
ROCKY MOUNTAIN
INSTITUTE

Integrative design for radical efficiency at lower cost

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Edwin H. Land (1909–91)

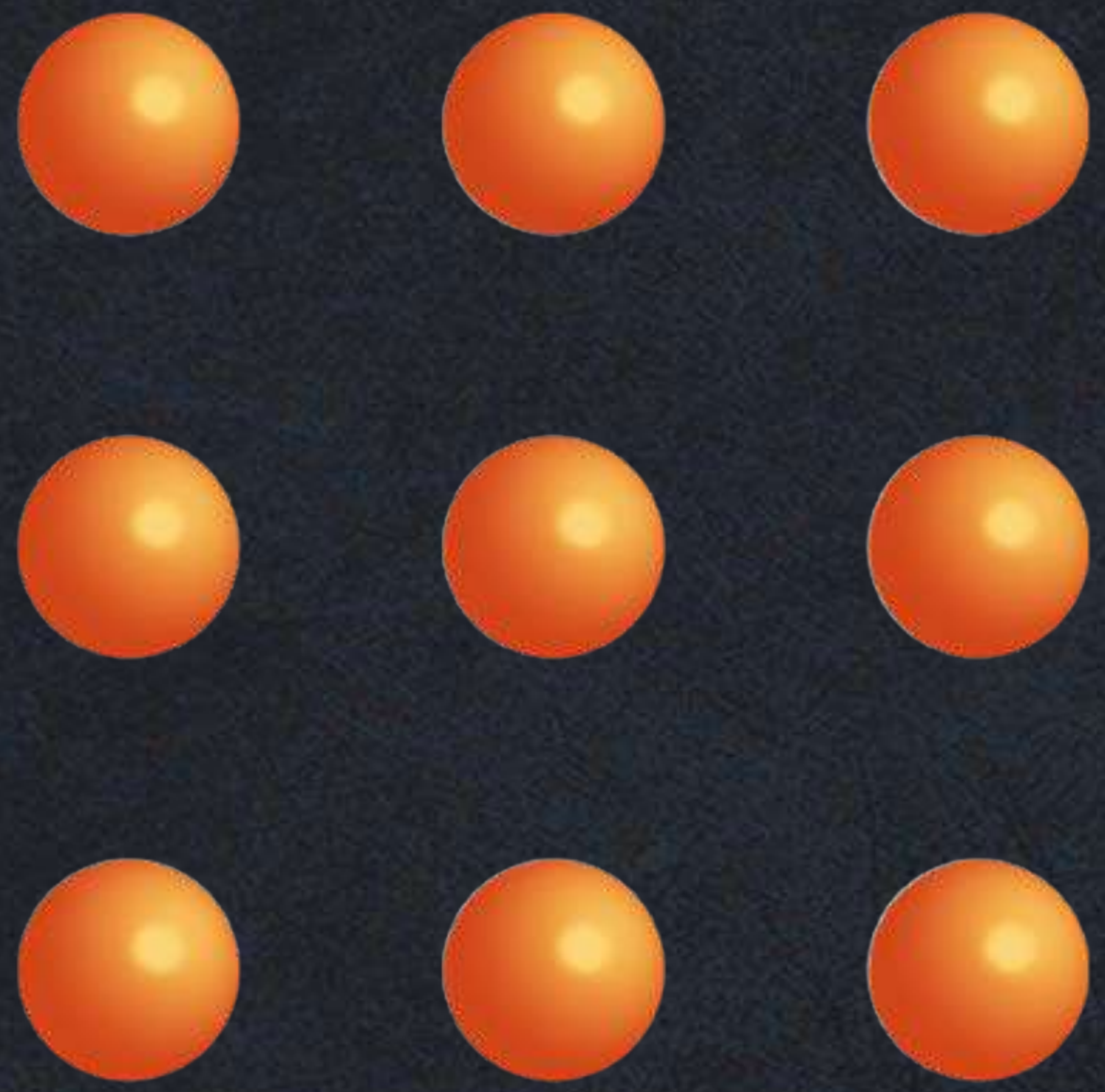
“People who seem to have had a new idea have often just stopped having an old idea.”

不忘初心

Bú wàng chū xīn
Hoshin wasuru bekarazu
Don’t forget original mind

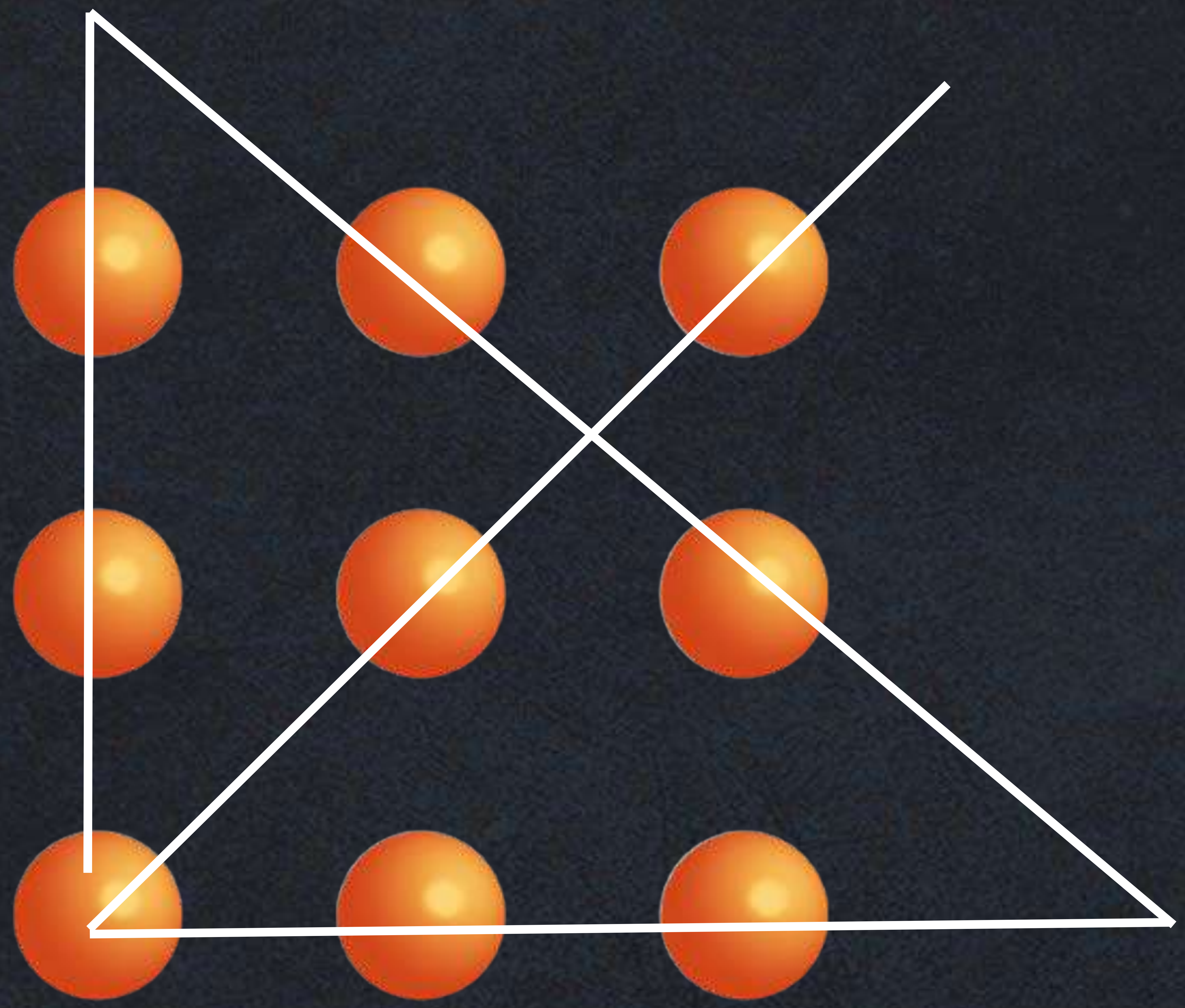
–Avataṃsaka Sūtra, མདོཕལཔོཆེ,
華嚴經, 대방광불화엄경

The Nine Dots Problem



Art by Chris Lotspeich…

The Nine Dots Problem



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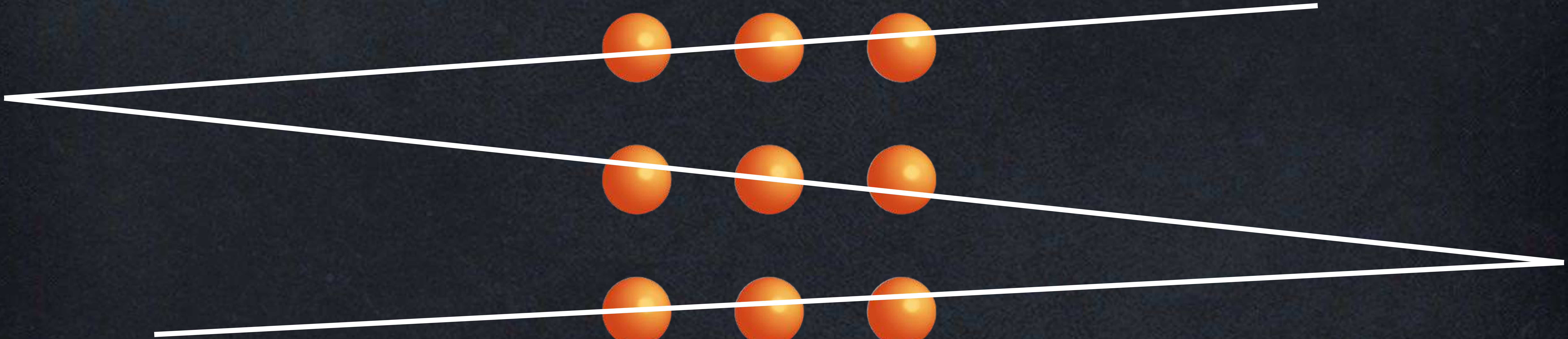
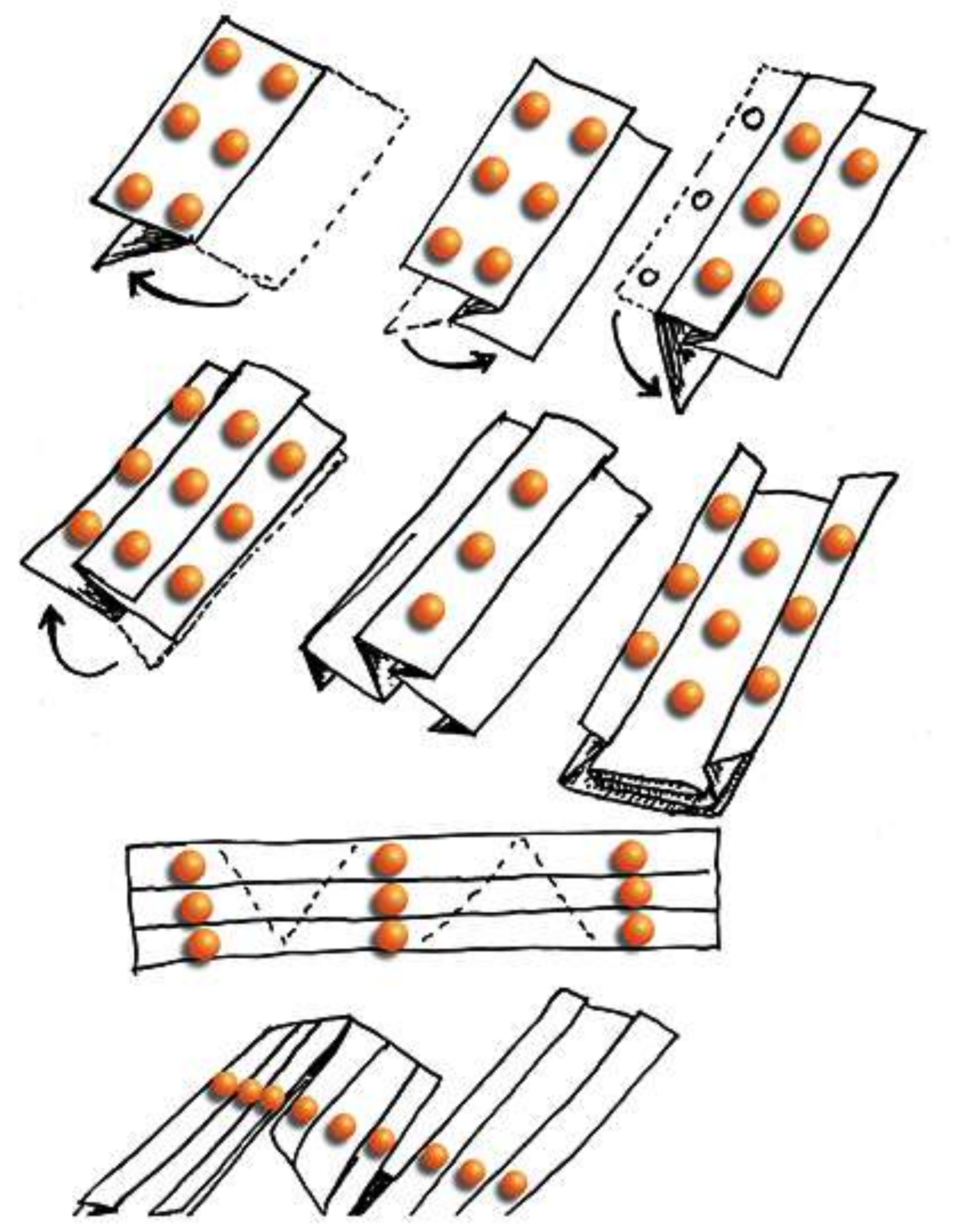
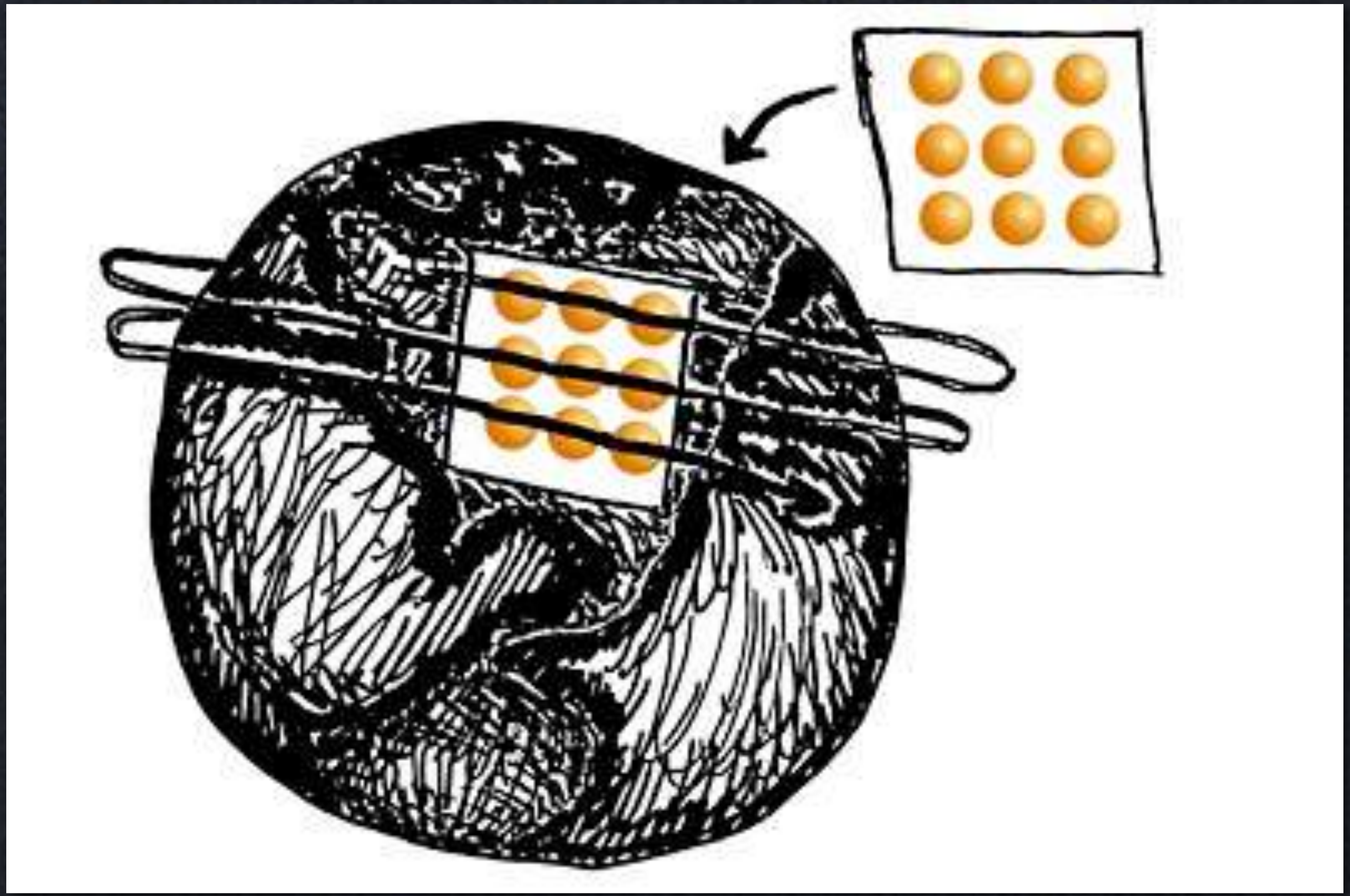
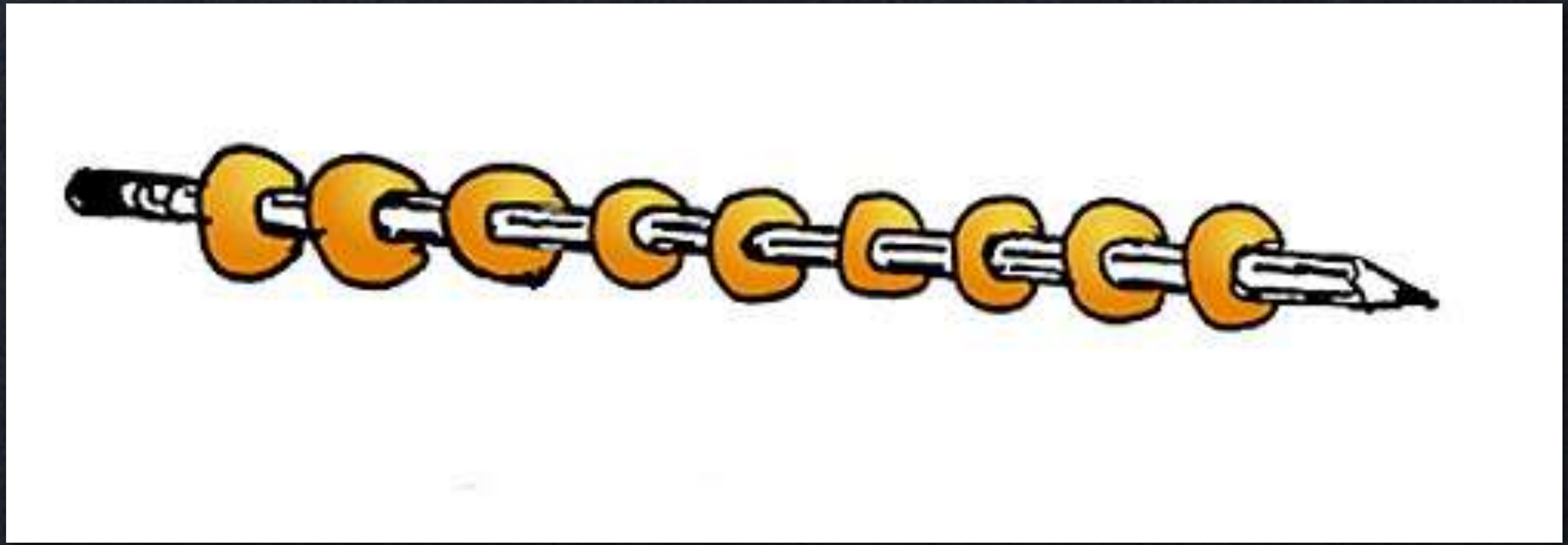




