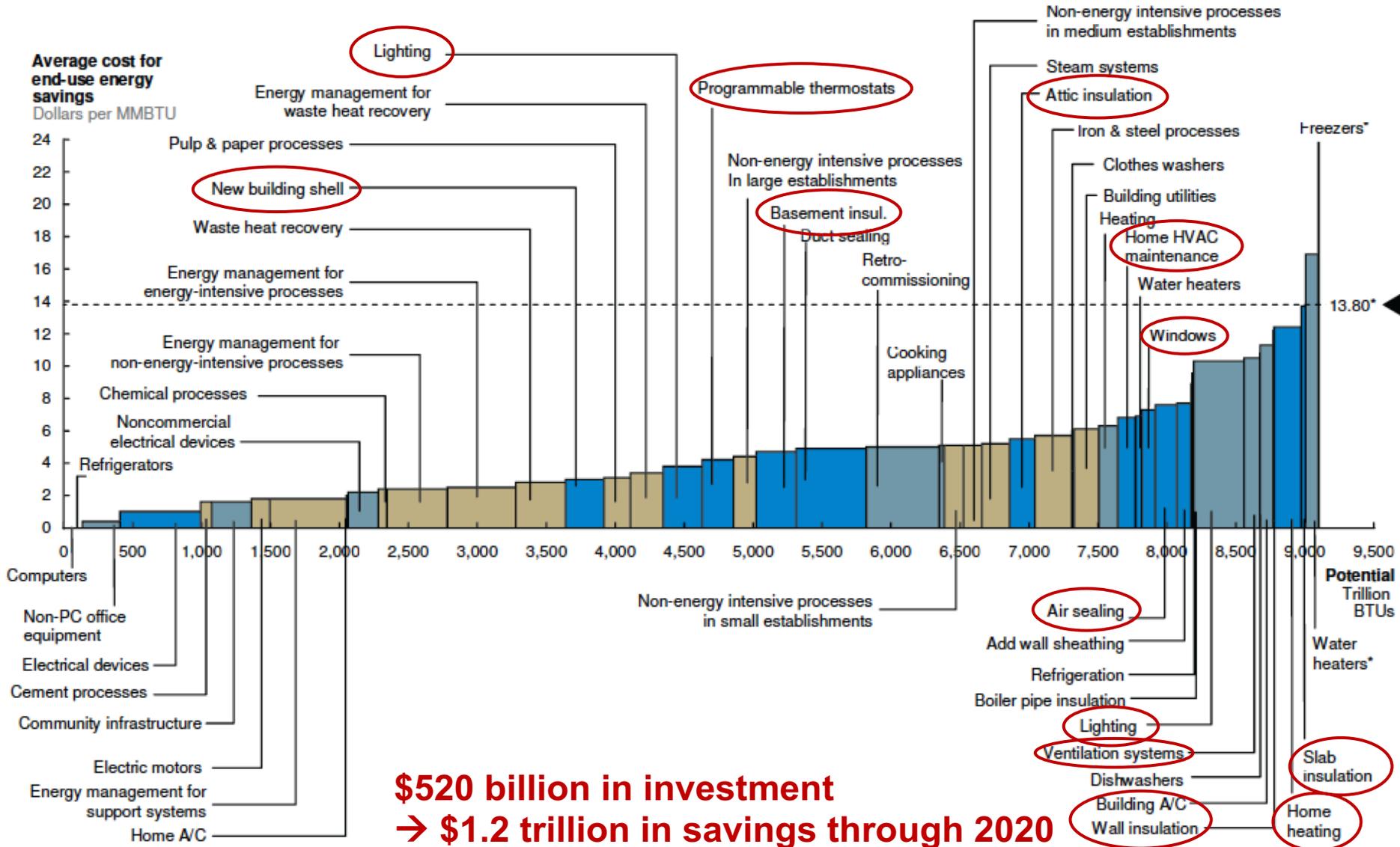


Paths toward *lower energy* buildings

- 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”**

Energy efficiency is actually *inexpensive*

Residential Commercial Industrial



Energy savings in commercial buildings: Example

- 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

Empire State Building

Performance Year 2 M&V Report

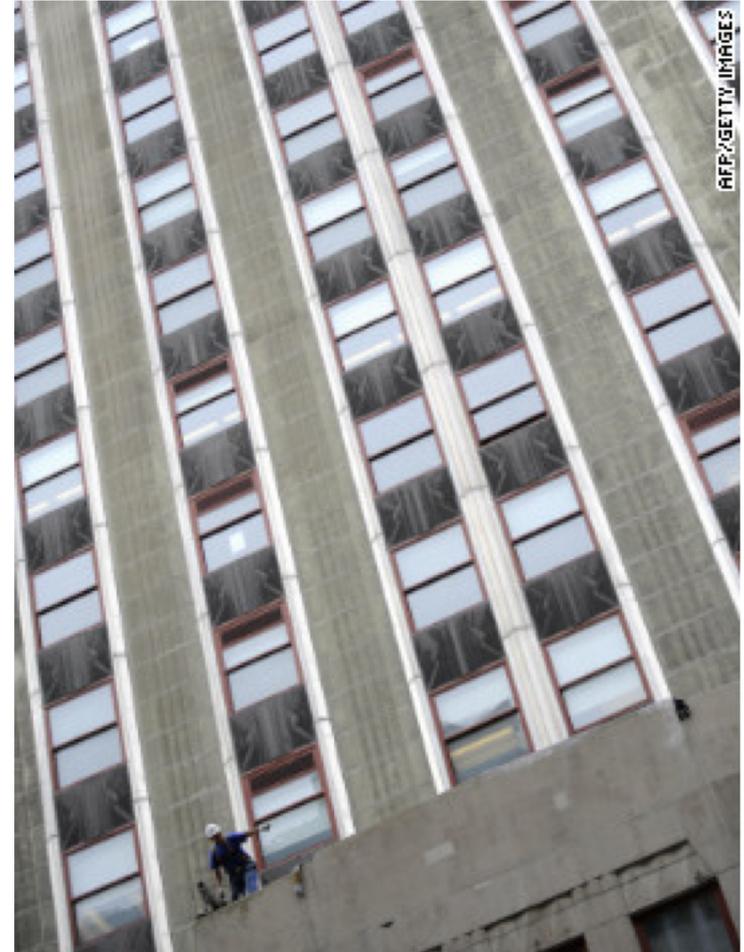
March 1, 2013 Rev.1 (August 15, 2013)



