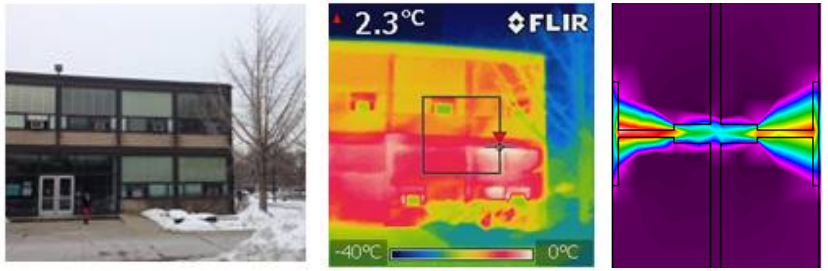
CAE 331/513 Building Science

Fall 2019



November 21, 2019

Energy efficient building design

Built Environment Research @ IIT

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

www.built-envi.com

Twitter: @built_envi

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Illinois Institute of Technology

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Last time and today

Last time:

- Demonstrated BEopt and EnergyPlus for load calculations and energy simulation

Today:

- Hand back HW 5
- HW 6 due today (will accept until Tuesday Nov 26)
- Energy efficient building design

BUILDING ENERGY USE DATA

Energy use intensity (EUI)

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

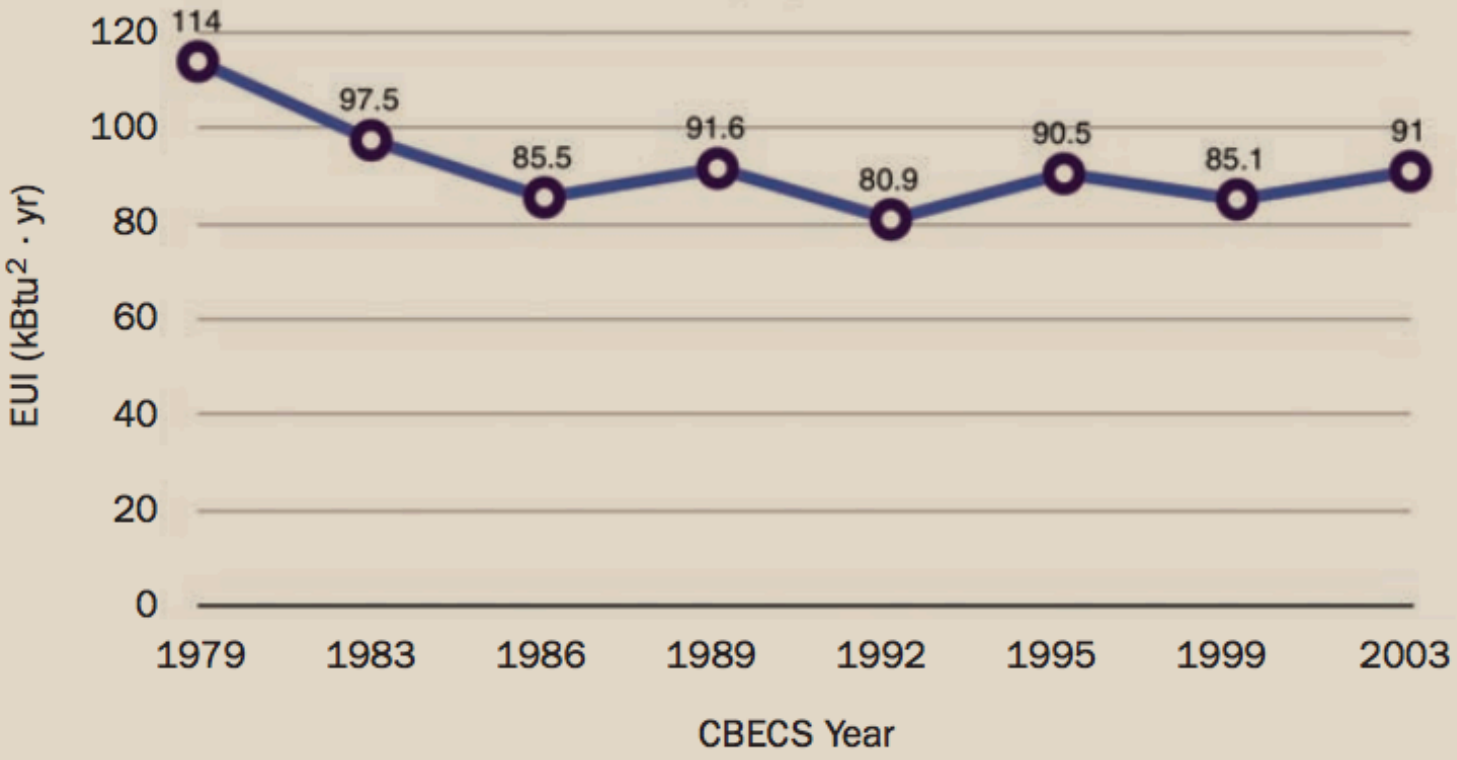
$$\frac{\text{Annual Building Energy Use (kBtus or MJ)}}{\text{Building Area } (ft^2 \text{ or } m^2)} = \text{EUI}$$

- Can be calculated on a source (primary) or site (secondary) energy basis

- Has EUI been increasing or decreasing in the U.S.?

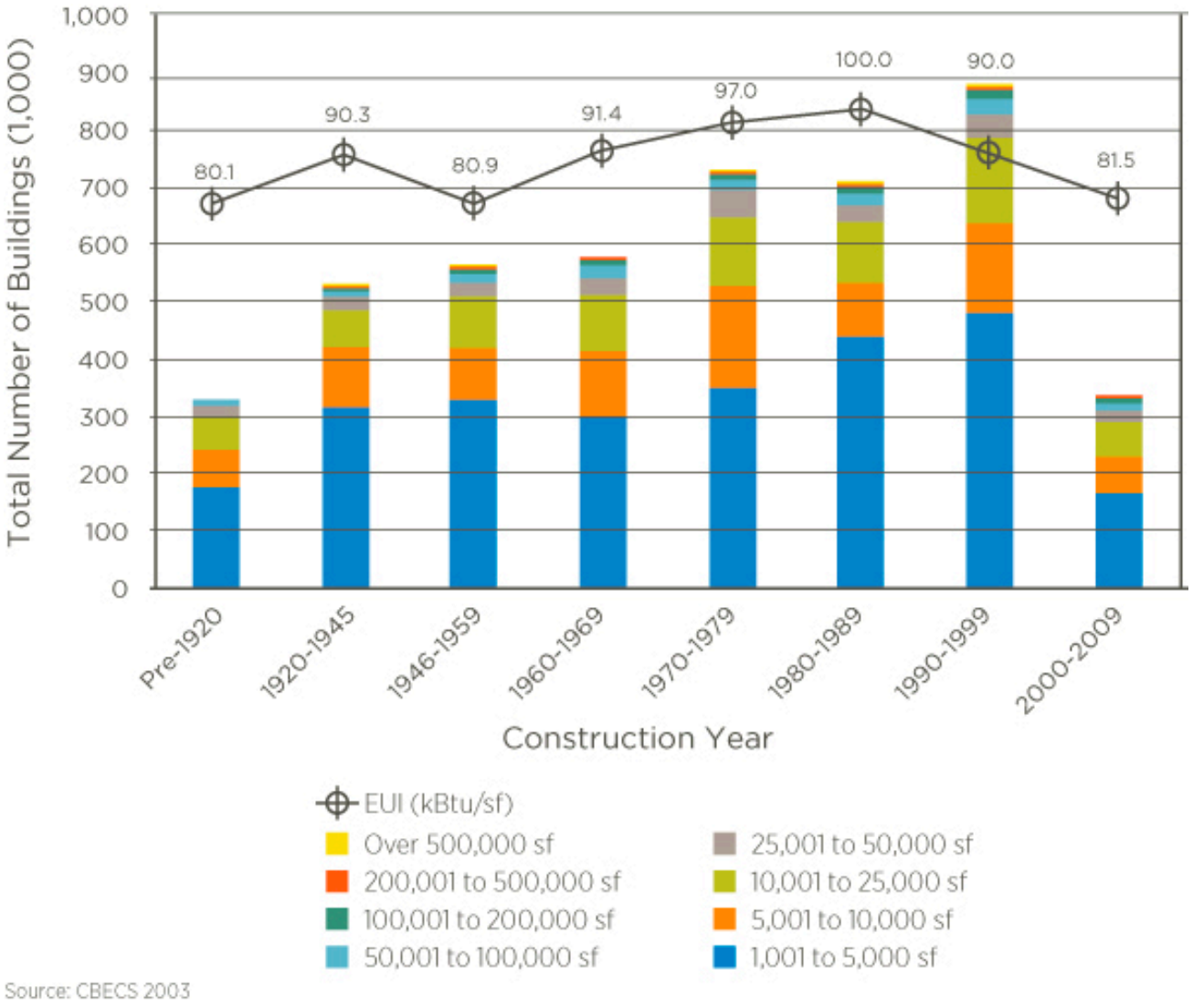
Energy use intensity (EUI)

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



Energy Information Administration
Commercial Buildings Energy Consumption Survey

Energy use intensity (EUI) – by building size/vintage



Source: CBECS 2003

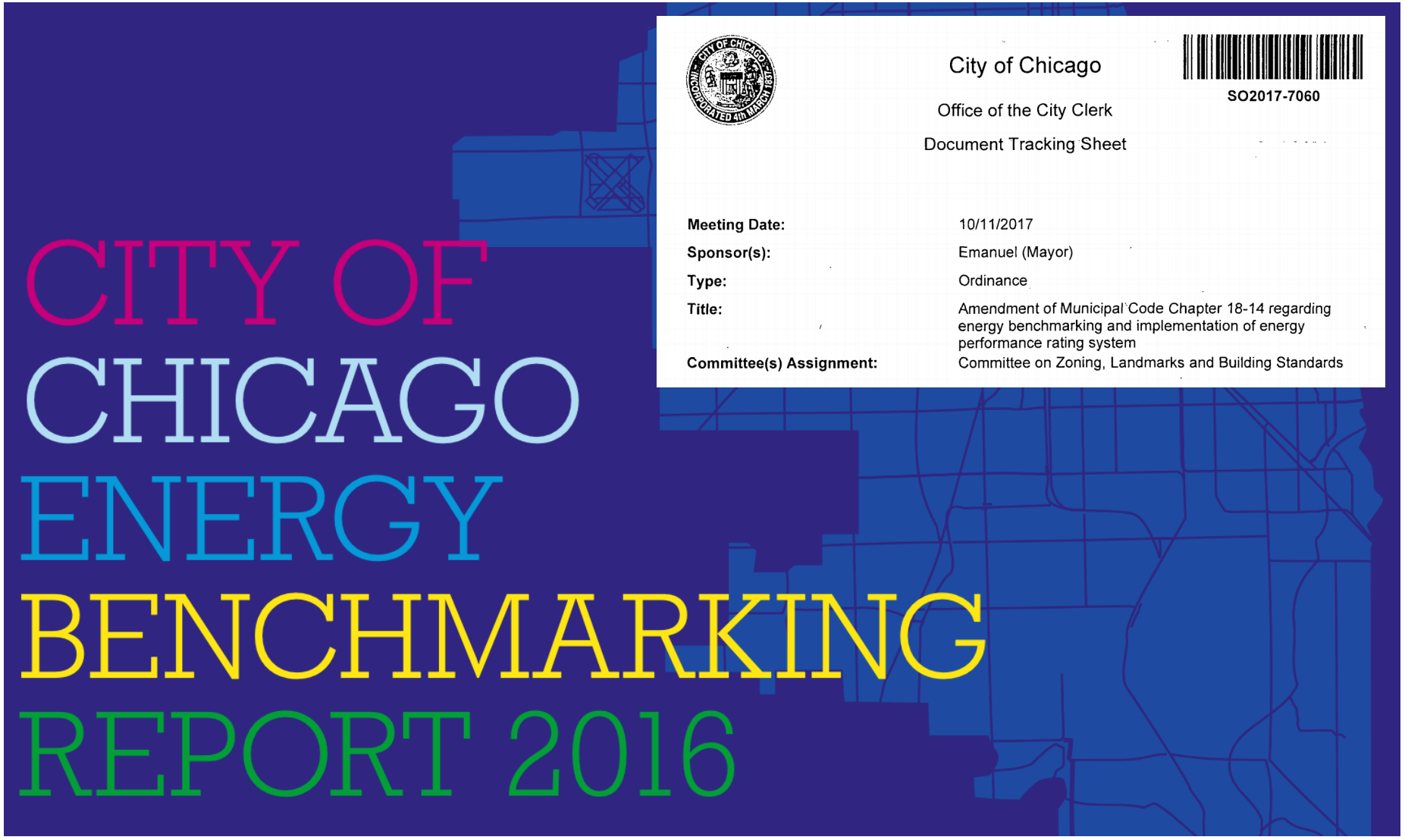
https://www.buildings.com/article-details/articleid/16360/title/eui-of-u-s-buildings-by-size-and-vintage

Energy use intensity (EUI) – by building type

Market Sector	Property type	Source EUI (kBtu/ft2)	Site EUI (kBtu/ft2)
Banking/Financial Services	Bank Branch	209.9	88.3
Banking/Financial Services	Financial Office	116.4	52.9
Education	College/University	180.6	84.3
Education	K-12 School	104.4	48.5
Education	Pre-school/Daycare	131.5	64.8
Education	Vocational School/Adult Education	110.4	52.4
Public Assembly	Convention Center/Meeting Hall	109.6	56.1
Public Assembly	Recreation/Athletic Centers	112.0	50.8
Public Assembly	Entertainment	112.0	56.2
Public Assembly	Worship Facility	58.4	30.5
Food Sales & Service	Convenience Store	592.6	231.4
Food Sales & Service	Bar/Nightclub	297	130.7
Food Sales & Service	Fast Food Restaurant	886.4	402.7
Food Sales & Service	Restaurant	573.7	325.6
Food Sales & Service	Supermarket/Grocery Store	444	196
Food Sales & Service	Wholesale Club/Supercenter	120	51.4
Healthcare	Ambulatory Surgical Center	138.3	62.0
Healthcare	Hospital (General Medical & Surgical)	426.9	234.3
Healthcare	Other/Specialty Hospital	433.9	206.7
Healthcare	Medical Office	121.7	51.2
Healthcare	Outpatient Rehabilitation/Physical Therapy	138.3	62.0
Healthcare	Urgent Care/Clinic/Other Outpatient	145.8	64.5
Lodging/Residential	Barracks	107.5	57.9
Lodging/Residential	Hotel	146.7	63.0
Lodging/Residential	Multifamily Housing	118.1	59.6
Lodging/Residential	Prison/Incarceration	156.4	69.9
Lodging/Residential	Residence Hall/Dormitory	107.5	57.9
Lodging/Residential	Residential Care Facility	213.2	99.0
Mixed Use	Mixed Use Property	89.3	40.1
Office	Medical Office	121.7	51.2
Office	Office	116.4	52.9
Office	Veterinary Office	145.8	64.5

https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager/understand-metrics/what-energy

Energy use intensity (EUI) – Chicago



https://www.chicago.gov/city/en/depts/mayor/supp_info/chicago-energy-benchmarking/Chicago_Energy_Benchmarking_Reports_Data.html

Energy use intensity (EUI) – Chicago

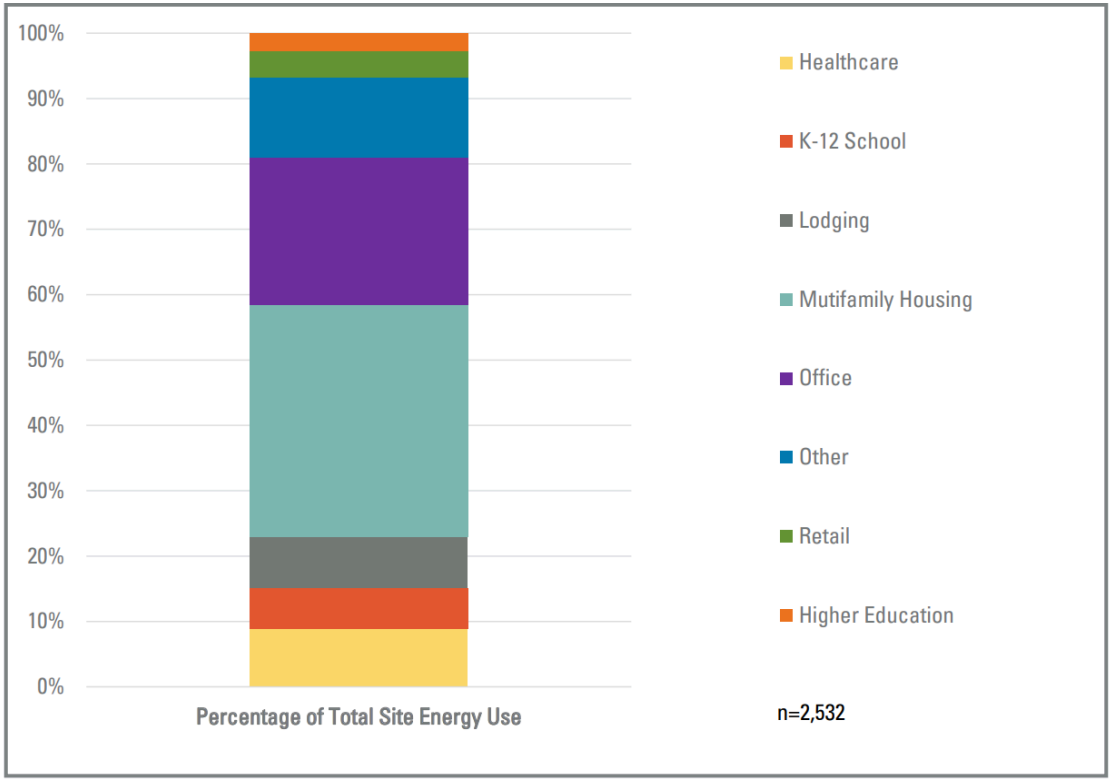
REACH

Under **Chicago Energy Benchmarking**, **88%** of large buildings reported energy use in **2018**, up from **85%** in **2017**.

https://www.chicago.gov/content/dam/city/progs/env/EnergyBenchmark/2018_Chicago_Energy_Benchmarking%20Report.pdf