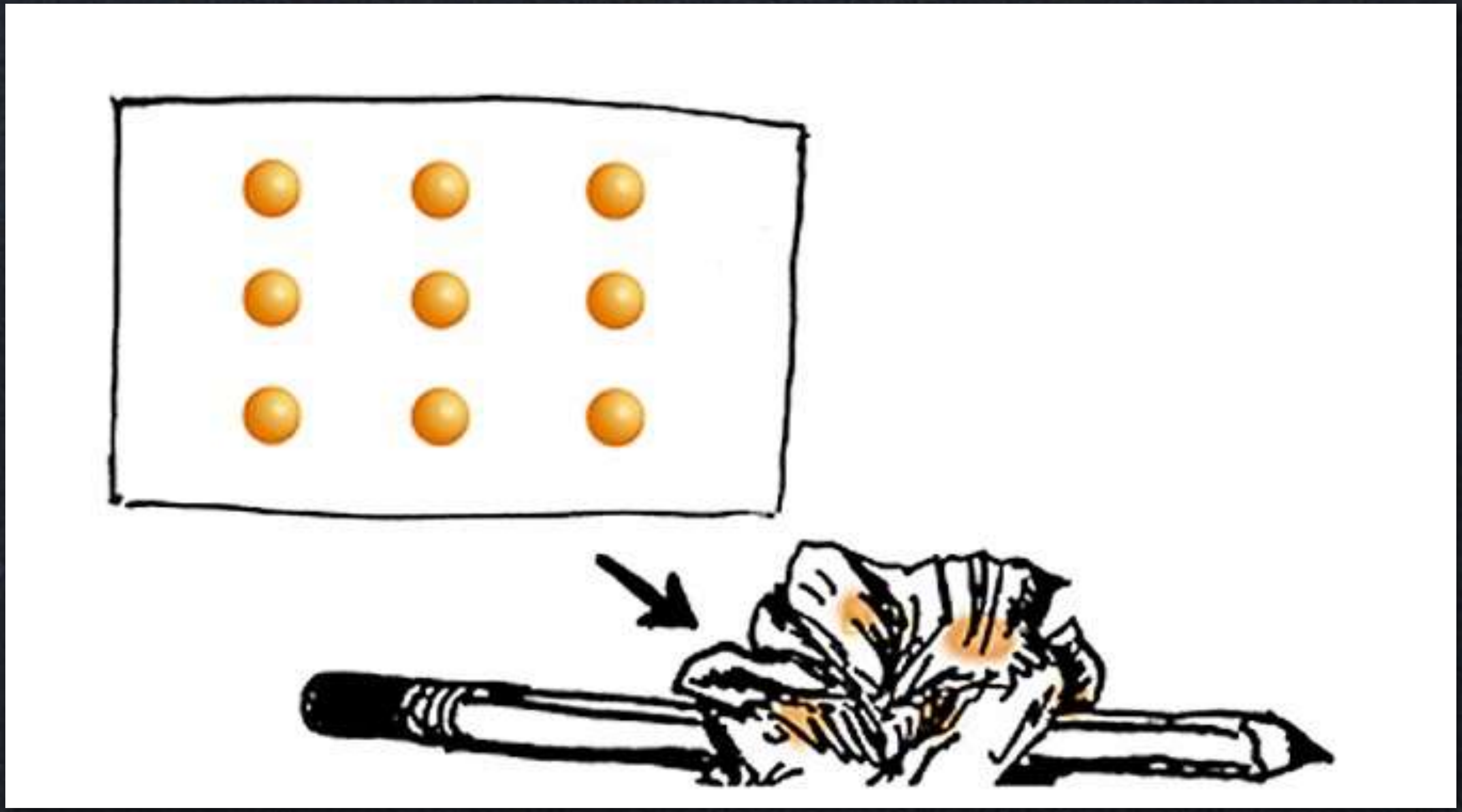
origami solution



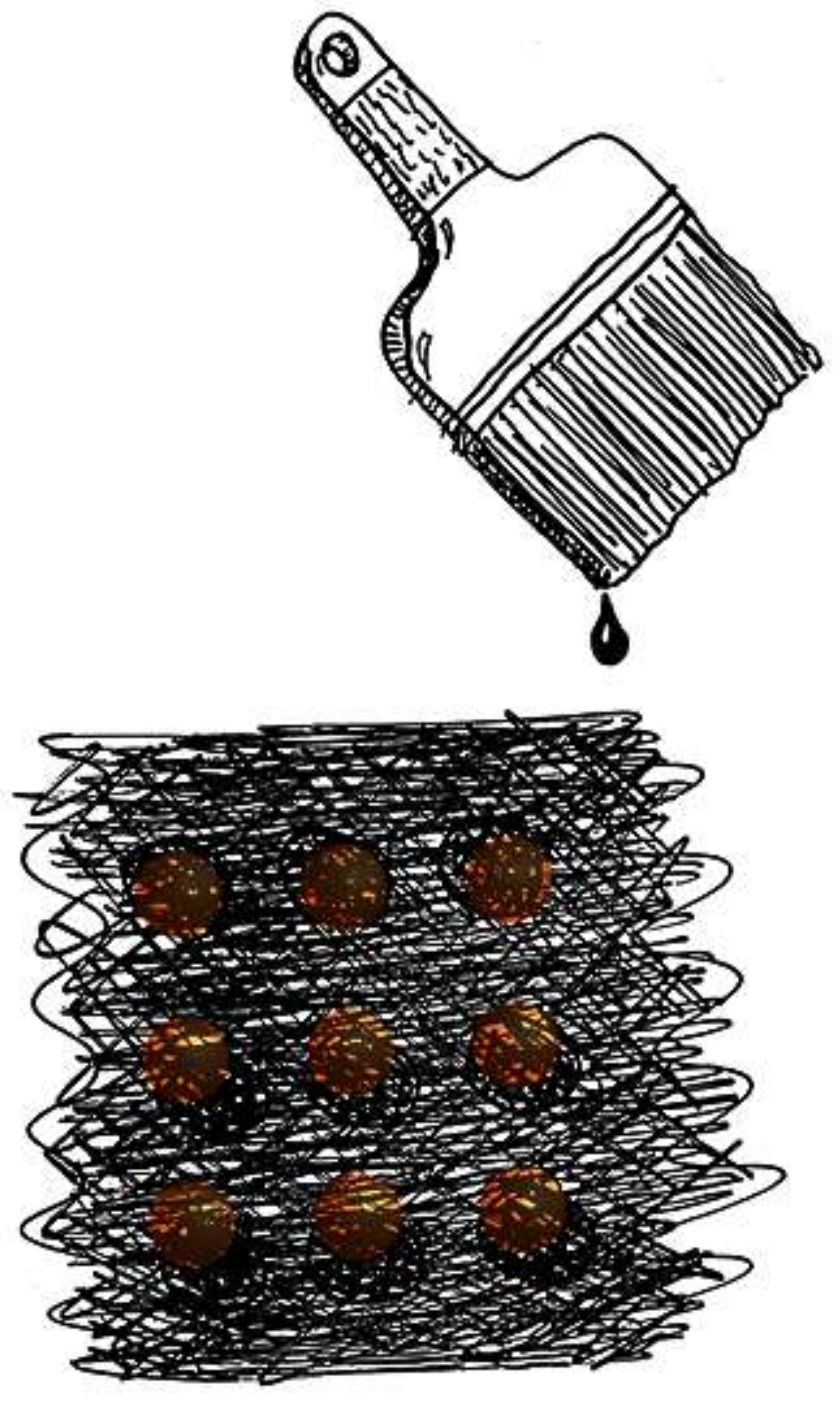
geographer’s
solution



mechanical
engineer's
solution



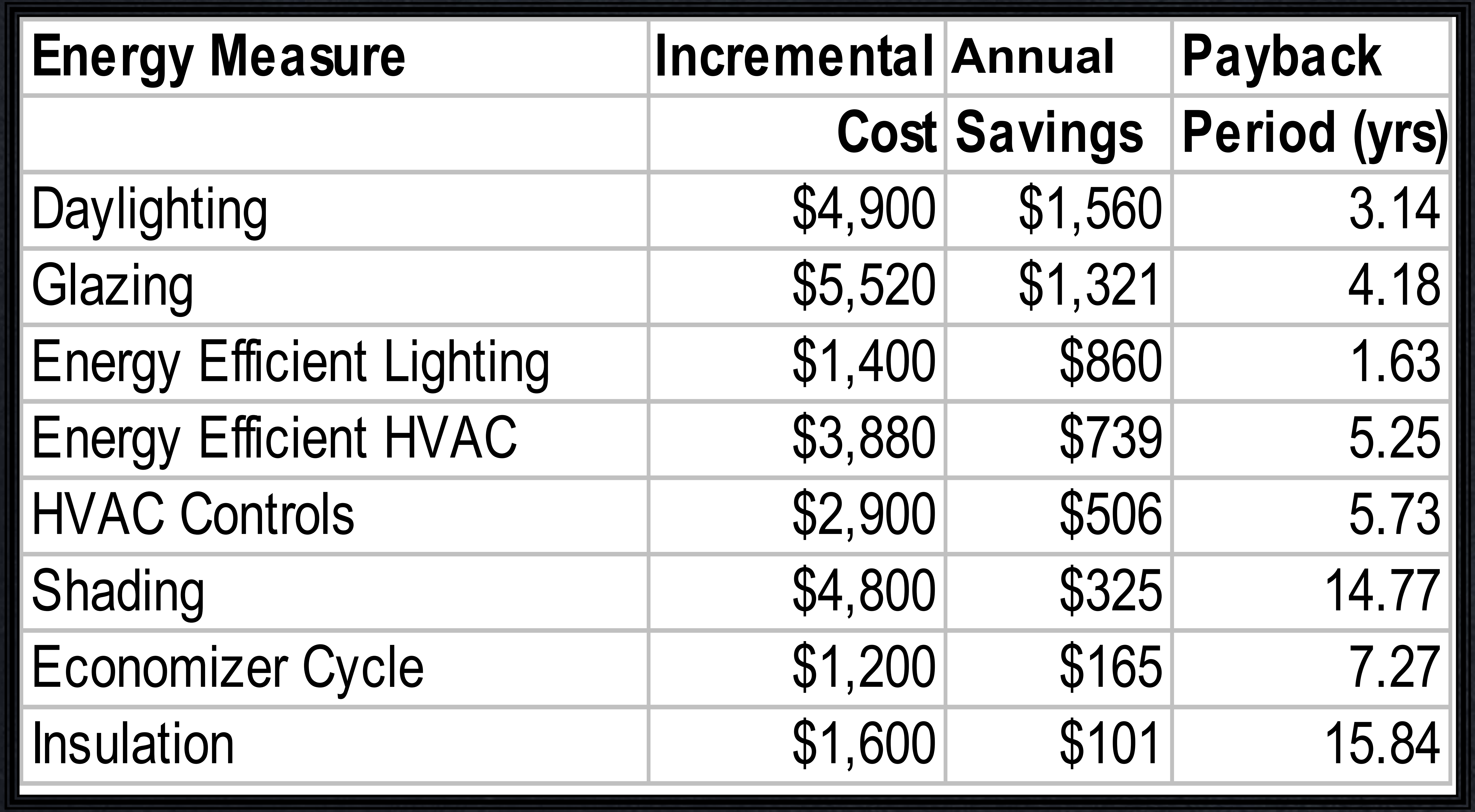
statistician’s
solution



“wide line”
solution

Component-optimization *vs*. integrative design

Typical analysis for a 1,208-m^2 Denver office



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

Each improvement by itself is too expensive for a cash-short developer.

