
ROCKY MOUNTAIN
INSTITUTE

Integrative design for radical energy efficiency at lower cost

Intel keynote, ACEEE 2019 Summer Study on Energy Efficiency in Industry
Portland, Oregon, 13 August 2019

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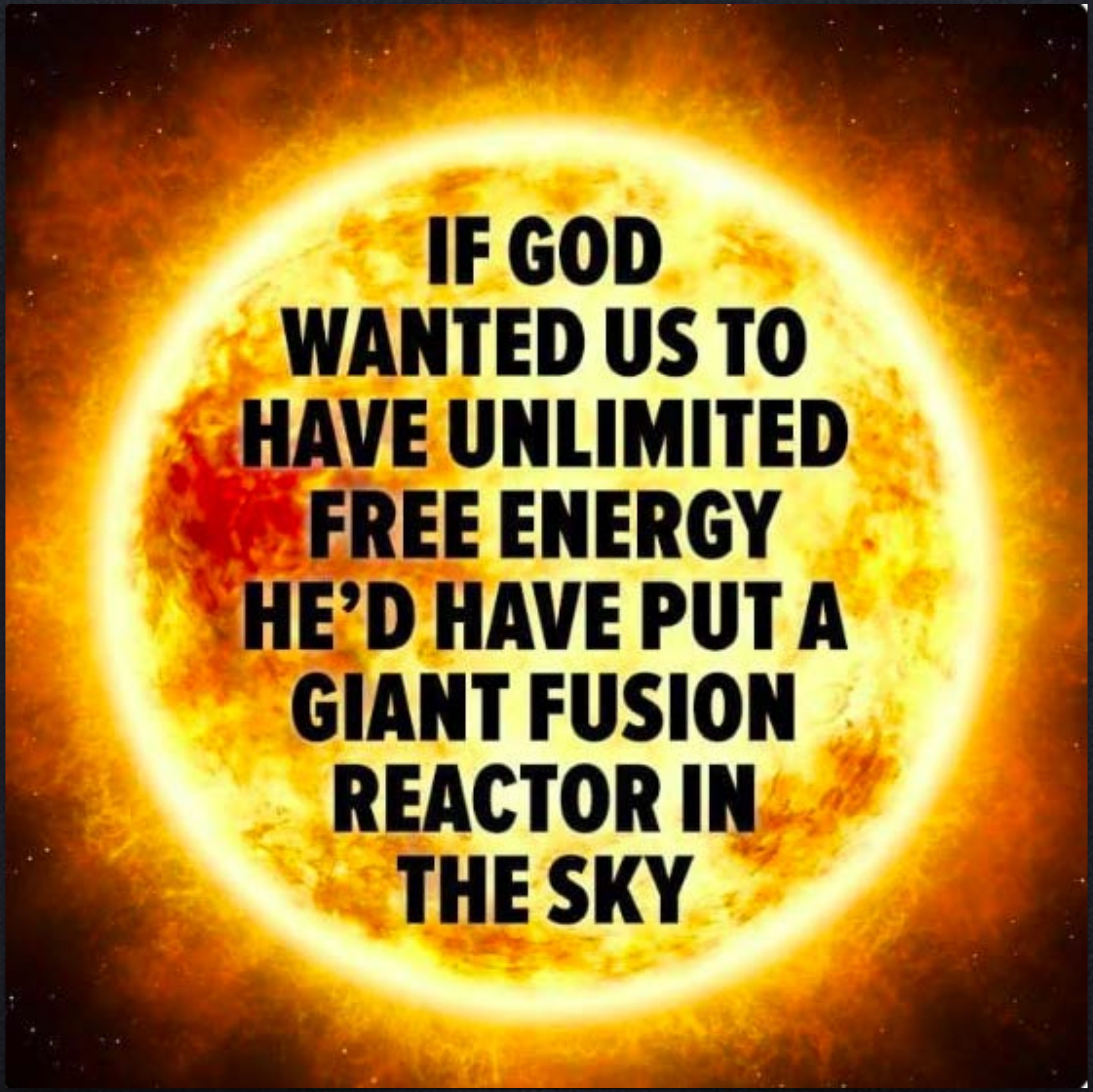
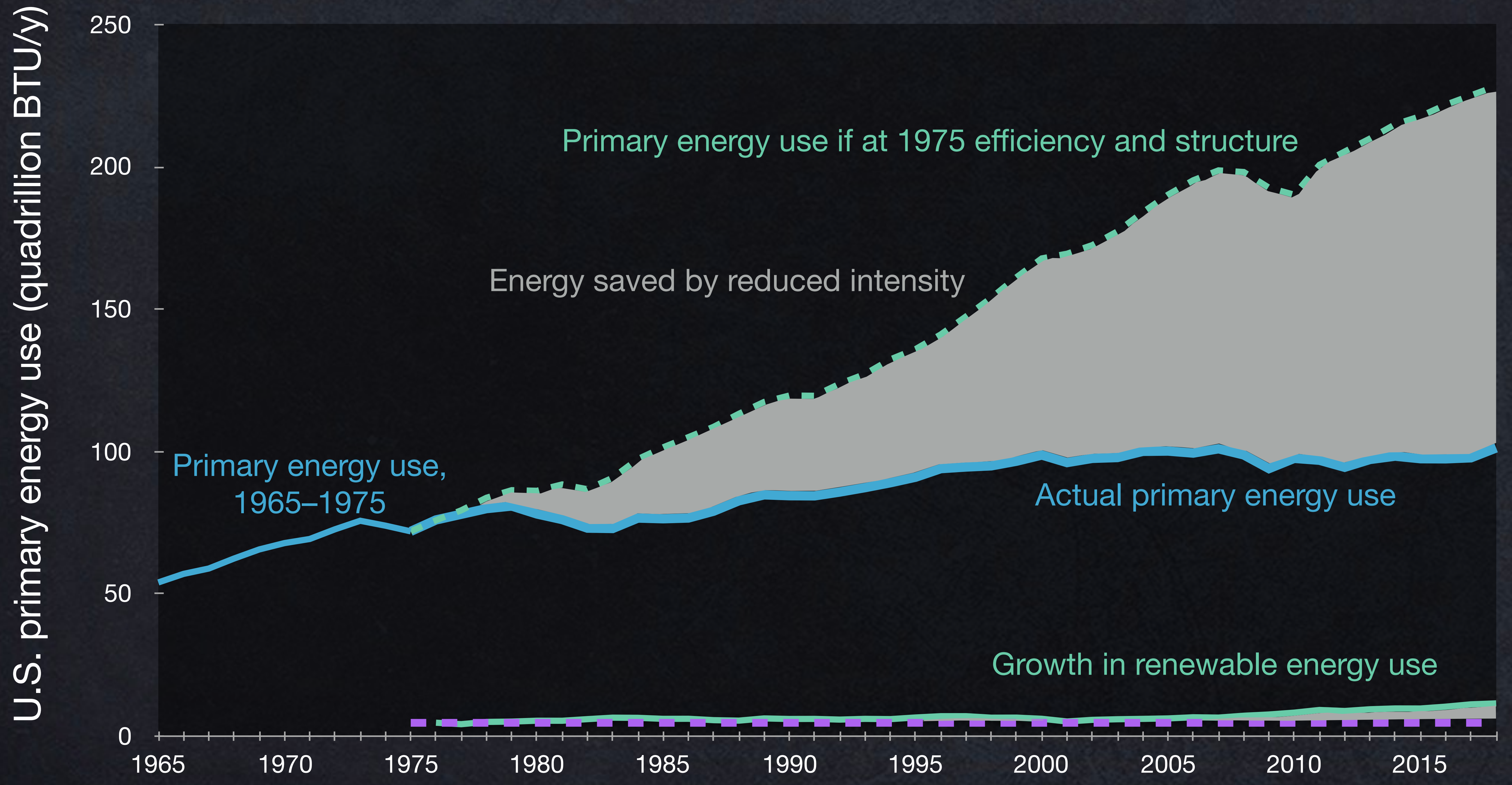
Clean watts are the easy part