Energy use intensity (EUI) – Chicago

Figure 5: Percentage of Site Energy Use by Property Type



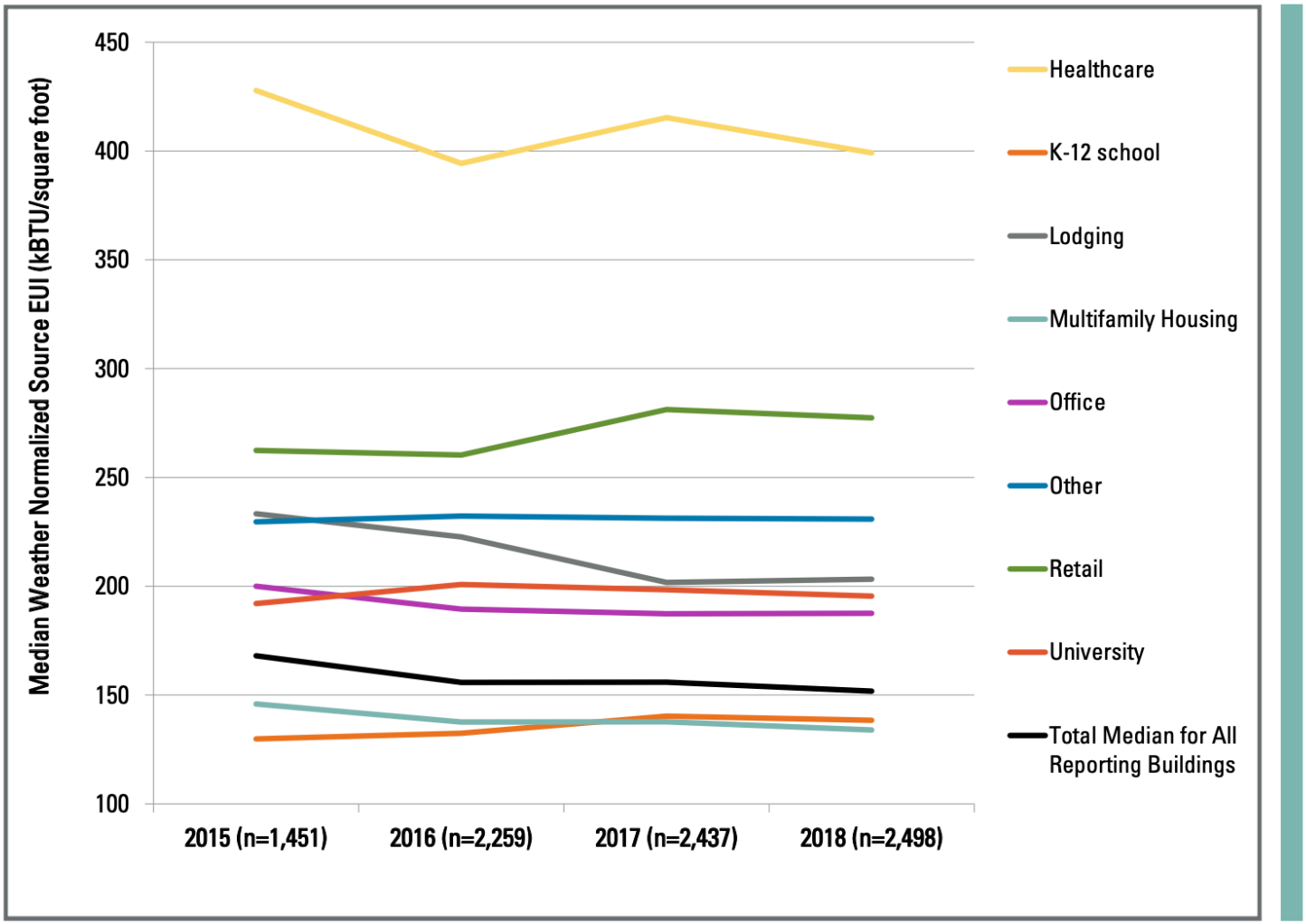
Download the data directly:

https://data.cityofchicago.org/Environment-Sustainable-Development/Chicago-Energy-Benchmarking-2017-Data-Reported-in-/j2ev-2azp

https://www.chicago.gov/content/dam/city/progs/env/EnergyBenchmark/2018_Chicago_Energy_Benchmarking%20Report.pdf

Energy use intensity (EUI) – Chicago

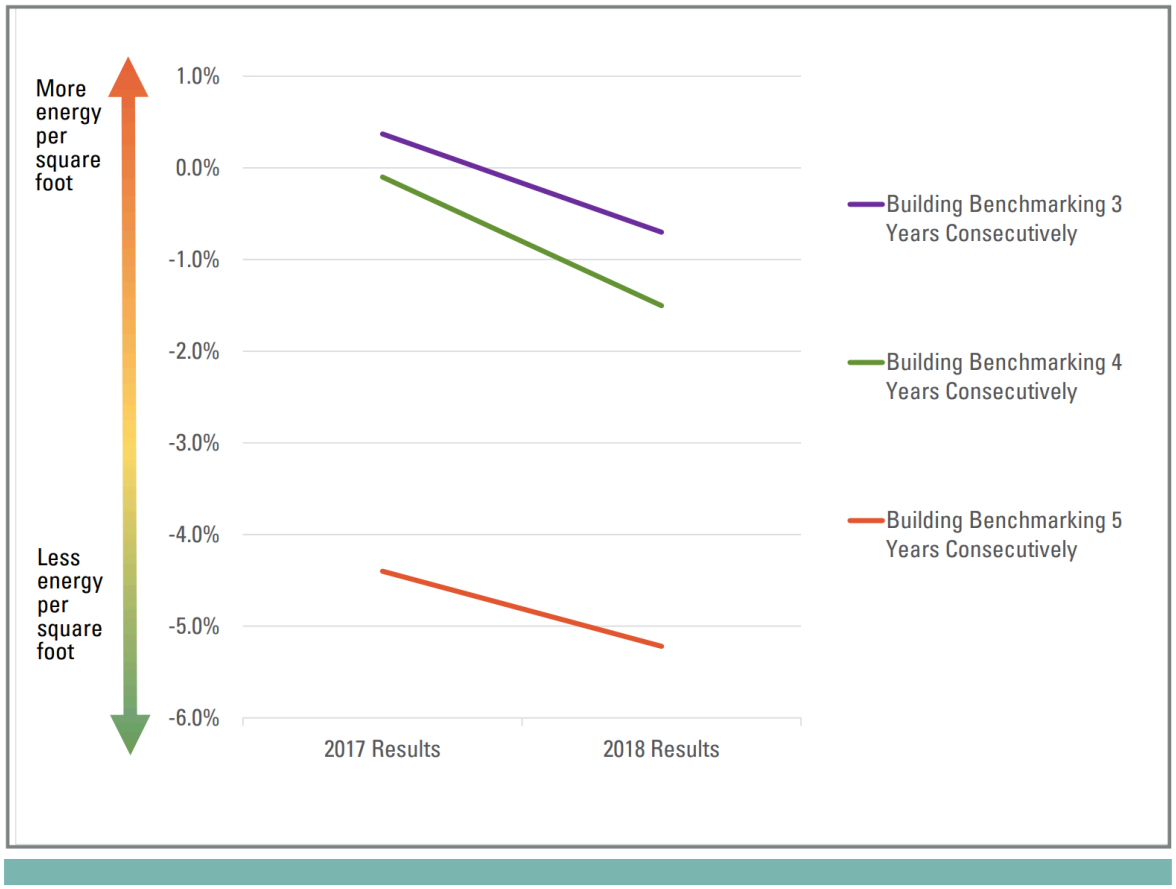
Figure 10: Median Source EUI from 2015 – 2018



https://www.chicago.gov/content/dam/city/progs/env/EnergyBenchmark/2018_Chicago_Energy_Benchmarking%20Report.pdf

Energy use intensity (EUI) – Chicago

Figure 8: Energy Reductions for Properties Benchmarking for Three or More Years Consecutively



https://www.chicago.gov/content/dam/city/progs/env/EnergyBenchmark/2018_Chicago_Energy_Benchmarking%20Report.pdf

DESIGNING FOR EFFICIENCY

Designing for efficiency

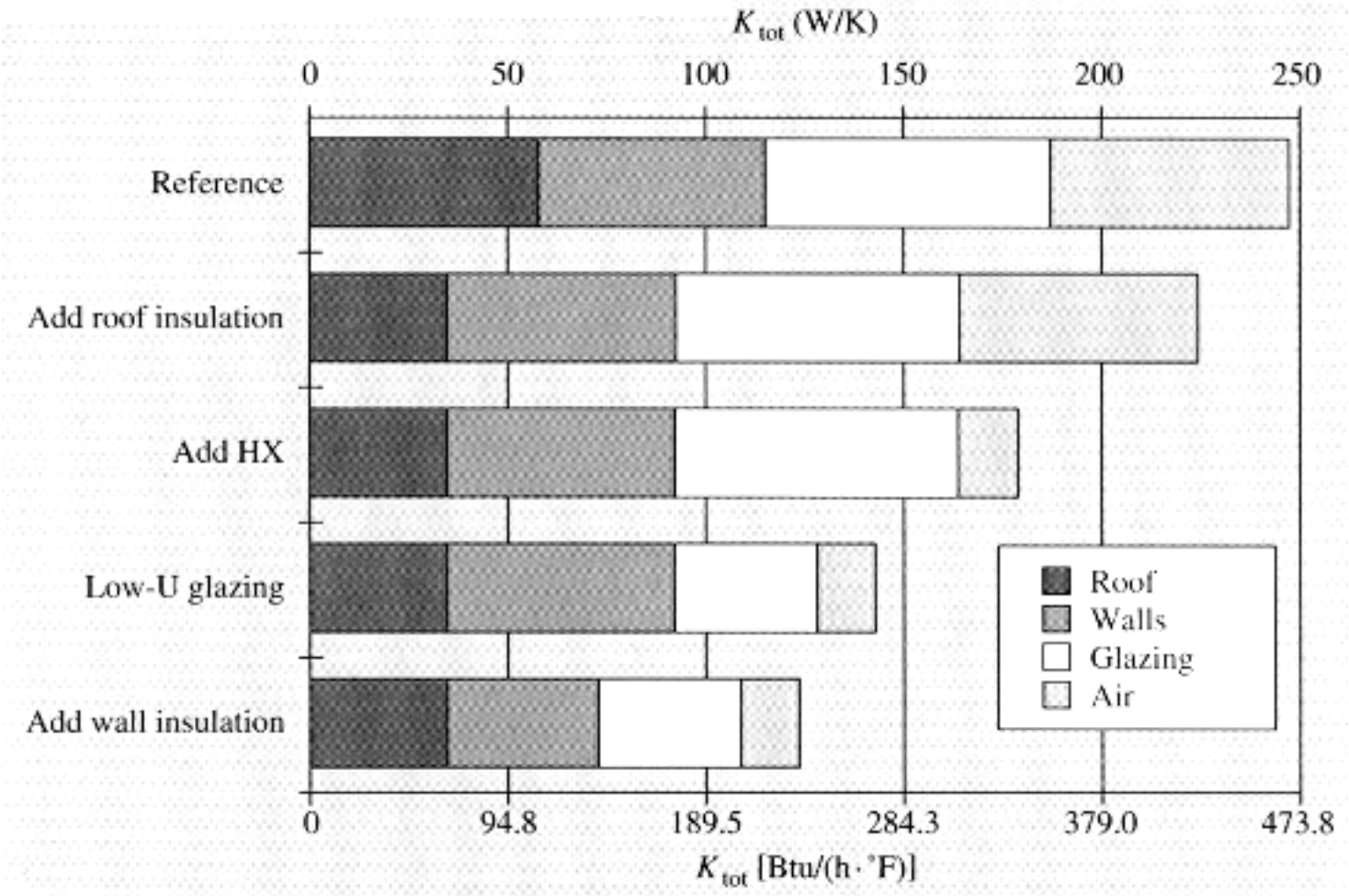
- We can't change outdoor conditions (e.g., temperature, solar radiation, or HDD and CDD)
  - So what can we do to reduce energy consumption?

- 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

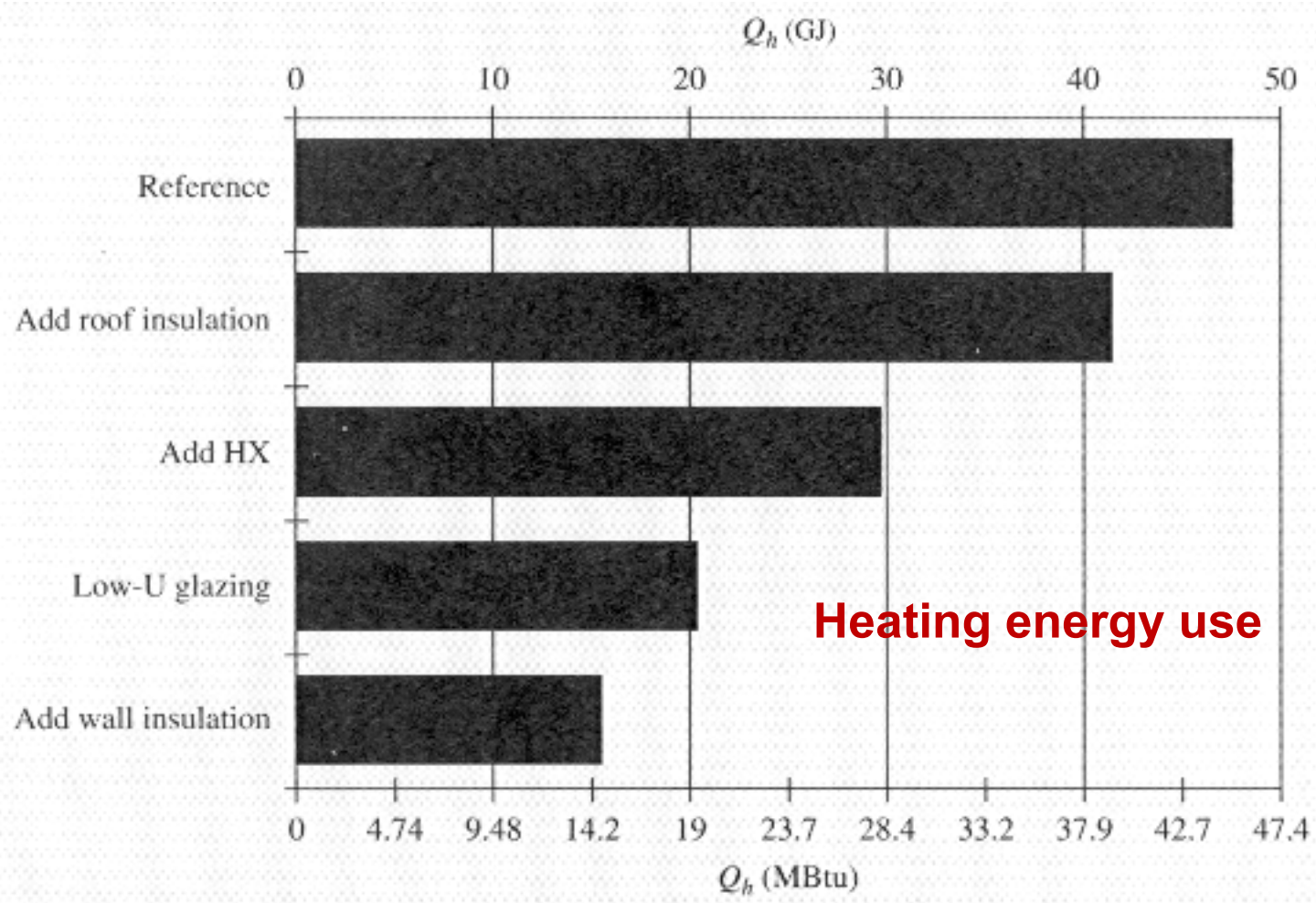
Parametric changes early in design phase

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



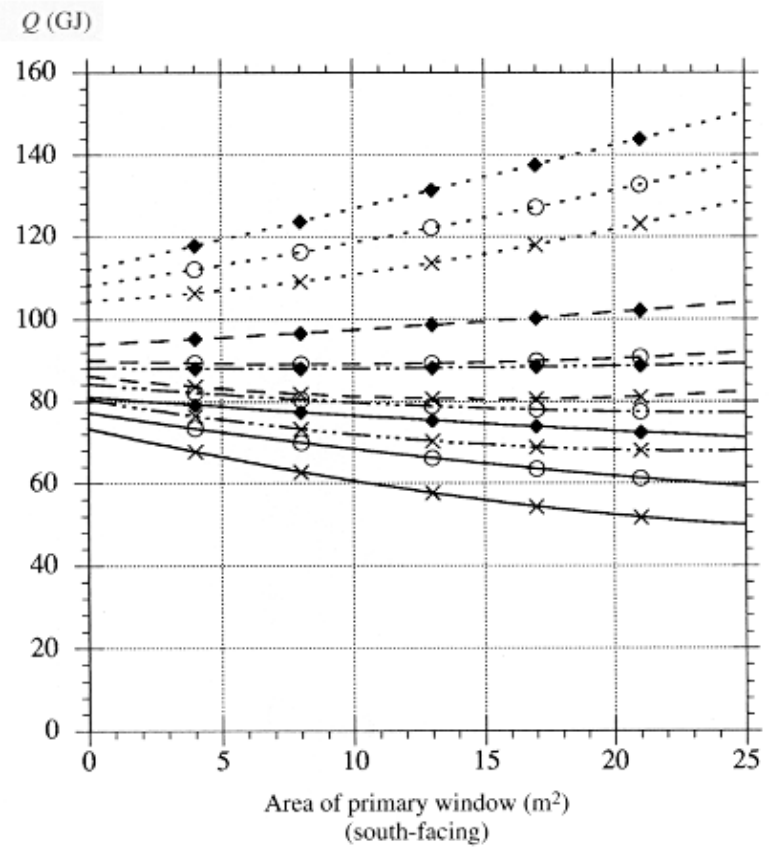
Parametric changes early in design phase

