Advanced Energy Efficiency for Buildings
Global drivers of building green

**Materials:** Construction uses 3bn T/y of raw materials—**40%** of total global use—tied up for ~50–100 y

**Energy:** **40%** of the world’s energy builds and operates buildings, which directly use 49% of Sing. electricity and emit 25% of Sing. CO₂

**Water:** The building industry uses **16%** of global fresh water

**People:** The “built environment” is humanity’s largest artifact...and in modern cities, most people spend over **90%** of their time indoors

“We shape our buildings and afterwards our buildings shape our lives.”

—Churchill
What has reduced energy intensity already done? What more can it do?

- During 1975–2006, the U.S. made a dollar of real GDP with 48% less total energy, 54% less oil, 64% less directly used natural gas, 17% less electricity, and two-thirds less water
  - Despite stagnant light-vehicle efficiency for >20 years, and perverse incentives rewarding electricity sales in 48 states
  - Nobody noticed: U.S. hasn’t paid attention since the mid-1980s

- Today’s best end-use efficiencies could deliver better U.S. energy services at 1/6 the cost while saving half the oil and gas and at least three-fourths of the electricity, at an average cost 1/8 of their current prices

- NIES: “Japan has the technological potential to reduce its CO₂ emissions by 70% compared to the 1990 level, while satisfying the expected demand for energy services in 2050.” Extra cost: ~0.1% of GDP
Efficiency is a rapidly moving target

Japan’s standards aim to cut el. use 30% from ~1997 levels for refrigerators, 16% for TVs, 83% for PCs, 14% for air conditioners,…; all can go much lower.
1989 supply curve for saveable U.S. electricity (vs. 1986 frozen efficiency)

Best 1989 technology, thoroughly retrofitted; no integrative design

Similar S, DK, D, UK...

EPRI found 40–60% saving 2000 potential

Now conservative: savings keep getting bigger and cheaper faster than they’re being depleted

Measured technical cost and performance data for ~1,000 technologies (RMI 1986–92, 6 vol, 2,509 pp, 5,135 notes)
The efficiency resource is getting bigger and cheaper faster than we use it

- 1984–89: negawatt potential ×2, real cost ÷3 (RMI)
- Since 1990, add mass production (often offshore), cheaper electronics, competition, better technology

  Thanks to Jim Rogers PE for most of these examples, which we've converted to constant dollars
  - Compact fluorescent lamps: 85–94% cheaper 1983–2003 (>1b/y)
  - Electronic T8 ballasts: >90% cheaper 1990–2003 (& lux/W up 30%)
  - Direct/indirect luminaires: gone from premium to cheapest option
  - Industrial variable-speed drives: ~83–97% cheaper since 1990
  - Window a/c: 69% cheaper than 1993, 13% more efficient, digital
  - Low-E window coatings: ~84% cheaper than five years ago

- Delivery: scaleup, streamlining, integration
  - E.g., a NE lighting retrofit firm halves the normal contractor price

- Design integration: huge, least exploited resource
  - Hardly used yet...but typically makes very big savings cost <0!
-44 to +46°C with no heating/cooling equipment, less construction cost

- Lovins house / RMI HQ, Snowmass, Colorado, ’84
  - Saves 99% of space & water heating energy, 90% of home el.
    (372 m² use ~120 Wav costing ~$5/month @ $0.07/kWh)
  - 10-month payback in 1983

- PG&E ACT², Davis CA, ’94
  - Mature-market cost −$1,800
  - Present-valued maint. −$1,600
  - 82% design saving from 1992 California Title 24 code

- Prof. Soontorn Boonyatikarn house, Bangkok, Thailand, ’96
  - 84% less a/c capacity, ~90% less a/c energy, better comfort
  - No extra construction cost

Key: integrative design—multiple benefits from single expenditures
Rocky Mountain bananas with no furnace?
Old design mentality: always diminishing returns...
High efficiency doesn’t always raise even components’ capital cost

- Motor Master database shows no correlation between efficiency and trade price for North American motors (1,800-rpm TEFC Design B) up to at least 220 kW

- Same for industrial pumps, most rooftop chillers, refrigerators, televisions,...