Reduced energy intensity has had 30× the impact of renewable growth

(United States, 1965–2018p, not weather-normalized, EIA data)

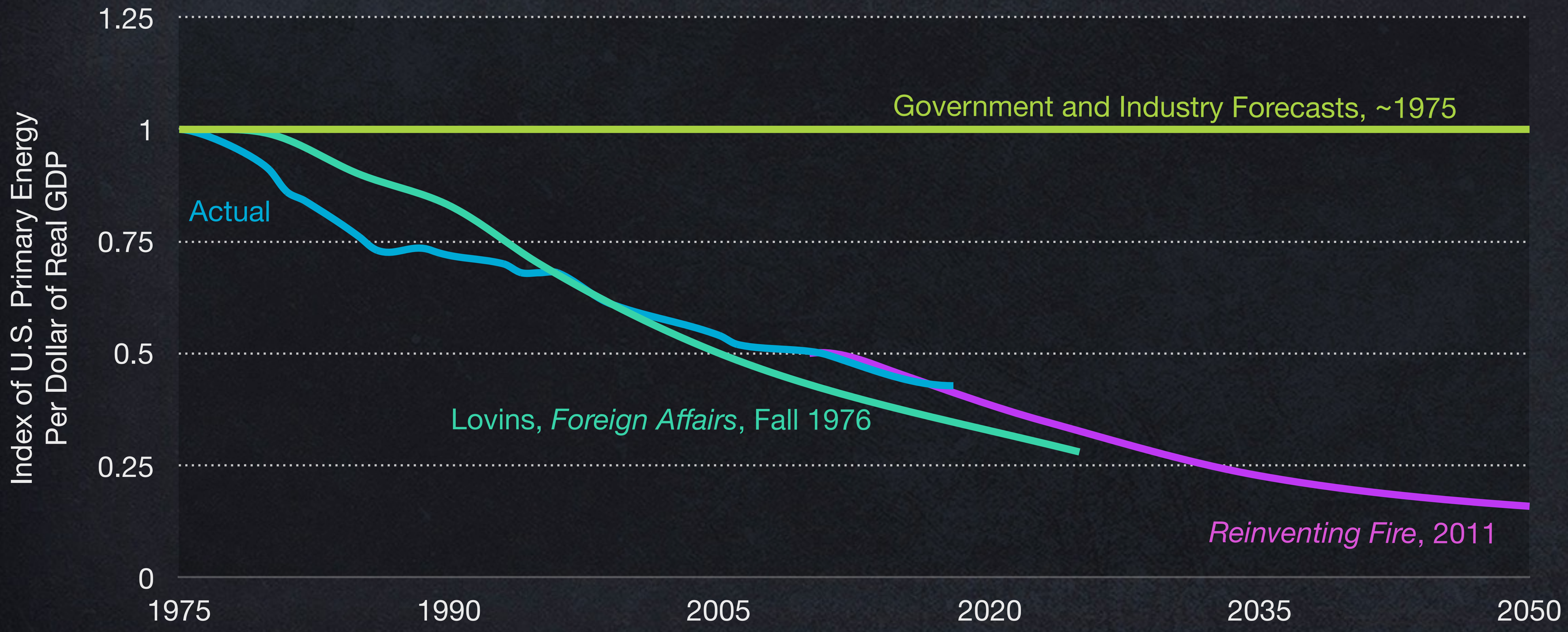


1975–2018p savings from intensity reduction: 2,589 qBTU

1975–2018p growth in total renewable output: 87 qBTU

Heresy Happens

US primary energy intensity, 1975–2017



How low can we go in the energy limbo?