ECMs in the Empire State Building

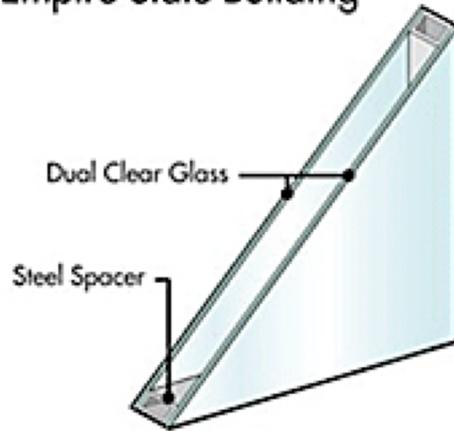
Window retrofits

- Upgraded over 6500 double-hung insulated glazing units



ECMs in the Empire State Building

Existing Windows in the Empire State Building



Original windows:

- U-value = $0.58 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$
- SHGC = 0.65

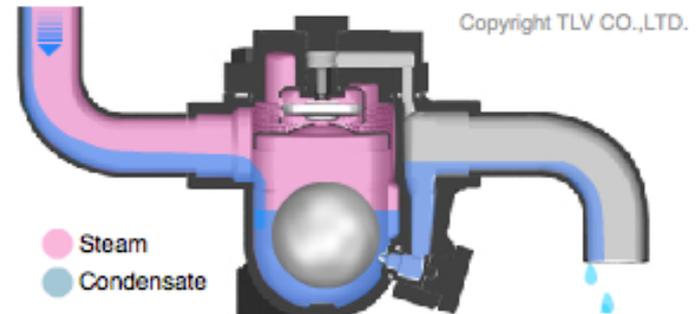
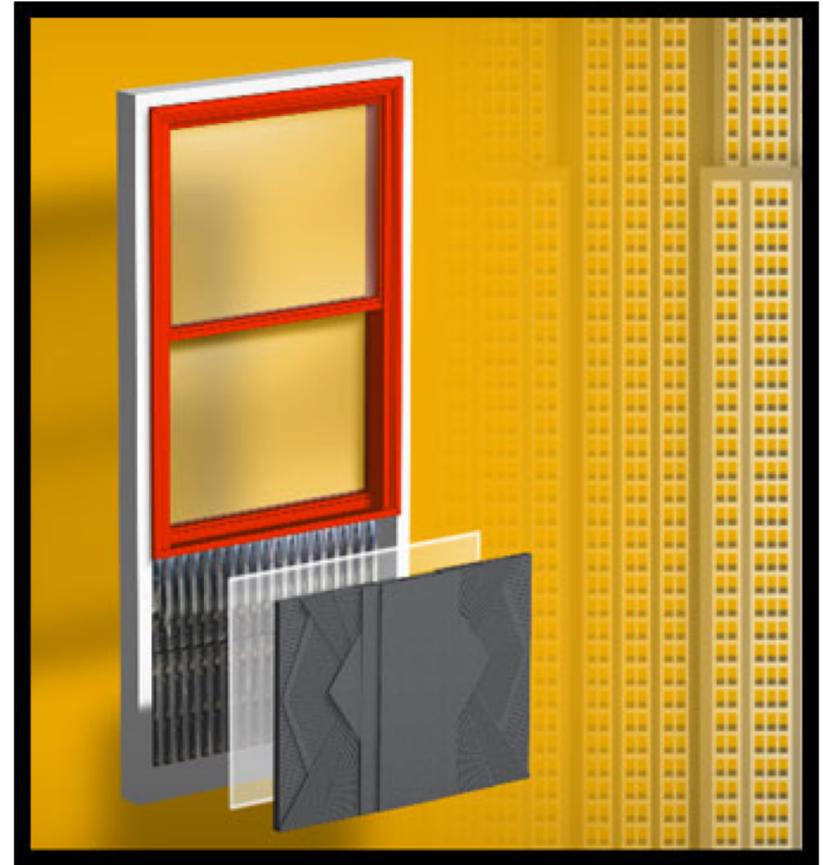
New windows (krypton + argon):

- U-value = $0.37 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$ 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

ECMs 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/h·ft²·°F
- New insulation:
 - U-value = 0.12 Btu/h·ft²·°F
- Also upgraded control system and added “steam traps”



