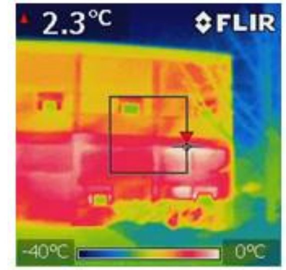
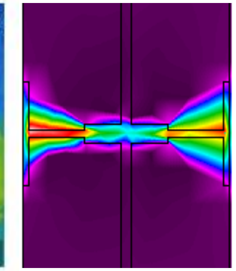
CAE 331/513
Building Science
Fall 2017





November 28, 2017
Energy estimation and design for efficiency

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Last time

- Radiant time series (RTS) method for cooling load calculations
- Demonstrated Trane Trace 700 for load calculations
- Began building energy simulation

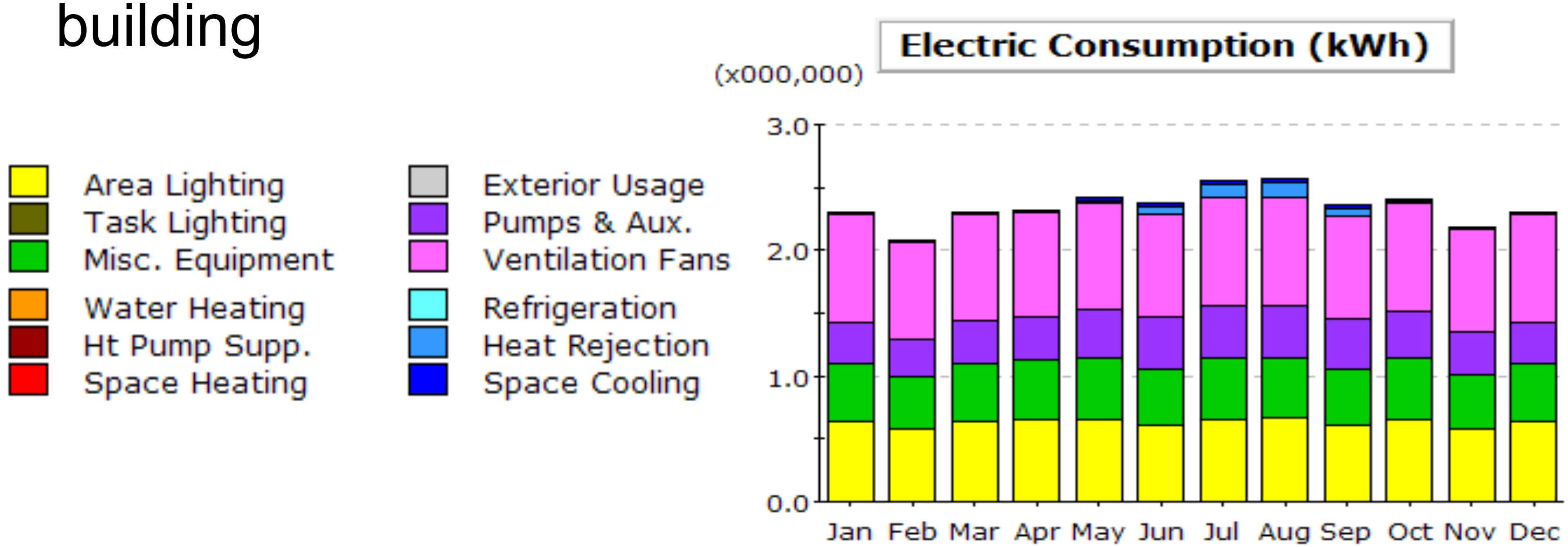
BUILDING ENERGY ESTIMATION

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
- Whole building energy simulation goes a few steps further:
  - 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
  - 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.)
  - 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 of a building



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

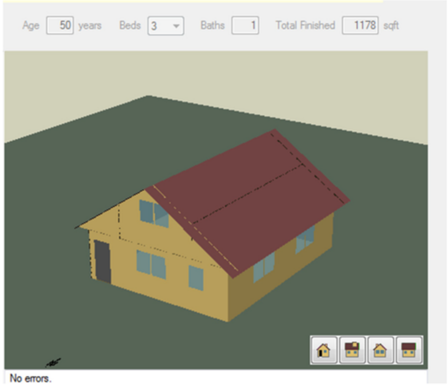
Building energy models are best used to understand design options and trade-offs (i.e., relative comparisons)

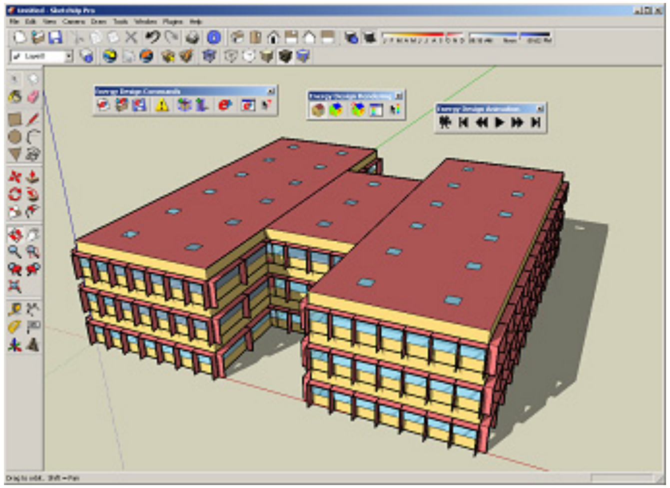
Building energy modeling

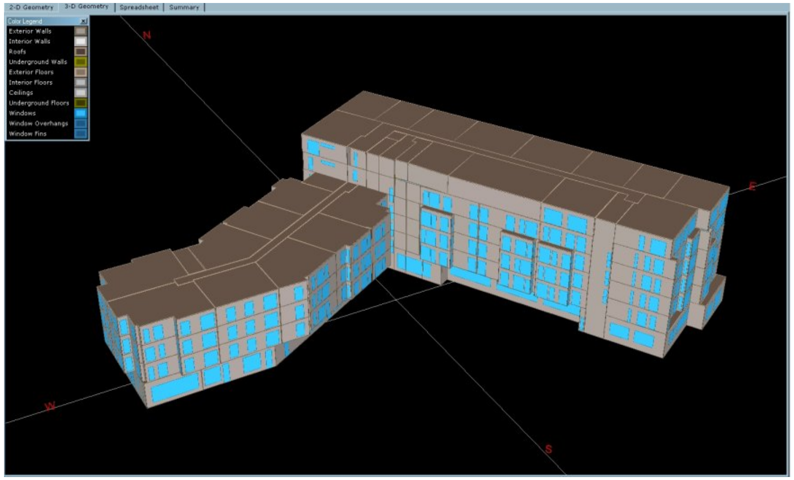
There are many software packages available (some are free)

Examples:

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



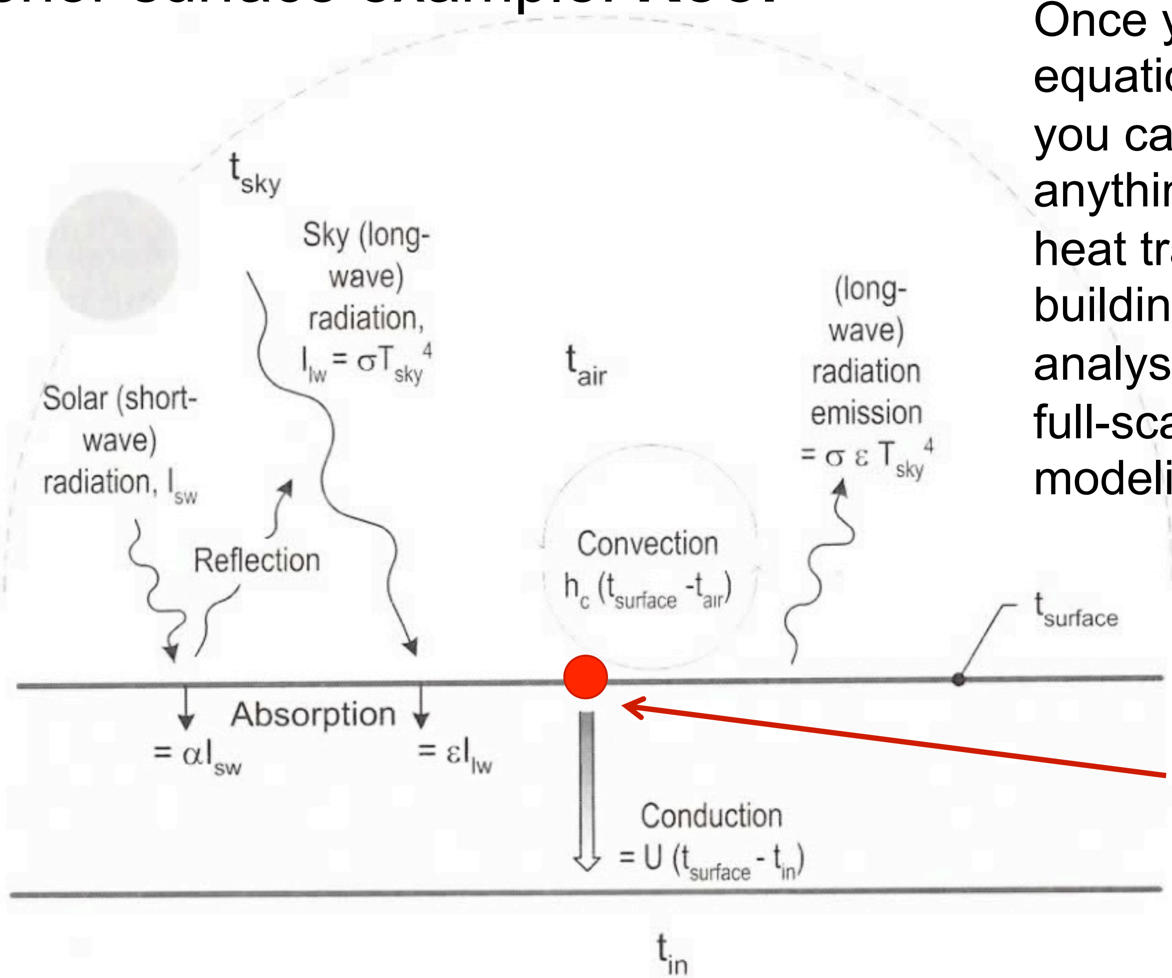




http://apps1.eere.energy.gov/buildings/tools_directory/subjects.cfm/pagename=subjects/pagename_menu=whole_building_analysis/pagename_submenu=energy_simulation

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

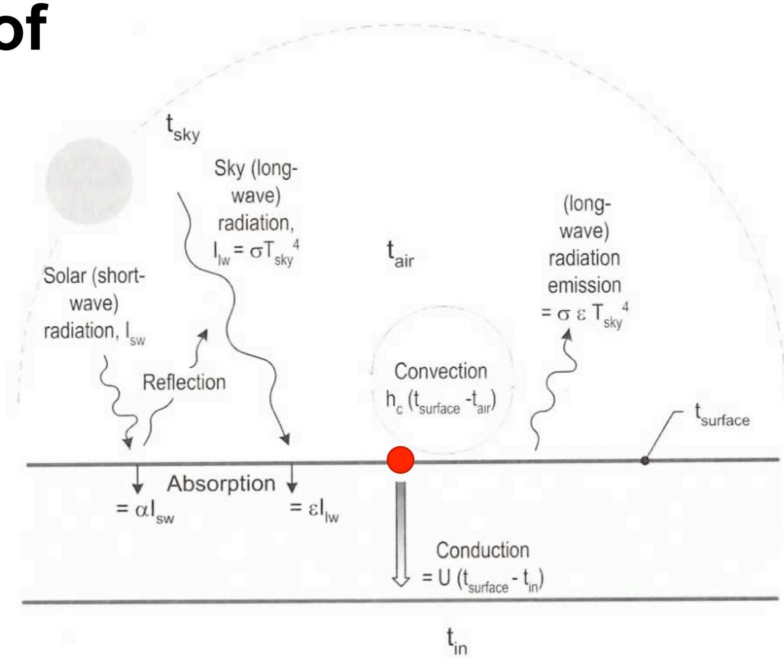
Steady-state energy balance at this exterior surface:
What enters must also leave (no storage)

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

Surface energy balance example

- Exterior surface example: **Roof**

$$\boxed{\sum q = 0}$$



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

At steady state, net energy balance is zero

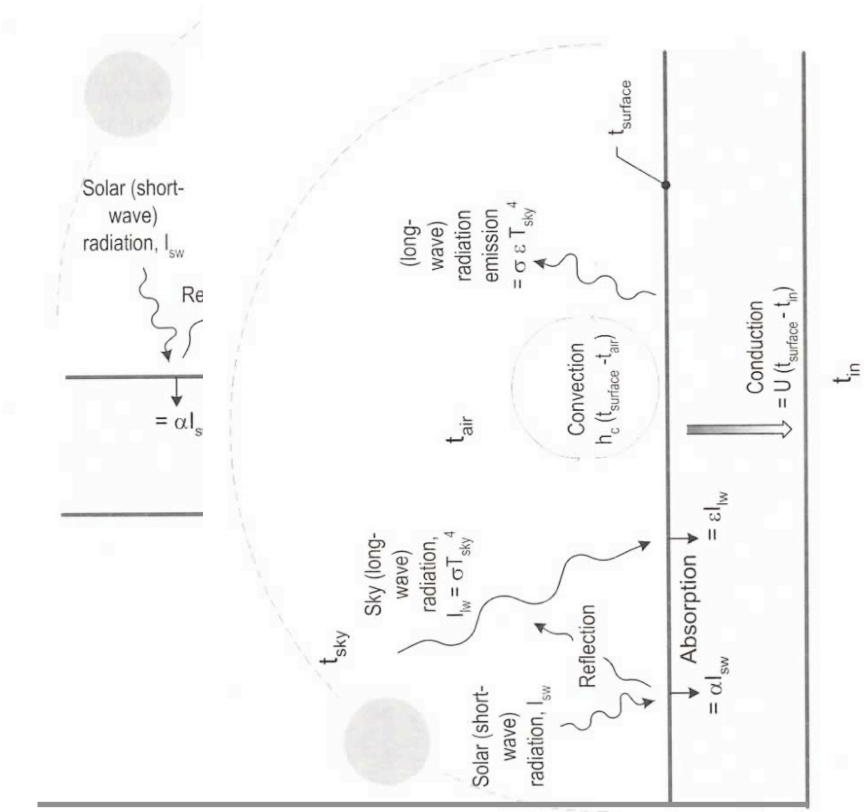
- Because of T^4 term, often requires iteration

Solar gain	αI_{solar}	$q_{sw,solar}$
Surface-sky radiation	$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface}^4)$	$+q_{lw,surface-sky}$
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:

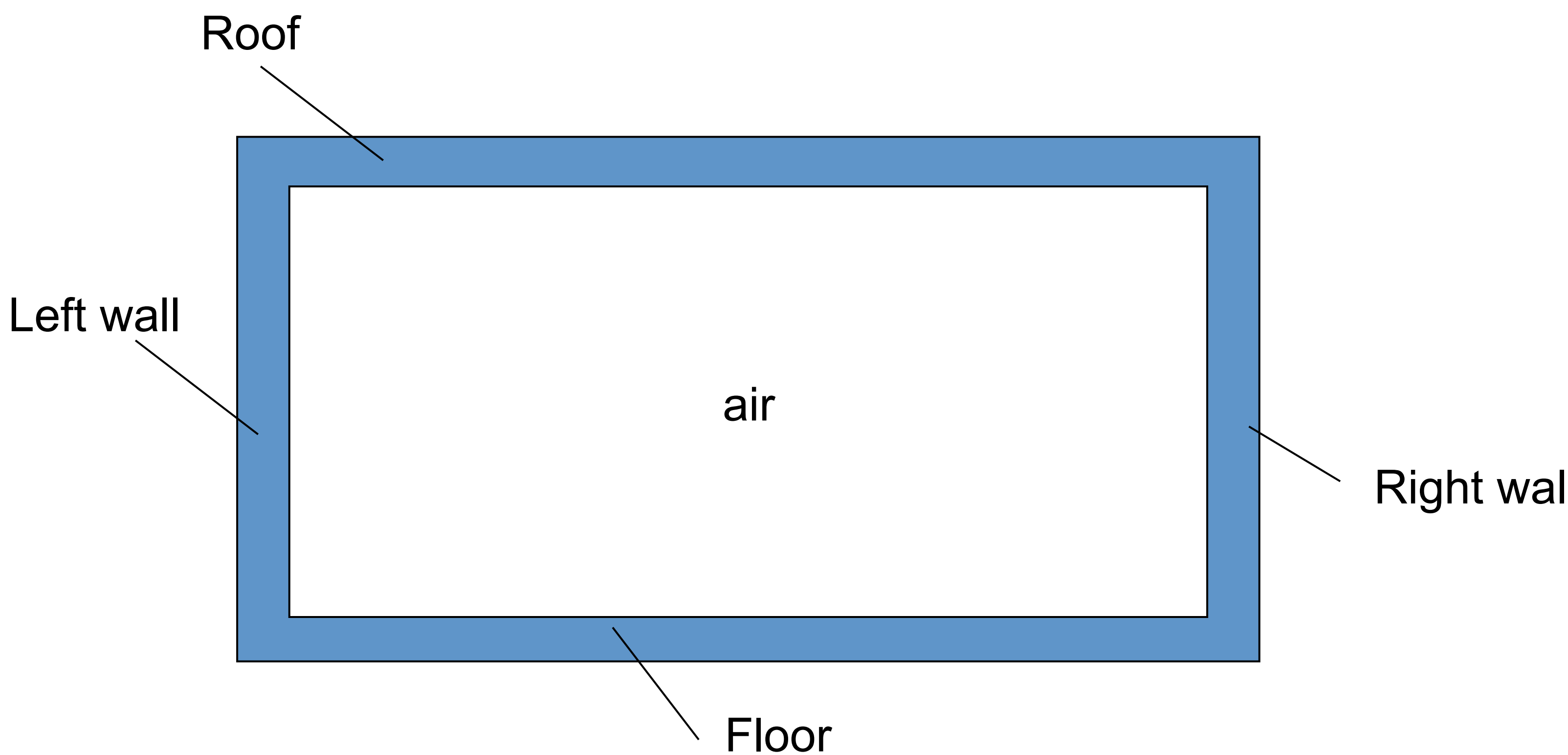
$$q_{solar} + q_{lwr} + q_{conv} - q_{cond} = 0$$



Ground

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

Simplest 'box' model



Elements are connected by:

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

Slide courtesy Atila Novoselac, University of Texas at Austin

Bringing all modes (and nodes) together

- For an example room like this, you would setup a system of equations where the temperature at each node (either a surface or within a material) is unknown
  - 12 material nodes + 1 indoor air node

