BUILDING ENERGY EFFICIENCY

Ravi Prasher, Technology Development Program Manager, Intel Corporation

Colin McCormick, Building Technologies Program, U.S. Department of Energy

March 1, 2010

ARPA-E Pre-Summit Workshop

www.arpa-e.energy.gov

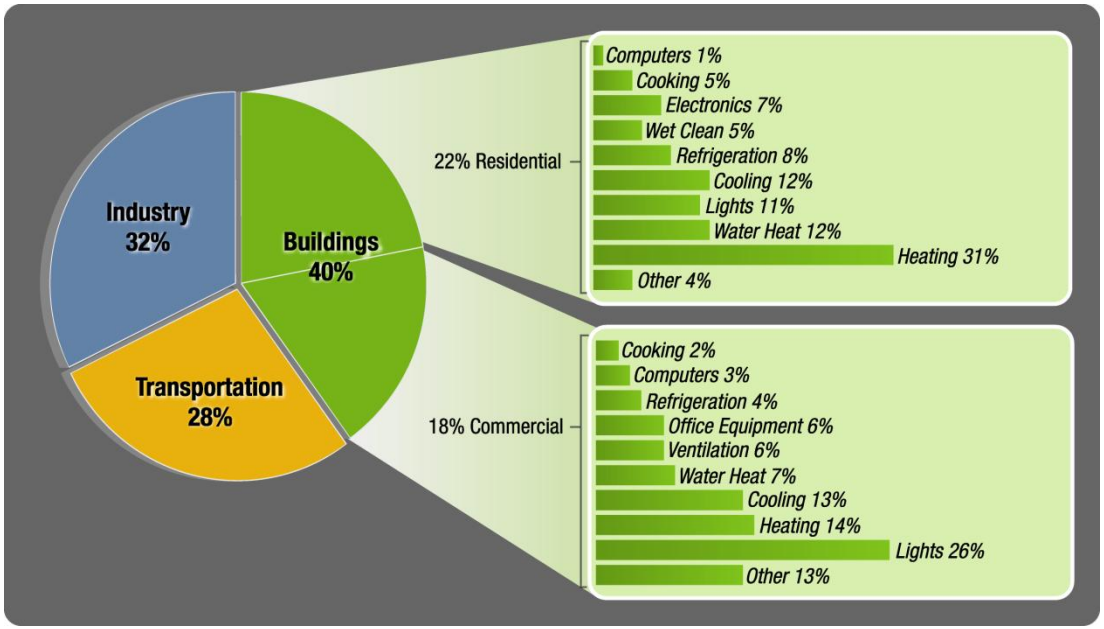
"There is a growing realization that we should be able to build buildings that will decrease energy use by 80 percent with investments that will pay for themselves in less than 15 years. Buildings consume 40 percent of the energy in the U.S., so that energy efficient buildings can decrease our carbon emissions by one third."

Secretary Chu, Caltech Commencement, June 12, 2009

BUILDINGS PLAY A KEY ROLE IN AMERICA'S ENERGY FUTURE

Buildings construction/renovation contributed **9.5% to US GDP** and employs approximately **8 million people**. Buildings' utility bills totaled **$370 Billion** in 2005.

Buildings use 72% of nation's electricity and 55% of its natural gas.



By 2030, Business as Usual

- 16% growth in electricity demand
- Additional 200 GW of electricity at cost of $500-1000B, or $25-50B/yr

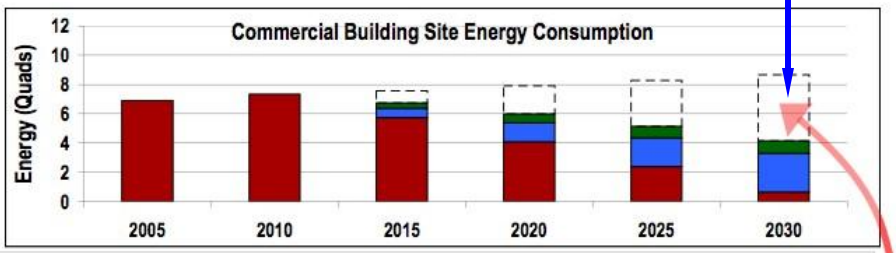
Buildings Can Provide Grid-Level Storage

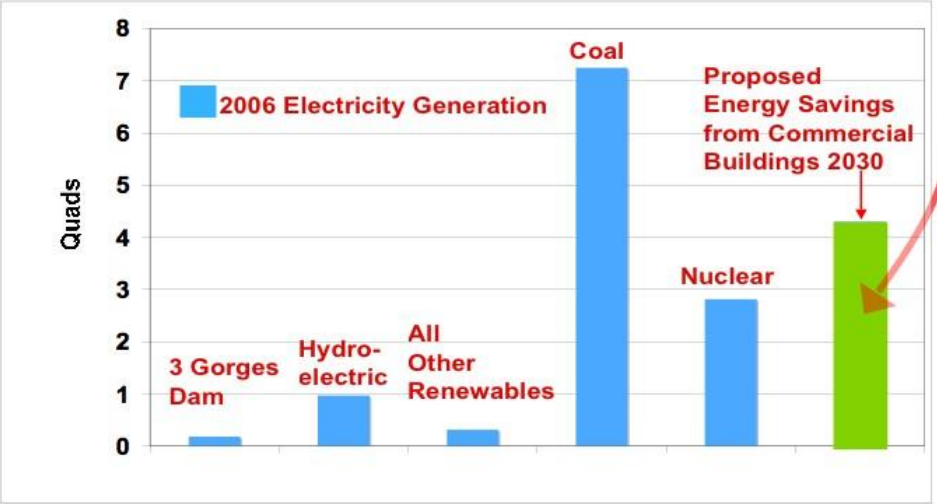
Source: *Buildings Energy Data Book 2007*

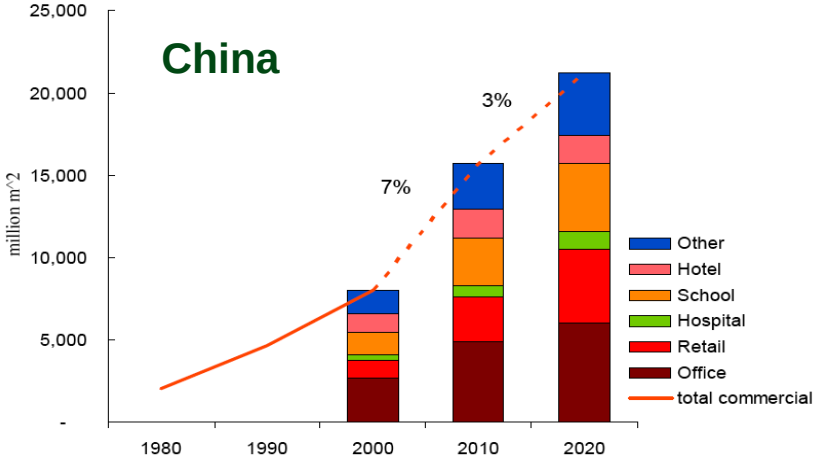
COMMERCIAL BUILDINGS OFFER A SIGNIFICANT OPPORTUNITY FOR ENERGY SAVINGS

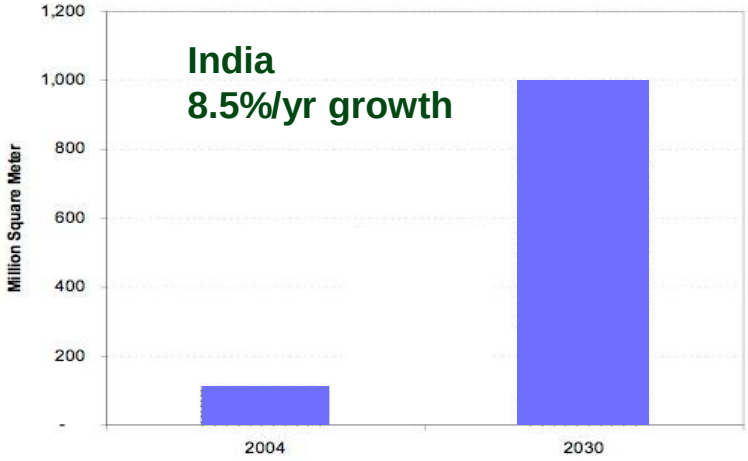
New: 80% reduction

Existing: 50% reduction



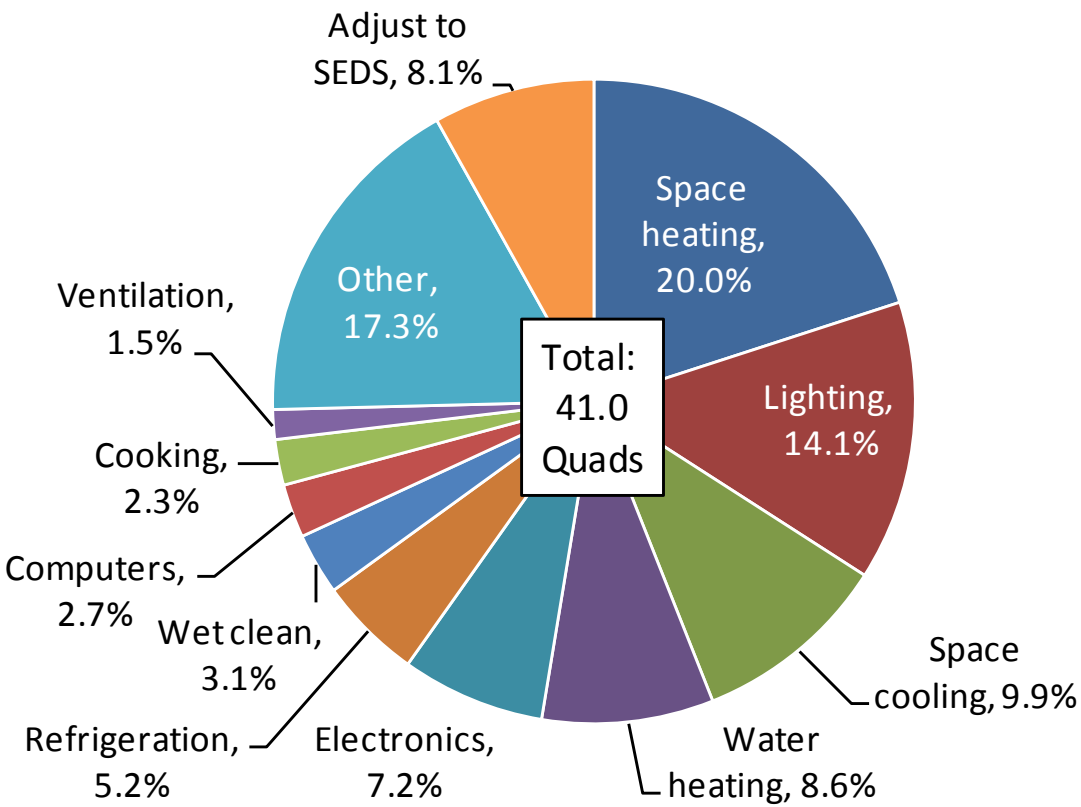






TOTAL PRIMARY ENERGY CONSUMPTION BY BUILDINGS (2010)