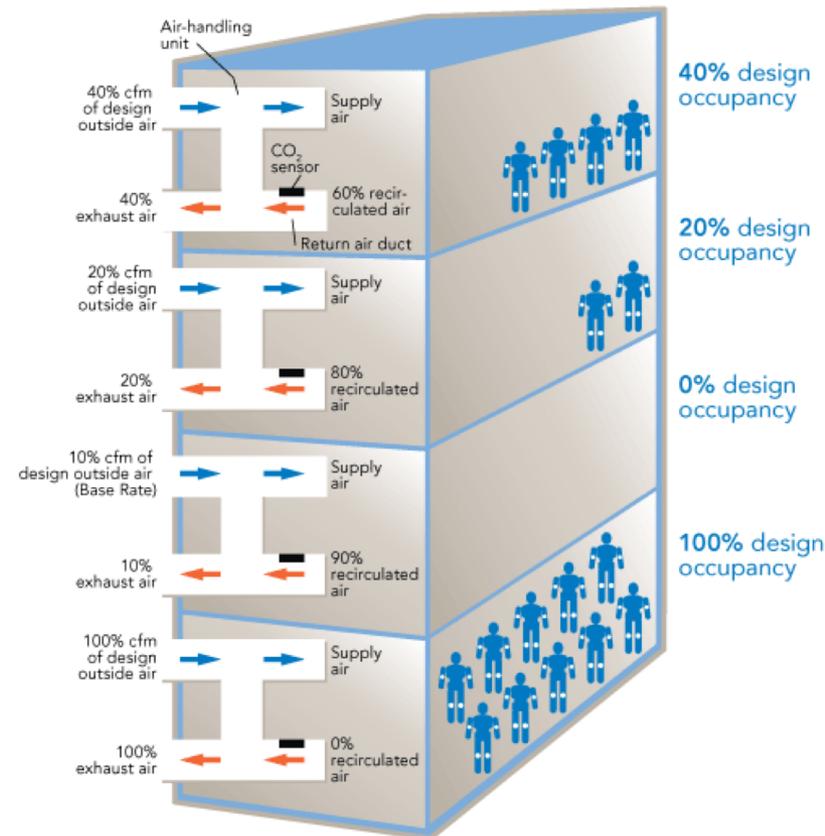
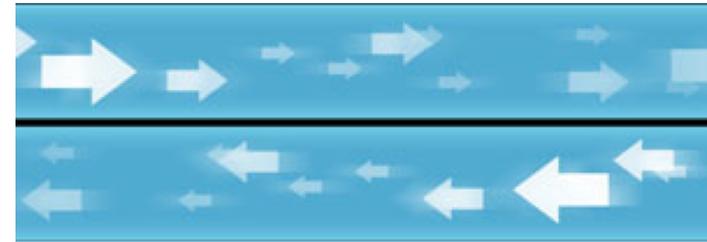
ECMs in the Empire State Building



ECMs in the Empire State Building

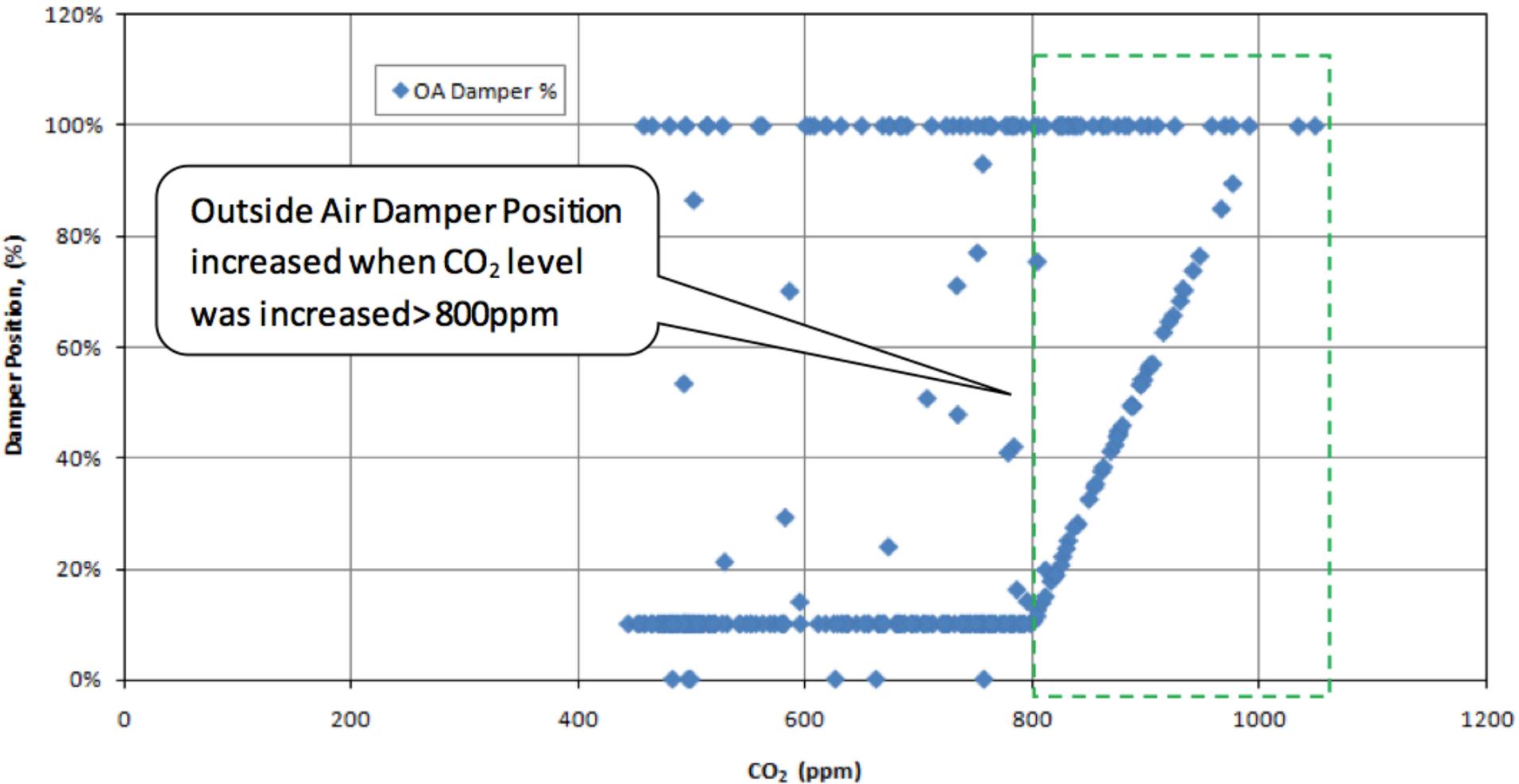
Building automation system (BAS)