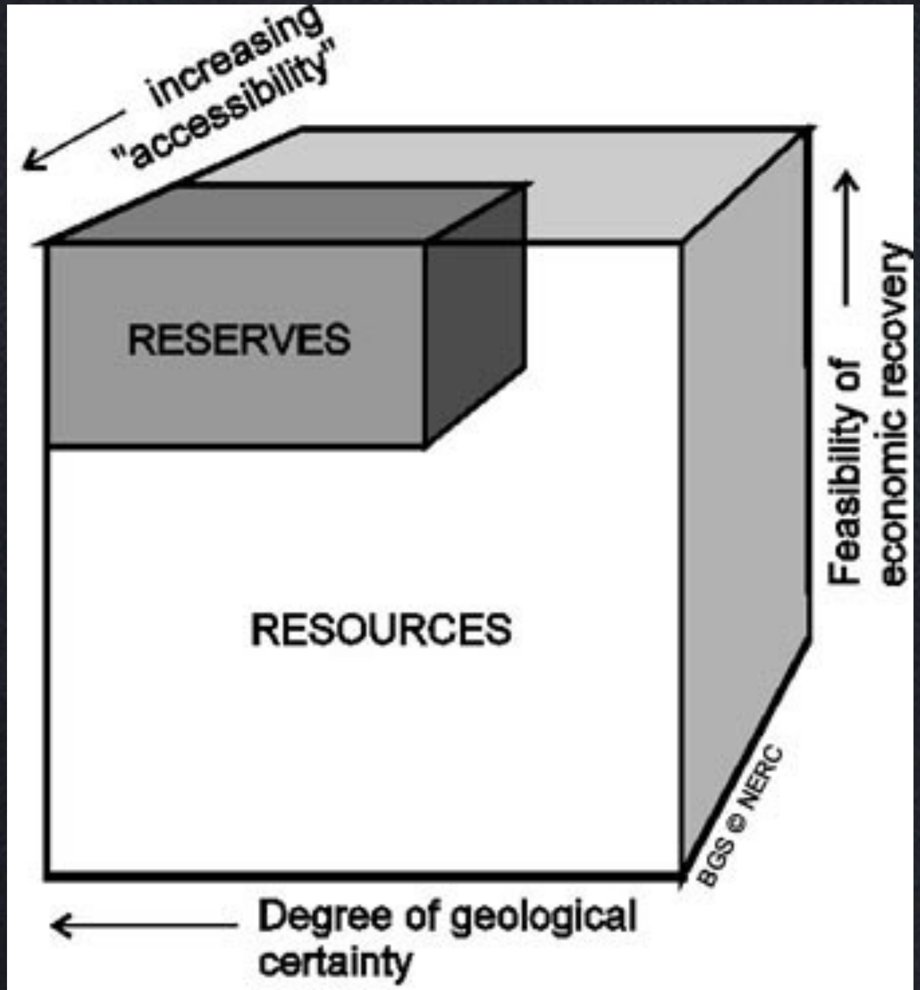
steelasophical.com

"…85% of energy demand could be practically avoided using current knowledge and available technologies"

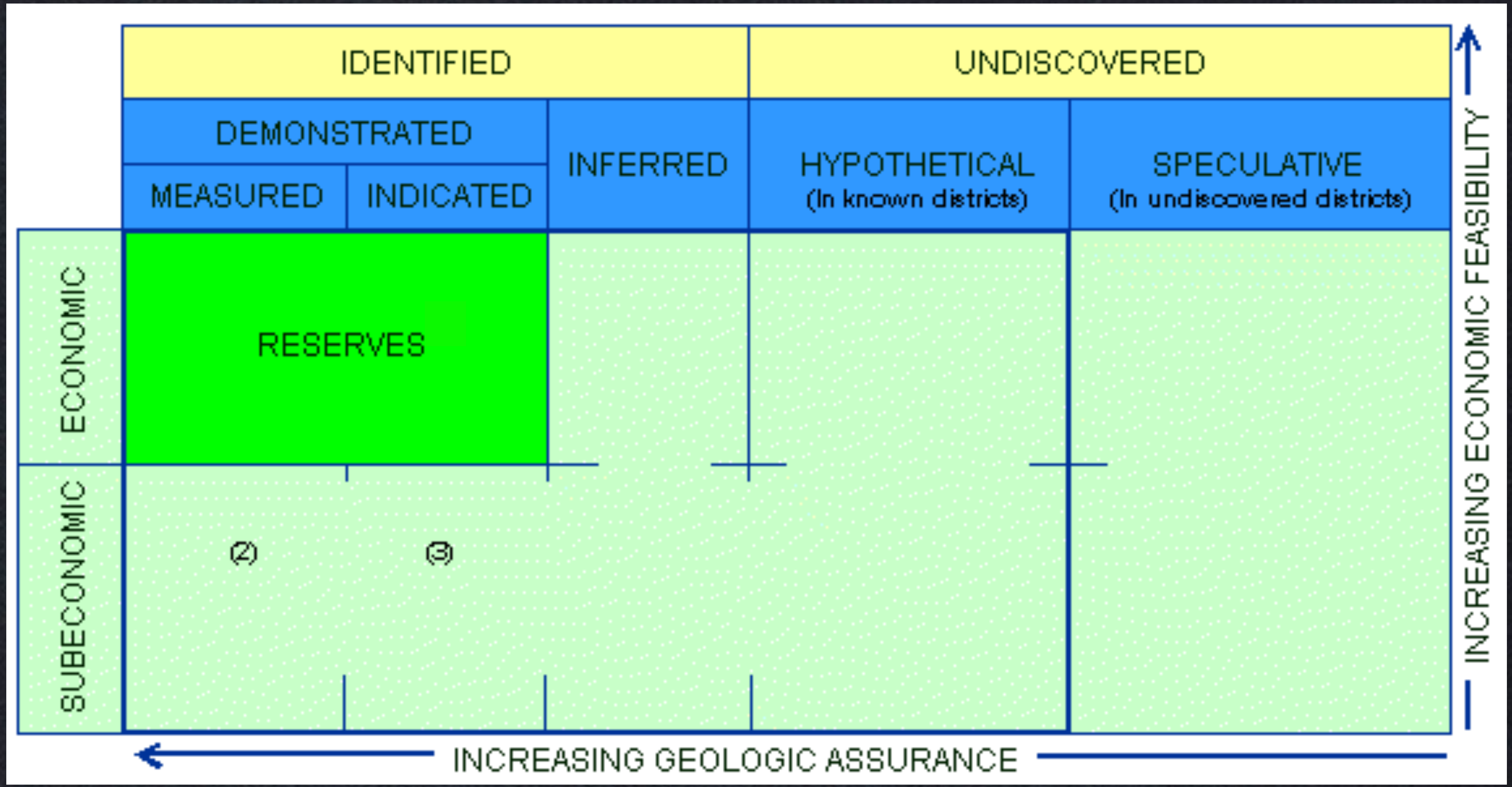
Cullen J Allwood J (2010) Theoretical efficiency limits in energy conversion devices, *Energy* **35**(5):2059–2069, doi:10.1016/j.energy.2010.01.024

