MIT – Energy Initiatives Series

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

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

CLIMATE SUMMIT

WHAT IF IT'S A BIG HOAX AND WE CREATE A BETTER WORLD FOR NOTHING?

- ENERGY INDEPENDENCE
- PRESERVE RAINFORESTS
- SUSTAINABILITY
- GREEN JOBS
- LIVABLE CITIES
- RENEWABLES
- CLEAN WATER, AIR
- HEALTHY CHILDREN

etc. etc.

Cartoon by Joel Pett, USA Today, Dec 2009
Why comfort?

Source: www.cartoonaday.com
Why buildings?
Trends - U.S. CO₂ 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

- Transportation: 28%
- Buildings: 40%
- Industry: 32%

**22% Residential**
- Space Heating: 28.1%
- Space Cooling: 14.3%
- Water Heating: 14.1%
- Lighting: 10.9%
- Electronics: 7.9%
- Refrigeration: 6.7%
- Wet Clean: 4.8%
- Cooking: 4.5%
- Computers: 2.5%
- Other: 3.5%
- Adjust to SEDS*: 2.8%

**38.0% Commercial**
- Lighting: 21.7%
- Space Heating: 15.5%
- Space Cooling: 13.4%
- Ventilation: 9.1%
- Refrigeration: 6.9%
- Water Heating: 4.2%
- Electronics: 4.1%
- Computers: 3.8%
- Cooking: 1.3%
- Other: 12.8%
- Adjust to SEDS*: 7.3%

But doesn’t it cost a lot to reduce energy & greenhouse gases?
40% of avoided emissions would result in negative cost (savings)!
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

The 2030 Challenge

Source: ©2015 2030, Inc. / Architecture 2030. All Rights Reserved.
*Using no fossil fuel GHG-emitting energy to operate.

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

Source: ©2010 2030, Inc. / Architecture 2030. All Rights Reserved.

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

The Name Game
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
<table>
<thead>
<tr>
<th>Definitions</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net zero <strong>site</strong> energy building</td>
<td>Building produces as much energy as it consumes when measured on site</td>
</tr>
<tr>
<td>Net zero <strong>source</strong> energy building</td>
<td>Building produces the same amount of energy as the amount of source (primary) energy it consumes.</td>
</tr>
<tr>
<td>Net zero energy <strong>cost</strong></td>
<td>Cost of the energy added to the grid by the building is same as the cost of the energy consumed by it.</td>
</tr>
<tr>
<td>Net zero <strong>emission</strong></td>
<td>Net emission due to building energy consumption is zero.</td>
</tr>
</tbody>
</table>
Zero Net Energy Buildings - Setting priorities

- Shading
- Daylighting
- Climate-response architecture
- Mechanical systems
- Electrical systems

Use renewables after you’ve done everything else!

Source: Two Degrees, Chap 6, McGregor, Roberts & Cousins
Zero Net Energy Buildings - Setting priorities

- Mechanical systems
- Electrical systems
- Shading
- Daylighting
- Climate-response architecture

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

ZNE are usually 20 EUI or less!!

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

Growth of ZNE and Ultra-Low Energy Buildings

- ZNE Verified
- ZNE Emerging
- Ultra-Low Energy

Building Count

© 2016 New Buildings Institute | newbuildings.org

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

<table>
<thead>
<tr>
<th>State</th>
<th>Ultralow Verified</th>
<th>ZNE Emerging</th>
<th>ZNE Verified</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>17</td>
<td>119</td>
<td>18</td>
<td>154</td>
</tr>
<tr>
<td>OR</td>
<td>4</td>
<td>14</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>NY</td>
<td>0</td>
<td>11</td>
<td>3</td>
<td>14</td>
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<td>MA</td>
<td>3</td>
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<td>14</td>
</tr>
<tr>
<td>FL</td>
<td>2</td>
<td>6</td>
<td>5</td>
<td>13</td>
</tr>
</tbody>
</table>

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

Large ZNE and Ultralow Energy Building Growth

- 25k - 50k sf
- 50k - 100k sf
- Over 100k sf

Building Count

- 1995
- 2000
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
- Sep-16

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?

Figure 10
NUMBER OF CASE STUDIES WITH EACH HVAC SYSTEM TYPE

![Bar chart showing number of case studies with each HVAC system type]

![Pie chart showing number of HVAC technologies per case study]

ASRHAEX High Performance Magazine, Fall 2016
Trends in ZNE (& ultra-low energy) – HVAC type?

Passive Solutions 1st

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)

Forced Air

Ceiling Fans

Chilled Beams

Radiant
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.
Comfort zones (ASHRAE Standard 55)

In practice: 71 – 75°F
Saving (significant!) energy with a wider dead band

Wider dead band reduces HVAC energy 7-15% per °C
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

Sources: US Department of Labor 2010, BLS 2011; EOMA 2010
Indoor Environmental Quality (IEQ)

Thermal comfort

Lighting / visual comfort

Indoor air quality

Acoustics
Are people comfortable in existing buildings?

I can't hear myself think.

It's really hard to type with your mittens on.

Another day at the sweat shop.

Turn down the #@$!* heat.

It's too quiet in here.

Another day working in the dark, literally.

I think I can see my breath.

Turn up the #@$!* heat.

Our new task force on cubicle comfort has been very effective. They've eliminated any trace of it.

You could fly a kite in this breeze.

I can still smell Wally's chili.

You don't think this air moved since 1957.
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


N = 53,000 occupants,
351 buildings

When Median < 0,
> 50% are dissatisfied
Paradigm shifts in the energy/comfort nexus

Artificial/active $\rightarrow$ Natural/passive/hybrid

Centralized $\rightarrow$ Personal control

Air $\rightarrow$ Water (radiant)

Thermal neutrality $\rightarrow$ Thermal delight
Artificial / Active

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

Replaced optimum temperature with a range

80% acceptability limits
90% acceptability limits

mean monthly outdoor air temperature (°C)
indoor operative temperature (°C)

5 10 15 20 25 30 35
50 F 59 F 68 F 77 F 86 F 95 F
86.0 F 82.4 F 78.8 F 75.2 F 71.6 F 68.0 F 64.4 F 60.8 F
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
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 < 25°C

- **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

- North Coast
- Bay Area
- Central Coast
- Southern Coast
- Central Valley
- South East

**Legend:**
- **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
1st generation PCS: desktop fan & foot warmer

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

Optional user interface

Fan and control unit

Foot warmer

occupancy sensing pressure plate

4W

average 30W
2nd generation PCS: heated & cooled chair

- Low power use, max:
  - 14 W for heating
  - 3.6 W 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

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 64-84°F 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

Occupants

- Selectively distribute chairs
  - Critical zones
  - Conflicting comfort needs
  - Single zone, multiple rooms

HVAC

- Zone control
- AHU control

(*) 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

Heat Capacity of this much air

=  

Heat Capacity of this much 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
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.
New/ongoing tests at LBNL’s FlexLab

SIDE-BY-SIDE COMPARISON OF COOLING RATES FOR RADIANT AND FORCED AIR SYSTEMS
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
THE ECONOMICS OF BIOPHILIA

14 PATTERNS OF BIOPHILIC DESIGN
IMPROVING HEALTH & WELL-BEING IN THE BUILT ENVIRONMENT

WHY DESIGNING WITH NATURE IN MIND MAKES FINANCIAL SENSE

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 performance

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

Qualifying criteria

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

Selection

- Submission of design, operation, and survey
- Jury review
Clif Bar Headquarters, Emeryville, CA.
Zero Net Energy retrofit & winner of Living Building Award

www.cbe.berkeley.edu

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