- “In God we trust”; all others bring data

New design mentality: expanding returns, “tunneling through the cost barrier”
New design mentality: expanding returns, “tunneling through the cost barrier”

To see how, please visit www.rmi.org/stanford
Two ways to tunnel through the cost barrier

1. Multiple benefits from single expenditures
   ◊ Save energy and capital costs...10 benefits from superwindows, 18 from efficient motors & lighting ballasts,...
   ◊ Throughout the design: e.g., RMI HQ’s arch has 12 functions but just one cost
     ○ Supports greenhouse glazing, supports roof purlins, distributes varying cantilevered loads, mounts atrium lights, acoustics, esthetics, thermal mass, controls atrium’s solar gain seasonally (to prevent north-side overheating), collects hot water and hot air, distributes daylight, vents excess heat
     ○ Most components of the building do at least three jobs
   ◊ A Lotus Elise car has a front-end component with seven functions but just one cost
   ◊ Designing this way—as nature does—is more fun!
Typical analysis

<table>
<thead>
<tr>
<th>Energy Measure</th>
<th>Incremental Cost</th>
<th>Savings</th>
<th>Payback Period (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daylighting</td>
<td>$4,900</td>
<td>$1,560</td>
<td>3.14</td>
</tr>
<tr>
<td>Glazing</td>
<td>$5,520</td>
<td>$1,321</td>
<td>4.18</td>
</tr>
<tr>
<td>Energy Efficient Lighting</td>
<td>$1,400</td>
<td>$860</td>
<td>1.63</td>
</tr>
<tr>
<td>Energy Efficient HVAC</td>
<td>$3,880</td>
<td>$739</td>
<td>5.25</td>
</tr>
<tr>
<td>HVAC Controls</td>
<td>$2,900</td>
<td>$506</td>
<td>5.73</td>
</tr>
<tr>
<td>Shading</td>
<td>$4,800</td>
<td>$325</td>
<td>14.77</td>
</tr>
<tr>
<td>Economizer Cycle</td>
<td>$1,200</td>
<td>$165</td>
<td>7.27</td>
</tr>
<tr>
<td>Insulation</td>
<td>$1,600</td>
<td>$101</td>
<td>15.84</td>
</tr>
</tbody>
</table>

Whole-system design: a 1,208-m² Denver office
Whole-system design: a 1,208-m² Denver office

Whole-building analysis

- Added construction costs: $26,200
- Capital cost *reductions*: $21,860
- Incremental construction cost: $4,340
- Energy savings (70%): $4,500/year
- Simple payback: about 1 year
- ROI: about 100%

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<tr>
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<td>$1,600</td>
</tr>
<tr>
<td>Fewer E &amp; W Windows</td>
<td>-$4,160</td>
</tr>
<tr>
<td>Small &amp; Different HVAC</td>
<td>-$17,700</td>
</tr>
</tbody>
</table>
Incremental costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>$67,500</td>
</tr>
<tr>
<td>Daylighting</td>
<td>$18,000</td>
</tr>
<tr>
<td>Insulation</td>
<td>$17,200</td>
</tr>
<tr>
<td>Lighting</td>
<td>$21,000</td>
</tr>
<tr>
<td>HVAC</td>
<td>-$160,000</td>
</tr>
<tr>
<td>Total</td>
<td>-$36,300</td>
</tr>
</tbody>
</table>

Energy savings: $75,000/year
Counting superwindows’ ten hidden benefits

0. Saved heating energy (4–9× double glazing’s insulating value)—the only benefit normally counted

1. Save cooling energy, + fan/pump energy ∝ flow³
2. Radiant comfort (half of comfort sensation)
3. Downsize/eliminate space-conditioning capacity
4. Lower construction cost (avoids ducts, etc.)
5. No perimeter zone heating
6. Reduced fading from ∼20× less UV <380 nm
7. Reduced noise
8. Less/no condensation and sash rot
9. Improved daylighting
10. Human productivity

All “tuned” to each building elevation (9 flavours of suspended film; many glass types, tints, spacings, fill gases/mixtures)

L: ∼50-μm Heat Mirror® suspended selective film with argon or krypton fill. R: A two-film k-0.45 unit. Film can also be coated on both sides for an even higher insulating value—even k-0.29 with 6 selective films + Xe.

