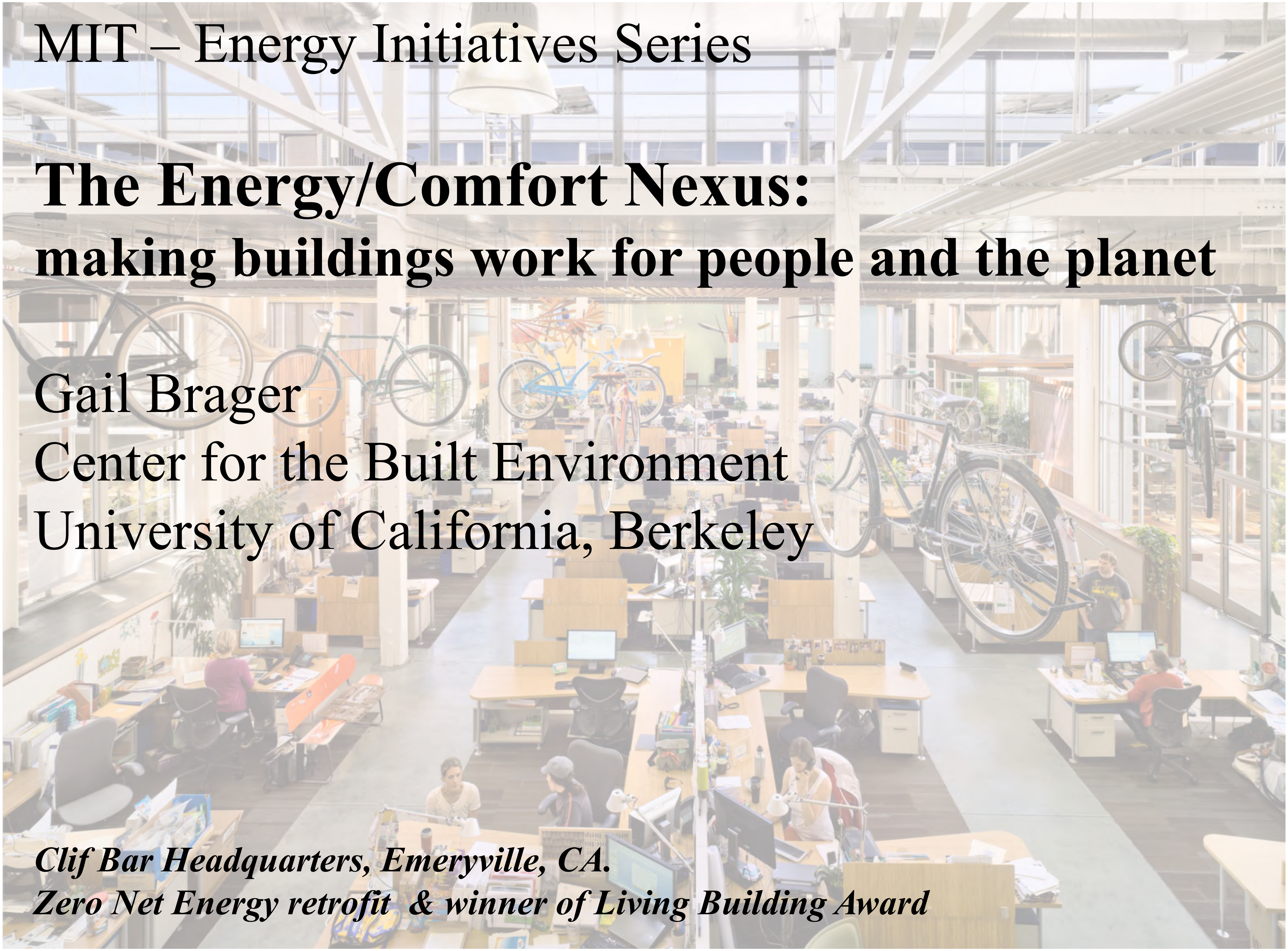


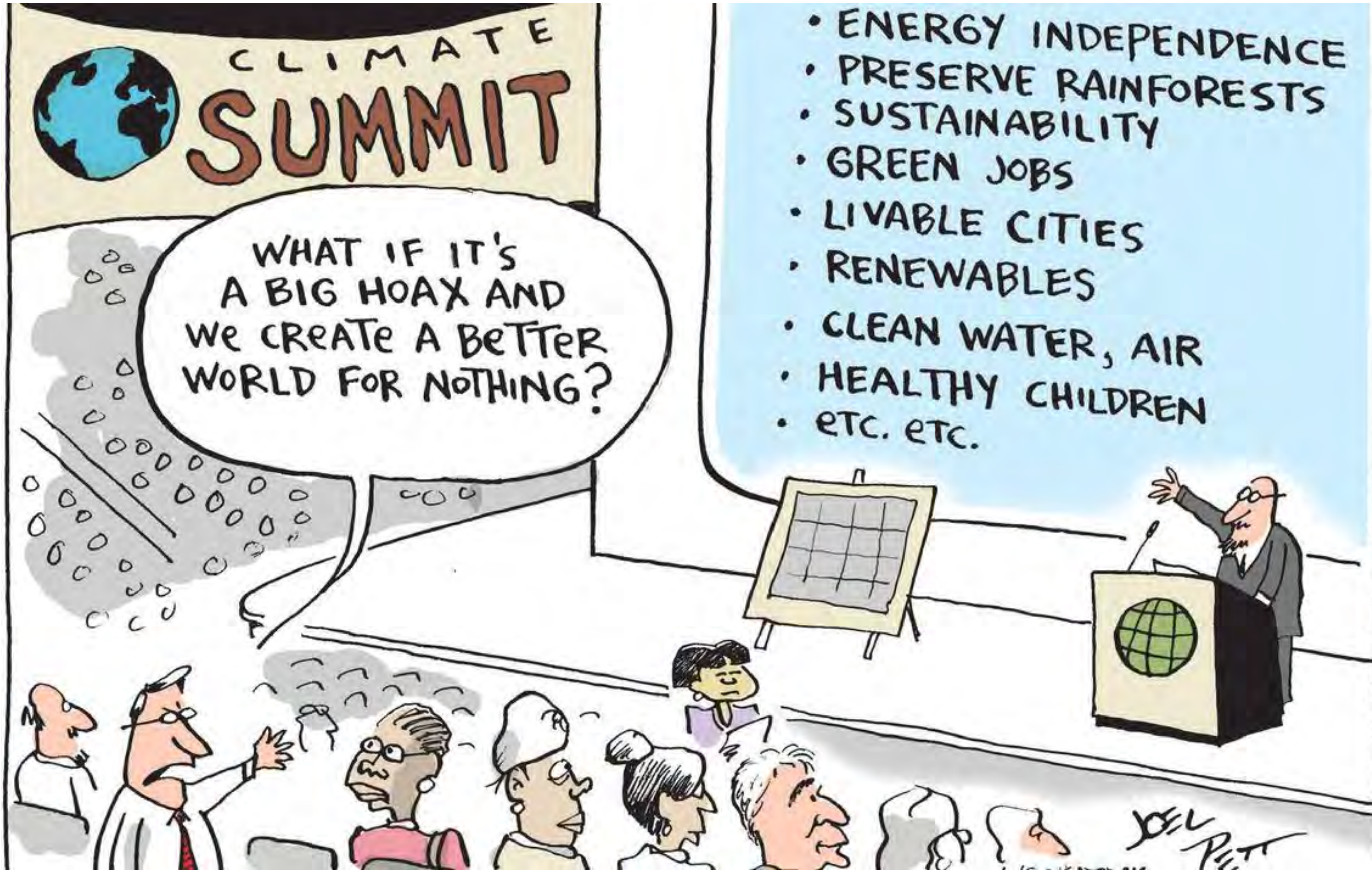
MIT – Energy Initiatives Series

The Energy/Comfort Nexus:
making buildings work for people and the planet

Gail Brager
Center for the Built Environment
University of California, Berkeley

Clif Bar Headquarters, Emeryville, CA.
Zero Net Energy retrofit & winner of Living Building Award

Why energy ?



Cartoon by Joel Pett, USA Today, Dec 2009

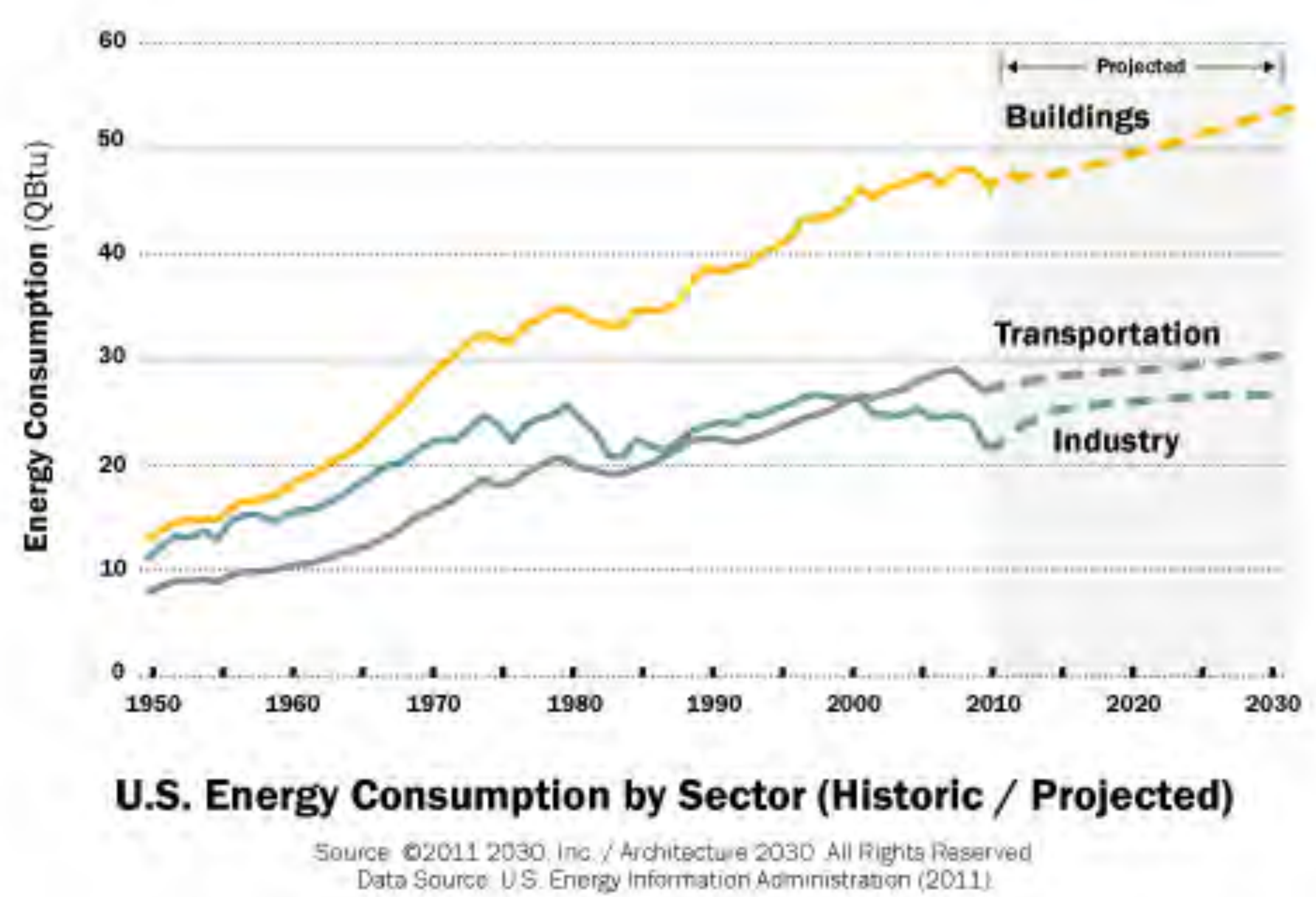
Why comfort?

Source: www.cartoonaday.com

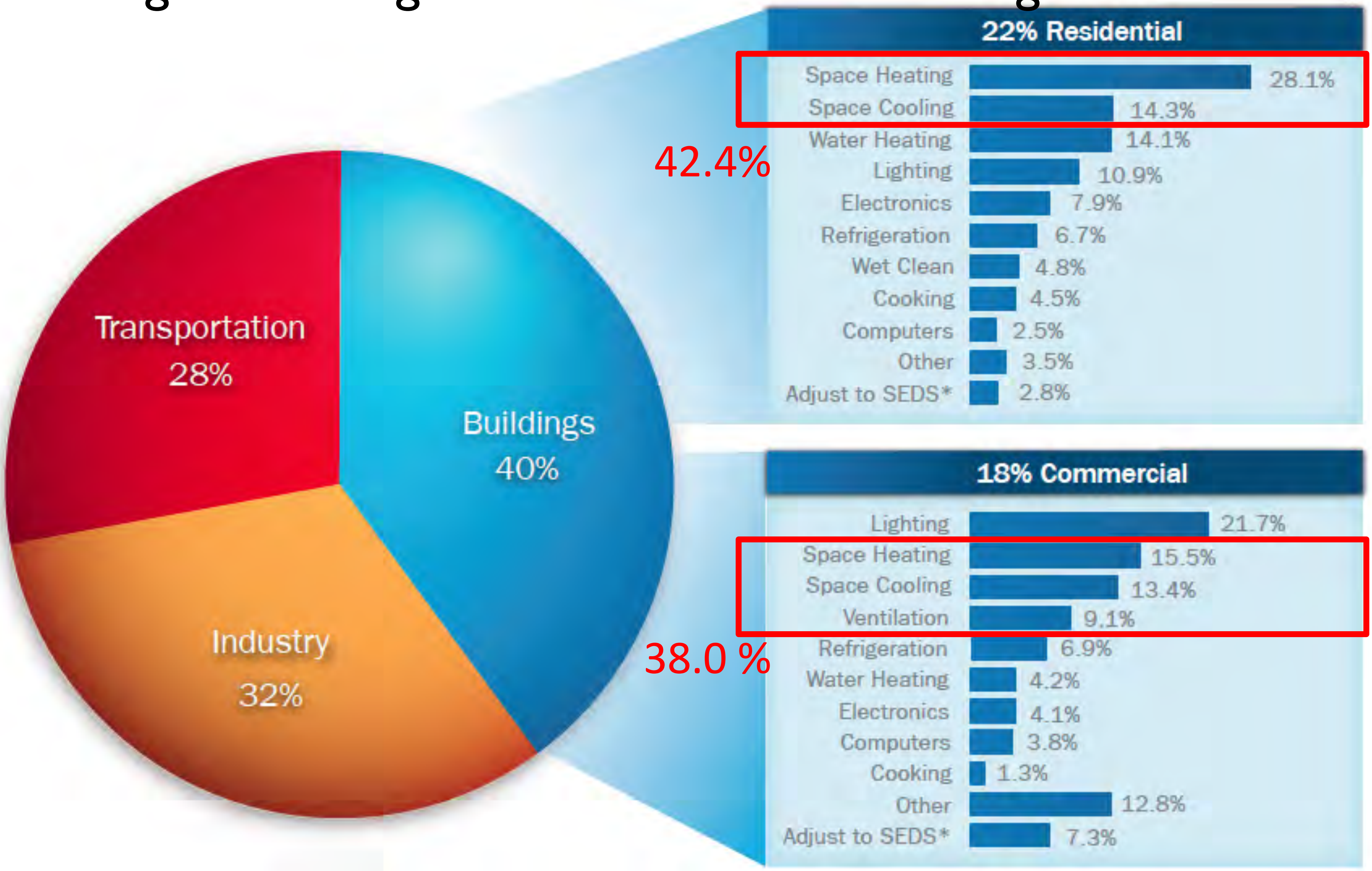
Why buildings?

Trends - U.S. CO_2 Emissions by Sector

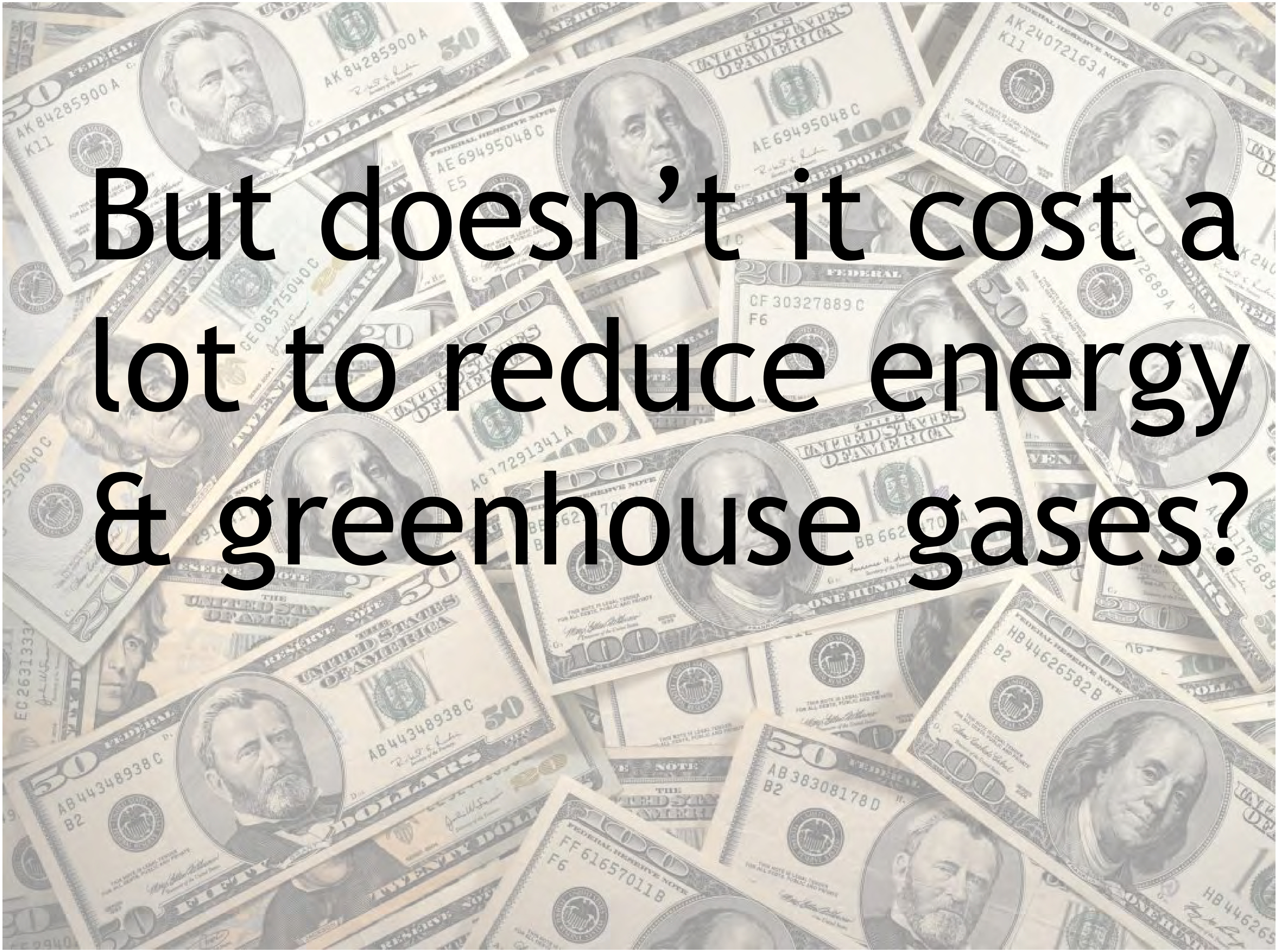
Buildings are responsible for nearly ½ of CO2 emissions in the U.S.



Energy use in buildings
– a significant % goes to thermal conditioning

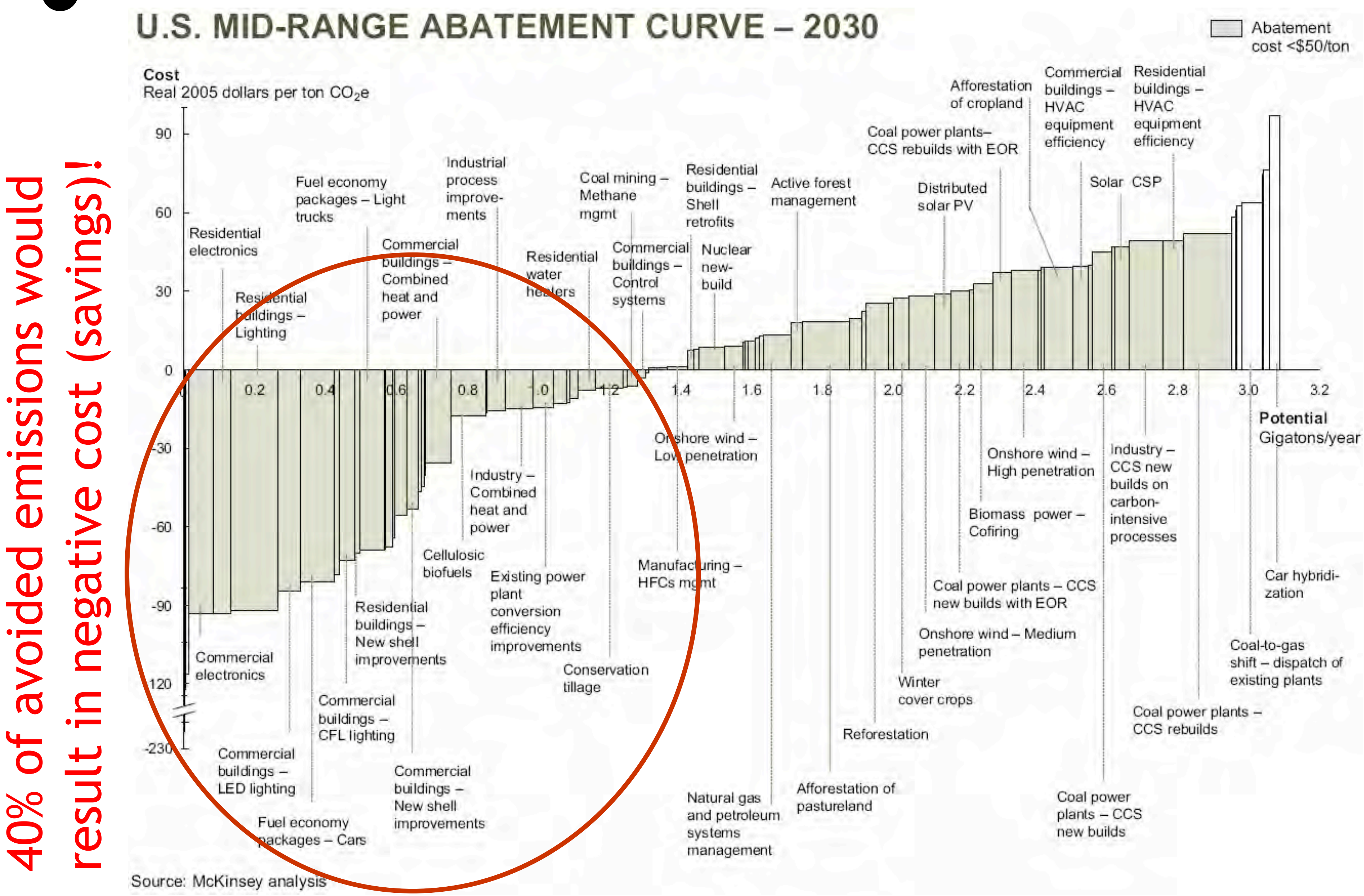


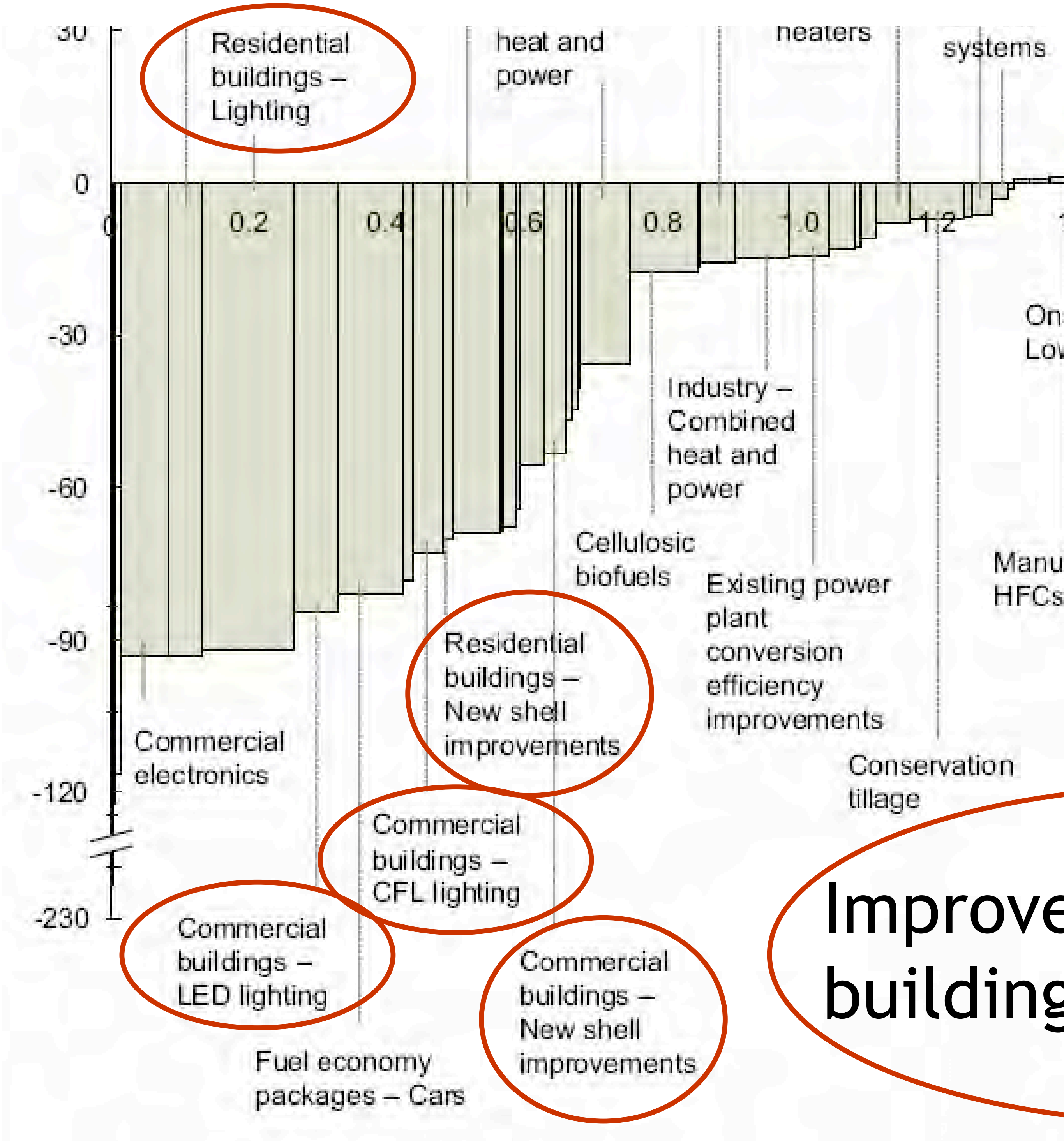
- US DOE Quadrennial Technology Review, http://energy.gov/sites/prod/files/ReportOnTheFirstQTR.pdf



But doesn’t it cost a lot to reduce energy & greenhouse gases?