- Reduced overall outdoor air intake by using “demand controlled ventilation” (DCV) and modulating dampers
 - Uses CO₂ to measure occupancy
- Original BAS:
 - No controls, OA = from 0.25 cfm/ft²
- New BAS:
 - Keep OA low until CO₂ in return air = 800 ppm and better controls for OA economizer
 - New OA = from 0.12 cfm/ft²



ECMs in the Empire State Building

AHU 52.5 OA Damper % Vs CO₂ Level



ECMs in the Empire State Building

Chiller plant retrofit

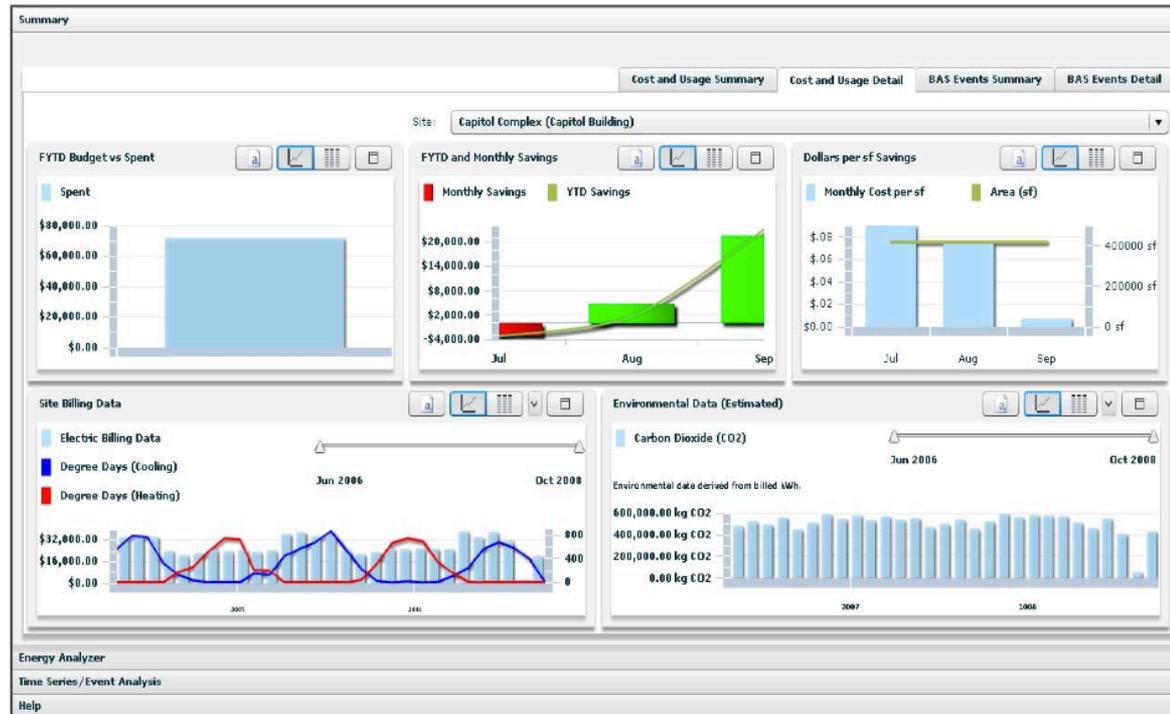
- Replaced compressors with variable speed drives (VSDs)
 - Better part load efficiency
- Replaced evaporator and condenser tubes
 - Increase UA of heat exchangers
- Increased chilled water supply T and added “reset”
 - Decreases only when T_{out} is high
- Valve changes and VSD automation
- Cooling tower fan switched to automated VSD



ECMs 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.