Two ways to tunnel through the cost barrier

1. Multiple benefits from single expenditures
   - Save energy and capital costs...10 benefits from superwindows, 18 from efficient motors & lighting ballasts,...
   - Throughout the design: e.g., RMI HQ’s arch has 12 functions, one cost

2. Piggyback on retrofits
   - A 19,000-m² Chicago office could save 3/4 of energy at same cost as normal 20-y renovation — and greatly improve human performance—if retrofit is coordinated with façade renewal
Cost can be negative even for retrofits of big buildings

- 19,000-m², 20-year-old curtainwall office near Chicago (hot & humid summer, very cold winter)
- Dark-glass window units’ edge-seals were failing
- Replace not with similar but with superwindows
  - Let in nearly 6× more light, 0.9× as much unwanted heat, reduce heat loss and noise by 3–4×, cost $8.4/m²_{glass} more
- Add deep daylighting, plus very efficient lights (3 W/m²) and office eqt (2 W/m²); peak cooling –76%
- Replace big old cooling system with a new one 4× smaller, 3.8× more efficient, $0.2 million cheaper
- That capital saving pays for all the extra costs
- 75% energy saving—*cheaper* than usual renovation
Efficiency’s marketable side-benefits often worth $10^{1-2}\times$ more than lower bills

- Efficient buildings raise labour productivity $\sim 6-16\%$
  - A typical 2005 office paid $\sim 164\times$ as much for people as for energy

- Efficient lighting systems improve visibility & beauty
  - 20–26% faster learning (per test scores) in well-daylit schools
  - 40% higher retail sales/m²-y in well-daylit stores

- Efficient motors are more reliable, quiet, controllable

- Efficient refrigerators keep food fresher, longer

- Efficient hospitals have faster healing, less pain, fewer infections, better financials

- Efficient supermarkets sell more and safer food

- Side-benefits more than double industrial efficiency’s returns and savings (e.g., in USA steel sector)
Office productivity gains are $164\times$ more valuable than energy savings

Occupants’ salaries, w/o equipment & benefits, are $\sim 85-92\%$ of the average U.S. cost of office operation. *Salaries, benefits, and equipment total $164\times$ energy costs.* Before Romm & Browning (RMI, 1994), nobody had looked for productivity effects because business schools mistaught the “Hawthorne effect,” so MBAs believed such effects were a myth. Now they’re turning up everywhere.

Key U.S. office operating costs, $/\text{ft}^2\cdot\text{y}$

A 0.6\% gain in labor productivity would be equivalent on the bottom line to *eliminating* the energy bill

Efficient, green offices generally exhibit a 6–16\% gain in labor productivity—10–26\times more valuable than a zero energy bill—so what could such design do for sick people?

Stop & Shop supermarket
Foxboro, MA, USA

- 38% energy savings
- Higher per-cart sales
- Improved customer satisfaction
- Preferred by employees

Skylights: 60–90% Daylight
Schools in Curitiba, Brazil

- Of the two classroom window units on the top right, the second has a light shelf inside and outside
Curitiba daylighting retrofit experiment

- Top classroom with no lightshelf has high luminance ratios, making the room feel dark compared to the bright window.
- Bottom classroom under same condition but with lightshelf appears bright with moderate luminance ratios.
- No electric lights are on in either photo.
- The lower room saves 75% of electricity, so that class can afford to buy books.
- Students also learn ~20–26% faster in well-daylit classrooms.
- What’s the multiplier from education to national development?

Courtesy of Greg Franta FAIA, ENSAR Group, Boulder, Colorado
People who seem to have had a new idea have often just stopped having an old idea

Edwin Land
The Nine Dots Problem
The Nine Dots Problem
The Nine Dots Problem
origami solution
geographer’s solution
mechanical engineer’s solution
statistician's solution
New design mentality

- Redesigning a standard (supposedly optimized) industrial pumping loop cut power from 70.8 to 5.3 kW (–92%), cost less to build, and worked better
  - Just two changes in design mentality
New design mentality, an example

1. Big pipes, small pumps (not the opposite)
No new technologies, just two design changes

2. Lay out the pipes first, then the equipment (not the reverse)
No new technologies, just two design changes

- Fat, short, straight pipes — not thin, long, crooked pipes!
- Benefits counted
  - 92% (12x) less pumping energy
  - Lower capital cost
- “Bonus” benefit also captured
  - 70 kW lower heat loss from pipes
- Additional benefits not counted
  - Less space, weight, and noise
  - Clean layout for easy maintenance access
  - But needs little maintenance—more reliable
  - Longer equipment life
- Count these and save...~98%?
Why systems?