Costs of Reducing Global Warming



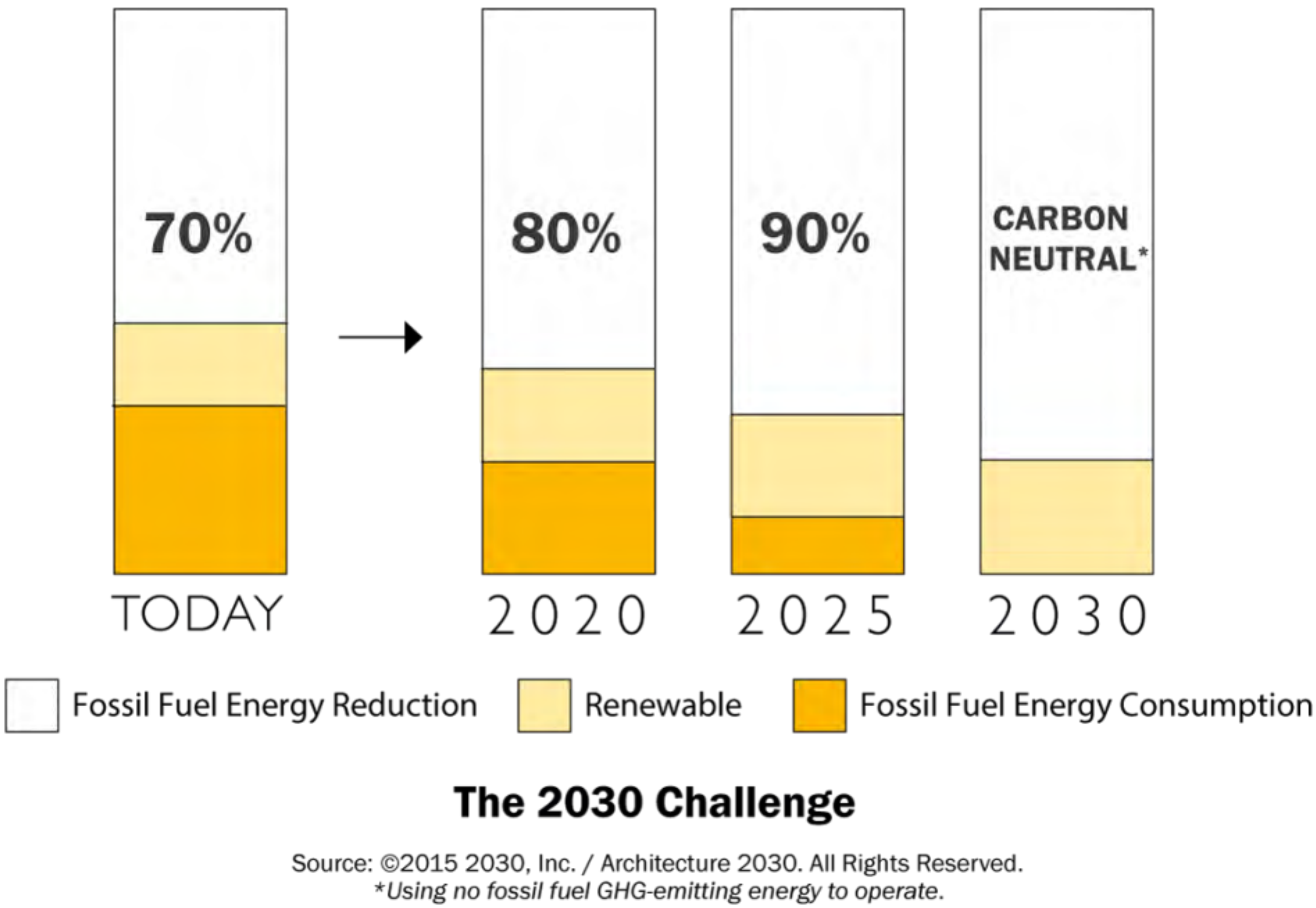


Improved lighting and building envelopes!

The Architecture 2030 Challenge

All new buildings, developments, and major renovations shall be carbon-neutral by 2030.

Tiered % reduction below average for that bldg type



http://architecture2030.org/2030_challenges/2030-challenge/

Meeting the Architecture 2030 Challenge

DESIGN STRATEGIES

The largest energy reductions can be achieved through design.

TECHNOLOGIES AND SYSTEMS

Including on-site renewable energy systems.

OFF-SITE RENEWABLE ENERGY

20% maximum.

Meeting the 2030 Challenge

http://architecture2030.org/2030_challenges/2030-challenge/

Zero Net Energy Buildings (ZNE)

Over a year …. The building generates at least as much as it uses

Zero Net Energy Buildings (ZNE)

Over a year …. The building generates at least as much as it uses

<u>The Name Game</u>

Net zero energy
Net zero site energy
Net zero source energy
Net zero energy emissions
Net zero energy costs
Zero net ready
Ultra-low energy (*)
Zero net energy

- Verified
- Emerging

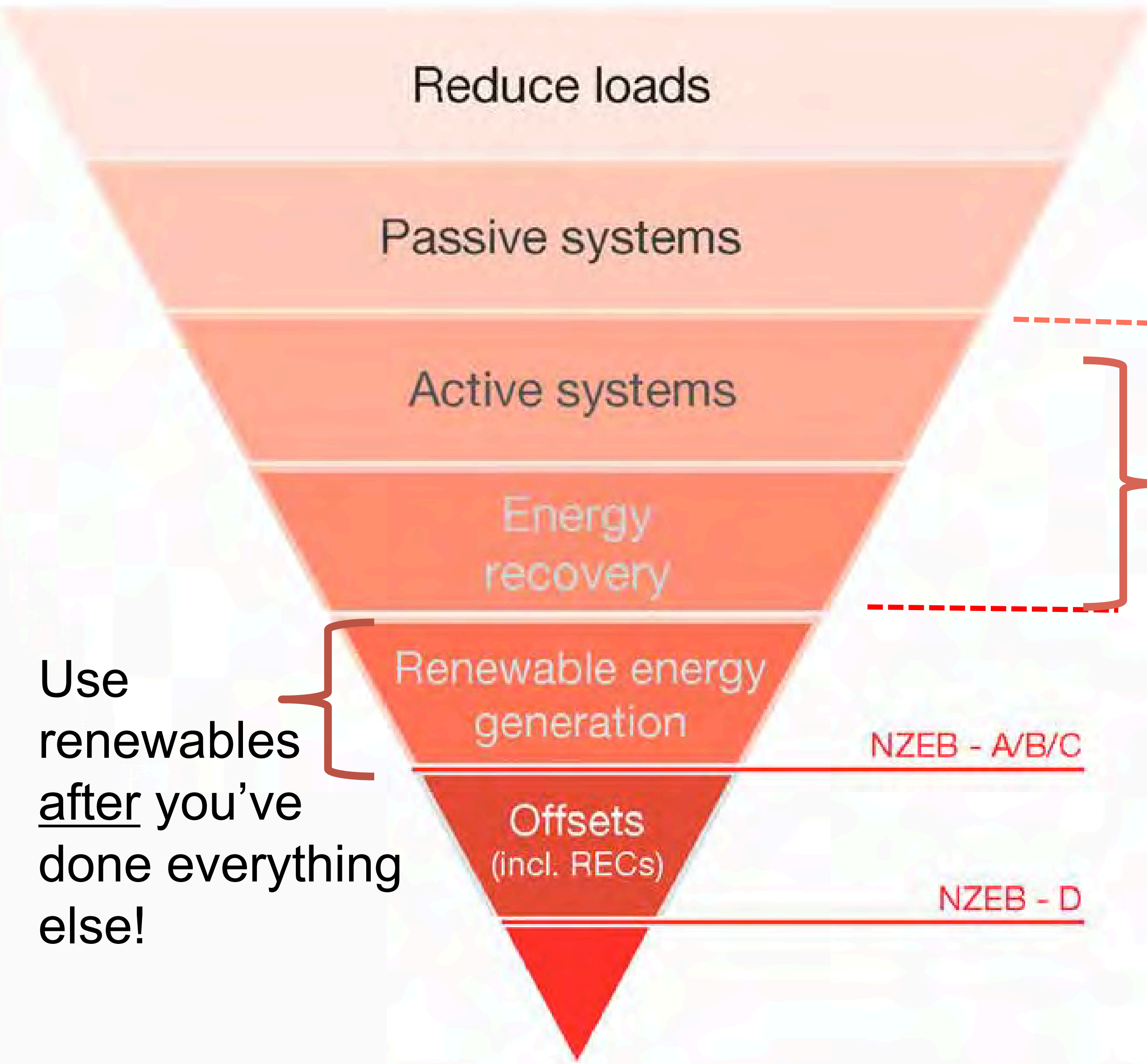
* similar to ZNE in energy use reduction, but haven't invested in on-site renewables

Zero Net Energy Buildings (ZNE)

Definitions	**Descriptions**
Net zero **site** energy building	Building produces as much energy as it consumes when measured on site
Net zero **source** energy building	Building produces the same amount of energy as the amount of source (primary) energy it consumes.
Net zero energy **cost**	Cost of the energy added to the grid by the building is same as the cost of the energy consumed by it.
Net zero **emission**	Net emission due to building energy consumption is zero.

P. Torcellini et al., Zero energy buildings: a critical look at the definition, www.nrel.gov/docs/fy06osti/39833.pdf

Zero Net Energy Buildings - Setting priorities



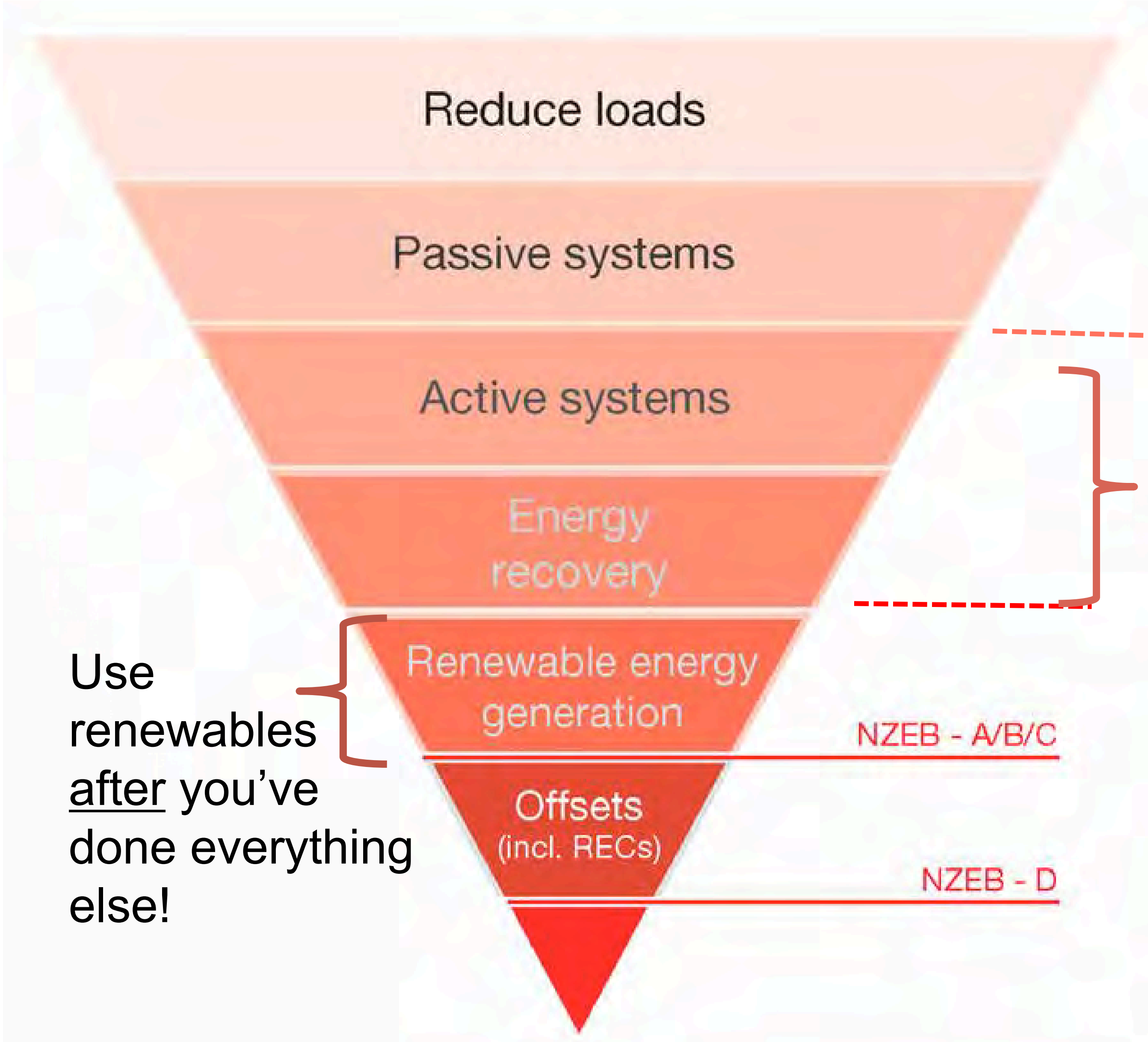
- Shading
- Daylighting
- Climate-response architecture

- Mechanical systems
- Electrical systems

Use renewables <u>after</u> you've done everything else!

Source: <u>Two Degrees</u>, Chap 6, McGregor, Roberts & Cousins

Zero Net Energy Buildings – Setting priorities



- Shading
- Daylighting
- Climate-response architecture

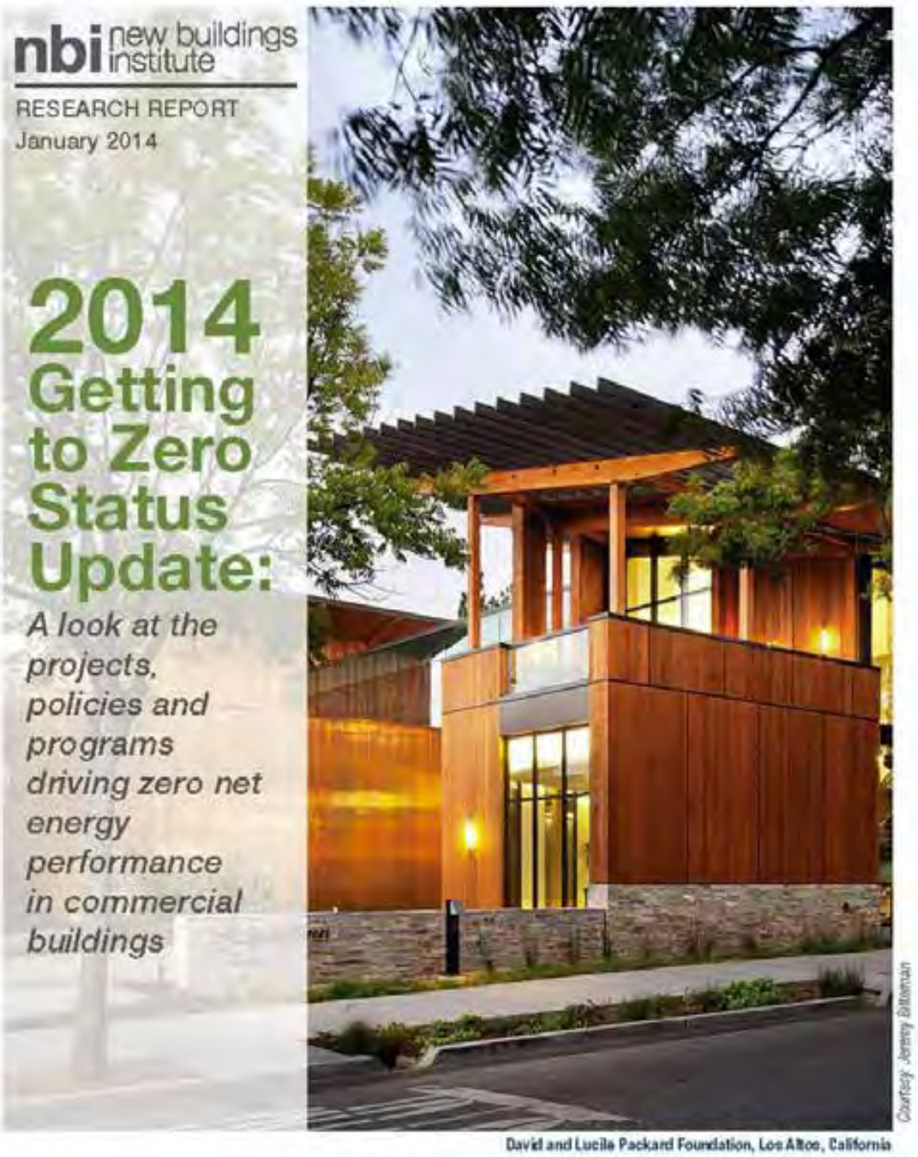
- Mechanical systems
- Electrical systems

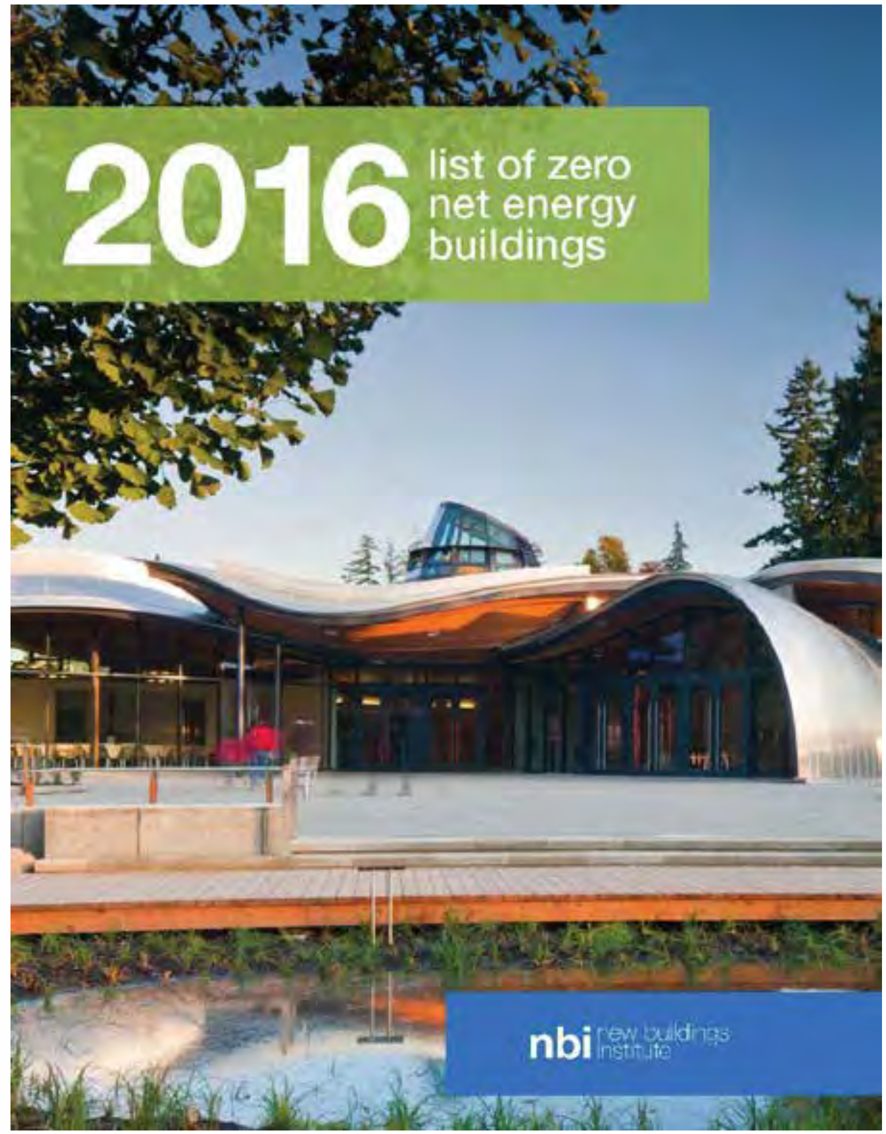
Use renewables after you've done everything else!

Leaky bucket analogy

Source: Two Degrees, Chap 6, McGregor, Roberts & Cousins

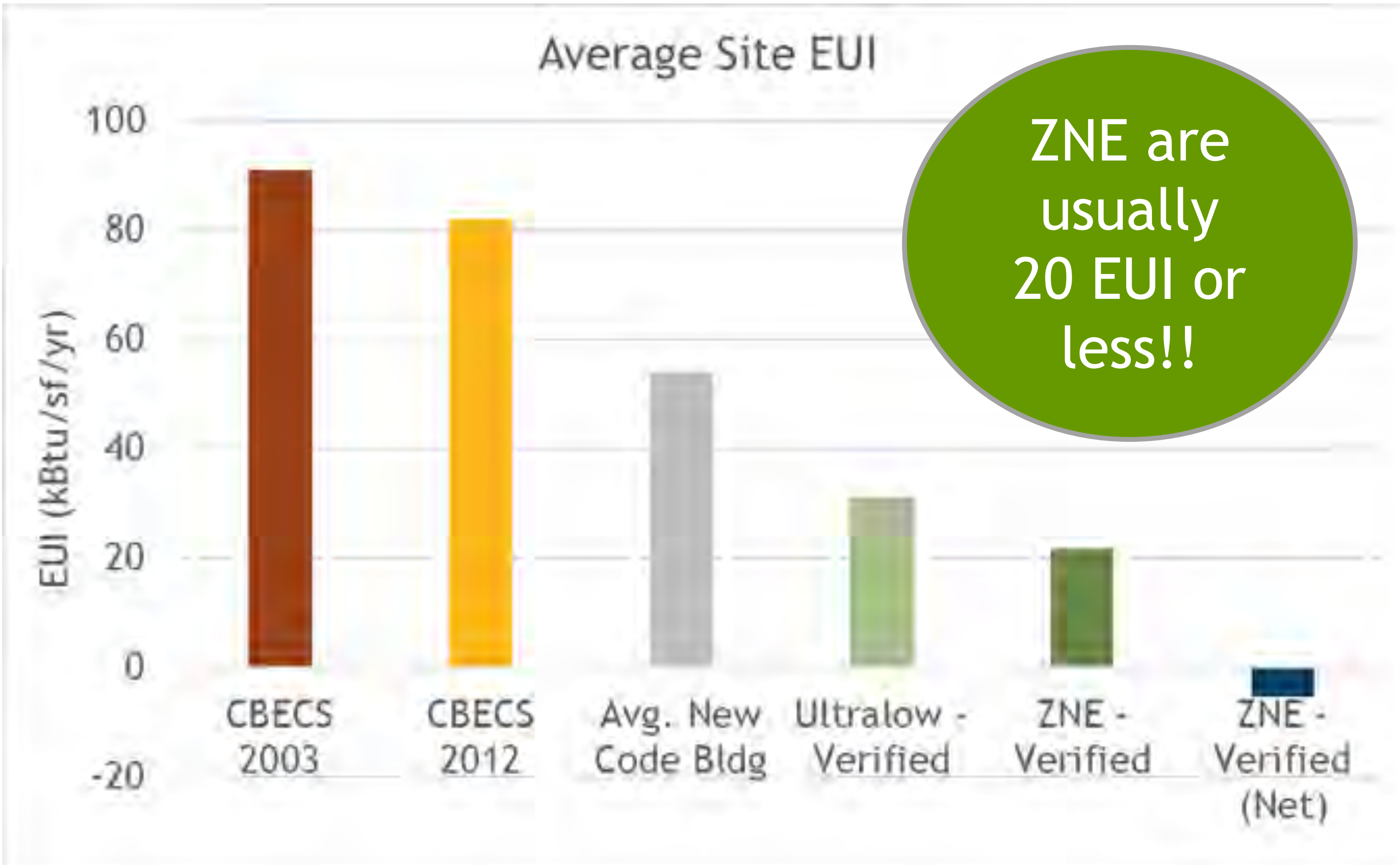
Trends in Zero Net Energy Buildings





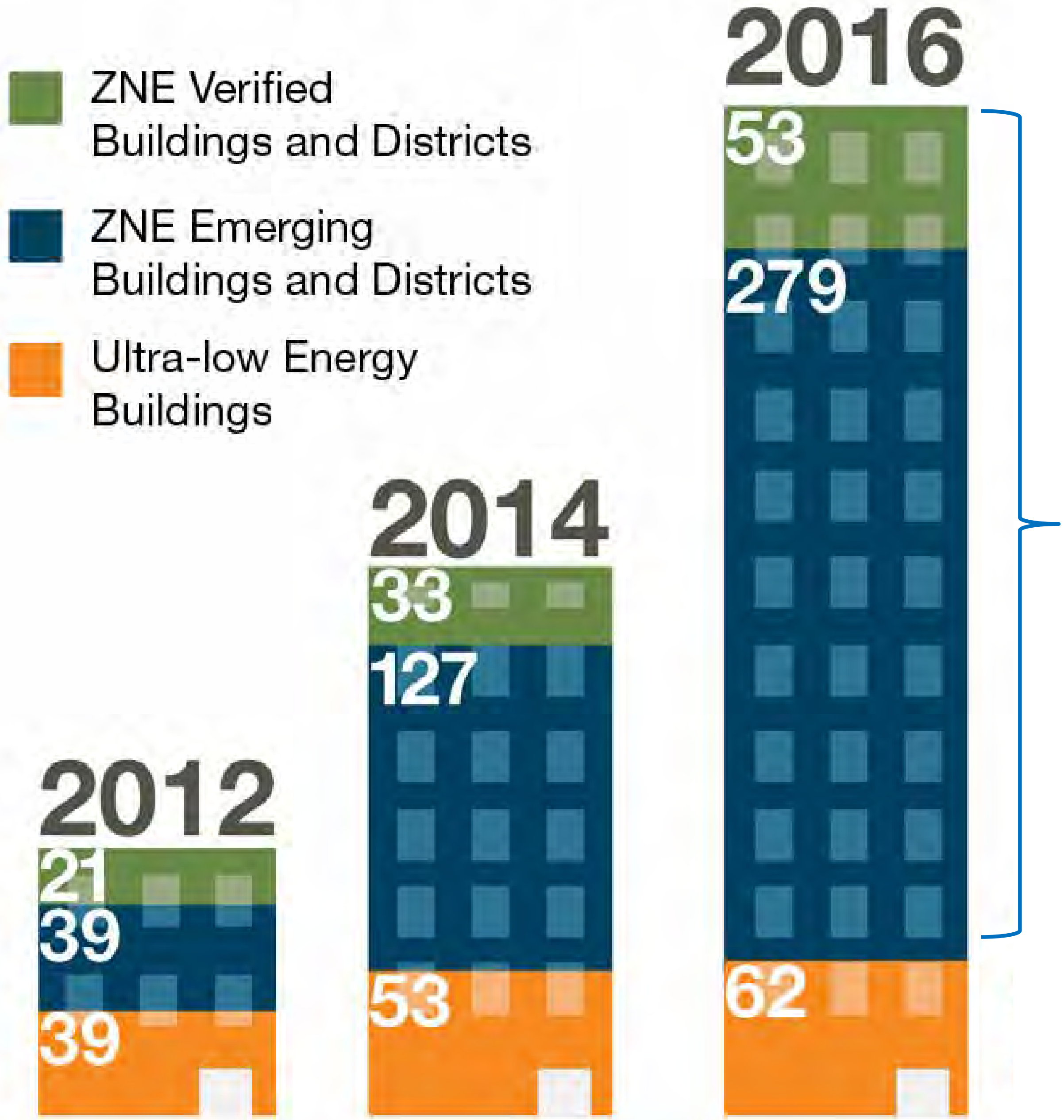
New Buildings Institute reports

Trends in ZNE (& ultra-low energy) – EUI?