Heat Xfer @ external surfaces:
Radiation and convection

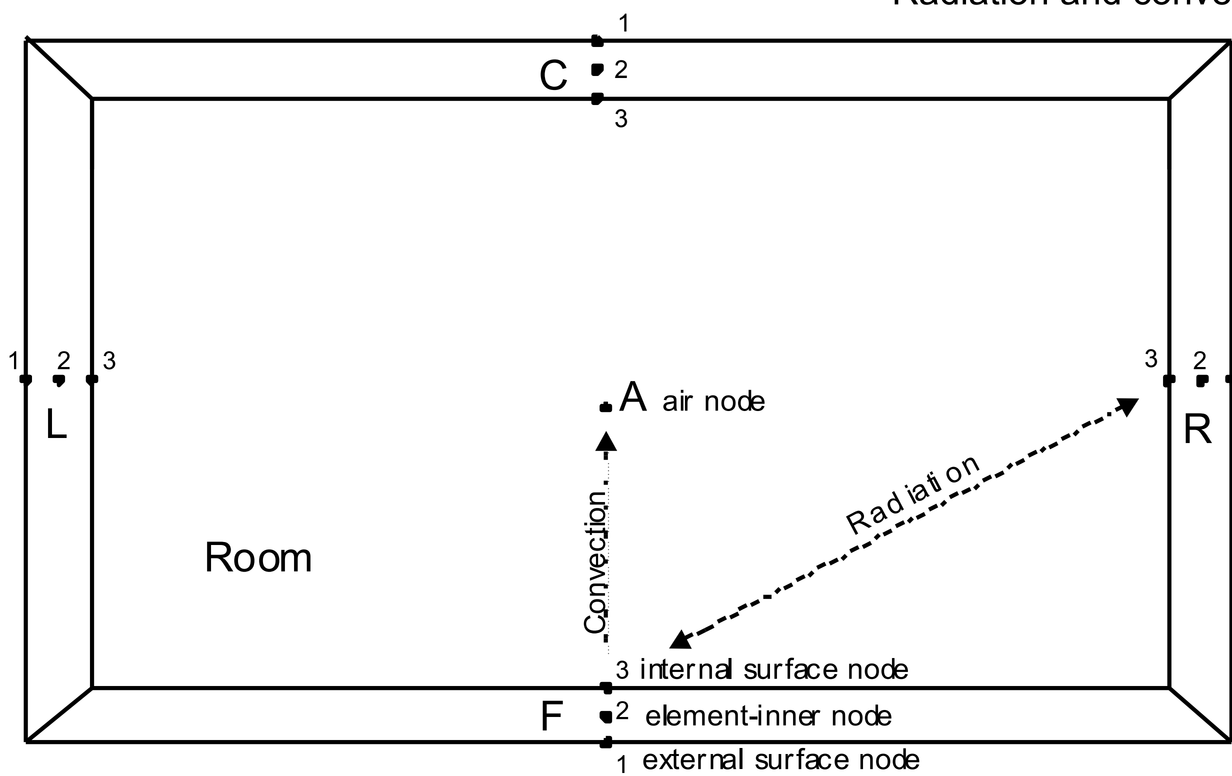
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

$$mc_p \frac{dT}{dt} = \sum q_{at\ boundaries}$$

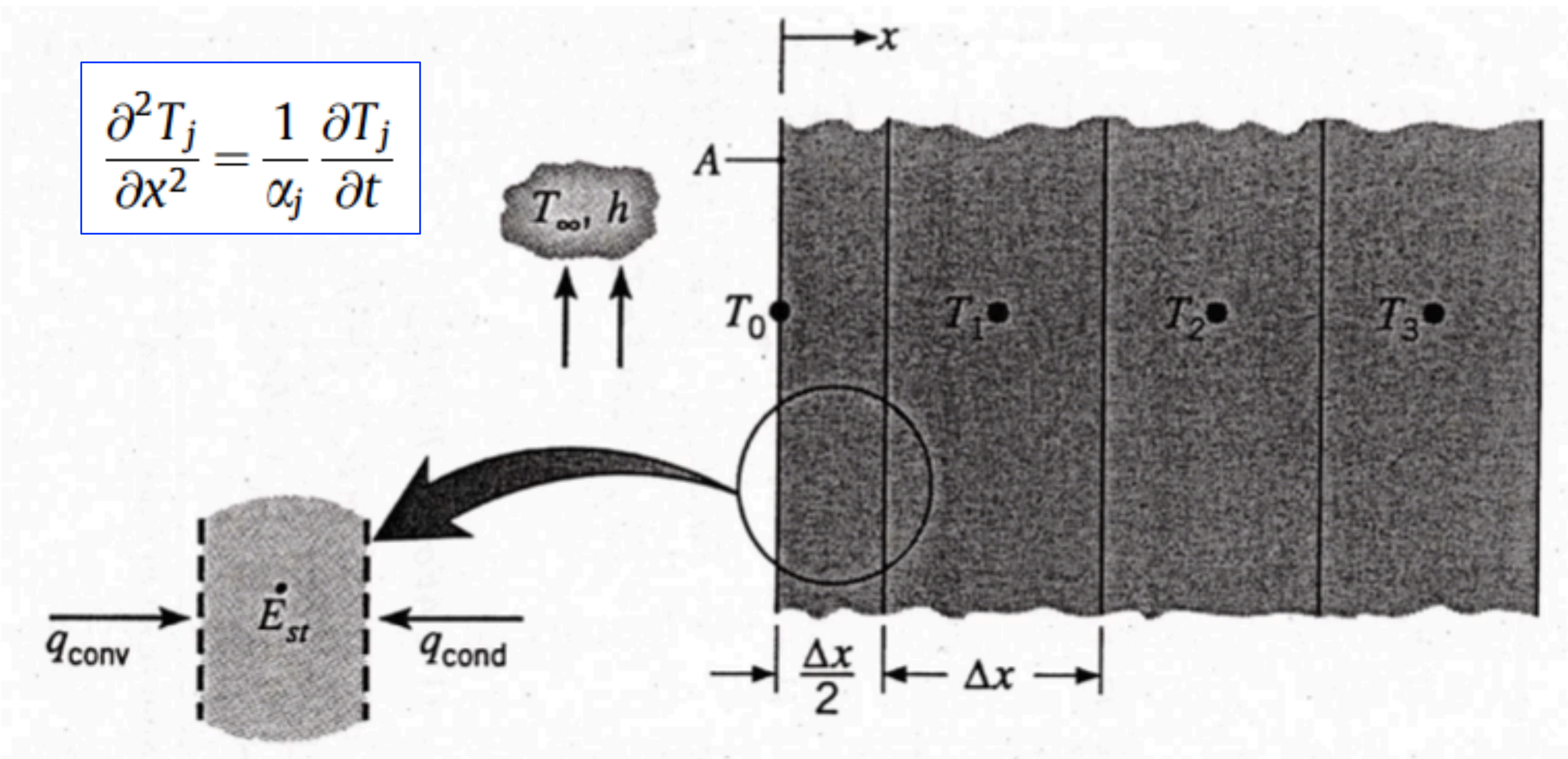
Unsteady conduction (storage) is based on density and heat capacity of material



Modeling thermal mass: Transient (unsteady) conduction

- Divide material assembly into multiple nodes

$$\boxed{\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t}}$$



Modeling thermal mass: Lumped capacitance model

- Wall example: Exterior surface balance at T_1 changes

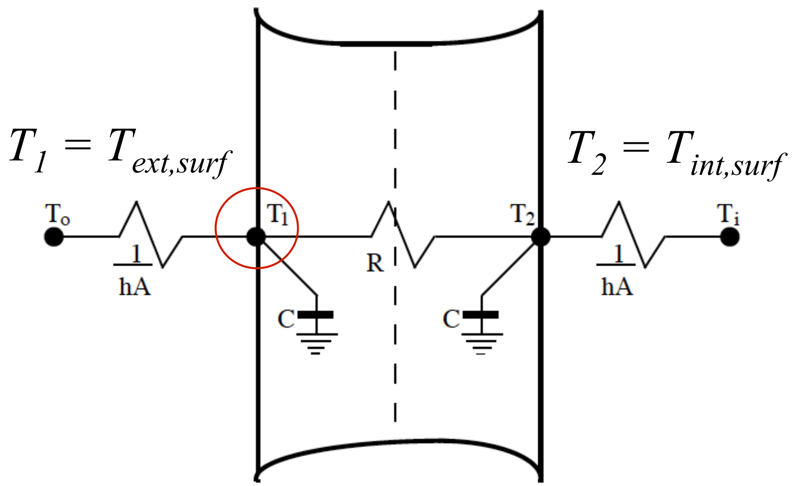


Figure 9. Two Node State Space Example.

From:

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

To:

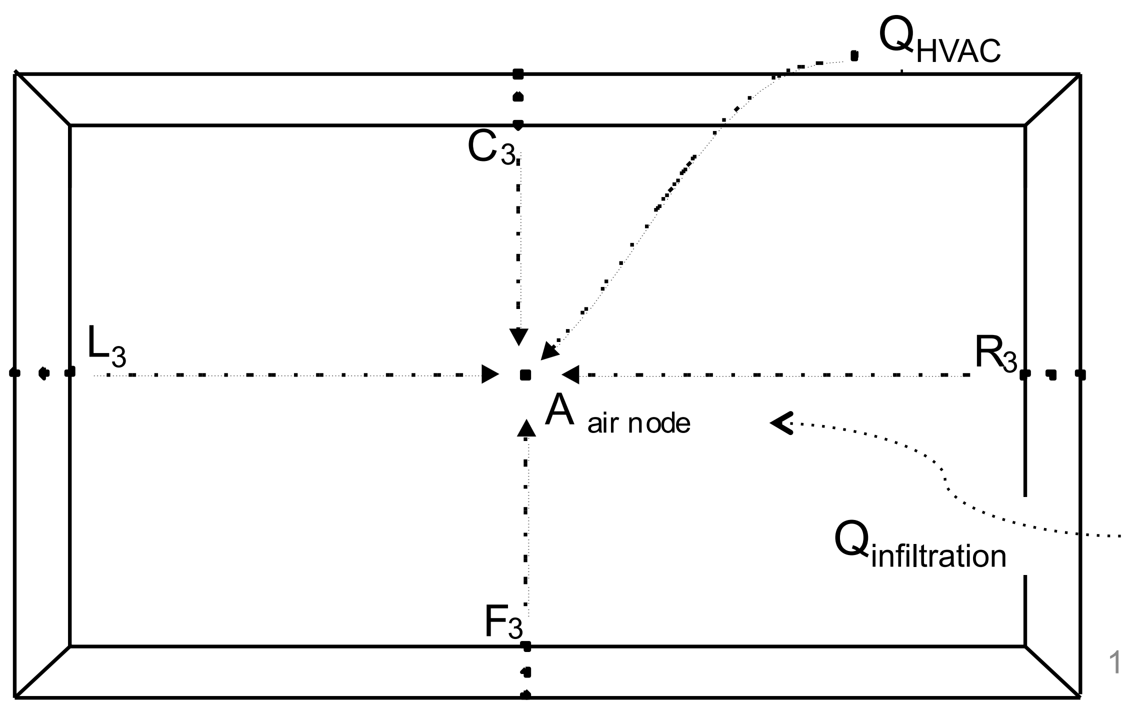
$$\begin{aligned} &q_{sw,solar} \\ &+q_{lw,surface-sky} \\ &+q_{lw,surface-ground} \\ &+q_{convection} \\ &-q_{conduction} = \rho C_p \frac{L}{2}\frac{dT}{dt} \end{aligned}$$

Unsteady energy balance for air node

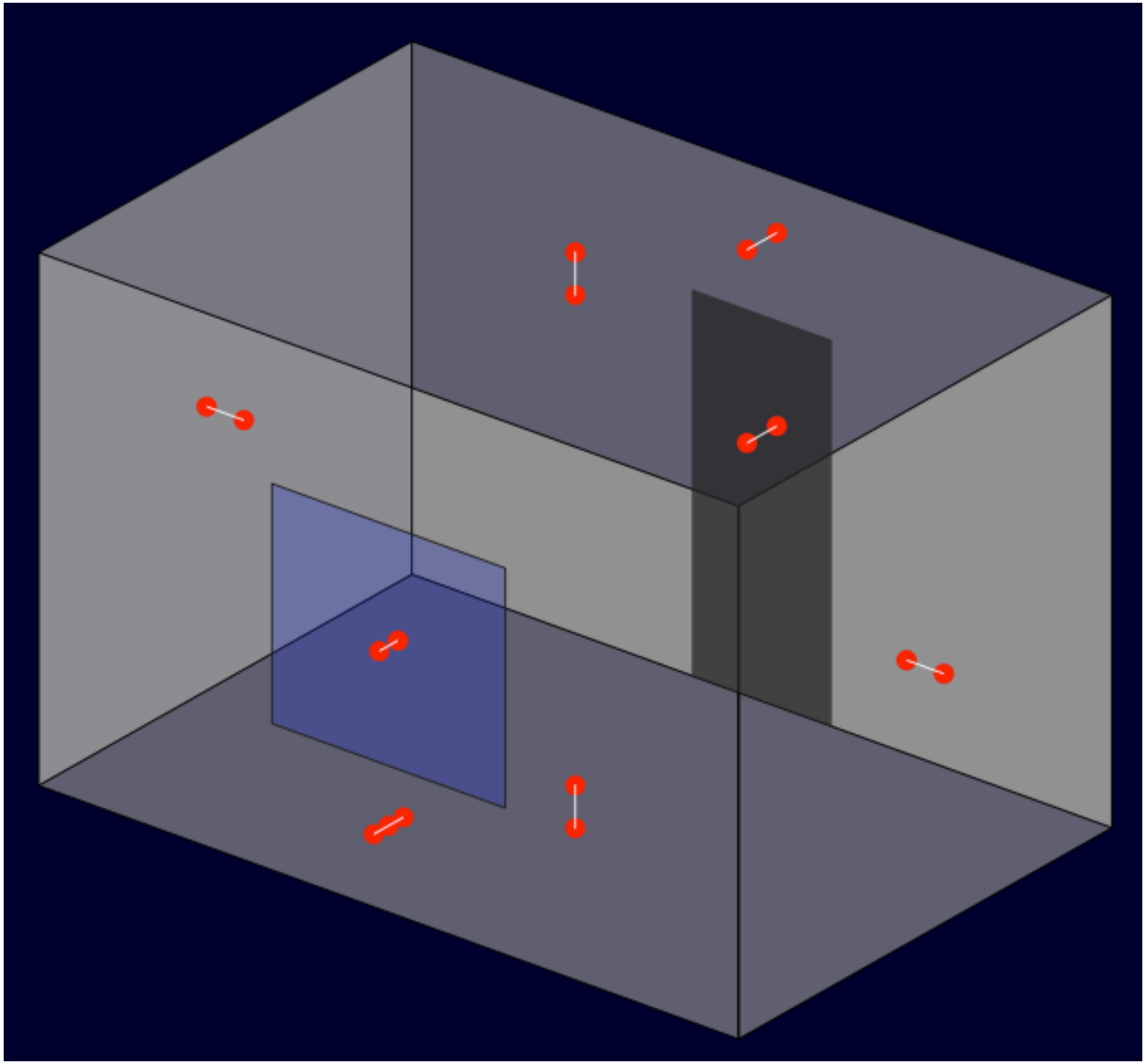
- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and surface)