Most people think efficient systems are about energy-efficient equipment and expensive gadgets.

This is like saying that using the best ingredients will ensure a tasty dish.

Efficient systems are actually the result of whole-system design.

Even the finest and rarest ingredients won’t make our dish tasty unless:

- we use a good recipe,
- combining the right ingredients,
- in the right sequence, manner, and proportions.
Why pumping systems?

- Pumping is the world’s biggest use of motors.
- Motors use 3/5 of all electricity, so emit 20% of all fossil-fuel CO₂.
- A big motor running constantly uses its capital cost in electricity every few weeks.
- RMI (1989) and EPRI (1990) found ~1/2 of typical industrial motor-system energy could be saved by retrofits costing <$0.005 (1986 $) per saved kWh—a ~16-month payback at a $0.05/kWh tariff. Why so cheap? Buy 7 savings, get 28 more for free! (Cheaper now.)
- Downstream savings are often bigger and cheaper—so minimize flow and friction first.
Compounding losses...or savings...so start saving at the *downstream* end to save ten times as much energy at the power plant.

Also makes upstream equipment smaller, simpler, cheaper.
It’s often remarkably simple

Boolean pipe layout

99%  1%

VS.

hydraulic pipe layout

99%  1%
High-efficiency pumping / piping retrofit
(Rumsey Engineers, Oakland Museum)

15 “negapumps”

Notice smooth piping design
– 45°s and Ys

Downsized condenser-water pumps, ~75% energy saving
Which of these layouts has less capex & energy use?

Condenser water plant: traditional design

...or how about this?

- Less space, weight, friction, energy
- Fewer parts, smaller pumps and motors, less installation labor
- Less O&M, higher uptime
So how do we do this magic?

“Like Chinese cooking. Use everything. Eat the feet.”

— LEE Eng Lock, Singapore efficiency engineer

Chinese food is world-famous for using every part and wasting nothing. Why not do everything else that way too?
The right steps in the right order: lighting

1. Improve visual quality of task
2. Improve geometry of space, cavity reflectance
3. Improve lighting quality (cut veiling reflections and discomfort glare)
4. Optimize lighting quantity
5. Harvest/distribute natural light
6. Optimize luminaires
7. Controls, maintenance, training
The right steps in the right order: space cooling

0. Cool the people, not the building
1. Expand comfort envelope (check assumptions!)
2. Minimize unwanted heat gains
3. Passive cooling
   • Ventilative, radiative, ground-/H₂O-coupling, icepond
4. Active nonrefrigerative cooling
   • Evap, desiccant (CDQ), absorp., hybrids: COP >100
   • Direct/indirect evap + VFD recip in CA: COP 25
5. Superefficient refrigerative cooling: COP 6.8 (0.52 kW/t) (Singapore water-cld. centrif. system @ design)
6. Coolth storage and controls
7. Cumulative energy saving: ~90–100%, better comfort, lower capital cost, better uptime

A worthy goal: extirpate refrigerative air conditioning, including big commercial (responsible for ~1/2 of China’s growth in peak el. demand)
350-m² Bangkok house by Prof. Suntoorn Boonyatikarn

- 1996 private home
- 1/10th normal air conditioning usage
- Deep overhangs, superwindows, dark roof (!)

- Better comfort
- Normal construction cost
- Integrated design
350-m² Bangkok house by Prof. Suntoorn Boonyatikarn
350-m² Bangkok house by Prof. Suntoorn Boonyatikarn

Singapore homes could do at least this well…but refrigerative air conditioning isn’t the only & may not be the best choice.
Stanford’s Carnegie Institute for Global Ecology wet-lab building

- NightSky (radiant roof spray), draft-tower, and air-economizer cooling, COP \( \geq 50 \) (\( \leq 0.07 \) kW/t); would double with optimized pumping-system design
- Efficient shell, daylit, high occupant satisfaction
- Normal capital cost
- \( \sim 20\% \rightarrow 10\% \) normal CA energy use, despite weird safety rules requiring high-rate ventilation of empty, dark labs
- This usage excludes the small server farm, whose efficiency is the next logical target

1,012 m\(^2\), $4,002/m\(^2\) in 2004—normal cost; energy data posted at http://globalecology.stanford.edu/DGE/CIWDGE/CIWDGE.HTML
**Superefficient big refrigerative HVAC too**