Cullen J Allwood J Borgstein E (2011) Reducing Energy Demand: What Are the Practical Limits? *Envtl Sci Tech* **45**(4):1171–1718, doi:10.1021/es102641n

Geological reserves are a small part of resources



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

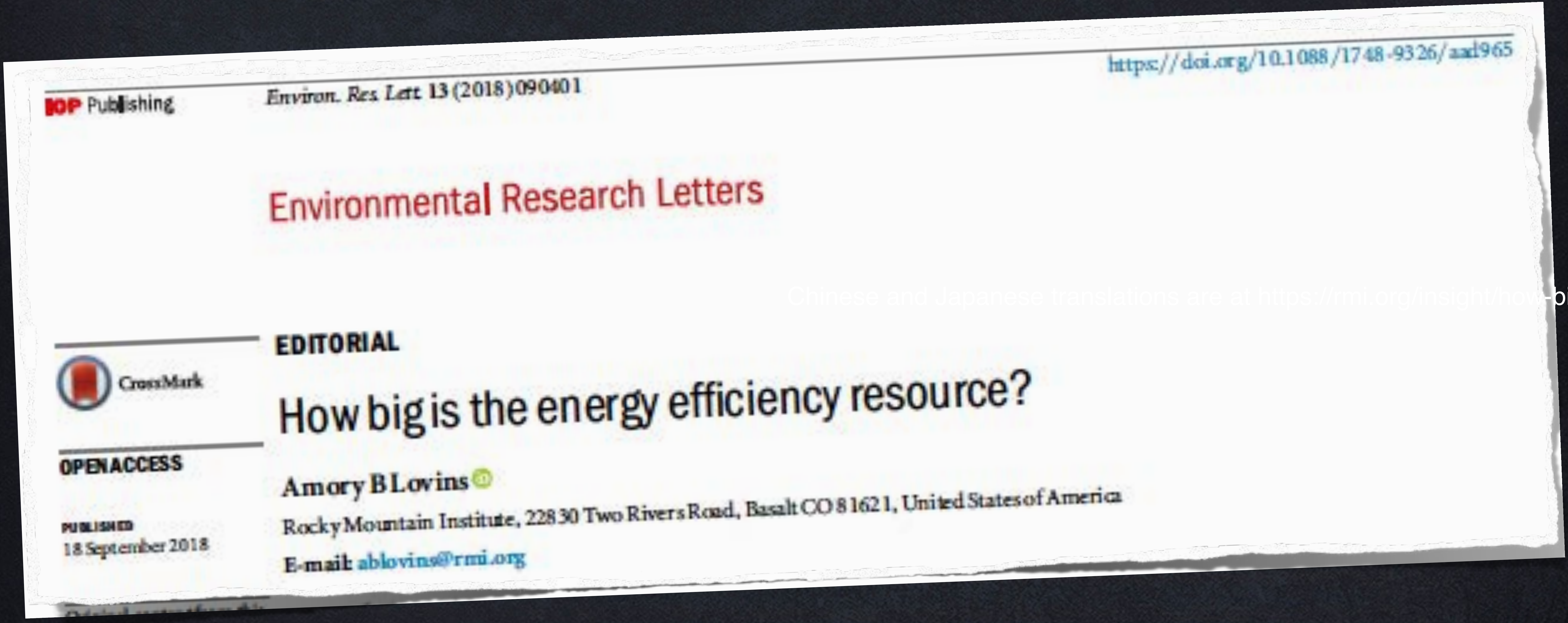


One of many variants of the canonical McKelvey diagram used by the US Geological Survey and worldwide

Orebodies are limited. Energy efficiency isn't (practically).

A major scientific paper on integrative design

https://doi.org/10.1088/1748-9326/aad965



IOP Publishing

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https://doi.org/10.1088/1748-9326/aad965

Environmental Research Letters

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EDITORIAL

How big is the energy efficiency resource?