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

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

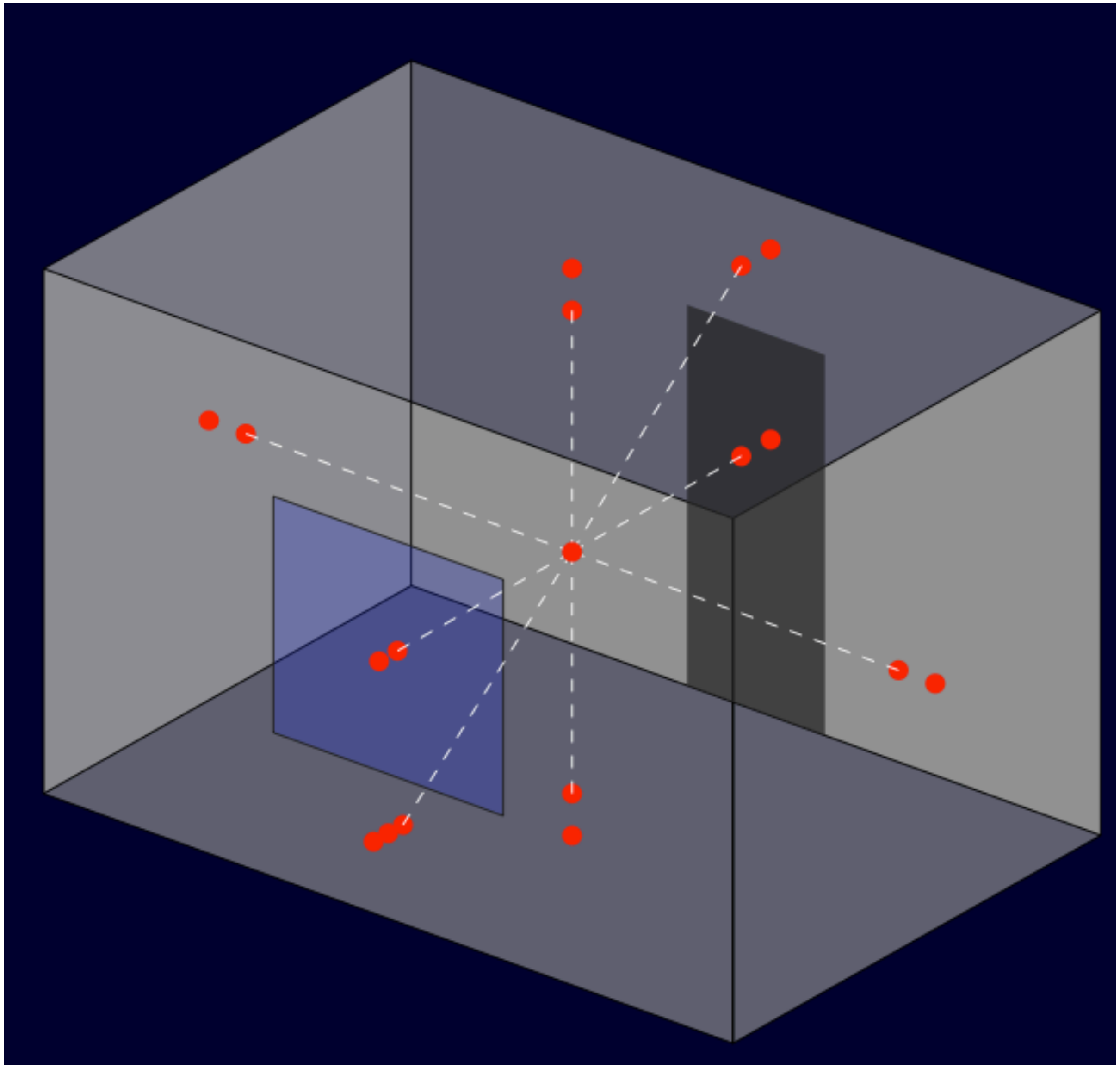


Simplest ‘box’ model: Conduction elements



http://www.ibpsa.us/pub/simbuild2008/presentations/SB08-PPT-IS06-Augenbroe.pdf

Simplest ‘box’ model: Interior convection elements



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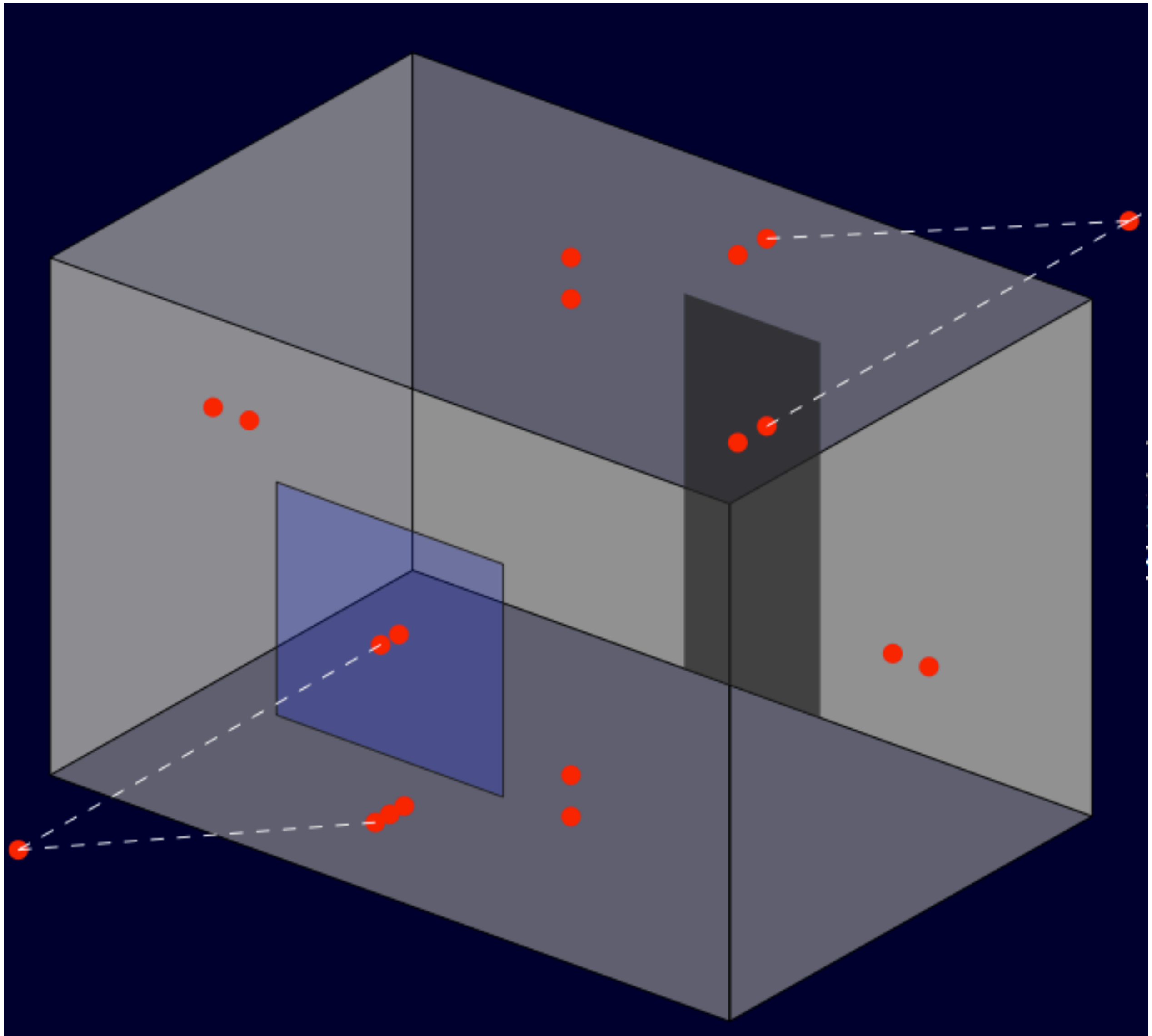
Simplest ‘box’ model: Exterior convection elements



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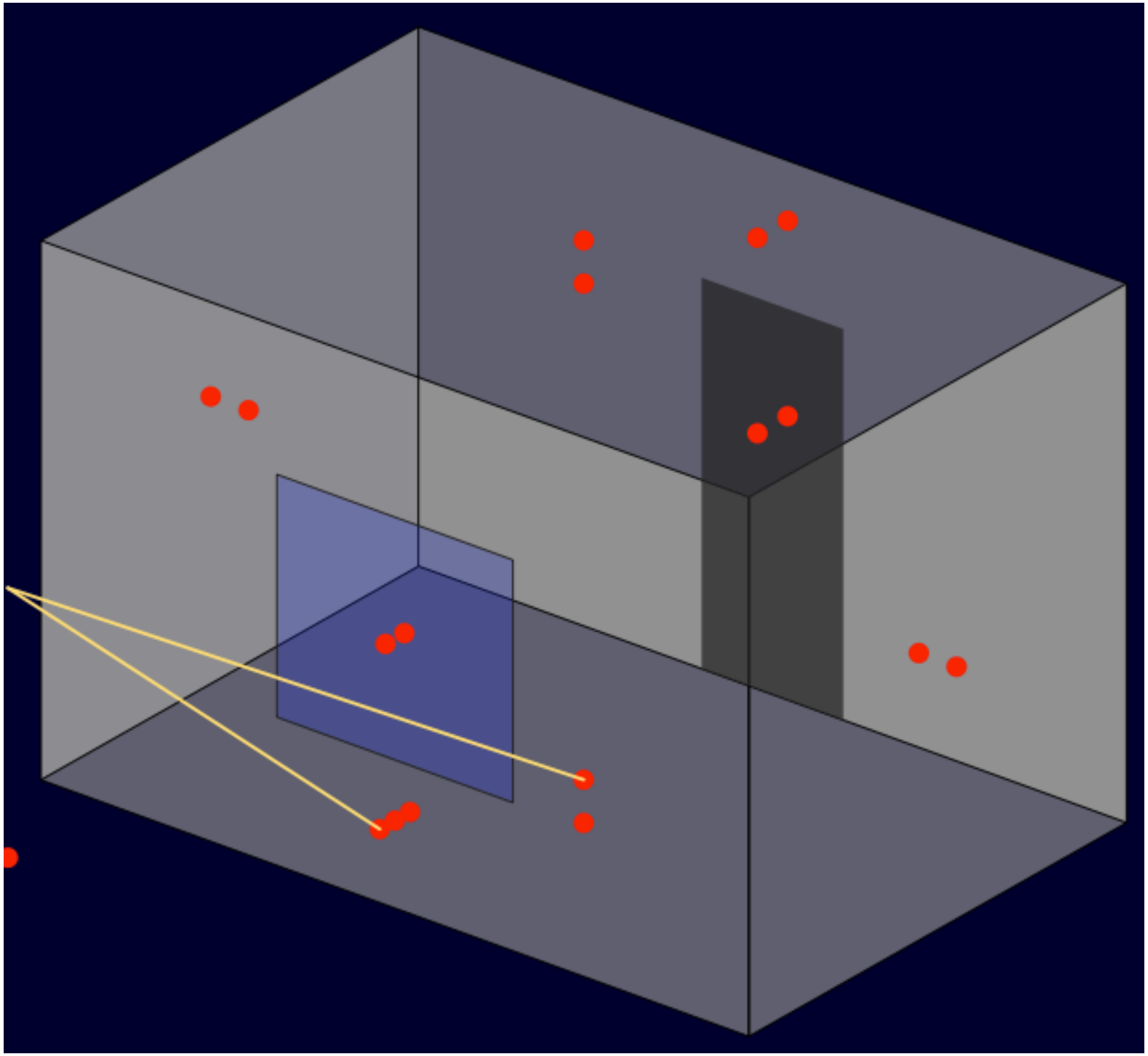
Simplest 'box' model: Solar (direct + diffuse)



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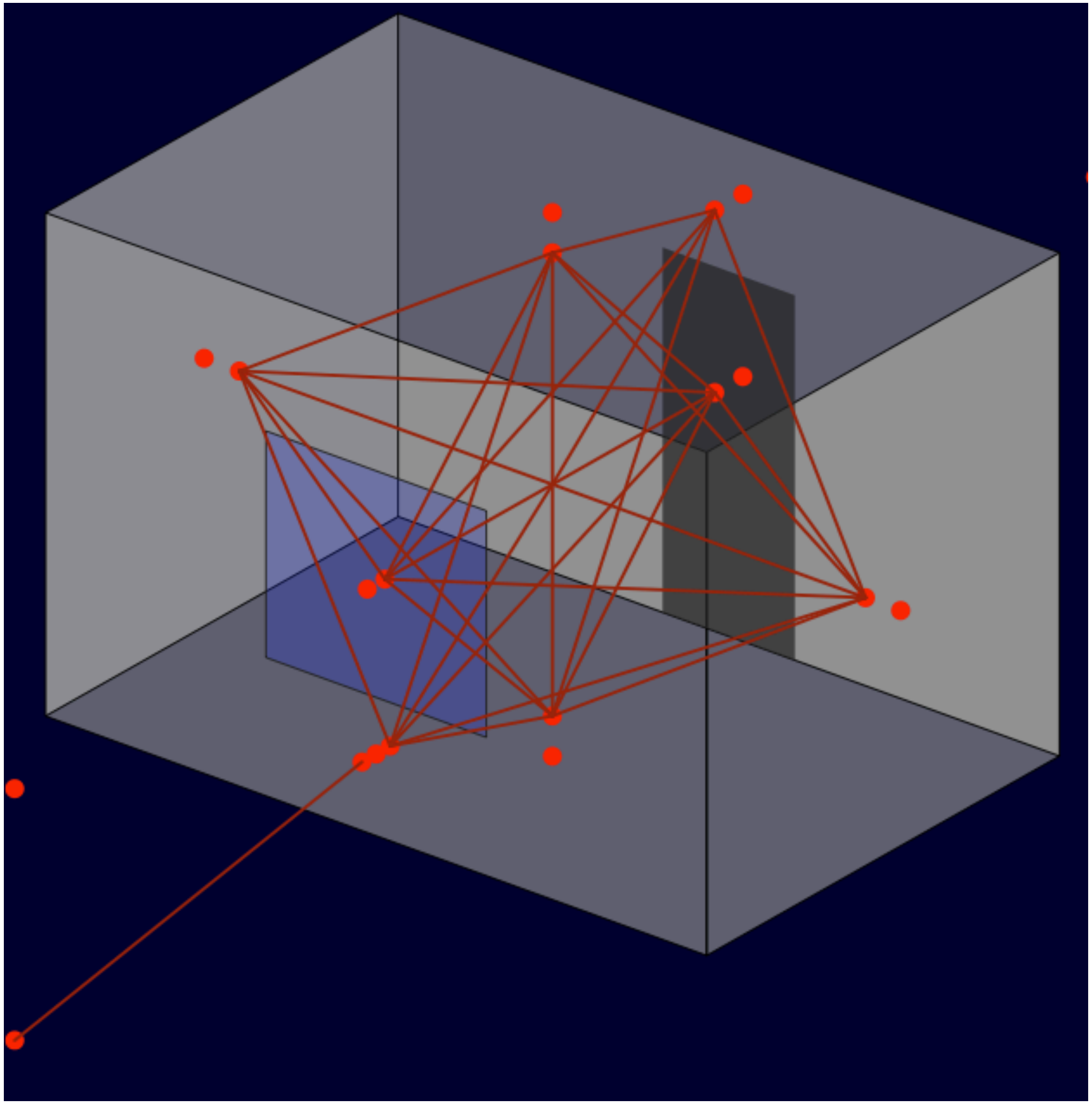
Simplest 'box' model: Long wave radiation elements



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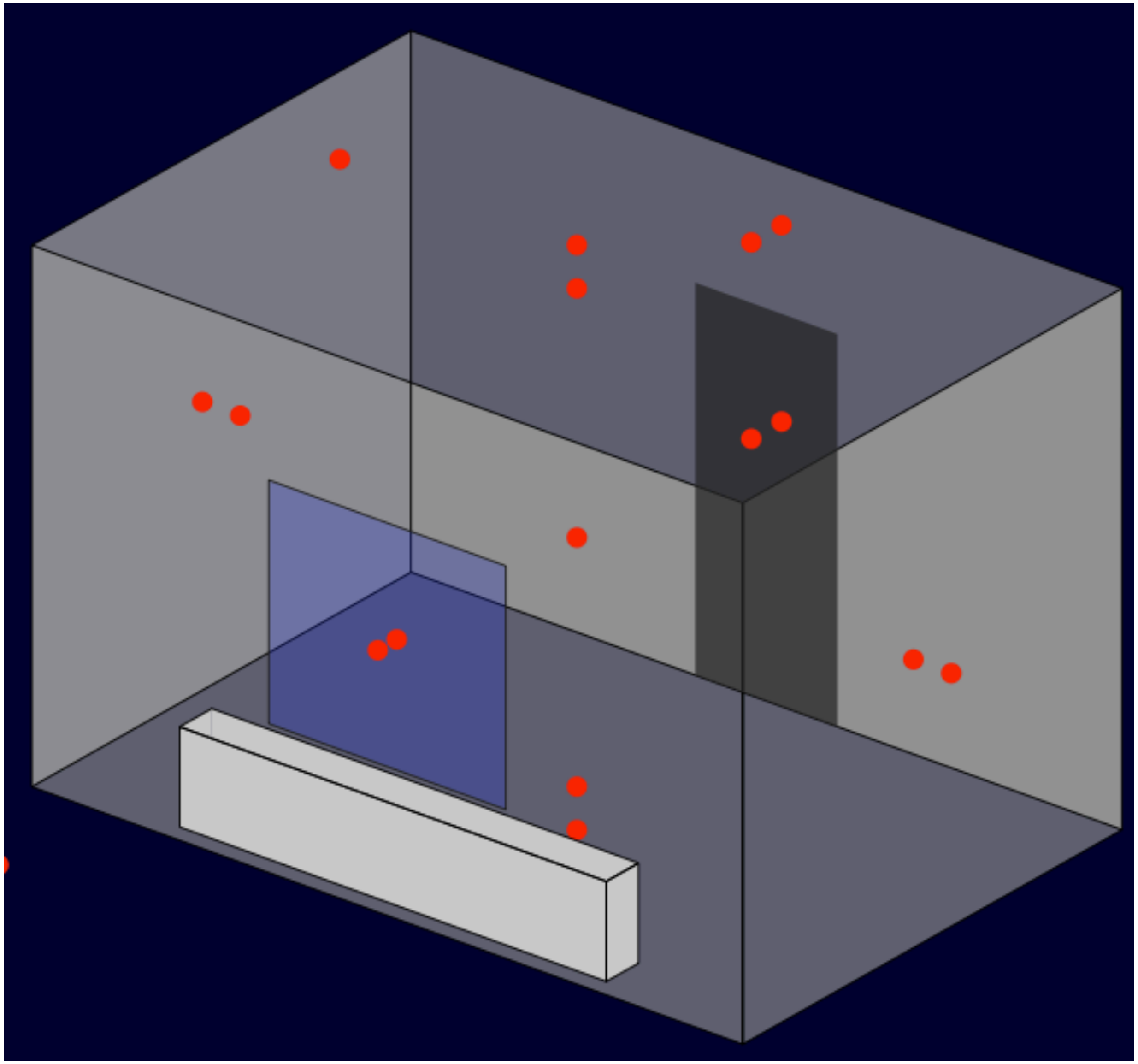
Simplest ‘box’ model: Internal mass (e.g., furniture)



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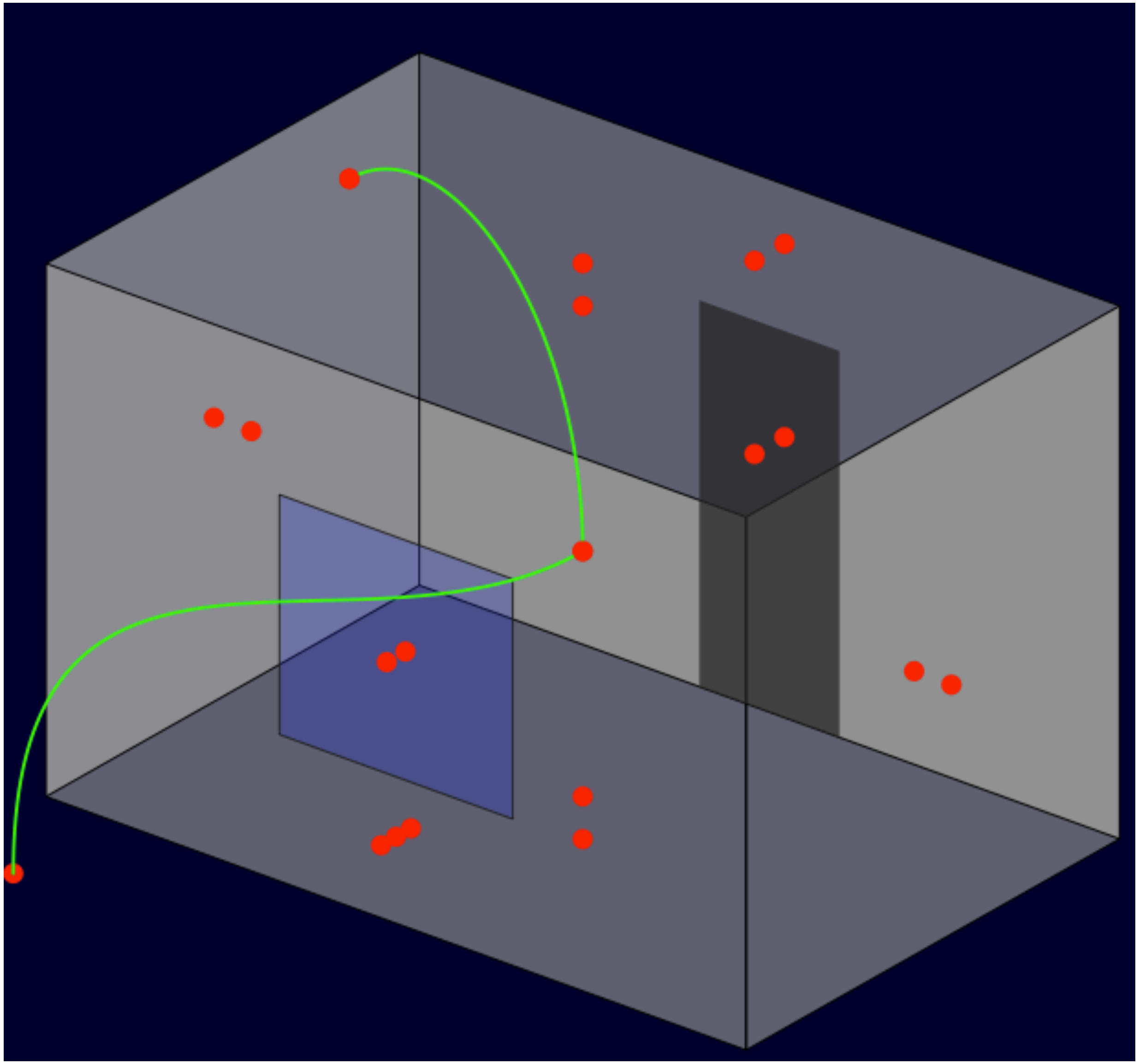
Simplest ‘box’ model: Ventilation/infiltration elements