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

Trends in ZNE (& ultra-low energy) – how many?

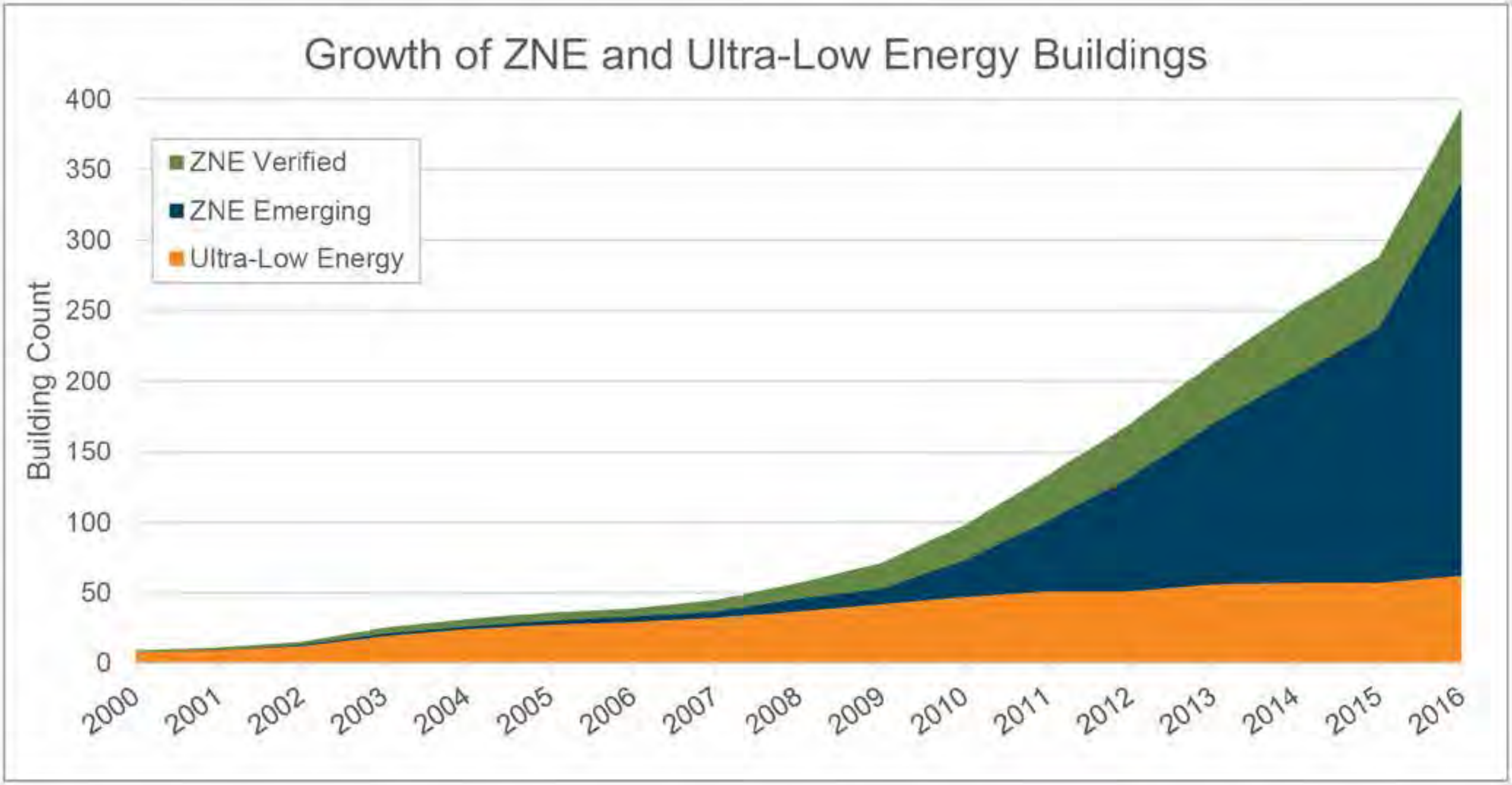


ZNE:
60 → 160 → 332

more than doubled during last 2-year periods

New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

Trends in ZNE (& ultra-low energy) – how many?

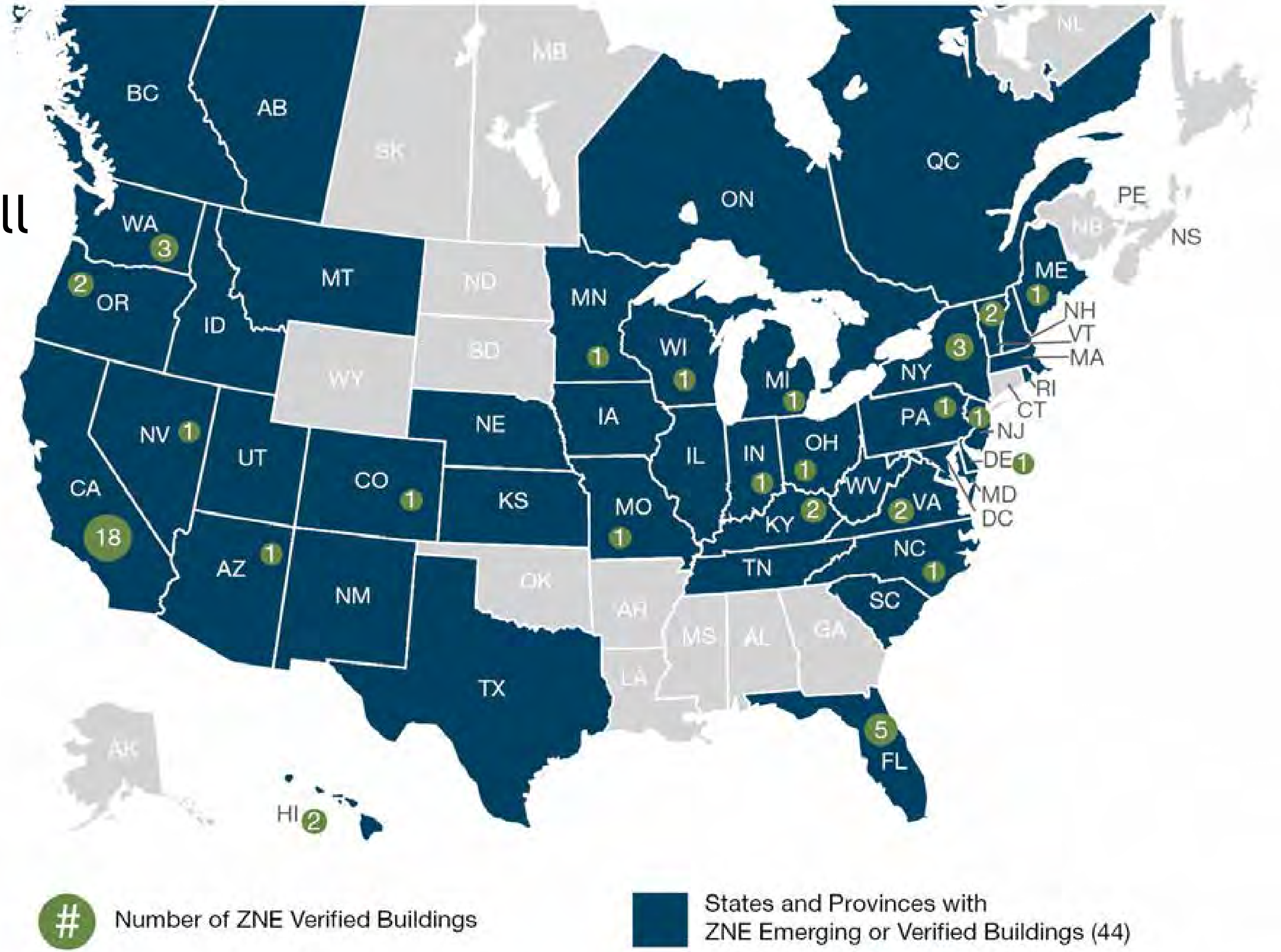


nbi new buildings institute

New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

Trends in ZNE – where?

Nearly all climate zones



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

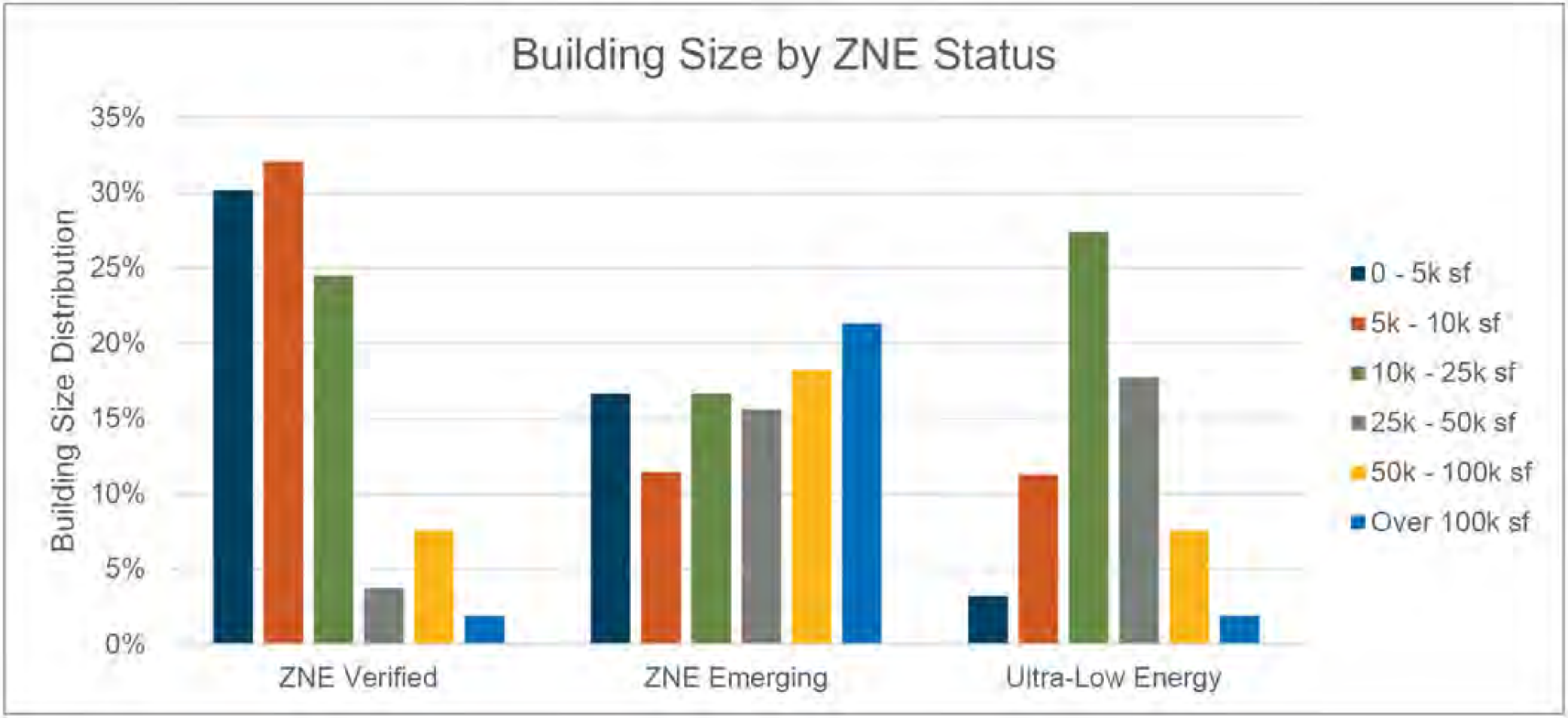
Trends in ZNE (& ultra-low energy) – where?

Massachusetts in top 5 states of ZNE

State	Ultralow Verified	ZNE Emerging	ZNE Verified	Grand Total
CA	17	119	18	154
OR	4	14	2	20
NY	0	11	3	14
MA	3	11	0	14
FL	2	6	5	13

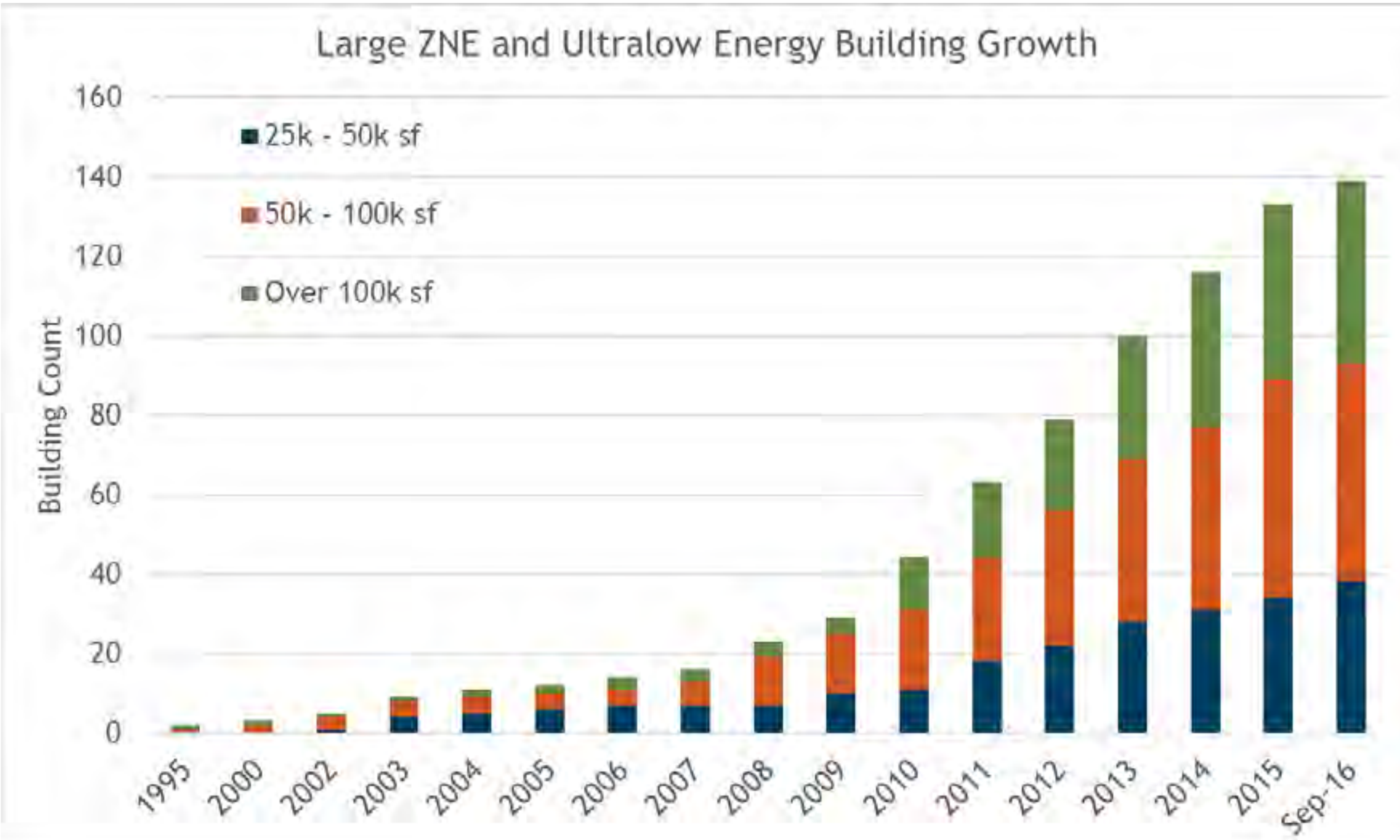
New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

Trends in ZNE (& ultra-low energy) – how big?



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

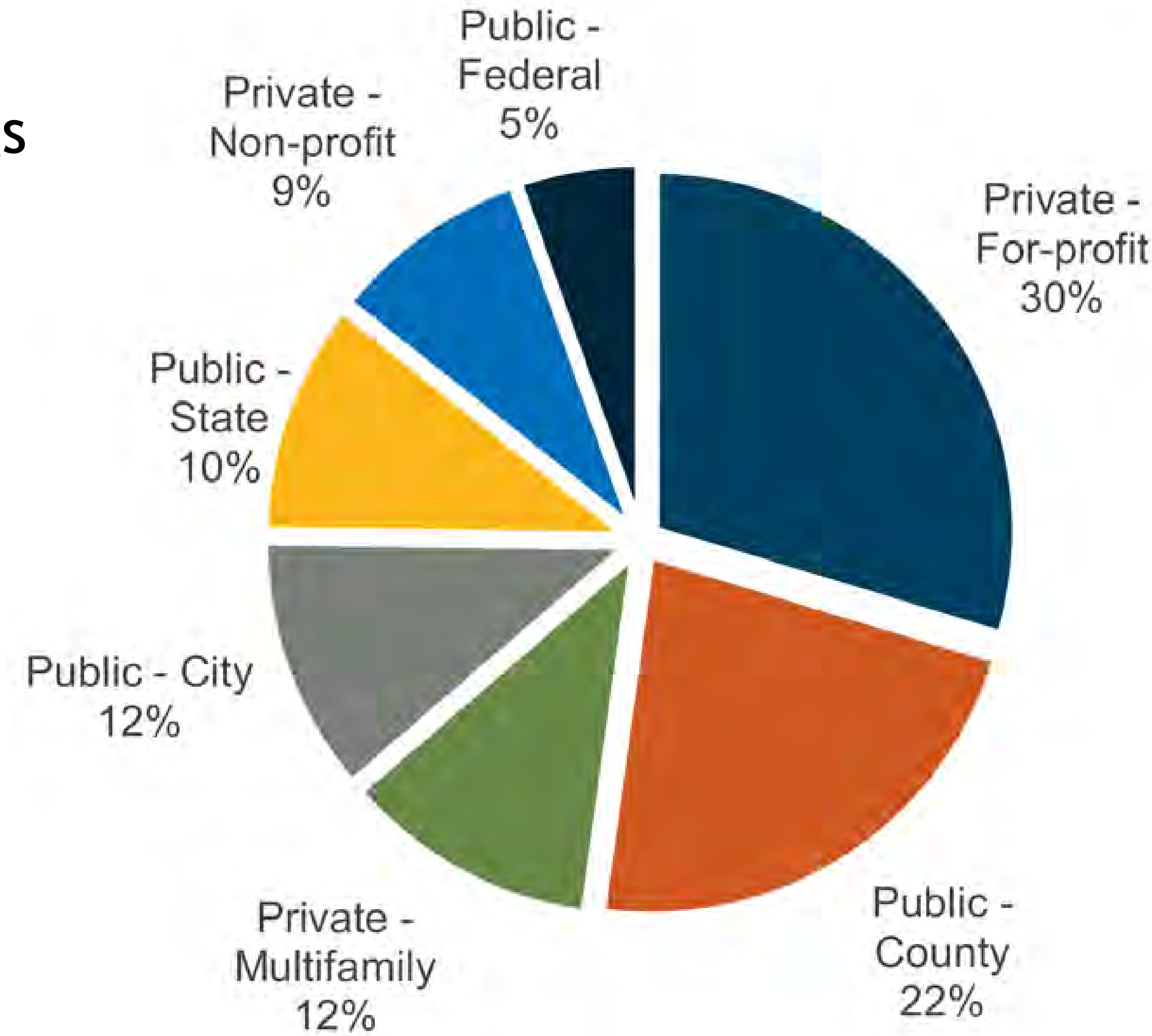
Trends in ZNE – growth by size



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

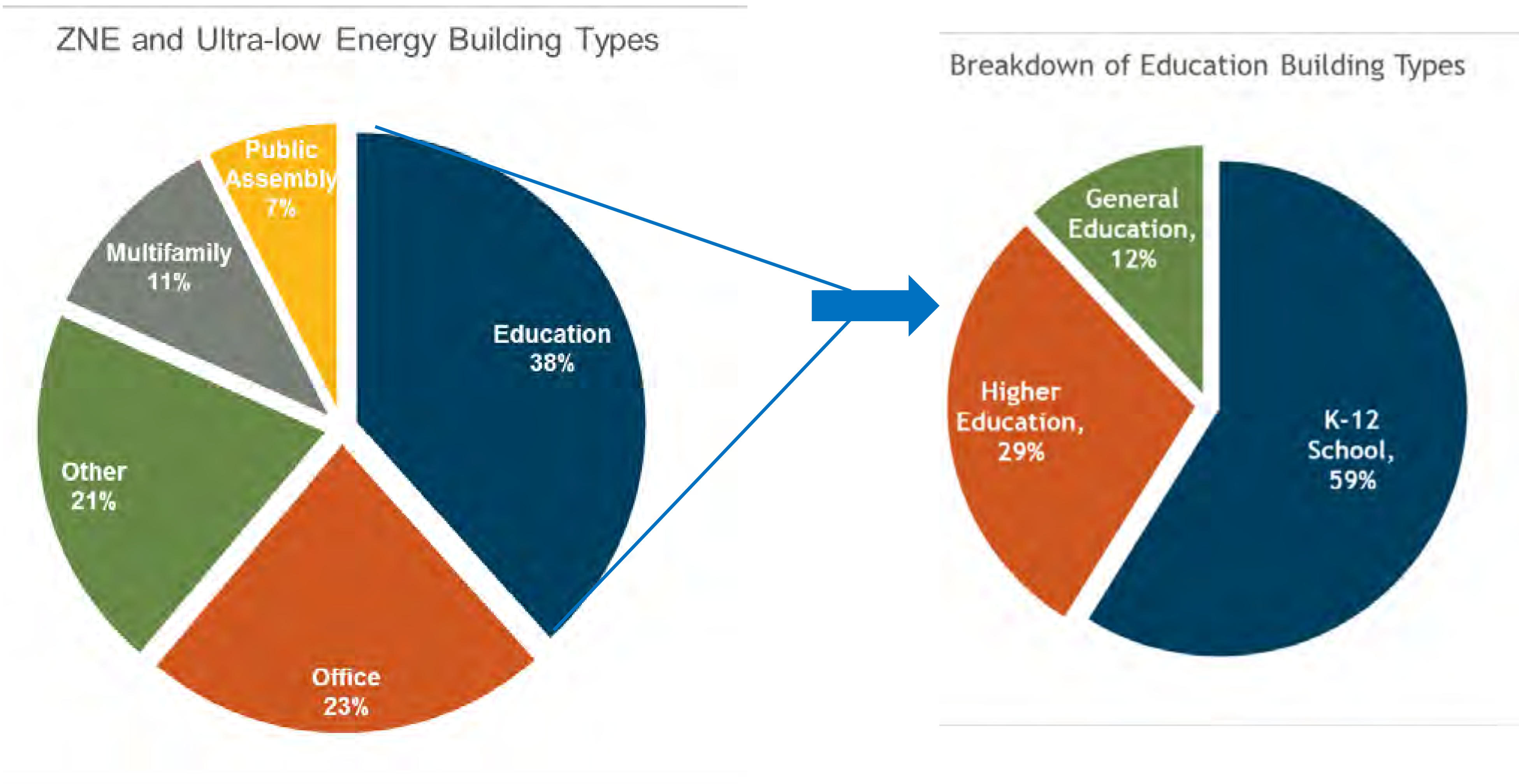
Trends in ZNE (& ultra-low energy) – who owns?

2/3 are public buildings



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

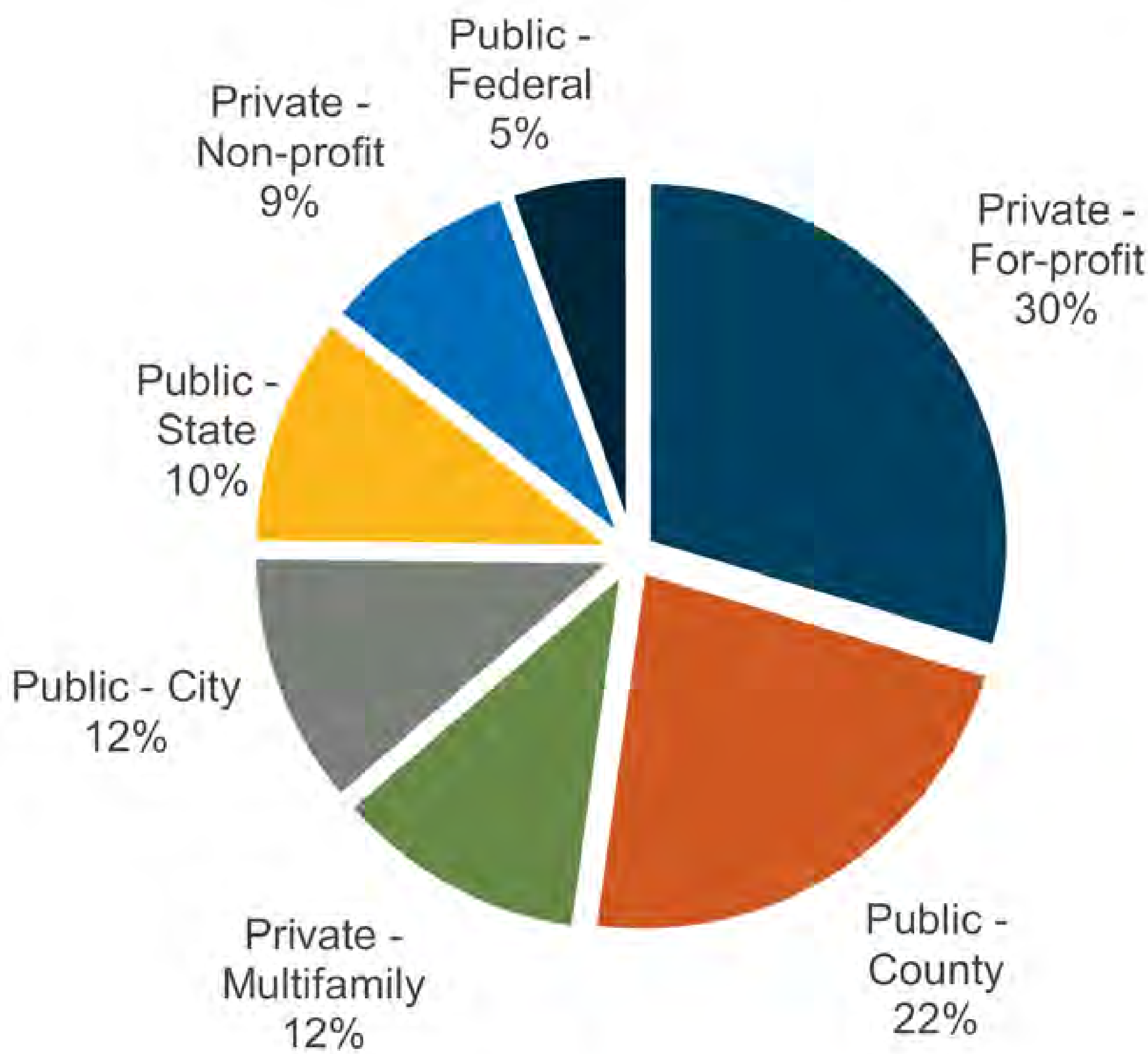
Trends in ZNE (& ultra-low energy) – what types?



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

Trends in ZNE (& ultra-low energy) – who owns?