Component-optimization *vs*. integrative design

Analysis for a typical 1,208-m^2 Denver office

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Energy Efficient Lighting	$1,400
Energy Efficient HVAC	$3,880
HVAC Controls	$2,900
Shading	$4,800
Economizer Cycle	$1,200
Insulation	$1,600
Fewer E & W Windows	-$4,160
Small & Different HVAC	-$17,700

$26,200

–$21,820

net investment: $4,350

saving ~$4,500/y in energy—
a 1-y payback

Multiple benefits from single expenditures

Save energy and capital costs throughout the design

- 10 benefits from superwindows
- 18 from efficient motors and dimming ballasts
- A front-end part in a Lotus *Elise* car has 7 functions but one cost
- My home's central arch has 12 functions but one cost

Grand Forks (North Dakota) office—subarctic

Incremental costs

Windows	$67,500
Daylighting	$18,000
Insulation	$17,200
Lighting	$21,000
HVAC	–$160,000
Total	–$36,300

Energy savings: $75,000/year

Greg Franta FAIA, deceased Team Leader, RMI/ENSAR Built Environment

Lovins House, Old Snowmass, Colorado (1983)

US office buildings: 3–4× energy efficiency worth 4× its cost

(site energy intensities in kWh/m^2-y; US office median ~293)

~277➞173 (–38%)

2010 retrofit

284➞85 (–70%)

2013 retrofit

...➞108 (–63%)

2010–11 new

...51 (–83%)

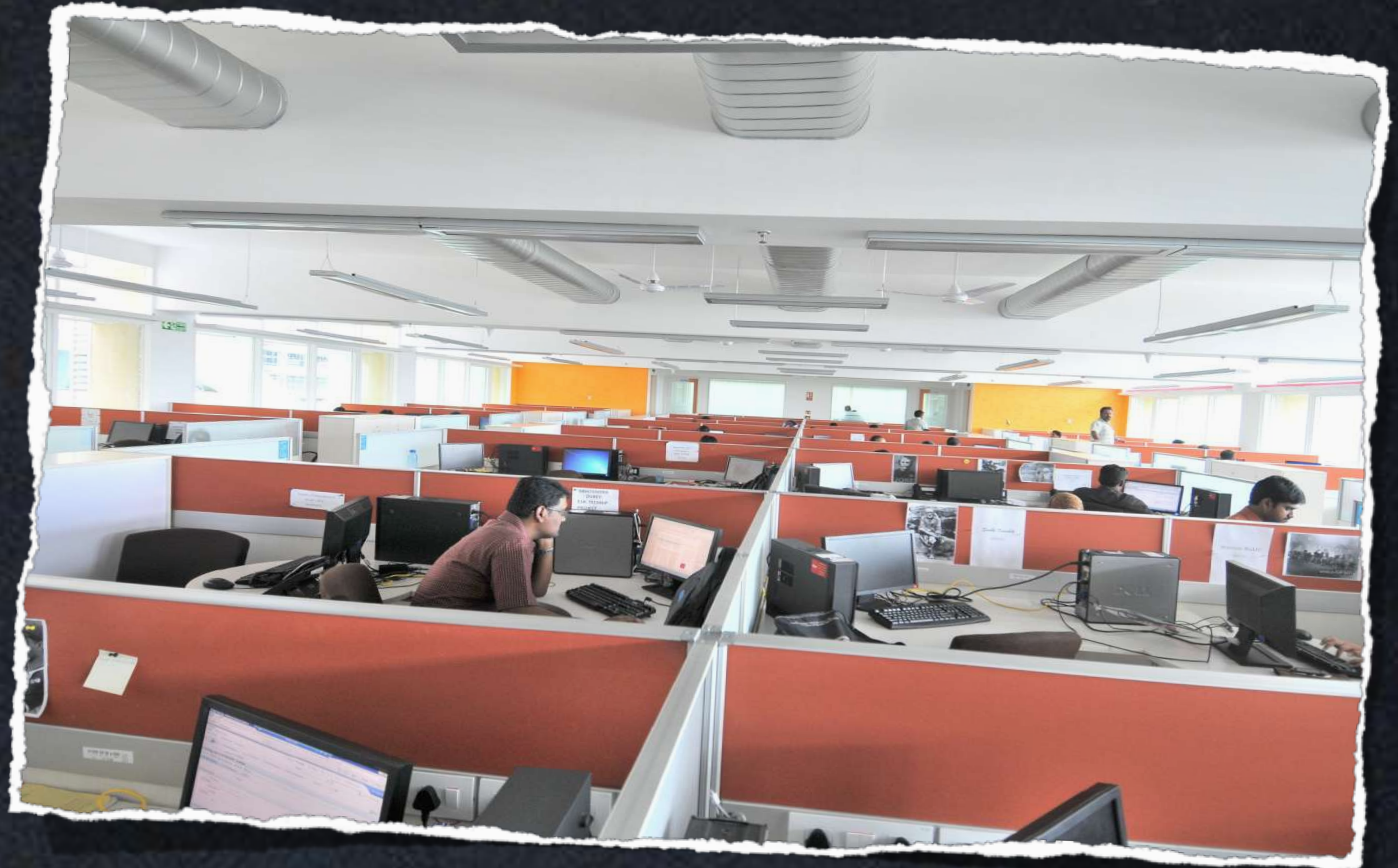
2015 new

...21 (–93%)

…and in Germany,
2013 new
(office and flat)

Yet all the technologies in the 2015 example existed well before 2005!

5x-more-efficient new Indian commercial buildings

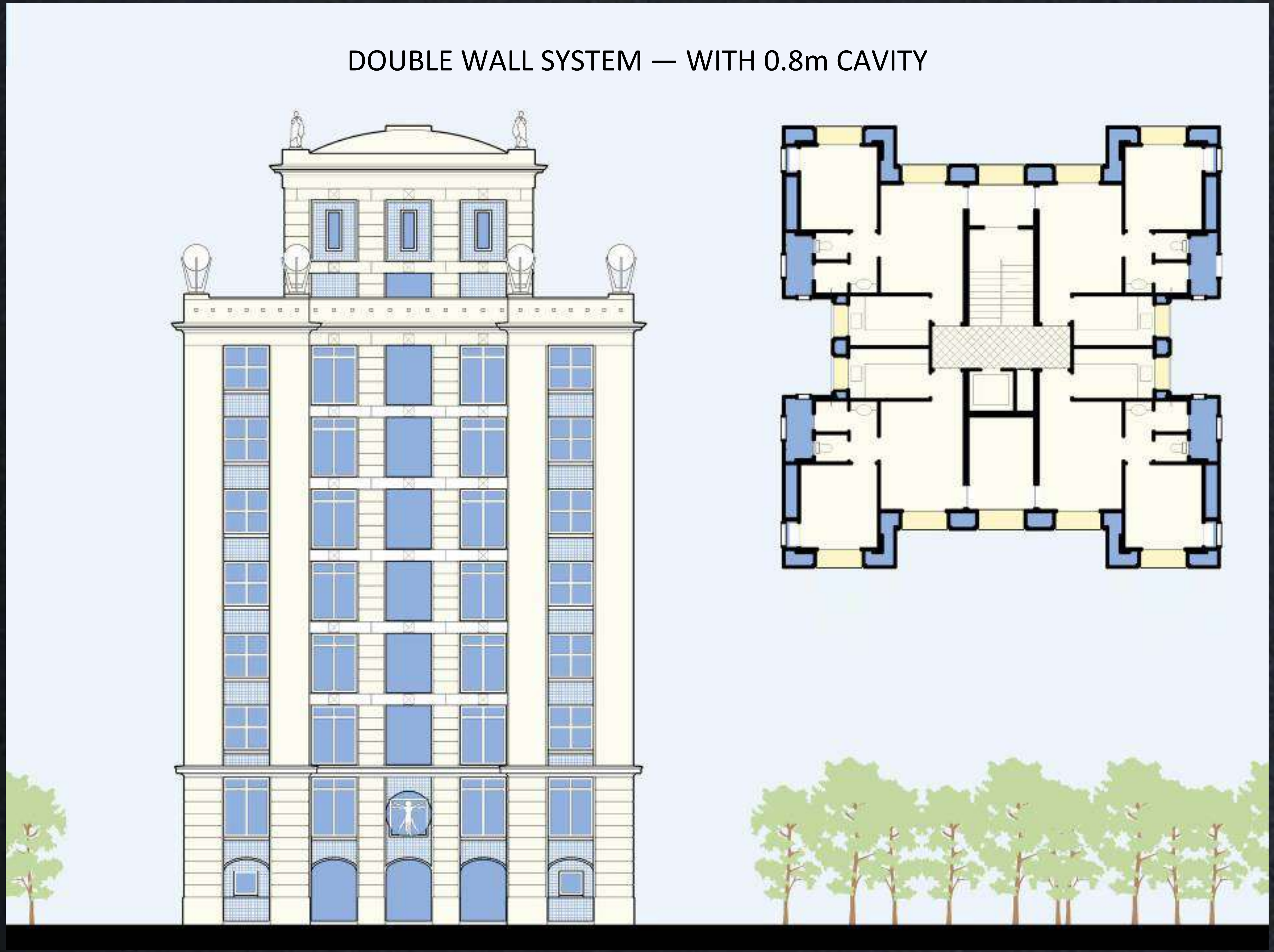


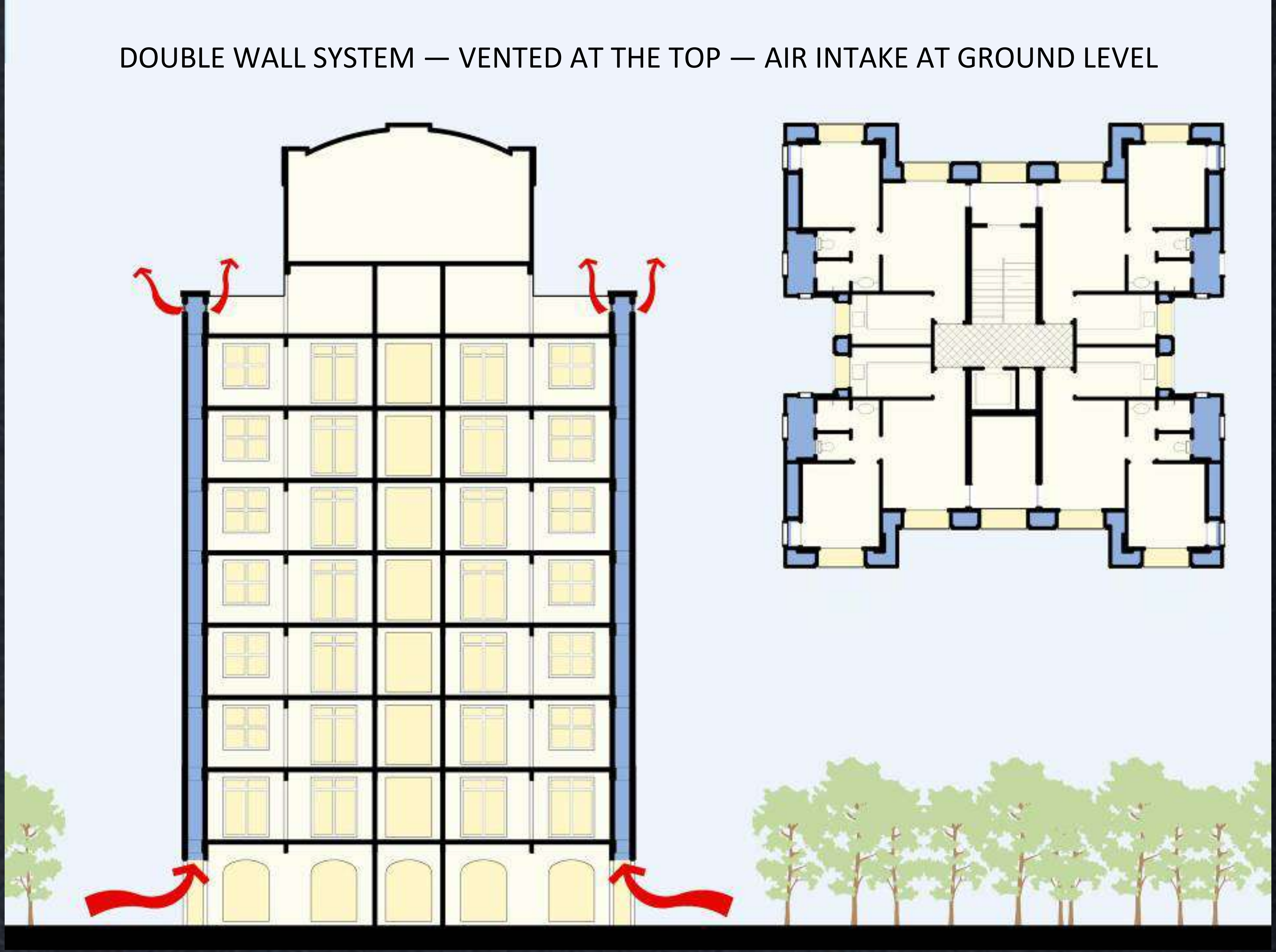
Infosys's 1.5 million m^2 of 22k-m^2 office blocks (2009–14) in six Indian cities:
Site energy use (EPI) fell 80%, to 66 kWh/m^2-y
with construction cost 10–20% *lower* than usual, and comfort better

Courtesy of Peter Rumsey PE FASHRAE (Senior Advisor, RMI) and Rohan Parikh (then at Infosys in Bengaluru, now at McBERL)