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

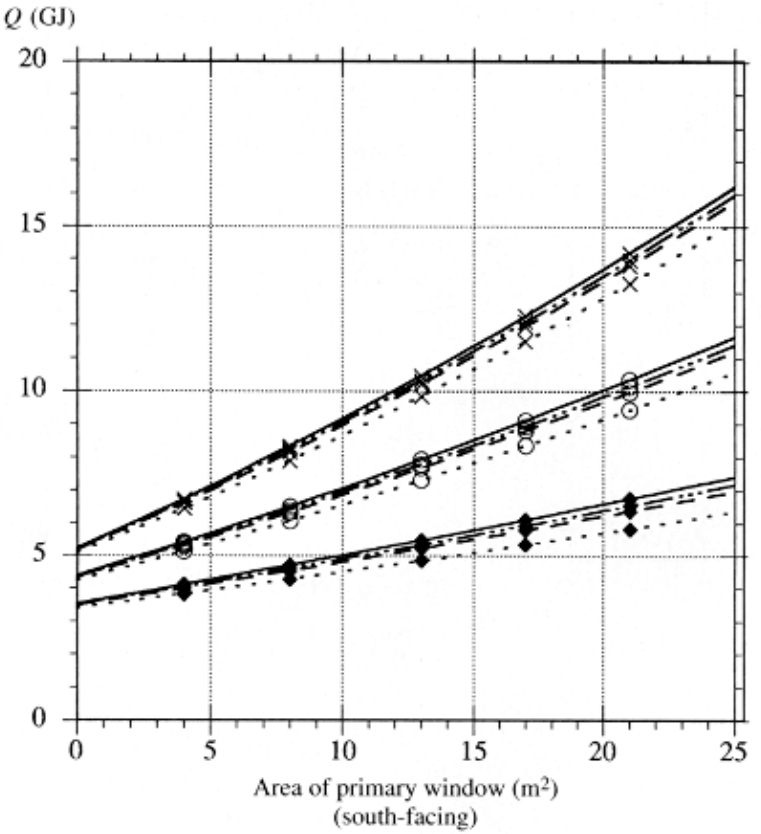


Parametric changes early in design phase

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



SC	U W/(m² · K) [Btu/(h · ft² · °F)]
1.0	5.713 (1.006)
1.0	2.675 (0.471)
1.0	1.715 (0.302)
1.0	0.534 (0.094)
0.7	5.713 (1.006)
0.7	2.675 (0.471)
0.7	1.715 (0.302)
0.7	0.534 (0.094)
0.4	5.713 (1.006)
0.4	2.675 (0.471)
0.4	1.715 (0.302)
0.4	0.534 (0.094)

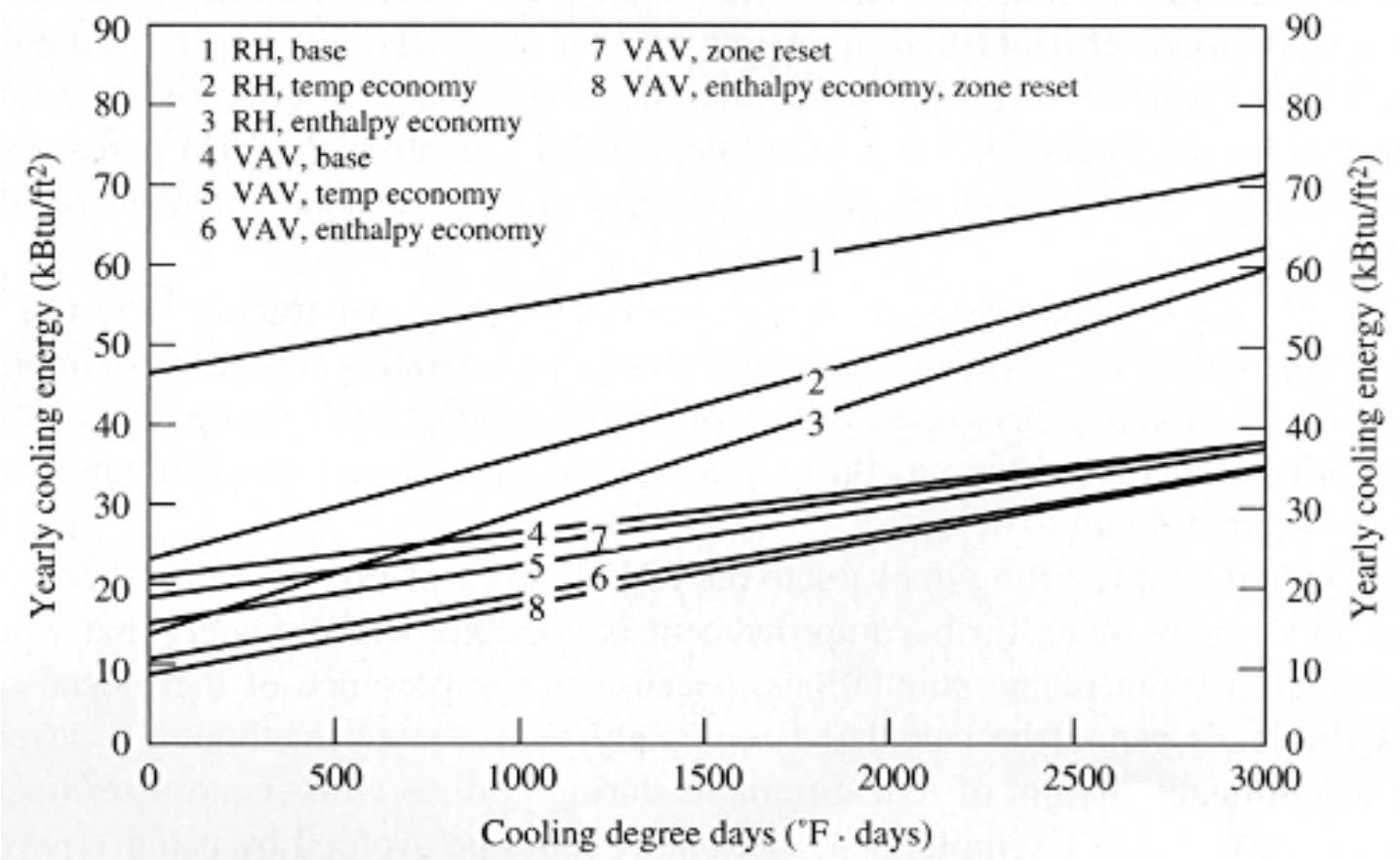


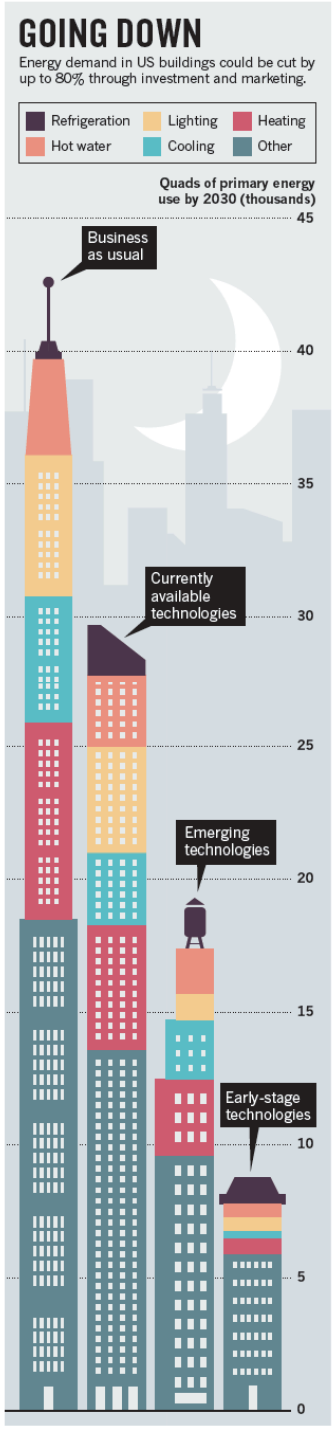
Heating

Cooling

Parametric changes early in design phase

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





Paths toward *lower energy* buildings

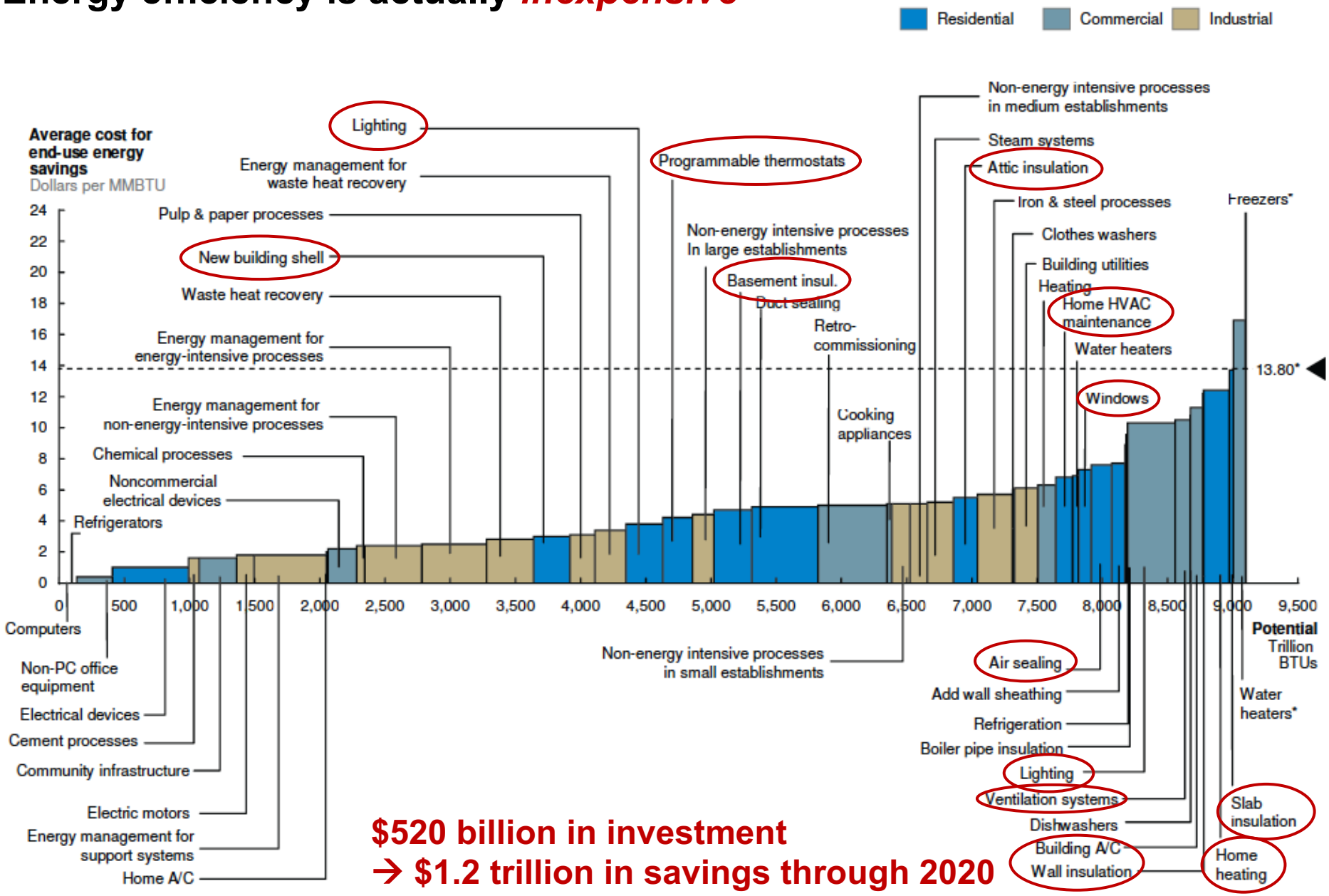
- Efficient building ***systems***
  - Mechanical systems
  - Mechanical driving forces
  - Controls and equipment

- ***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*

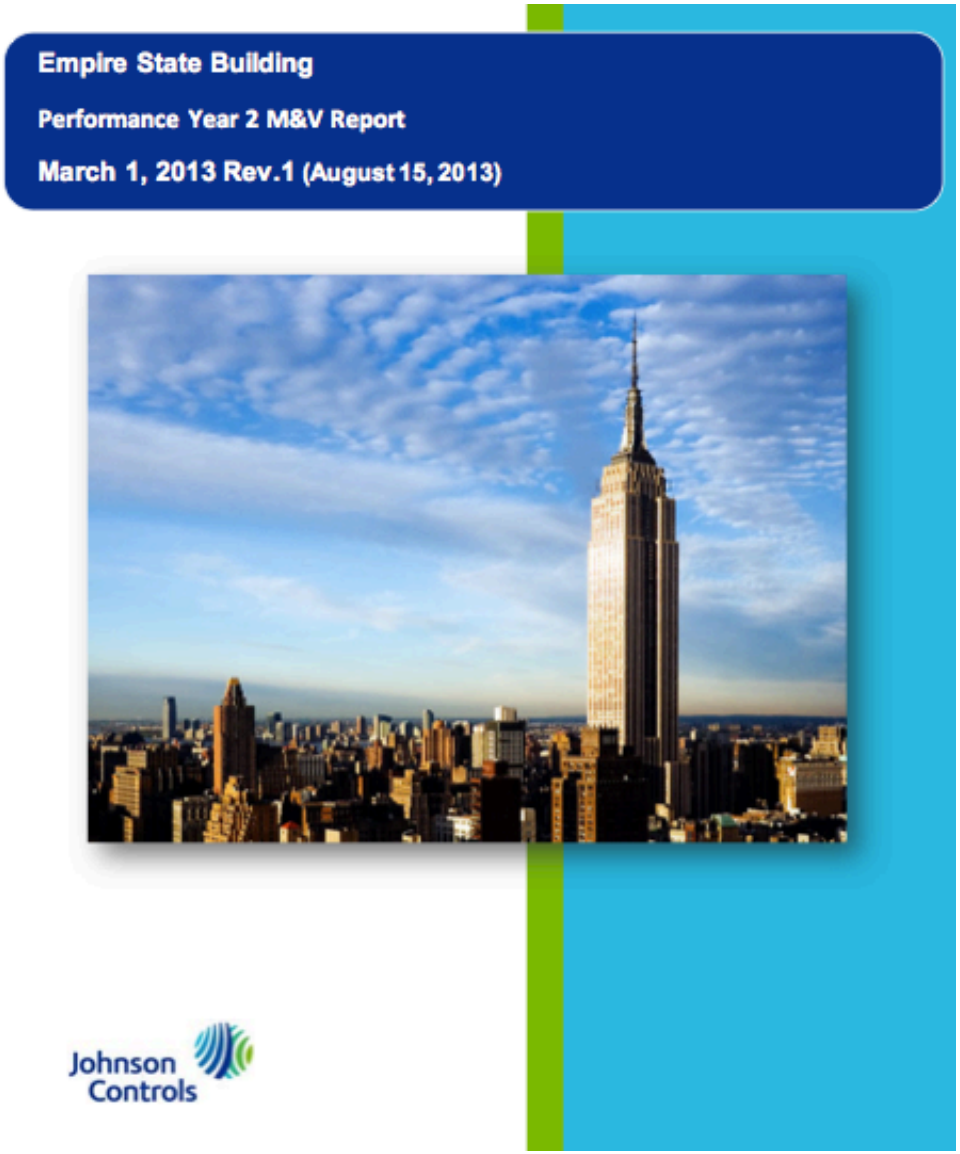


$520 billion in investment
→ $1.2 trillion in savings through 2020

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

Energy savings in commercial buildings: Example

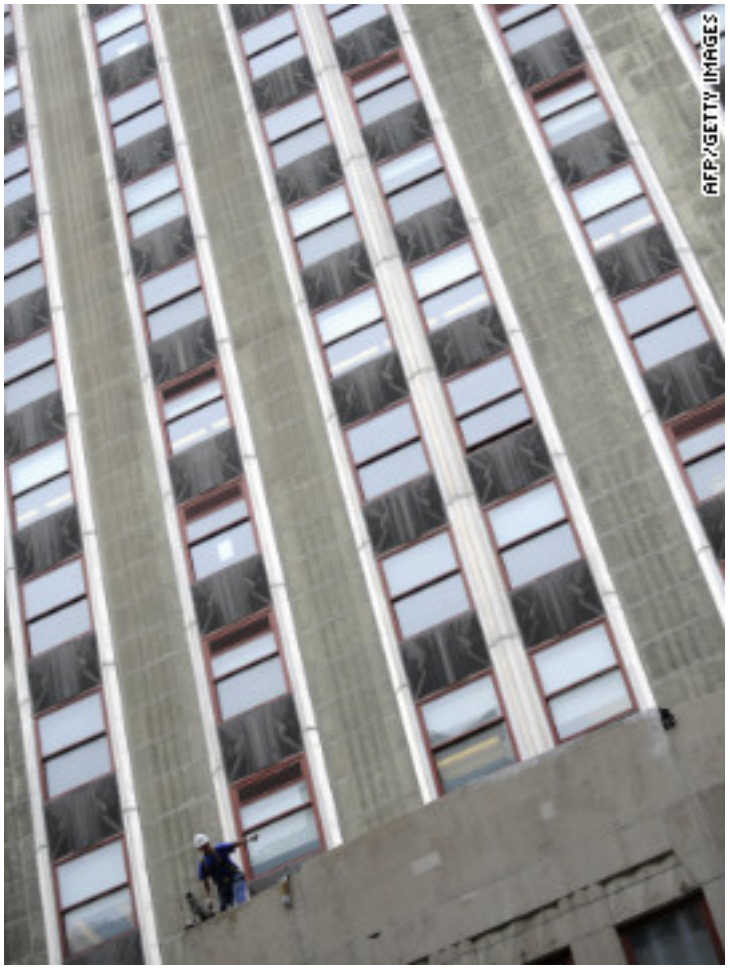
- Empire State Building
  - New York, NY
- Implemented 5 energy conservation measures (ECMs) in 2011
  - Window retrofit
  - Radiator insulation and steam traps
  - Building automation system
  - Chiller retrofit
  - Tenant energy management
- Collected data and compared modeled savings versus measured