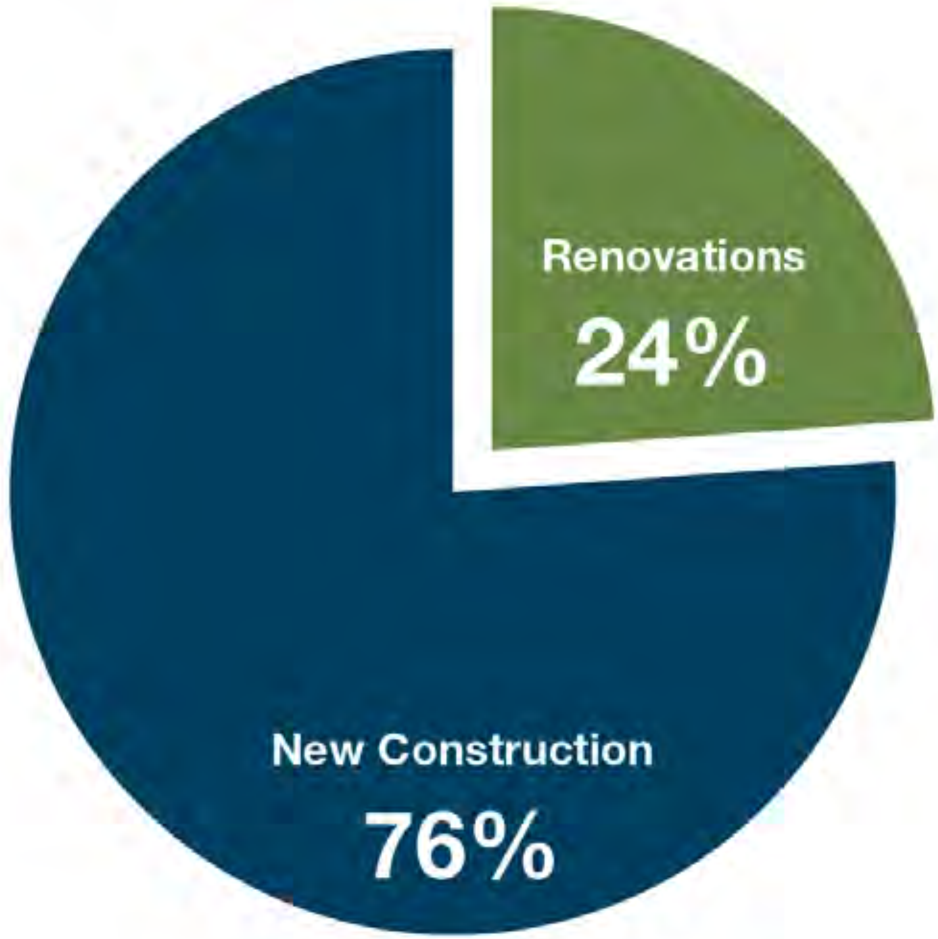
2/3 are public buildings



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

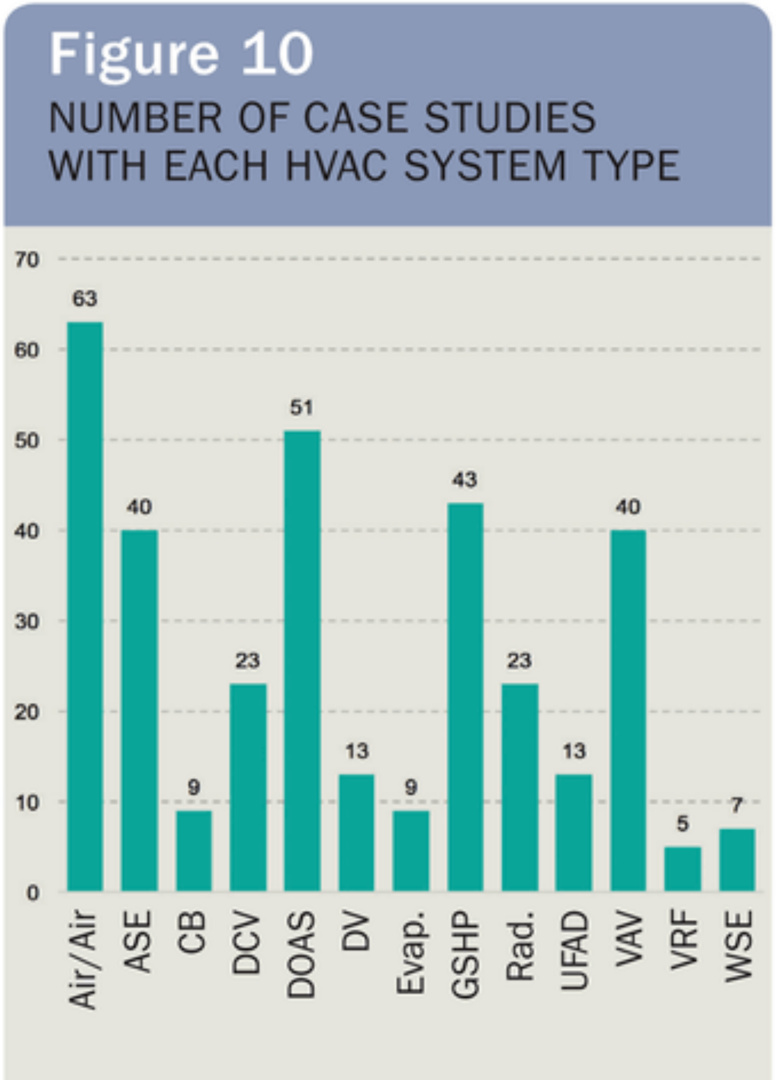
Trends in ZNE (& ultra-low energy) - new vs. existing

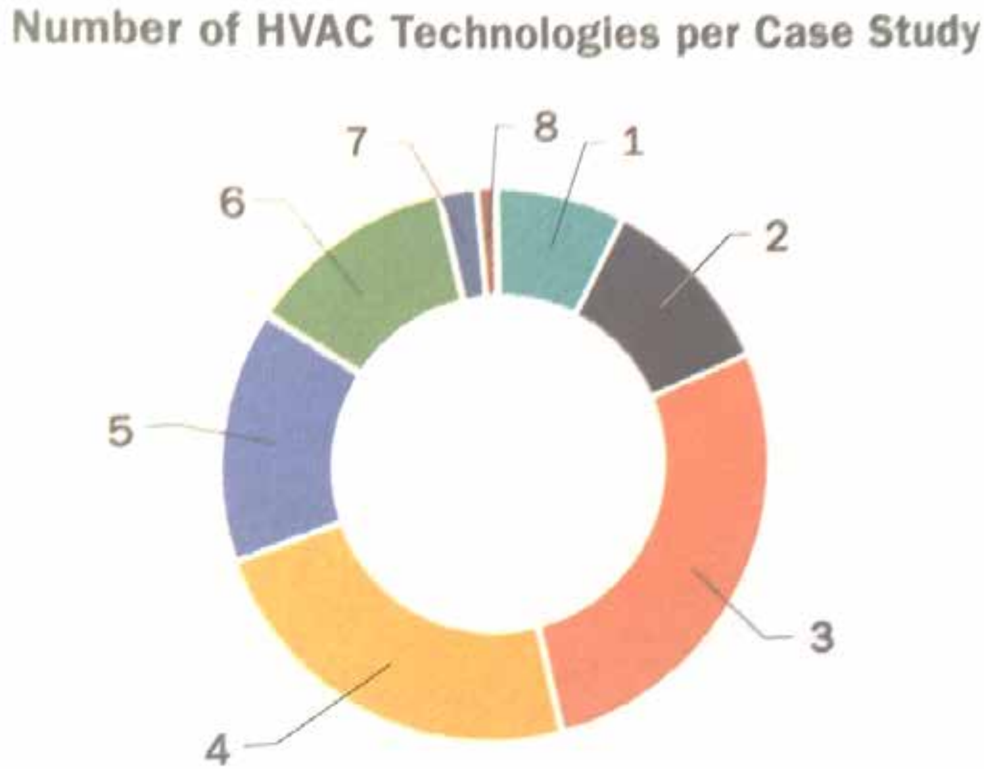
1/4 are renovations



New Buildings Institute, Getting to zero status update, 2016, newbuildings.org

Trends in ZNE (& ultra-low energy) – HVAC type?





ASRHAE High Performance Magazine, Fall 2016

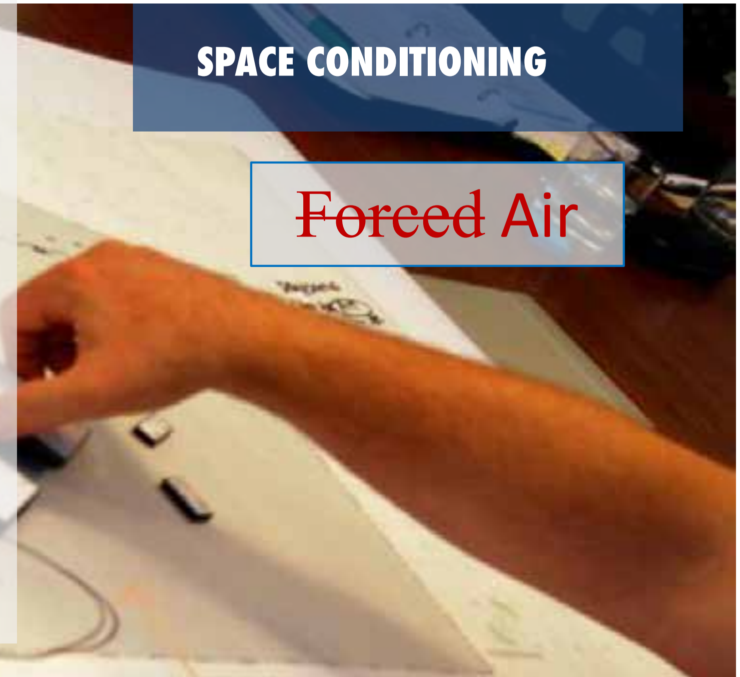
Trends in ZNE (& ultra-low energy) – HVAC type?

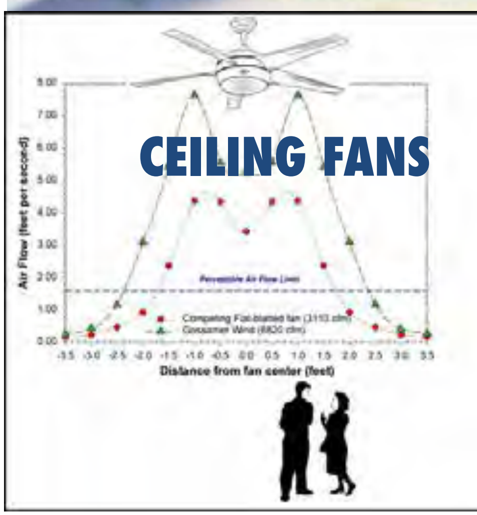
Passive Solutions 1st

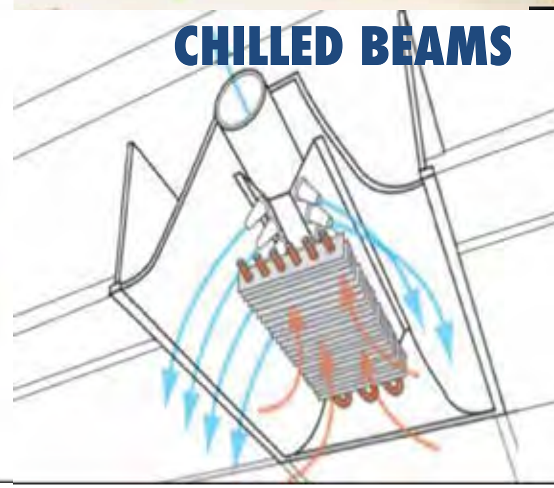
then

HVAC

- Ground Source **Heat Pumps**
- **Radiant** Heating/Cooling & Chilled Beams
- **Energy Recovery** Systems – air and water
- Ventilation
  - Natural
  - **Dedicated Outdoor Air Systems** (DOAS)
  - Demand Control Ventilation (DCV)







The Energy/Comfort Nexus

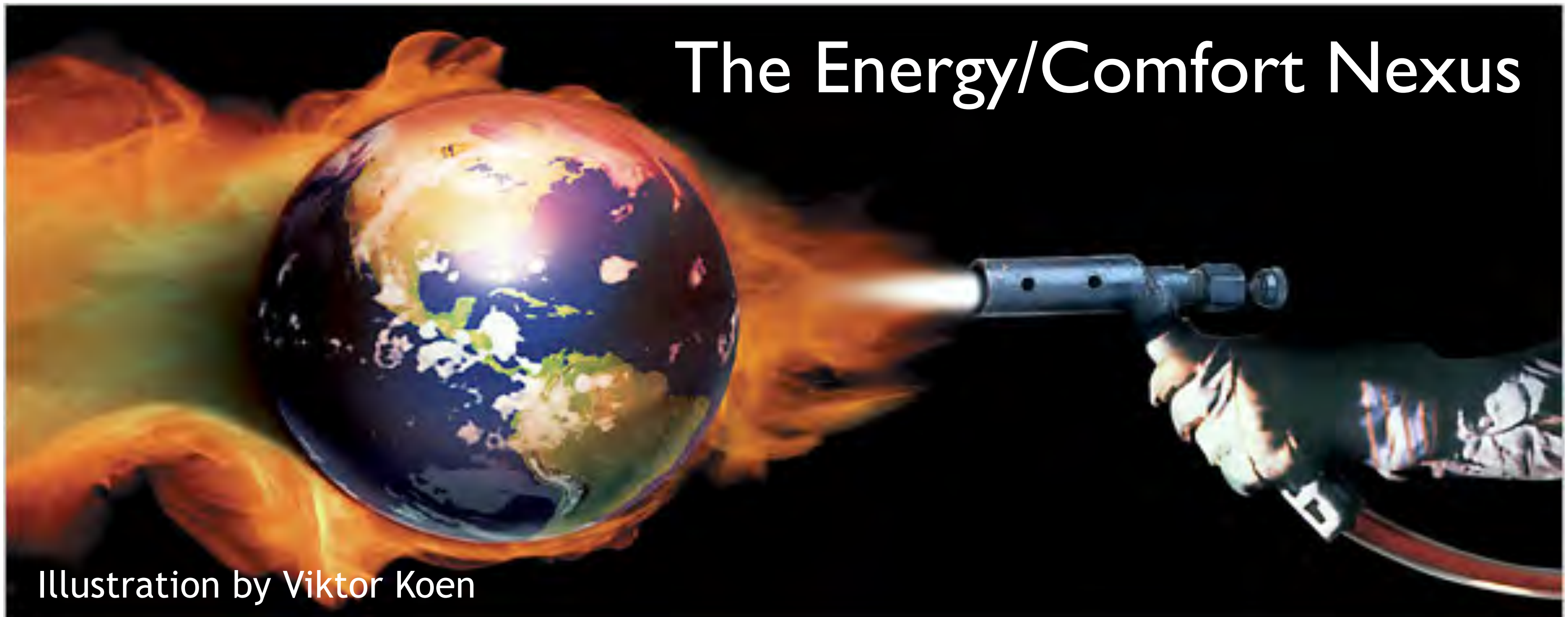
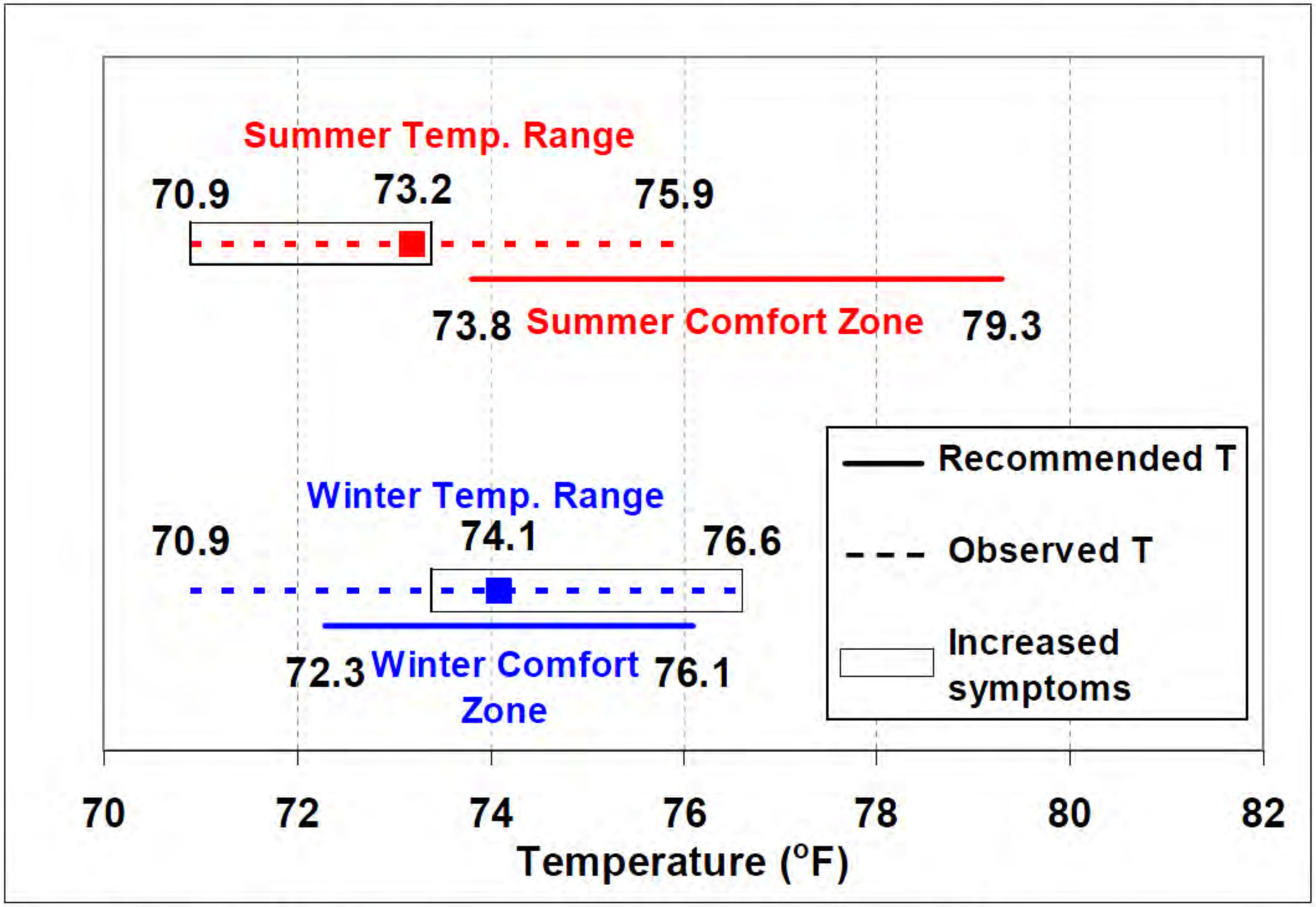


Illustration by Viktor Koen

Illustration by David Lehrer

Energy vs. comfort is a false dichotomy

We are overcooling buildings in summer, wasting energy and making people uncomfortable.



Source: Mendell, MJ, Mirer. AG (2009) Indoor Air 19(4): 291 - 302

Comfort zones (ASHRAE Standard 55)

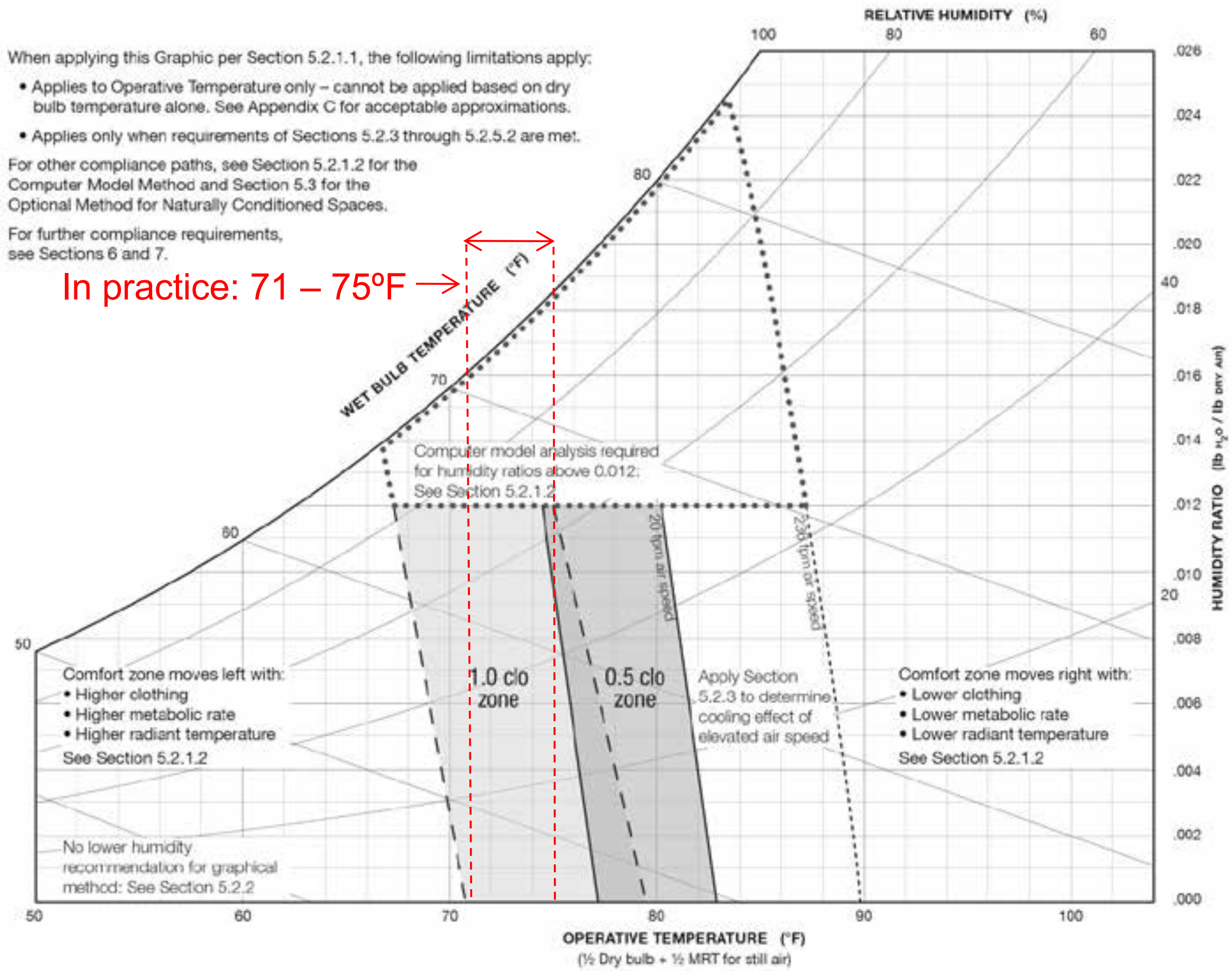
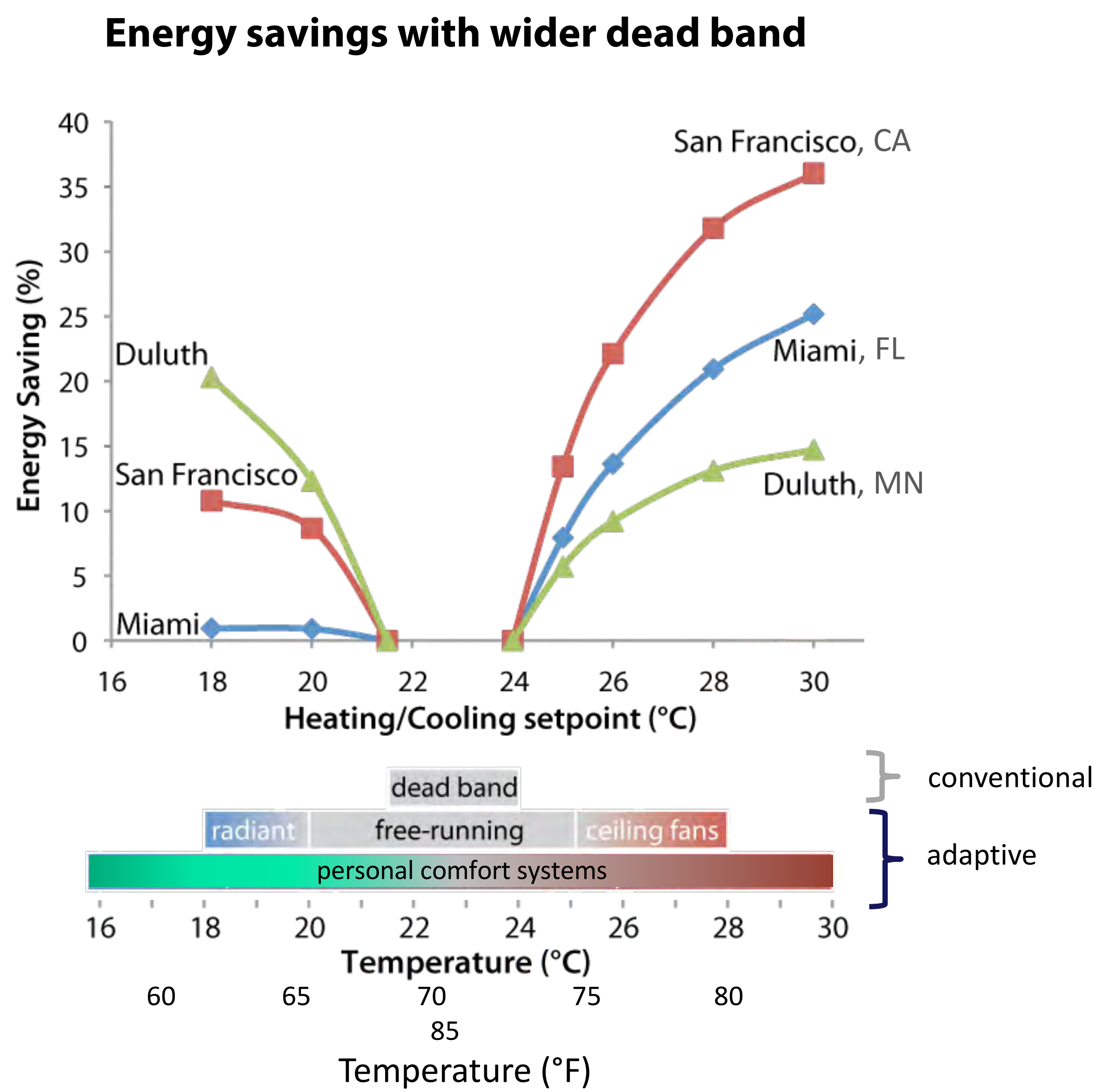


Figure 5.2.1.1 (IP) Acceptable range of operative temperature and humidity for spaces that meet the criteria specified in Section 5.2.1.1.
1.1 met, 0.5 & 1.0 clo

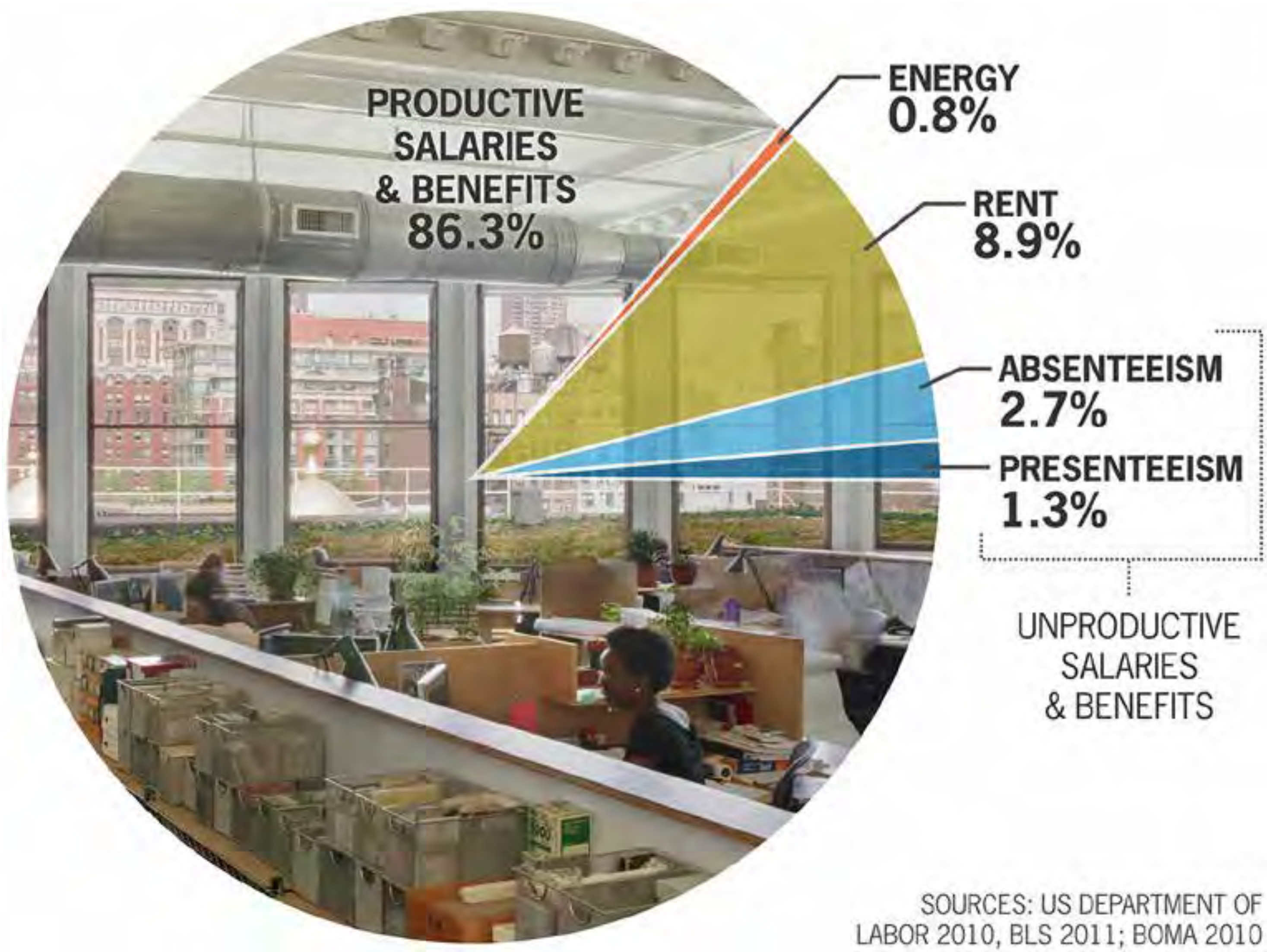
Saving (significant!) energy with a wider dead band

Wider dead band reduces HVAC energy 7-15% per ºC
How can we make people comfortable at the same time?