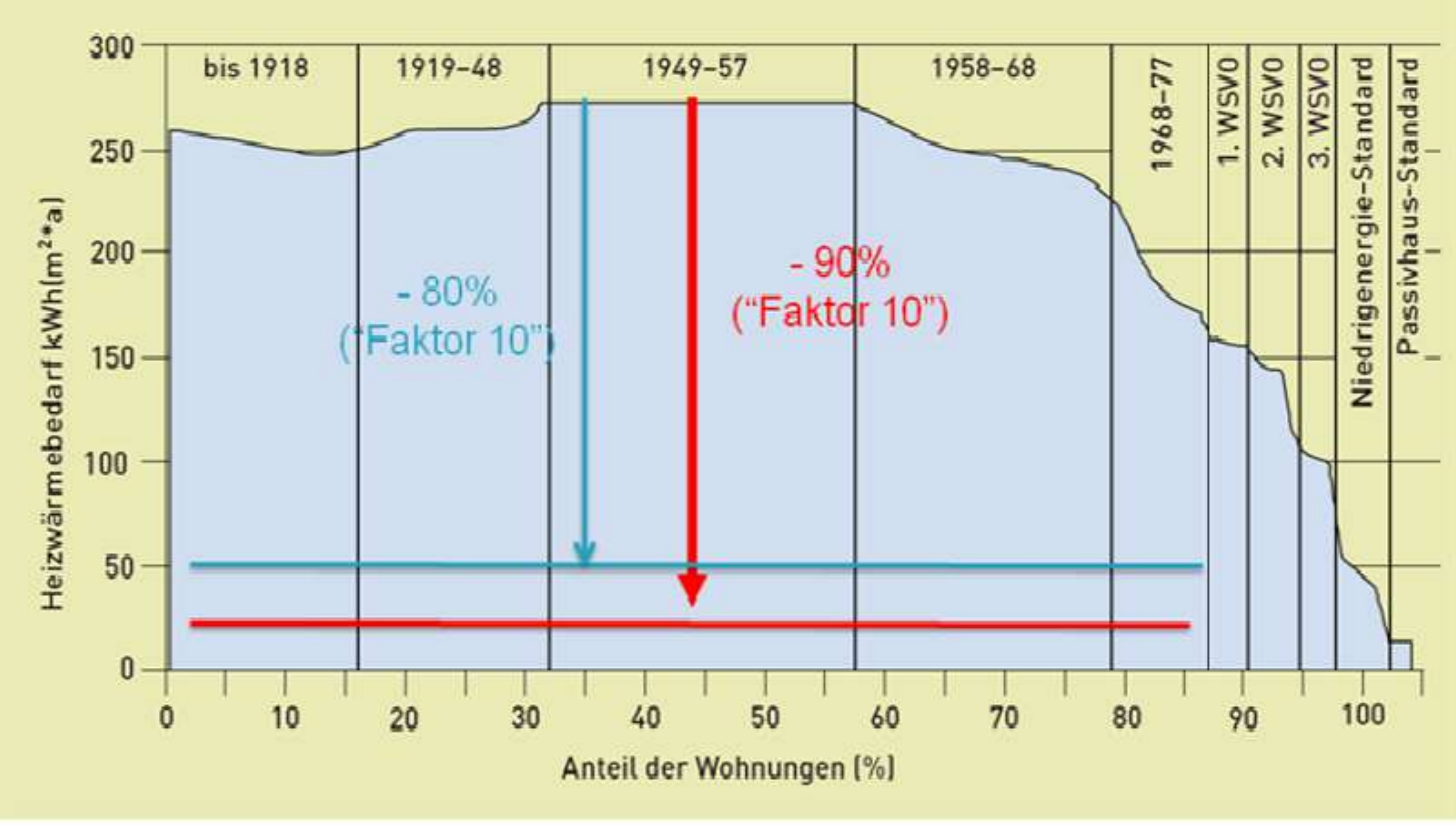
Cooling midrise apartment buildings in India

Design courtesy of Dhiru Thadani AIA



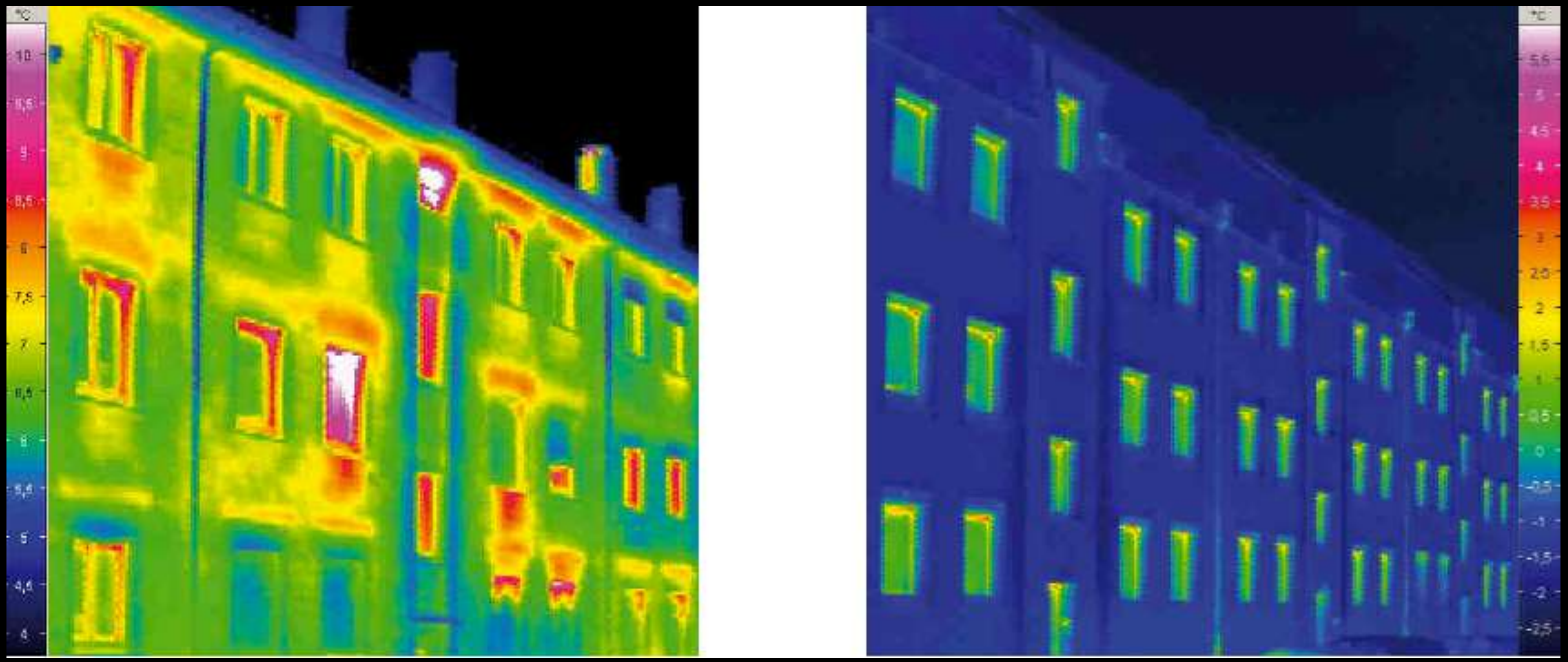


These convective double-wall building envelopes need little or no air conditioning, cost 2% more; 0.2 million m^2 were successfully built 1998–2000 in Powai and Thane near Mumbai



Quellen: ARENHA 1993, IWU 1994, Bundesarchitektenkammer 1995, Schulze Darup 1998/2000

"Factor-Ten Modernizations" (retrofits) in Hannover (from proKlima 2010): L 15 kWh/m²y, R 21 kWh/m²y



Before and after passive-house treatment

Installing *in*terior superinsulation

Landkreis Nienburg/Weser, *Klimaschutzkonzept*, Anhang III, 2011, target GmbH (Hannover)

“Energiesprong” unsubsidized mass retrofit of public housing

Before: 5 Dutch units, each with
annual energy bills ~€1.5–2k

After: net-zero-energy,
expected to be financed
just from energy savings
by industrializing the
€460k (soon €40k)/unit retrofit

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: they should just emulate best practice.

Germany’s 2017 analysis of national building-sector improvement potential: save the climate while saving money and making good durable jobs

Figure VI: Key energetic parameters of the transformation pathways for the entire building sector

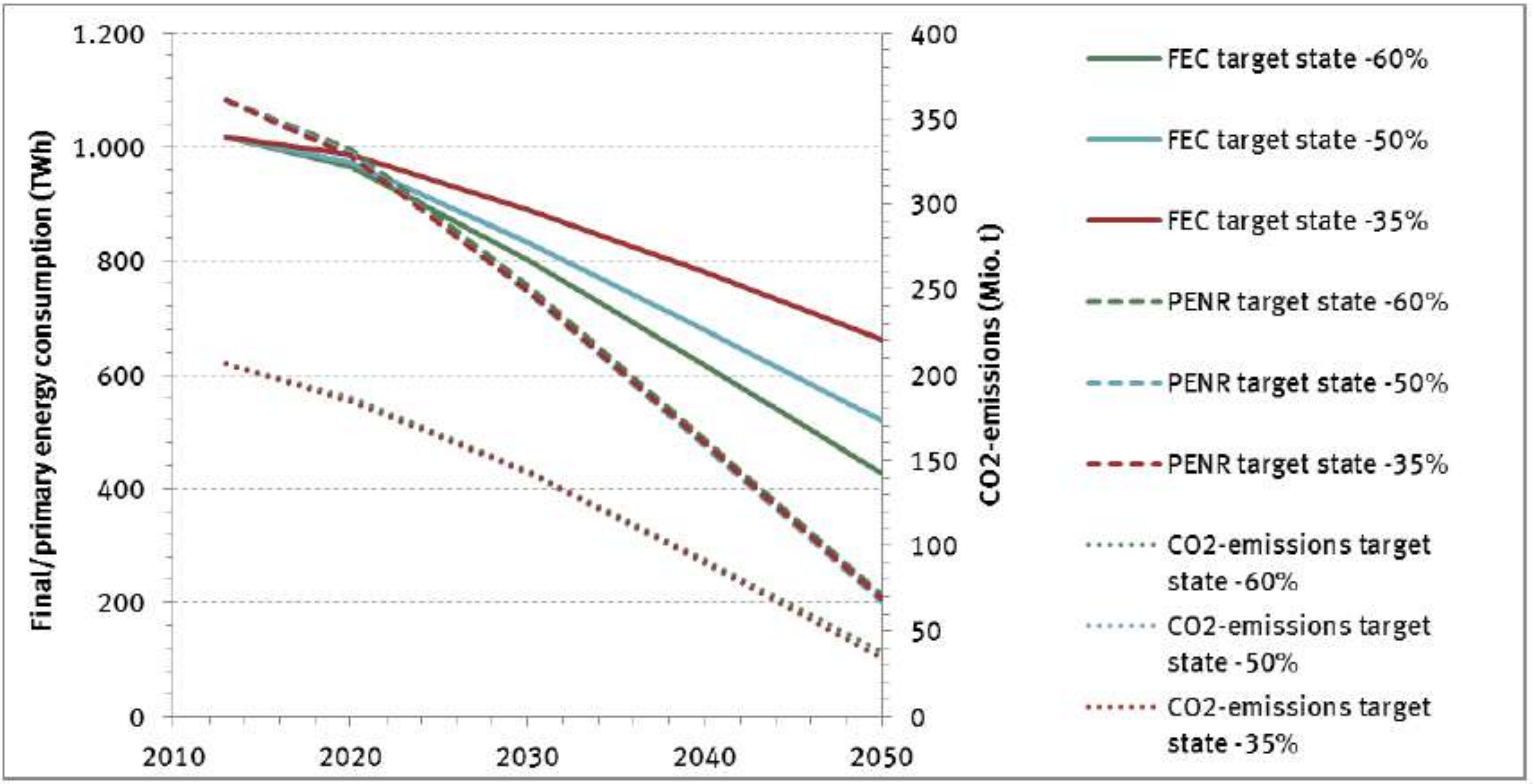
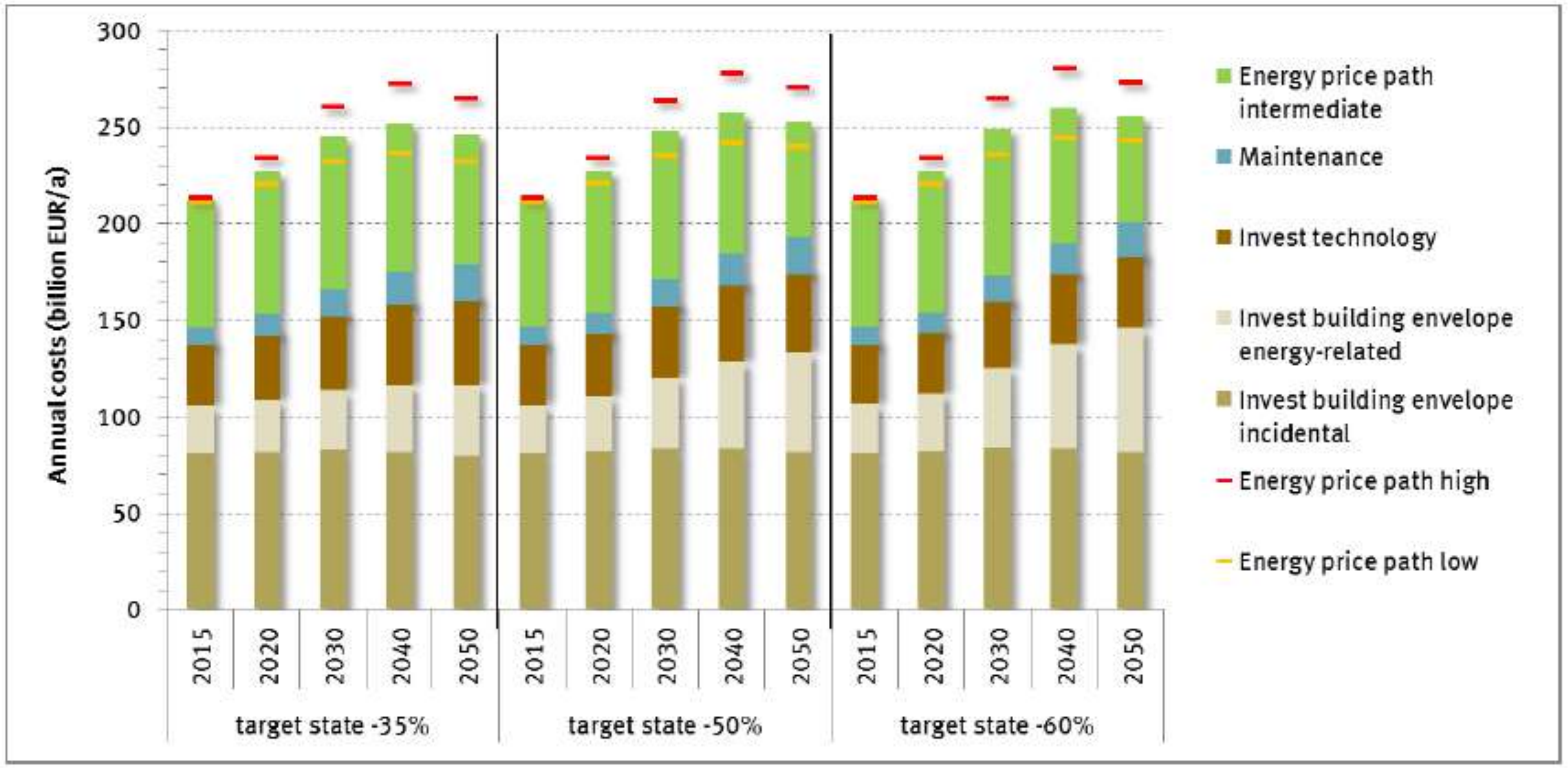


Figure VII: Annual costs of the transformation pathways for the entire building sector

