Integrative design for radical energy efficiency and profitable climate protection

[please insert Japanese title here]

REvision 2021, Tōkyō, 10 March 2021

3.11から10年ー新しいエネルギーの未来を目指す

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Geological reserves are a small part of resources

Schematic comparison of reserves and resources (by NERC for British Geological Survey)

One of many variants of the canonical McKelvey diagram used by the US Geological Survey and worldwide

Orebodies are limited. Energy efficiency isn’t (practically).
A major scientific paper on integrative design
Edwin H. Land (1909–91)

“People who seem to have had a new idea have often just stopped having an old idea.”

Bù wàng chū xīn
Shoshin wasuru bekarazu
Don’t forget original mind

–Avatamsaka Sūtra, 空華厳経, 華嚴經, 대방광불화엄경
Lovins House, Old Snowmass, Colorado (1982–3)
Sequence of integrative building design

- Define the desired service (thermal comfort, cooked food, access, illumination, …)
- Optimize whole systems, not just parts: costly windows cut total construction cost
  ➡️ Efficiency shrinks or eliminates HVAC; saved capital cost buys the efficiency
- Start at the end (saving first at the point of service delivery)
- Reward designers with performance-based fees and Integrated Project Delivery
- Do the right steps, in the right order, at the right time
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 and humidity gains
3. Passive cooling
   - Ventilative, radiative, ground-/H₂O-coupling, icepond
4. Active nonrefrigerative cooling
   - Evap, desiccant (CDQ), ab/adsorption, hybrids: COP >100
   - Direct/indirect evap + VFD recip in CA: COP 25
5. Superefficient refrigerative cooling: COP 6.8 (0.52 kW/t) for a big water-cooled centrifugal system at Singapore design hour—better comfort, lower capital cost
6. Coolth storage and controls
7. Cumulative cooling-system energy saving: ~90–100% with better comfort, lower capital cost, better uptime, small to zero climate impact
US office buildings: >5–10x best-efficiency gains in 5 years
(site energy intensities in kWh/m²-y; US office median ~293)

~277→173 (–38%)
2010 retrofit

284→85 (–70%)
2013 retrofit

...→108 (–63%)
2010–11 new

...36 (–88%)
2015 new

...21 (–93%)
...and in Germany, 2013 new
(office and flat)

yet all these technologies existed well before 2005!
Component-optimization vs. integrative design

Typical analysis for a 1,208-m² Denver office

<table>
<thead>
<tr>
<th>Energy Measure</th>
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<th>Annual Savings</th>
<th>Payback Period (yrs)</th>
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...each improvement by itself is too expensive for a cash-short developer.
## Component-optimization vs. integrative design

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<td>Fewer E &amp; W Windows</td>
<td>-$4,160</td>
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<td>Small &amp; Different HVAC</td>
<td>-$17,700</td>
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**Investment:**

- Total Cost: $26,200
- Net Investment: $4,350

**Saving:**

- ~$4,500/y in energy—a 1-y payback
Integrative Design in Retrofitting the Empire State Building
Empire State Building retrofit sequence

Avoided Chiller Plant Retrofit – $17.4M

- $4.4M in year 1
- $4.4M in year 2
- $4.4M in year 3

Annual Saved Operating Costs...

$4M in Windows
$2.7M in Radiative Barrier
$5.6M in Direct Digital Controls
$2.4M in Variable-Air-Volume Air-Handling Units
$8.7M in Lighting & Plug Loads
$8.7M in Avoided Chiller Plant Retrofit

Costs:
- $2.4M
- $5.6M
- $2.7M
- $4M
Infosys’s 1.5 million m² of 22k-m² office blocks (2009–14) in six cities:

*Energy Performance Index fell 80%, to 66 kWh/m²-y* with capital cost 10% to 20% *lower* than usual, and comfort better

Courtesy of Peter Rumsey PE FASHRAE (Senior Advisor, RMI) and Rohan Parikh (then at Infosys, Bangalore, now at McBERL)
IPCC AR5 WG3 pp 702–704 (2014) reports that high-ambition European new (left) and retrofit (right) buildings show no significant increase in the cost of saved energy up to ≥90% savings. Some examples do show higher costs, but they needn’t: whatever exists is possible.
Oak Brook Tower retrofit design (1992)