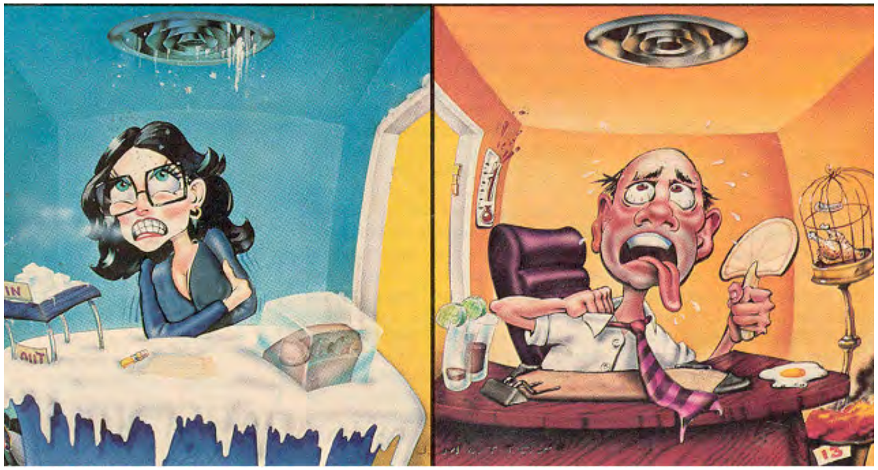
Hoyt, T., E. Arens, H. Zhang, 2105, "Extending air temperature setpoints." *Building and Environment*

Energy vs. Rent vs. People costs are 1:10:100



Source: Terrapin Bright Green 2012

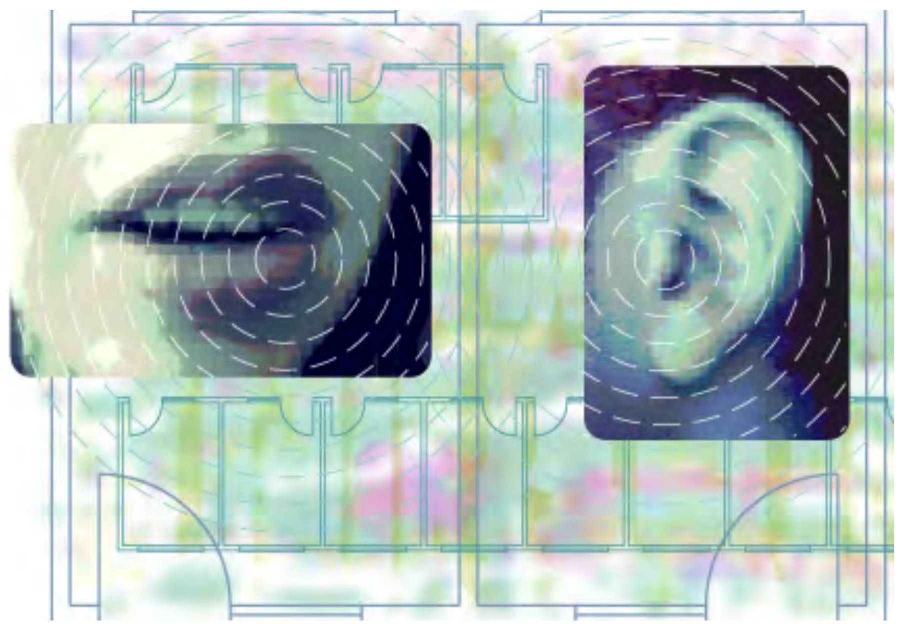
Indoor Environmental Quality (IEQ)



Thermal comfort

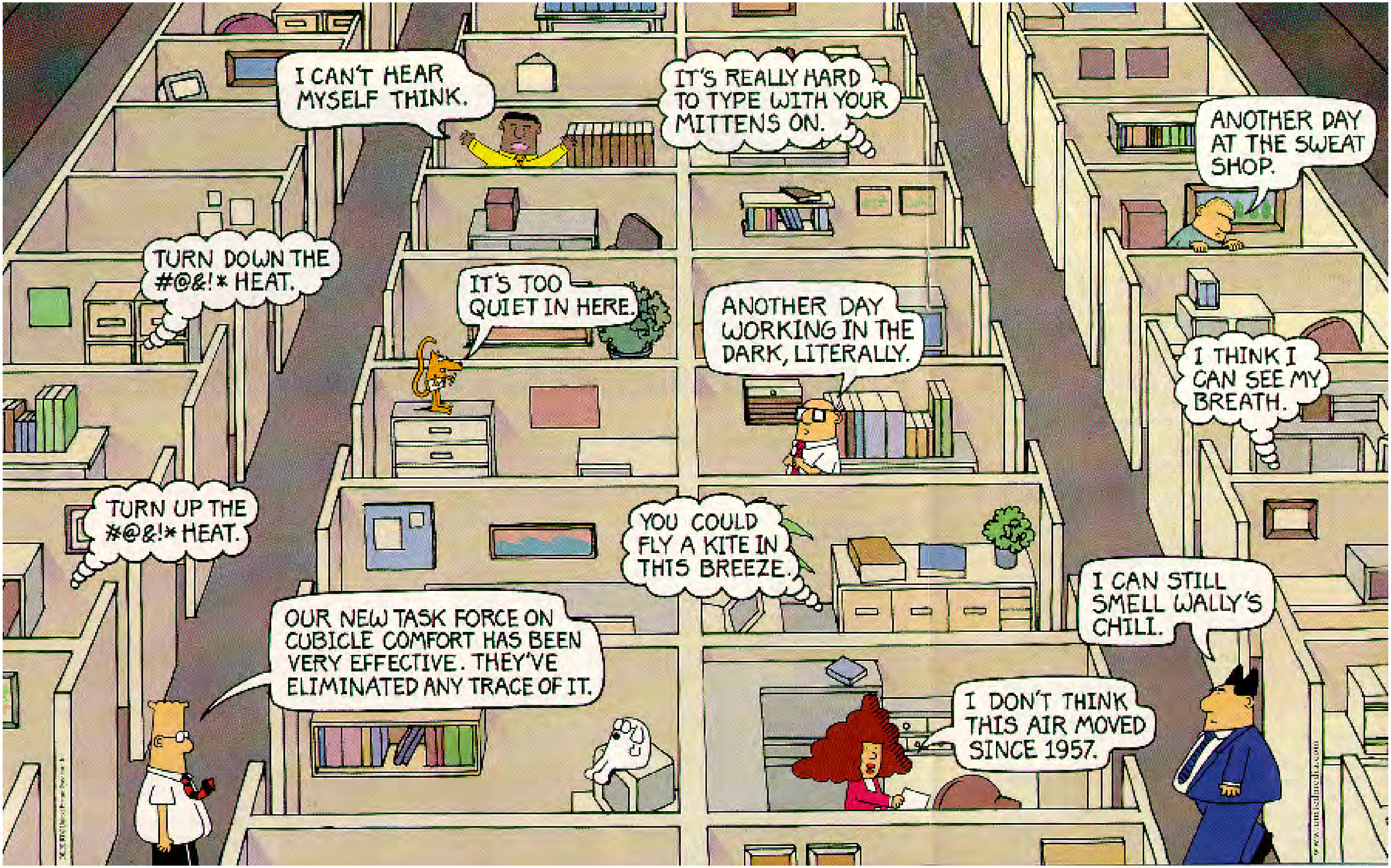
Lighting / visual comfort

Indoor air quality



Acoustics

Are people comfortable in existing buildings?

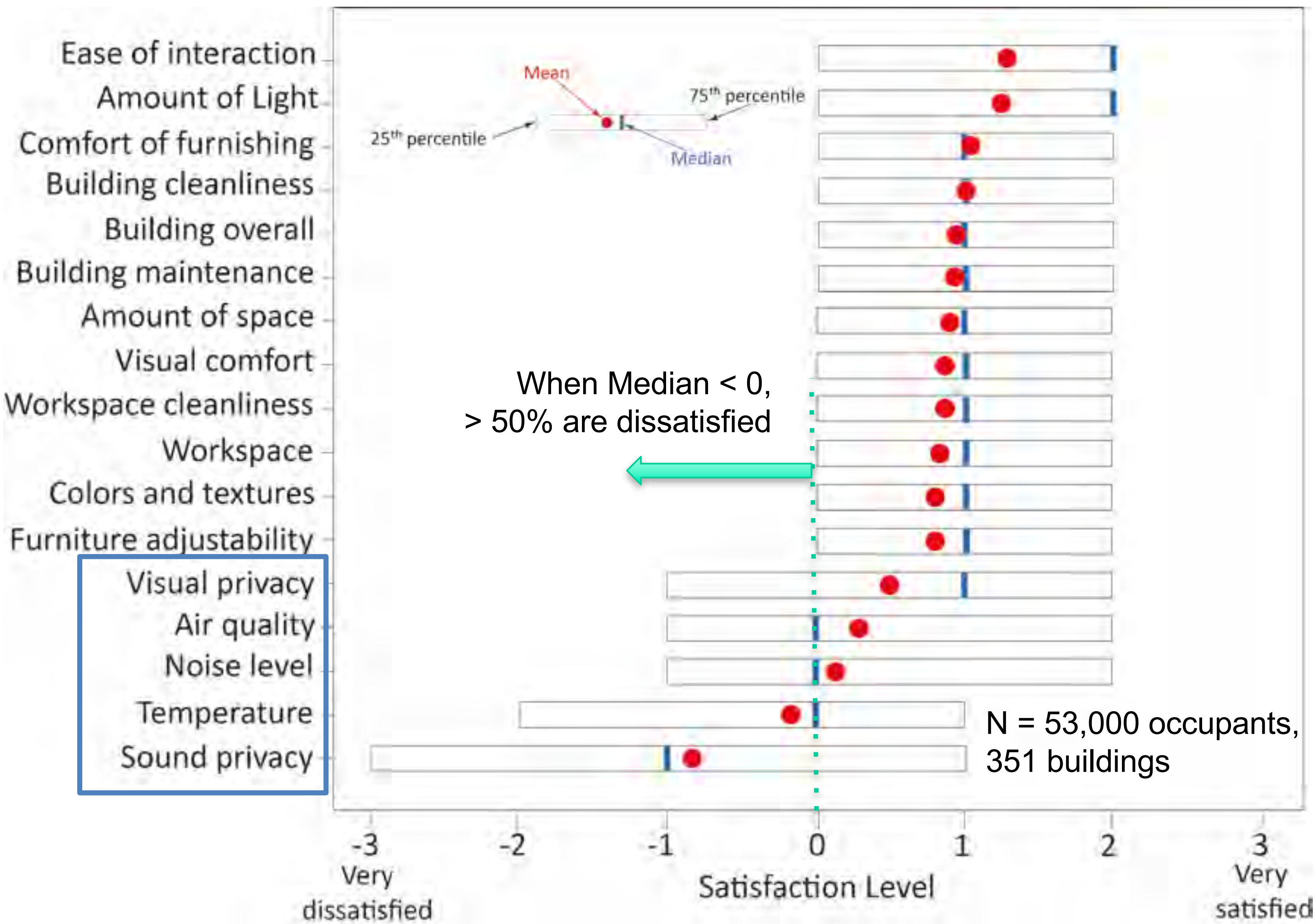


CBE web-based occupant satisfaction surveys

- Standardized method for studying building performance from occupants' point of view
- Rich database for evaluation of new technologies
  - 1000+ buildings
  - 100,000+ responses
- Uses
  - Commissioning
  - Diagnostics
  - Benchmarking
  - Research

CBE occupant satisfaction survey, office buildings

– > 50% are dissatisfied with temperature



- Frontczak M, Schiavon S, et al. 2011. Indoor Air Journal

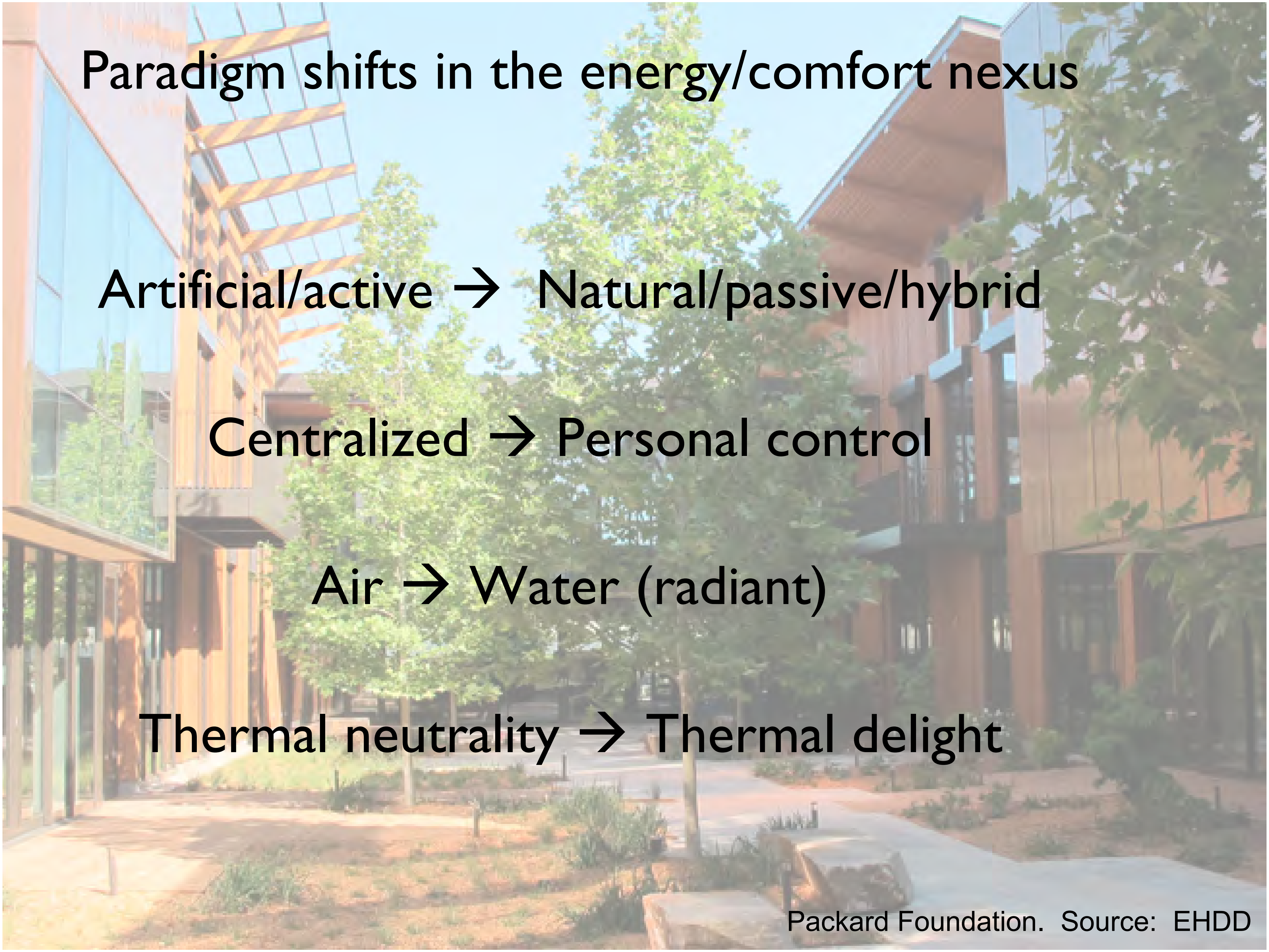
Paradigm shifts in the energy/comfort nexus

Artificial/active → Natural/passive/hybrid

Centralized → Personal control

Air → Water (radiant)

Thermal neutrality → Thermal delight



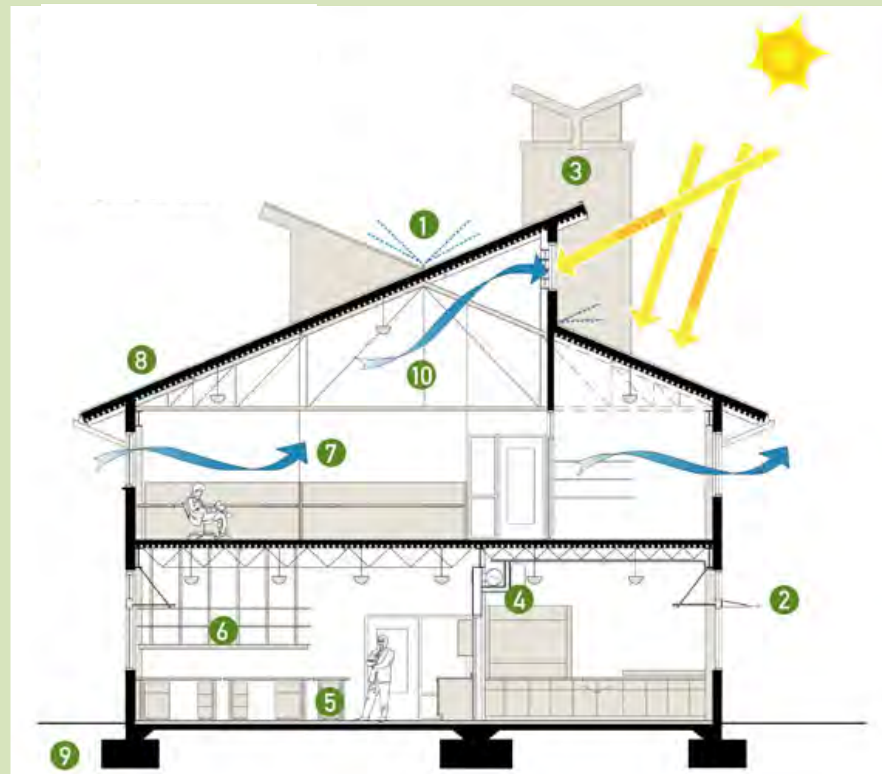
Packard Foundation. Source: EHDD

meh

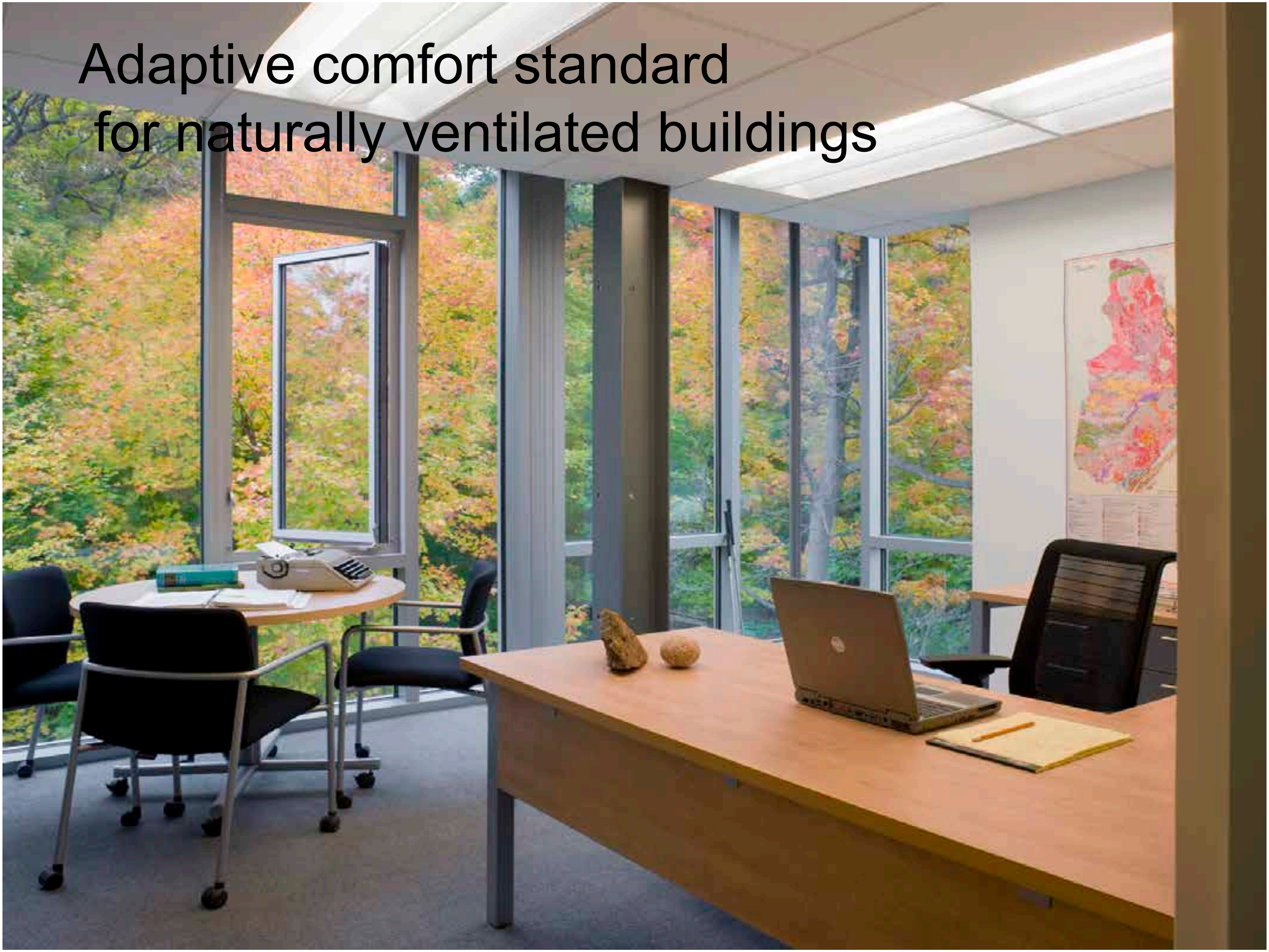
Artificial / Active

yay!