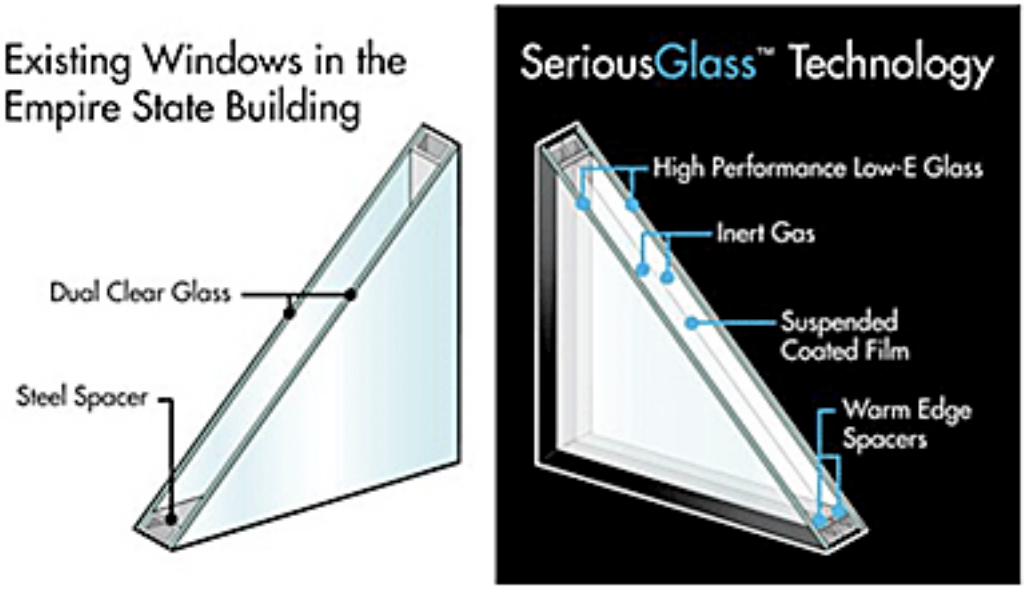
ECMs in the Empire State Building

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

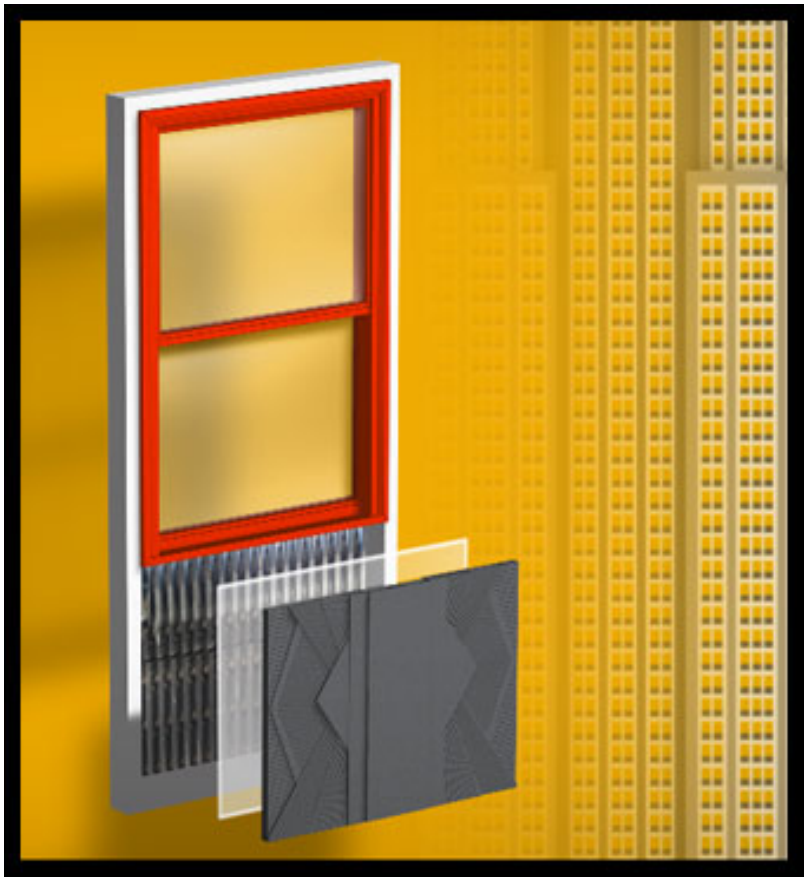
ECMs in the Empire State Building

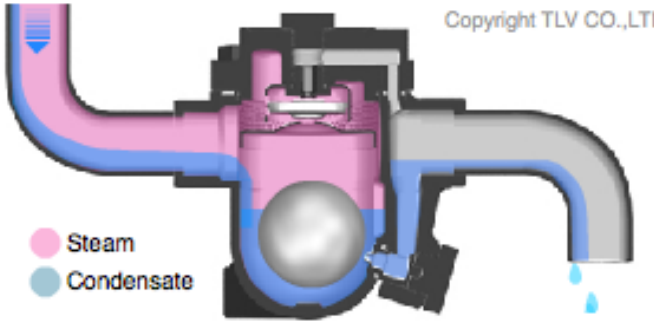
Radiator system

- 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”





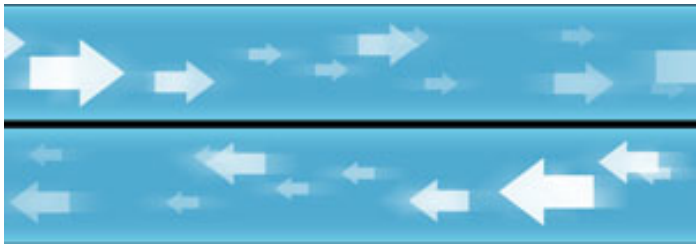
ECMs in the Empire State Building

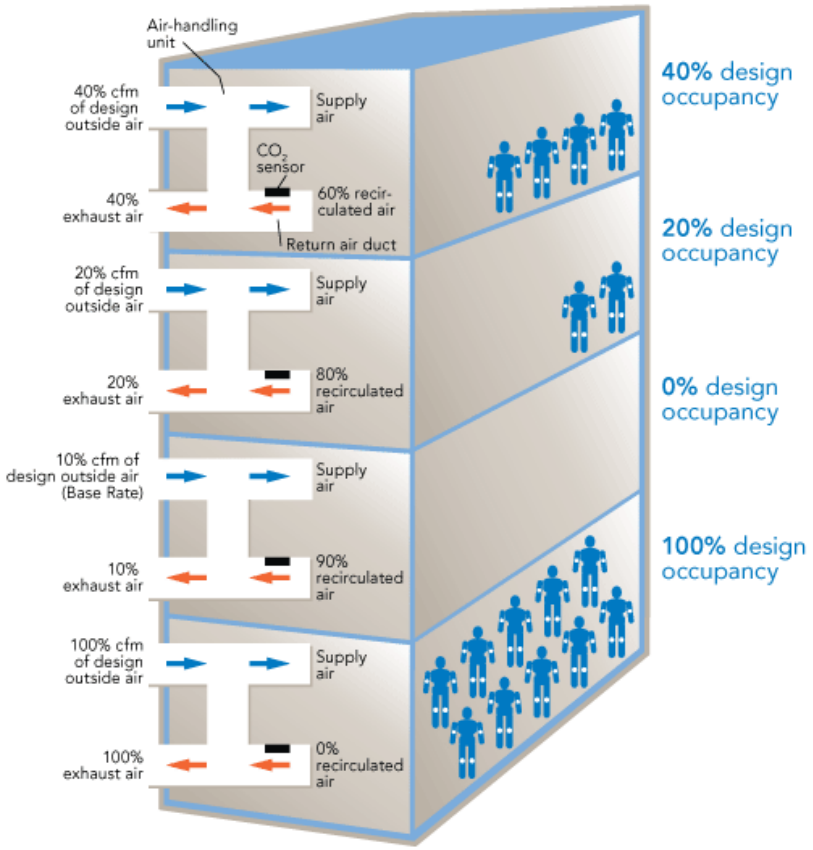
ECMs in the Empire State Building

Building automation system (BAS)

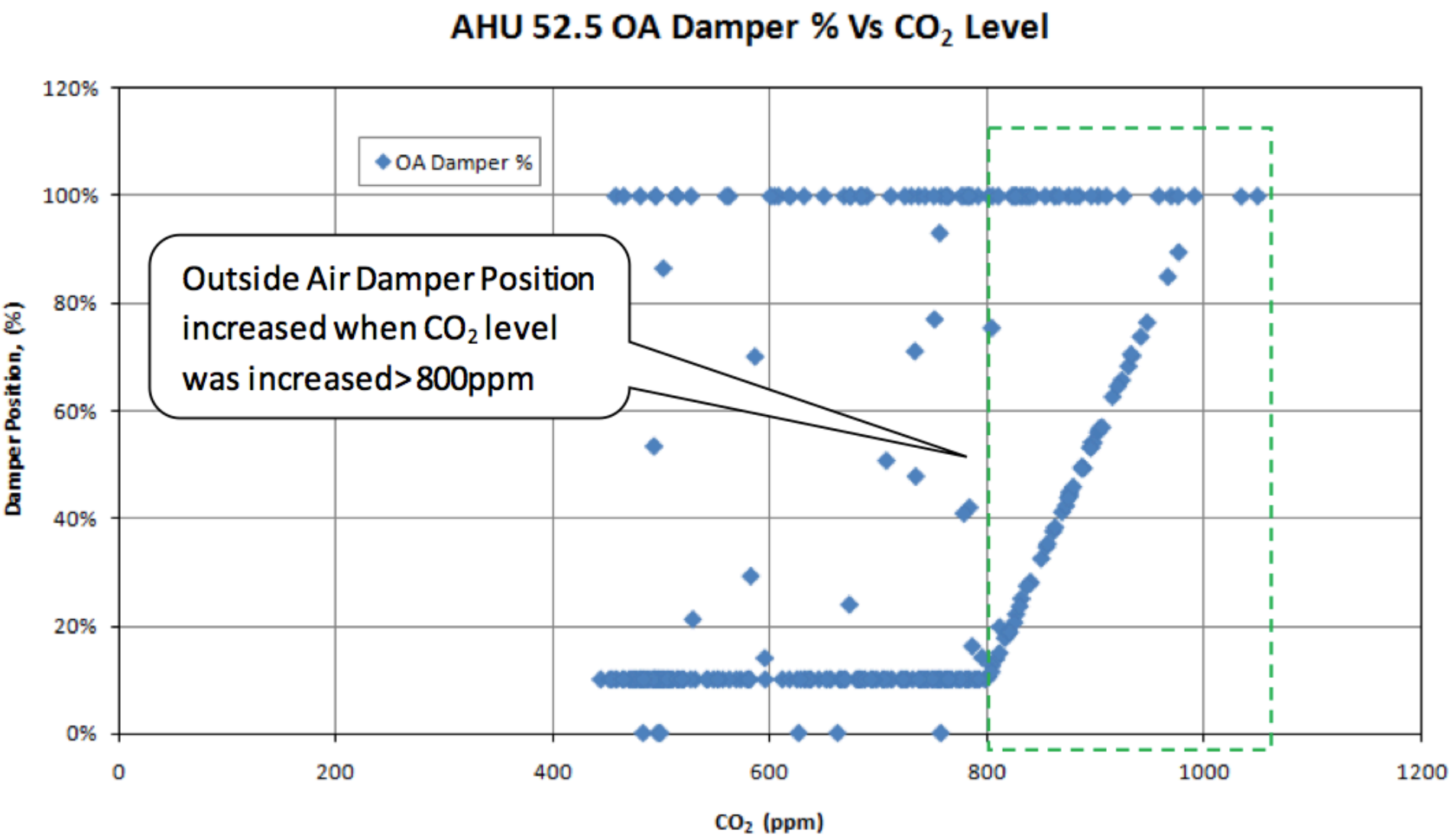
- Reduced overall outdoor air intake by using “demand controlled ventilation” (DCV) and modulating dampers
  - Uses CO_2 to measure occupancy

- 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.

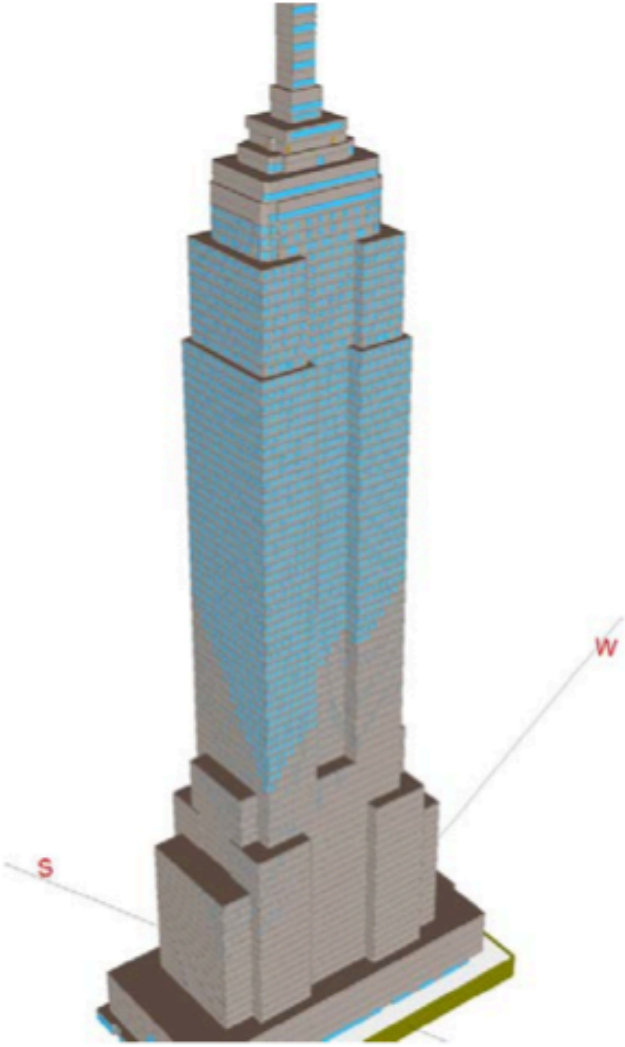
Energy simulation to predict costs and GHG savings

eQUEST Model Setup Overview

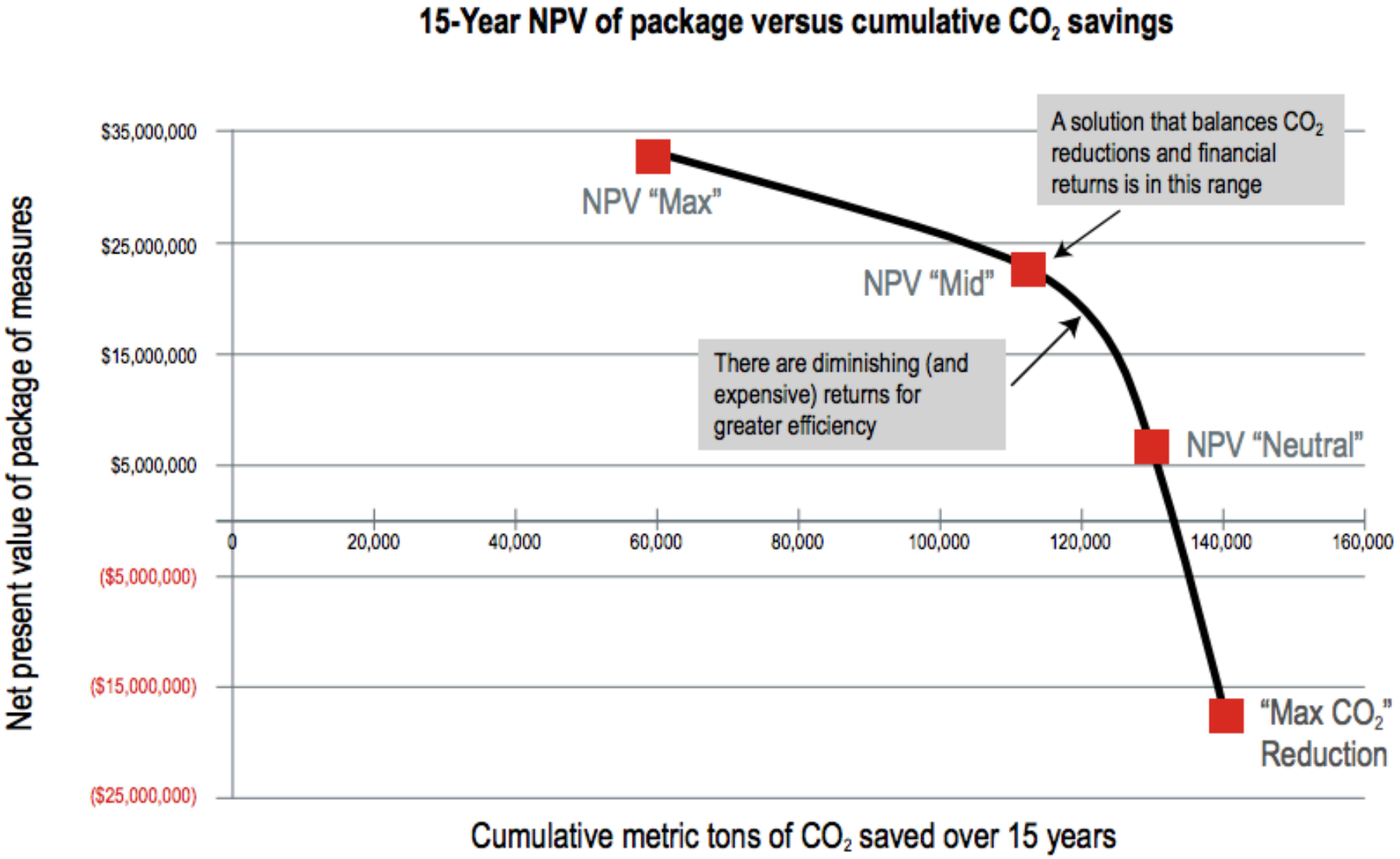
Modeling Software	eQUEST v3.64, build 7130
Model Author	Quest Energy Group, LLC 1620 W Fountainhead Pkwy #303 Tempe, AZ 85282 +1 480 467 2480