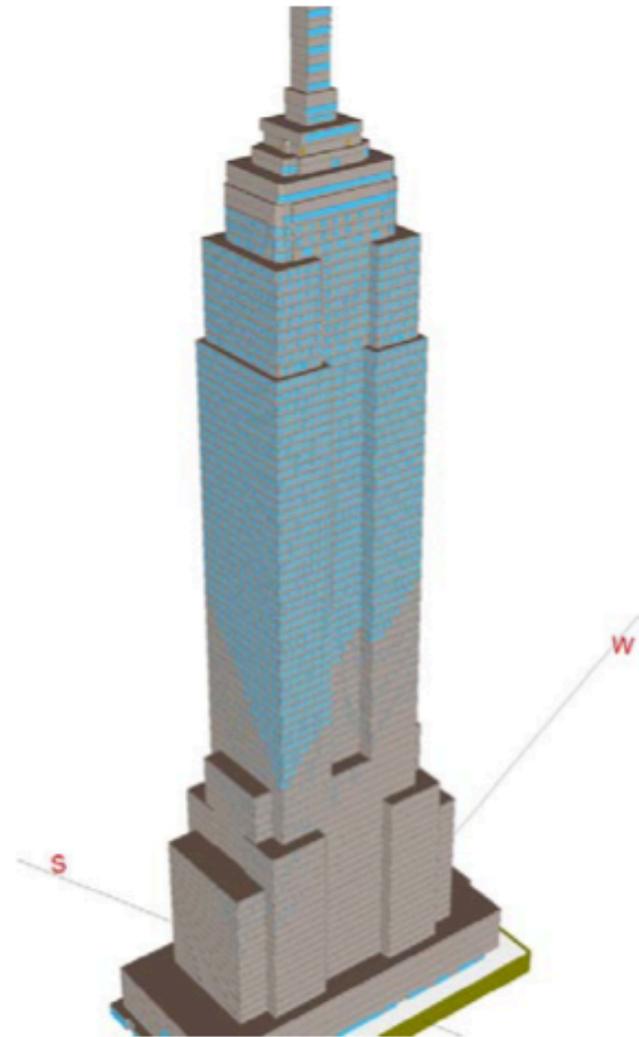
Energy simulation to predict costs and GHG savings

EQUEST MODEL SETUP OVERVIEW

Modeling Software	eQUEST v3.64, build 7130
Model Author	Quest Energy Group, LLC 1620 W Fountainhead Pkwy #303 Tempe, AZ 85282 +1 480 467 2480

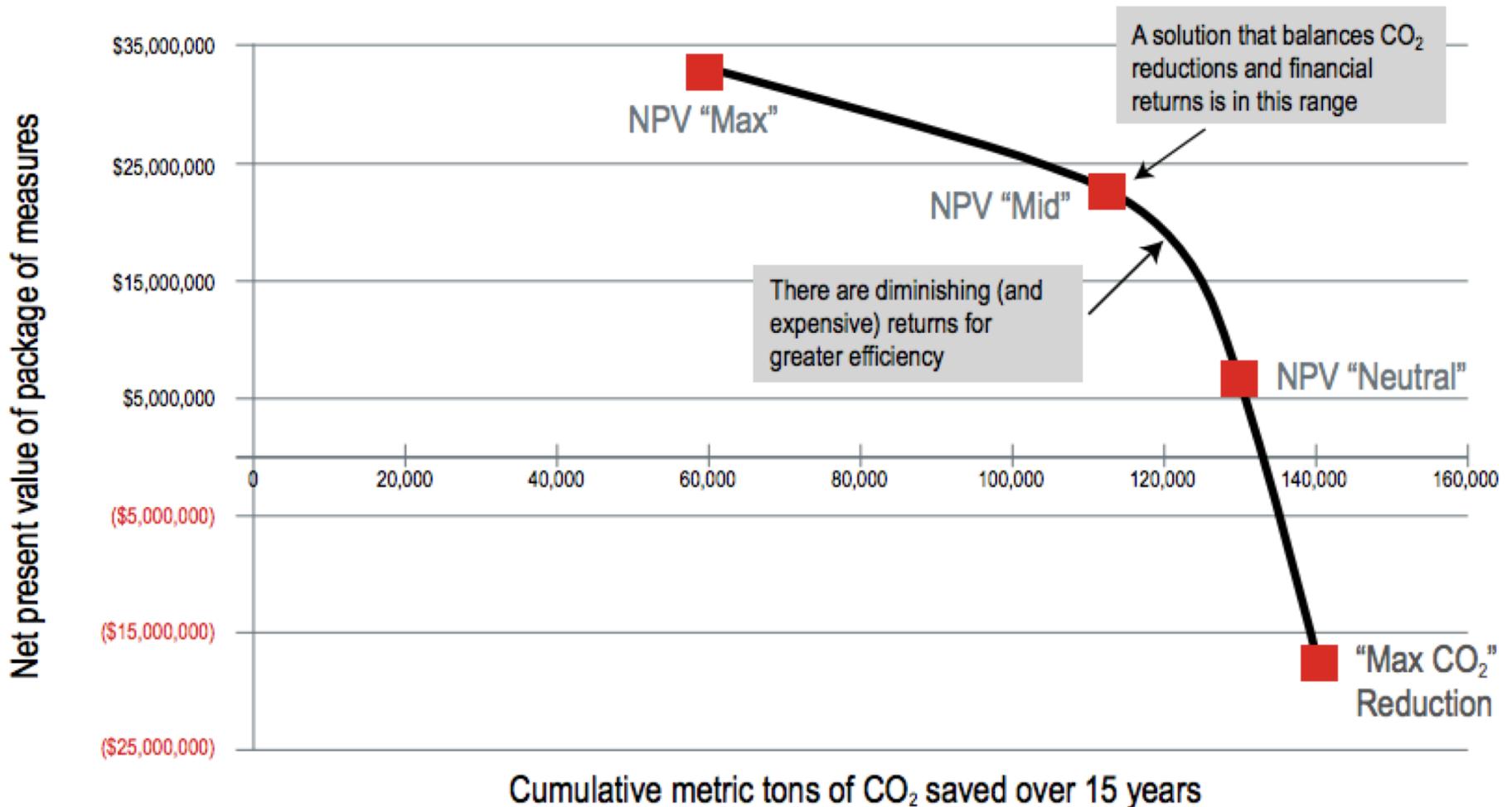
Model Build

- A detailed architectural model of the building was created based on archive drawings, photos taken at the site, and site inspections. Site inspections included verifying wall and roof constructions, external shading, and glass types.
- Schedules based on building operation were used in the model.
- Lighting demand and energy (schedules) were put into the model based on the lighting information provided by JLL.
- Representative internal equipment loads by space type (office, corridor, etc.) were incorporated into the model.