Natural / Passive (& Hybrid)



Adaptive comfort standard for naturally ventilated buildings



Adaptive comfort standard for naturally ventilated buildings

- 21,000 observations (indoor climate & surveys)
  - 160 buildings
  - 4 continents
  - broad range of climate zones.
- Separate analysis for :
  - centrally-controlled air-conditioned (HVAC)
  - naturally ventilated (NV)
- Statistical models produced an adaptive comfort standard for ASHRAE Std. 55

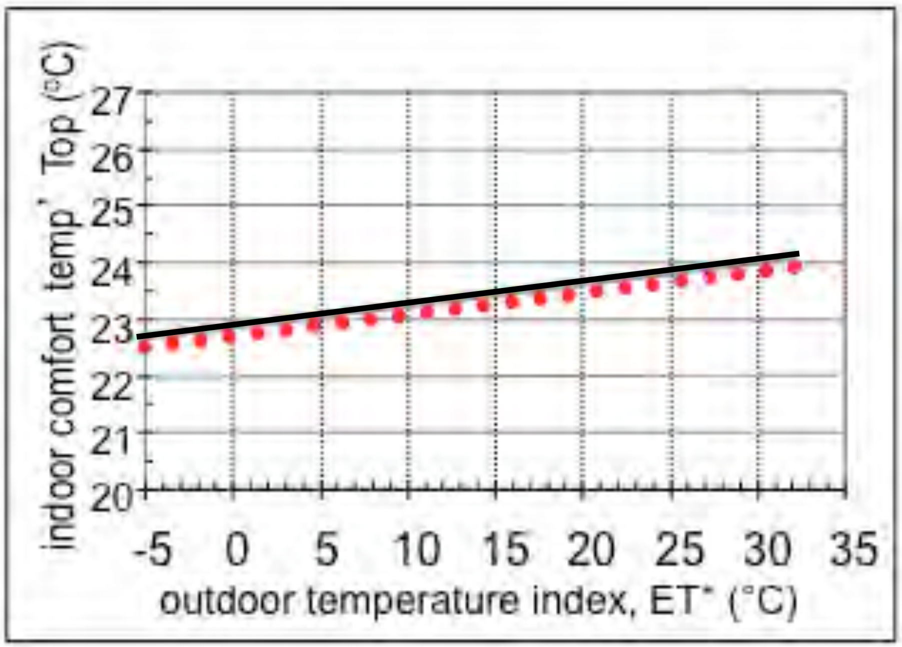
Conventional vs. adaptive approaches

- **Conventional standards**
  - **Based on laboratory studies**
    (Laboratory ≠ Real buildings)
  - **One-size-fits all:**
    Universally applied to all climates, cultures, and building types

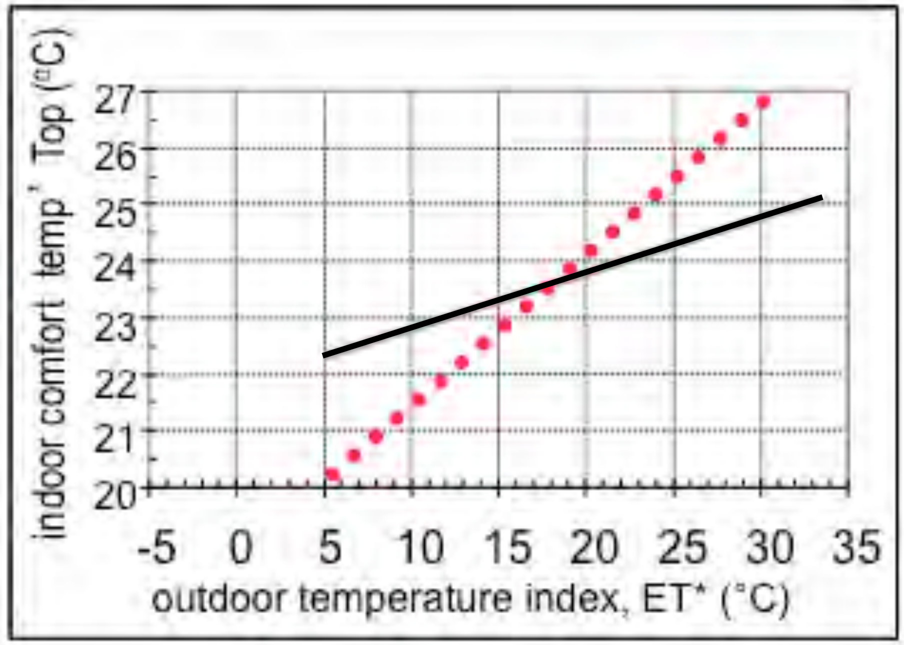
- **Adaptive comfort theory**
  - **Based on field data**
  - **3 types of adaptation:**
    - physiological
    - behavioral
    - psychological
  - **Satisfaction influenced by expectations & context**

Selected results: field studies

Centrally-controlled HVAC bldgs



Naturally ventilated bldgs



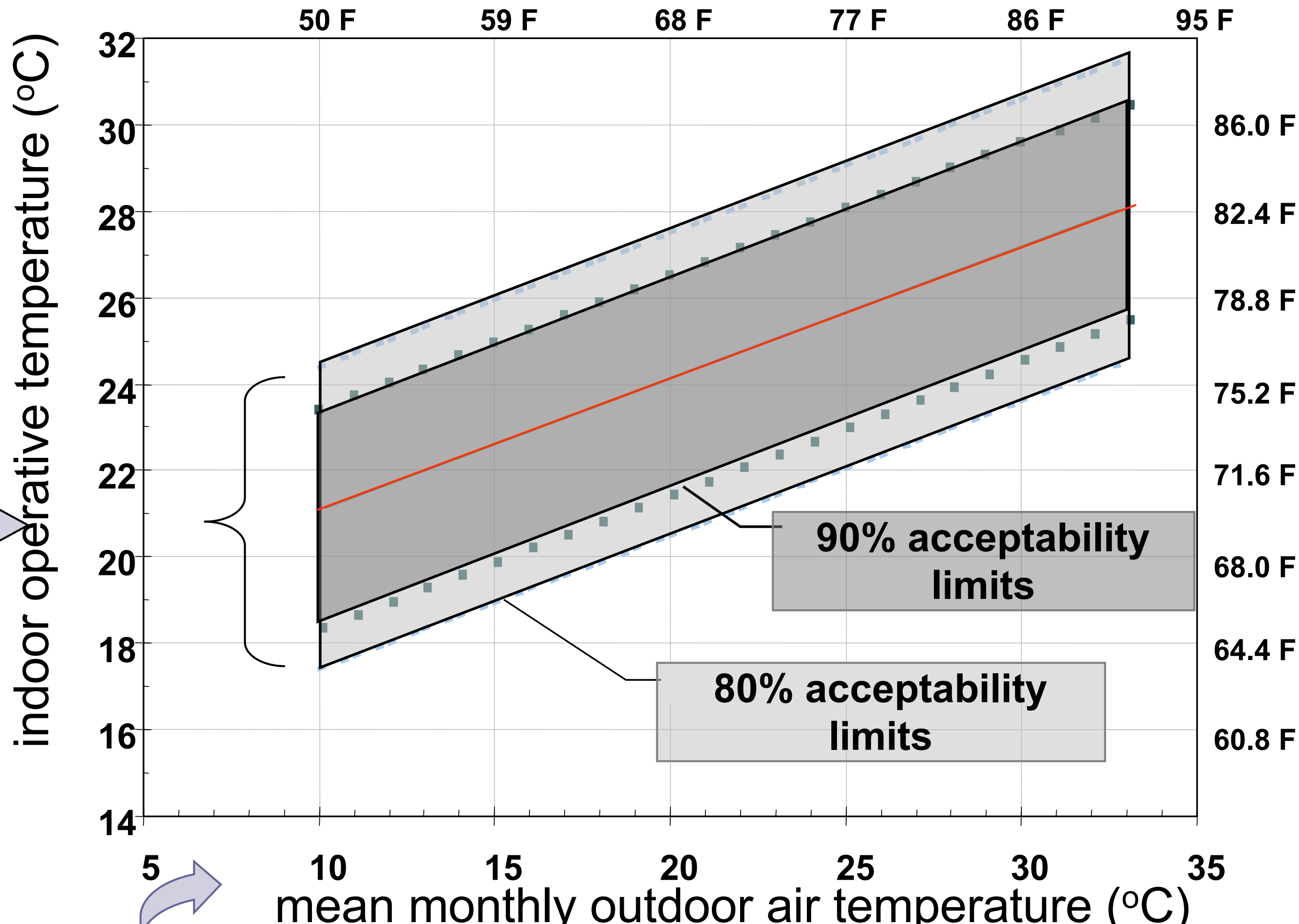
Lines are weighted linear regresssions through the data points (*not shown*)

—— Predicted: Lab-based heat-balance model

•••• Observed: Field-based adaptive model

deDear and Brager

Adaptive Comfort Standard in ASHRAE Std. 55

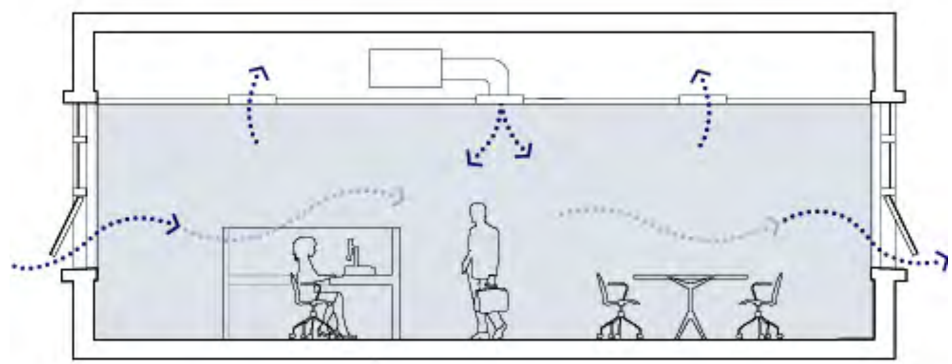


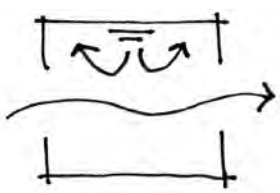
Replaced optimum temperature with a range

Replaced ET* as climate index
Also replaced monthly with running mean

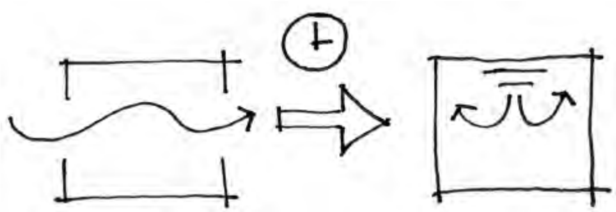
Mixed-mode buildings – a hybrid approach

- Operable windows
  + mechanical cooling
- Different configurations

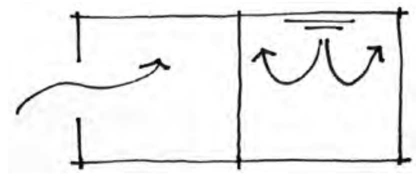




Concurrent
- same space
- same time



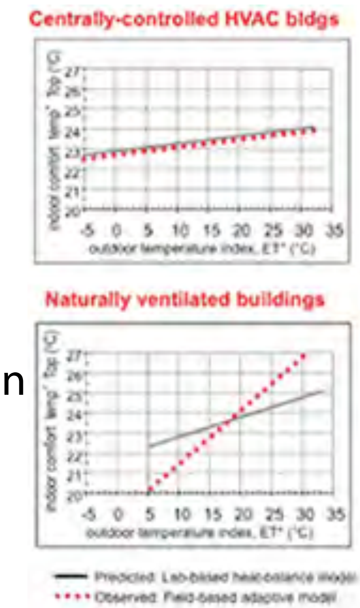
Change-over
- same space
- different times

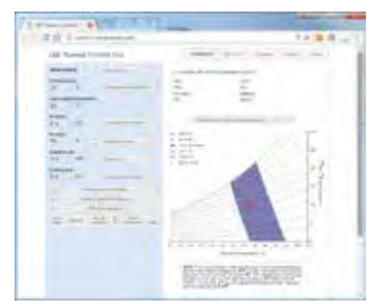


Zoned
- different spaces
- same time

Comfort and energy performance with NV and MM

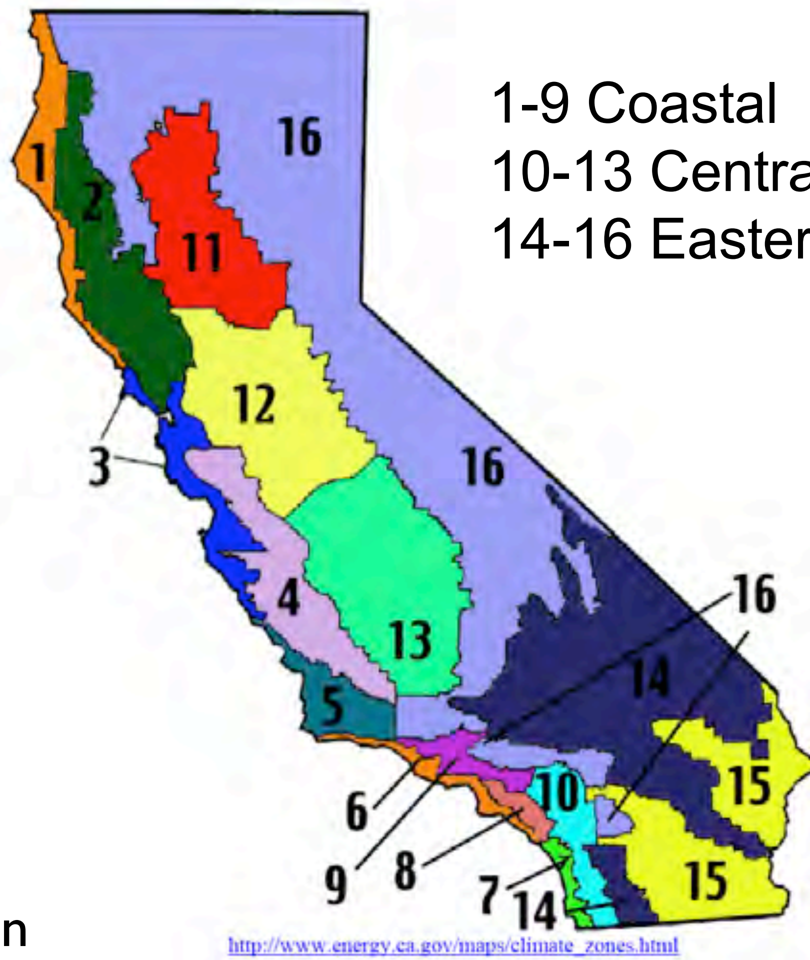
- **Adaptive comfort model development**
  Simulation and field study studies identified appropriate comfort model for NV buildings
- **Occupant satisfaction in mixed-mode (MM) buildings**
  Improved thermal, air quality and overall satisfaction using occupant survey results
- **Window control signaling systems**
  Insights on design, occupants responses and behaviors from 16 buildings
- **Feasibility of MM buildings in California**
  Comfort exceedance using low-energy cooling strategies (radiant + MM)
- **High-performance facade case studies**
  Documenting performance, comfort and lessons learned
- **Comfort tool development**
  CBE developed SolarCal calculator adopted by ASHRAE





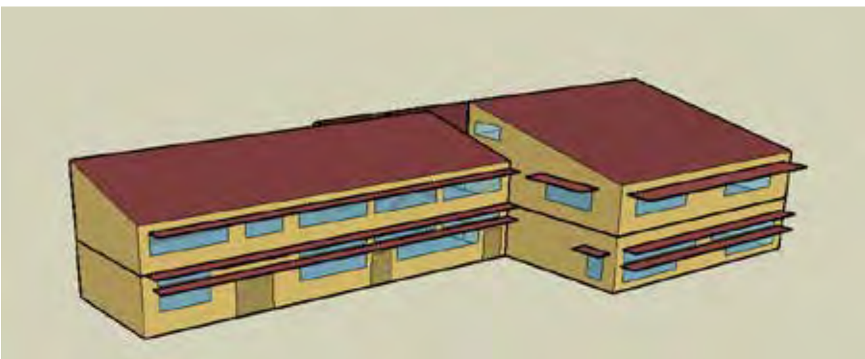
MM Climate Feasibility

- Assess climatic feasibility using metrics of comfort and energy across CA's 16 climate zones
- 3 basic systems:
  - **High energy baseline**: Conventional forced air VAV system with chiller
  - **Low energy baseline**: Natural ventilation with night flush
  - **Mixed-mode system**: Radiant cooling with natural ventilation



1-9 Coastal
10-13 Central
14-16 Eastern

Simulation: case study building



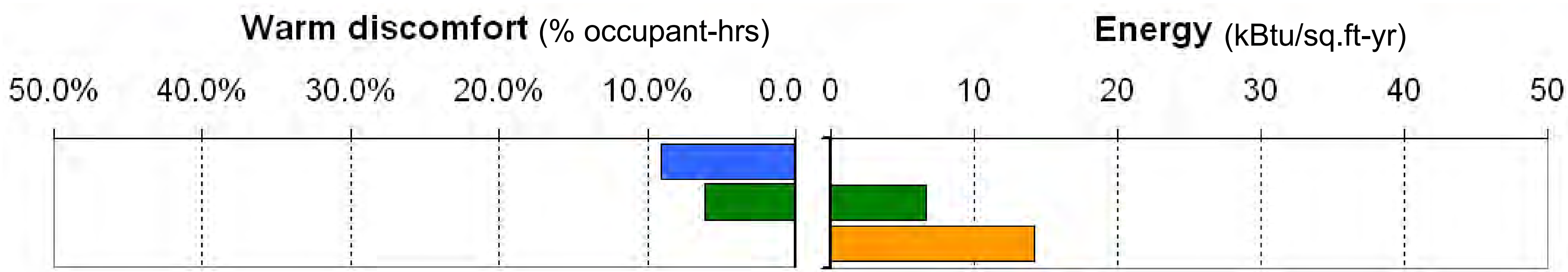
- Case study building Kirsch Center at DeAnza College
- Van der Ryn Architect

- Simplified model
- 6 zones, 39 windows
- Designed for parametric studies

- Air tight, low gains, well shaded
- Air flow network
  - Pressure coefficients calculated with Cp Generator
- Radiant floors
  - Cooling tower charges slab overnight (free running during the day)
- Autosized VAV system

NV, MM & VAV: comparing performance

Hypothetical comparison (to explain graph)

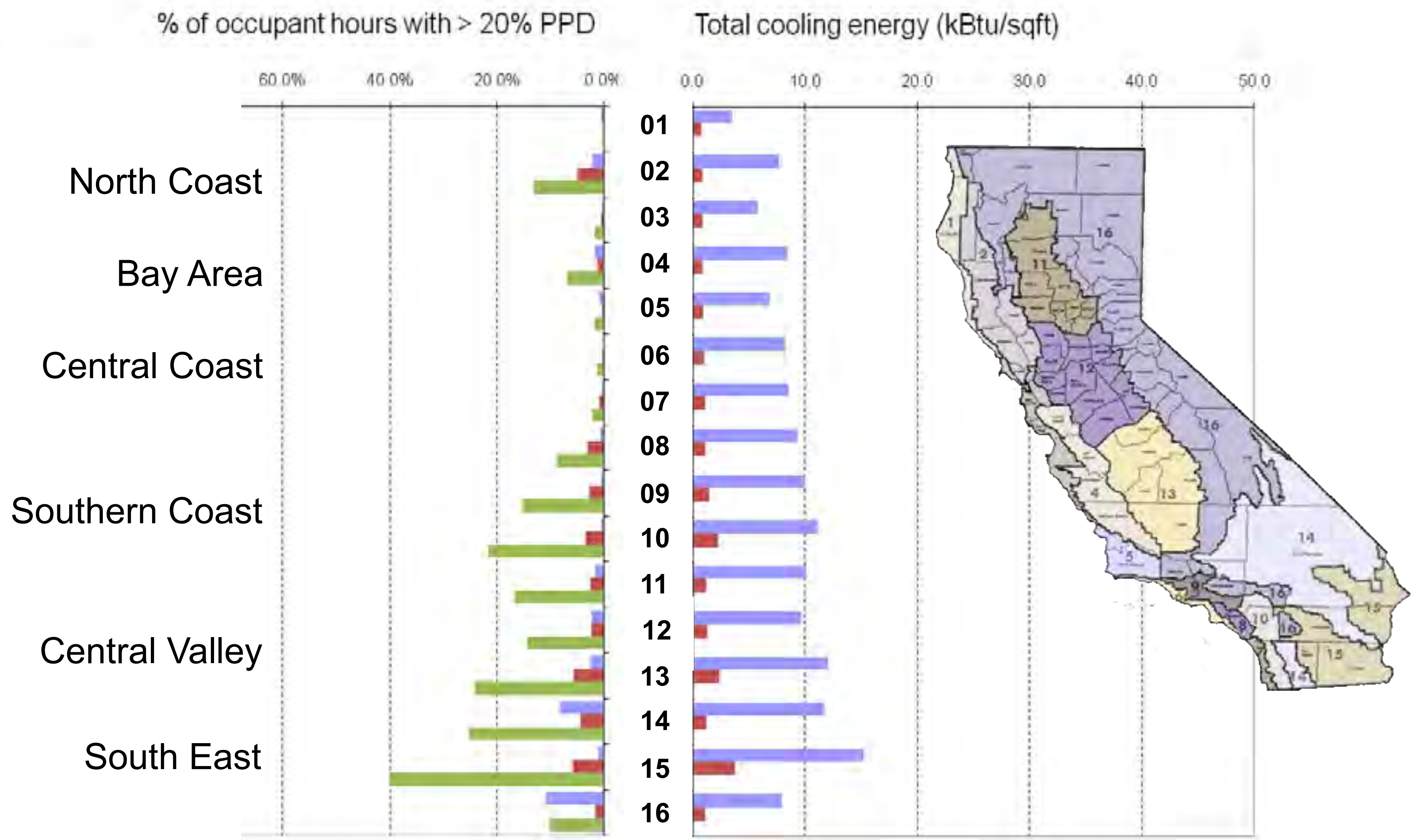


Natural Ventilation Only:
Night Vent with day vent for Tout < 25C

Mixed-Mode, Radiant Slab w/ NV:
Same as above with night cooling of slab via cooling tower

Sealed VAV:
Reference case; standard VAV with DX units

Mixed-mode: nutshell of our results



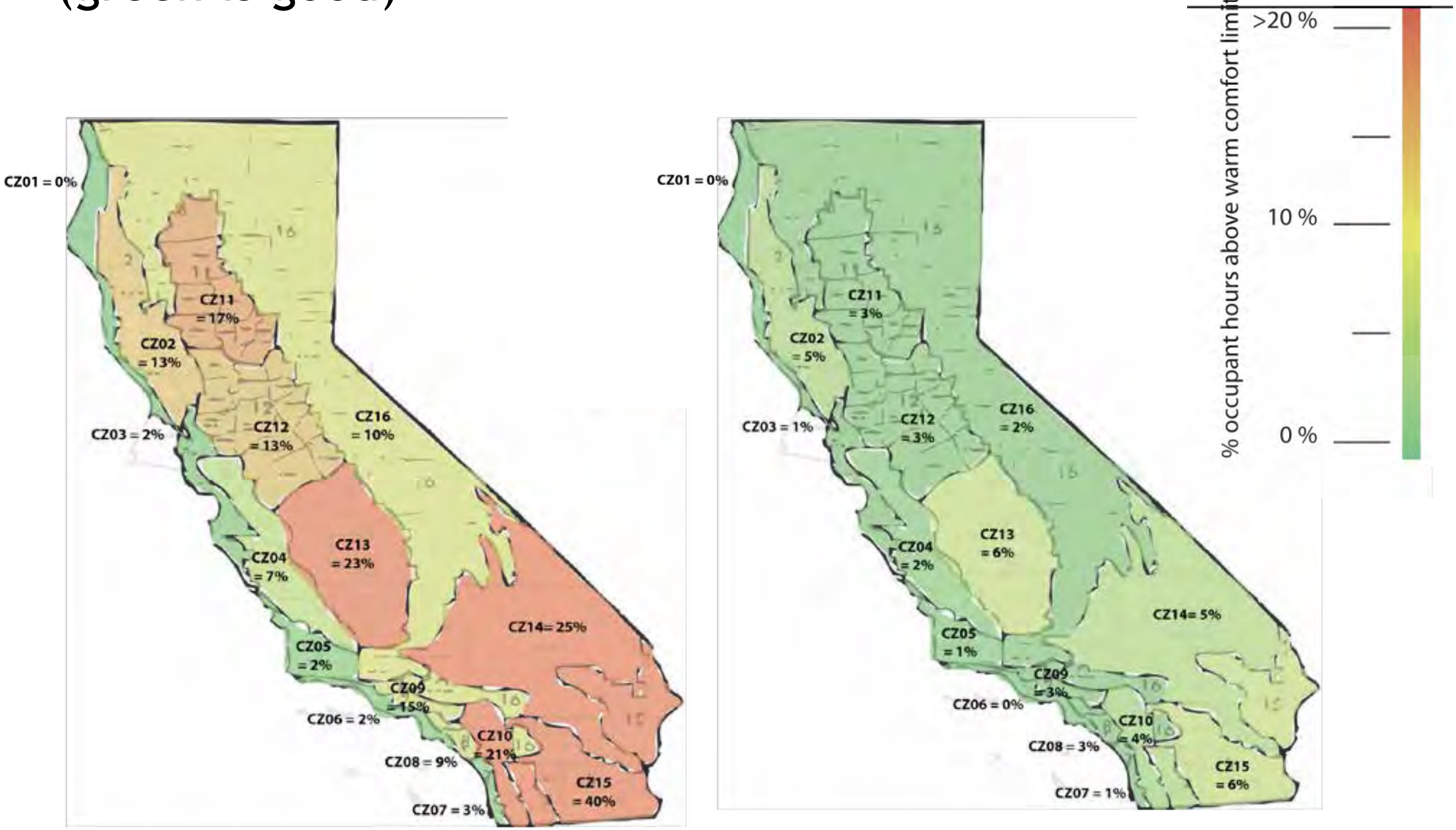
NV Only: Night Vent with day vent for Tout < 25C

MM: Rad Slab w/ NV: Same as above with night cooling of slab via cooling tower

Sealed VAV: Reference case; standard VAV with DX units

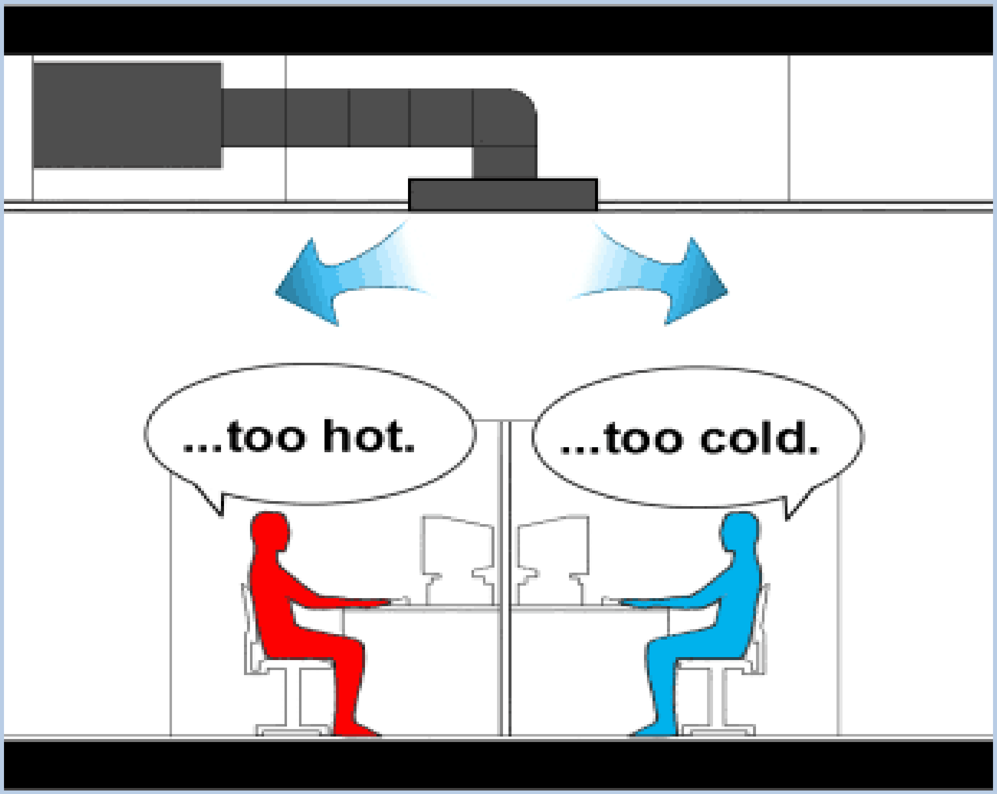
Natural ventilation vs. Mixed mode

% occupied hours above warm adaptive comfort limit
(green is good)



meh

Centralized control

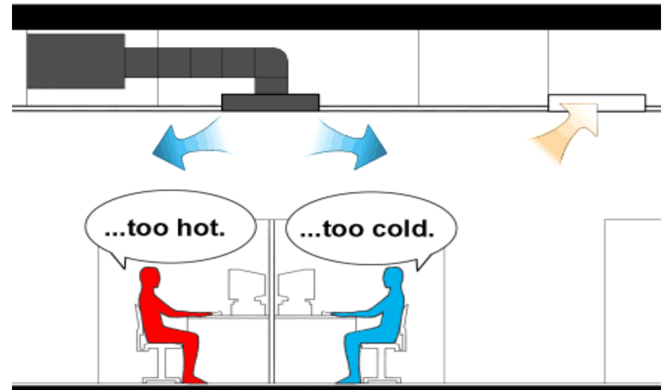


yay!