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Chinese and Japanese translations are at https://rmi.org/insight/how-big-

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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

Bù wàng chū xīn

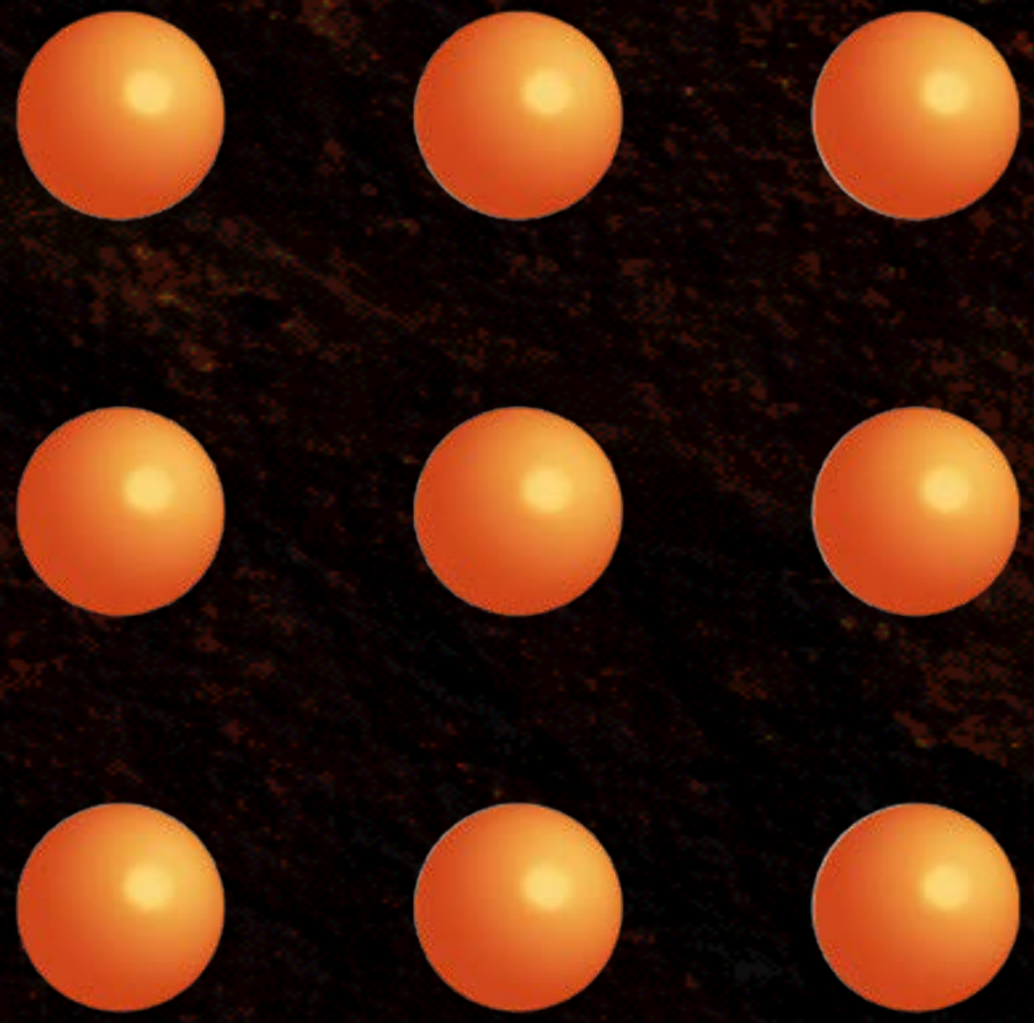
Shoshin wasuru bekarazu

初心忘るべからず

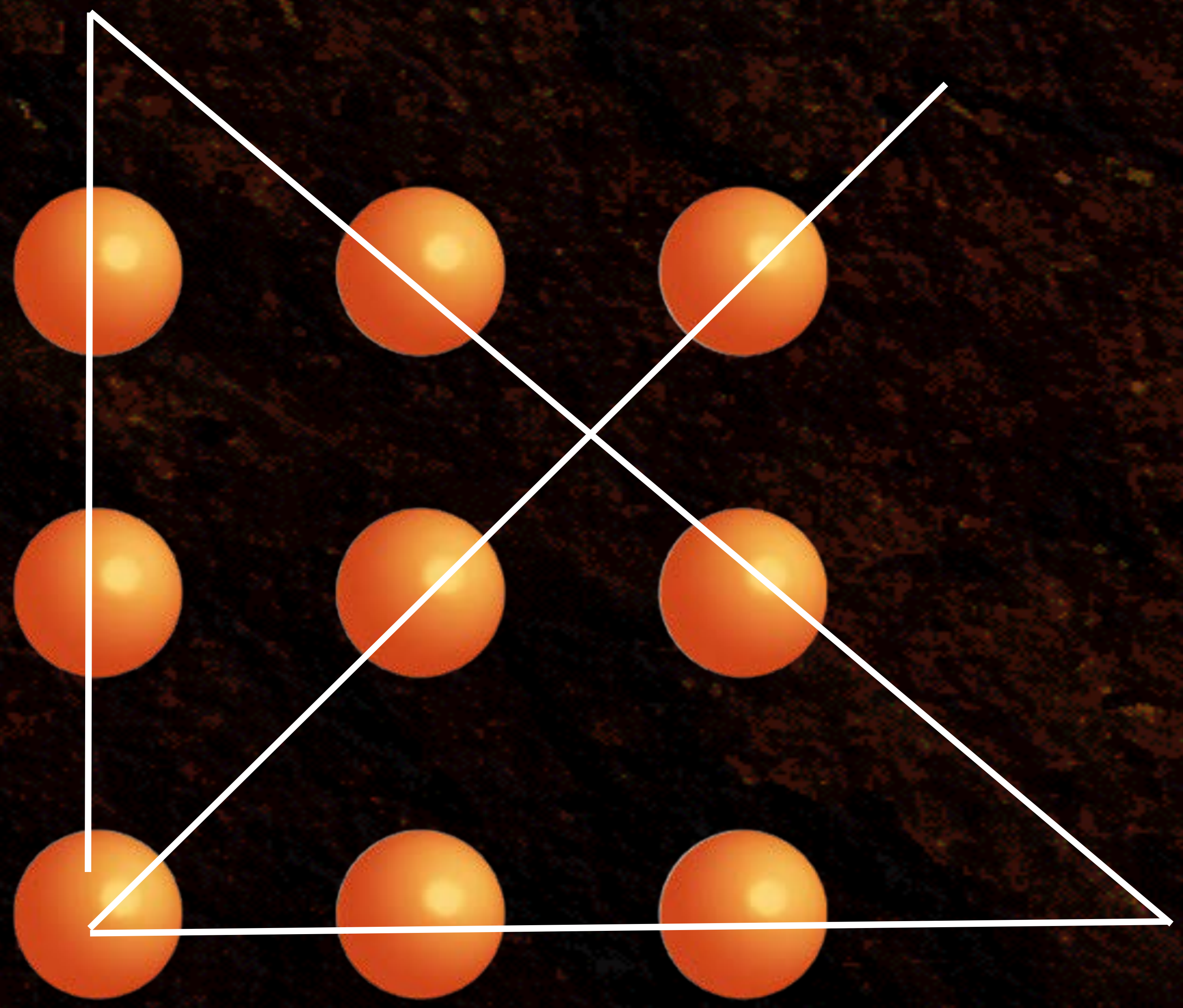
Don’t forget original mind

–Avataṃsaka Sūtra, མདོཕལཔོཆེ,
華嚴經, 대방광불화엄경

The Nine Dots Problem