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



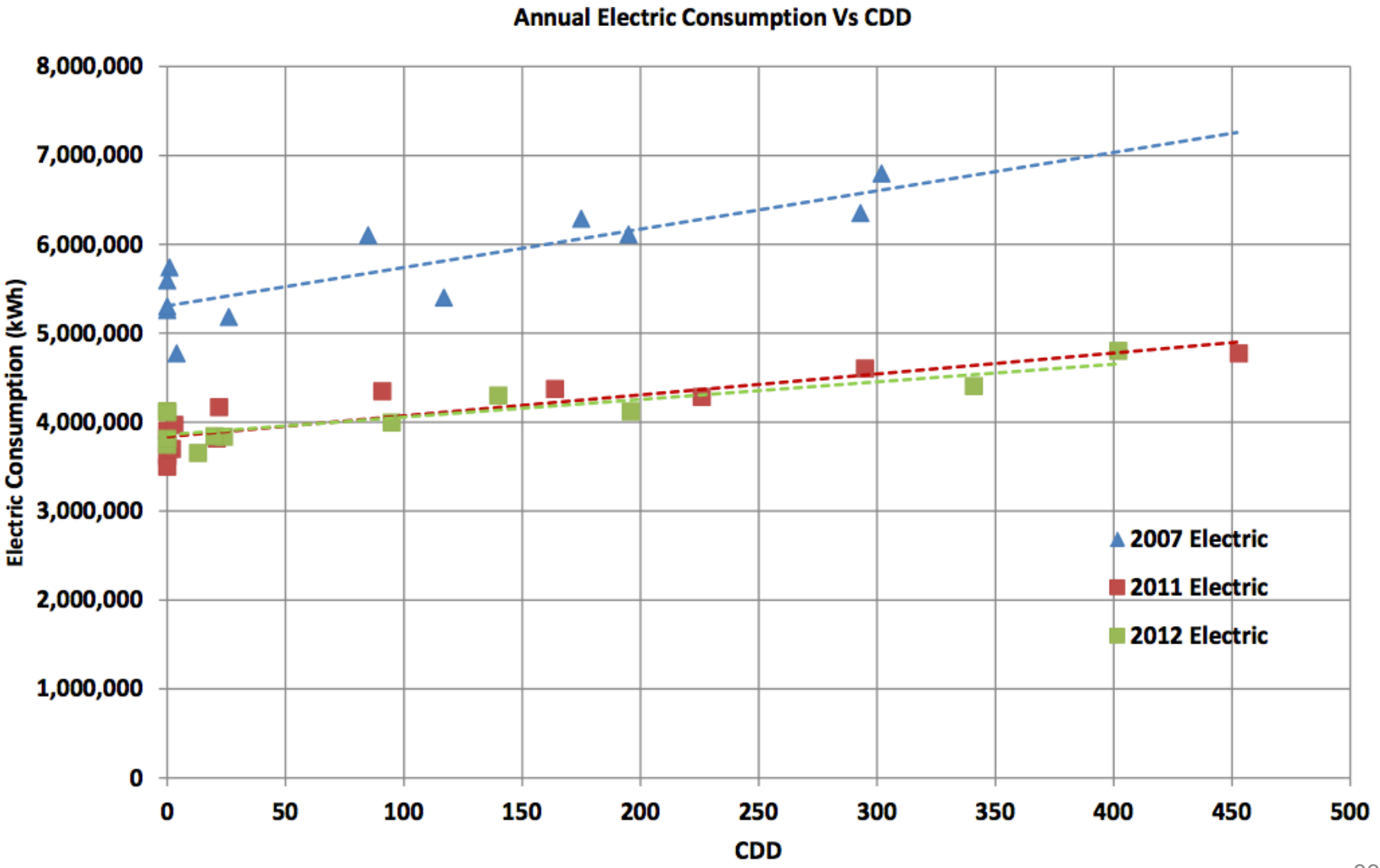
http://www.buildingefficiencyinitiative.org/sites/default/files/legacy/InstituteBE/media/Library/Resources/Existing-Building-Retrofits/ESB-White-paper.pdf

Predicted costs and savings in the ESB

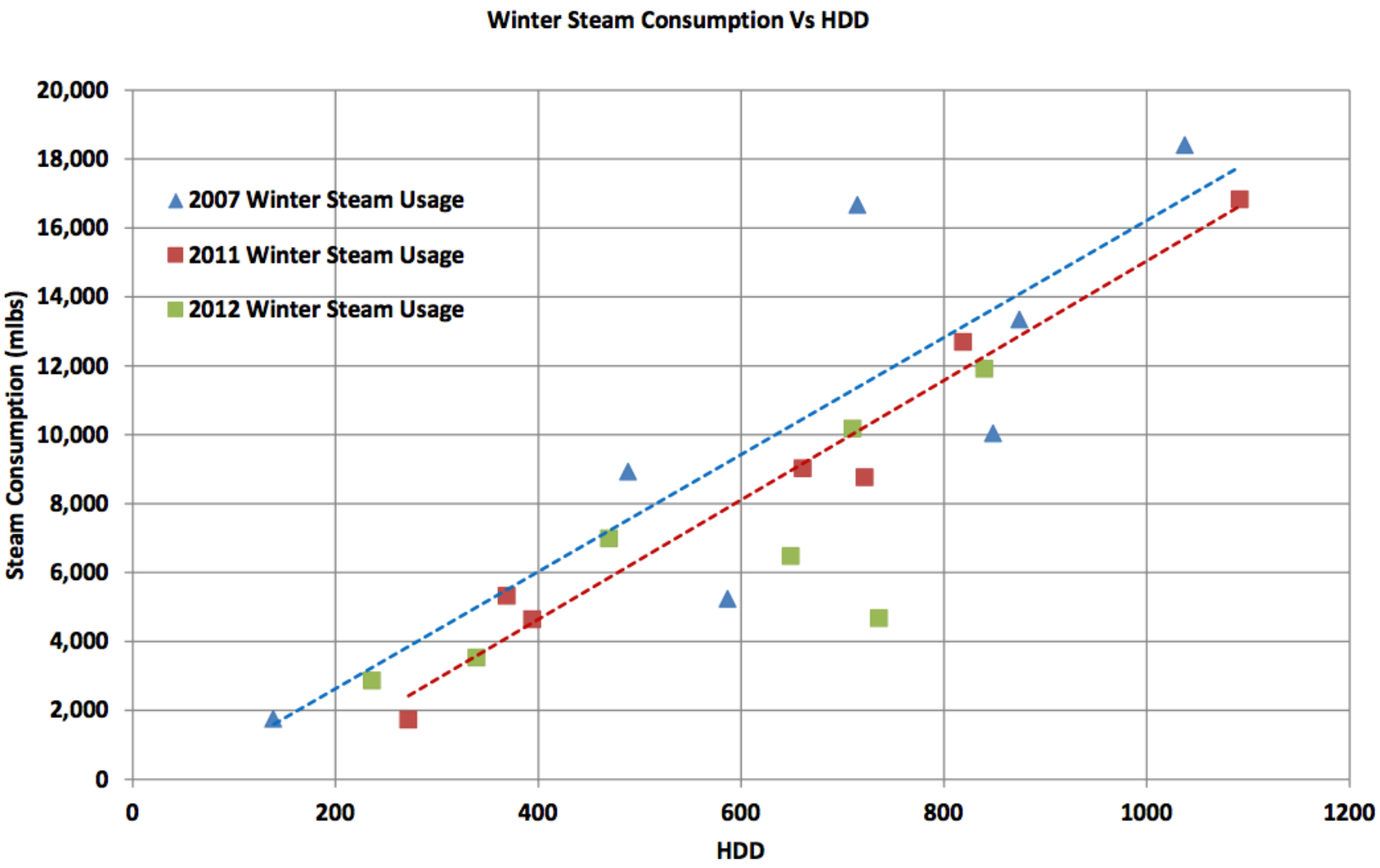
Project Description	*Projected Capital Cost*	*2008 Capital Budget*	*Incremental Cost*	*EstimatedAnnual Energy Savings**
Windows	$4.5m	$455k	$4m	$410k
Radiative Barrier	$2.7m	$0	$2.7m	$190k
DDC Controls	$7.6m	$2m	$5.6m	$741k
Demand Control Vent	Inc. above	$0	Inc. above	$117k
Chiller Plant Retrofit	$5.1m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

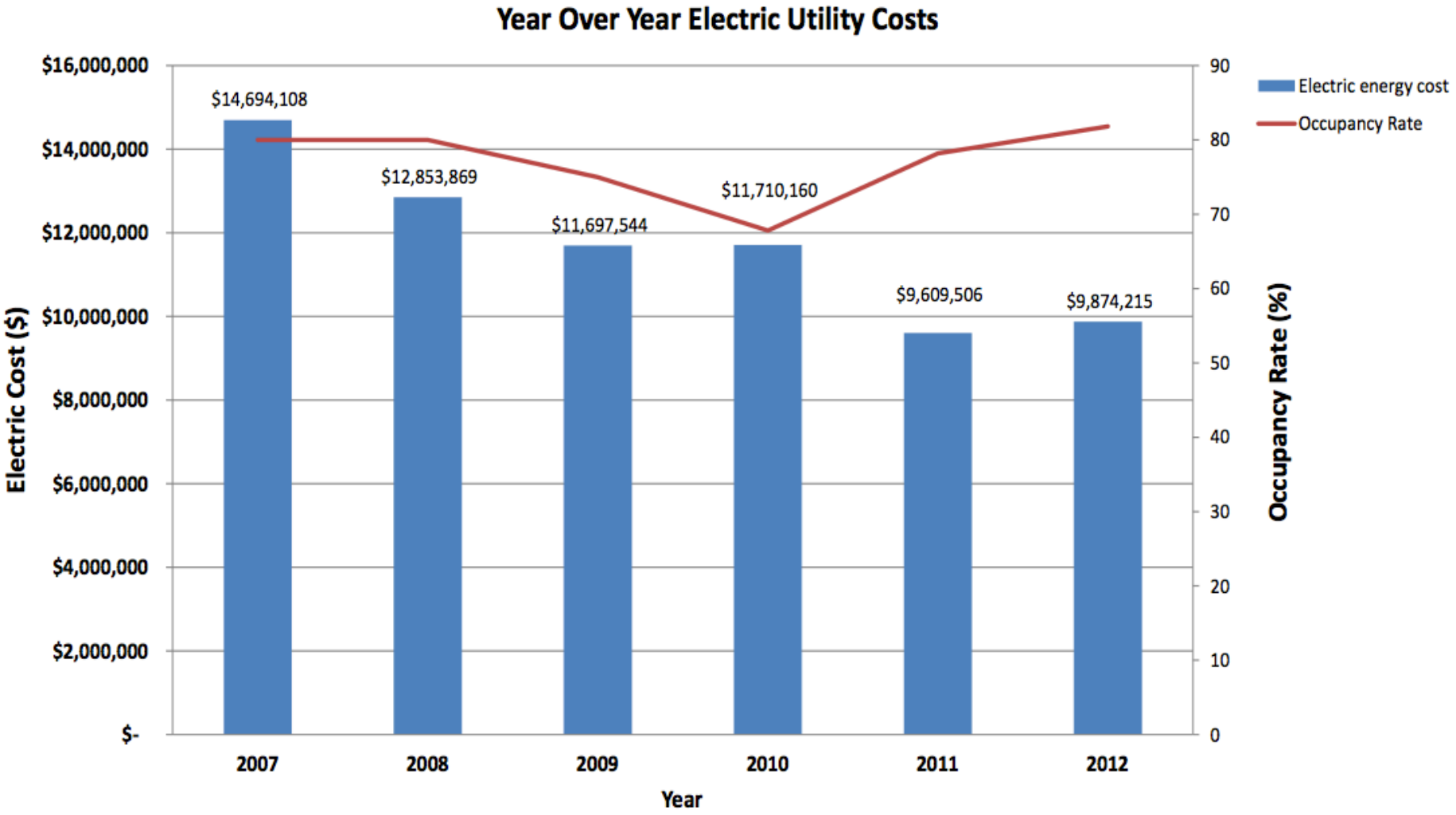
Measured performance in the Empire State Building



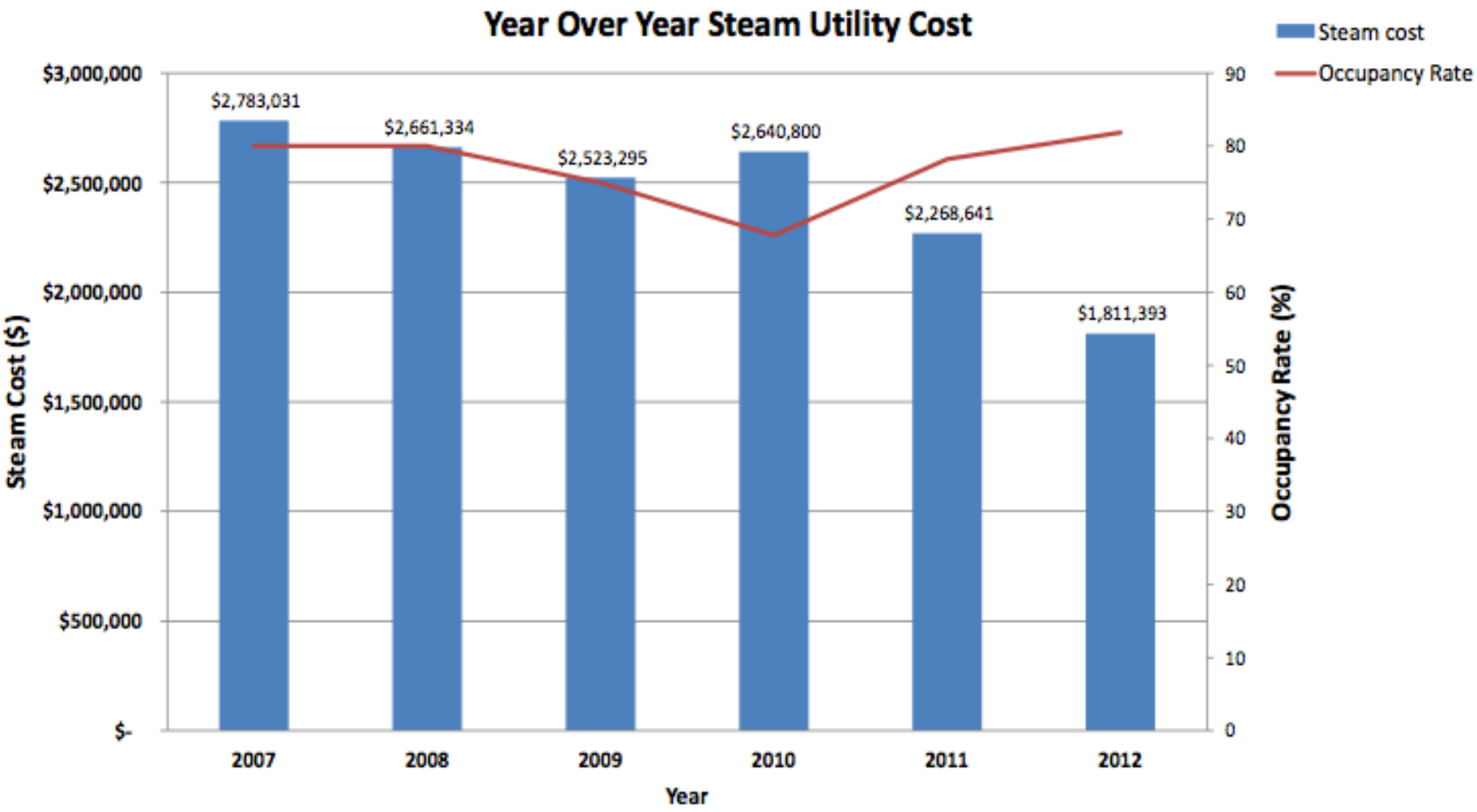
Measured performance in the Empire State Building



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!**

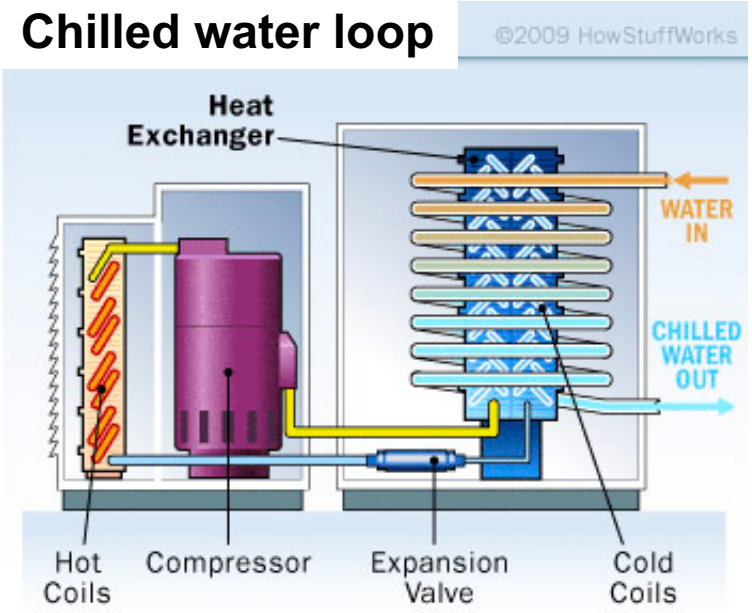
- For building science, we now understand enough fundamental concepts to drive lower-energy buildings
  - Basic building physics
  - HVAC loads
  - Internal gains
  - HVAC equipment efficiency
- Building energy simulation can drive **decision making**

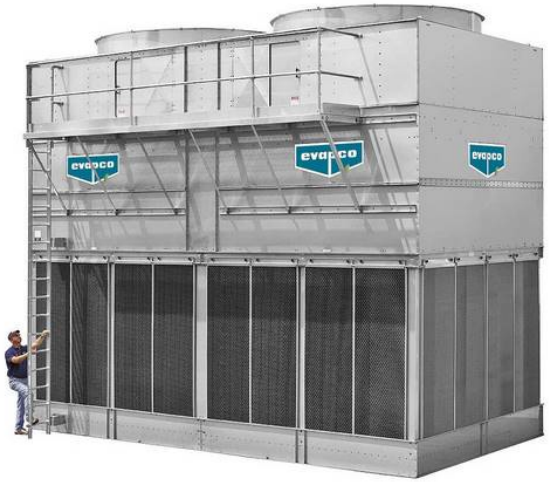
SAVING ENERGY IN LARGER HVAC SYSTEMS

Large central commercial systems: Chillers

Air cooled chiller
Smaller capacity

Chilled water loop





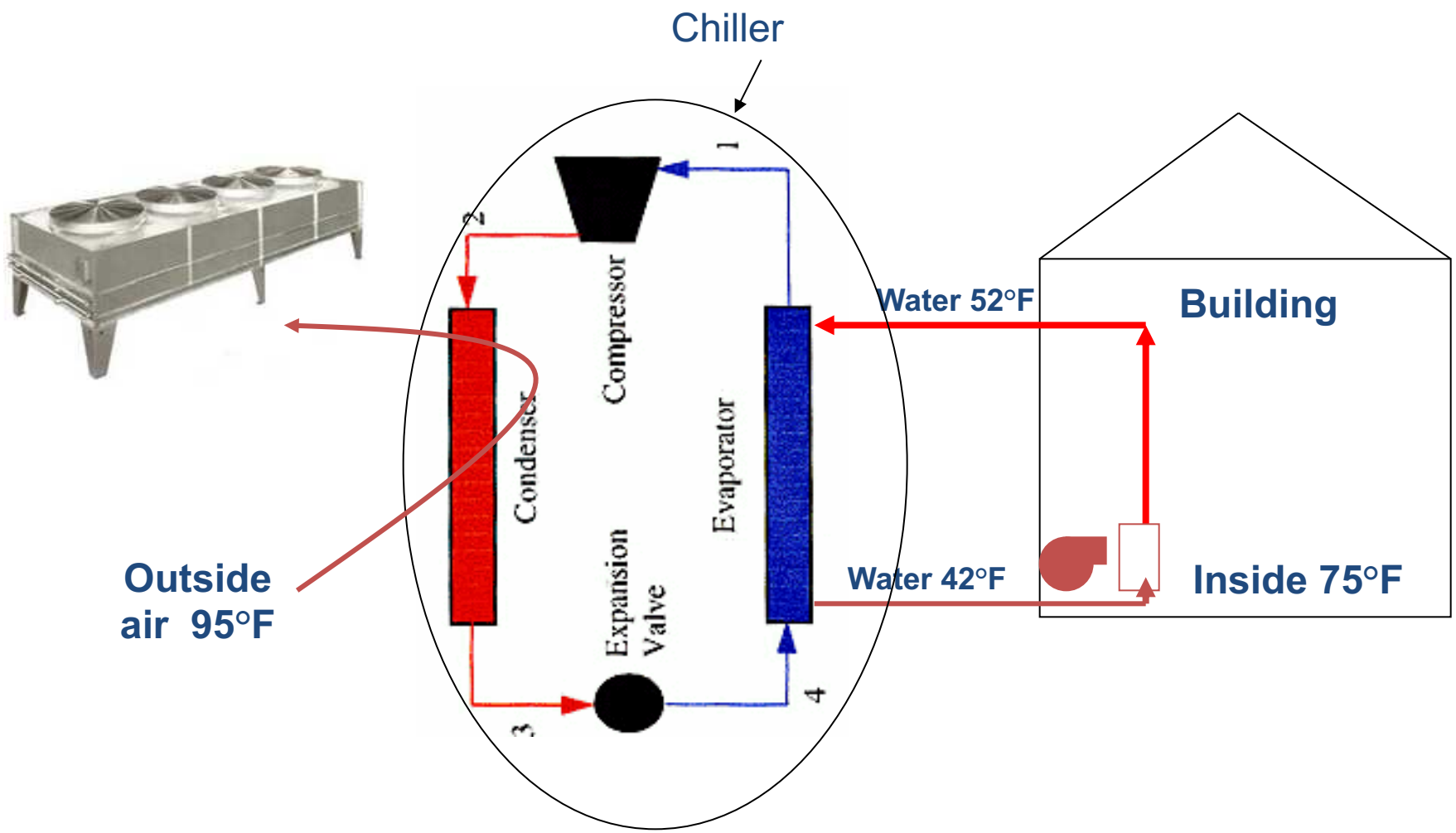
Water-cooled chiller
(w/ cooling tower – larger capacity & more efficient)