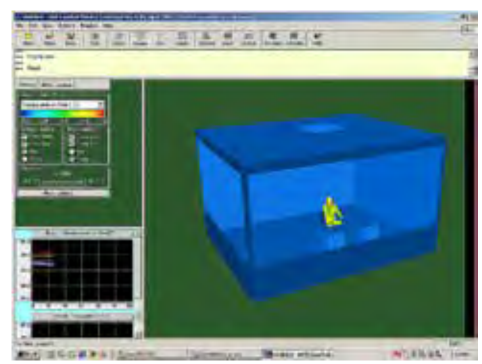
Personal control

Personal comfort systems (PCS)

- "Task/ambient" approach has been widely adopted for lighting
- Paradigm shift:
  - From space-based to person-based conditioning
  - From using static indoor environmental parameters to dynamic, variable and occupant-selected modes
- Multi-year research using simulations, laboratory, and field studies
- Development and testing of numerous devices



Traditional mixing overhead system

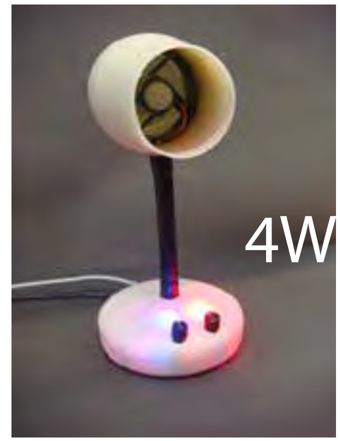


1st generation PCS: desktop fan & footwamer

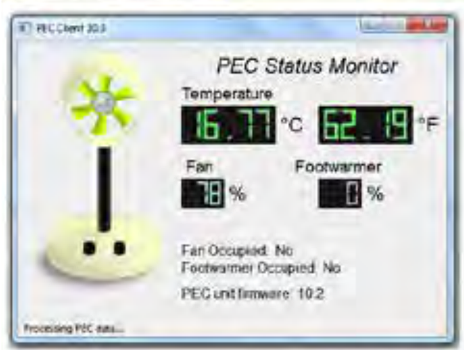
Provides control and monitoring of:

- User settings for fan and foot warmer
- Ambient air temperature
- Occupancy

Connection to internet via USB to computer to collect and send research data



Fan and control unit



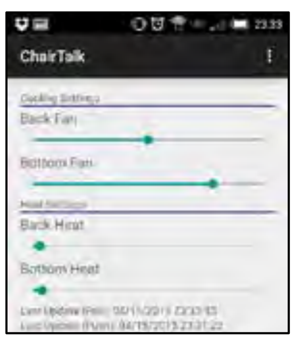
Optional user interface

Foot warmer

occupancy sensing pressure plate

2nd generation PCS: heated & cooled chair

- Low power use, max:
  - 14 W for heating
  - 3.6W for cooling
- User controls for cooling and heating
- Saves energy by allowing wider HVAC temperature setpoints
- Rechargeable battery
- WiFi and Bluetooth communication with BMS
- Collects temp, humidity, occupancy & usage data
- 50 built for research



Touchscreen

Phone app

Pasut,W., H. Zhang, E. Arens, Y. Zhai 2014, Energy efficient comfort with a heated/cooled chair, *Proceedings of the 13th International Conference Indoor Air 2014*, July 7 – 11.

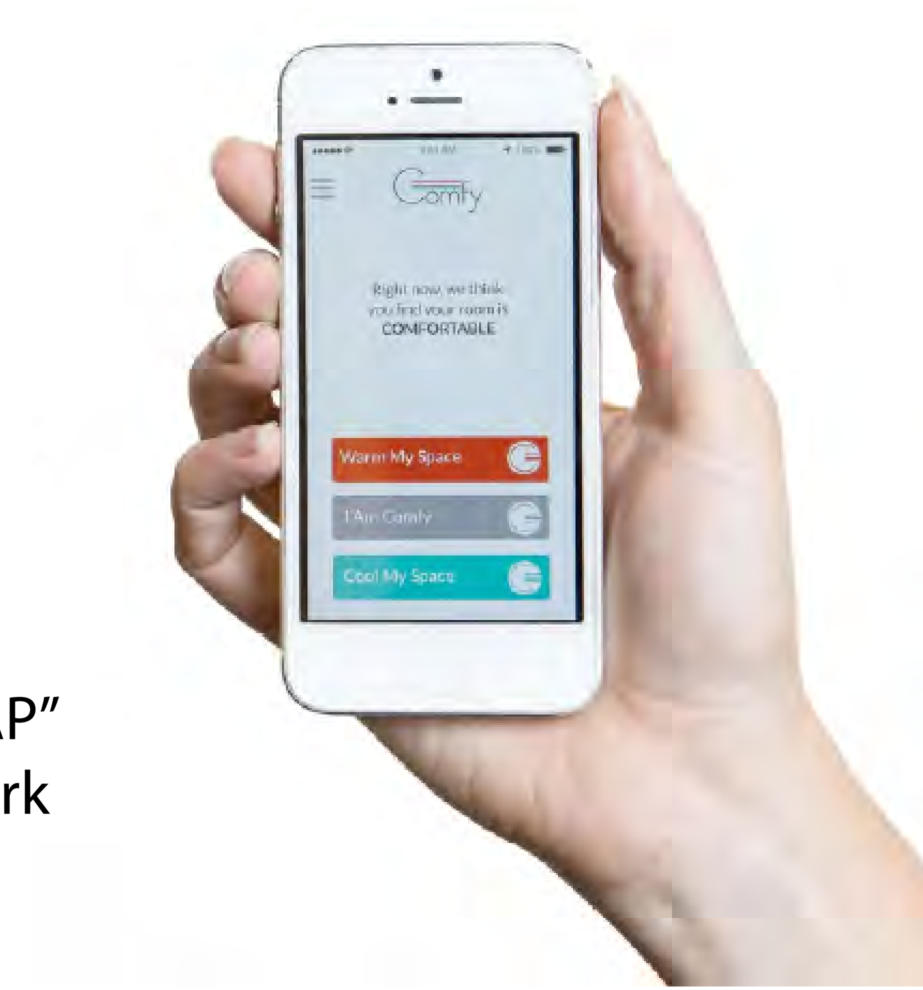
Demonstrated energy savings and comfort

- Field testing prototypes in multiple sites
  - Summer/winter
  - NV, VAV, radiant
  - With and without PCS (chairs, fans, food warmers, legwarmers)
- Comfort:
  At 64-84ºF more than 90% of subjects were comfortable with the chair and a desk fan
- Energy:
  Field tests have demonstrated energy savings of 60% with improved comfort



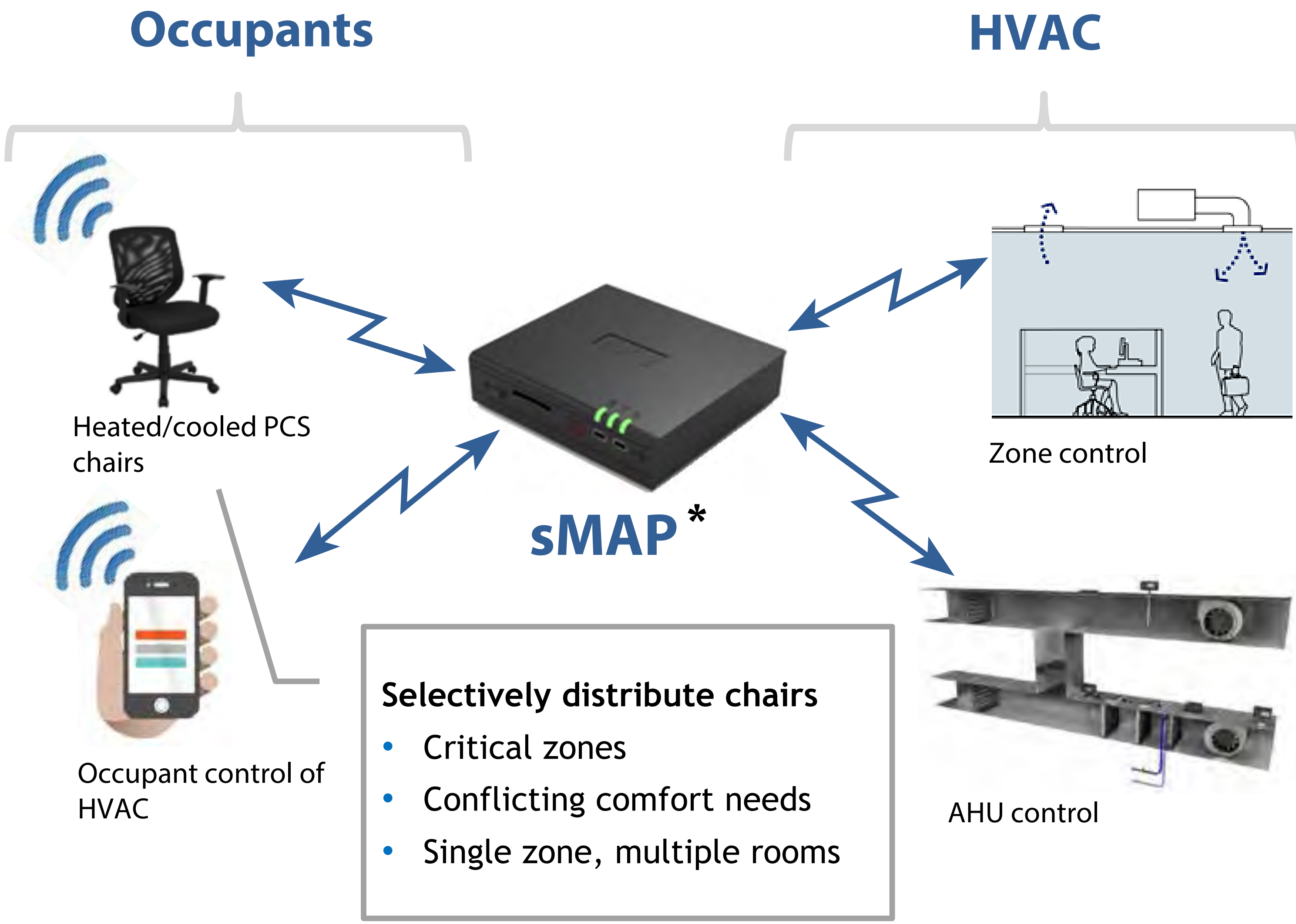

How can technology improve our personal control and experience? Occupant-in-the-loop controls

- "Comfy" founded by former UC Berkeley students (EECS, Architecture, CBE)
- Occupants make comfort requests, with social functions for shared environments
- Integrates with HVAC controls
- Based on principles from "sMAP" building information framework



Comfy on a mobile device

Occupant-in-the-loop controls



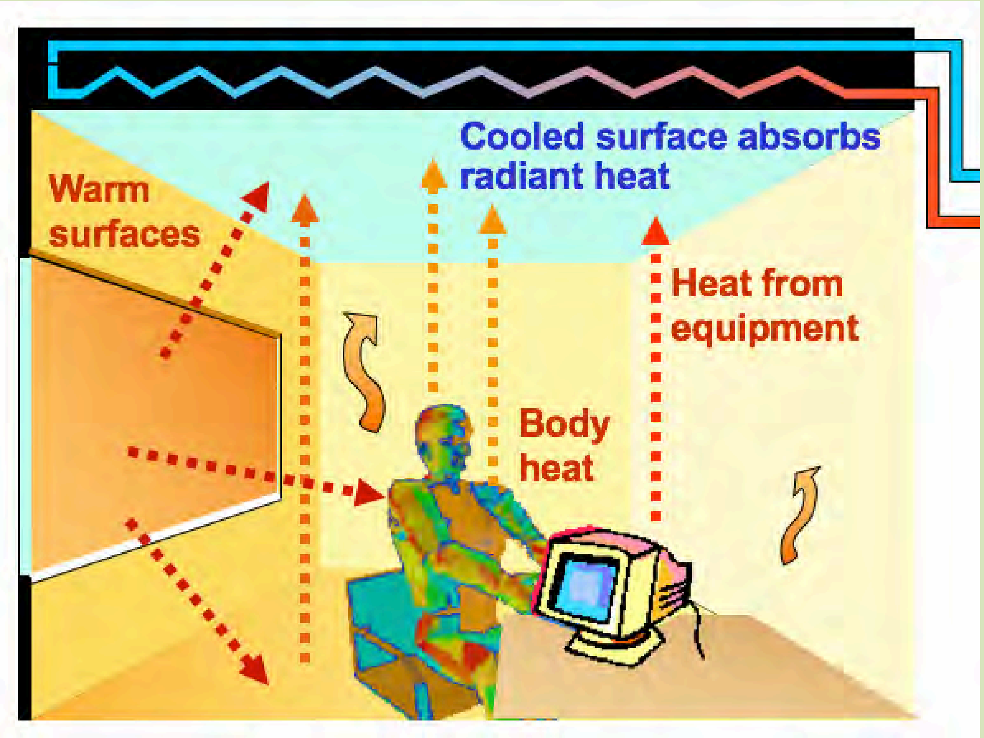
(*) Simple Measurement and Actuation Profile (sMAP) software, developed at UC Berkeley EECS Dept, connects to bldg's BACneet and allows rapid access and visualization of data from different sources

meh

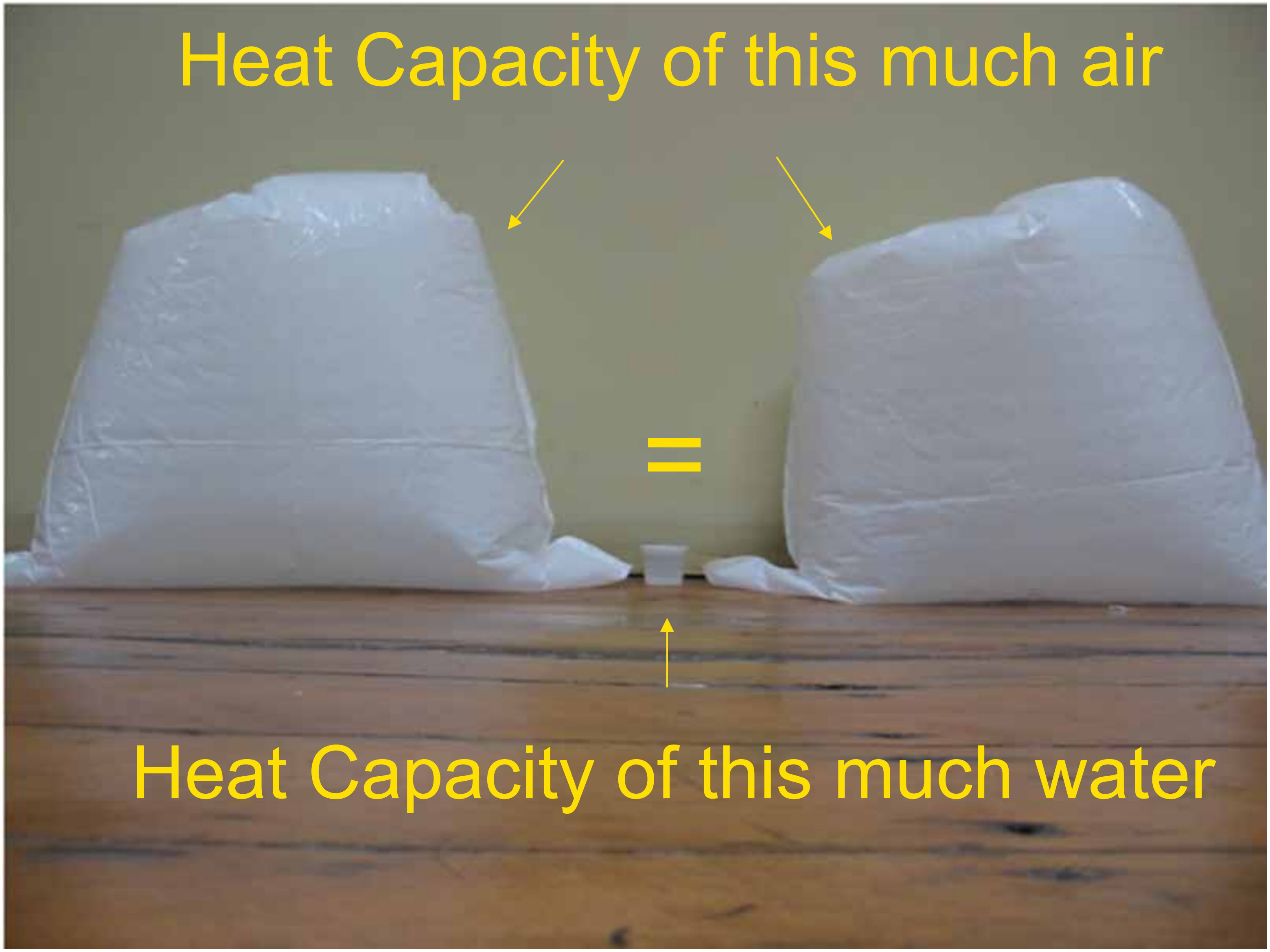
Air

yay!

Radiant



Heat capacity of air vs. water



Source: Peter Rumsey

Air vs radiant: decoupling of thermal & ventilation

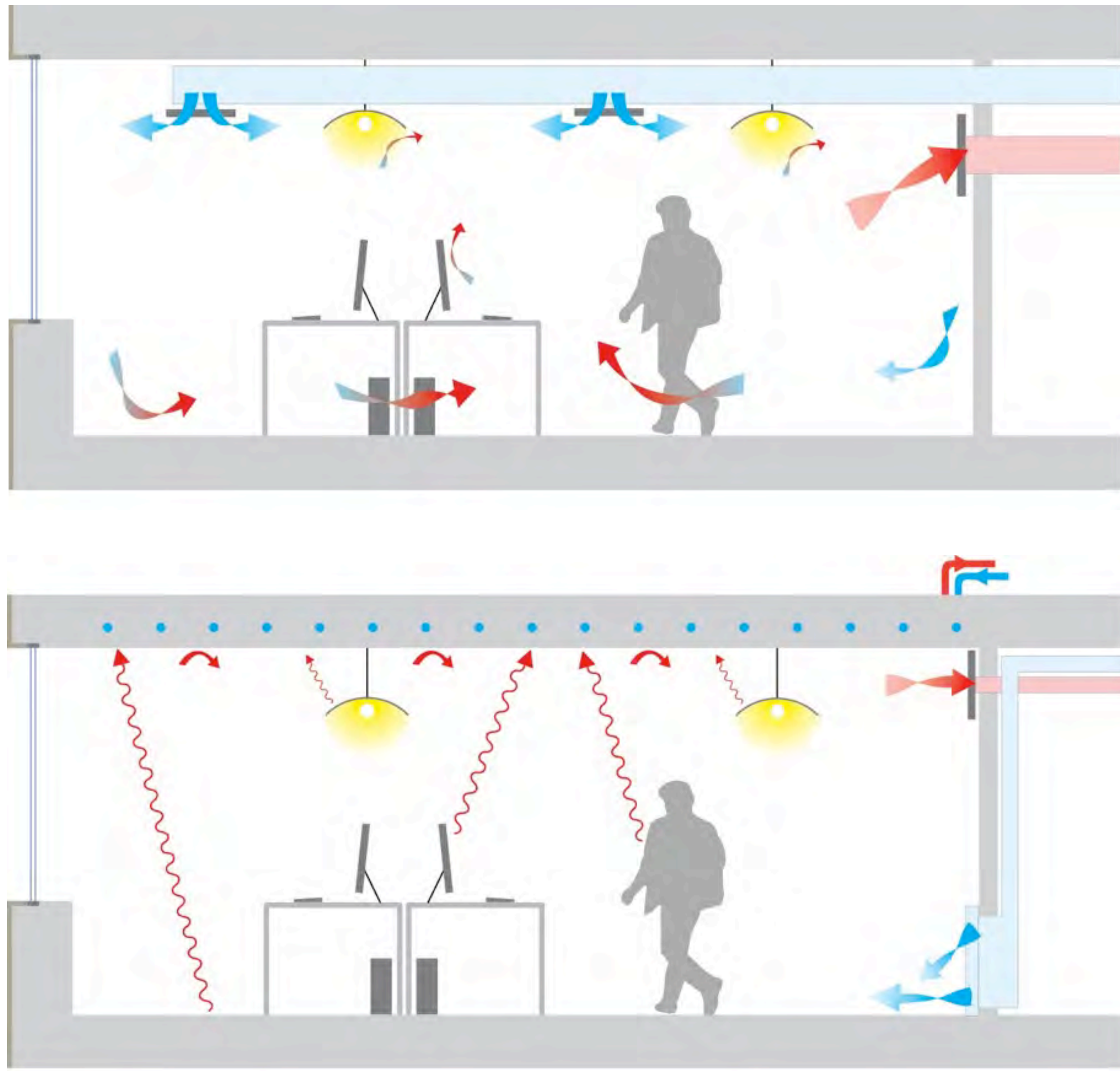


Image credit: Caroline Karmann

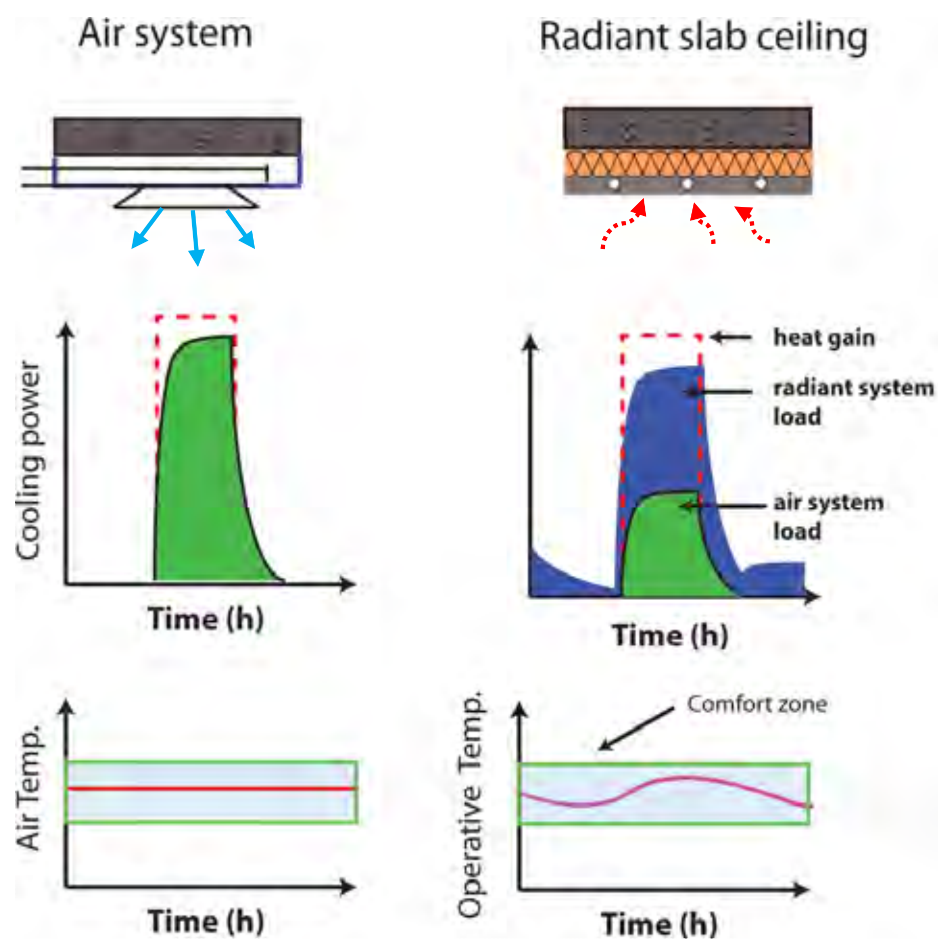
Air systems vs. Radiant systems

Air systems

- Ventilation + space conditioning
- Design to meet a single peak cooling load value
- Remove heat using convection

Radiant systems

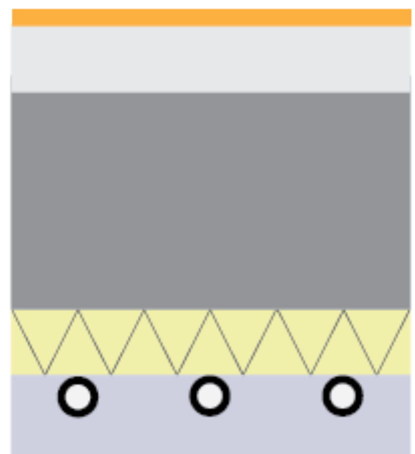
- Decoupled ventilation and space conditioning
- Allow pre-conditioning the radiant layer
- Remove heat using convection + radiation
- → Traditional cooling load calculations don't account for complexities of radiant systems



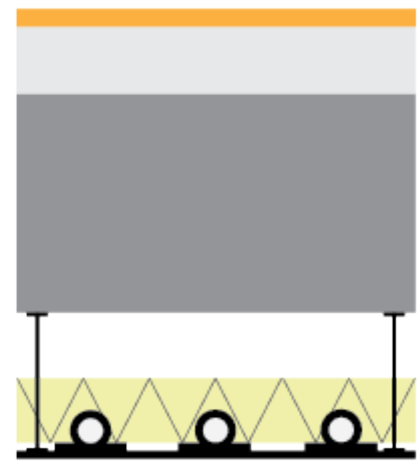
Radiant system types (high/low mass)