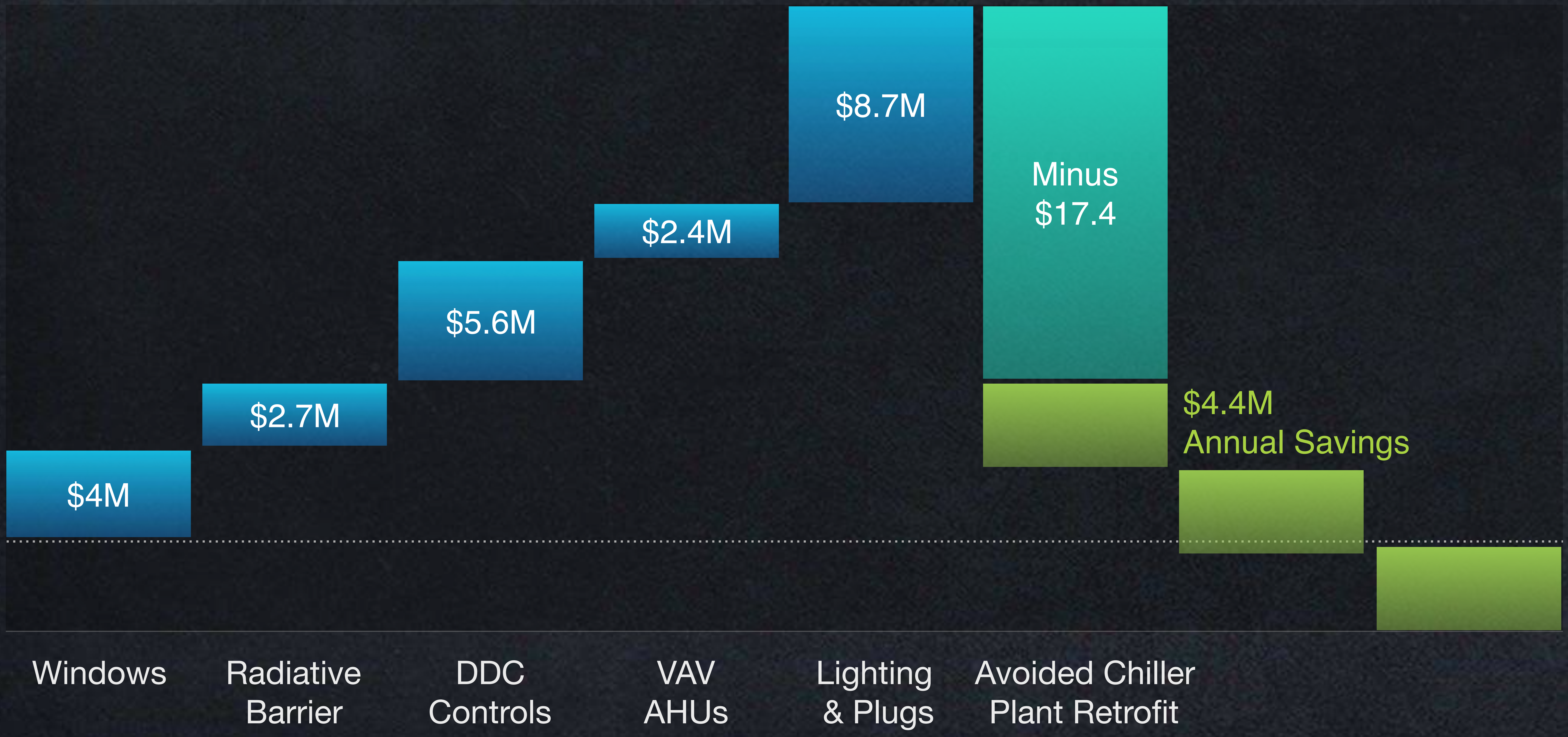


81–86% (mainly 84–86%) CO_2 reductions from buildings’ primary energy (L) via diverse trajectories with similar costs (R)—*all far cheaper than business-as-usual*

Umweltbundesamt (Berlin), *Klimaneutraler Gebäudebestand 2050*, Nov 2017

Integrative Design in Retrofitting the Empire State Building

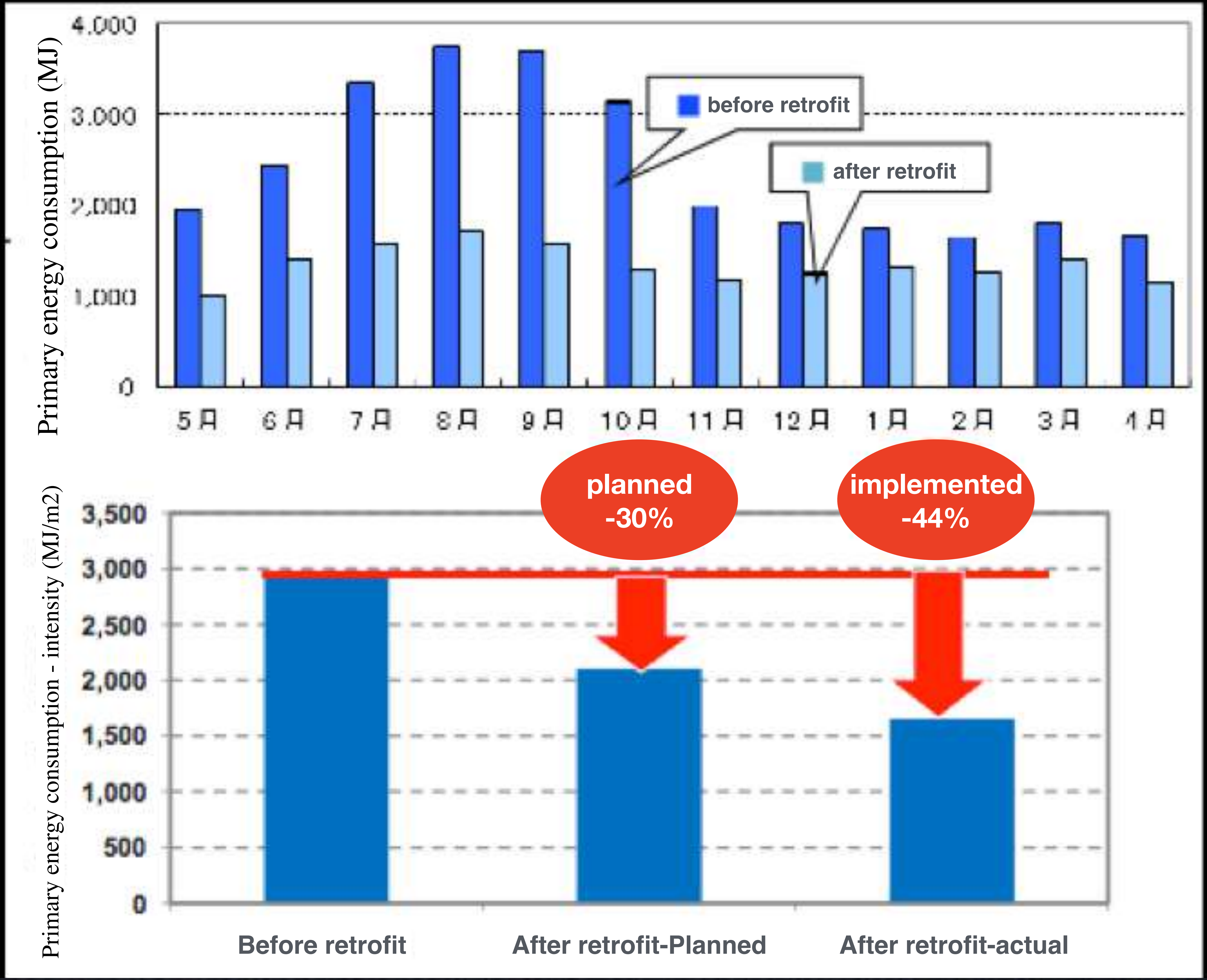
Integrative Design in Retrofitting the Empire State Building



Similar results in a Japanese office, without superwindows

Rohm HQ, Kyoto
44% energy saving by retrofit
2-years payback

Courtesy of Yanase Masaake-san via Iida Tetsunaru-san



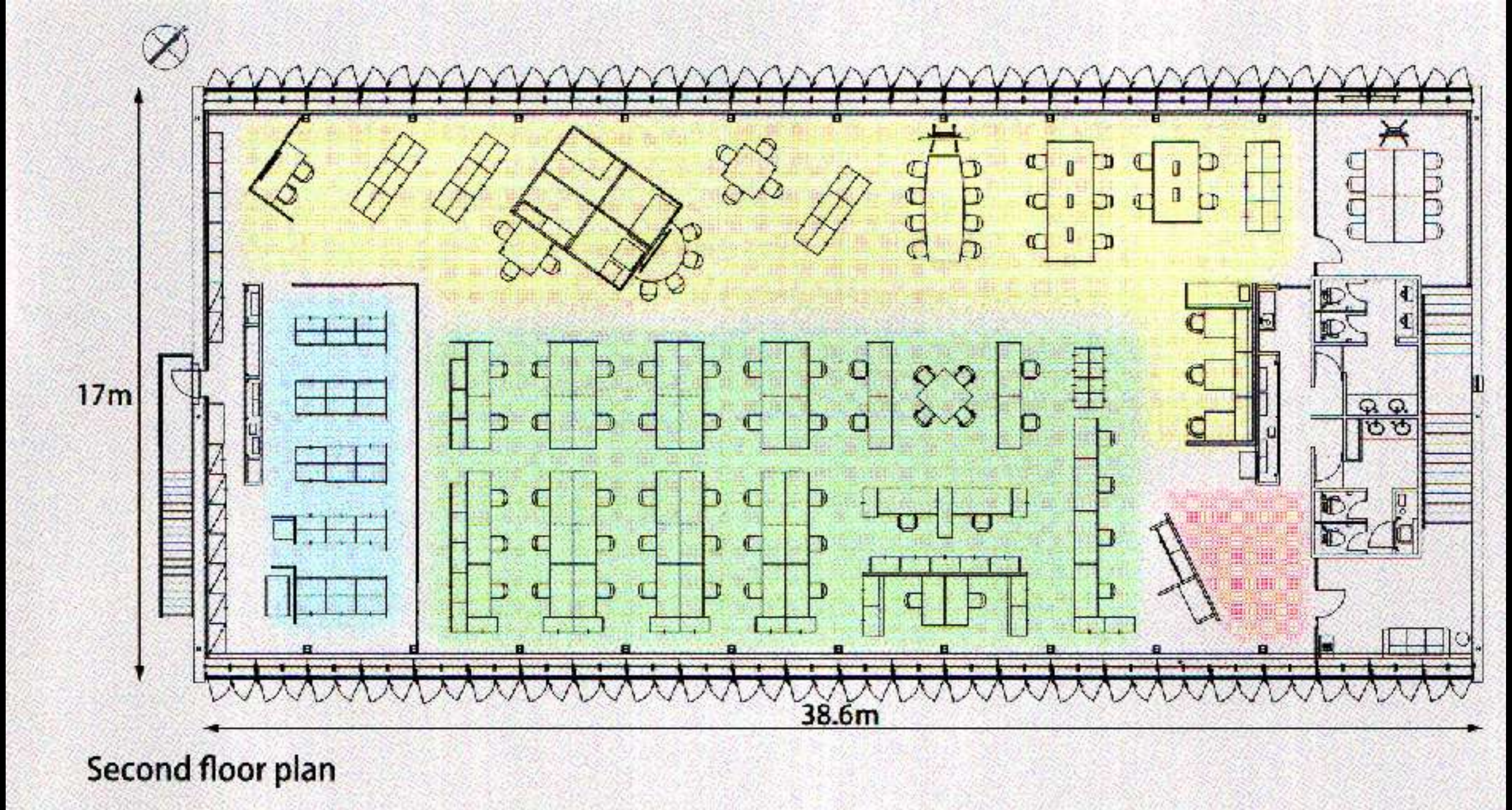
75% *retrofit* saving in an office like ~80% of Japan's offices

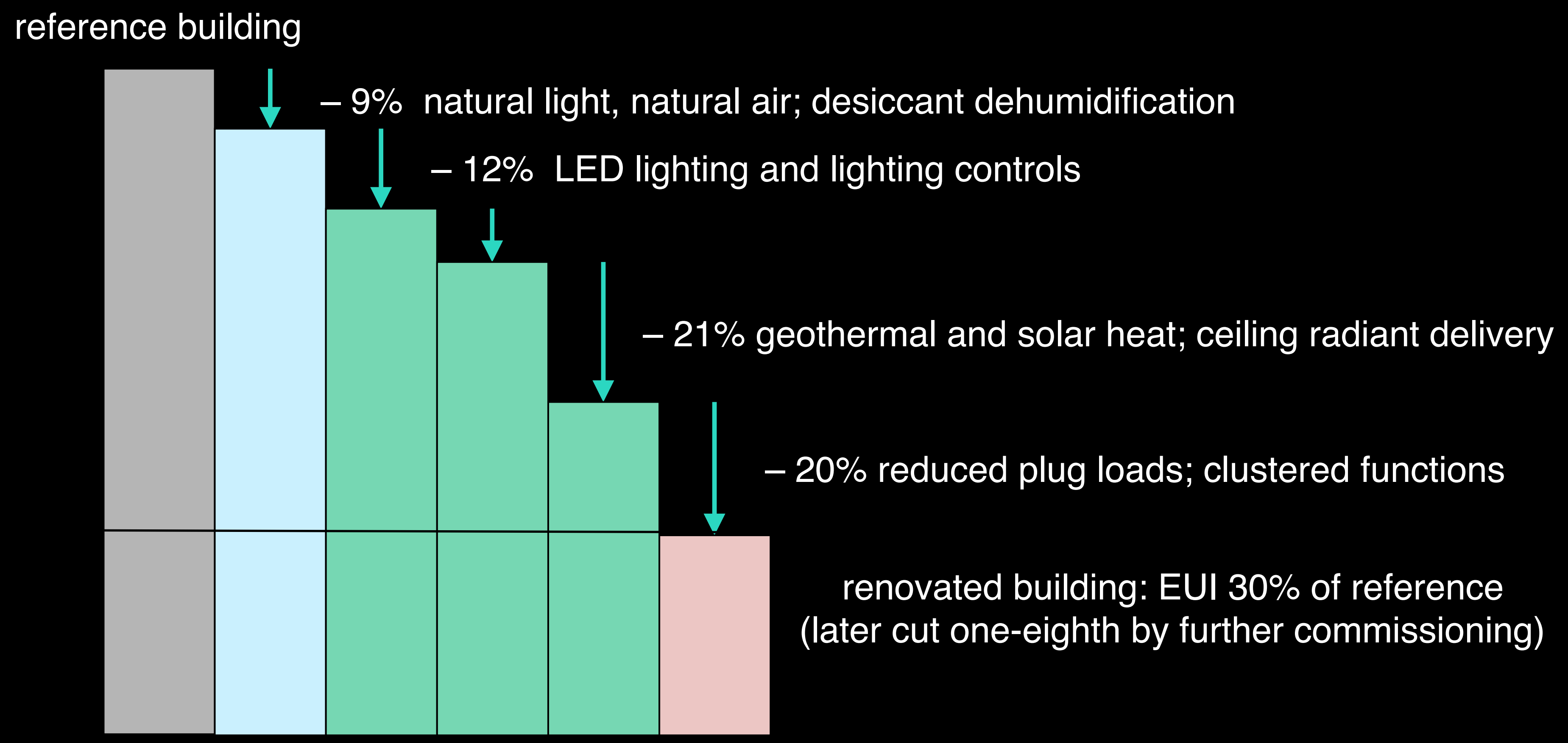
Takenaka's 1318-m^2 two-story Higashi Kantō office, Chiba-shi