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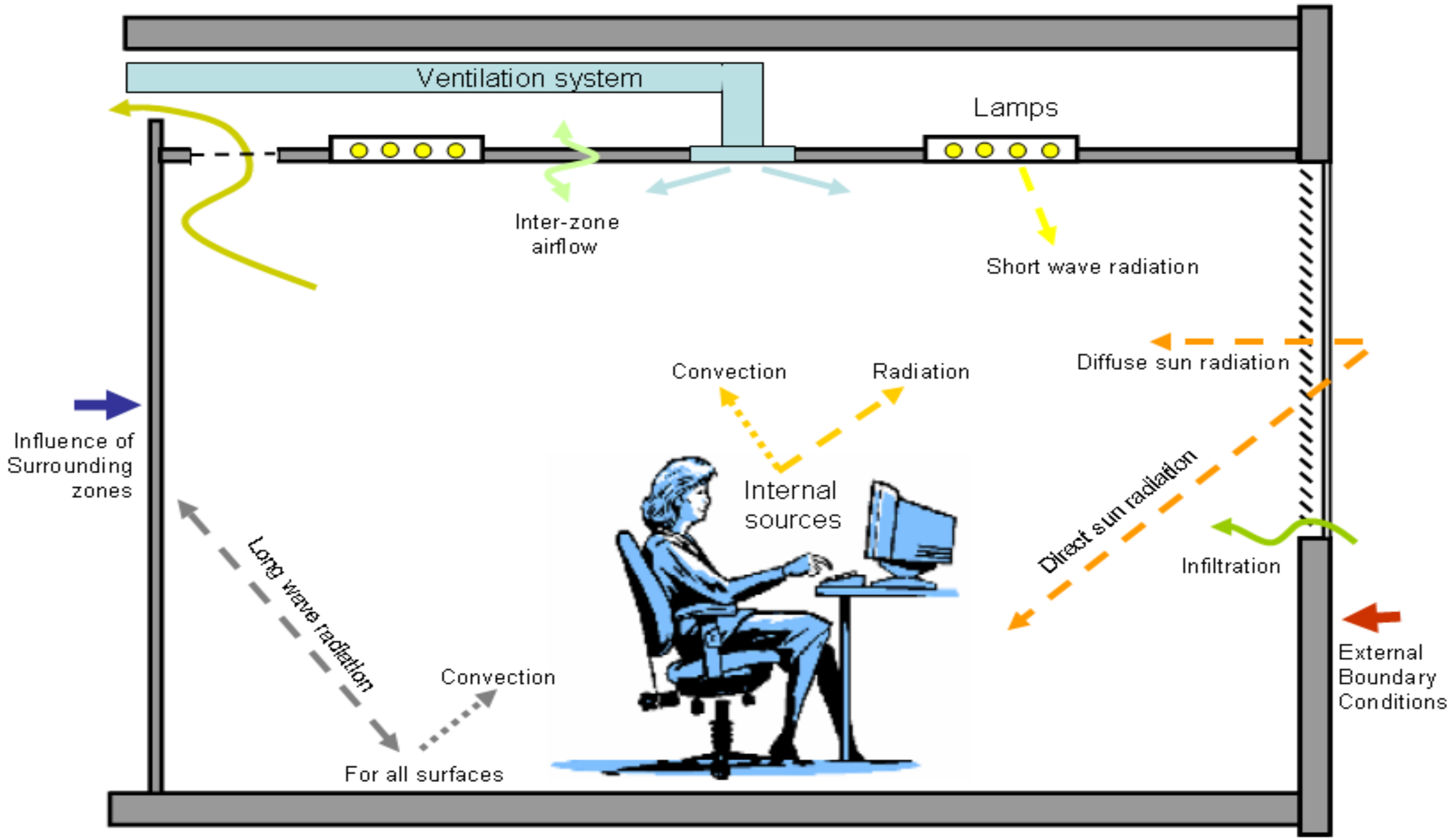
Adding occupants, equipment, and lights



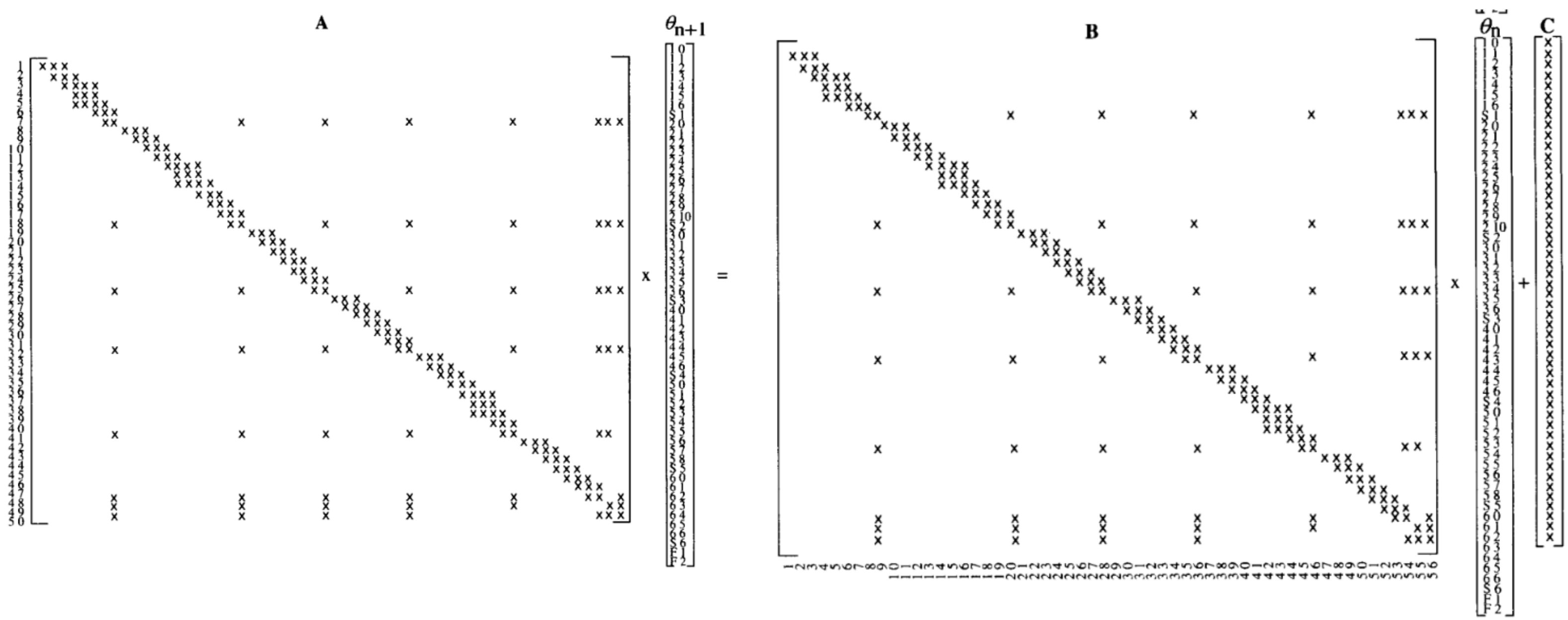
Slide courtesy Atila Novoselac, University of Texas at Austin

Solving the system of equations

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

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

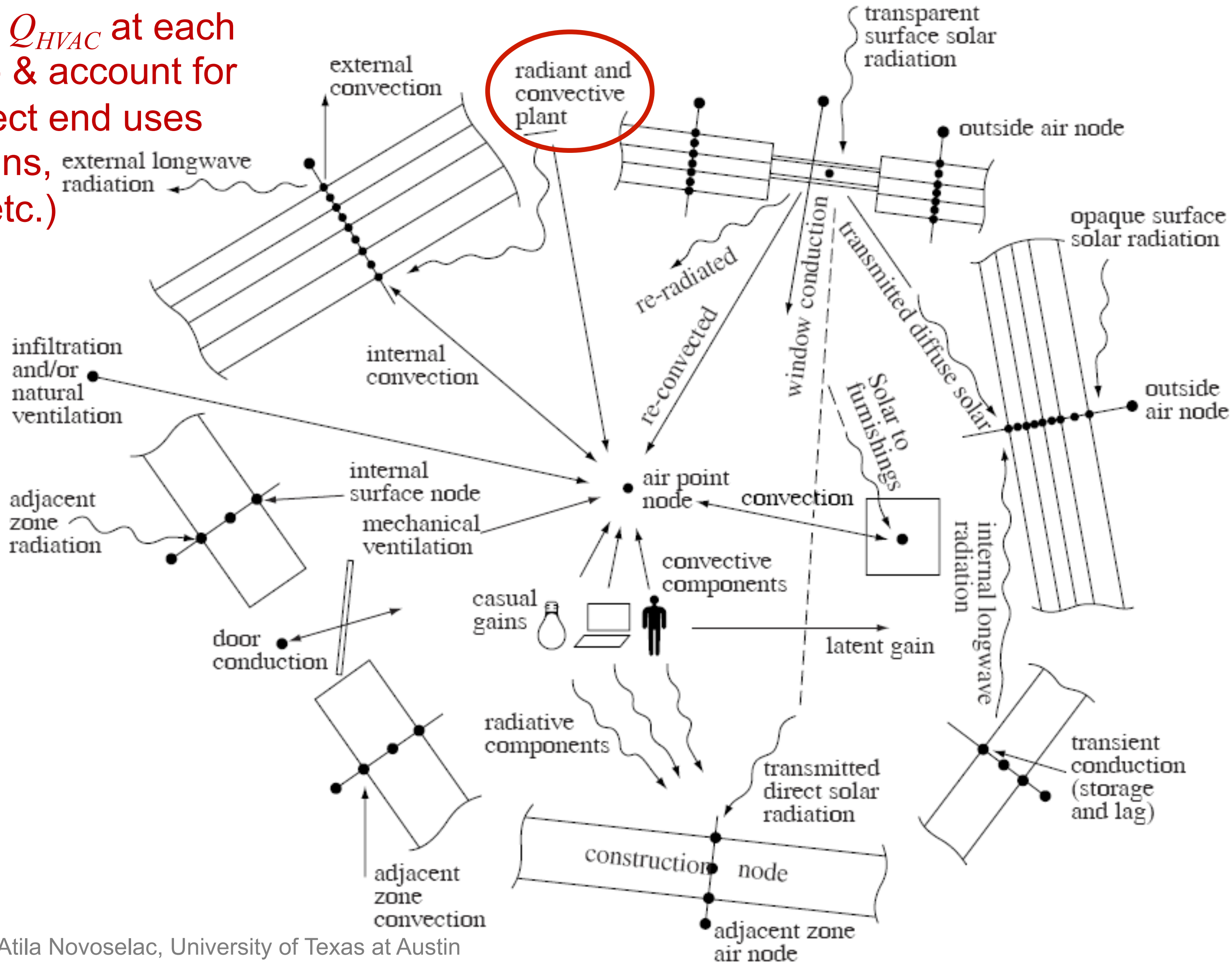
where **A** is a sparse matrix of future time-row coefficients of the nodal temperature or heat injection terms of the conservation equations, **B** the corresponding matrix established at the present time-row, **C** a column matrix of known boundary excitations relating to the present and future time-rows,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



Clarke 2001 *Energy Simulation in Building Design*

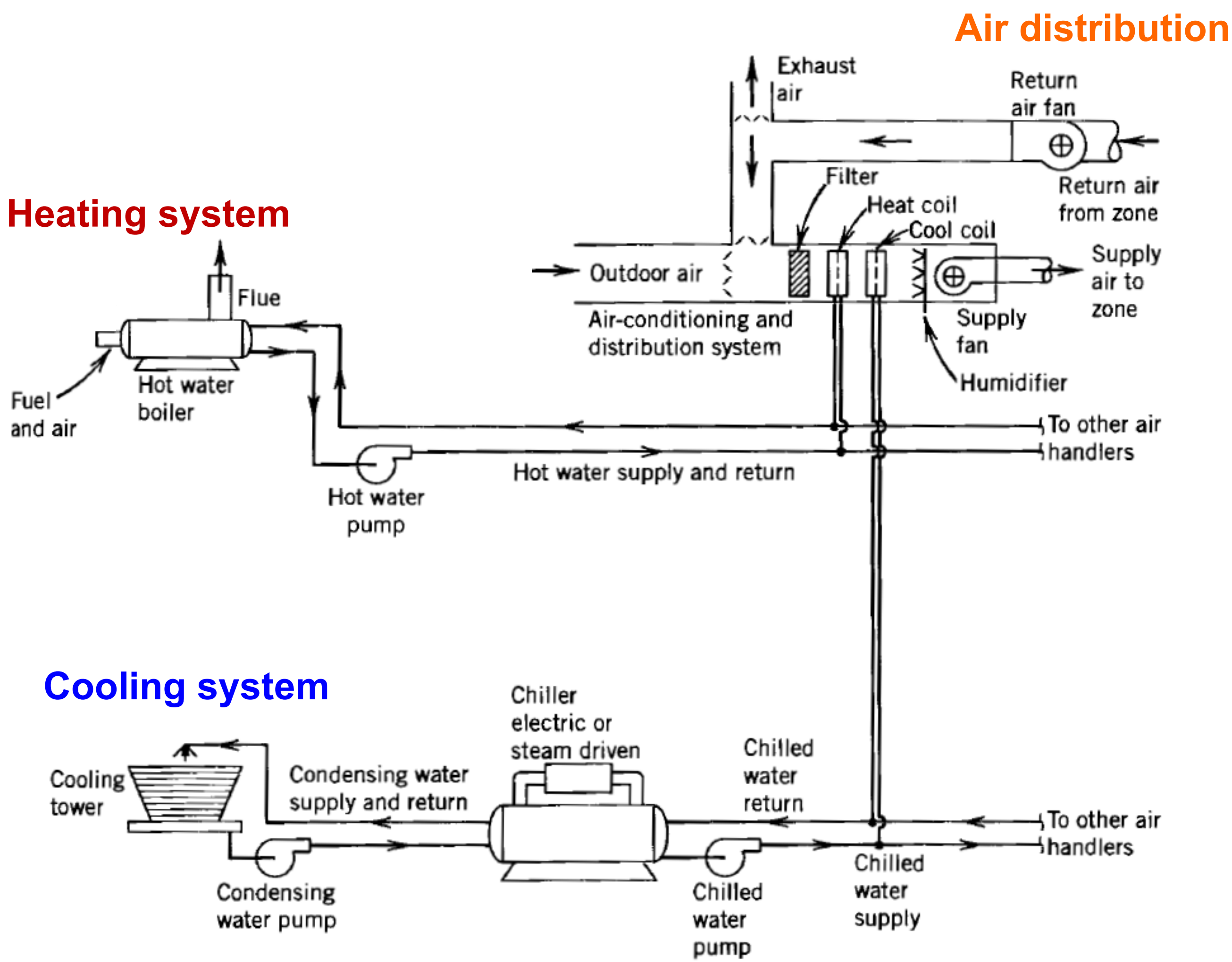
Whole building energy simulation

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

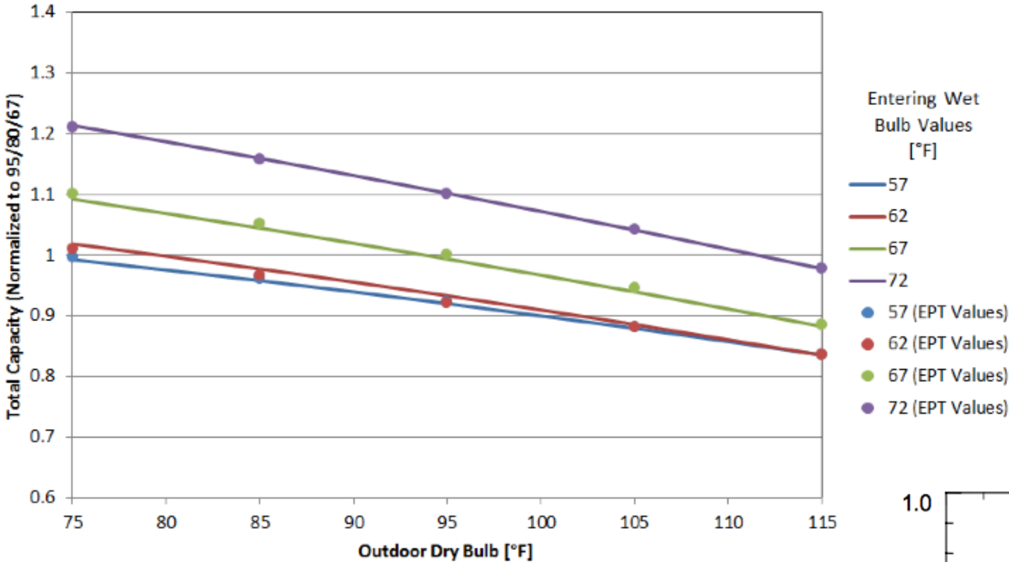
$EIRFPLR$ – Energy Input Ratio as function of Part Load Ratio

PLR – Part Load Ratio

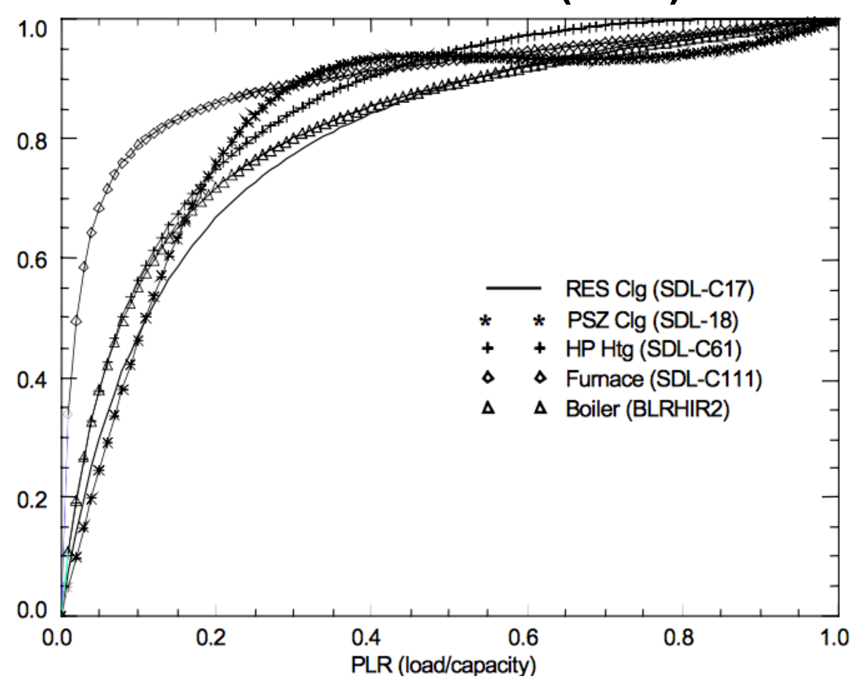
$$\mathrm{P}_{elec} = \frac{Q_{cooling,load}}{COP}$$