Chillers use vapor compression or absorption systems to produce chilled water for cooling spaces

Air-cooled chillers

Air-cooled chiller

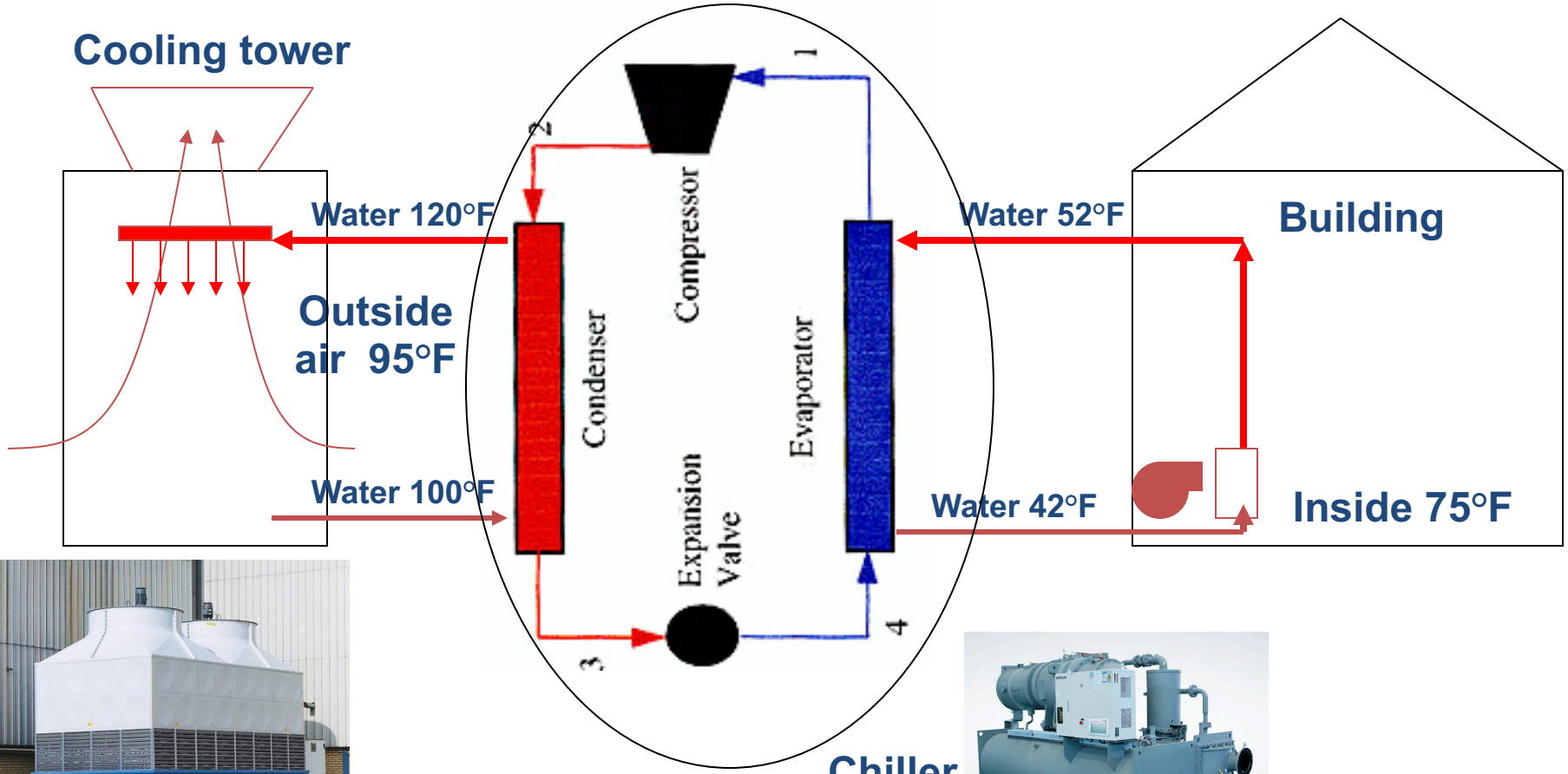
Transfer heat from evaporator coil to outdoor air



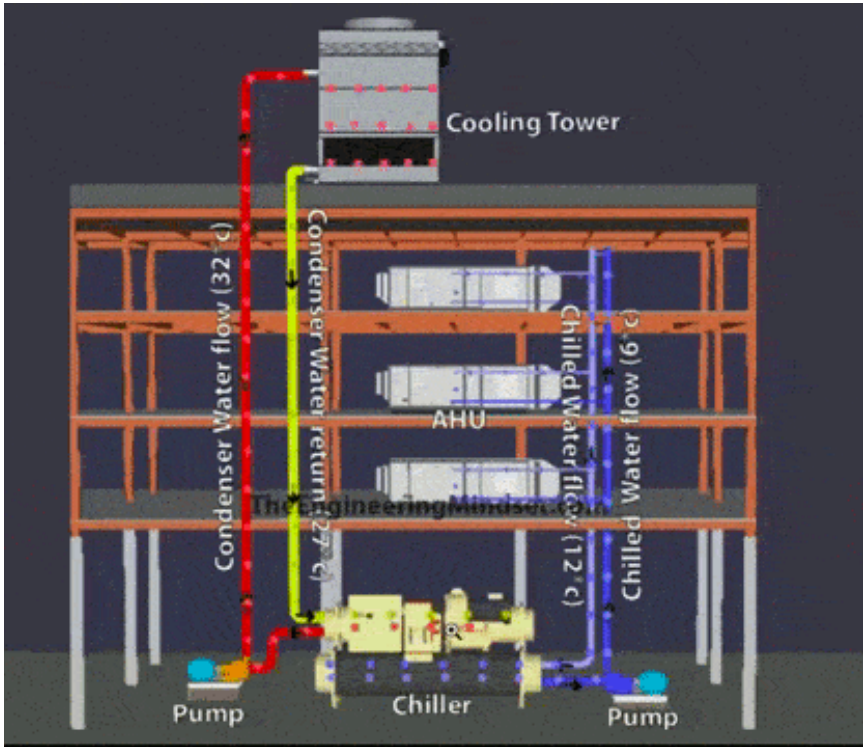
Water-cooled chillers

Water-cooled chiller

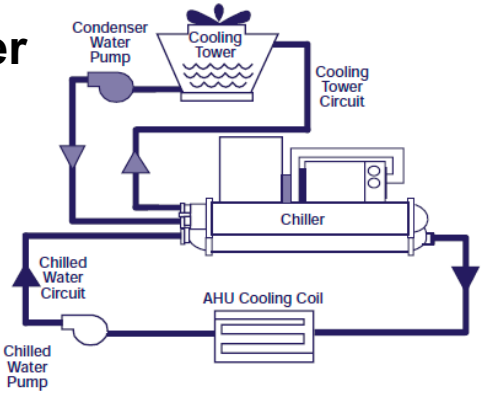
Transfer heat from evaporator coil to outdoor air through water cycle

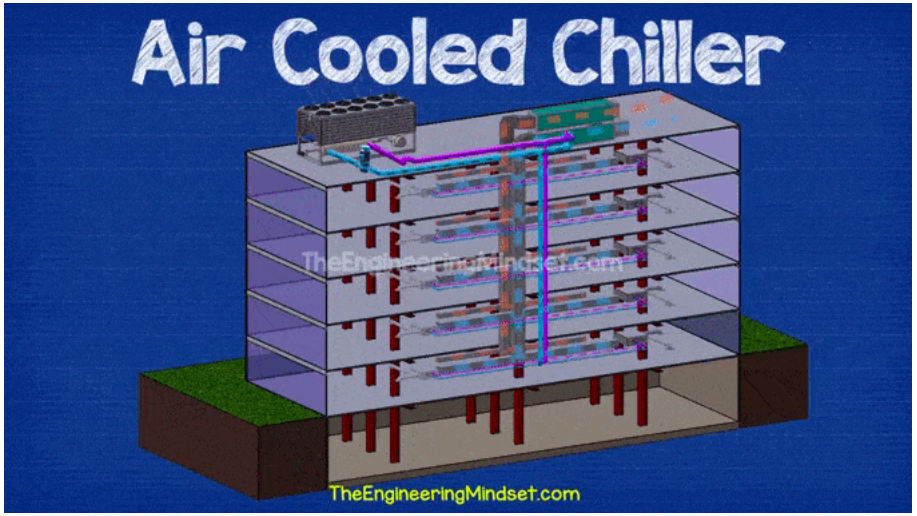


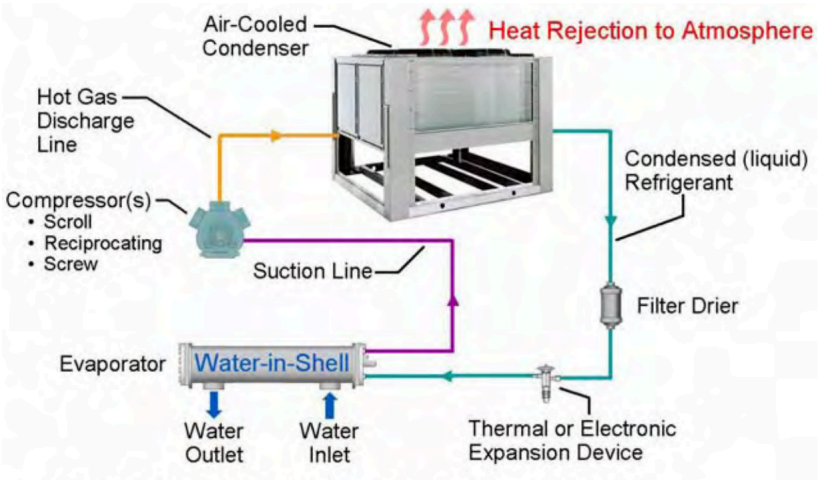
Air vs. water cooled chillers



Water-cooled chiller & cooling tower







Air-cooled chiller

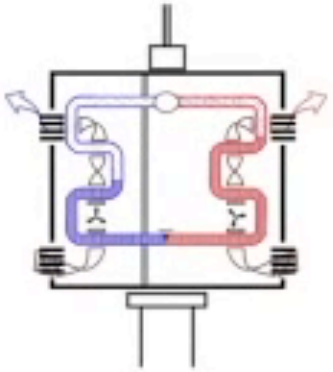
Useful videos on chillers

- Chillers and air handling units
  - https://www.youtube.com/watch?v=UmWWZdJR1hQ
- Air cooled chillers
  - https://www.youtube.com/watch?v=Ic5a9E2ykjo
- Water cooled chillers and cooling towers
  - https://www.youtube.com/watch?v=1cvFlBLo4u0

Economizers

Air Conditioning for Big Buildings

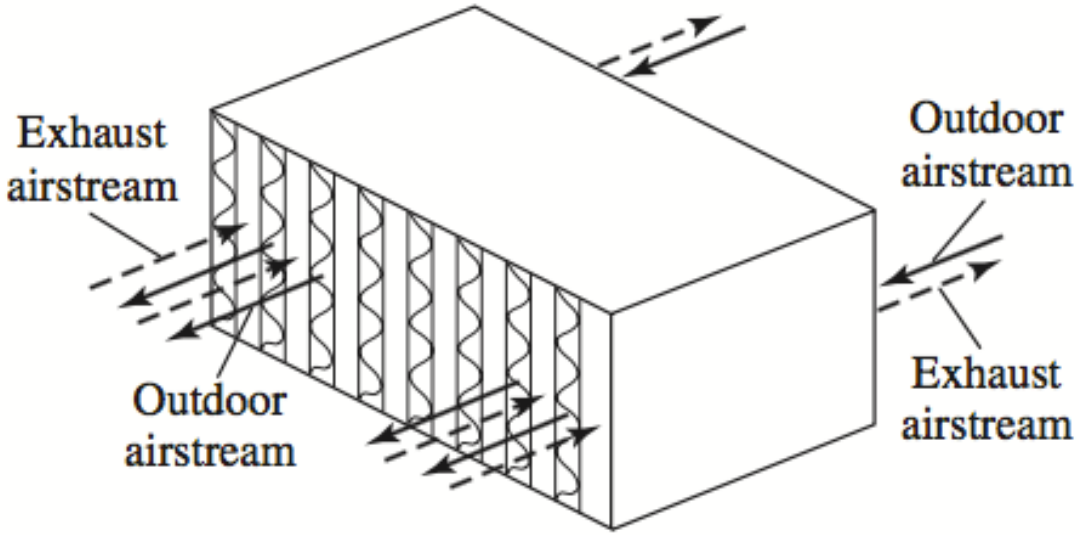
by: Michael Ermann and Clark Coots



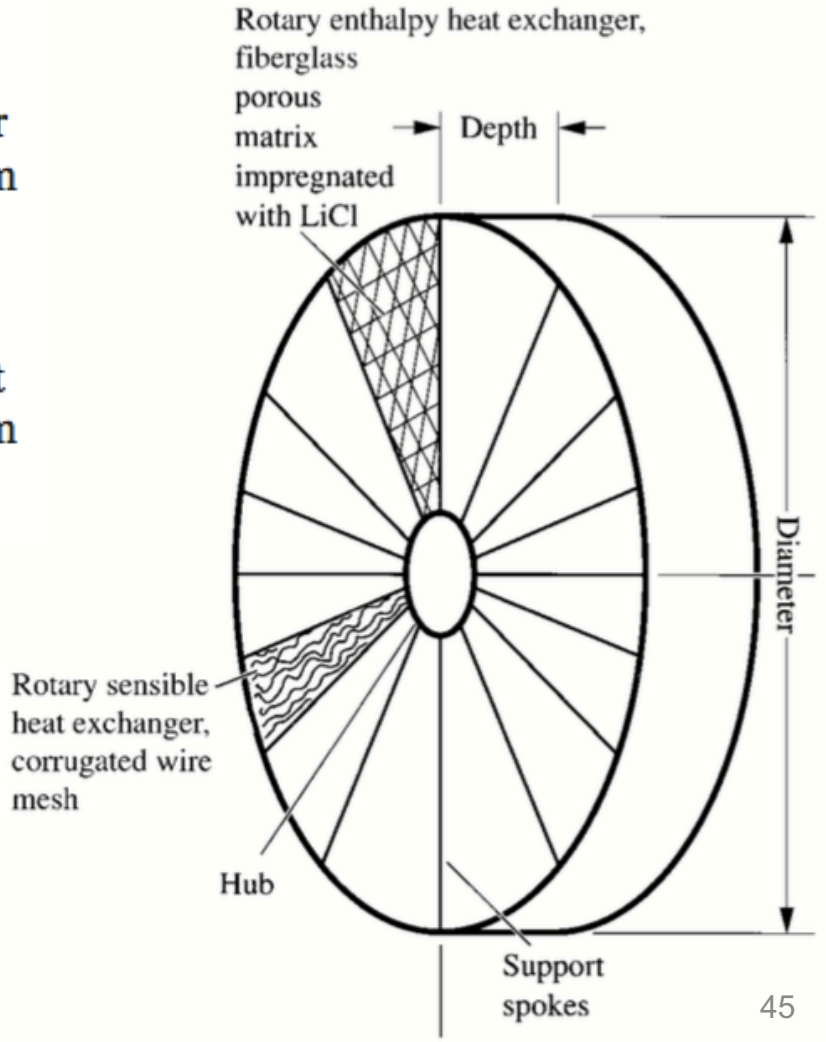
https://www.youtube.com/watch?v=j1nYipLAv0U