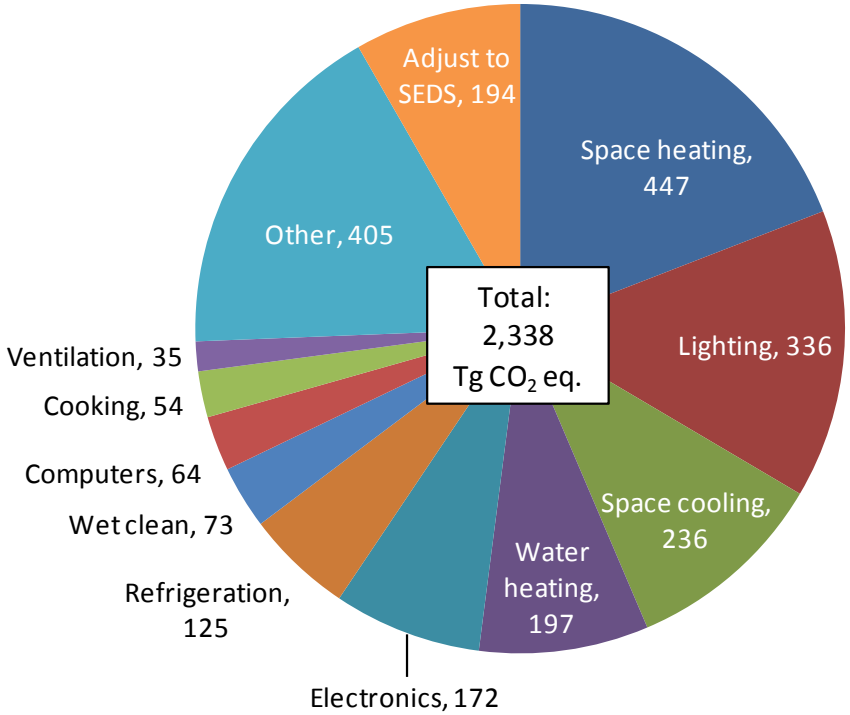
- ***HVAC (space heating, space cooling, and ventilation): 31.4%***
- ***Lighting: 14.1%***
- ***Water heating: 8.6%***
- ***Increasing miscellaneous loads***
- ***Air conditioning is a key driver of peak electricity demand.***



Source: 2009 Buildings Energy Data Book (http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=1.1.5)

TOTAL CO_2 EMISSIONS BY BUILDINGS (2010)

- ***Buildings are responsible for ~ 40% of CO_2 emissions in the U.S.***
- ***Buildings are responsible for ~ 2,300 Tg CO_2 eq. (MMT)***
- ***Cooling alone is responsible for ~ 5% of CO_2 emissions in the U.S.***



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FRAGMENTATION OF INDUSTRY AND PROCESS

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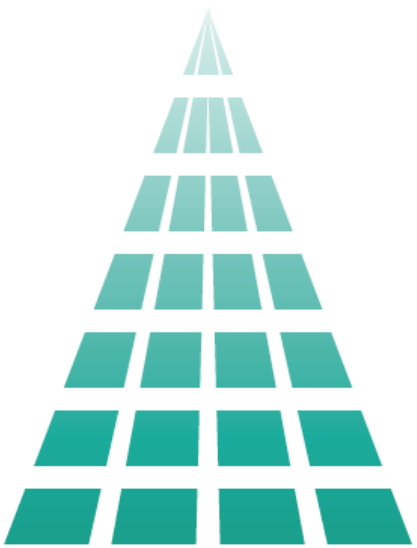


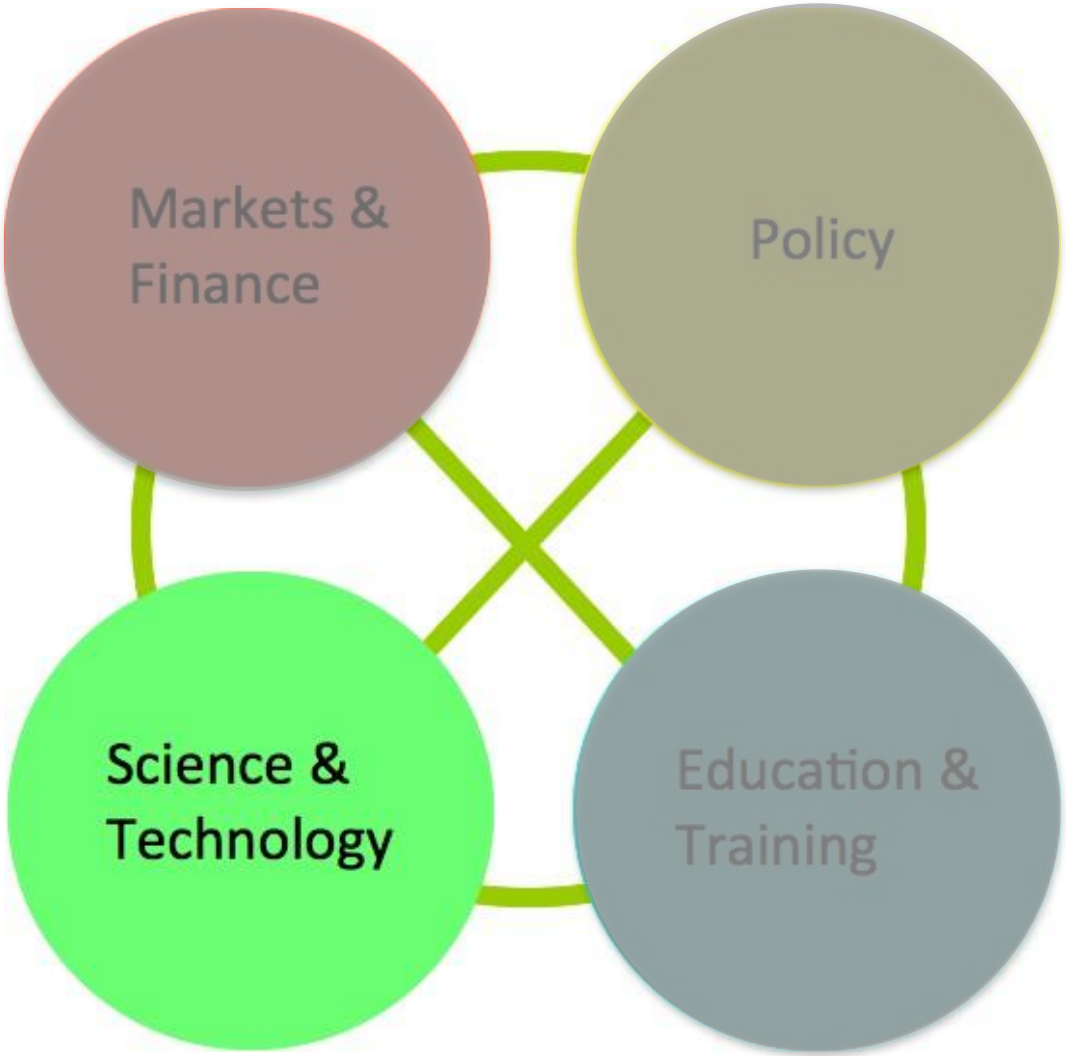
Professional and Trade Responsibilities (Functional gaps)	Building Delivery Process (Management discontinuities)	Operational Islands (Ineffective coordination; poor communication)

Need:

- **Tools to integrate process & communities**
- **Tools to integrate building design and operations**
- **Align incentives**

Courtesy: World Business Council for Sustainable Development (WBCSD) Report on Energy Efficiency in Buildings, July 2008

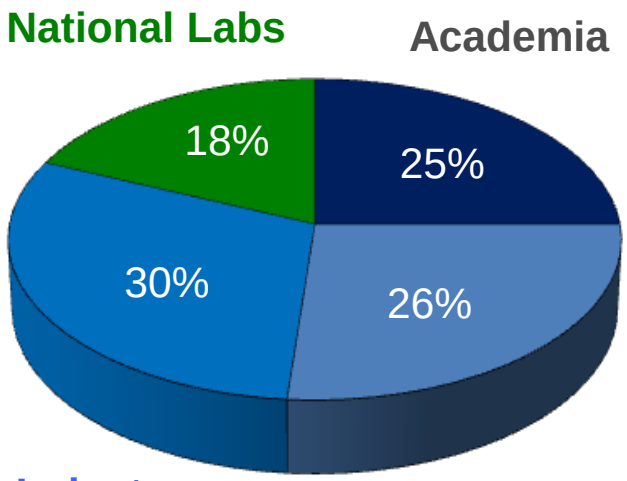
SYNERGISTIC APPROACH



ARPA-E & EERE BUILDINGS WORKSHOP

DECEMBER 15, 2009

Breakdown of 76 attendees by affiliation



DOE, DOD, NSF, NIST, GSA, OSTP

Representative Attendees

	David Culler University of California, Berkeley	Member of National Academy of Engineering Credited with pioneering work on sensor networks & computer architecture
	Sanjay Sarma Massachusetts Institute of Technology	Credited with developing many standards and technologies that form the foundation of the commercial RFID industry.
	Sam Baldwin DOE, Office of Energy Efficiency and Renewable Energy	Chief Technology Officer and Member, Board of Directors
	Satyen Mukherjee Phillips Research	Chief scientist and senior director for research strategy in North America
	Ron Judkoff National Renewable Energy Laboratory	Director, Center for Buildings and Thermal Systems
	Jeff Snyder California Institute of Technology	Thermoelectric Materials and Devices

KEY QUESTIONS

- What is the state-of-the-art and where do we want to be?
- What are the gaps, challenges, and barriers?
- What are the potential approaches to overcoming the barriers?
- What are the specific performance and cost metrics?
- What is the time horizon for goals?
- What are the challenges and barriers for validation and adoption?
- What levels of investment do we need to develop and deploy these technologies?
- What is the return on investment?

ACHIEVING EFFICIENT BUILDINGS IS VERY CHALLENGING, BUT EXISTING EXAMPLES & INVESTMENT AREAS PROVIDE HOPE

Dr. J Michael McQuade, United Technologies Corp.

Buildings Systems Grand Challenges to Increase Energy Efficiency

- Greatest efficiency improvements may lie in exploitation of otherwise detrimental sub-system interactions
- Efficient designs must also deal with uncertainties and bottlenecks in design and operation
- Investments are required to achieve aware, interactive, reconfigurable buildings

WE SHOULD STRIVE TO BRIDGE THE TRADEOFF THAT EXISTS BETWEEN ENERGY CONSUMPTION AND PERFORMANCE

Yi Jiang
Tsinghua University

What is the approach to reach the low energy goal for buildings?