HVAC system models

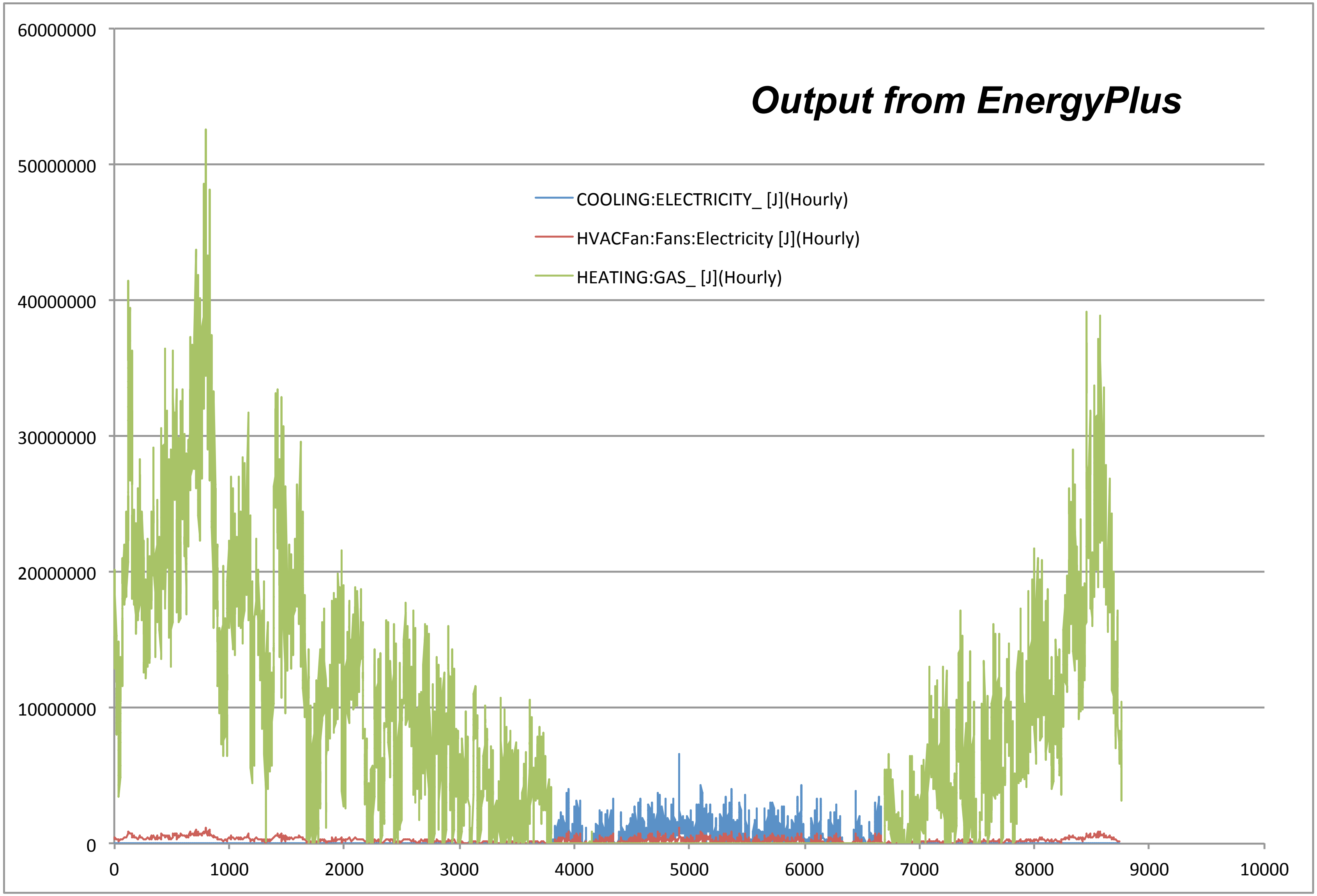
Outdoor conditions



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

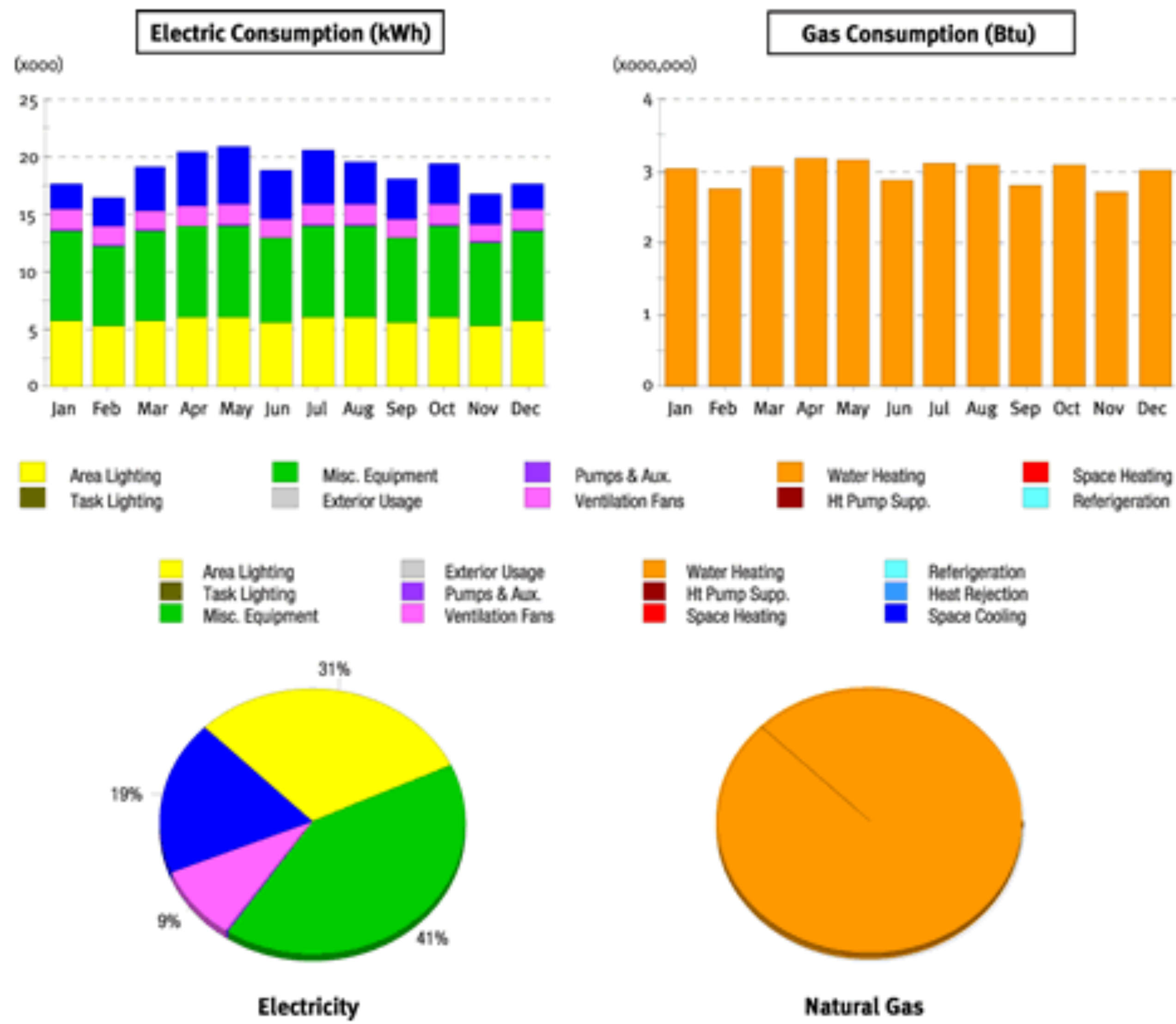
~$1500 in annual energy costs in this home

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

Output from EnergyPlus

Annual energy simulation results (eQUEST)

eQUEST



http://www.doe2.com/download/equest/eQUESTv3-Overview.pdf

Energy use intensity (EUI)

- Energy use intensity (EUI) = energy use per floor area
  - $kBTU/ft^2$ (MJ/m^2)

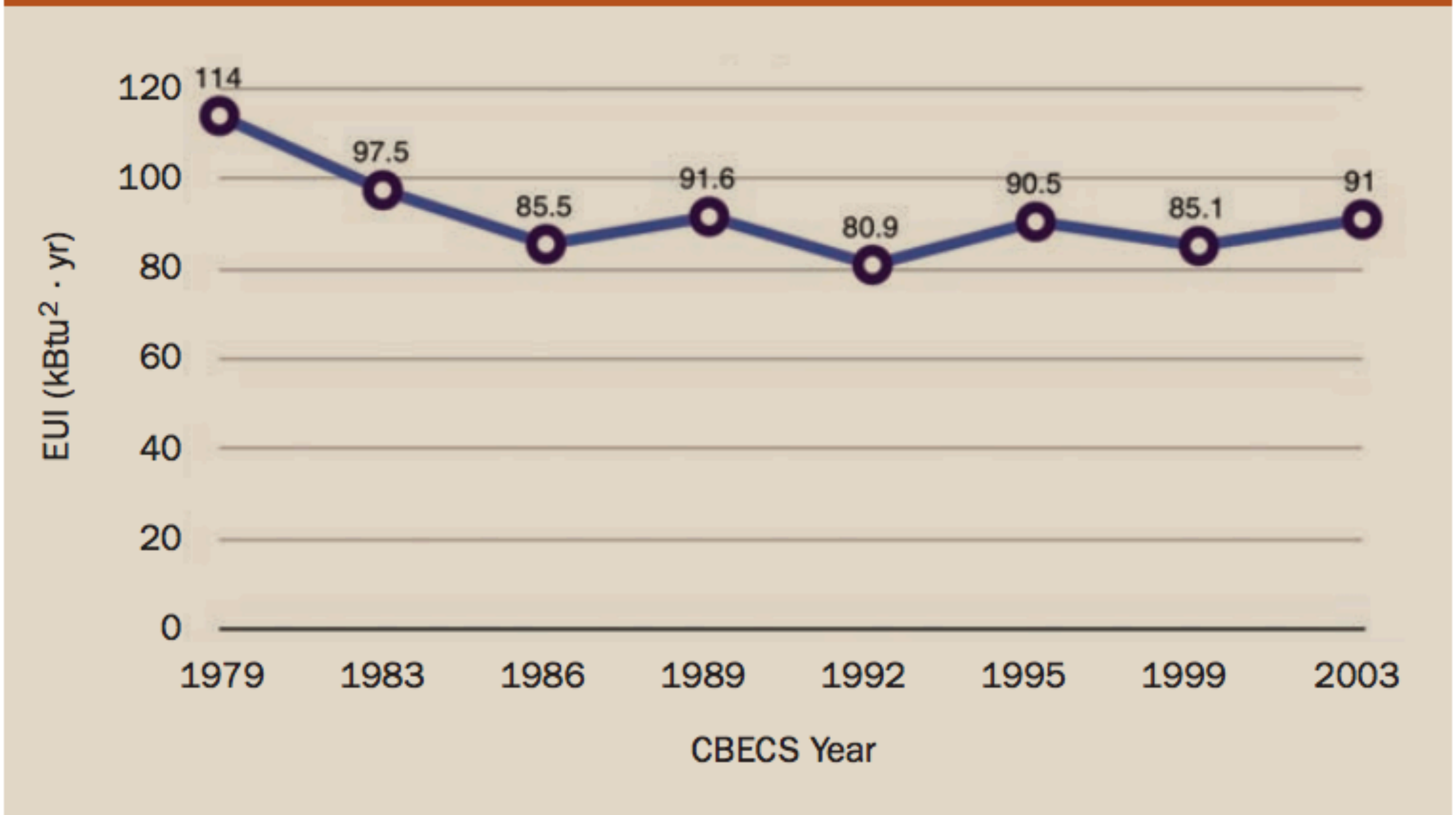
$$\frac{\text{Annual Building Energy Use}\ (\text{kBtus or MJ})}{\text{Building Area}\ (\text{ft}^2 \text{ or m}^2)} = \text{EUI}$$

- 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

Important input parameters for energy simulation

- Time steps
  - Too short and calculations take forever
  - Too long and solutions diverge
- 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)

DESIGNING FOR ENERGY EFFICIENCY

Designing for efficiency

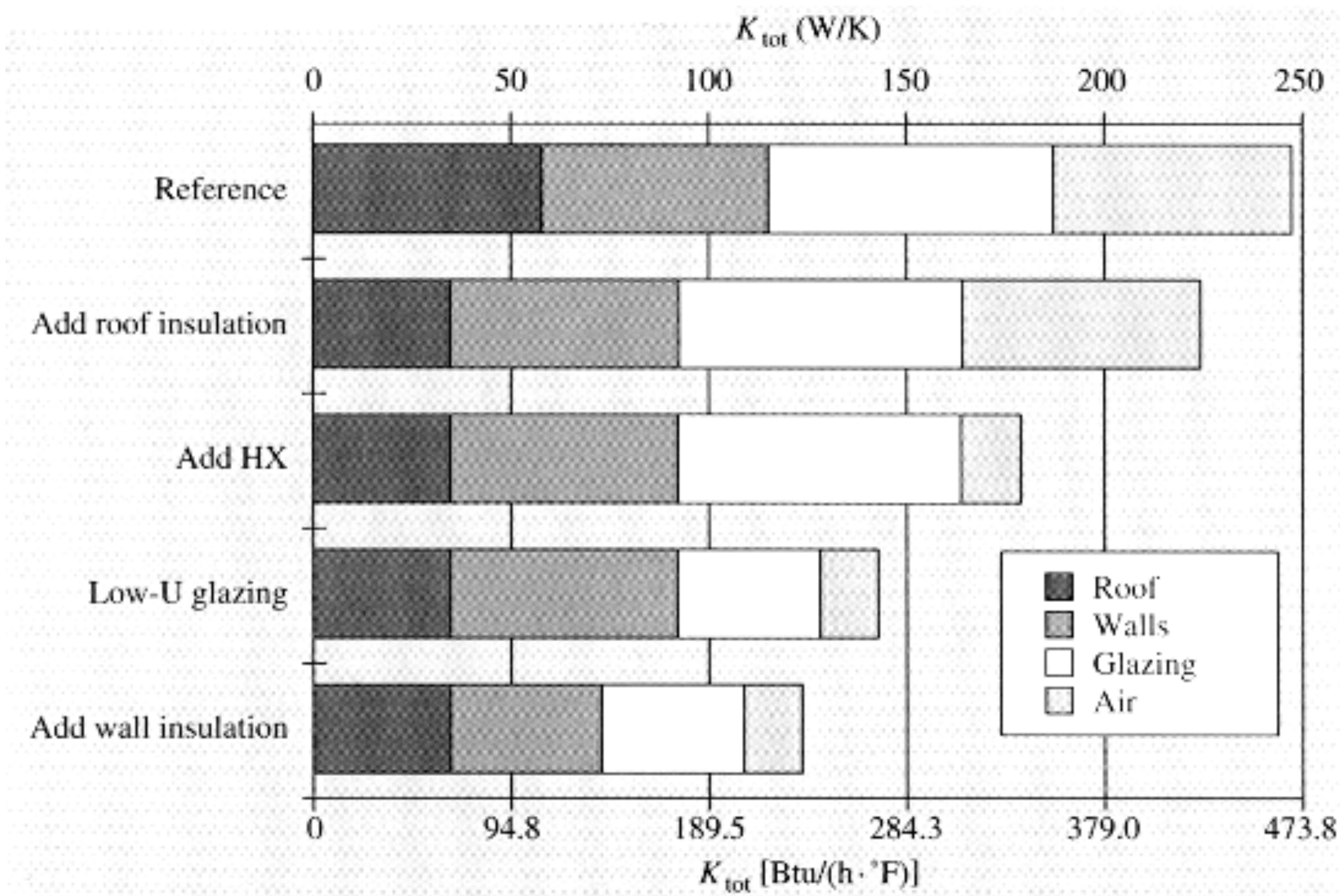
- We can't change outdoor conditions (e.g., temperature, solar radiation, or HDD and CDD)
  - So what can we do to reduce energy consumption?

- 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

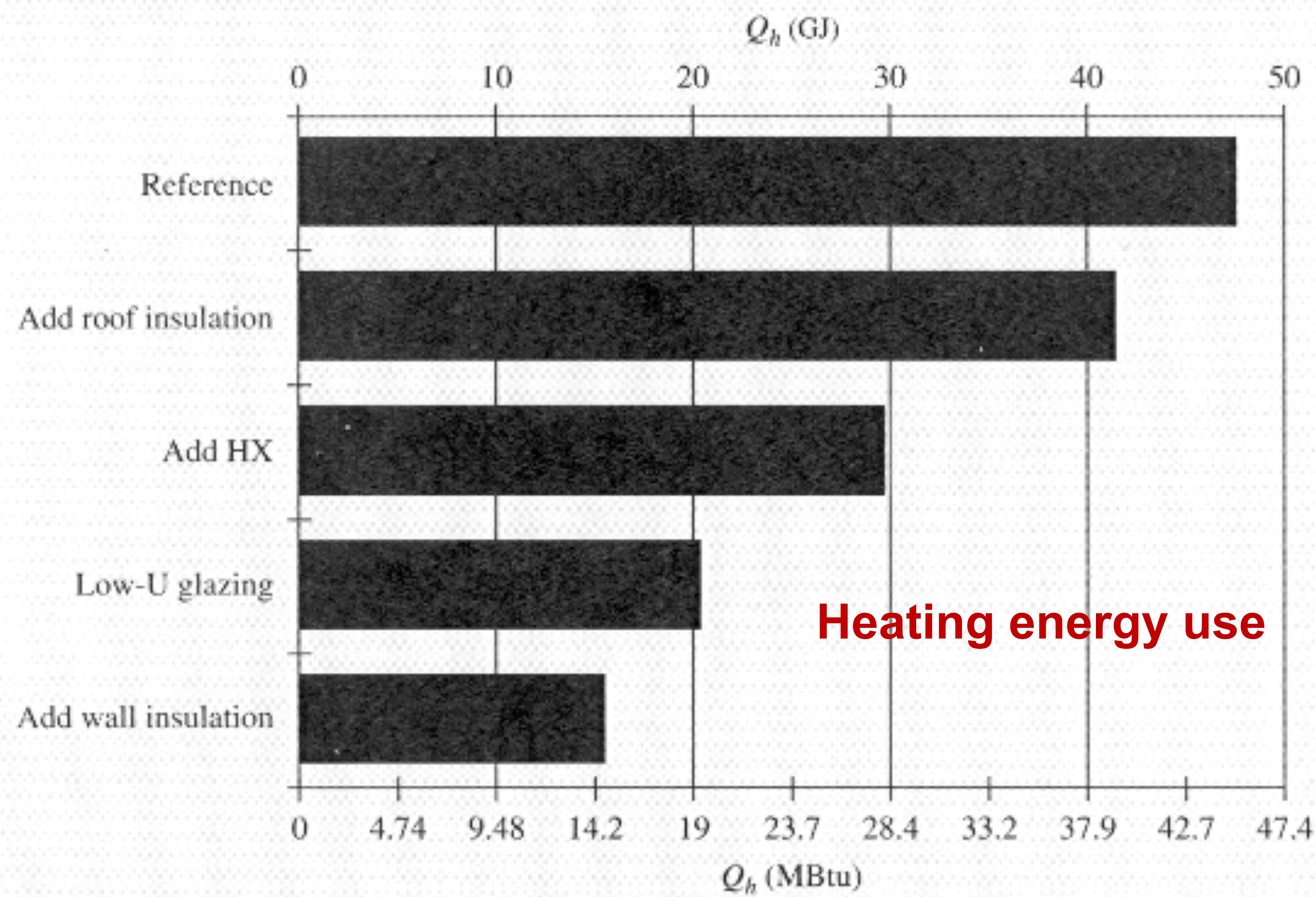
Parametric changes early in design phase