Energy simulation to predict costs and GHG savings

15-Year NPV of package versus cumulative CO₂ savings



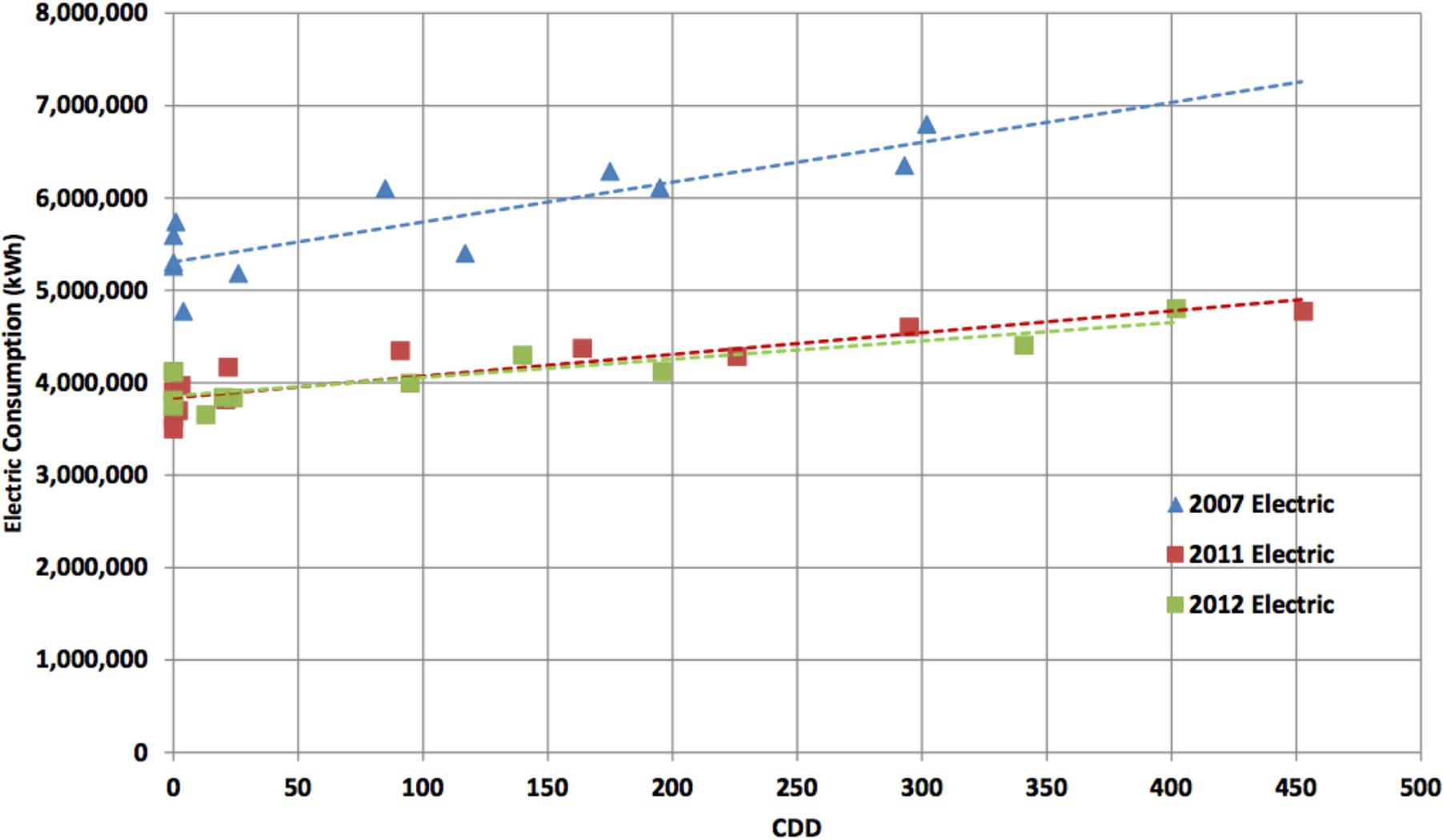
Predicted costs and savings in the ESB

<i>Project Description</i>	<i>Projected Capital Cost</i>	<i>2008 Capital Budget</i>	<i>Incremental Cost</i>	<i>Estimated Annual Energy Savings*</i>
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
<i>Power Generation (optional)</i>	\$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