Built 2003, renovated 2015

Latest primary EUI = 348 MJ/m^{2}y, ~75% below original ~1400

Now a Positive-Energy Building





reference building

– 9% natural light, natural air; desiccant dehumidification

– 12% LED lighting and lighting controls

– 21% geothermal and solar heat; ceiling radiant delivery

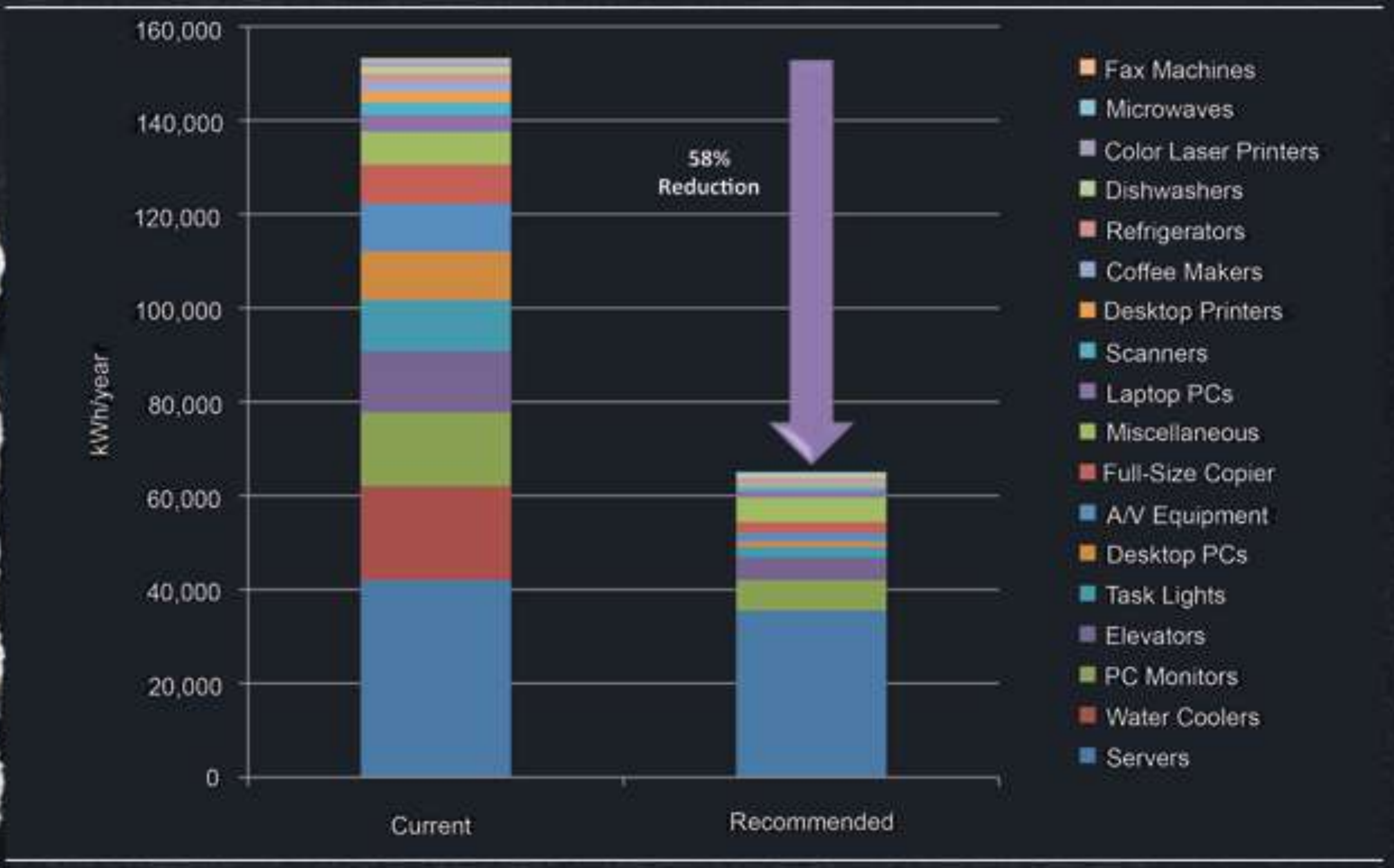
– 20% reduced plug loads; clustered functions

renovated building: EUI 30% of reference
(later cut one-eighth by further commissioning)

Expected reductions in EUI of Higashi Kanto office, by Takenaka categories. Company sources indicate reference EUI about 1400 MJ/m^2-yr, renovated building EUI about 400 MJ/m^2-yr. Source: R.H. Knapp from Takenaka.

Sources: 竹中工務店東関東支店ZEB 化改修: 田中 宏治, ㈱竹中工務店 設計部設備部門;

Packard Foundation Headquarters
Los Altos, CA, 2012



18,606-m^2 1974 Chicago curtainwall office tower: a 1994 retrofit integrative design

Oak Brook Regency Tower West, 1515 W. 22nd St., Oak Brook, Illinois
http://www.rejournals.com/wp-content/uploads/2013/07/OBRTExterior1.jpg

18,606-m^2 1974 Chicago curtainwall office tower: a 1994 retrofit integrative design

76%

calculated energy saving

−30…+40

$/m^2 approx. marginal investment

−5

months' payback (typical)

RetroFit
DEPOT

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

Unknown Store

Fossil Ridge High School, Fort Collins, CO (Greg Franta

USGBC Headquarters

USGBC Headquarters

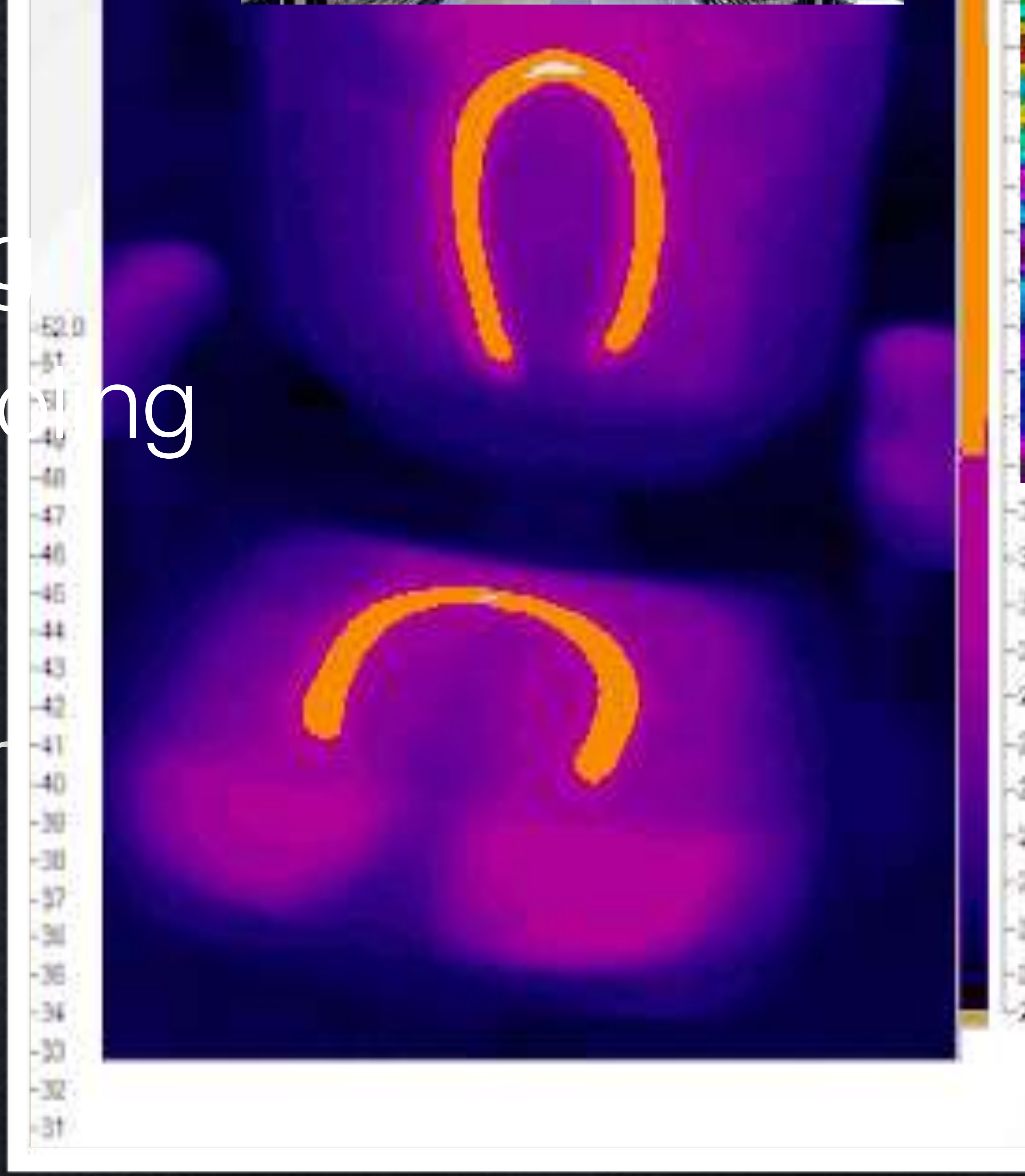
Stop and Shop Grocery Store

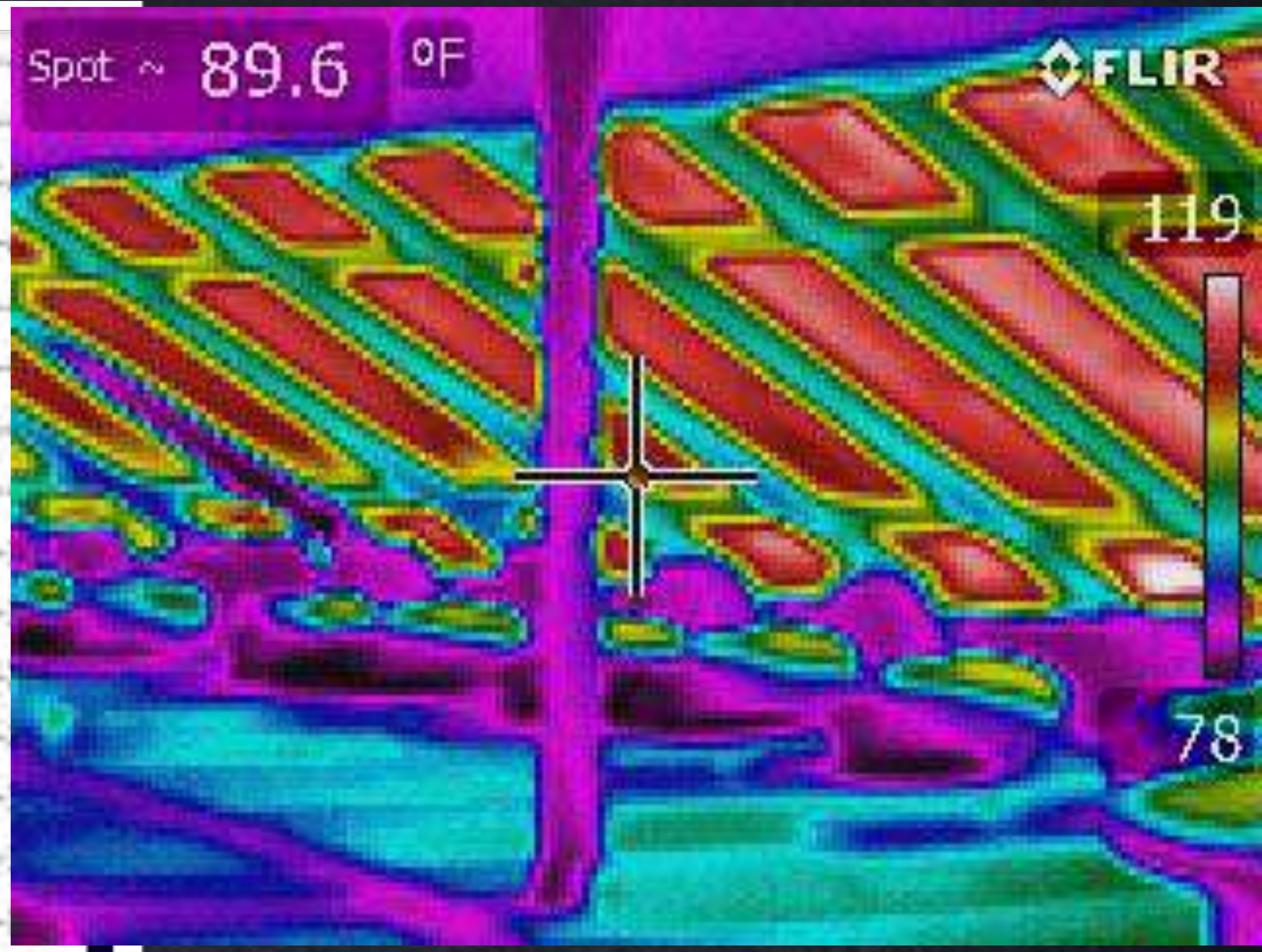
Photos courtesy of Clanton & Associates, Boulder, CO

The right steps in the right order: space cooling

0. Cool the people, not the building
1. Expand comfort envelope
2. Minimize unwanted heat gains
3. Passive cooling
4. Active nonrefrigerative cooling
5. Superefficient refrigerative cooling
6. Coolth storage and controls

Res y, m , higher uptime



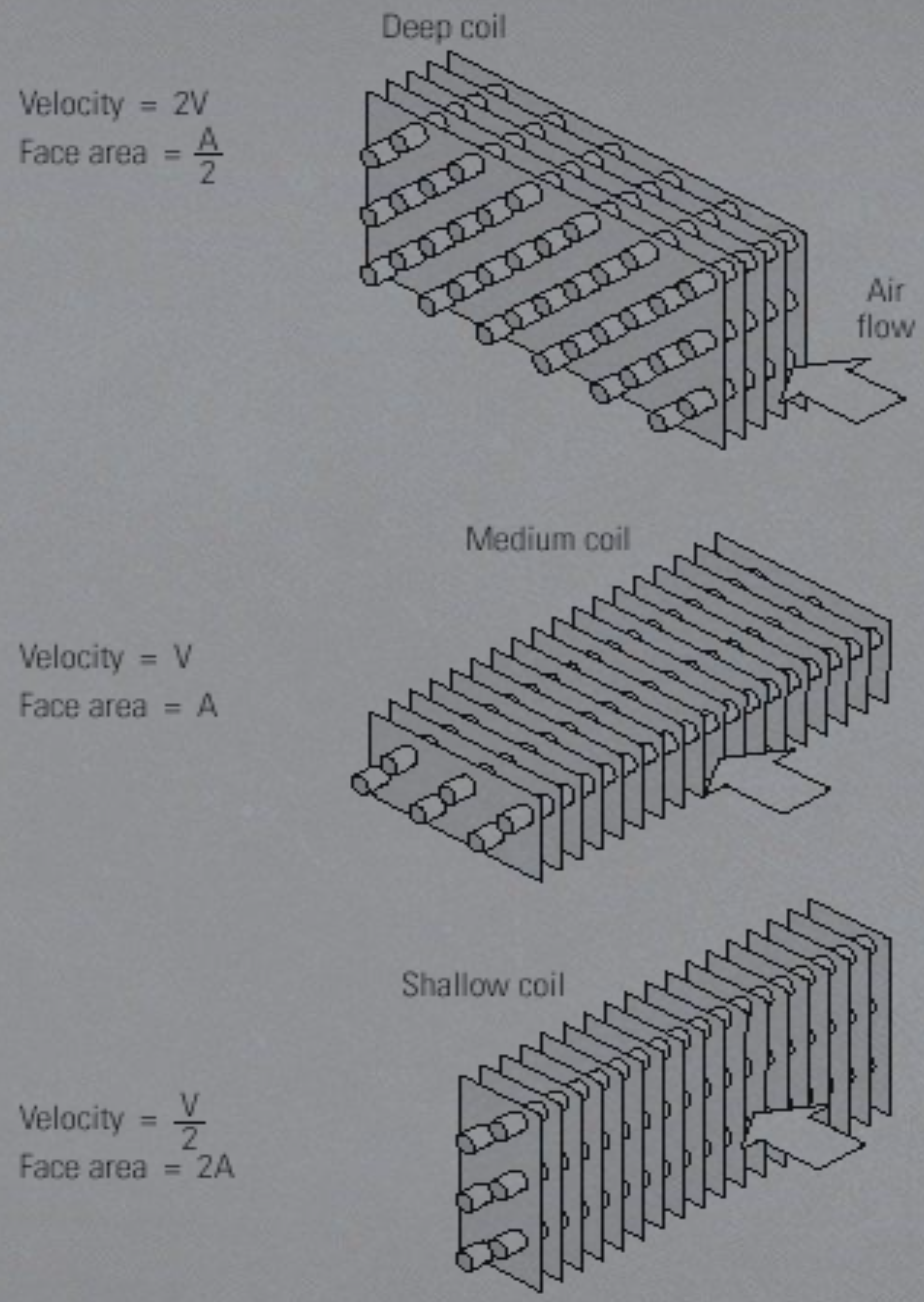


Superefficient big refrigerative HVAC too

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

Element	Std kW/t (COP)	**Best kW/t (COP)**	**How to do it**
Supply fan	0.60	0.061	Best vaneaxial, ~0.2–0.7 kPa TSH (less w/UFDV), VAV
ChWP	0.16	0.018	120–150 kPa head, efficient pump/motor, no pri/sec
Chiller	0.75	0.481	0.6–1 Cº approaches, optimal impeller speed
CWP	0.14	0.018	90 kPa head, efficient pump/motor
CT 	0.10	0.010	Big fill area, big slow fan at variable speed
TOTAL	*1.75 (COP 2.01)*	*0.588 COP 5.98, 3× better)*	*Better comfort, lower capital cost*