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



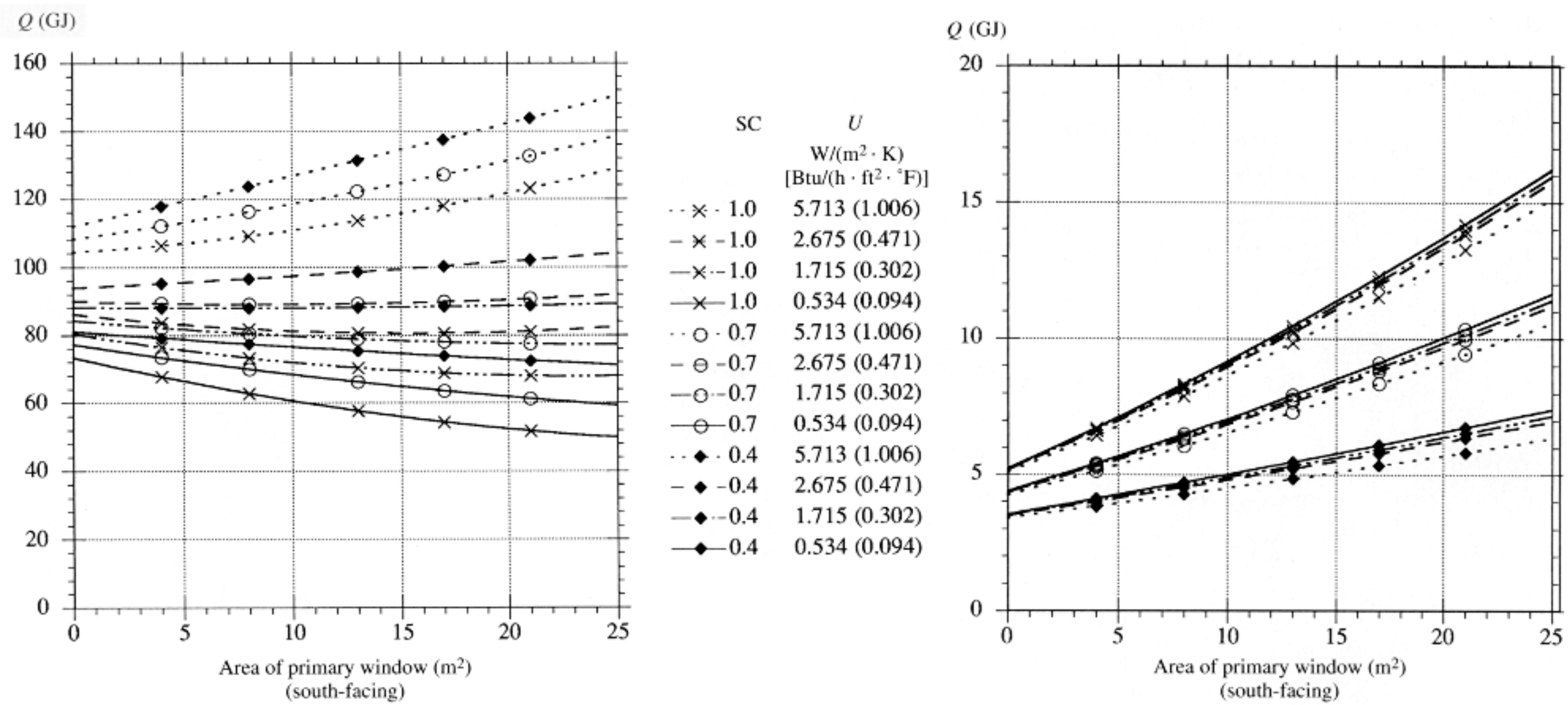
Parametric changes early in design phase

- 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

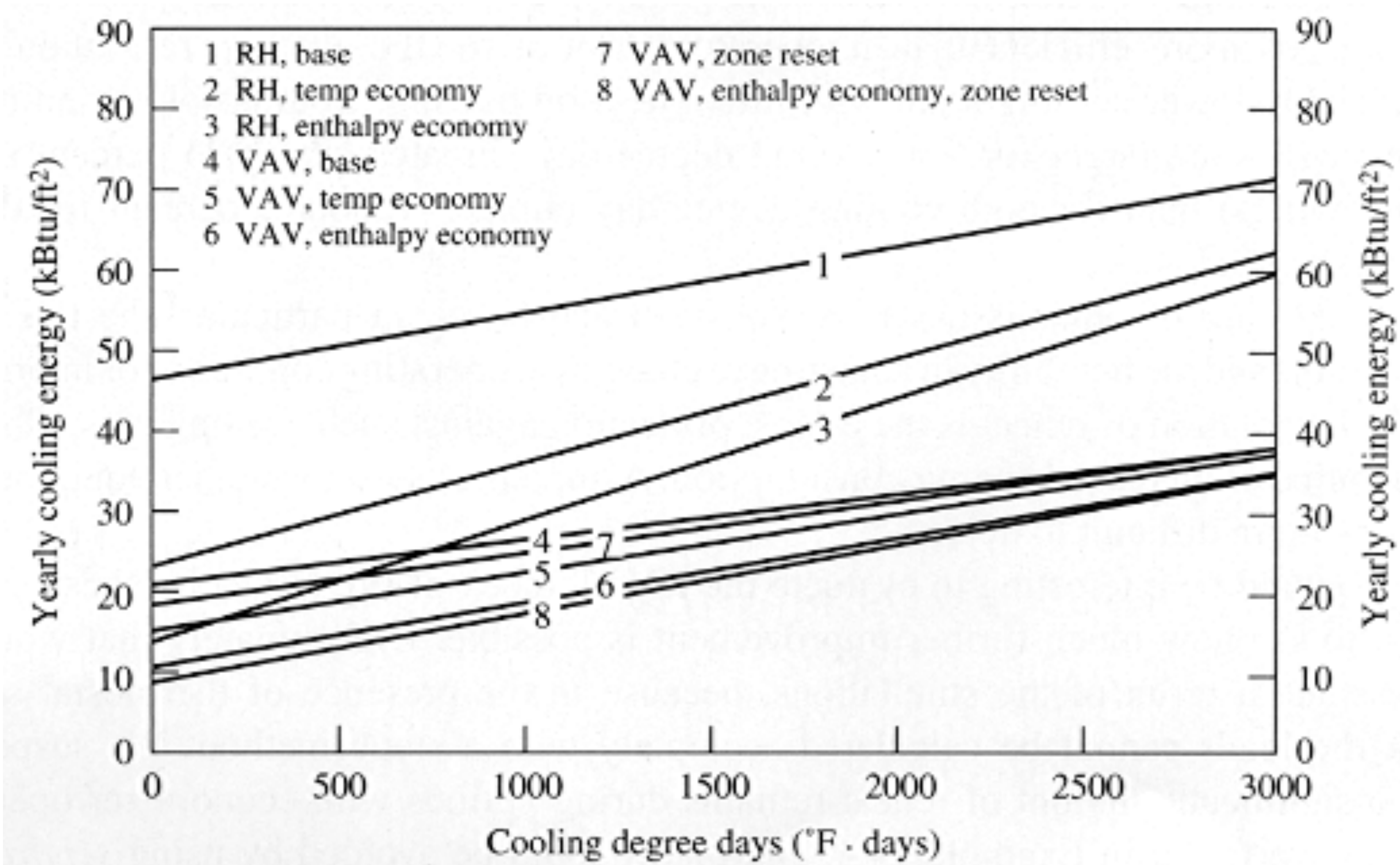


Heating

Cooling

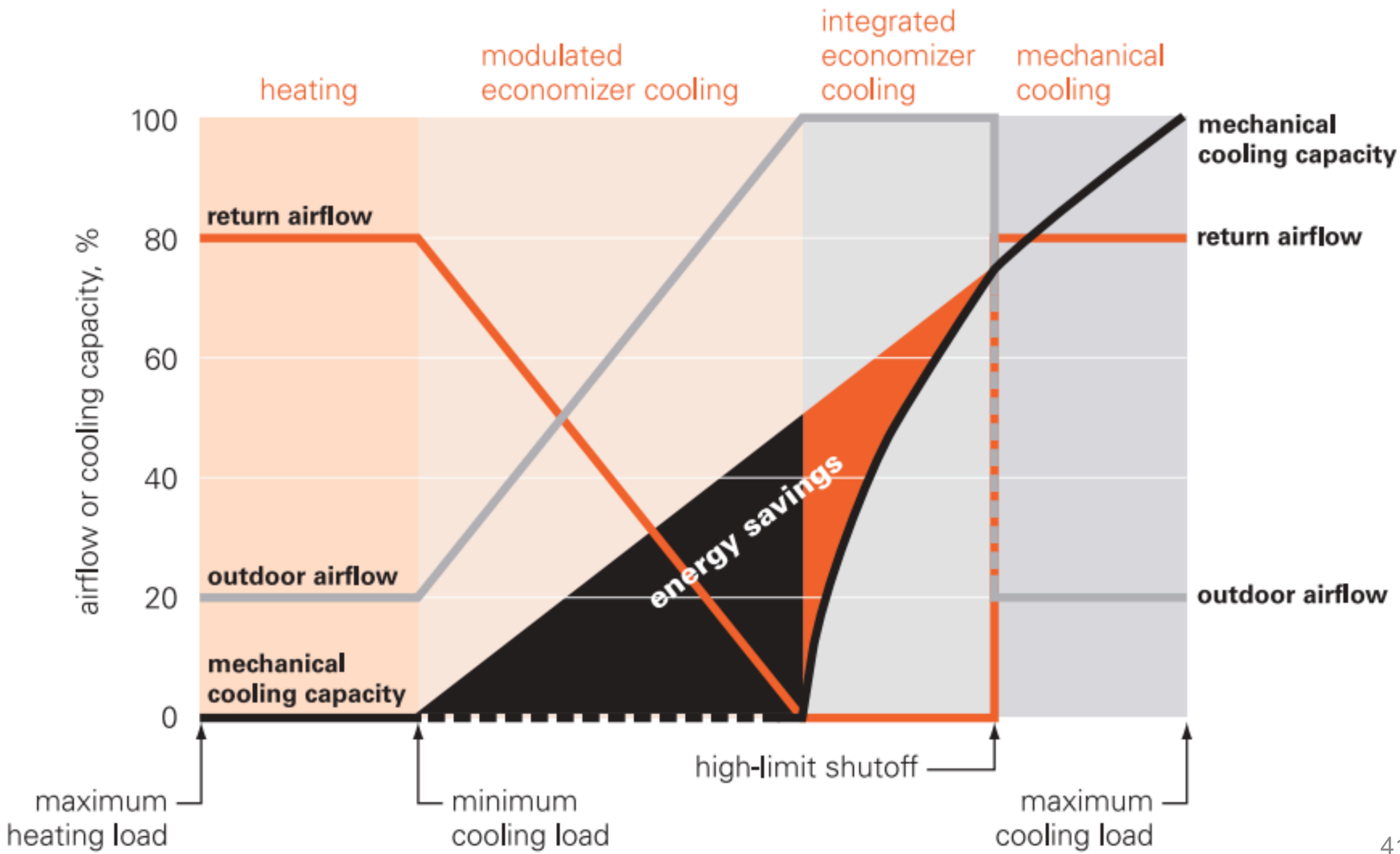
Parametric changes early in design phase

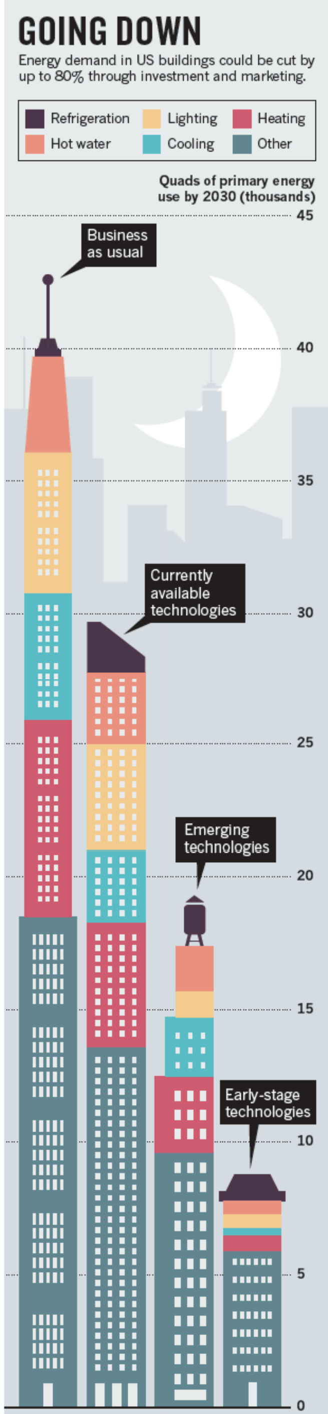
- We can change HVAC types (example in an office)



Parametric changes early in design phase

- What is an economizer?





Paths toward *lower energy* buildings

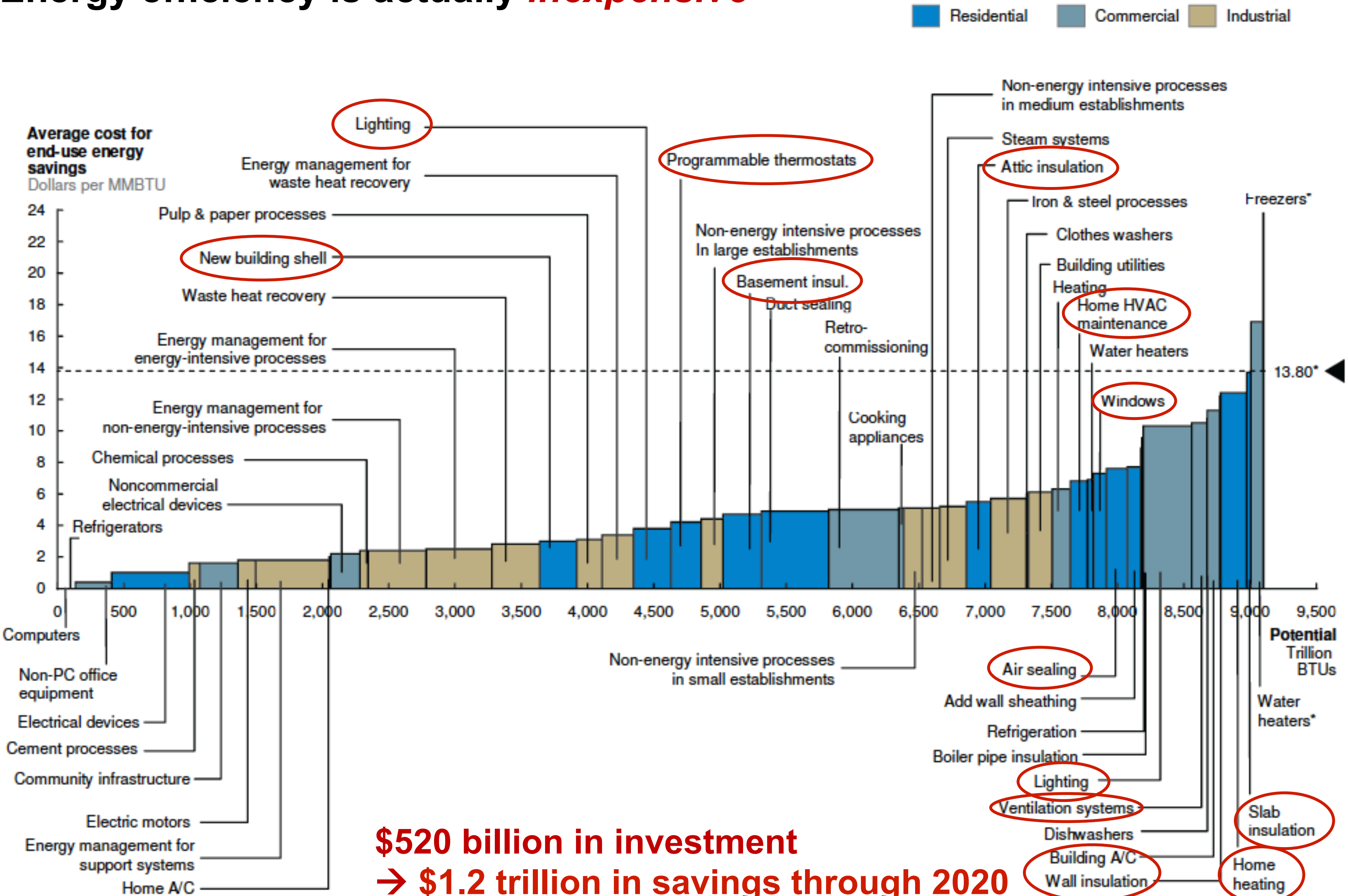
- Efficient building ***systems***
  - Mechanical systems
  - Mechanical driving forces
  - Controls and equipment