(10^5+ m^2 water-cooled centrifugal, Singapore, turbulent induction air delivery — but underfloor displacement could save even more energy)

<table>
<thead>
<tr>
<th>Element</th>
<th>Std kW/t (COP)</th>
<th>Best kW/t (COP)</th>
<th>How to do it</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply fan</td>
<td>0.60</td>
<td>0.061</td>
<td>Best vaneaxial, ~0.2–0.7 kPa TSH (less w/UFDV), VAV</td>
</tr>
<tr>
<td>ChWP</td>
<td>0.16</td>
<td>0.018</td>
<td>120–150 kPa head, efficient pump/motor, no pri/sec</td>
</tr>
<tr>
<td>Chiller</td>
<td>0.75</td>
<td>0.481</td>
<td>0.6–1 Cº approaches, optimal impeller speed</td>
</tr>
<tr>
<td>CWP</td>
<td>0.14</td>
<td>0.018</td>
<td>90 kPa head, efficient pump/motor</td>
</tr>
<tr>
<td>CT</td>
<td>0.10</td>
<td>0.010</td>
<td>Big fill area, big slow fan at variable speed</td>
</tr>
</tbody>
</table>

**TOTAL**

1.75 (COP 2.01) 0.588 COP 5.98, 3× better

Better comfort, lower capital cost

Best Singapore practice w/dual ChW temp.: **0.52 total kW/t** including 0.41 chiller, **COP 6.8**
Low-face-velocity, high-coolant-velocity coils...

Just correct a 1921 W. Carrier error about how coils work.

Flow is laminar and condensation is dropwise, so turn the coil around sideways, run at <1 m/s; 29% better dehumidification, ΔP = 95%, ASHRAE comfort over the entire load range, smaller chiller/fan, smaller parasitics.
Air handling: basic physics

\[
\text{Fan motor kW} = \frac{\text{airflow (m}^3/\text{s}) \times \text{pressure drop (kPa)}}{\text{fan efficiency} \times \text{motor efficiency}}
\]

Static or static+dyanamic pressure yields static or total fanpower. To obtain fan motor hp from cfm (ft³/min) and inches w.g., divide by 6,354

\~2\times \text{opportunities: fan eff.} \ (\geq 0.82, \text{usually vane-axial}), \ \text{motor system eff.} \ (\text{MotorMaster best, right-sized, high power factor, ...—35 improvements}), \ \text{VFDs}

\~5–10\times \text{(or greater) opportunities:}

- \textbf{Reduce flow:} air-change rates (base on actual health goals and real-time sensors), displacement

- \textbf{Reduce pressure drop:} System design, wring out friction (e.g. duct layout & sizing), low face velocity
  - 60- vs. 50-cm duct saves 60\% of fanpower (\(\Delta P \propto d^{-5.1}\))

\textbf{COMBINE ALL OF THESE, then downsize chillers}
**Grand Hyatt Singapore Commissioning Data**

<table>
<thead>
<tr>
<th>Description</th>
<th>Pre-retrofit</th>
<th>Post-retrofit</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller efficiency</td>
<td>0.75</td>
<td>0.485</td>
<td>35.33%</td>
</tr>
<tr>
<td>Cooling tower efficiency</td>
<td>0.03</td>
<td>0.025</td>
<td>16.67%</td>
</tr>
<tr>
<td>Chilled water pump efficiency</td>
<td>0.153</td>
<td>0.035</td>
<td>77.12%</td>
</tr>
<tr>
<td>Condenser water pump efficiency</td>
<td>0.116</td>
<td>0.035</td>
<td>69.83%</td>
</tr>
<tr>
<td>System efficiency</td>
<td>1.049</td>
<td>0.58</td>
<td>44.71%</td>
</tr>
</tbody>
</table>
Comparison of System kW (Before & After)

System kW (Before – 25th Nov to 19th Dec 2006)

Savings in kW

System kW (After – 1st May 2007 to 14th May 2006)

Chilled Water Ton
Johnson Diversey
Racine, Wisconsin
JohnsonDiversey (LEED-EB Gold)
Sturtevant, Wisconsin

32,528-m² project was ahead of schedule and US$4 million under budget

US$1,496/m² first cost, 10–15% below average

US$4.95/m²-y energy cost (79% lower than the then national average cost of US$23.67/m²-y)
Integrated office design