- There is a huge difference in building energy consumption between OECD and developing countries such as China
- Difference due to lifestyle difference - energy efficiency designs must take lifestyle into account
- **Decentralized, "part time part space" service system may be the US solution**
- **Other areas for study - independent control of temperature and humidity, evaporative cooling**

BREAKOUT SESSIONS

1. **Measurement & Communication *(sensors, data protocols, power)***
   - **Shyam Sunder (NIST)**
   - **David Culler (UC Berkeley)**
2. **Simulation & Computation *(computational models, calibration)***
   - **Ron Judkoff (NREL)**
   - **Michael Wetter (LBNL)**
3. **Systems Approach to Fault Diagnostics and Controls**
   - **Scott Bortoff (Mitsubishi Electric)**
   - **Srinivas Katipamula (PNNL)**
4. **Active and Passive Thermal Devices and Components**
   - **Ravi Prasher (Intel)**
   - **Sam Baldwin (DOE/EERE)**

KEY LESSONS

- **Highly efficient buildings exist today, but measured performance rarely meets design performance.**
- **Achieving designed performance requires labor-intensive, high-skill continuous operation & maintenance. This must be made easier.**
- **Solution will be part technical, part behavioral, part economic, part policy.**
- **Enormous opportunities exist in improved systems integration.**
- **Investable areas for building science components include:**
  - Lighting (Solid State lighting program in EERE)
  - Active building envelope technologies (controllable)
  - Long-duration, fast-charging/discharging thermal storage
  - Enhanced passive ventilation systems
  - Fast humidity control systems
  - High-efficiency, low-GWP refrigerant replacements/not-in-kind systems

MISMATCH BETWEEN MEASURED & DESIGNED PERFORMANCE

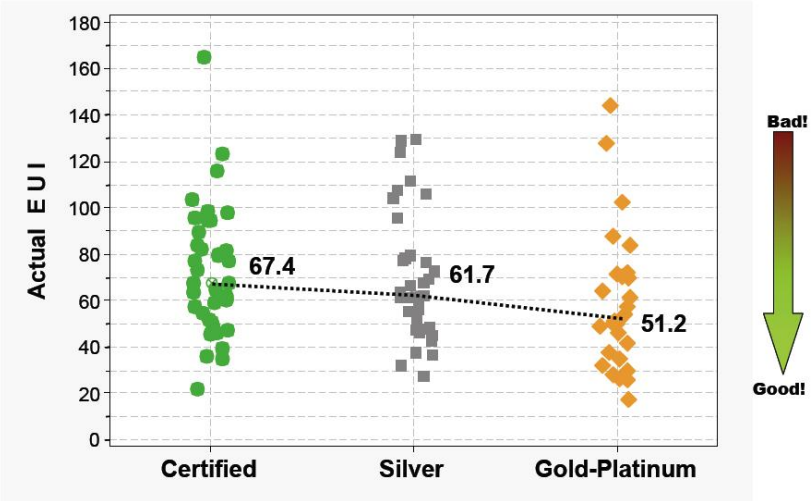
Analysis of 121 LEED-Rated Buildings

Low-to-Medium Energy Use Intensity Buildings

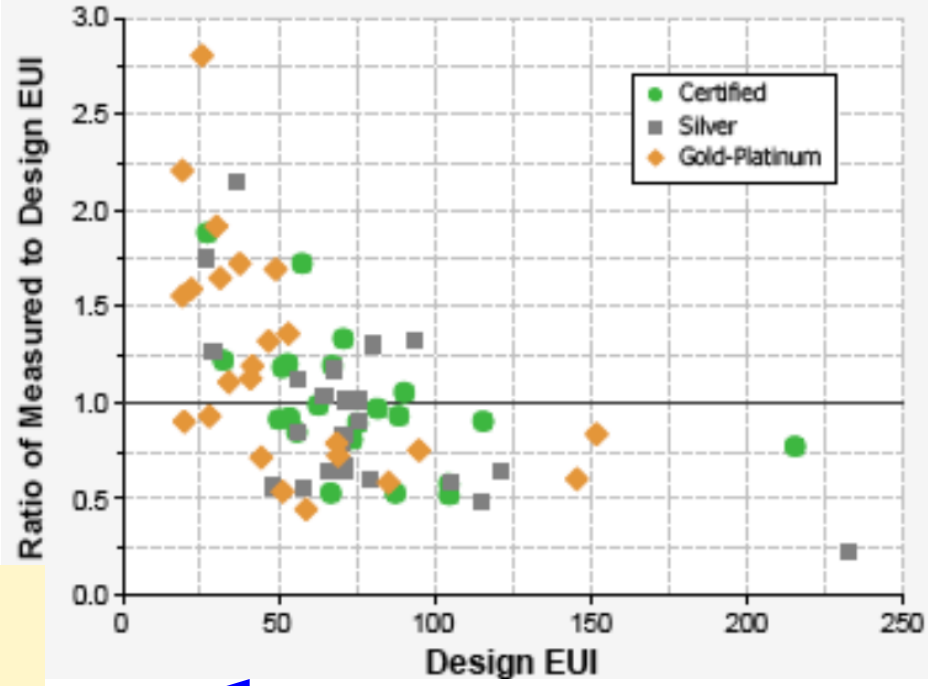
Labels/codes are for Design Performance, NOT based on Measured Performance.

The Spread

EUI in kBTU/sq.ft.-yr



Measured to Design Ratio



Gap

- Lack of Measurements & Policies Requiring it

Towards Zero-Net Energy

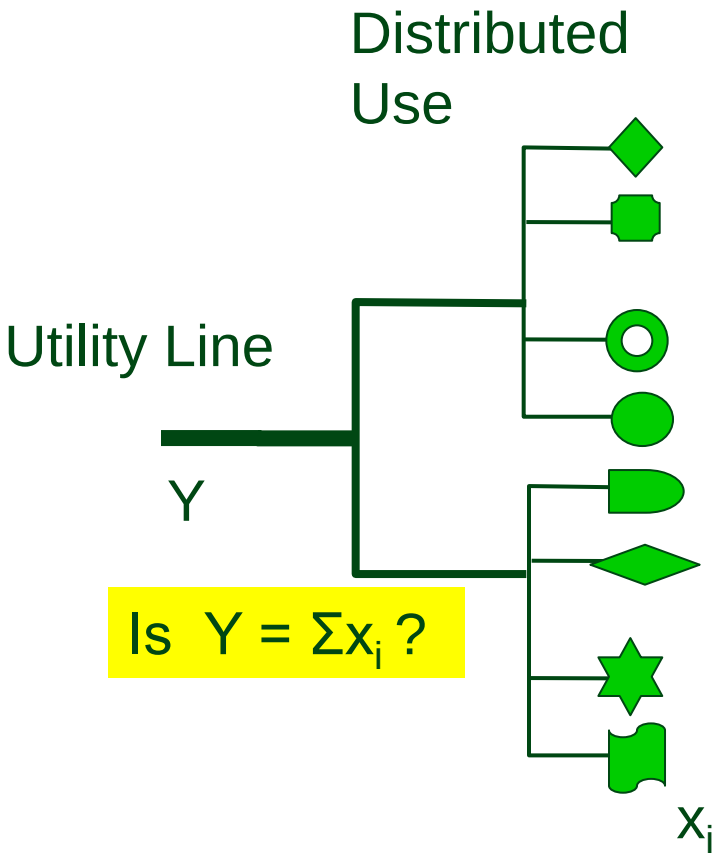
M. Frankel, "The Energy Performance of LEED Buildings," presented at the Summer Study on Energy Efficient Buildings, American Council of Energy Efficiency Economy, Asilomar Conference Center, Pacific Grove, CA, August 17-22, 2008.

MEASUREMENT & COMMUNICATION
SENSOR PARAMETERS

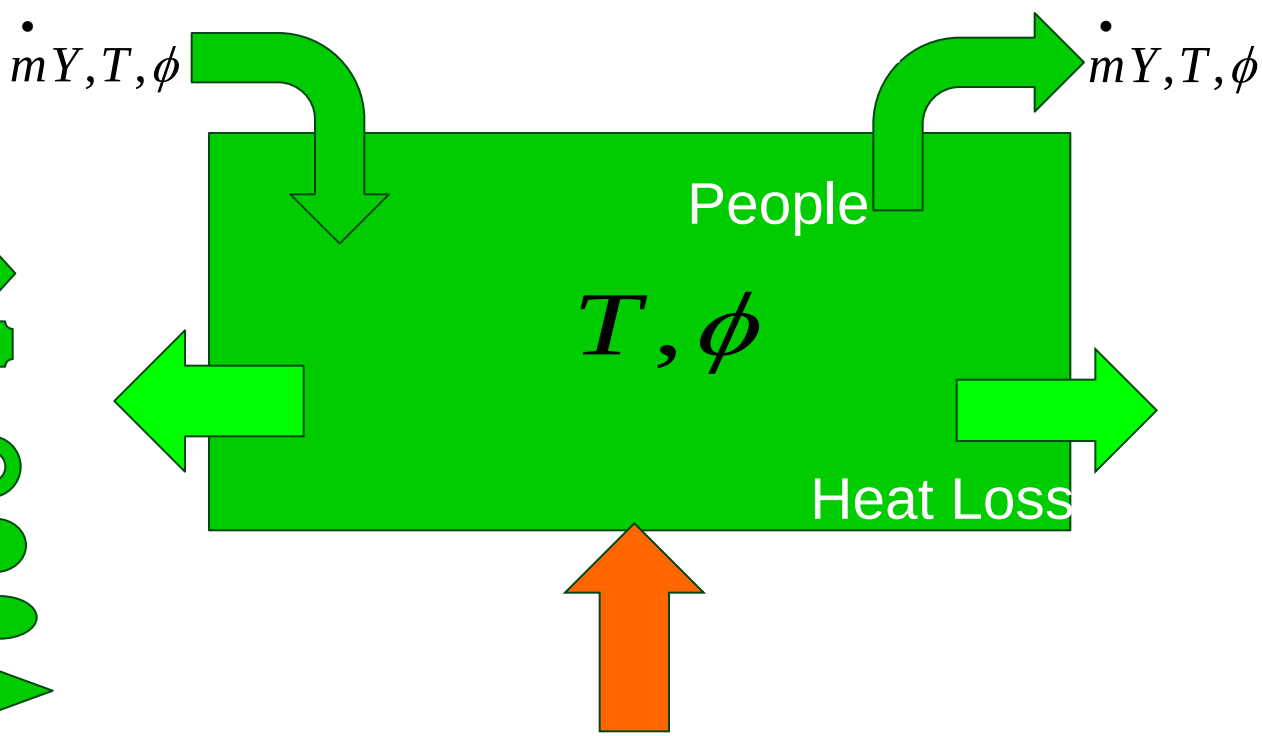
Key parameters	Future/desirable parameters
Mass flow (air, water, steam, fuel)	Carbon dioxide
Temperature, pressure, humidity	VOCs
Light levels	Biologics
Electrical power (sub-metering major equipment, tenant groups)	Occupant density
Indoor environmental quality	Plug load power consumption
Building boundary conditions or configuration (windows, doors, etc)	Granular equipment consumption (zonal)
Occupancy and comfort levels, acoustics	Parameterized personal comfort
External conditions (weather, insulation)	