- ***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*

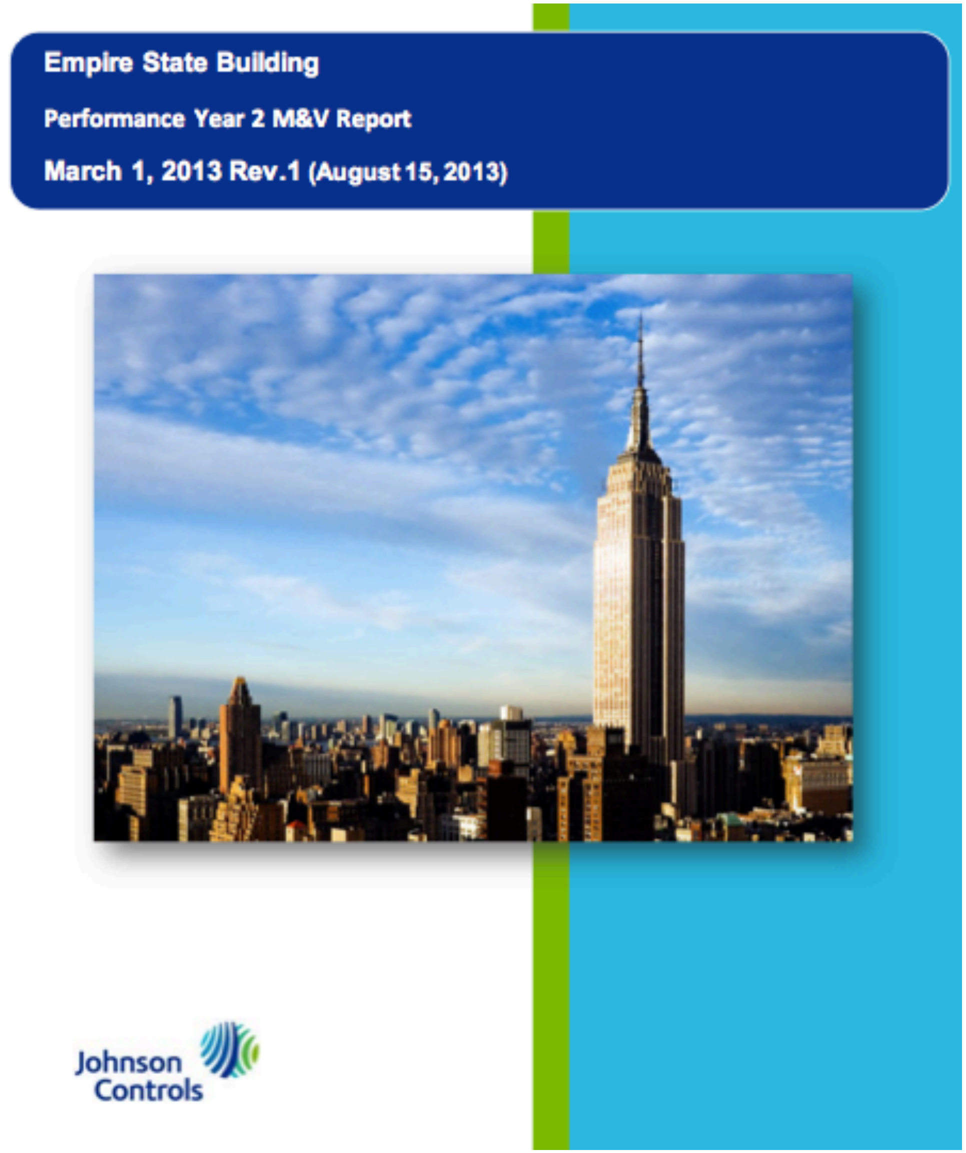


$520 billion in investment
→ $1.2 trillion in savings through 2020

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

Energy 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

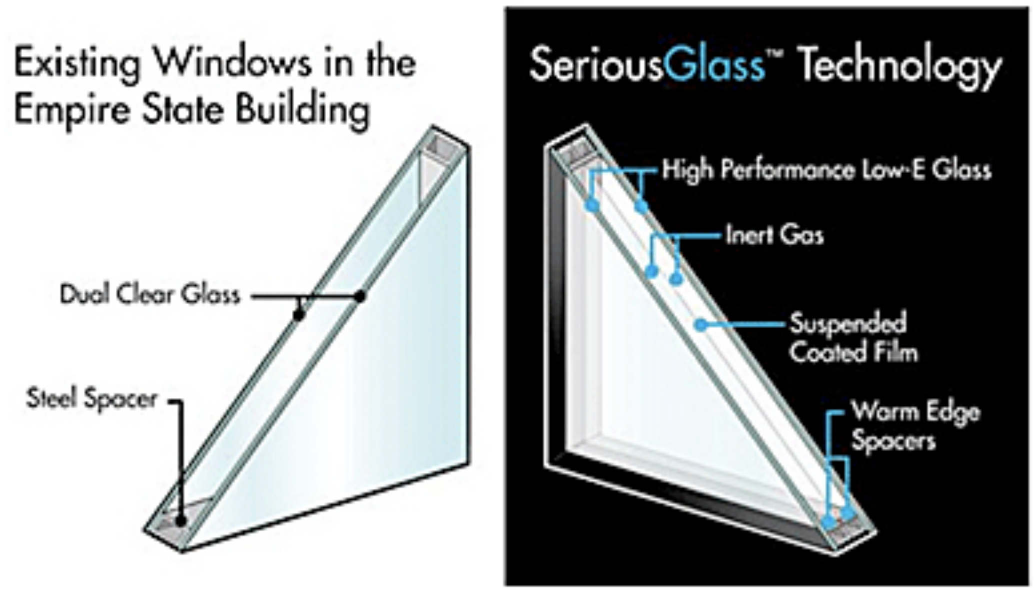


ECMs in the Empire State Building

Window retrofits

- Upgraded over 6500 double-hung insulated glazing units

ECMs in the Empire State Building



Original windows:

- U-value = 0.58 Btu/h·ft^2·°F
- SHGC = 0.65

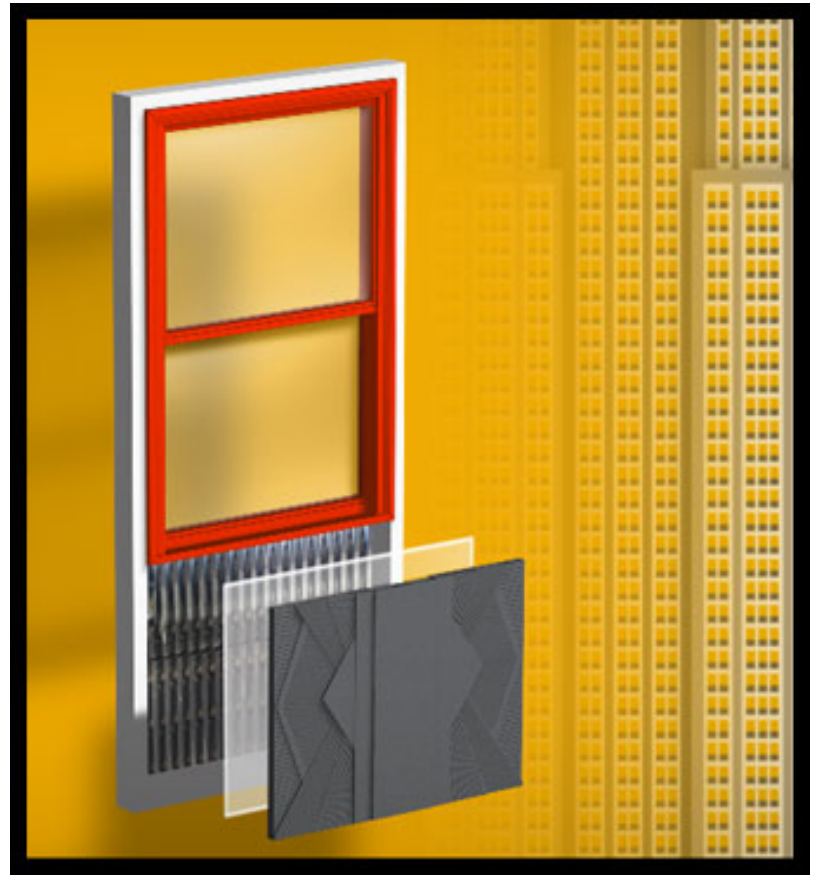
New windows (krypton + argon):

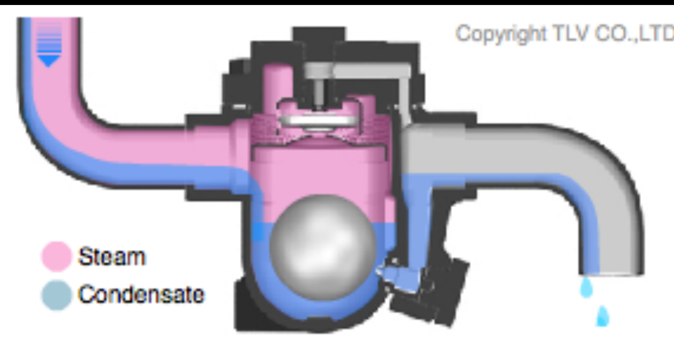
- U-value = 0.37 Btu/h·ft^2·°F on north wall and 0.38 on S-E-W walls
- SHGC = 0.45 on north wall and 0.33 on S-E-W walls

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·ft^2·°F
- New insulation:
  - U-value = 0.12 Btu/h·ft^2·°F
- Also upgraded control system and added “steam traps”



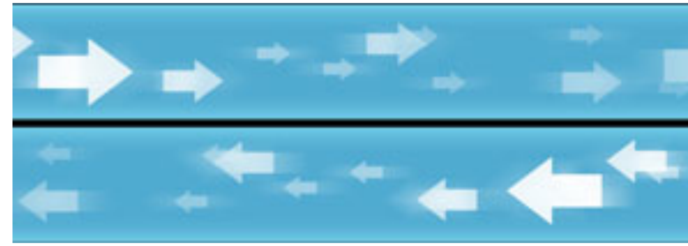


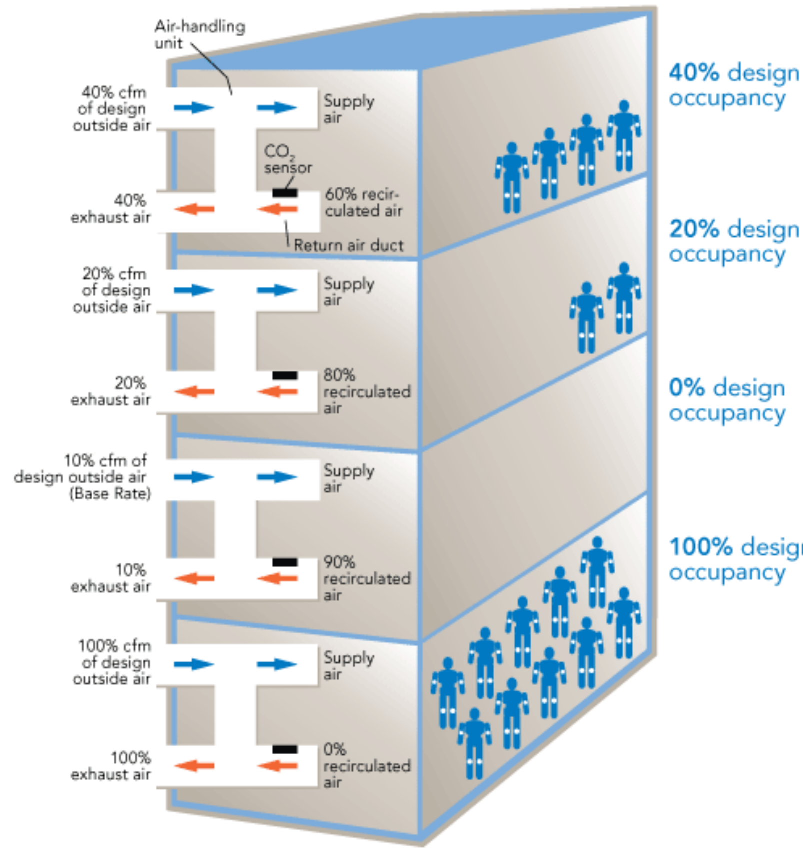
ECMs in the Empire State Building

ECMs in the Empire State Building

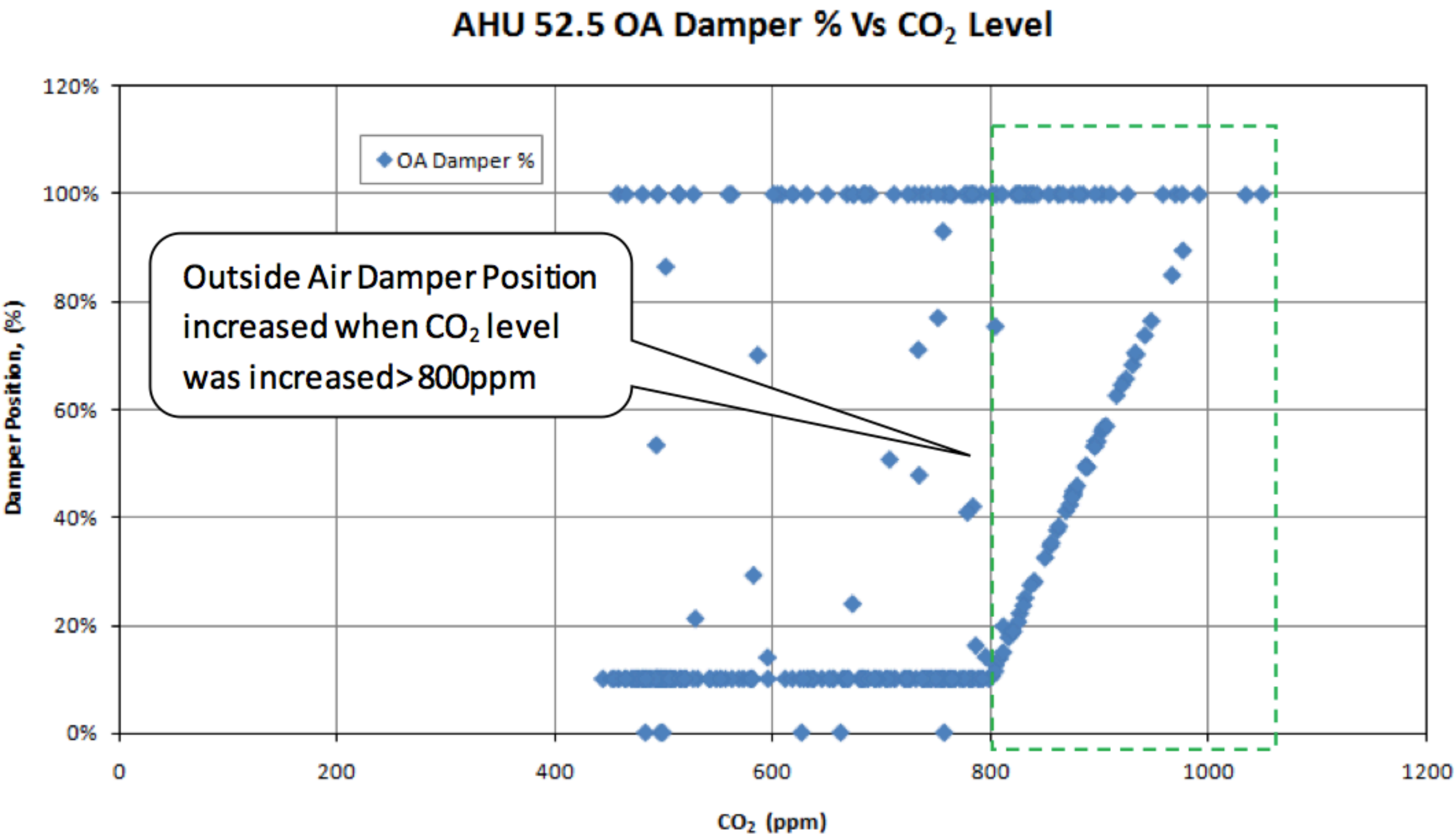
Building automation system (BAS)

- Reduced overall outdoor air intake by using “demand controlled ventilation” (DCV) and modulating dampers
  - Uses CO_2 to measure occupancy
- Original BAS:
  - No controls, OA = from 0.25 cfm/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 cfm/ft^2





ECMs in the Empire State Building



ECMs in the Empire State Building

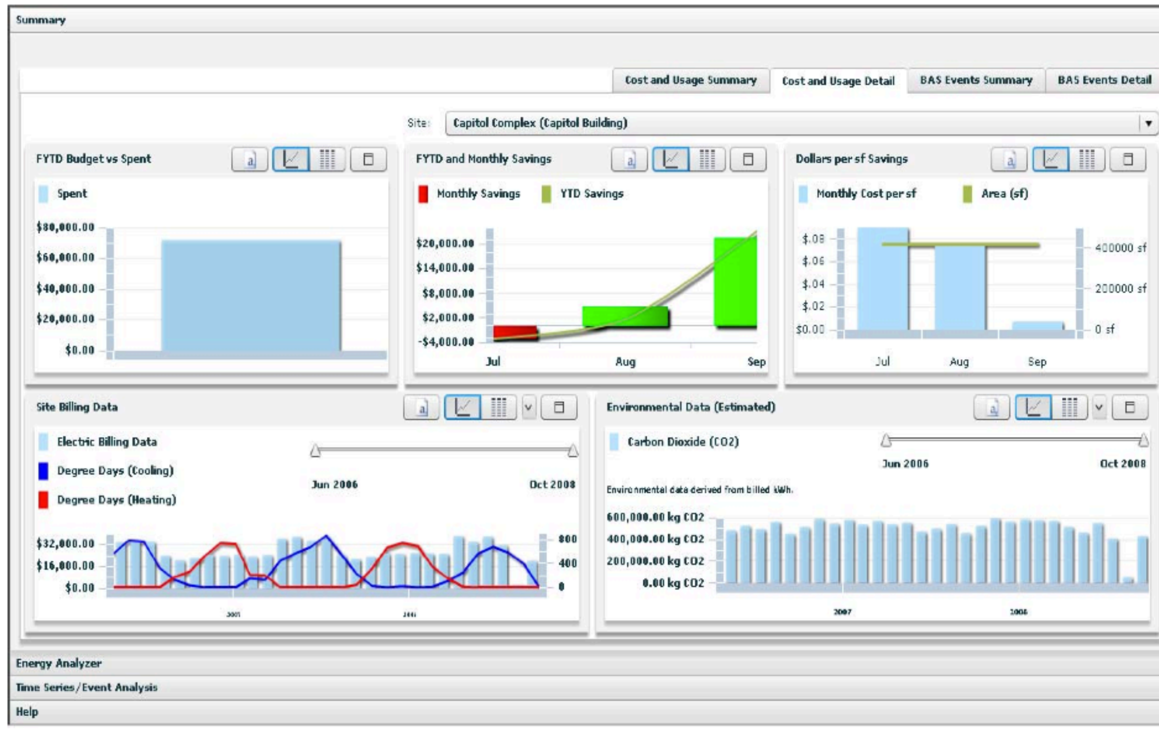
Chiller plant retrofit

- 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.