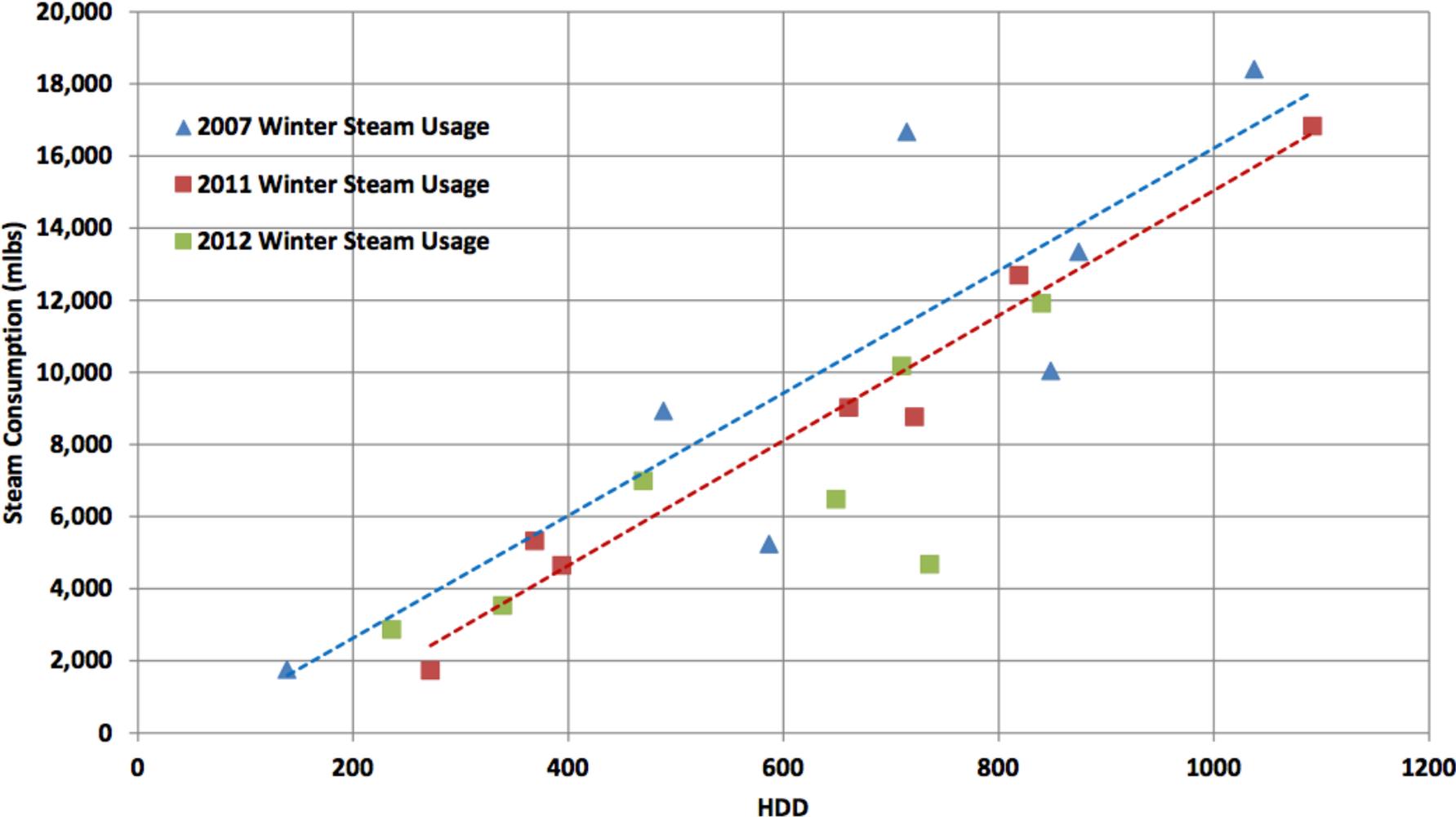
Measured performance in the Empire State Building