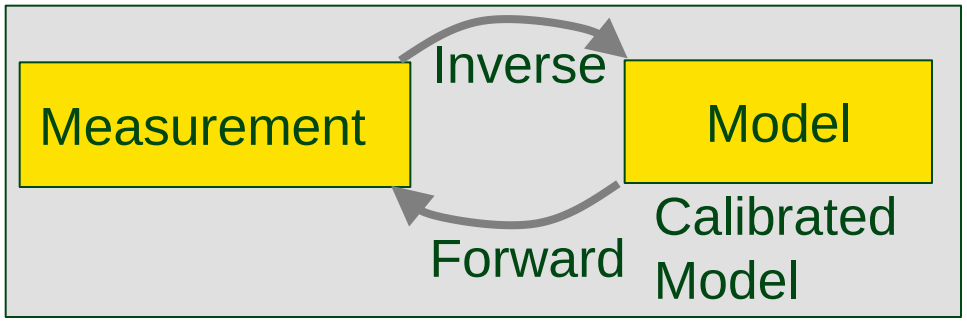
MEASURED PERFORMANCE IS LINKED TO MEASUREMENT TYPE

Measurement Type I: Conservation Laws



Is $Y = \Sigma x_i$?





MEASUREMENT & COMMUNICATION
SENSOR CHARACTERISTICS/BARRIERS

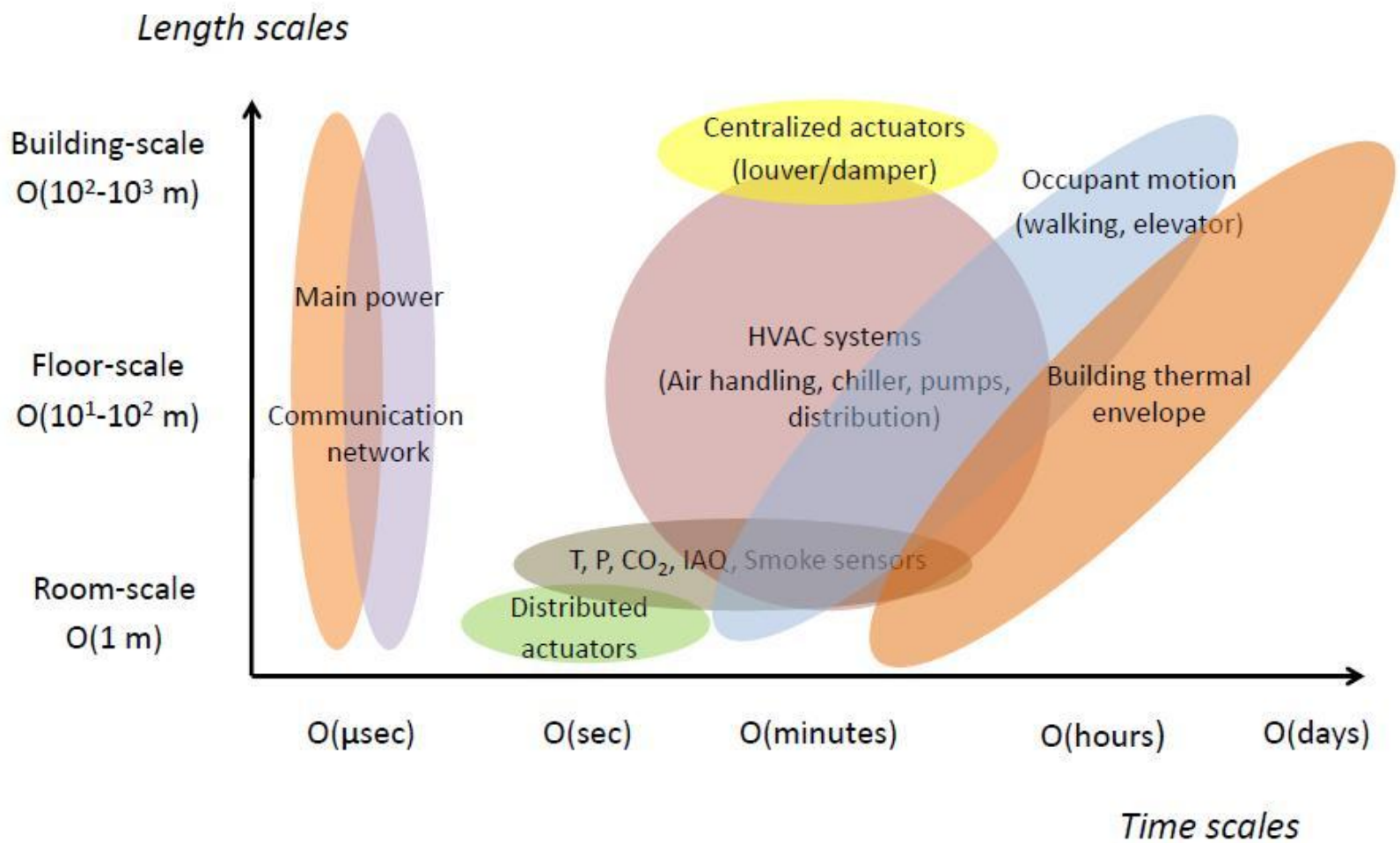
Key characteristics	Key barriers
Sensor density based on gradients	Sensor drift and mis-calibration
Location at equipment, exterior faces	Large dataset handling (search, etc)
Ease of access/maintenance	Inadequate meta-data
Dynamically configurable	Connectivity (wired/wireless?)
Integration with controls	Power (energy harvesting?)
Robust to single-point failure	Interoperability
Fully autonomous	Legacy systems, protocol changes (3-4 years)
Long sensor lifetime (20+ years?)	Expense/difficulty of mesh network?

SIMULATION & COMPUTATION

SIMULATION NEEDS/CHALLENGES

Issues	Needs
Modeling inefficient buildings is more difficult than efficient ones	Tools/interface tailored to different user groups
Occupant behavior in larger buildings is highly stochastic	Fast/real-time simulation
Weather data is hourly – hard to simulate at finer timescales	Ties into other toolsets (MATLAB, Mathworks, etc)
Wind data is at a single elevation (10 m) – large impact on buildings	Smooth transition from design model to operating model
Moisture is not well-modeled	Better inverse-modeling capability
Ground coupling is not well-modeled	Better theory of in-building convection
Equipment performance (esp. legacy) is not well-modeled	Communicating anticipated loads to utilities

SIMULATION & COMPUTATION
TIME AND LENGTH SCALES



Thanks to Michael McQuade, UTC

CHALLENGE: REDUCING GHG EMISSIONS FROM SPACE COOLING

- **Reduce energy consumption by cooling equipment**
- **Alternate refrigerants with GWP < 1**
- **On demand local cooling**

GHG EMISSIONS FROM HFC WORKING FLUIDS

- ***Standard residential A/C working fluid is moving from R-22 (production/import ban starts in 2010) to R-410A and other HFCs.***
- ***Standard vehicle A/C working fluid is moving from R-12 (production/import ban started in X) to R-134a.***
- ***R-410A 100-year GWP: 2,088.***
- ***R-404A 100-year GWP: 3,922.***

AZ-20 (Honeywell)

Puron (Carrier)

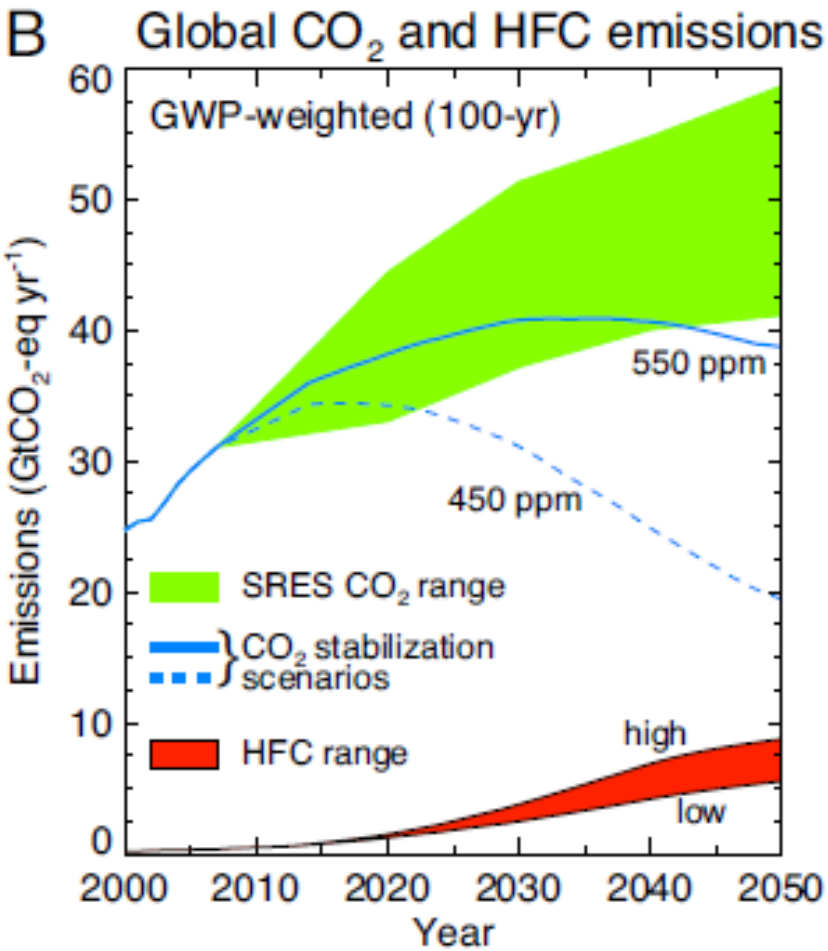
Forane 404A (Arkema)

Suva 410A (DuPont)

Sources:

1) *Velders et al, PNAS **106**, 10949 (2009), http://www.pnas.org/content/suppl/2009/06/22/0902817106.DCSupplemental/0902817106SI.pdf#nameddest=ST2*
2) *EPA: http://www.epa.gov/Ozone/snap/refrigerants/lists/homeac.html*