- RMI led design for Hines and Gensler
- Tightly integrated state-of-the-shelf choices
  - Deep daylighting, superefficient direct/indirect lighting, very efficient plug loads and HVAC
  - Underfloor displacement ventilation
  - No or almost no dropped ceiling
  - Tuned superwindows, careful shading/mass
  - Optimized structural bays
  - Optimized surface optics to reject solar heat
Integrated office design results

- Energy −50% without, or −75+% with, influence over tenant loads (approx.)
- 6 storeys in 23m lowrise limit, ceiling +12 cm
- Superlative lighting, thermal, & air quality
- Silent; individual worker air/thermal control
- Reconfiguration costs almost eliminated
- Same or slightly lower capital cost
- Simpler construction, 6 months faster
## Benchmarking a big new office

(≈10,000+ m², tropical; Japanese comparables; Singapore)

<table>
<thead>
<tr>
<th></th>
<th>standard US</th>
<th>better</th>
<th>best practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>site MJ/m²-y</td>
<td>1,100/1,737</td>
<td>450–680/566</td>
<td>100–230/293</td>
</tr>
<tr>
<td>el. kWh/m²-y</td>
<td>270/225/203</td>
<td>160/170/195</td>
<td>20–40/81/80</td>
</tr>
<tr>
<td>lighting W/m² as-used</td>
<td>16–24/12</td>
<td>10</td>
<td>1–3</td>
</tr>
<tr>
<td>plug W/m² as-used</td>
<td>50–90/12</td>
<td>10–20</td>
<td>2</td>
</tr>
<tr>
<td>glazing W/m²K COG</td>
<td>2.9</td>
<td>1.4</td>
<td>0.3–0.5</td>
</tr>
<tr>
<td>glazing T_{vis}/SC</td>
<td>1.0</td>
<td>1.2</td>
<td>&gt;2.0</td>
</tr>
<tr>
<td>perimeter heating</td>
<td>extensive</td>
<td>medium</td>
<td>none</td>
</tr>
<tr>
<td>roof α, ε</td>
<td>0.8, 0.2</td>
<td>0.4, 0.4</td>
<td>0.08, 0.97</td>
</tr>
<tr>
<td>m²/kW_{th} cooling</td>
<td>7–9</td>
<td>13–16</td>
<td>26–32+</td>
</tr>
<tr>
<td>cooling syst. COP</td>
<td>1.85</td>
<td>2.3</td>
<td>6.8–25+</td>
</tr>
<tr>
<td>relative cap. cost</td>
<td>1.0</td>
<td>1.03</td>
<td>0.95–0.97</td>
</tr>
<tr>
<td>relative space eff.</td>
<td>1.0</td>
<td>1.01</td>
<td>1.05–1.06</td>
</tr>
</tbody>
</table>

Japan standard: median of 40 buildings, Energy Conservation Center of Japan; better: average of six SHASEJ Junen Award-winning buildings; best: the most efficient of those six buildings (Nissei Yokkaichi Building); data courtesy of Urabe-san, CRIEPI, via Asano-sensei, Dept. of Mechanical Engineering, The University of Tokyo
## Benchmarking a big new office

(\textasciitilde 10,000+ \text{ m}^2, \text{ tropical}; \text{ Japanese comparables}; \text{ Sing. Nat’l. Libary})

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<td>el. kWh/m²-y</td>
<td>270/203</td>
<td>160/170/195</td>
<td>20–40/81</td>
</tr>
<tr>
<td>lighting W/m² as-used</td>
<td>16–24/12</td>
<td>10</td>
<td>1–3</td>
</tr>
<tr>
<td>plug W/m² as-used</td>
<td>50–90/12</td>
<td>10–20</td>
<td>2</td>
</tr>
<tr>
<td>glazing W/m²K COG</td>
<td>2.9</td>
<td>1.4</td>
<td>0.3–0.5</td>
</tr>
<tr>
<td>glazing T_{vis}/SC</td>
<td>1.0</td>
<td>1.2</td>
<td>&gt;2.0</td>
</tr>
<tr>
<td>perimeter heating</td>
<td>extensive</td>
<td>medium</td>
<td>none</td>
</tr>
<tr>
<td>roof ( \alpha, \epsilon )</td>
<td>0.8, 0.2</td>
<td>0.4, 0.4</td>
<td>0.08, 0.97</td>
</tr>
<tr>
<td>m²/kW_{th} cooling</td>
<td>7–9</td>
<td>13–16</td>
<td>26–32+</td>
</tr>
<tr>
<td>cooling syst. COP</td>
<td>1.85</td>
<td>2.3</td>
<td>6.8–25+</td>
</tr>
<tr>
<td>relative cap. cost</td>
<td>1.0</td>
<td>1.03</td>
<td>0.95–0.97</td>
</tr>
<tr>
<td>relative space eff.</td>
<td>1.0</td>
<td>1.01</td>
<td>1.05–1.06</td>
</tr>
</tbody>
</table>