Best Singapore practice with dual ChW temp., e.g. 4.5˚C condensing and 12˚C sensible: **0.52 total kW/t** including 0.41 chiller, **COP 6.8**

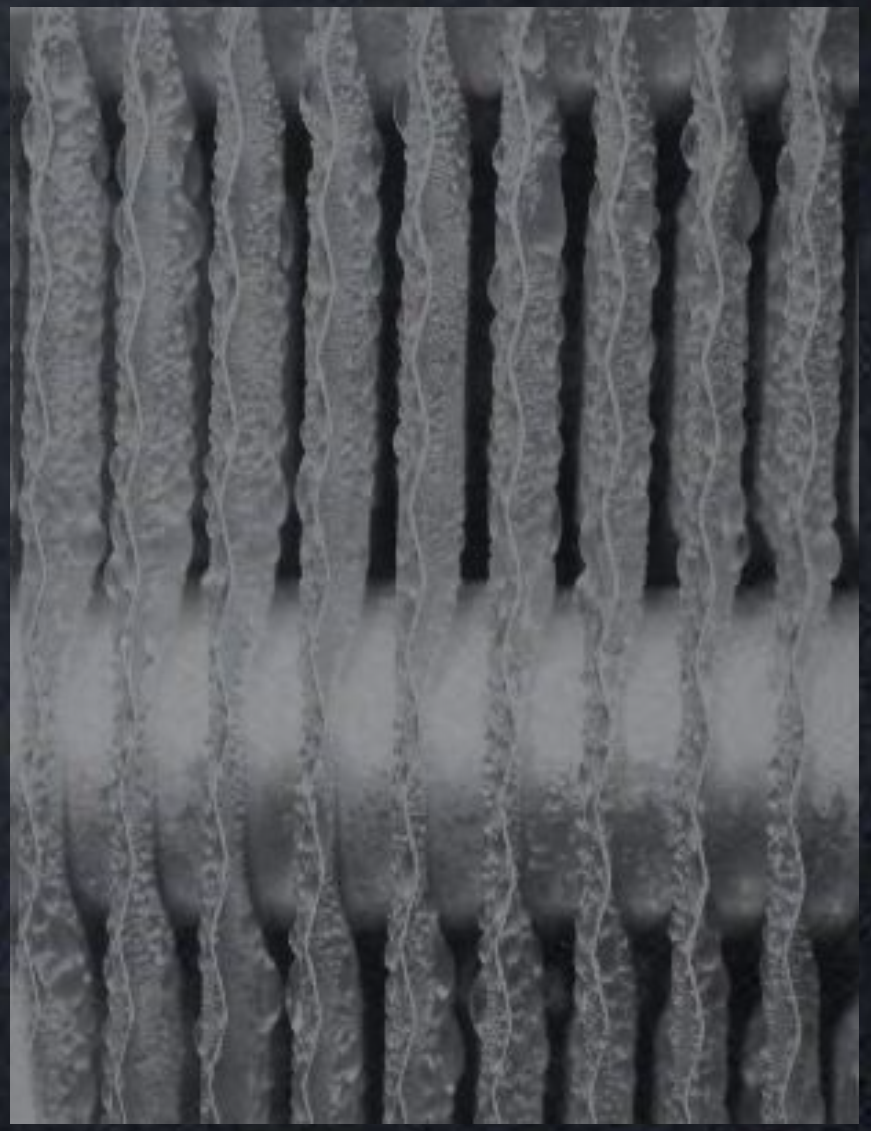


Source: Luxton and Shaw [25]

Low-face-velocity, high-coolant-velocity coils

Correct a 1921 mistake about how coils work

Flow is laminar and condensation is dropwise, so turn the coil around sideways, run at <1 m/s (<200 fpm):
29% better dehumidification,
ΔP –95%; smaller chiller, fan, and parasitic loads



Designing to save ~80–90% of pipe and duct friction—equivalent to about half the world's coal-fired electricity

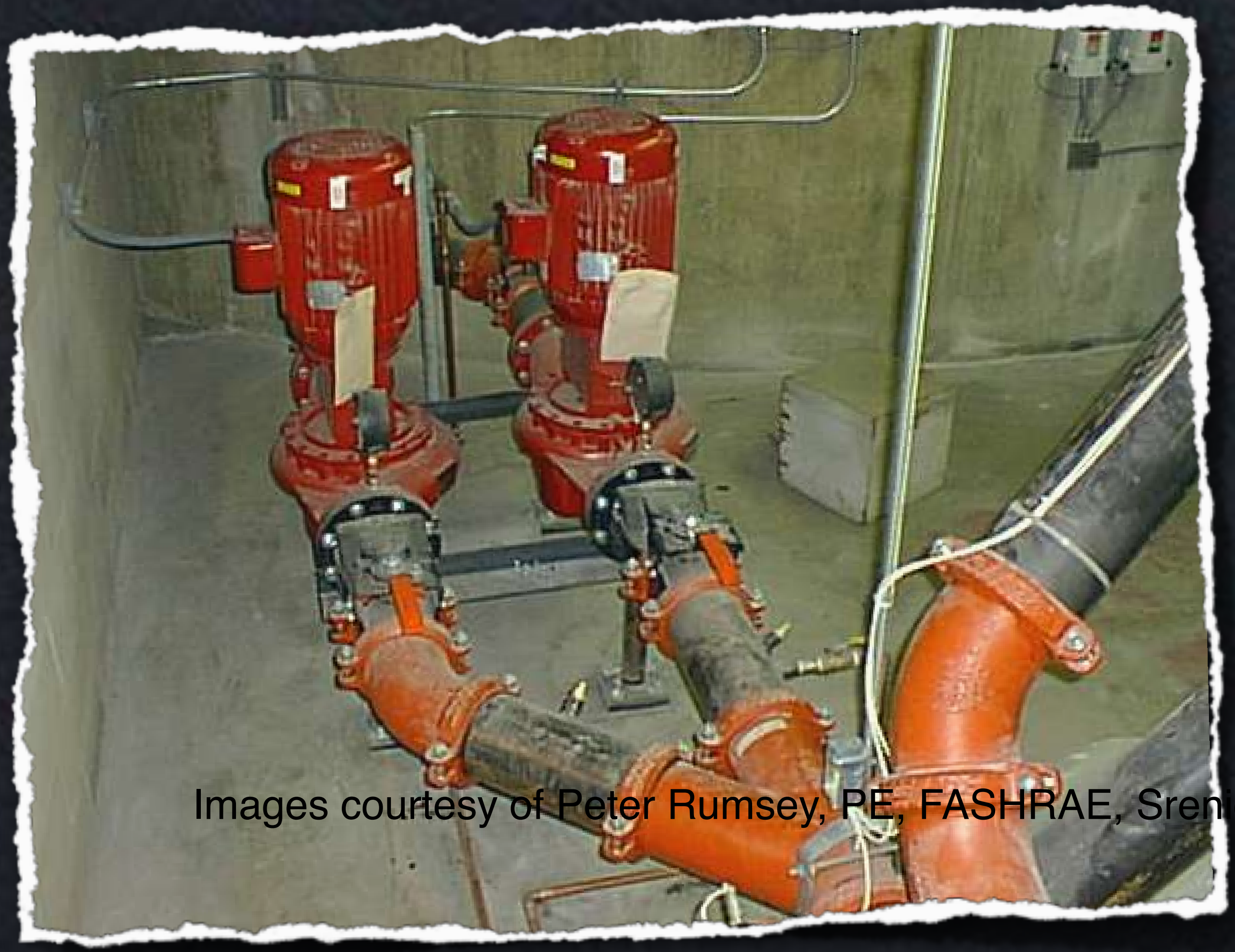
thin, long, crooked

→

fat, short, straight

Typical paybacks ≤1 y retrofit, ≤0 new-build
But not yet in any textbook, official study, or industry forecast

Retrofitted Low-Friction Piping Layout



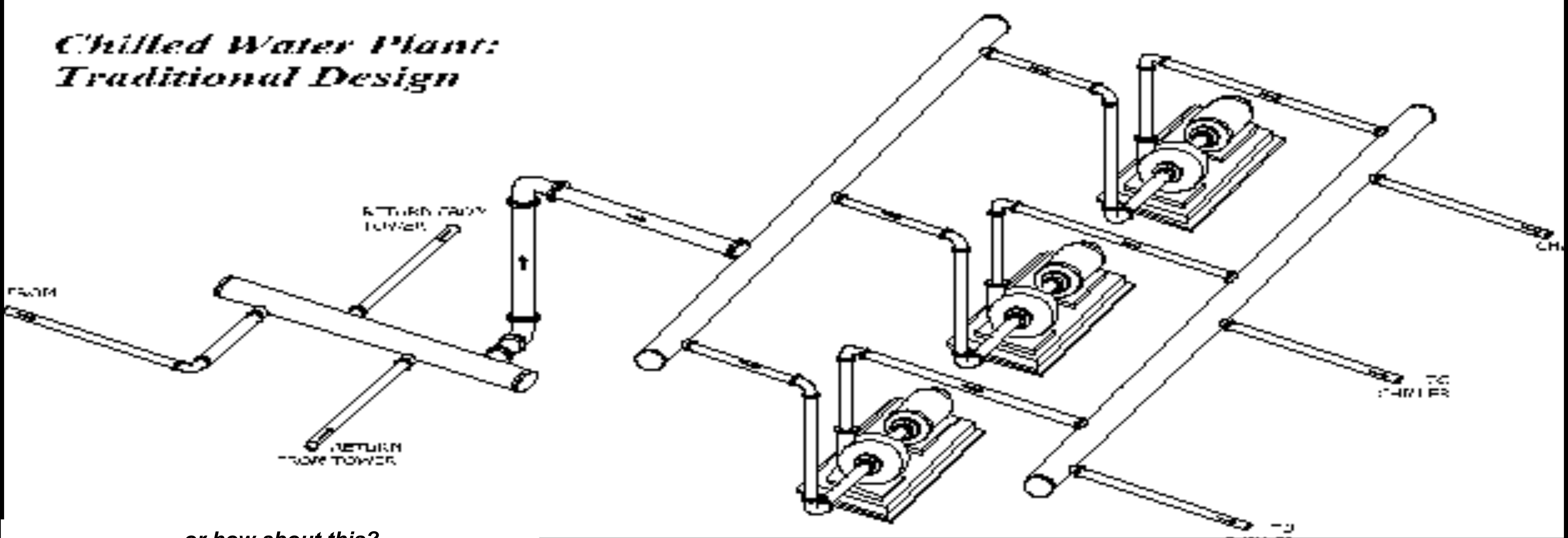
Images courtesy of Peter Rumsey, PE, FASHRAE, Srenior Advisor, Rocky Moutnain Institute