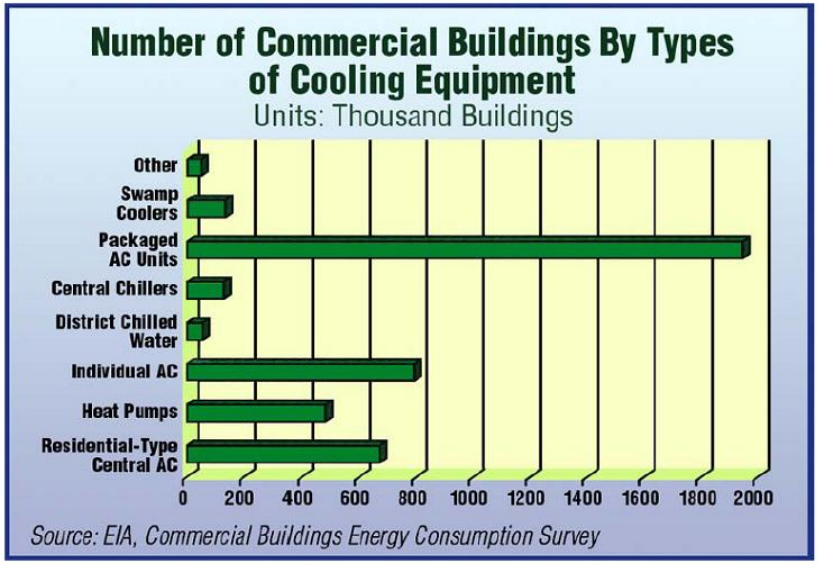
HFC EMISSIONS: AIR CONDITIONING & REFRIGERATION

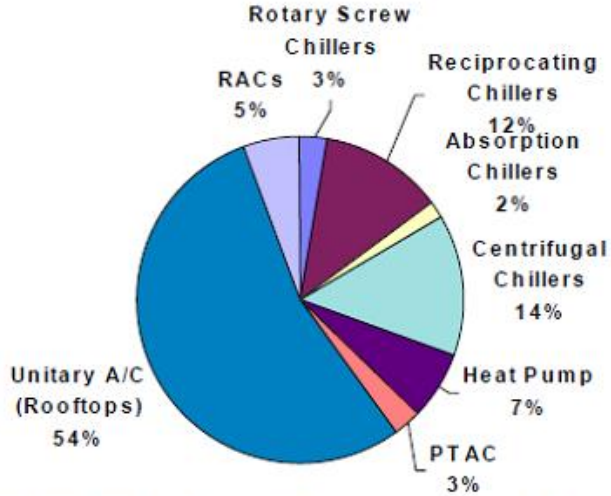


- **Under a 450-ppm stabilization scenario, HFCs are likely to contribute 28-45% of total GHG emissions in 2050, on a CO_2-eq basis.**
- **Growth is driven by demand for A/C and refrigeration in the developing world.**

*Source: Velders et al, PNAS **106**, 10949 (2009), http://www.pnas.org/content/suppl/2009/06/22/0902817106.DCSupplemental/0902817106SI.pdf#nameddest=ST2*

CURRENT COOLING SYSTEMS





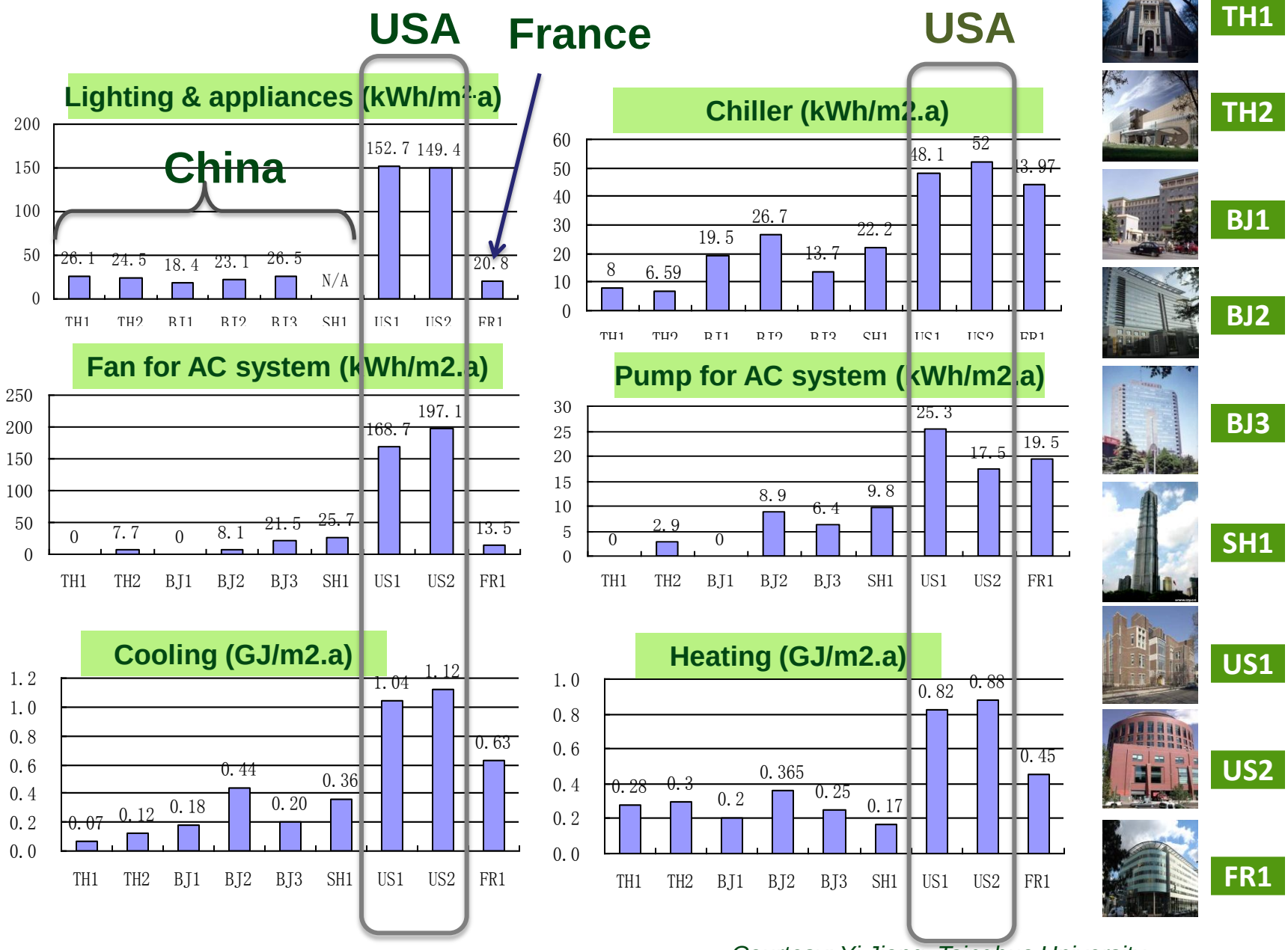
Commercial Building Cooling Energy Consumption in 1995 (from ADL, 2001)

COP = Cooling load/ electrical energy supplied

Cooling type	COP	Source
Air cooled systems	~4	EERE, DOE
Water cooled systems (evaporative cooling of condensers)	~7	EERE, DOE

Can we get COP same as water cooled chiller but without loss of water?

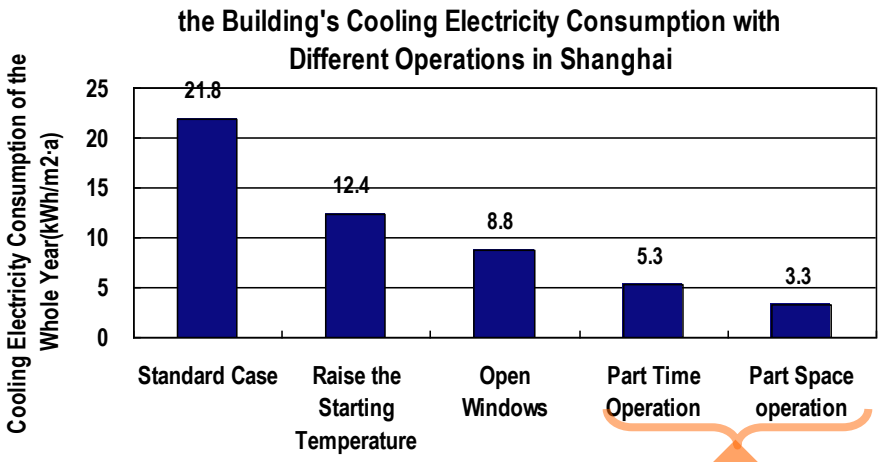
ENERGY END USE INTENSITIES IN BUILDINGS



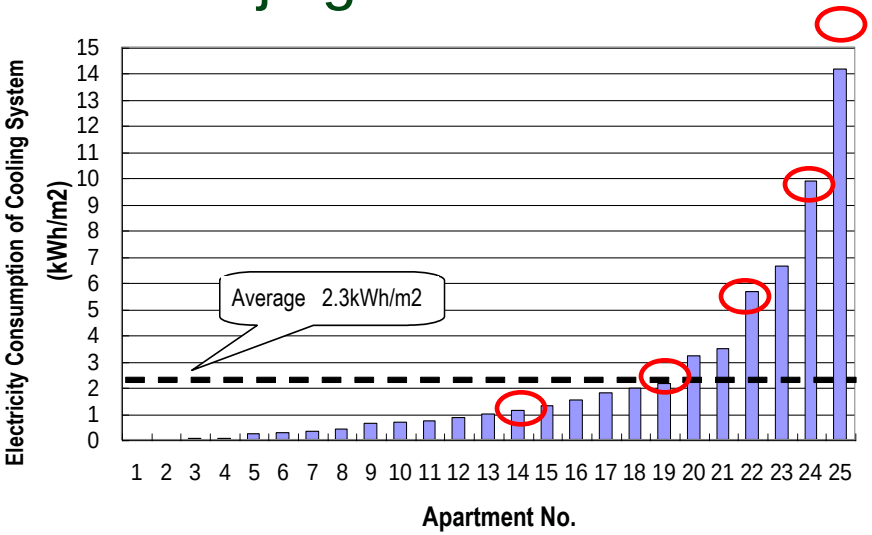
Courtesy: Yi Jiang, Tsinghua University

HOW BUILDINGS ARE OPERATED IS IMPORTANT

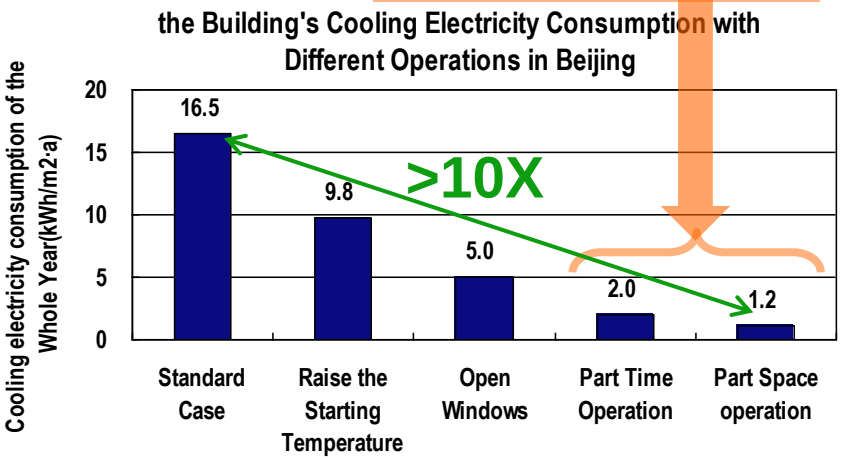
- Comparing with the energy consumption of the five cases
  - **Total cooling electricity consumption:**
    21.8kWh/m² to 3.3kWh/m²!