Japan standard: median of 40 buildings, Energy Conservation Center of Japan; better: average of six SHASEJ Junen Award-winning buildings; best: the most efficient of those six buildings (Nissei Yokkaichi Building); data courtesy of Urabe-san, CRIEPI, via Asano-sensei, Dept. of Mechanical Engineering, The University of Tokyo
## Benchmarking a new office

(\sim 10,000+ \text{ m}^2, \text{ semitropical climate})

<table>
<thead>
<tr>
<th>Metric</th>
<th>Standard US</th>
<th>Better</th>
<th>Best Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>site MJ/m(^2)-y</td>
<td>1,100</td>
<td>450–680</td>
<td>100–230</td>
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<tr>
<td>el. kWh/m(^2)-y</td>
<td>270</td>
<td>160</td>
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</tr>
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<tr>
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<td>2.9</td>
<td>1.4</td>
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</table>
United World College-Singapore

Double Campus Size
Integrated Design
Sustainable
Half the Energy
Iolani School
Natural Energy Laboratory of Hawaiʻi

LEED Platinum
NEHLA Ventilation design

The diagram shows the elements of the Visitor Center thermal chimney design, including the roof and exhaust, the helix-floor plenum, the fresh air inlet (Volcano), and the condensate water collection system.
The Pearl of Hangzhou China
Mixed Use (Retail, Offices, Residential)
LEED CS “Platinum” Rating
Bluewater Mall
Kent, UK

Sunshine & fresh breeze of outdoor street while filtering out noise and pollution.
Bluewater Mall
Kent, UK

Mall Environment

Daylight & Natural Ventilation via Roof
Bluewater Mall
Kent, UK

Computational Fluid Dynamics Analysis
To uplift the spirit of dwellers with interior spaces that capitalize on daylighting, radiate simple elegance, reflect timeless design, and are welcoming and comfortable.
University of Texas Houston
School of Nursing and Student Community Center

• blend of passive and mechanical strategies
• long elevations face east and west, but high-performance glazing keeps them cool
• dramatic downsizing of chiller
• underfloor air distribution
• desiccant system removes humidity
• solar cells and fuel cells
• considers health and environmental effects of material choices
Even a REIT-financed Bank One (now Chase) ~150,000-m² Chicago tower

- Underfloor displacement ventilation
- Advanced glazings
- Daylit (though no lightshelves)
- Average construction cost
- Recently sold for a near-record price, attributed substantially to its energy-related design features
Four Times Square, NYC

(Condé Nast Building)

- 149,000 m², 47 storeys
- non-toxic, low-energy materials
- 40% energy savings/m² despite doubled ventilation rates
- Gas absorption chillers
- Fuel cells
- Integral PV in spandrels on S & W elevations
- Ultrareliable power helped recruit premium tenants at premium rents
- Fiber-optic signage (signage required at lower floor(s))
- Experiment in Performance Based Fees rewarding savings, not costs
- Market average construction cost
Negawatts/renewables synergy:
Bundling PVs with end-use efficiency—a recent example

- Santa Rita Jail, Alameda County, California
- PowerLight 1.18 MW\textsubscript{p} project, 1.46 GWh/y, \(\sim\)1.25 ha of PVs
- Integrated with Cool Roof and ESCO efficiency retrofit (lighting, HVAC, controls, 1 GWh/y)
- Energy management optimizes use of PV output
- Dramatic (\(\sim\)0.7 MW\textsubscript{p}) load cut
- Gross project cost US$9M
- State incentives US$5M
- Gross savings US$15M/25 y
- IRR >10\%/y (Cty. hurdle rate)
- Works for PVs, so should work better for anything cheaper
Do certified green buildings cost more?