Thermally Activated
*Building System (**TABS**)*

Embedded
*Surface System (**ESS**)*

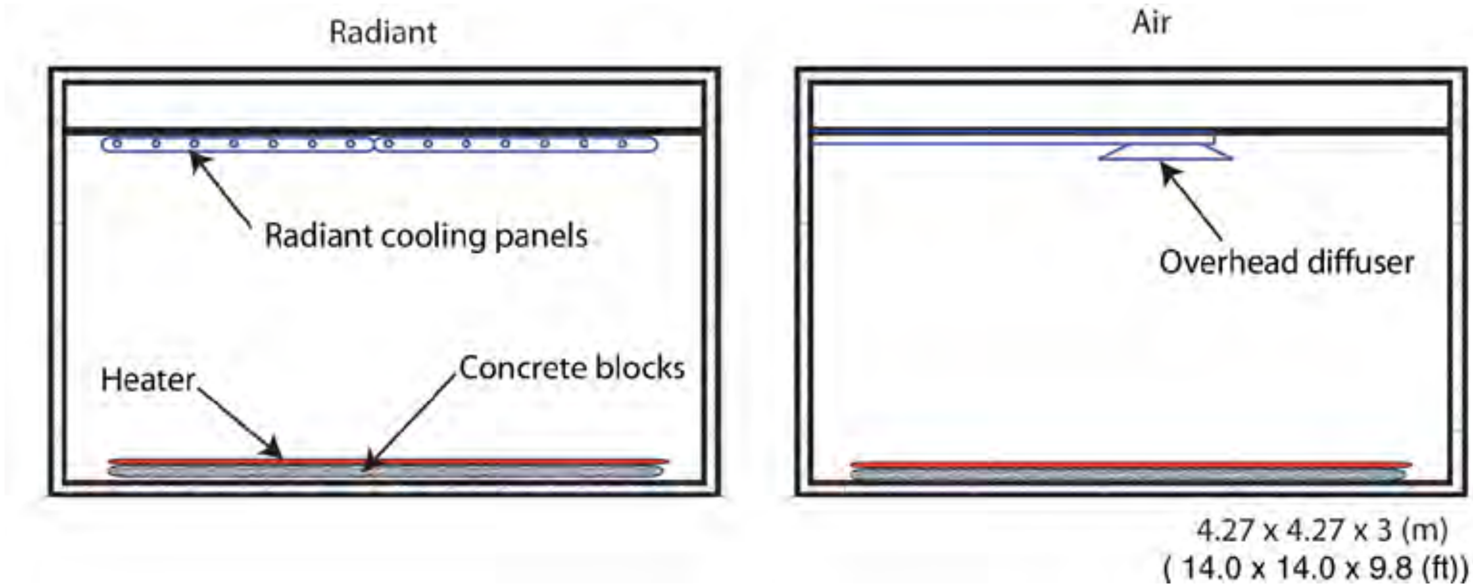


Radiant
*Panels (**RP**)*



Images source: Caroline Karmann

Cooling load differences: Laboratory tests



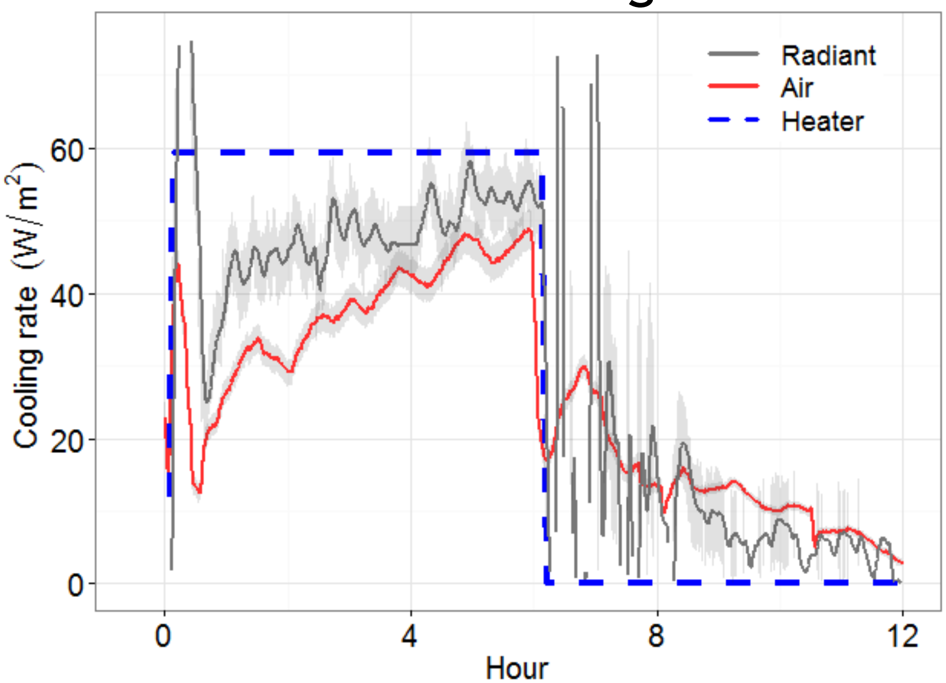
- Concrete pavers in floor as the non-active mass
- Constant heat gain applied in both settings, using thin electric resistance heating mat, loose mesh design to ceiling panels interact directly with with pavers below
- Constant operative temperature maintained to represent equivalent comfort (and it is prescribed as the control temperature for radiant systems)
- For each, 12-hour tests:
  - Heater on for 6 hours
  - Heater off for 6 hours

Feng Bauman Schiavon 2014 Experimental comparison Energy and Buildings

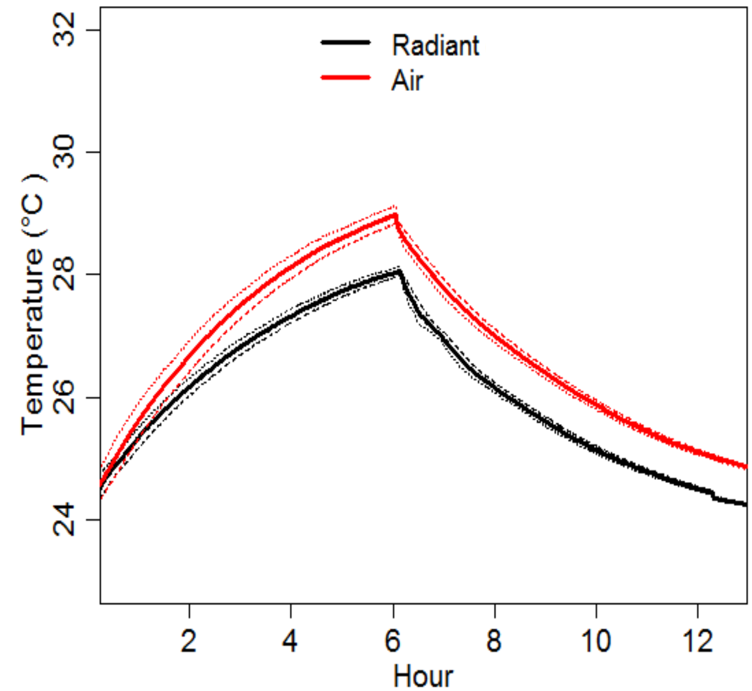
Cooling load differences: Laboratory results

- Radiant system has a higher cooling rate than the air system, up to 18% higher during peak cooling load
- Lower floor temperatures in radiant system shows that more heat was removed compared to air system

Instantaneous cooling rate



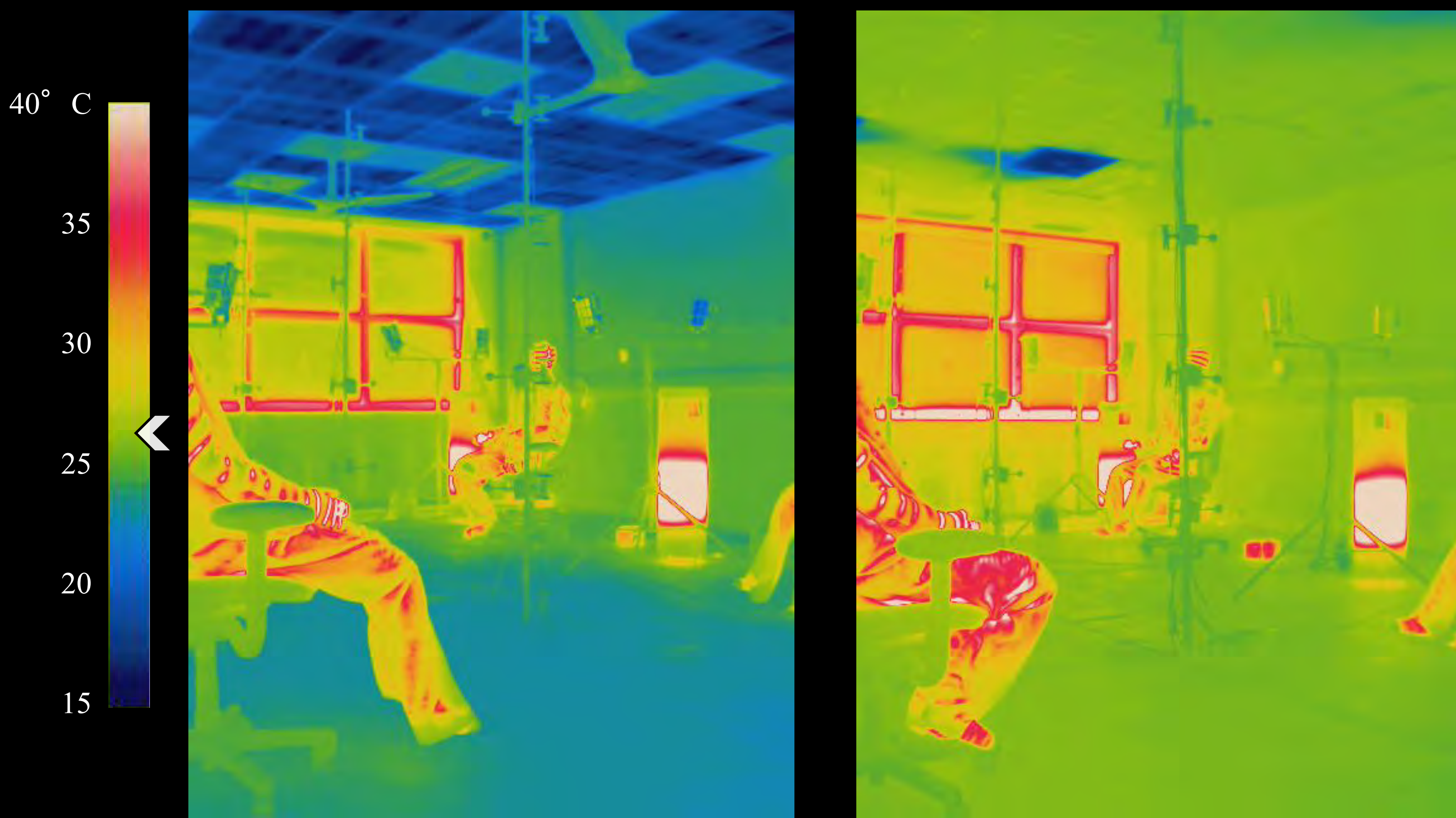
Temperature of concrete pavers in floor



Feng Bauman Schiavon 2014 Experimental comparison Energy and Buildings

New/ongoing tests at LBNL's FlexLab

Infrared comparison



RADIANT COOLING (CEILING)
OPERATIVE TEMP = 26° C

FORCED AIR COOLING
OPERATIVE TEMP = 26° C

- J. WOOLLEY

meh

Thermal neutrality

yay!

Thermal delight

Rich, variable, multi-sensory environments





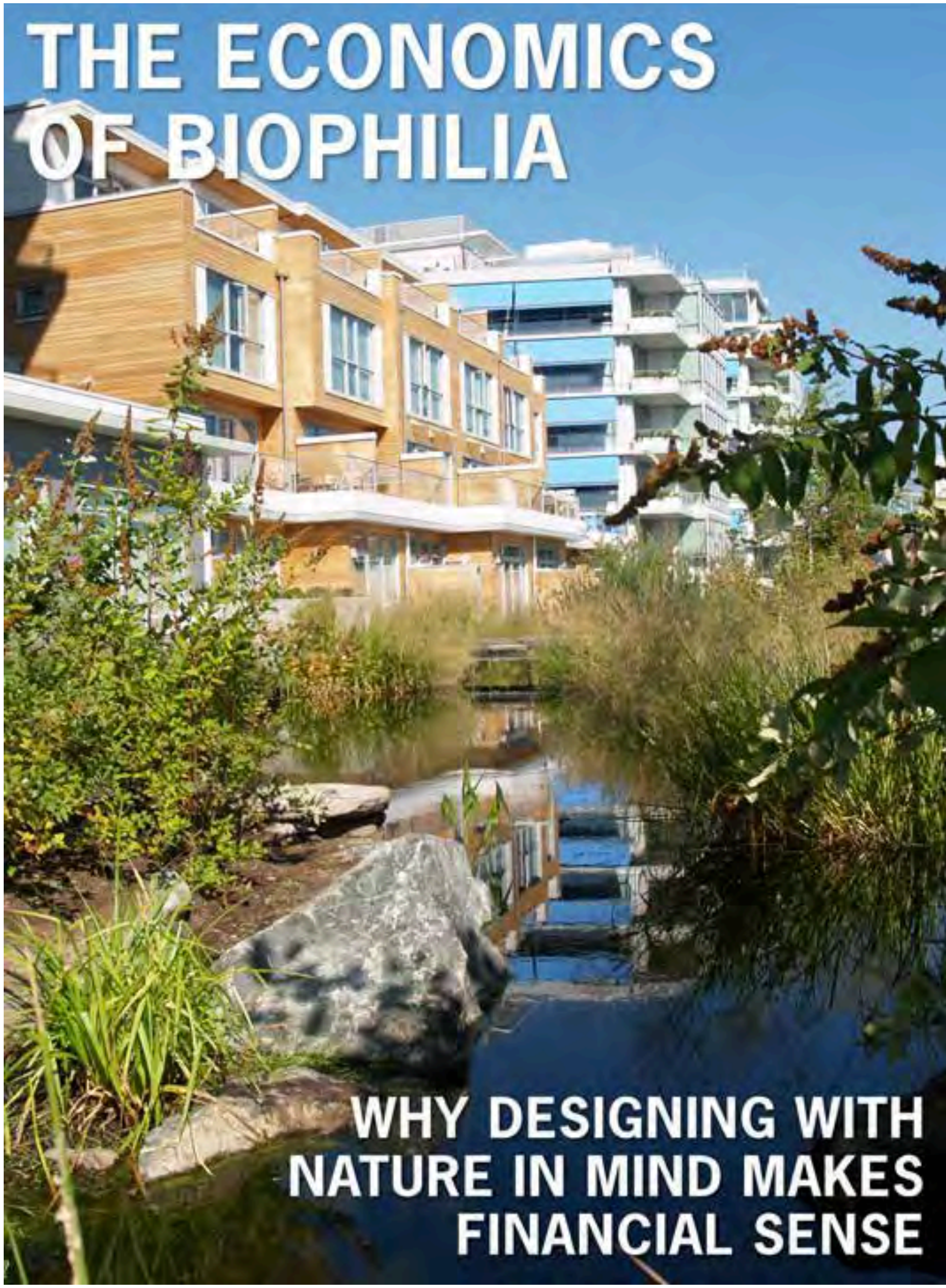

Experiential Monotony

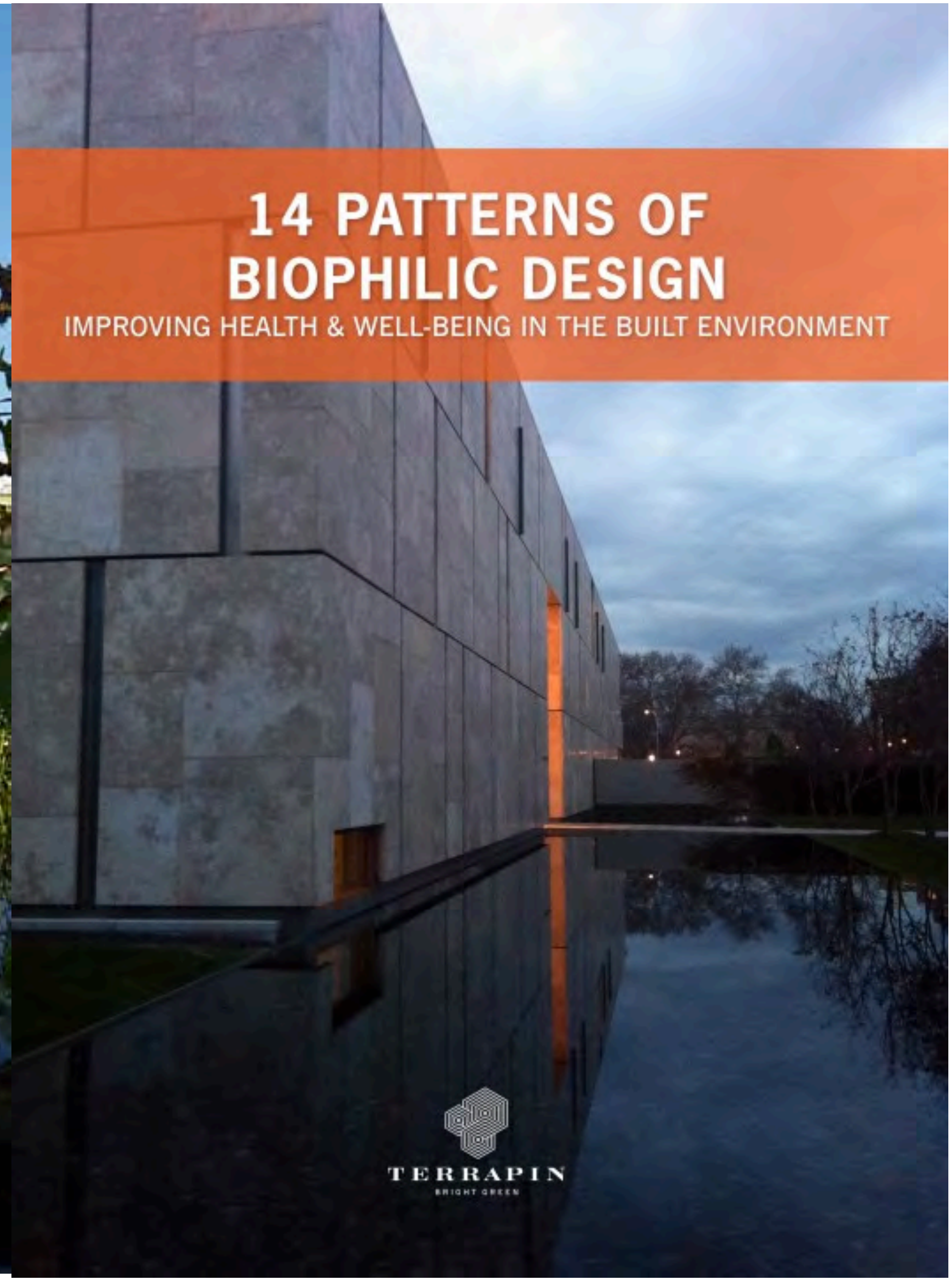




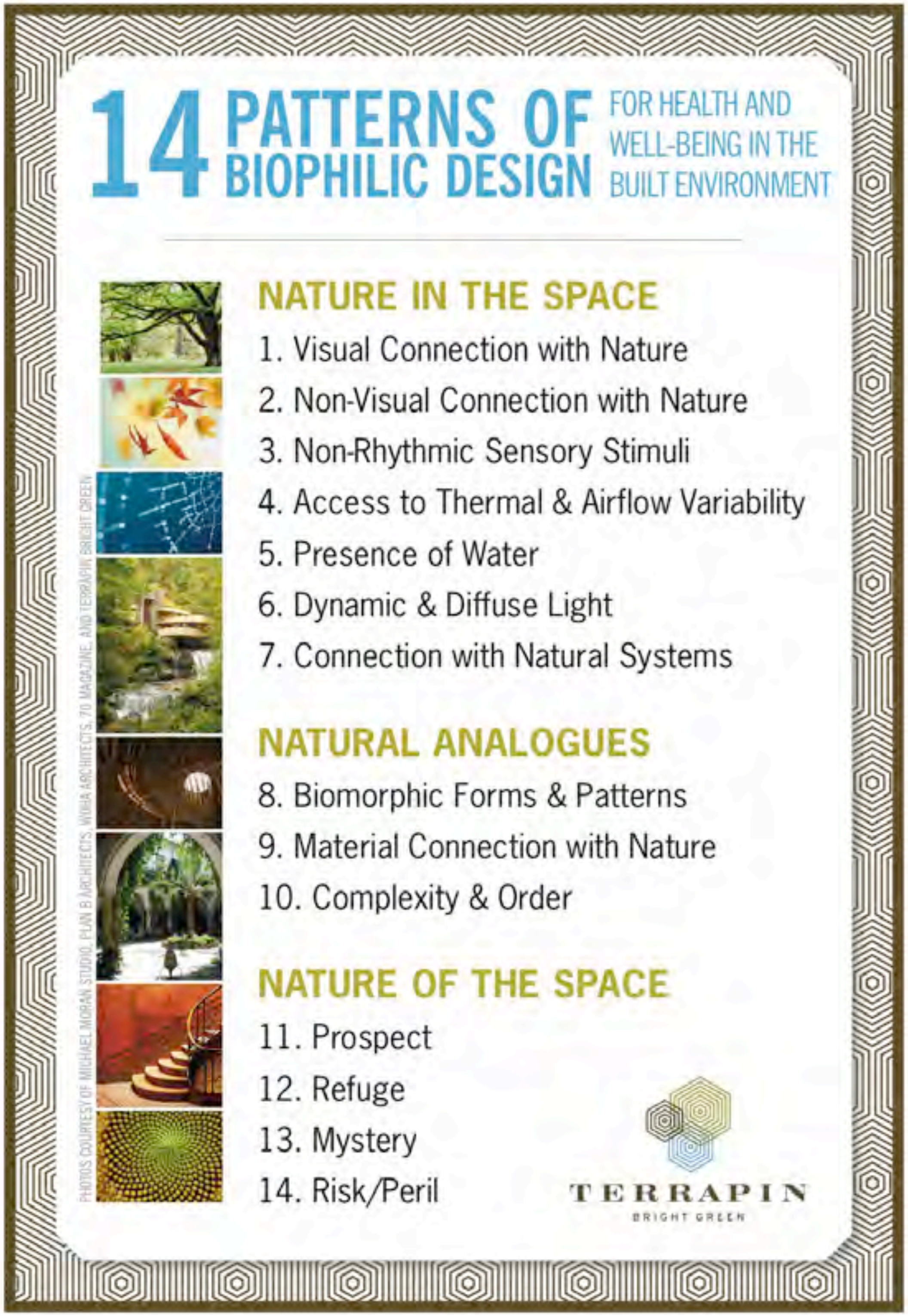








Source: www.terrapinbrightgreen.com

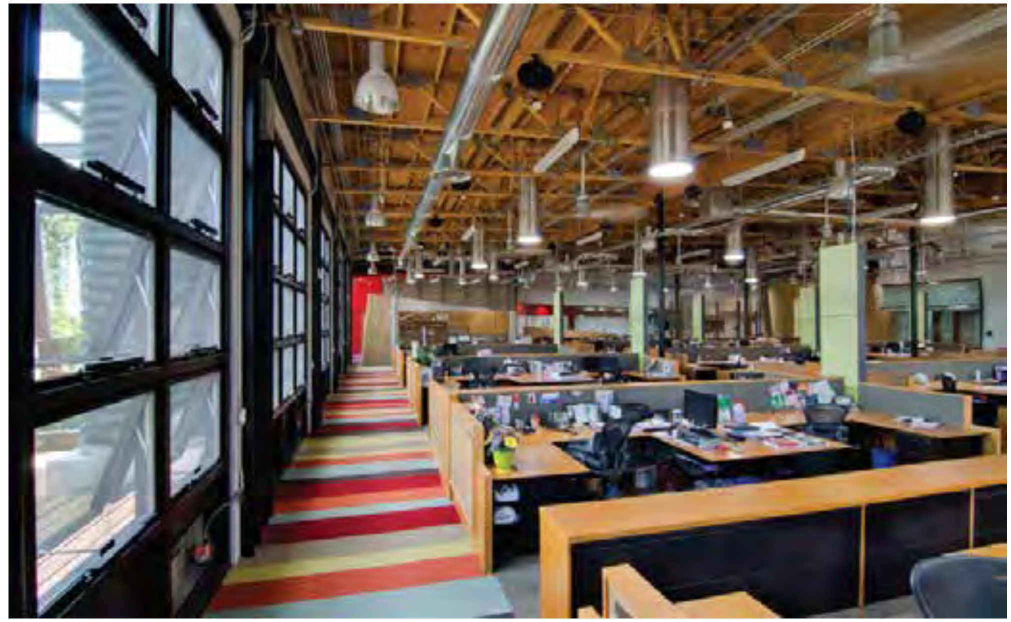


Benefits of Biophilic Design

- Psychological & physiological stress reduction
- Lowered blood pressure and heart rate
- Improved mental engagement / attentiveness
- Reduced attentional fatigue
- Increased physical / mental health
- Shift to positive emotional states
- Mental restoration, cognitive function
- Improved rates of healing
- Entrainment of circadian rhythms
- NO evidence of negative effects

www.terrapinbrightgreen.com

Occupant wellbeing
How can we reward GOOD buildings?



CBE Livable Buildings Awards
design + occupant experience + energy performanc

Awarded for exceptional performance in terms of occupant satisfaction, resource efficiency, and overall design

Qualifying criteria

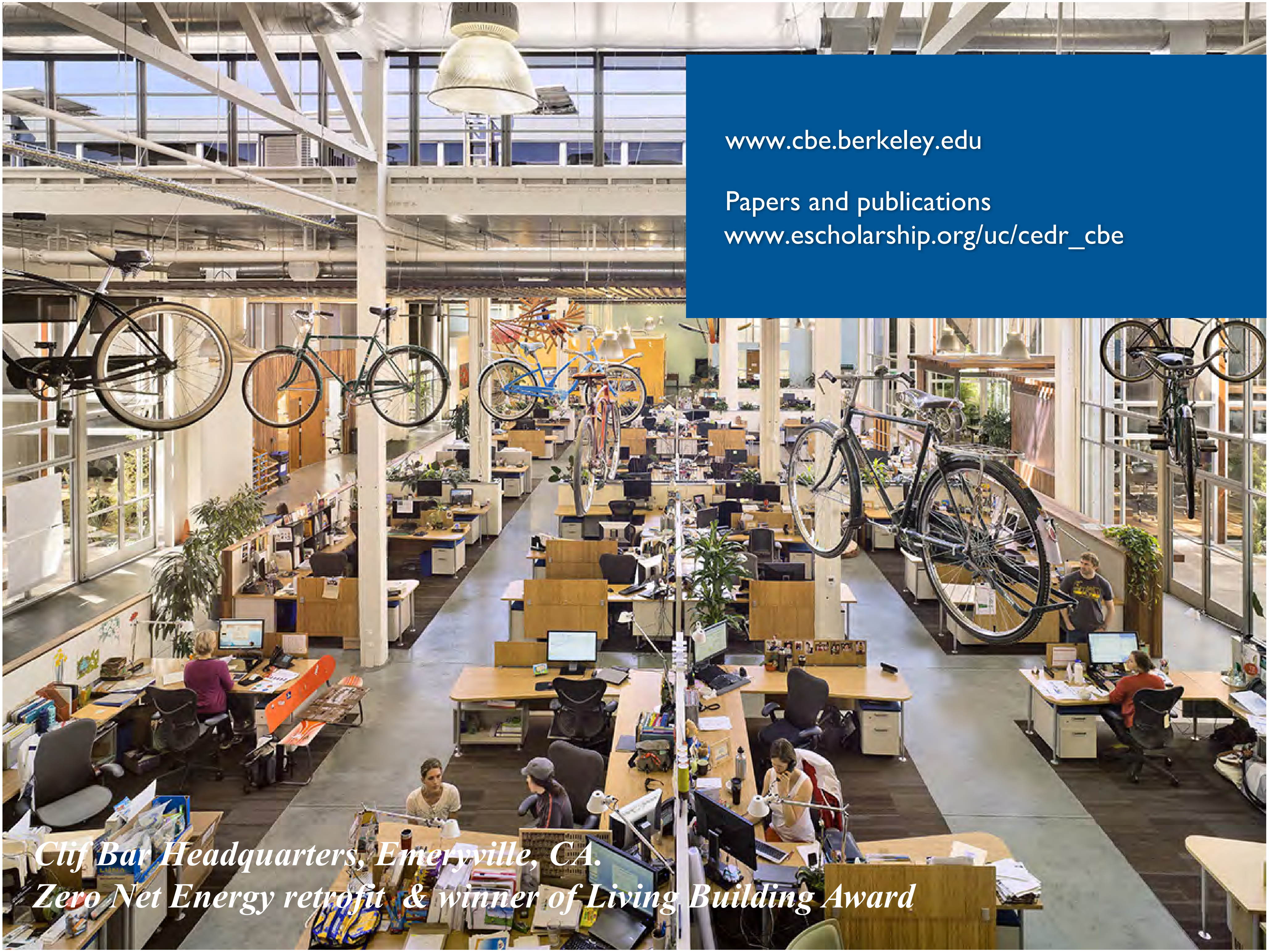
- Scores for all survey categories above 50th percentile
- Overall building score above 75th percentile

Selection

- Submission of design, operation, and survey
- Jury review

www.cbe.berkeley.edu

Papers and publications
www.escholarship.org/uc/cedr_cbe



Clif Bar Headquarters, Emeryville, CA.
Zero Net Energy retrofit & winner of Living Building Award