- Measured data & simulation data in Beijing



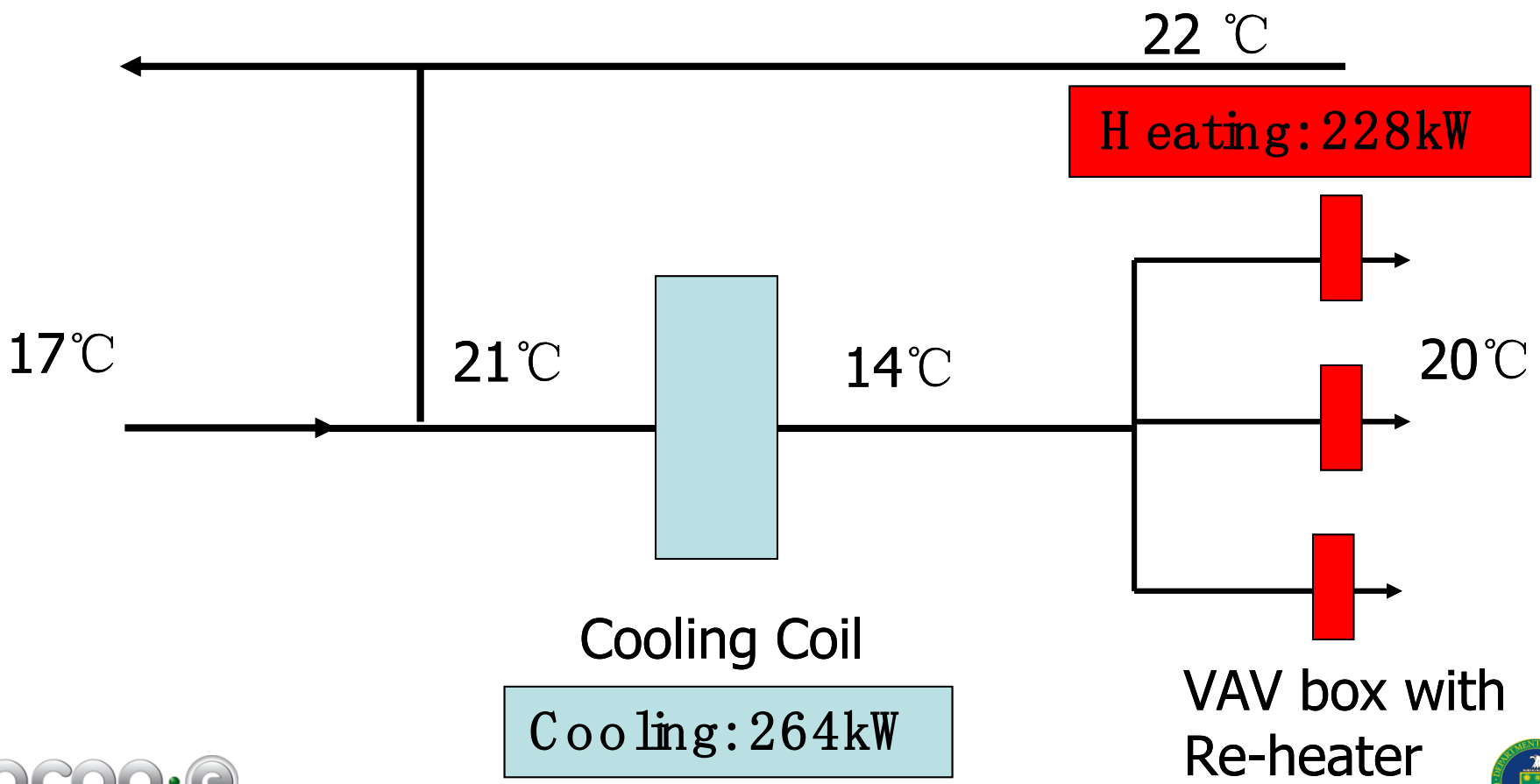
Cooling On Demand in Space & Time



Courtesy: Yi Jiang, Tsinghua University

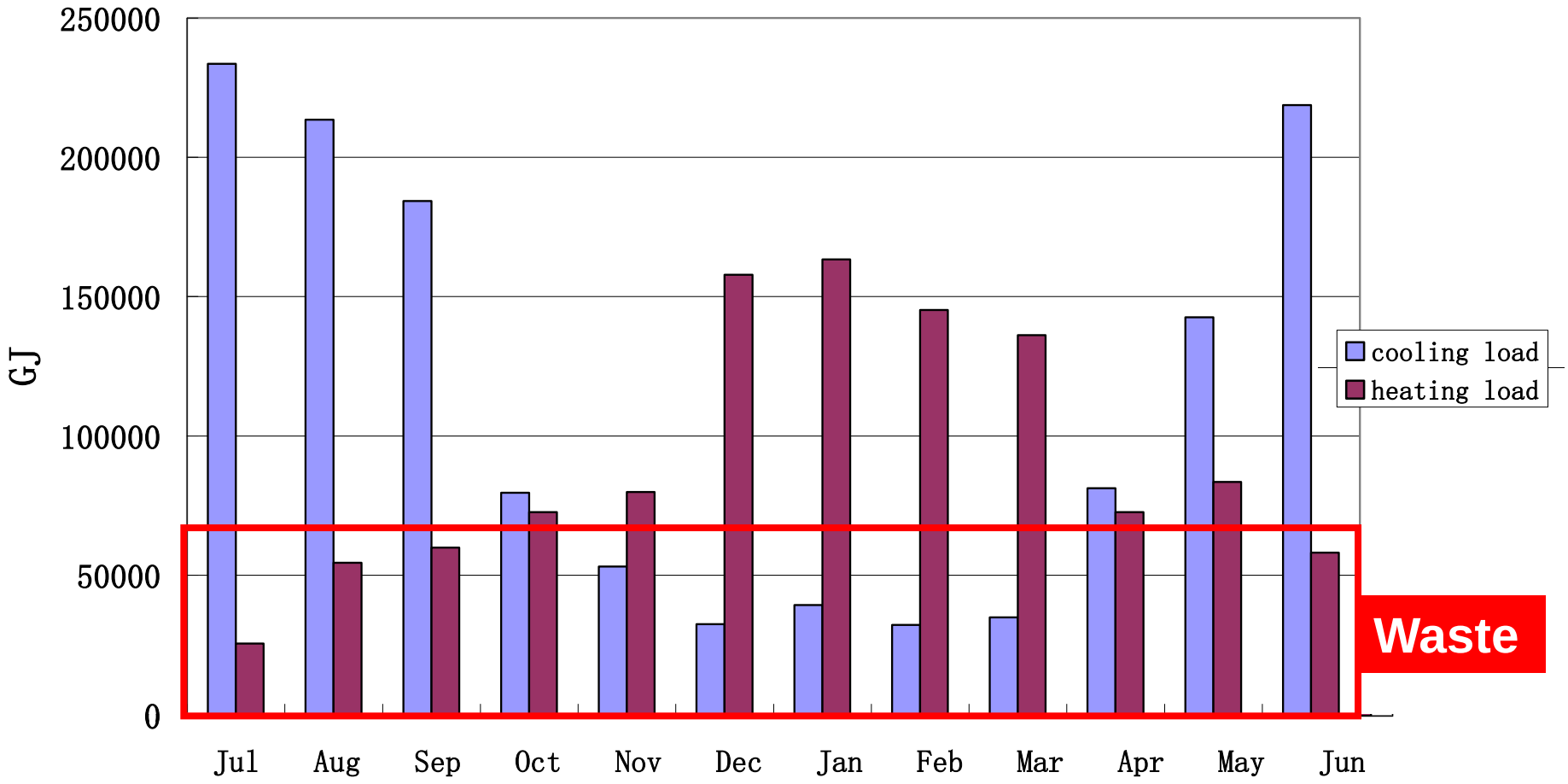
REHEAT FIGHTING WITH COOLING

A typical Air Handling Process in a US bldg: VAV + Reheat



Courtesy: Yi Jiang, Tsinghua University

HEATING & COOLING IN AN USA CAMPUS IN PHILADELPHIA

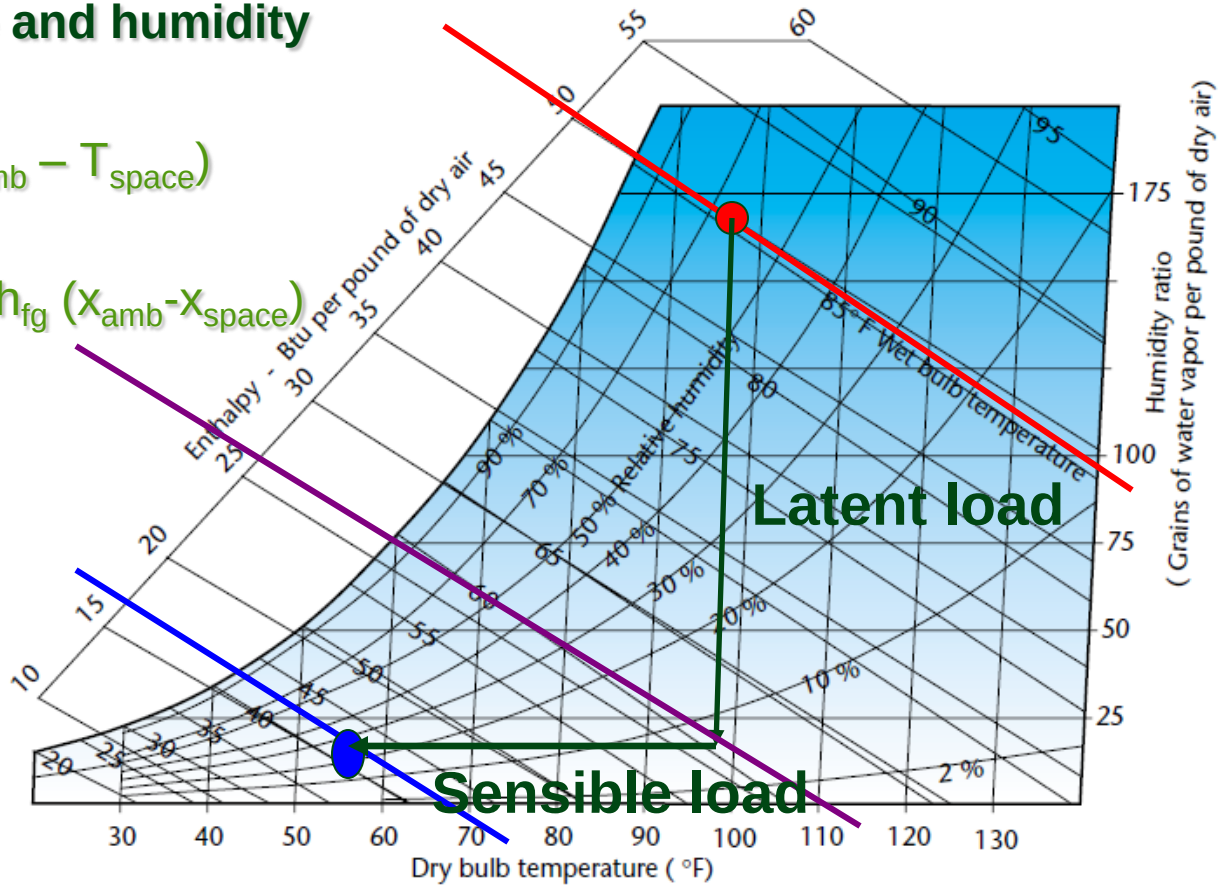


Courtesy: Yi Jiang, Tsinghua University

THERMAL LOADS ON A/C

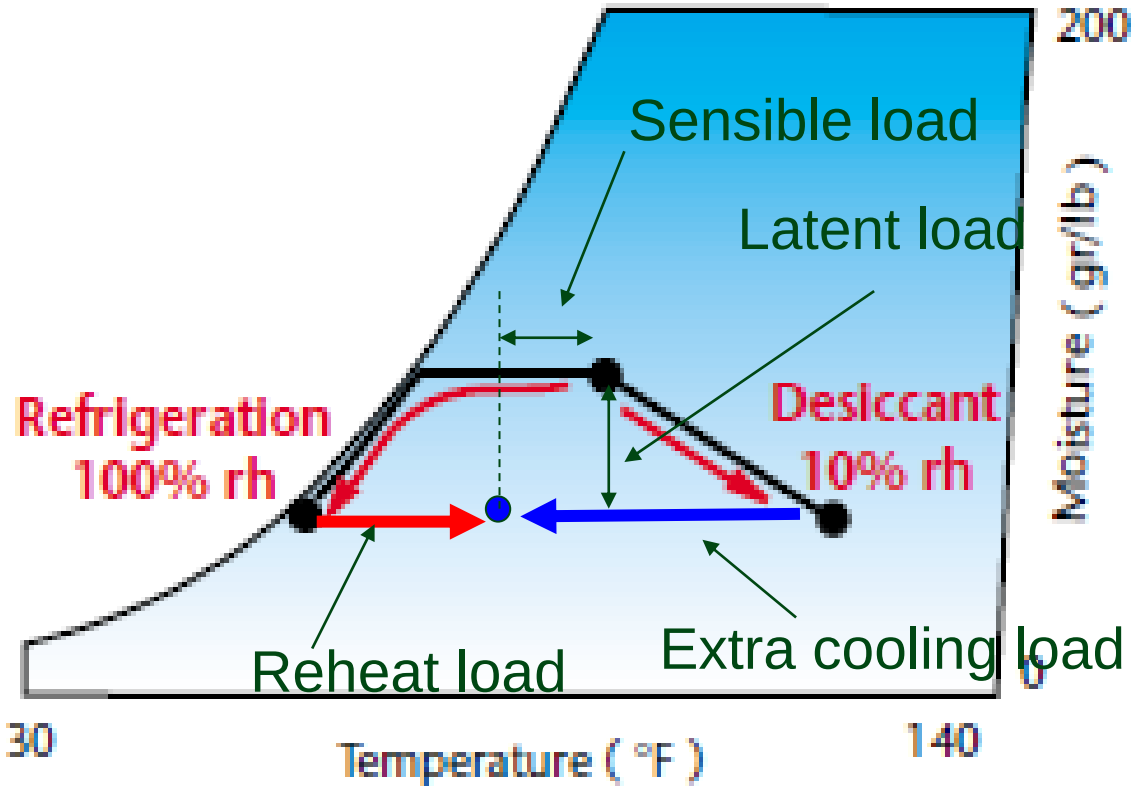