19,000 m², 20-year-old curtainwall office near Chicago (hot & humid summer, very cold winter); dark-glass window units’ edge-seals were failing, as happens each ~20 y

- Replace not with like but with superwindows
  - Let in nearly 6x more light, 0.9x as much unwanted heat, reduced heat loss and noise by 3–4x, cost $8.4 more per m² of glass
- Add deep daylighting, plus very efficient lights (3 W/m²) and office equipment (2 W/m²)
- Replace old cooling system with one 4x smaller, 3.8x more efficient, $0.2 million cheaper
- Capital savings more than repay all extra costs
- 75% energy savings, cheaper than usual renovation: nominal simple payback ~ 5 months
- Deep-retrofit portfolio tools: www.retrofitdepot.org
Pure-radiant-cooling 2019 breakthrough: outdoor comfort in the Singapore summer with shading but no chiller, no fan, and no condensation!

Two Swiss examples of state-of-the-art superefficient home appliances to save electricity and replace gas

9–20 kW, 200 krpm DHW heat pump
~8 cm diameter, >60% of Carnot efficiency
COP=6–15 for \(\Delta T=13–31^\circ C\), e.g. heating
to the needed 44°C from 13–31°C

A superior electric-conduction cooking system
2–4½× more efficient than induction; vacuum pots
Texas Instruments’ RFab (2005)
40% less energy, $230 million cheaper
Paul Westbrook, *The Joy of Efficiency*, July 2019
www.joyofefficiency.com

40% less energy to process a wafer pattern than TI’s previous best plant (6 miles away, 10 y older)

Spreading such methods cut TI’s specific energy use 62% in 12 y, water 56%, greenhouse gases 57%
RMI’s latest >$50b worth of integrative design in diverse industrial projects—retrofits and newbuilds
(solid = built, shaded = incomplete data, circle = not yet built)
Designing to save ~80–90% of pipe and duct friction—equivalent to about half the world’s coal-fired electricity

thin, long, crooked

fat, short, straight

Typical paybacks ≤1 y retrofit, ≤0 new-build
But not yet in any official study, industry forecast, or climate model
New design mentality, an example

No new technologies, just two design changes:

1. Big pipes, small pumps (not the opposite)

2. Lay out the pipes first, then the equipment (not the reverse)
Designing to save ~80–90% of pipe and duct friction—by making them fat, short, and straight

Big pipes, small pumps

Nonorthogonal layout, 3D diagonals, few & sweet bends
1.5 W/GPM
60,000 miles of blood vessels

7.5 W/GPM

15 W/GPM
Retrofitted Low-Friction Piping Layout

Images courtesy of Peter Rumsey, PE, FASHRAE
Which of these layouts uses less capital and energy?

- Less space, weight, friction, energy
- Fewer parts, smaller pumps and motors, less installation labor
- Less O&M, higher uptime
Power Plant: -70%
Power Grid: -9%
Motor/Drivetrain: -12%
Pump/Throttle: -55%
Pipe: -20%

100 Energy units

Delivered flow: 10%
Then cut utility losses by ~50%

...then cut support overhead by 90%

...then cut IT equipment's internal losses by 75%

First debloat software and ensure that every computation cycle is needed

Start saving downstream for data centers
Decarbonize industrial process heat indirectly… by elegantly frugal structural design.

Tension structures—~80–90% less material

Fabric forms—≥50% less material


Schlaich Bergermann—see the remarkable book Leicht Weit

https://www.shapeways.com/blog/archives/35854-3d-printed-bridges-now.html (Joris Laarman Lab, MK3D)

The artistic 3D-printed 12.5m stainless-steel bridge for Amsterdam’s Oudezijds Achterburgwal canal.
Start with tractive load, not powertrain

- 6% accelerates the car, ~0.3–0.5% moves the driver
- Most fuel use is caused by mass
- Each unit of energy saved at the wheels saves ~5 (formerly ~6–7) units of fuel in the tank
Migrating advanced composites from military and aerospace to automobiles (needing ~1000x higher volume and lower cost)

95% carbon composite, 1/3 lighter, 2/3 cheaper than 72%-metal base design (at the 100th copy)
Reinventing the wheels