The Nine Dots Problem



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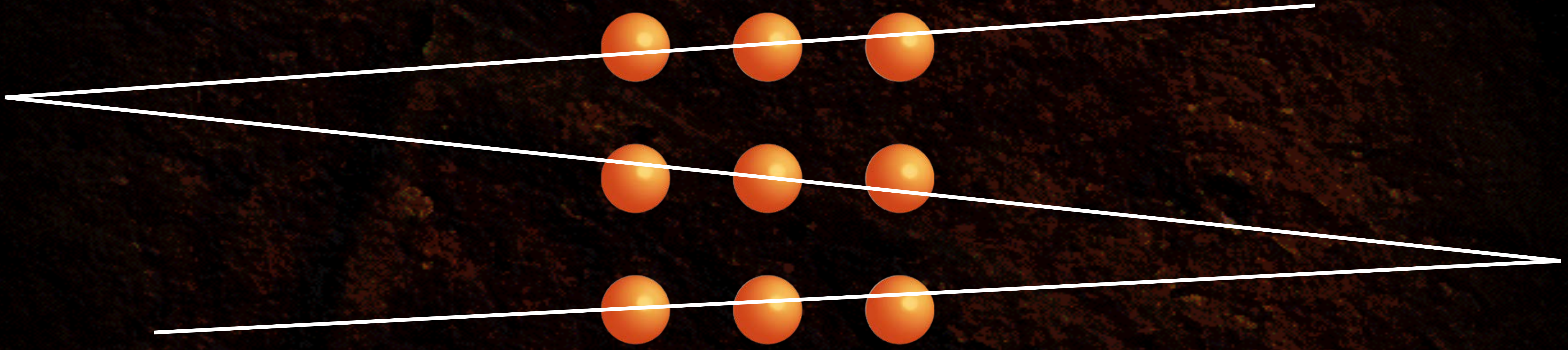
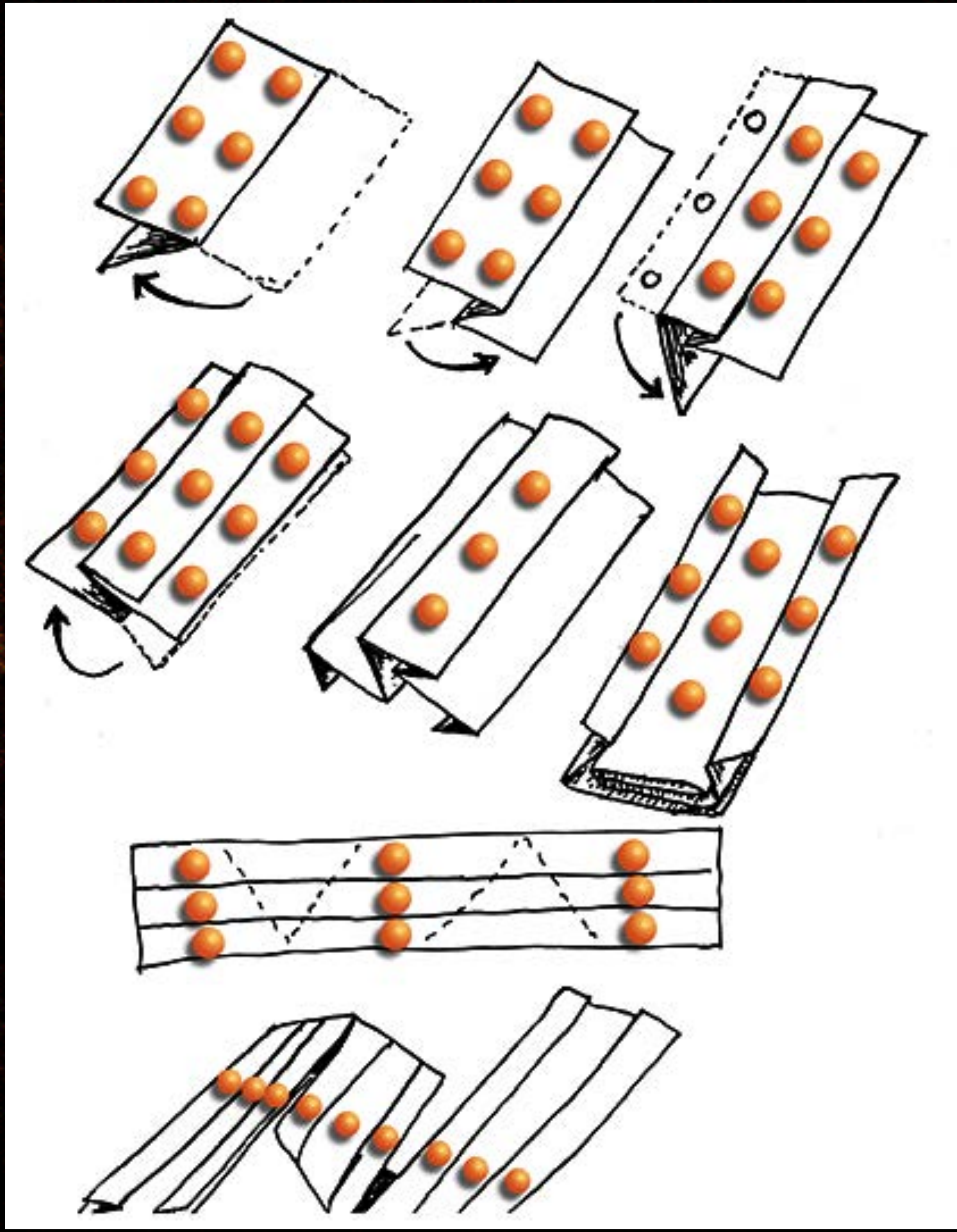
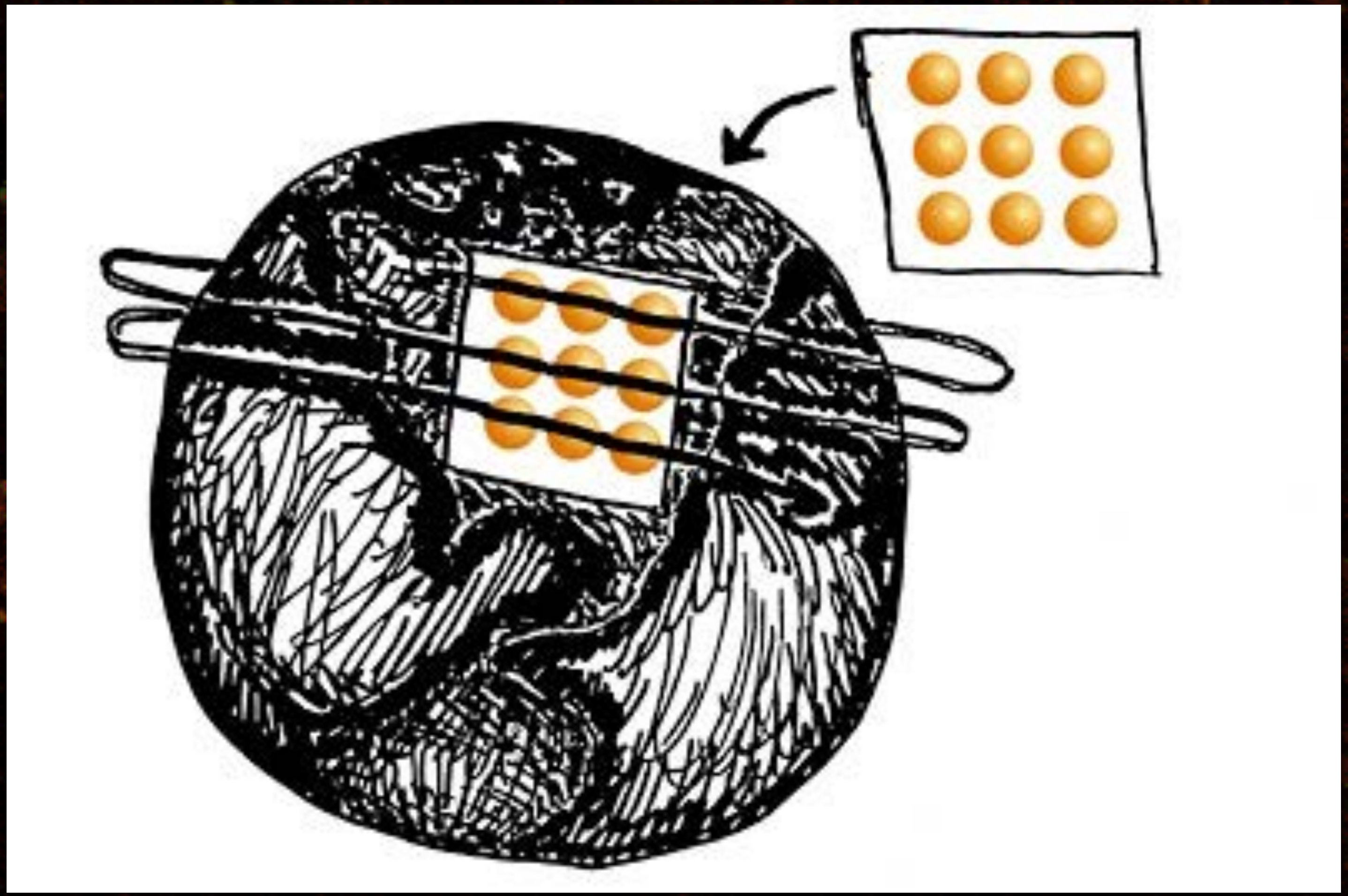
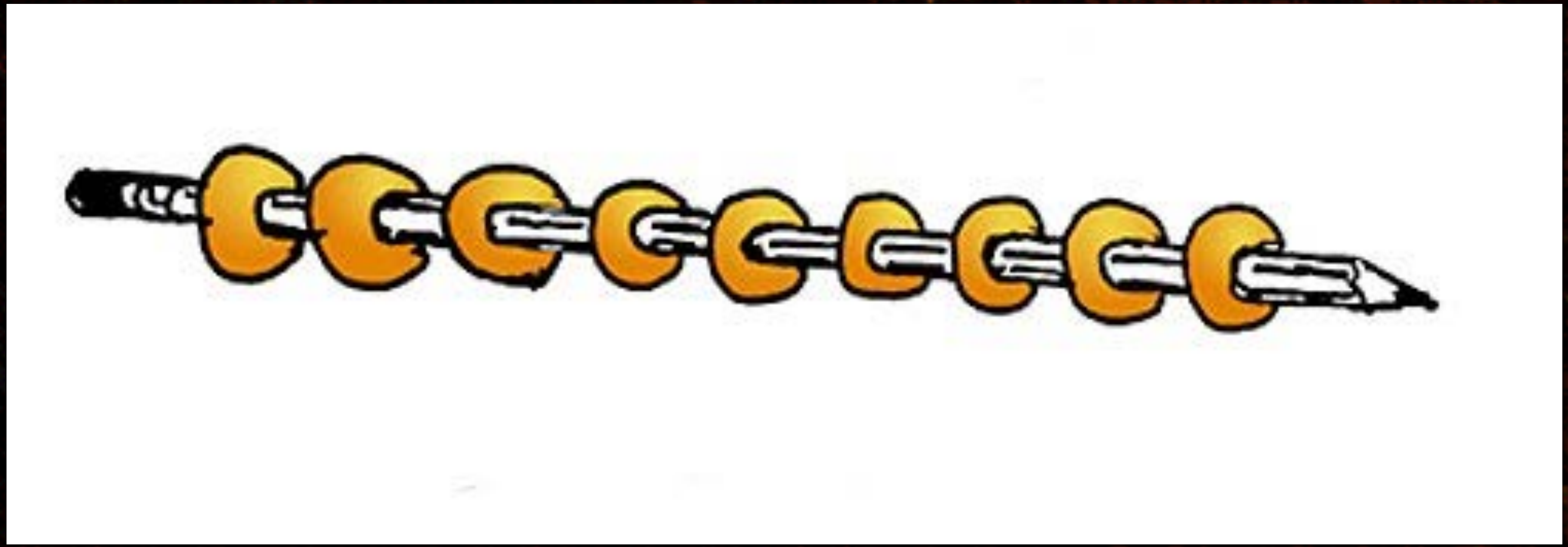