- **Reduction of temperature and humidity**
- **Two types of loads**
  - Sensible load: $mC_p\ (T_{amb} - T_{space})$
  - Latent/humidity load: $mh_{fg}\ (x_{amb} - x_{space})$

m = mass flow rate of air
C_p = specific heat of air
h_{fg} = latent heat of water
x = humidity ratio (mass of water vapor/mass of air)



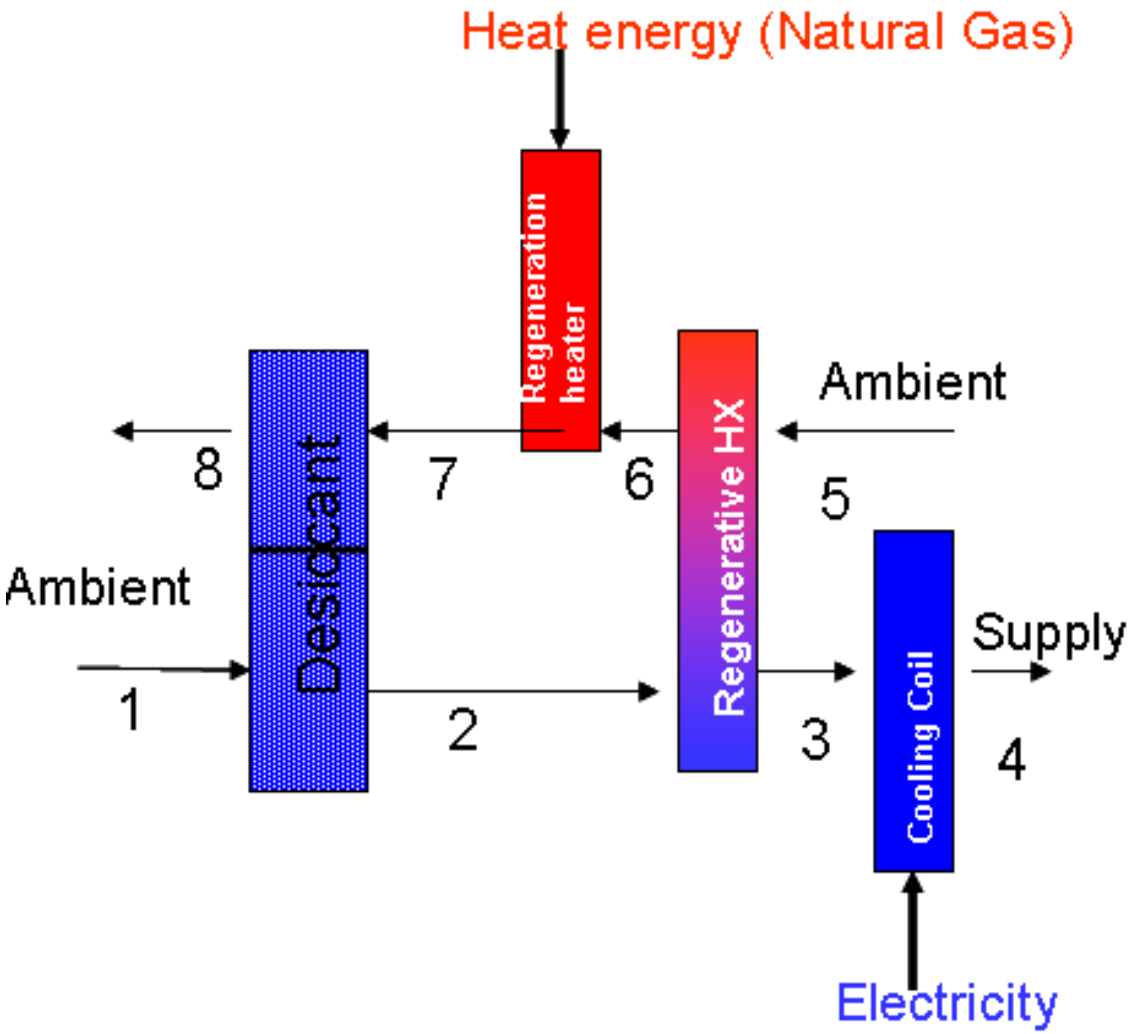
Minimum theoretical work required to go from 1 to 2 = Availability (exergy) of moist air

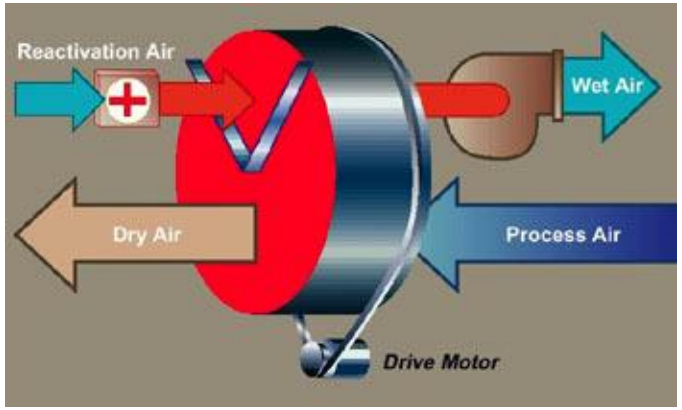
SEPARATE CONTROL OF HUMIDITY & SENSIBLE LOAD



Which is a more energy efficient path?