Heat/energy recovery systems

Air to air heat recovery



Rotary/enthalpy wheel



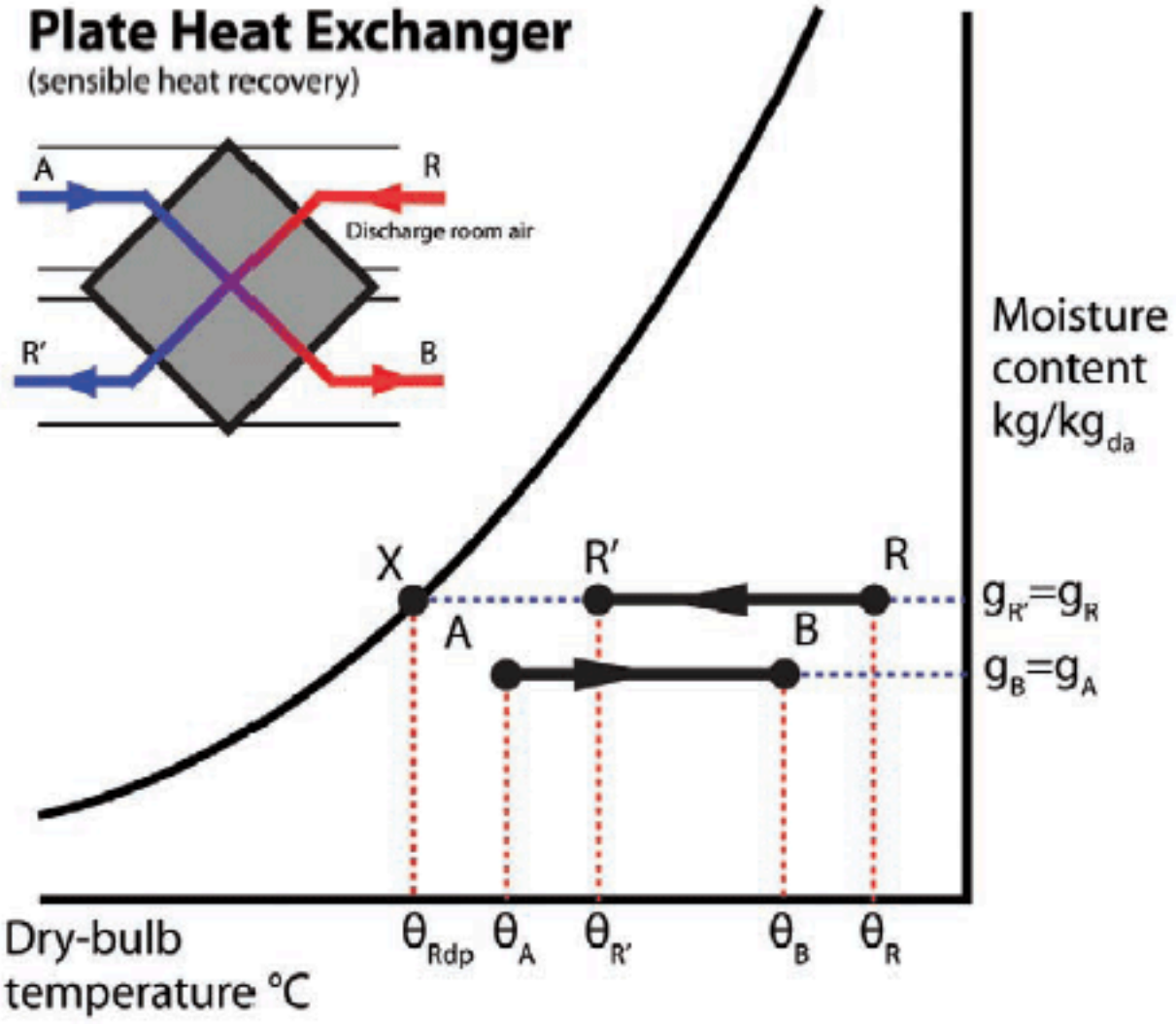
Heat/energy recovery systems

https://www.youtube.com/watch?v=QOSeIUK6dpQ

Heat/energy recovery systems

Plate heat exchanger or thermal wheel

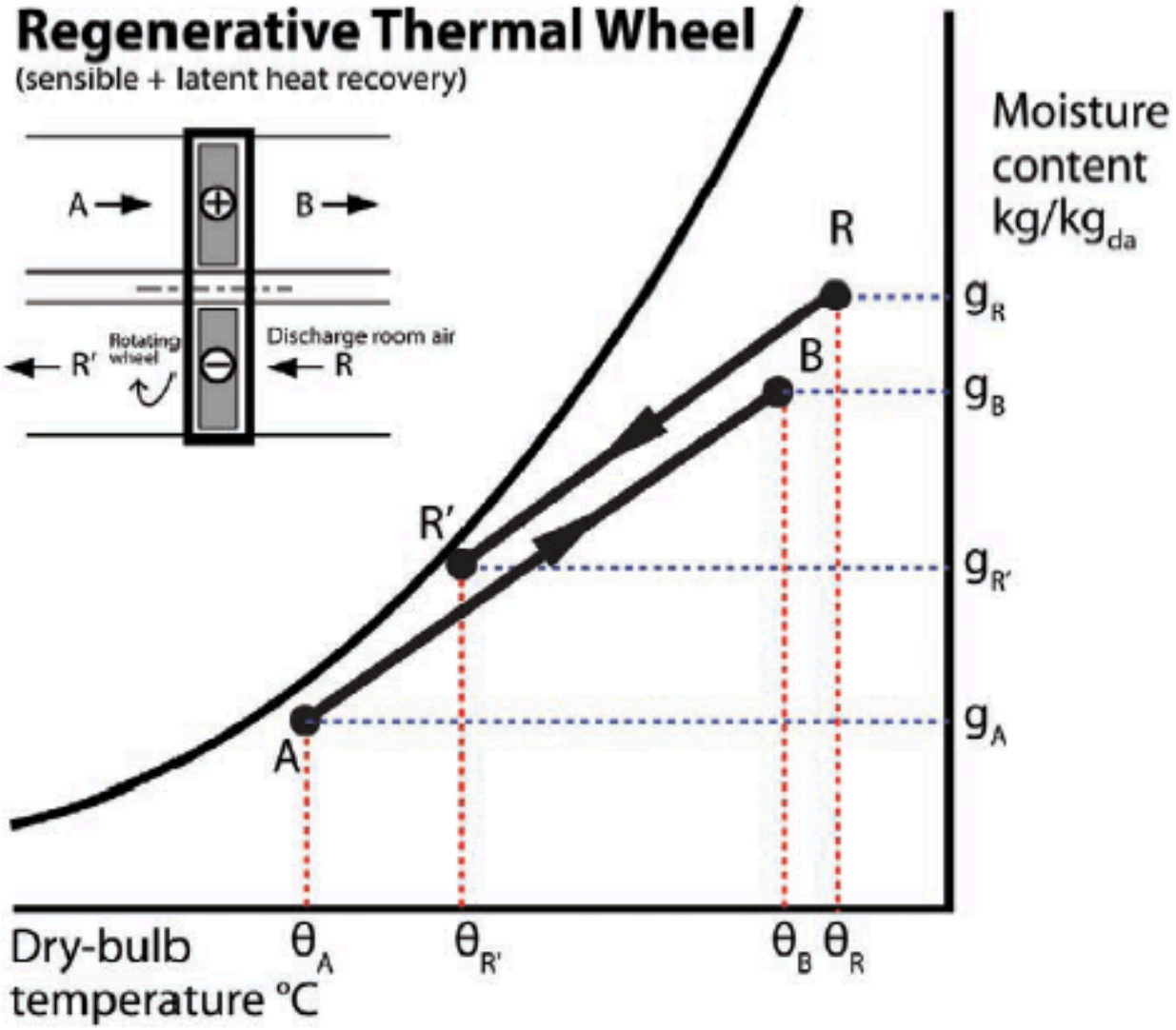
Figure 1 – Psychrometry of Plate Heat Exchanger



https://www.cibsejournal.com/cpd/modules/2009-12/

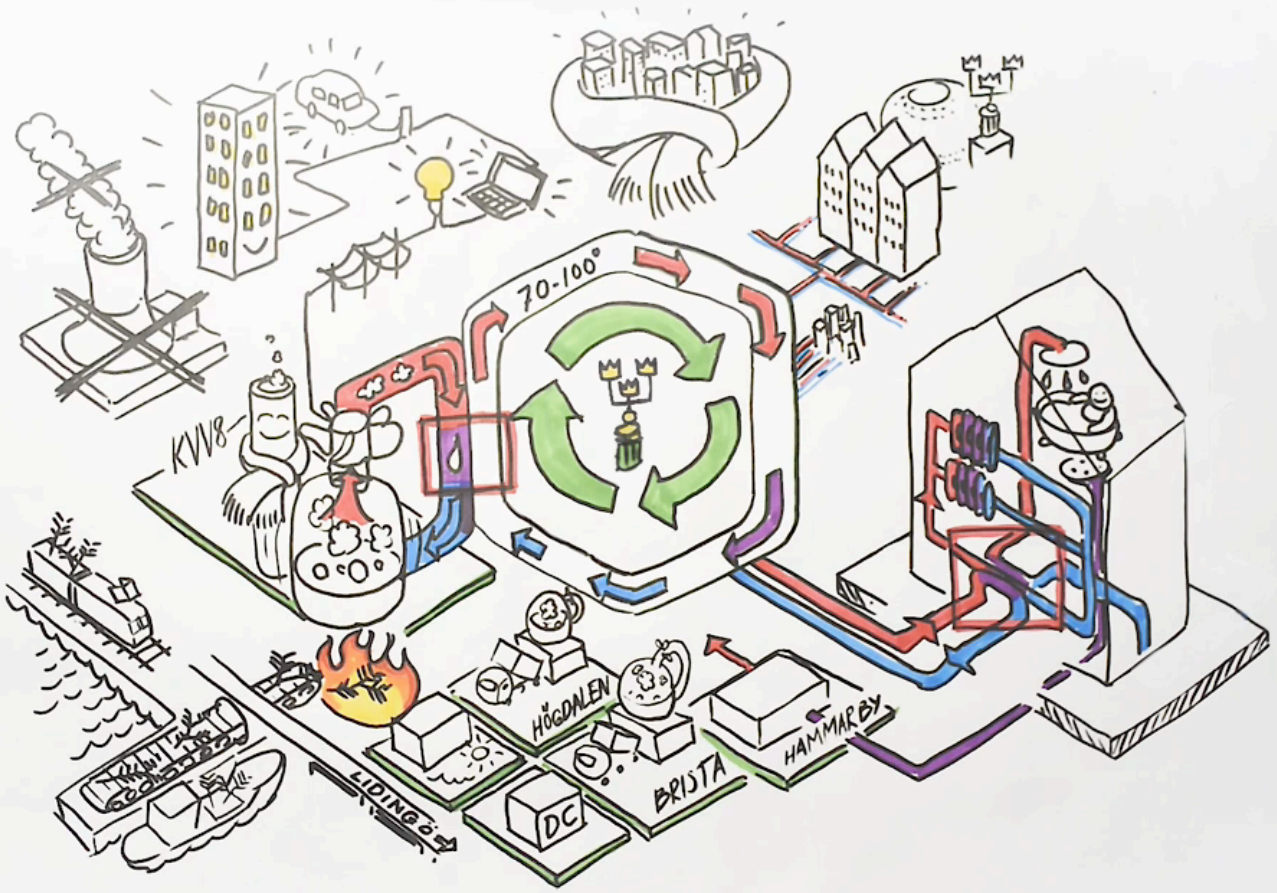
Energy recovery systems

Enthalpy wheel (sensible + latent)