Annual Electric Consumption Vs CDD

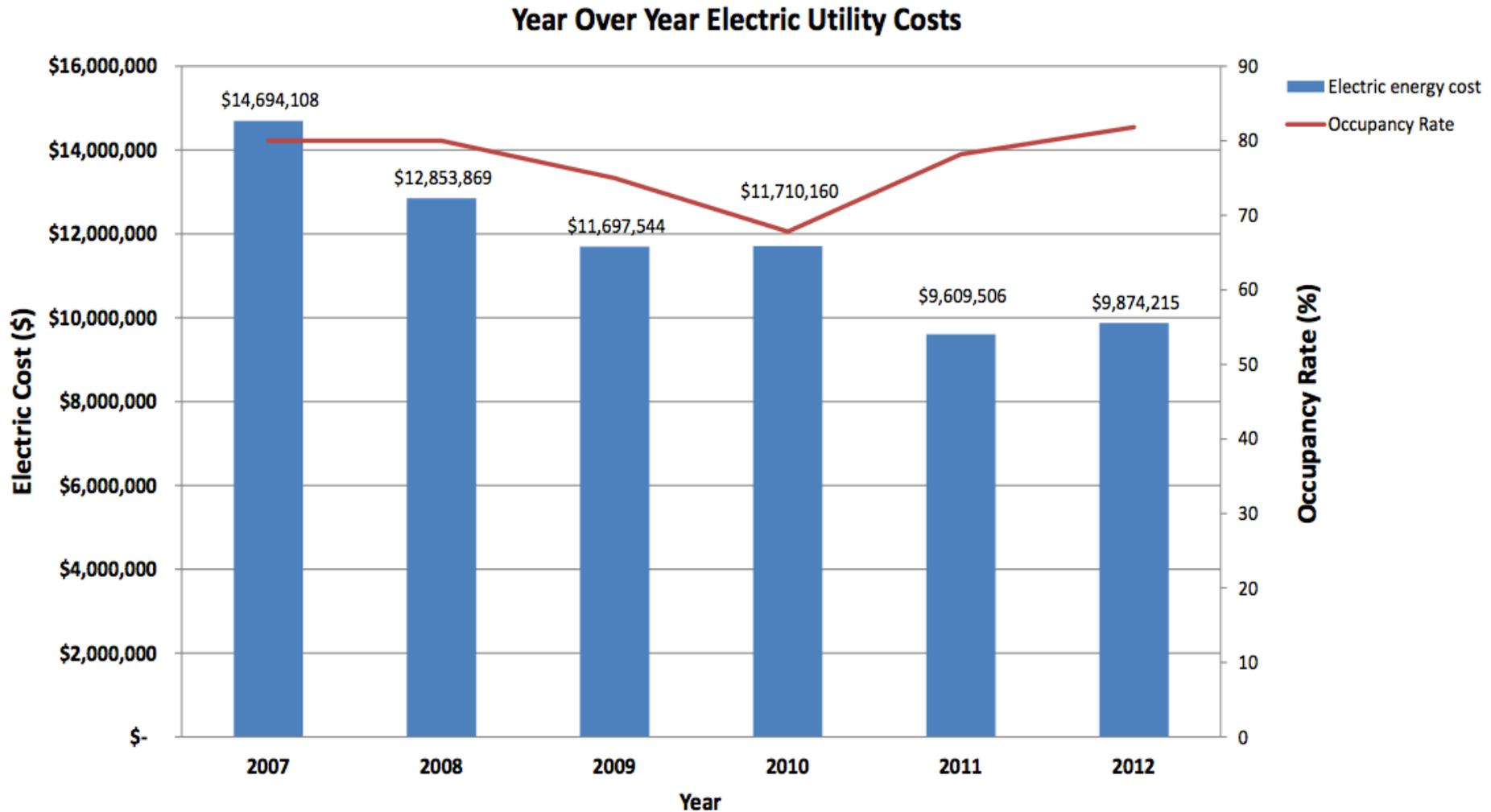


Measured performance in the Empire State Building

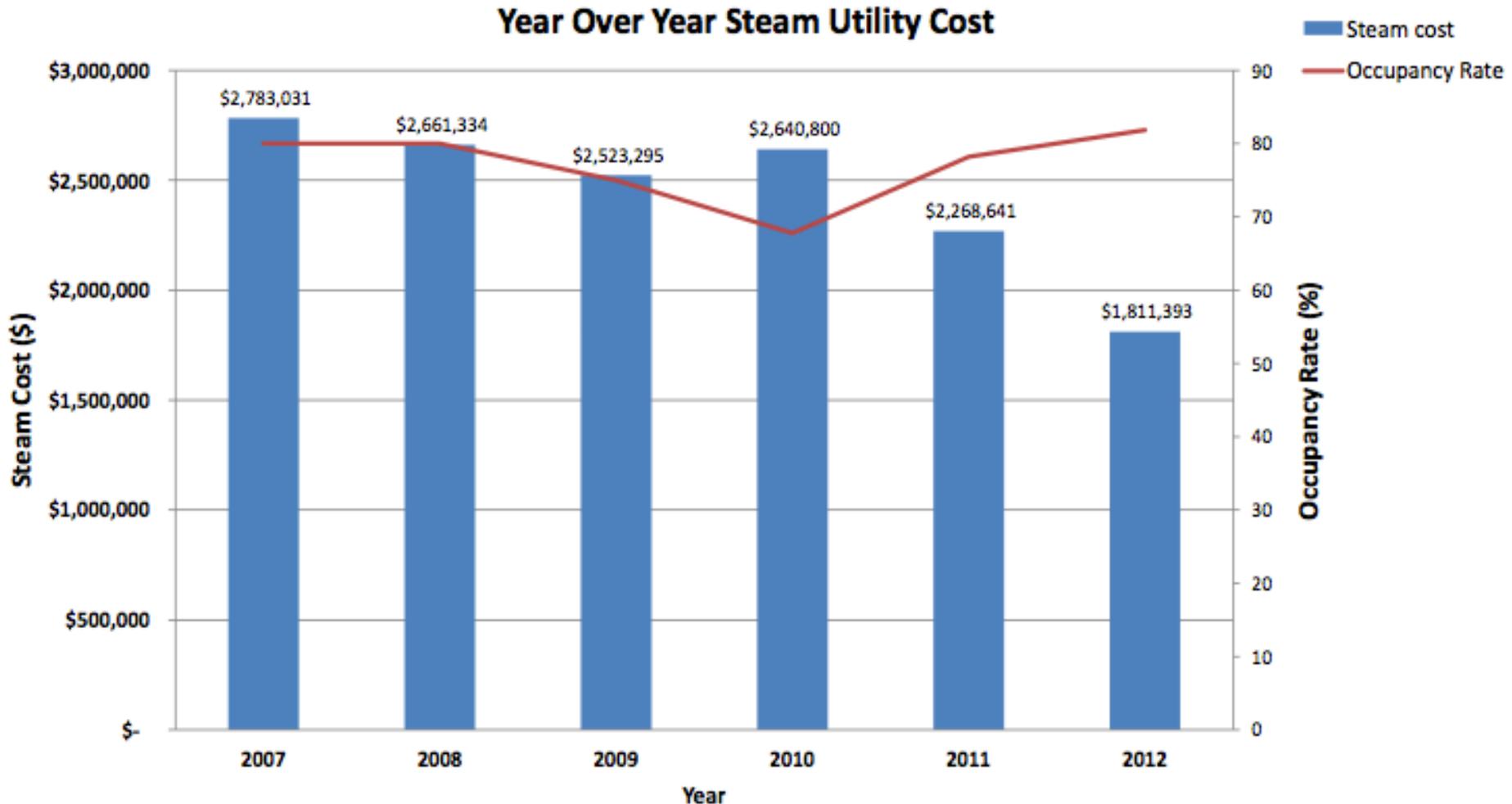
Winter Steam Consumption Vs HDD



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 per year**
 - Predicted (modeled) to save more than this (under-performing)
 - 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
- Building energy simulation can drive **decision making**