Hypercar *Revolution* midsize concept SUV (2000)
28 km/L on-road (gasoline) or $48_{\text{equiv}}$ (H₂)
carbon-fiber structure, ≤2-y retail payback

Toyota 1/X carbon-fiber concept PHEV sedan (2007)
*Prius* size, 1/2 fuel use (56 km/L), 1/3 weight

Bright *IDEA* 1-T 5-m³ aluminum fleet van (2009)
~42 km/L_{\text{equiv}} PHEV, 3–12×-eff., needs no subsidy

BMW *i3* 4-seat electric, carbon-fiber passenger cell
2013–24 mass-production, >150k sold for ~$41–45k
53–59 km/L, MY2019 247-km range (≥370 w/REx)
A competitive carbon-fiber electric car, 2013–

BMW’s sporty, 1250-kg 4x-efficiency i3 was profitable from the first unit, because it:

- pays for the carbon fiber by needing fewer batteries (which recharge faster)
- saves ~2.5–3.5 kg total for each kg of direct mass saved (Detroit says <1.3–1.5)
- needs two-thirds less capital, ~70% less water, ~50% less energy, space, time
- requires no conventional body shop or paint shop
- provides safe, clean, quiet, superior working conditions
- delivers 53 km/L_{equiv} (124 mpge) on US 5-cycle test, 59 Ger., ~62 old US cycle
- provides exceptional visibility, agility, traction, and crash safety
Integrative vehicle design more than doubles potential fuel savings.

“NeverCharge” solar-powered Hypercar®-class 2-seat el. vehicle (aptera.us): 400–1600-km range, but most drivers will need no recharging, because it’s so efficient (>146 km/L) that its solar cells capture enough energy for ~18,000 km/y. It has half a Tesla’s mass, and less air drag (at $C_d$ 0.13) than the side mirrors of a US pickup truck! Late-2021 release; $26–45k, dep. on range.
The secret sauce: organizing designers differently

“If we are to achieve results never before accomplished, we must employ methods never before attempted.” —Sir Francis Bacon
Decompounding mass and complexity also decompounds cost.

Exotic materials, low-volume special propulsion components, innovative design

Only ~40–50 kg C, 20–45 kWₜₚ, no paint?, radically simplified, little assembly,...

New design strategy, materials, and technologies
Design to win the future, not perpetuate the past

Present design space

New design space

Define the end point
Development targets
Risk management
Market introduction
Economic insight
Customer relationships
Technology introduction
Integration payoff areas

First production variant
Foundation Platform

Design “in the future”

C.L. “Kelly” Johnson (1910–90)
The revolution accelerates…

Tesla *Semi* Class 8 battery-electric truck (2021), >3× efficiency, 800-km full-load range (+ ~650 km w/30-minute recharge), 1.6-million-km warranty, 3–5× faster acceleration, 1/3-faster hill-climbing (5% grade), 2-y payback (could be 0 in this decade)

Celera 500L (Otto Aviation 2020 prototype—the commercial version will add windows), 8× *efficiency* (8–13 L/100 km vs ~78–118), >740 km/h, 8330-km range, 6× lower opex ($328/h); 6-seater can scale up to >20; good candidate for electrification

with more to come…
Structure as strong/tough as rubber but ~268× less dense (5.6 kg/m$^3$), made of thousands of identical injection-molded anisotropic parts, all covered by a tough polymer membrane of identical material, can yield any desired overall shape.

An optimized-shape airplane that completely and continuously adapts *passively* to match flight conditions can thus be made stiff, strong, but scalable in manufacturing and in microrobotic assembly, needing no separate flight surfaces.

4.27-m-wingspan model in NASA’s high-speed wind tunnel worked better than predicted; applicable to wind turbines.

What can integrative design do? ($\eta = \text{end-use efficiency}$)

- buildings: $\sim 4 - 10 \eta$
- automobiles: $\sim 4 - 8 \eta$
- trucks: $\sim 3 - 4 \eta$
- airplanes: $\sim 3 - 8 \eta$
- factories: $\sim 2 - 3 \eta$ old, $\sim 2 - 10 \eta$ new
- use of steel, cement, ...: $> 2 \eta$

so...world economy: $\sim 5 \eta$?
We just need a Vulcan mind-meld from a gifted integrative designer