Cou

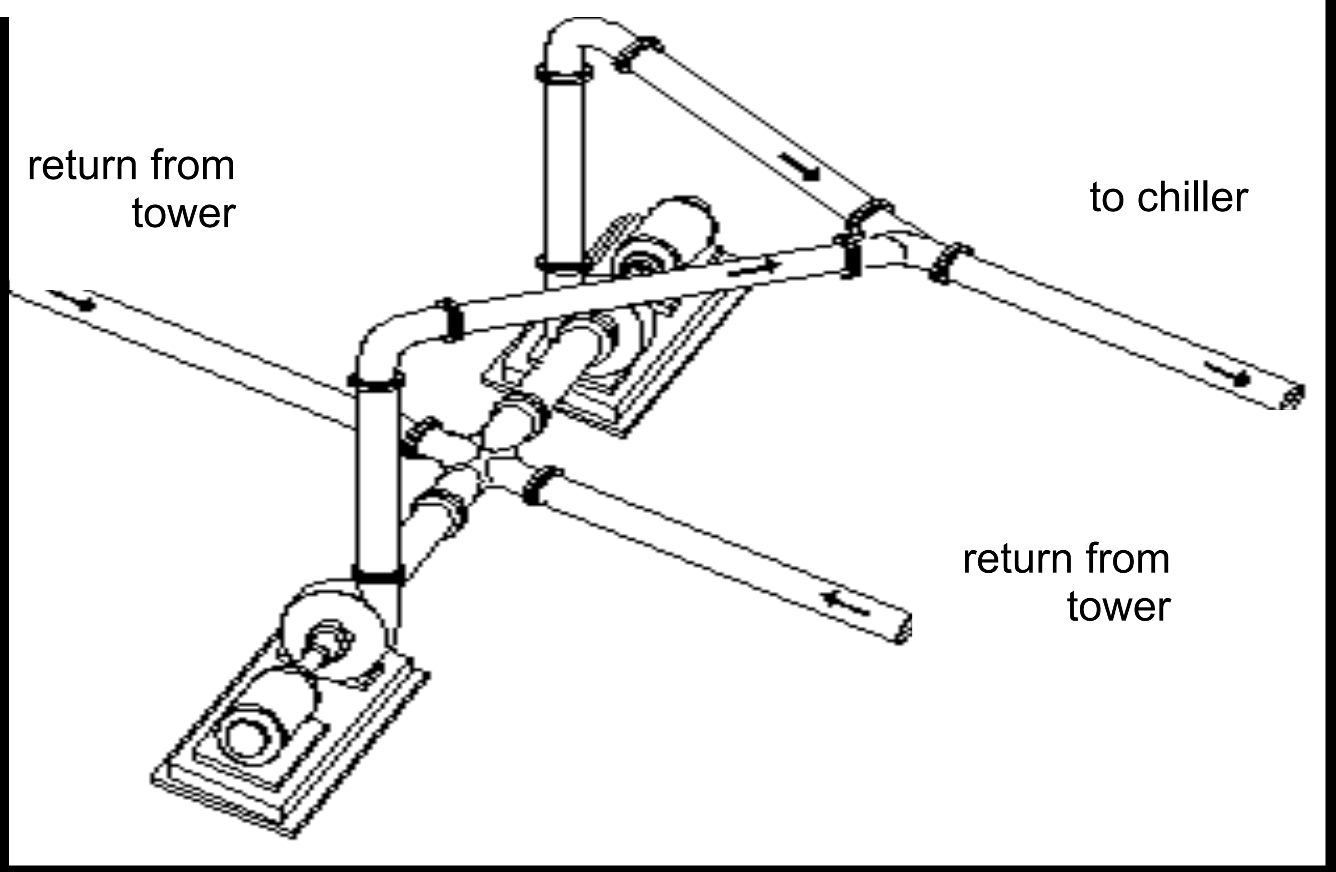
Courtesy of

Courtesy of Peter Rumsey, PE, FASHRAE, Senior Advisor, Rocky Mountain institute

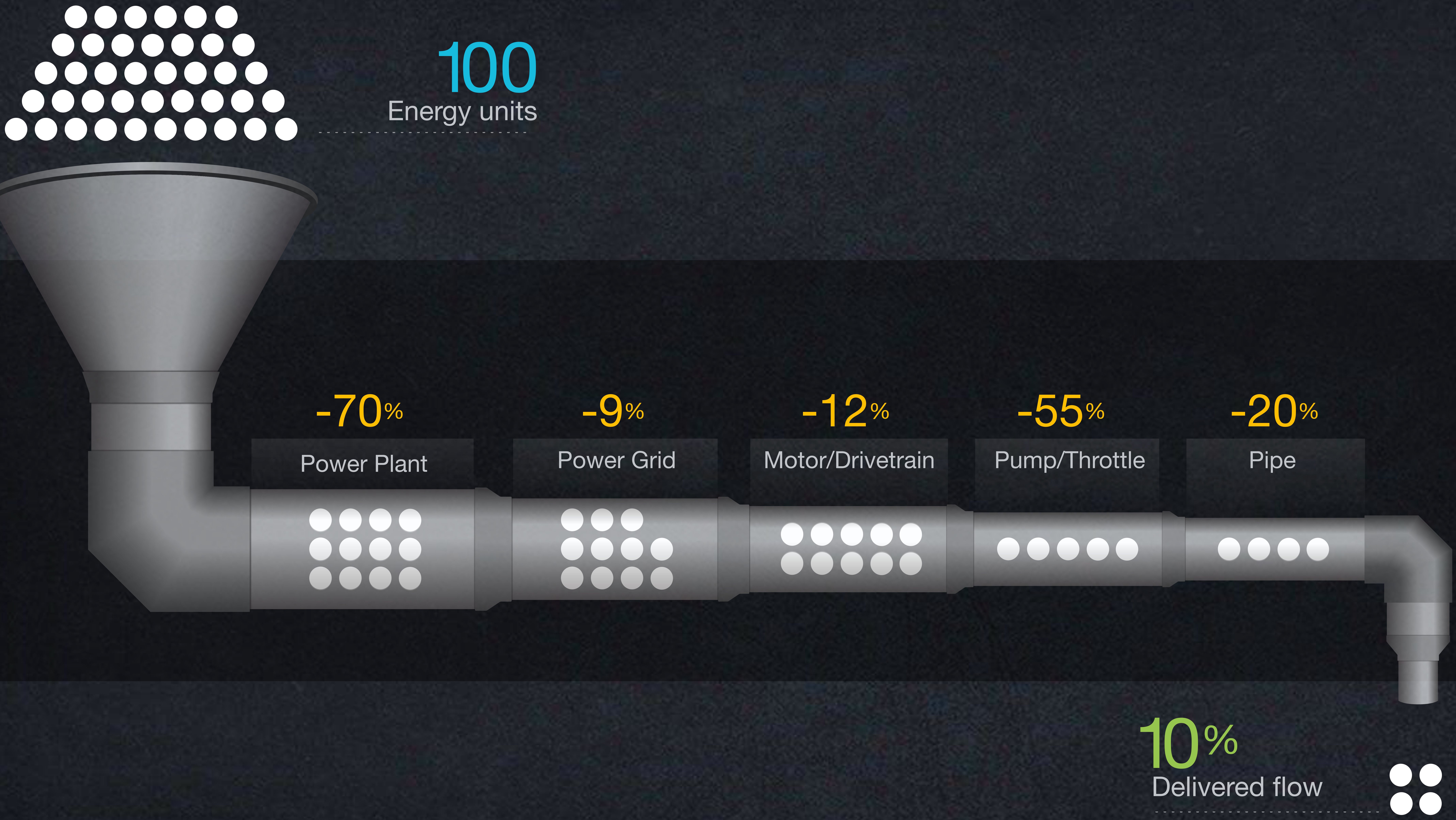
Which of these layouts uses less capital and energy?



…or how about this?



- Less space, weight, friction, energy
- Fewer parts, smaller pumps and motors, less installation labor
- Less O&M, higher uptime



100
Energy units

-70%
Power Plant

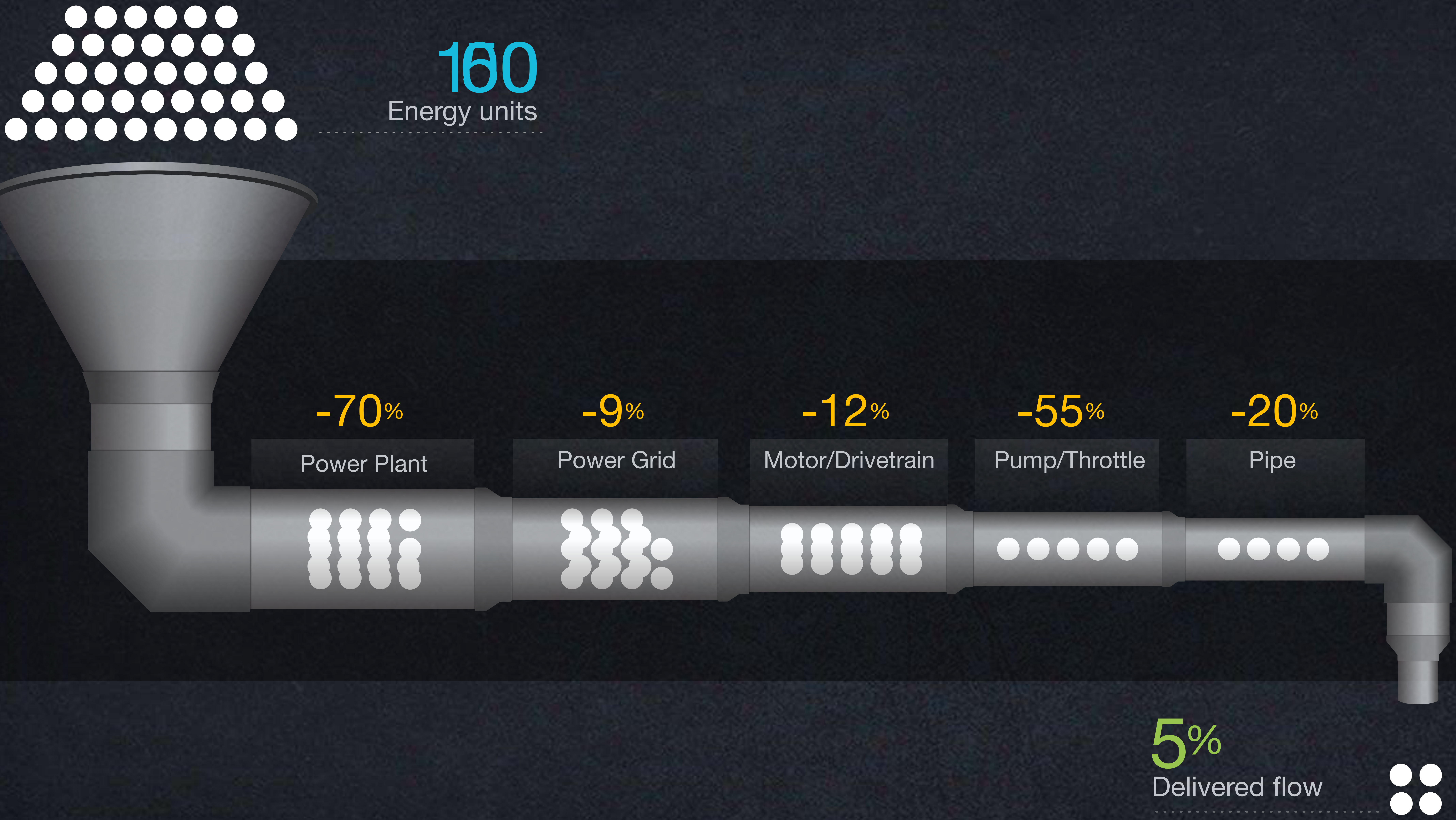
-9%
Power Grid

-12%
Motor/Drivetrain

-55%
Pump/Throttle

-20%
Pipe

10%
Delivered flow



100

Energy units

-70%

Power Plant

-9%

Power Grid

-12%

Motor/Drivetrain

-55%

Pump/Throttle

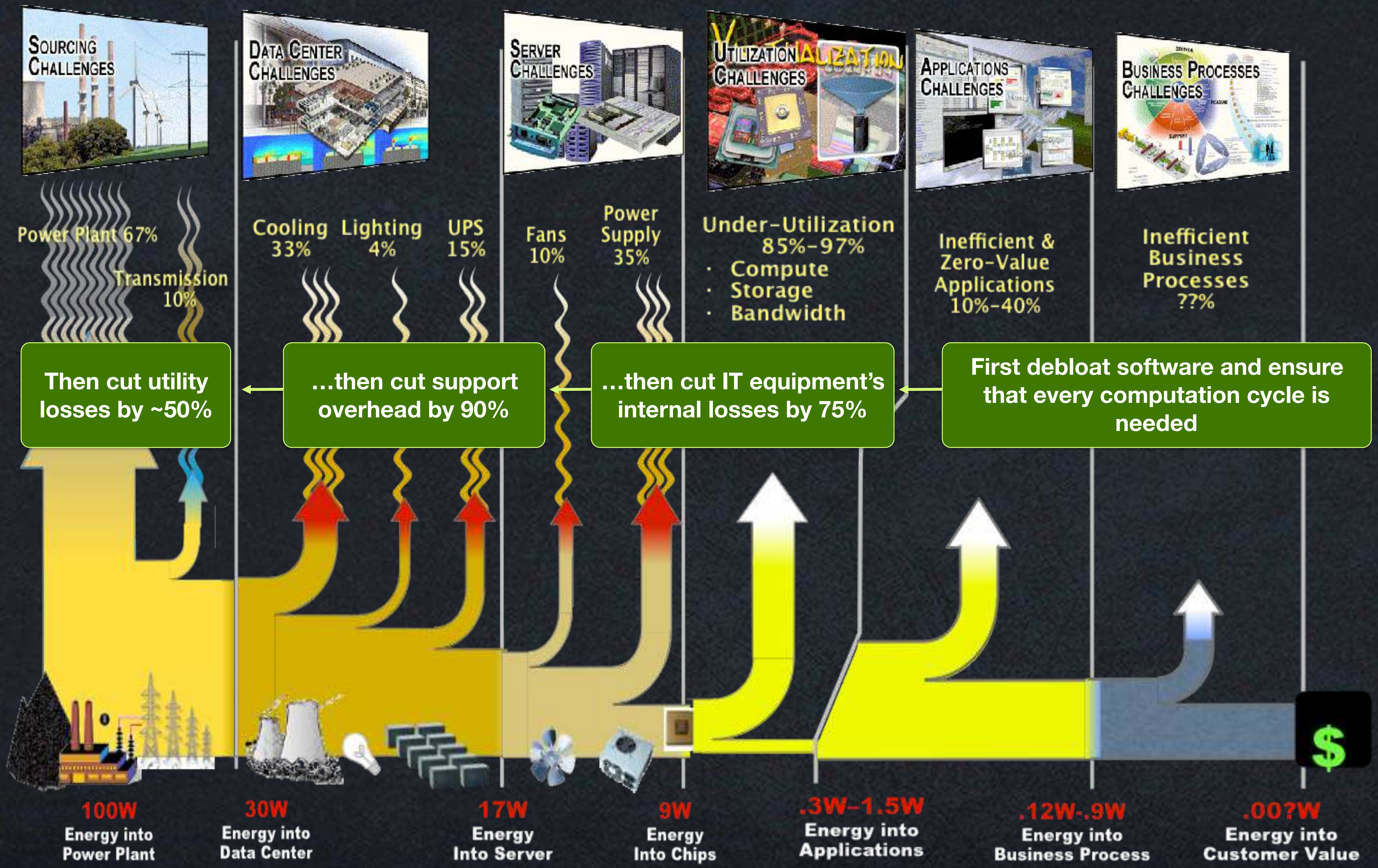
-20%

Pipe

5%

Delivered flow

Start saving downstream for data centers



First debloat software and ensure that every computation cycle is needed

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

…then cut support overhead by 90%

Then cut utility losses by ~50%

Principles of integrative building design

- Define the end-use (why cool a building if it can’t feel hot?)
- Optimize the building as a system: costly windows reduce total construction cost
    - ➡ Efficiency shrinks or eliminates HVAC; saved capital cost buys the efficiency
- Start saving downstream, at the point of use, shrinking capital cost upstream
- Do the right steps, in the right order, at the right time

And by the way…get rewarded for excelling in these achievements!

Designing for efficiency

- Task elimination before task: why do it?
- Eliminate *muda*, *muri*, *mura*
- Demand before supply
- Downstream before upstream
- Application before equipment
- People before hardware
- Passive before active
- Quality before quantity

Benchmarking a big new office

(~10,000+ m^2, semitropical climate, no PVs, USA; ~2012 Japan; 2015 1,451-m^2 RMI Innovation Center; ~2012 India

	Normal	*Better*	*Best*
delivered MJ/m^2-y	1,100/1,737	450–680/566	100–230/126/182/158–194
del. el. kWh/m^2-y (EPI)	270/203/~200–400	160/195	20–40/35/51/<75 (25 cooling)
lighting W/m^2 as-used	16–24/12	10	1–3/2/1/<1.6
plug W/m^2 as-used	50–90/12	10–20	2
glazing W/m^2K center-of-glass	2.9	1.4	0.3–0.5/0.43/1.1
glazing T_{vis}/SC	1.0	1.2	>2.0
perimeter heating	extensive	medium	none/none
roof α, ε	0.8, 0.2	0.4, 0.4	0.08, 0.97/0.1,0.9
m^2/kW_{th} cooling	7–9	13–16	26–32+/∞/20–26 (750–1000sf/TR)
cooling syst. COP	1.85	2.3/2.0–2.7	6.8–25+/–/>6.4 (<0.55 kW/TR)
relative cap. cost	1.0	1.03	0.95–0.97/1.11/0.85–0.90
relative space eff.	1.0	1.01	1.05–1.06/1.01

Japan Normal: 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, 293 MJ), now Takenaka Higashi Kantō 2015 retrofit, ~126 MJ; data courtesy of Urabe-san, CRIEPI, via Asano-sensei, Todai, & Rob Knapp; 2 W/m^2 lighting is Shimizu Building 2012. India: empirical Infosys new-office performance data from Rohan Parikh; standard estimate from Indian designers—100 of the 200–400 (nom ~250) is cooling.

The secret of great design integration:

No compromise!

“A pelican is not compromise between a seagull and a crow.” It is the best possible pelican (so far)—and after 90 million years, it’s a pretty good one.