DESICCANT SYSTEMS





BACKGROUND ON DESICCANTS

- **Desiccants material that absorb moisture**:
- **During moisture adsorption/absorption (sorption)**
  - Latent is converted to sensible heat: Water vapor converts to liquid
  - Heat is released due to sorption (typically small compared to L to S conversion)
  - Therefore process ~ isoenthalpic
- **During desorption in the regeneration of moisture to atmosphere**
  - Regeneration energy = sum of
    - Latent heat
    - Heat necessary to raise the desiccant to a temperature high enough to make its surface vapor pressure higher than that of surrounding air
  - Desorption rate (r) = A*exp ($-E_a/k_BT$): Arhenius Rate

Extra energy needed to to desorb the desiccant

MINIMUM THEORETICAL WORK FOR AIR CONDITIONING OF MOIST AIR

Availability (Exergy)

For sensible or mechanical cooling (Carnot)

$$w_s = c_{Pair}(T - T_{amb}) - T_{amb}\left[c_{Pair}\ln\left(\frac{T}{T_{amb}}\right)\right] + x\left(c_{Pvapor}(T - T_{amb}) - T_{amb}\left[c_{Pvapor}\ln\left(\frac{T}{T_{amb}}\right)\right]\right)$$

For dehumidification or latent load cooling (Entropy of mixing):

$$w_l = R_{air}T_{amb}\ln\left(\frac{P - P_{vapor}}{P - P_{vapor_amb}}\right) + xR_{vapor}T_{amb}\ln\left(\frac{P_{vapor}}{P_{vapor_amb}}\right)$$

Mina, Newell,& Jacobi, Int. J. Refrigeration, 28. 784 – 790 (2005)

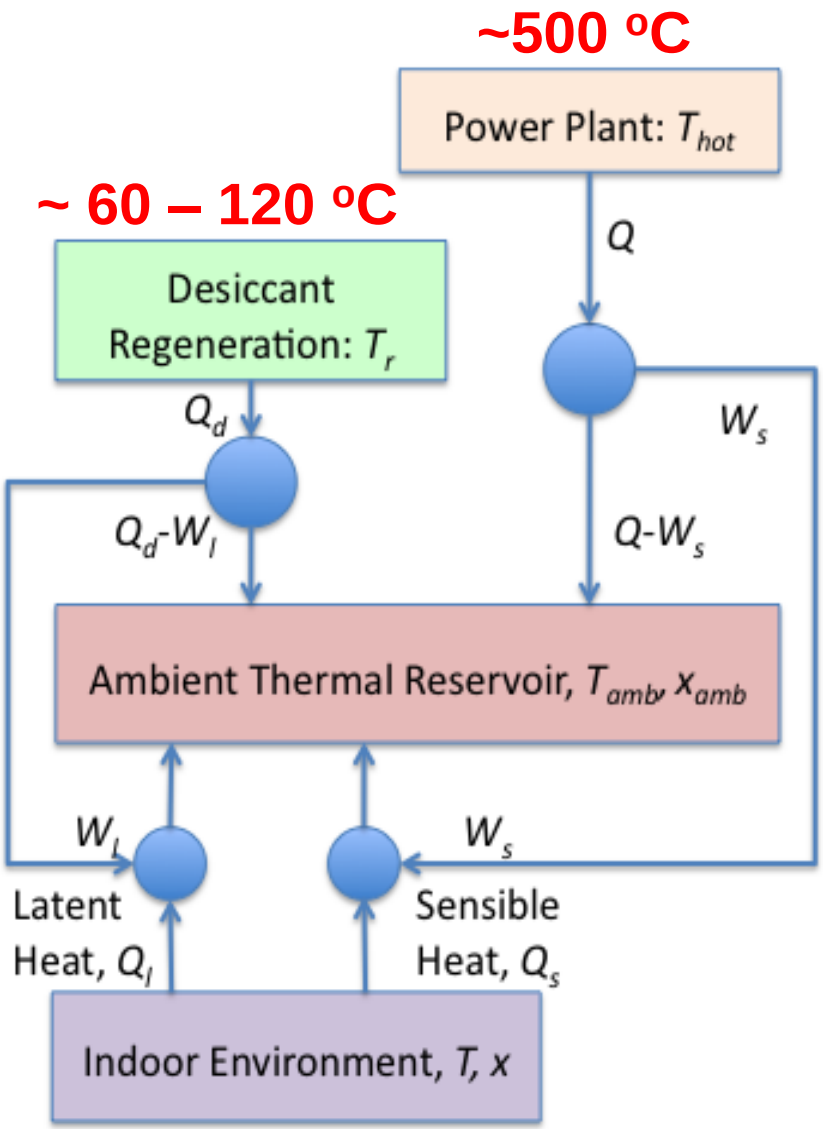
IDEAL SYSTEM AT THERMODYNAMIC LIMIT

Latent Heat

$$COP_{latent} = \frac{Q_l}{Q_d} = \frac{Q_l}{W_l / \eta_{Carnot}}$$

Ideal COP_{latent} = ~ 2.5-6.5

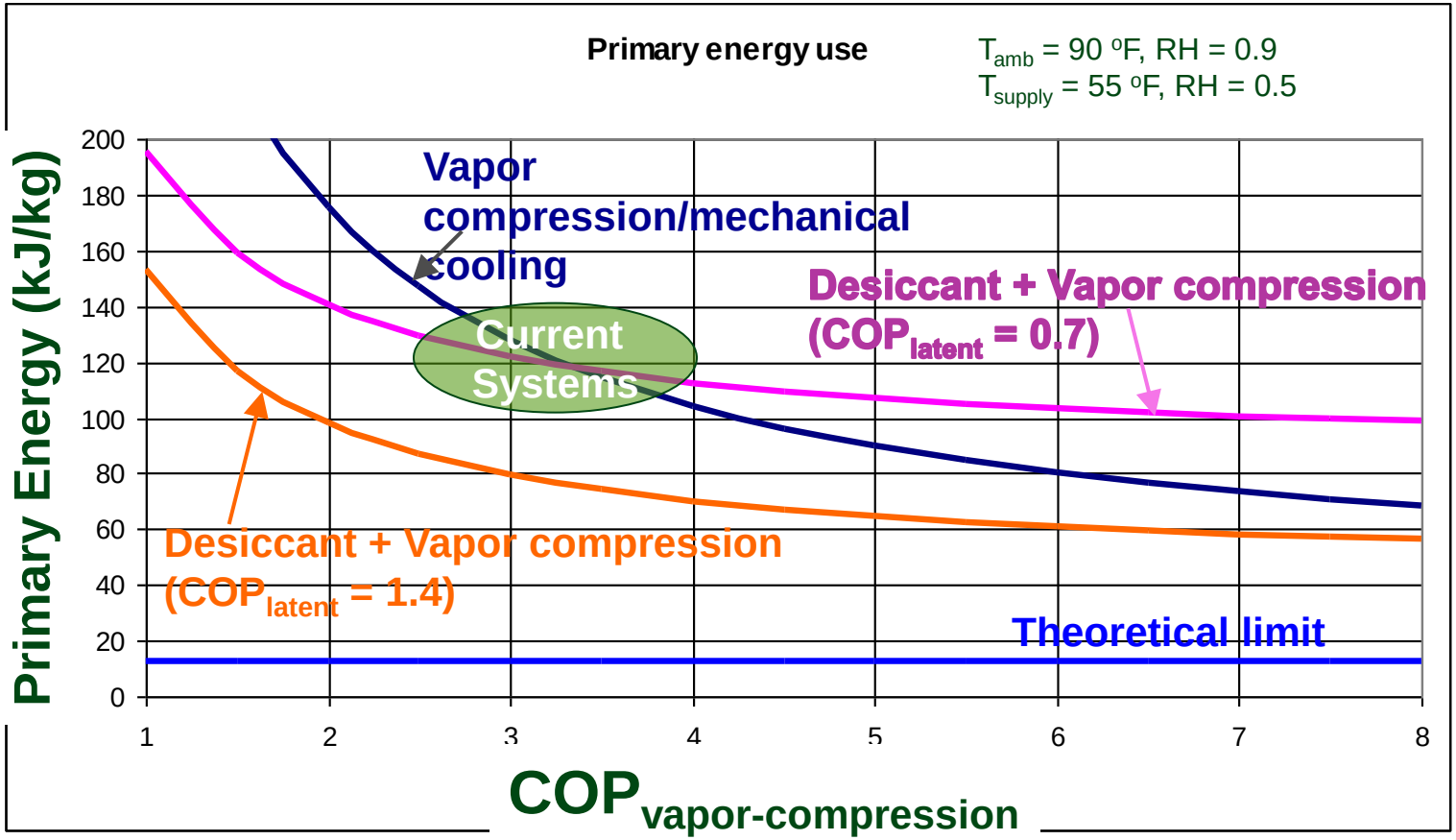
***Real COP* = ~ 0.7 – 1.0**



Sensible Heat

$$\eta_{Carnot} = \frac{W_s}{Q} = 1 - \frac{T_{amb}}{T_{hot}}$$

REAL SYSTEMS VS. THEORETICAL LIMIT

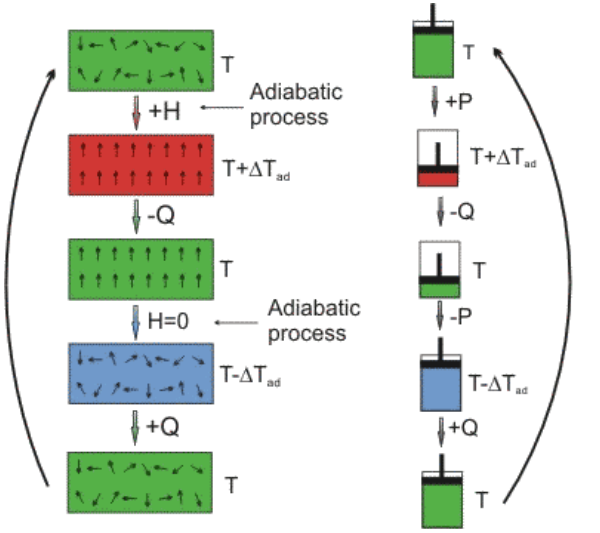


Difference between current energy input and ideal system can be reduced by 50% by

- **Increasing the COP of vapor compression (without loss of water!)**
- **Increasing the COP of the desiccant**

REFRIGERANTS WITH GLOBAL WARMING POTENTIAL (GWP) ≤ 1

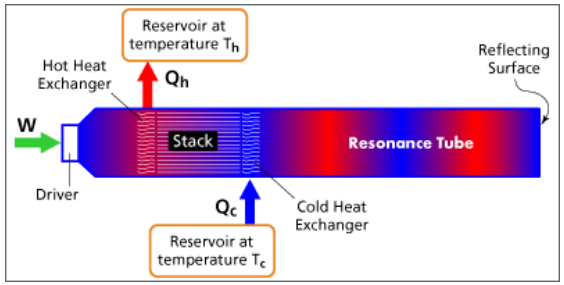
Magnetic refrigerants



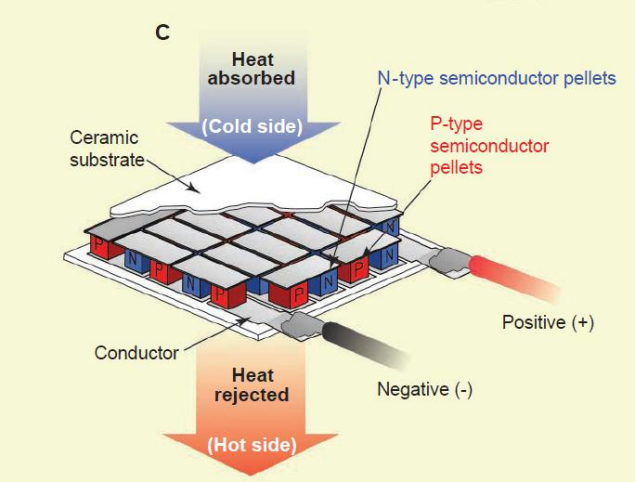
Magnetic refrigeration

Vapor cycle refrigeration

Thermoacoustic refrigeration



Thermoelectric refrigeration



Is it possible to get 1 Ton (3.5 kW) of cooling with COP >4?