https://www.cibsejournal.com/cpd/modules/2009-12/

District heating and combined heat and power

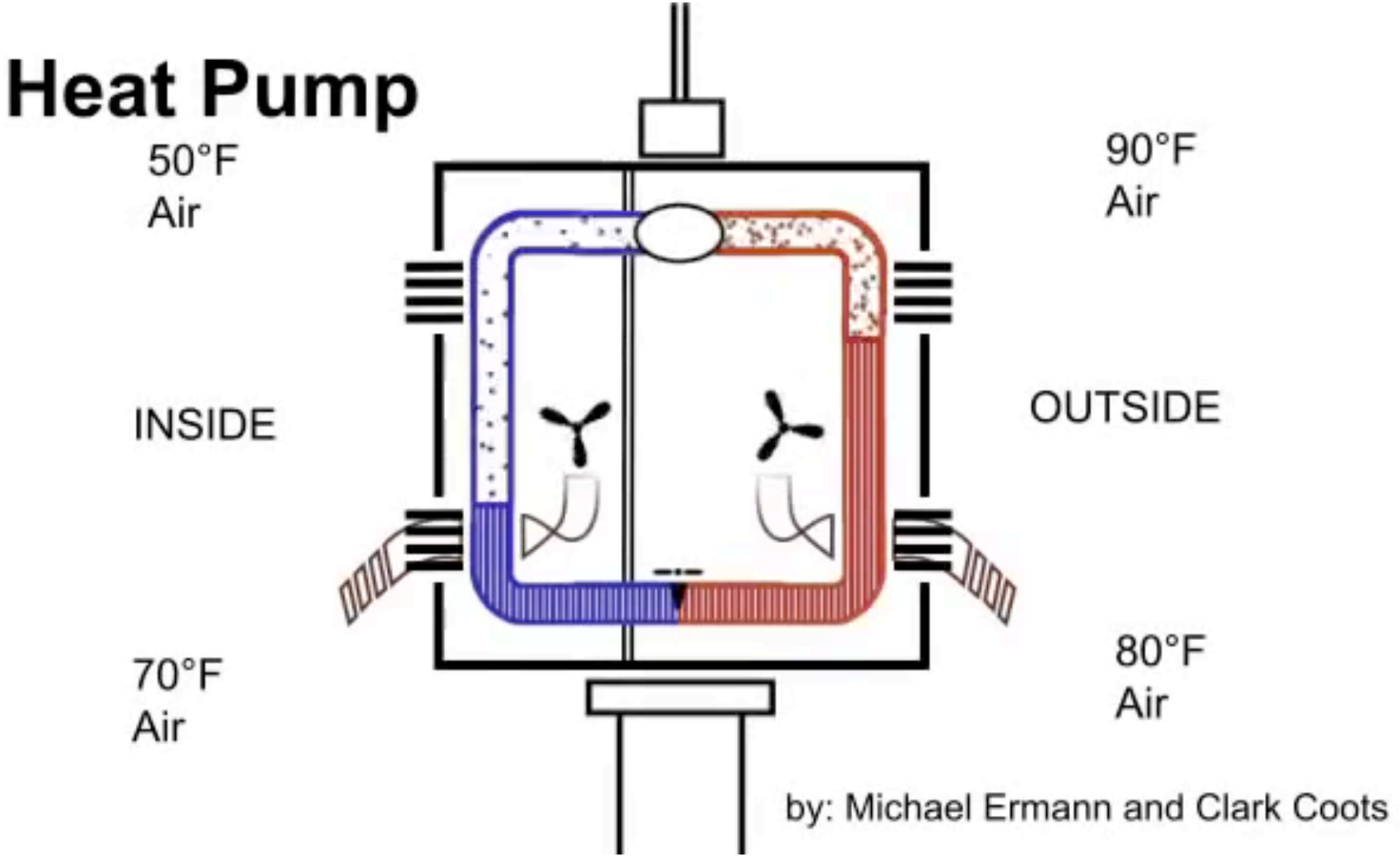


https://www.youtube.com/watch?v=MhJVsSkxg7s

District cooling

https://www.youtube.com/watch?v=7IZ3PBr7dO4

Heat pumps

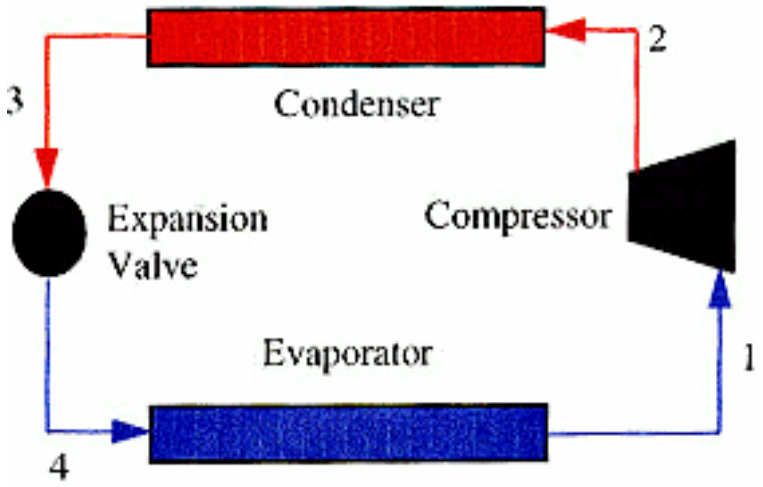


https://www.youtube.com/watch?v=NyNeh7wPQQk

Heat pumps

Cooling

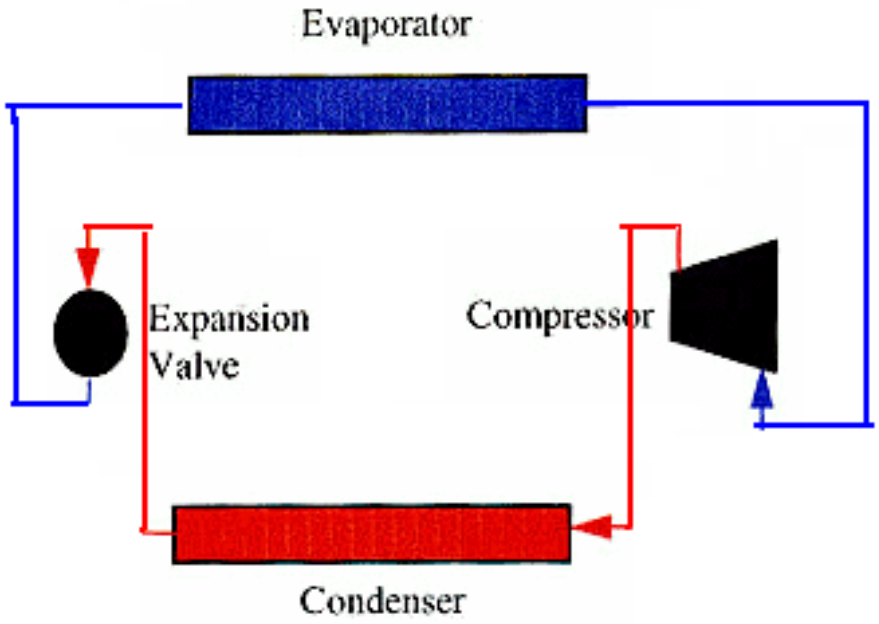
Outside 95°F



Inside 75°F

Heating

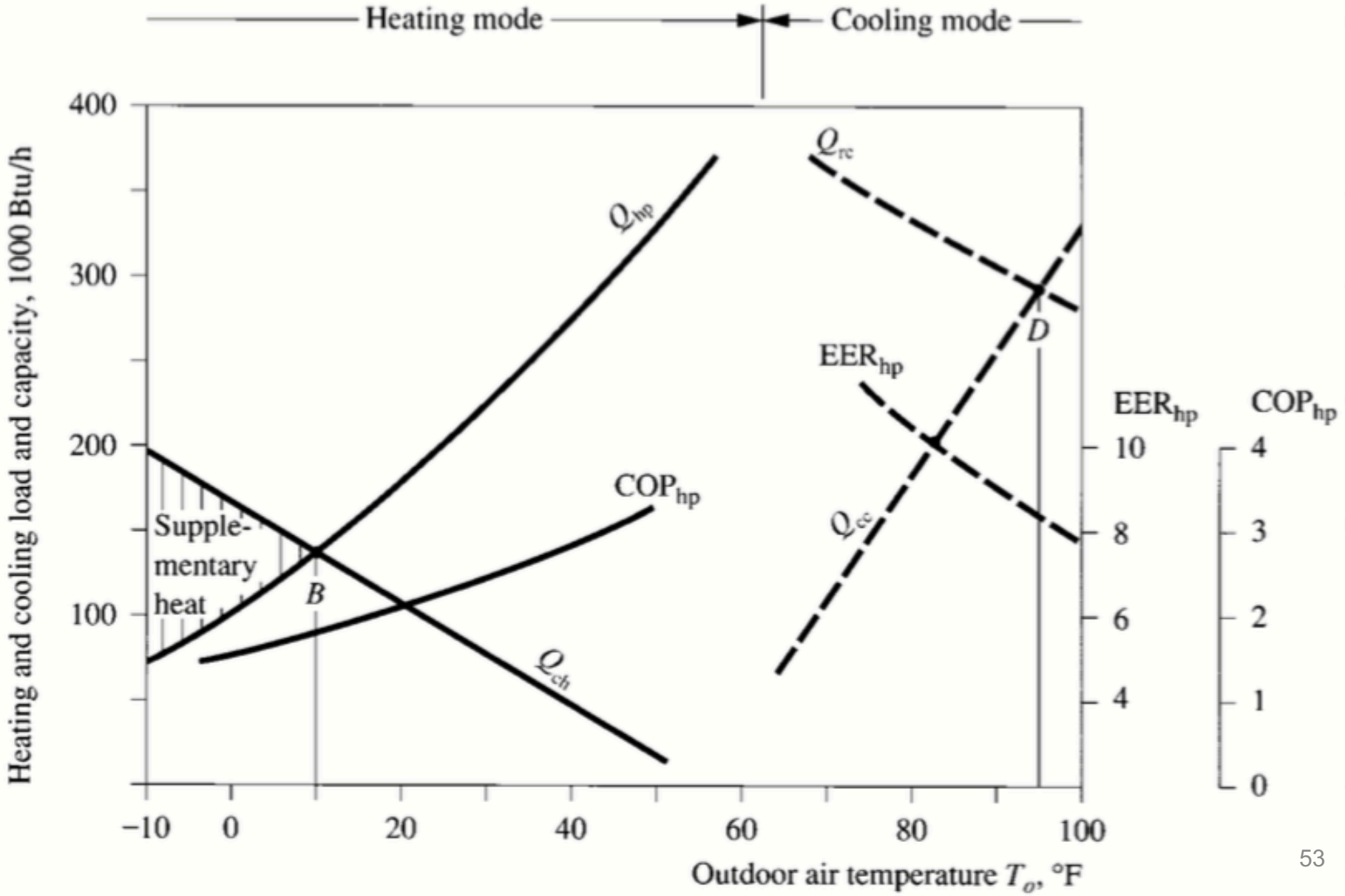
Outside 45°F



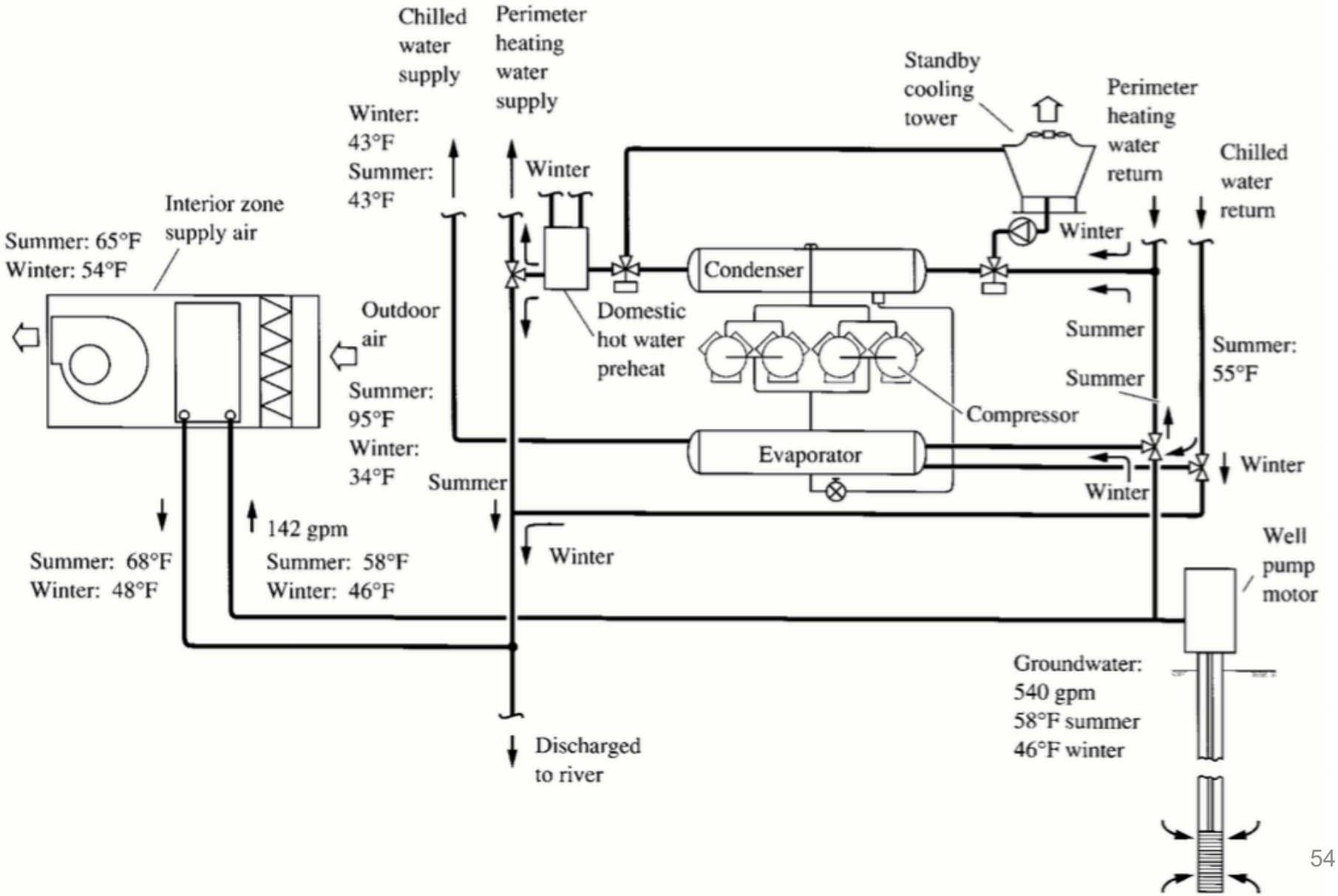
Inside 75°F

Air-conditioner run in reverse

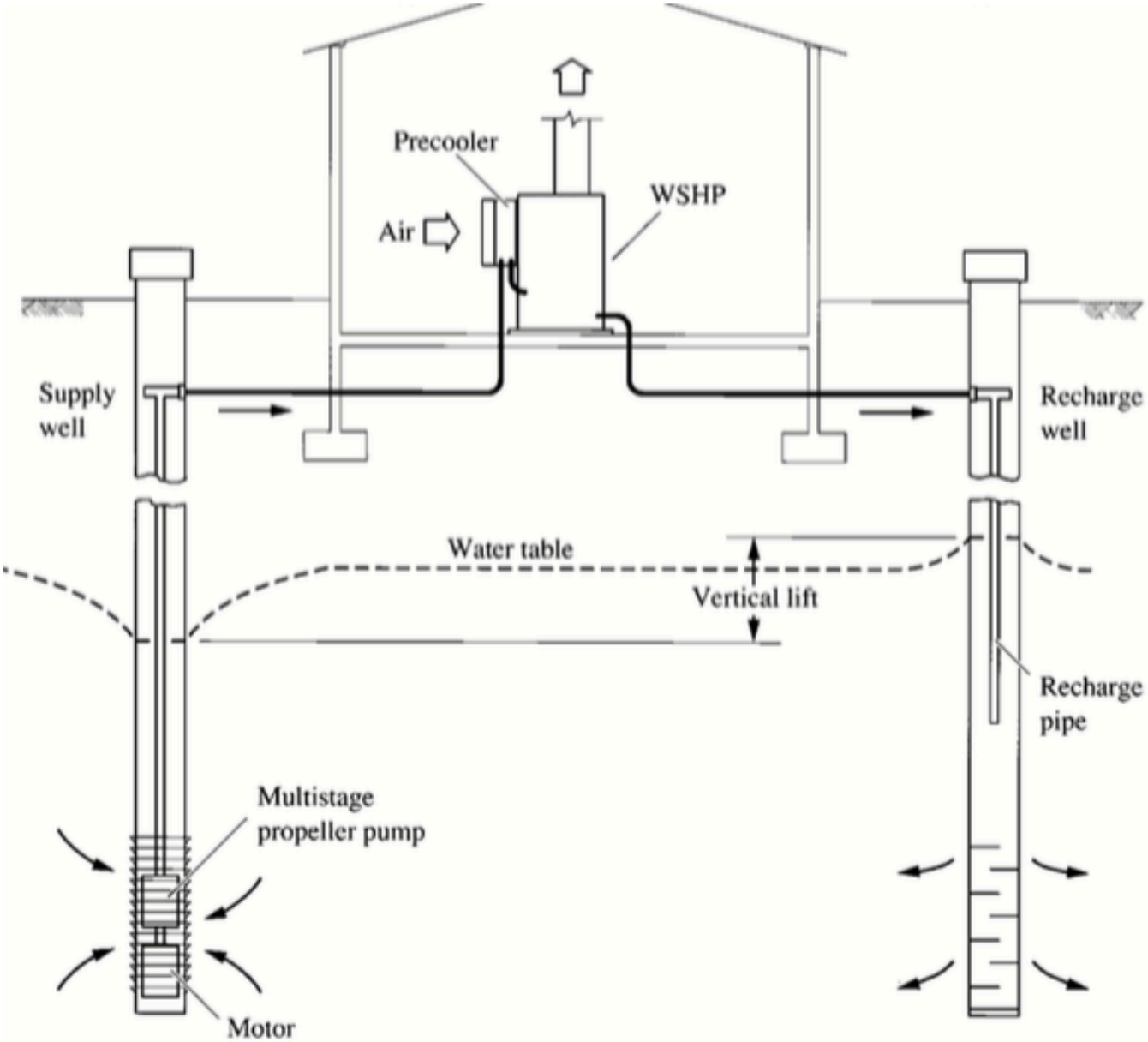
Air-source heat pumps



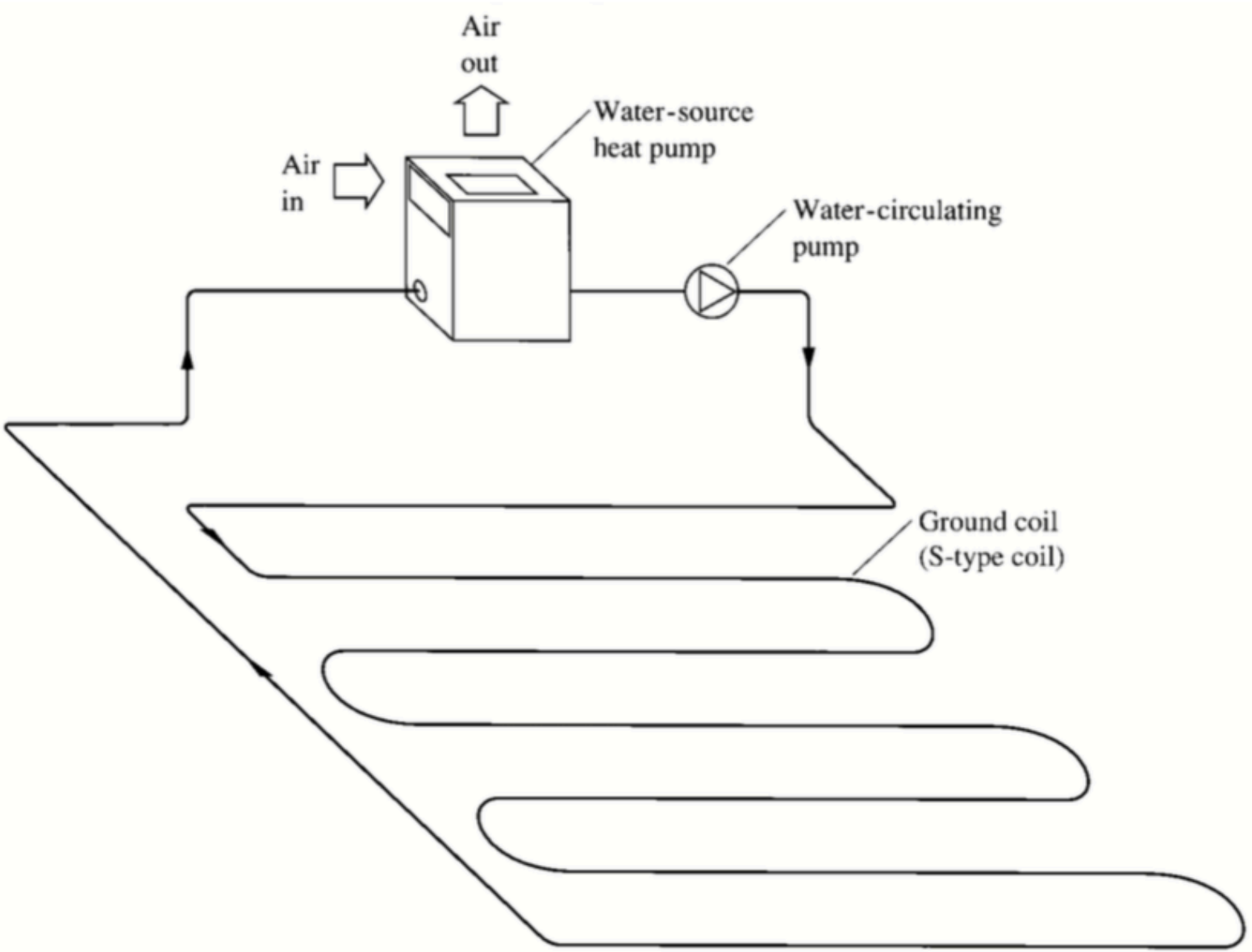
Ground-source heat pumps



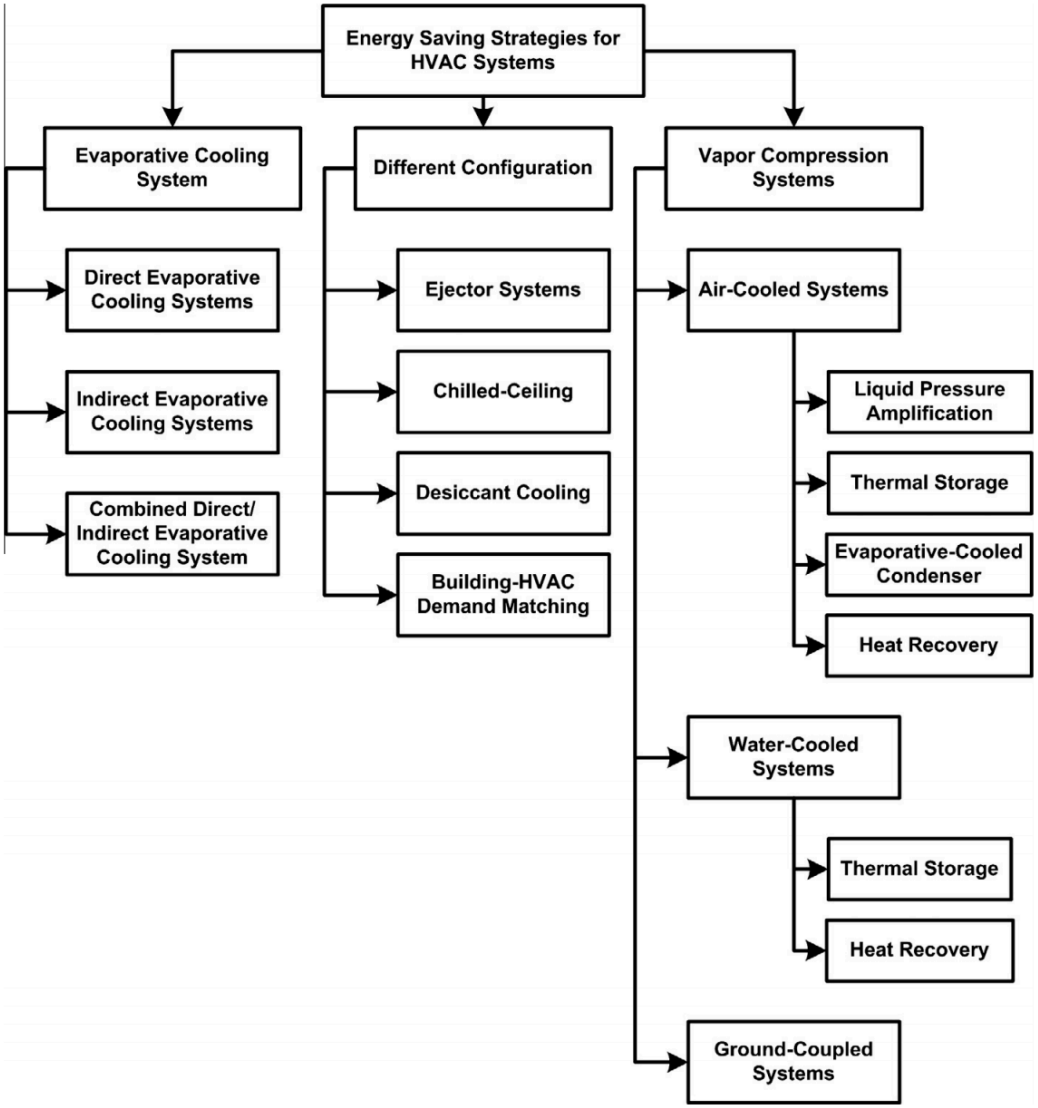
Ground-source heat pumps



Ground-source heat pumps



Which system do you choose?



It depends:

- Capital costs
- Operational costs
- Building size/loads
- Space limitations
- Water availability
- And more

Take CAE 464/517 HVAC Design in the spring!

Vakiloroaya et al. **2014** Energy Conservation & Management 77:728-754