- 33 diverse CA LEED buildings put up in past 10 y, averaged 1.84% extra capex (0 for five)
- Average benefits were 12–16× greater, yielding ROIs 25–40%/y (3-y average simple payback)
- Average 30% energy & 30–50% water savings—not yet tunneling through the cost barrier


- Contrasted 45 LEED-seeking with 93 comparable non-LEED buildings, all normalized for time and location
- Found no statistically significant correlation between LEED status and construction cost (which varied widely for both), even for specific types—classrooms, labs, and libraries

My suspicion: LEED documentation does cost a bit, but evolving analyses are showing that project capex correlates far less with green/non-green than with the experience of the design team
What does it take?

- Clear, strong leaders who get it
- Vision across boundaries
- Be careful, prudent, persistent, fearless
- Strong transdisciplinary design team
  - Hire experienced integrative designers, especially the MEs
- Inclusive charrette process; no “value eng’g”
- Specify component and system performance
- Measure to make sure you achieve goals
- Meticulous, unflagging attention to detail
- For retrofits, lease rider (soon at www.rmi.org)
- For new and old, performance-based fees
Performance-based design fees

- Corrects one of the roughly two dozen perverse incentives that have made the U.S. misallocate $1 trillion of capital just to air-conditioning‡
- Get paid for what you save, not what you spend
- Five successful experiments, simple protocol*
- Use models (Energy10, DOE-2,...) to back out changes in weather, occupancy, etc.
- Balanced rewards/penalties for over/under-performance vs. preset target (code or better)
- Distinguishes the best designers in the market
- Maybe “wellness doctor” relationship afterwards?

How tenant load affects occupancy cost

Market demand: 8–10 W/sf vs. measured data:
NYC financial servs: ~3–4
Av. office (0.9p+~1.1): ~2
Good NYC examples: <1.2
State-of-the-art: ~0.5

- electric $/sq ft-y at 10% cap rate, $2.4k/t
- rent $/sq ft-y
Shouldn’t our buildings...

- Make people healthier, happier, and higher-performing?
- Create delight when entered, well-being when occupied, regret when departed?
- Be designed for their last day of occupancy as much as their first day?
- Take nothing, waste nothing, and do no harm?
- Be net producers of energy, clean water, beauty, perhaps food, and right pedagogy?
- Cost less to build and operate?
- Be more flexible for unknowable future needs?
Zoos and offices, Victorian and now

(concept by Dr. Judith Heerwagen)
“The biophilia hypothesis boldly asserts the existence of a biologically based, inherent human need to affiliate with life and lifelike processes.”

—The Biophilia Hypothesis, Stephen R. Kellert and Edward O. Wilson

Strong evidence is now emerging that human health, happiness, and productivity are much improved by biophilic design—including faster healing in biophilic health-care facilities.
A biophilic building maximizes the occupant’s connection to the natural environment in order to create a more habitable, productive and healthy indoor environment.
Why is my passive-solar banana farm so pleasant to be in?

- Natural light
- Curves (do you have corners?)
- \(\alpha\)-tuned waterfall, no mechanical noise
- Good indoor air quality (construction + cleaning)
- High radiant / low air temperature, optimal humidity
- Moderately varying (not static) climate conditions
- Sight, smell, \(O_2\), ions, & (optionally) taste of plants
- Ever-changing jungle scenery, interesting wildlife
- Very low 60-Hz electromagnetic fields
- Maybe other attributes we don’t yet know about
Climate-adaptive, not climate-excluding, building design

- Millennia of vernacular architecture have provided comfort in harsh climates all over the world, at low resource cost, benignly.
- Now nature’s 3.8 billion years of design genius can reveal ways to get our comfort, air, water, and light for free.
- As always, the secret is integrative design—multiple coevolved functions for each element, harmoniously self-regulating.


www.biomimicry.net (The Biomimicry Institute)
Practical design keys to a broad and profitable efficiency revolution

- Optimize whole systems for multiple benefits
- Bust barriers, and reward what we want
- Faith, hope, clarity, and relentless patience
- This unprecedented cornucopia is the manual model: we must all actually go turn the crank!
- “Preach the gospel at all times. If necessary, use words.”

—St. Francis of Assissi