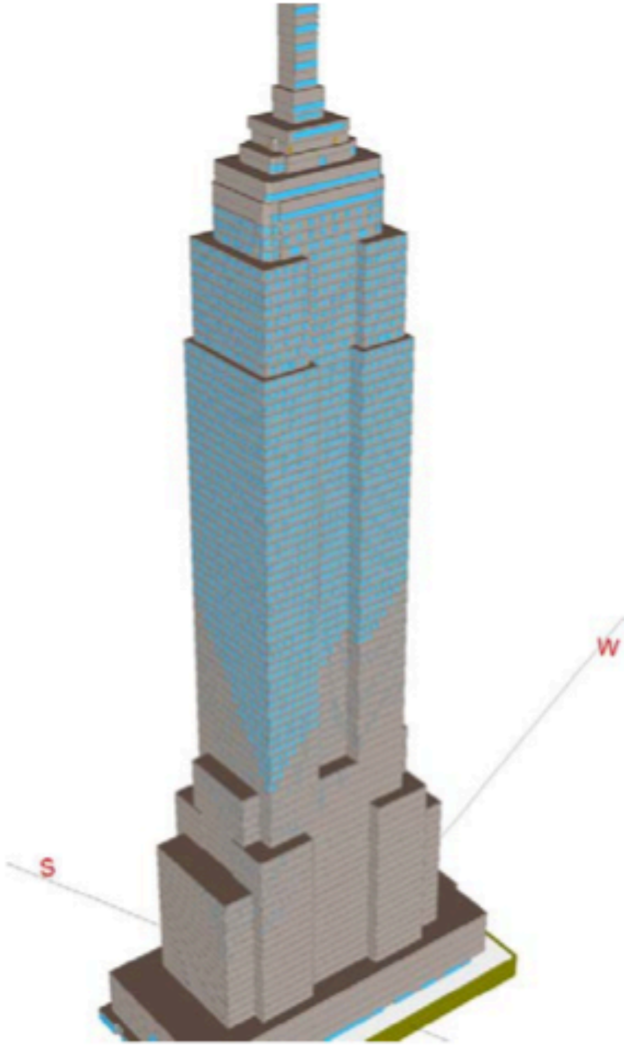
Energy simulation to predict costs and GHG savings

eQUEST Model Setup Overview

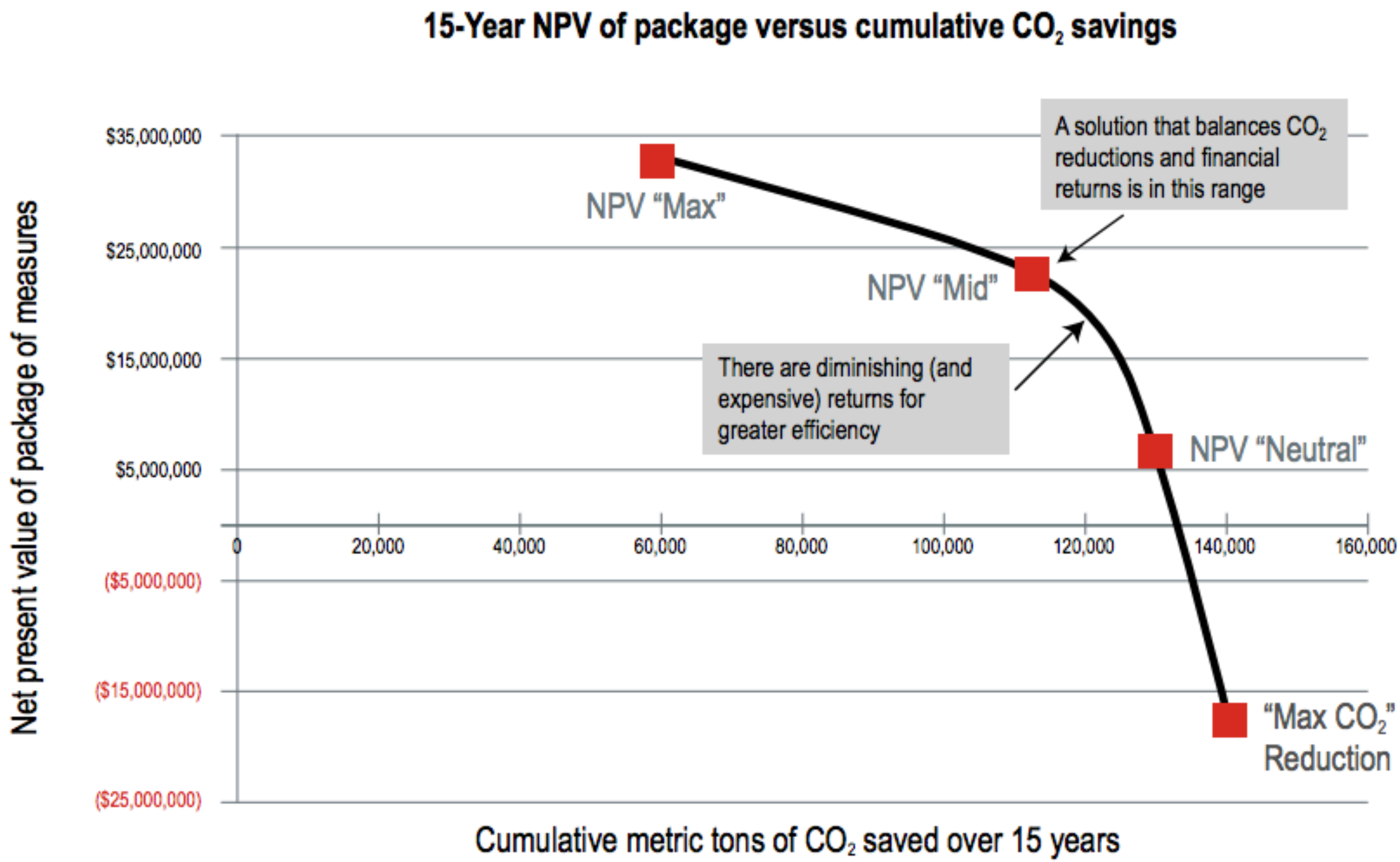
Modeling Software	eQUEST v3.64, build 7130
Model Author	Quest Energy Group, LLC 1620 W Fountainhead Pkwy #303 Tempe, AZ 85282 +1 480 467 2480

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



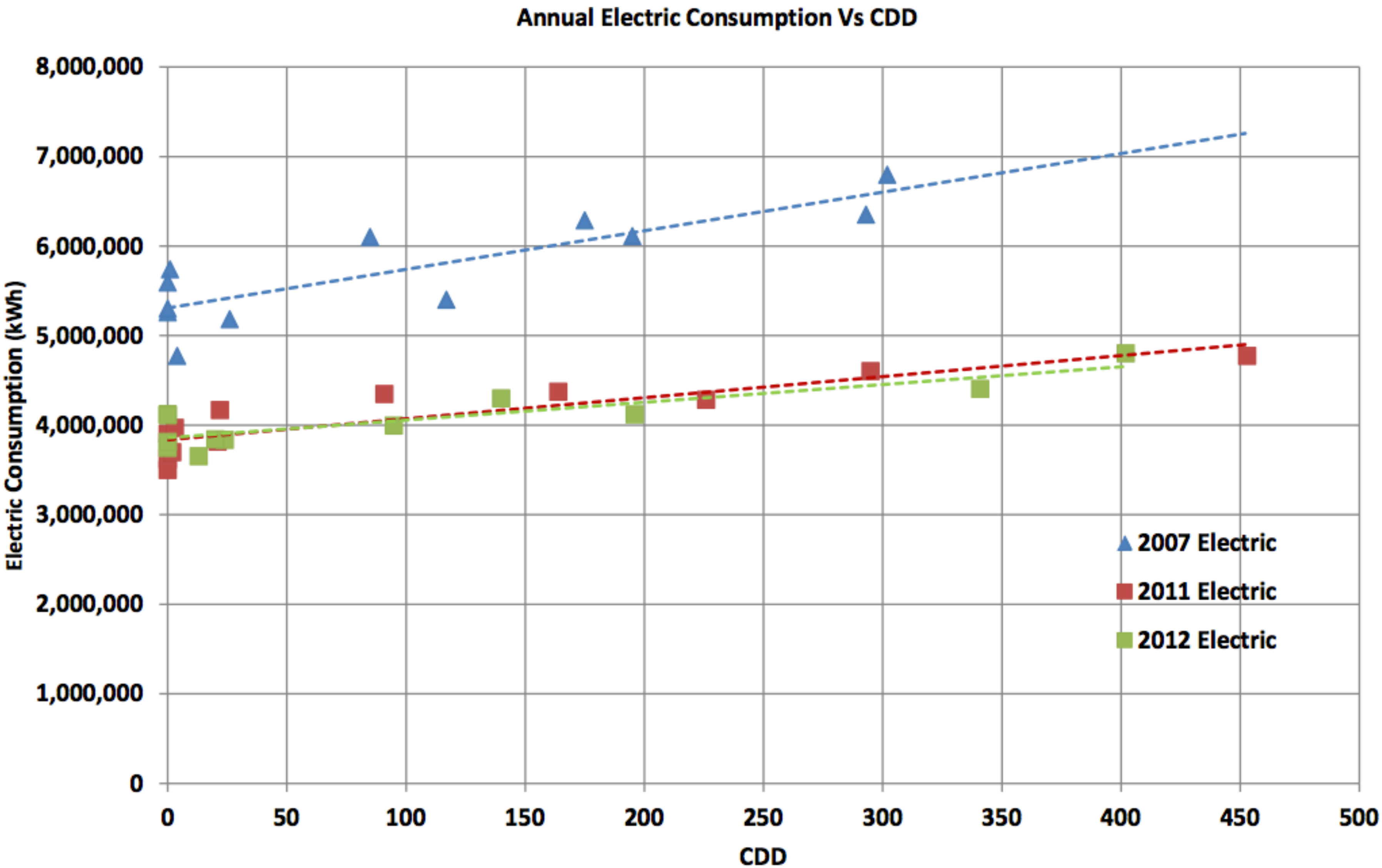
http://www.buildingefficiencyinitiative.org/sites/default/files/legacy/InstituteBE/media/Library/Resources/Existing-Building-Retrofits/ESB-White-paper.pdf

Predicted costs and savings in the ESB

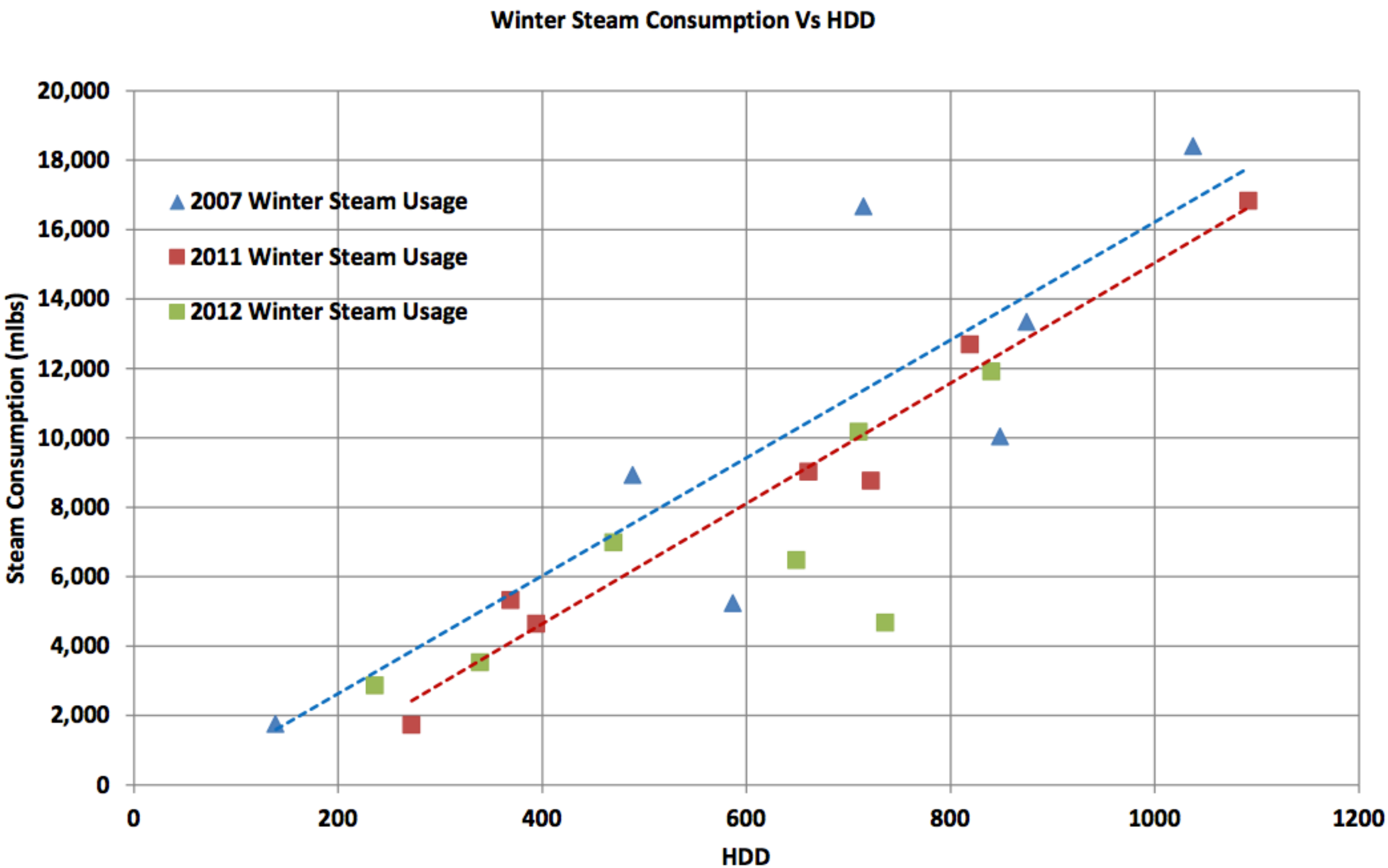
Project Description	*Projected Capital Cost*	*2008 Capital Budget*	*Incremental Cost*	*EstimatedAnnual Energy Savings**
Windows	$4.5m	$455k	$4m	$410k
Radiative Barrier	$2.7m	$0	$2.7m	$190k
DDC Controls	$7.6m	$2m	$5.6m	$741k
Demand Control Vent	Inc. above	$0	Inc. above	$117k
Chiller Plant Retrofit	$5.1m	$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

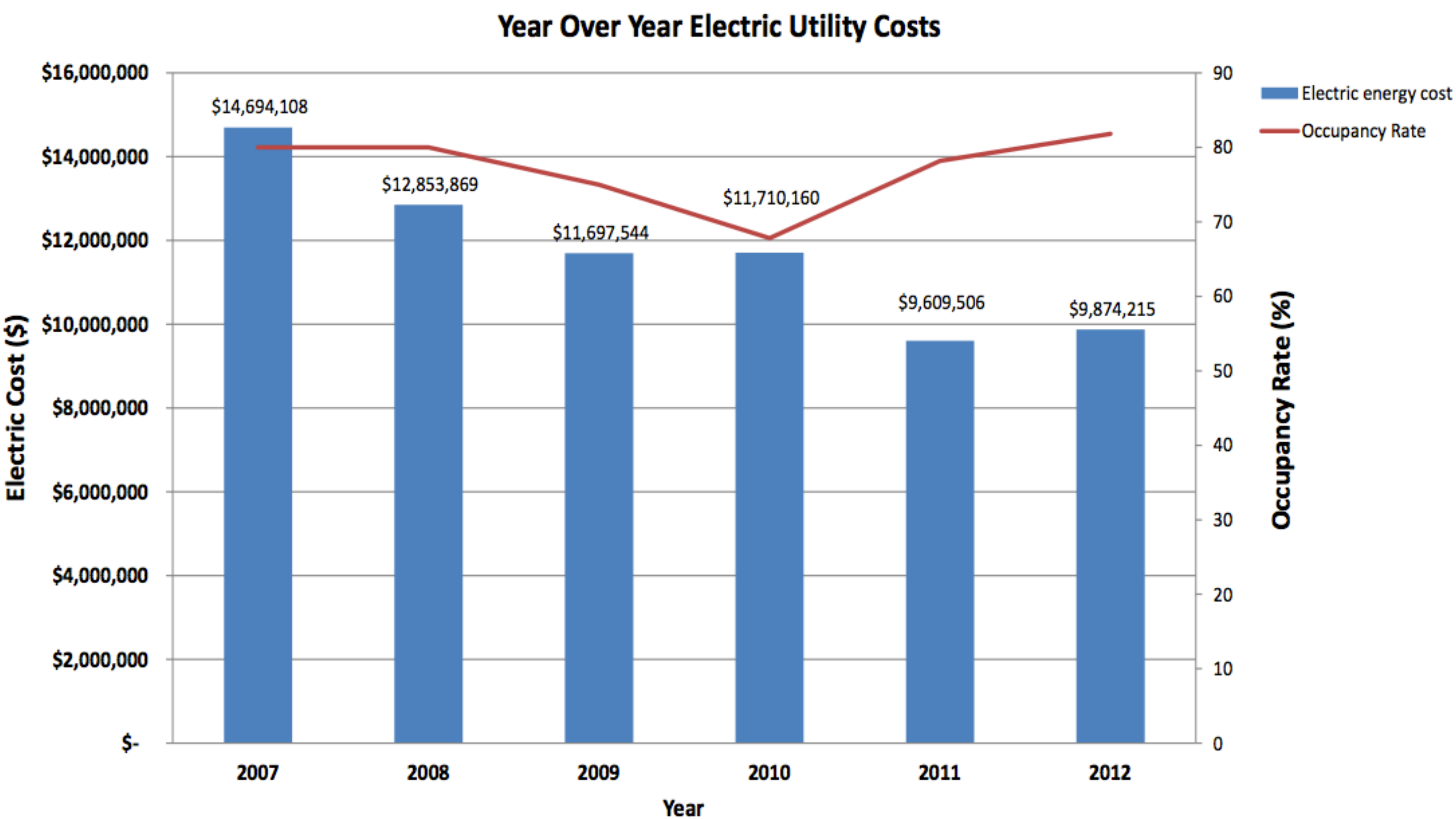
Measured performance in the Empire State Building



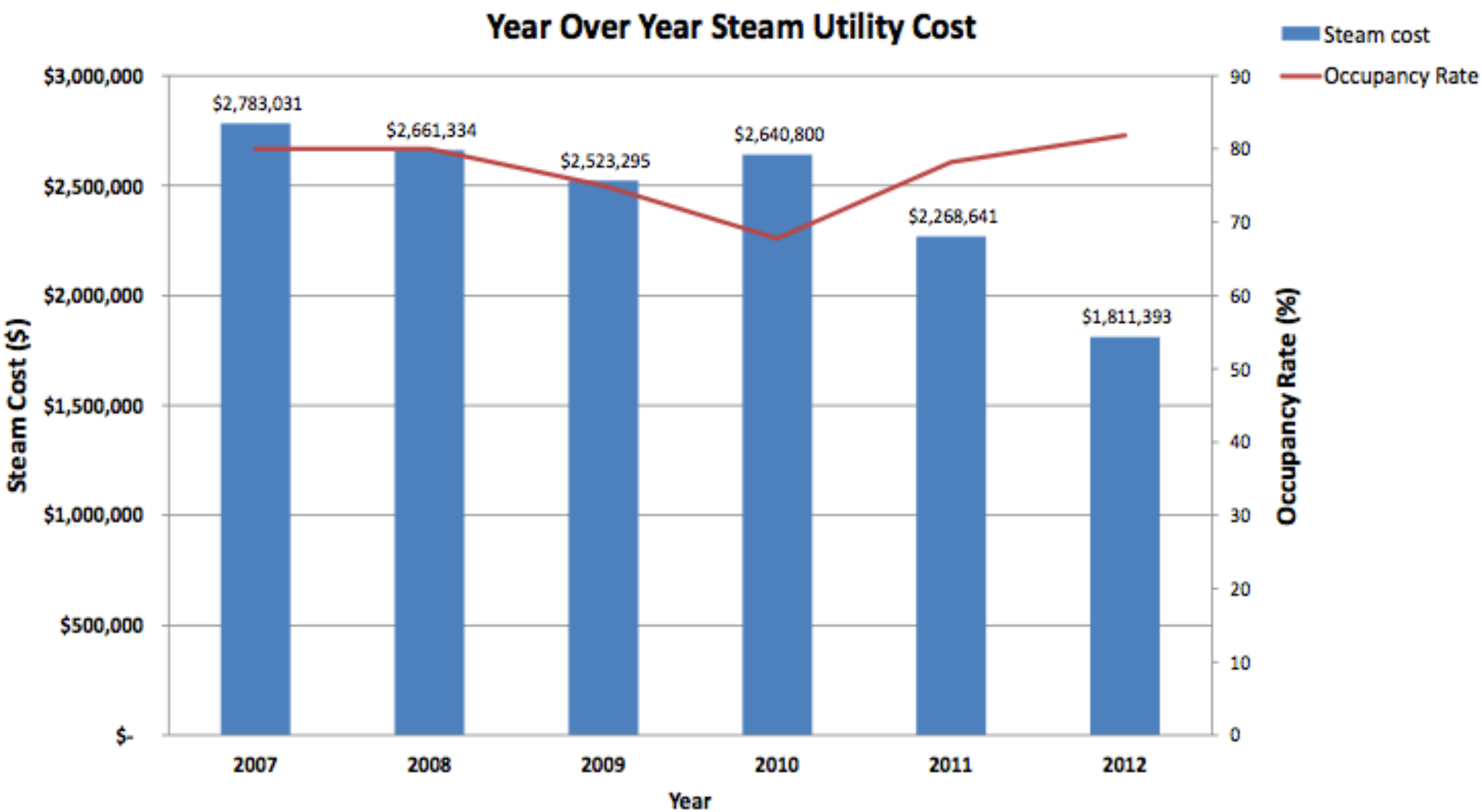
Measured performance in the Empire State Building



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 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