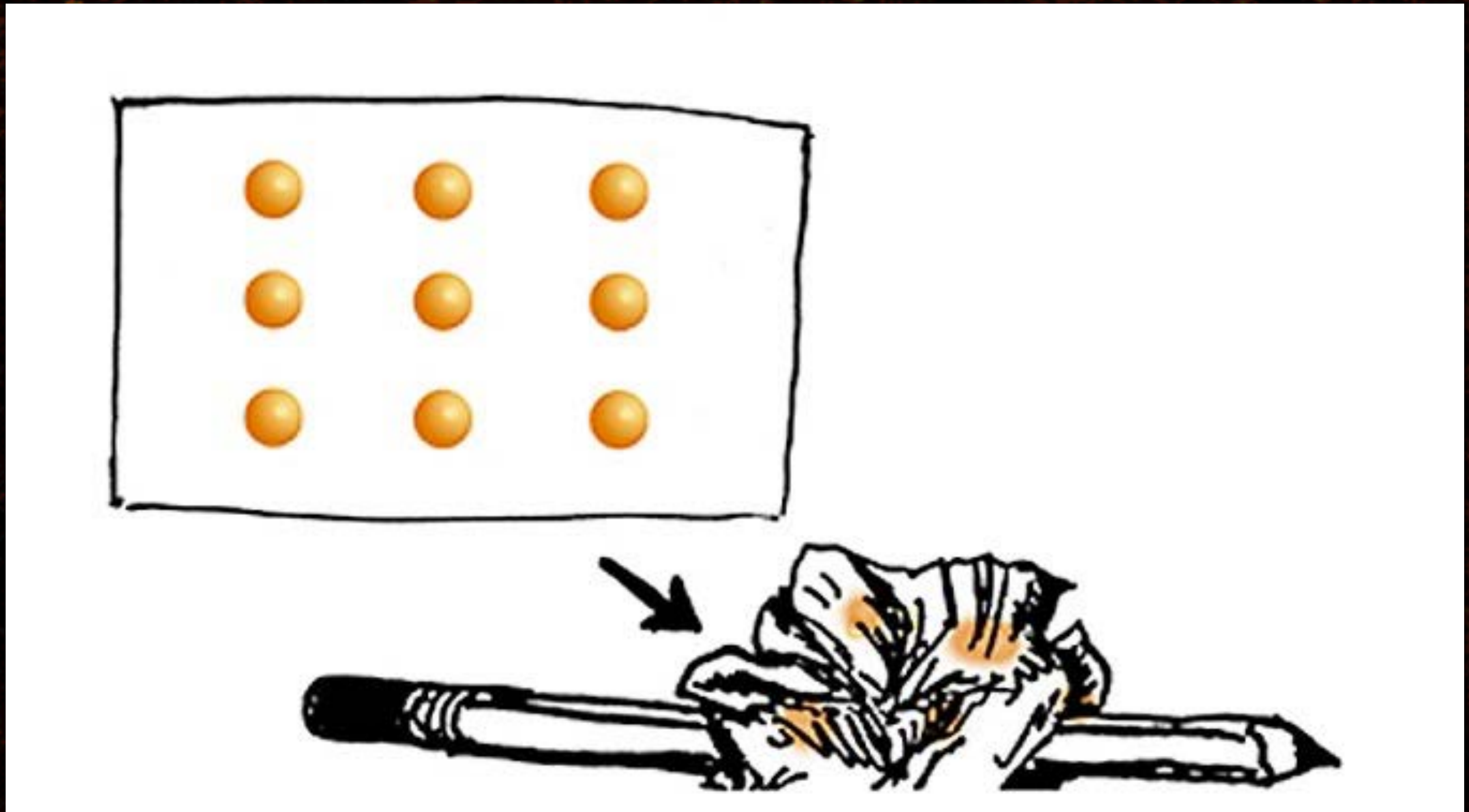
origami solution



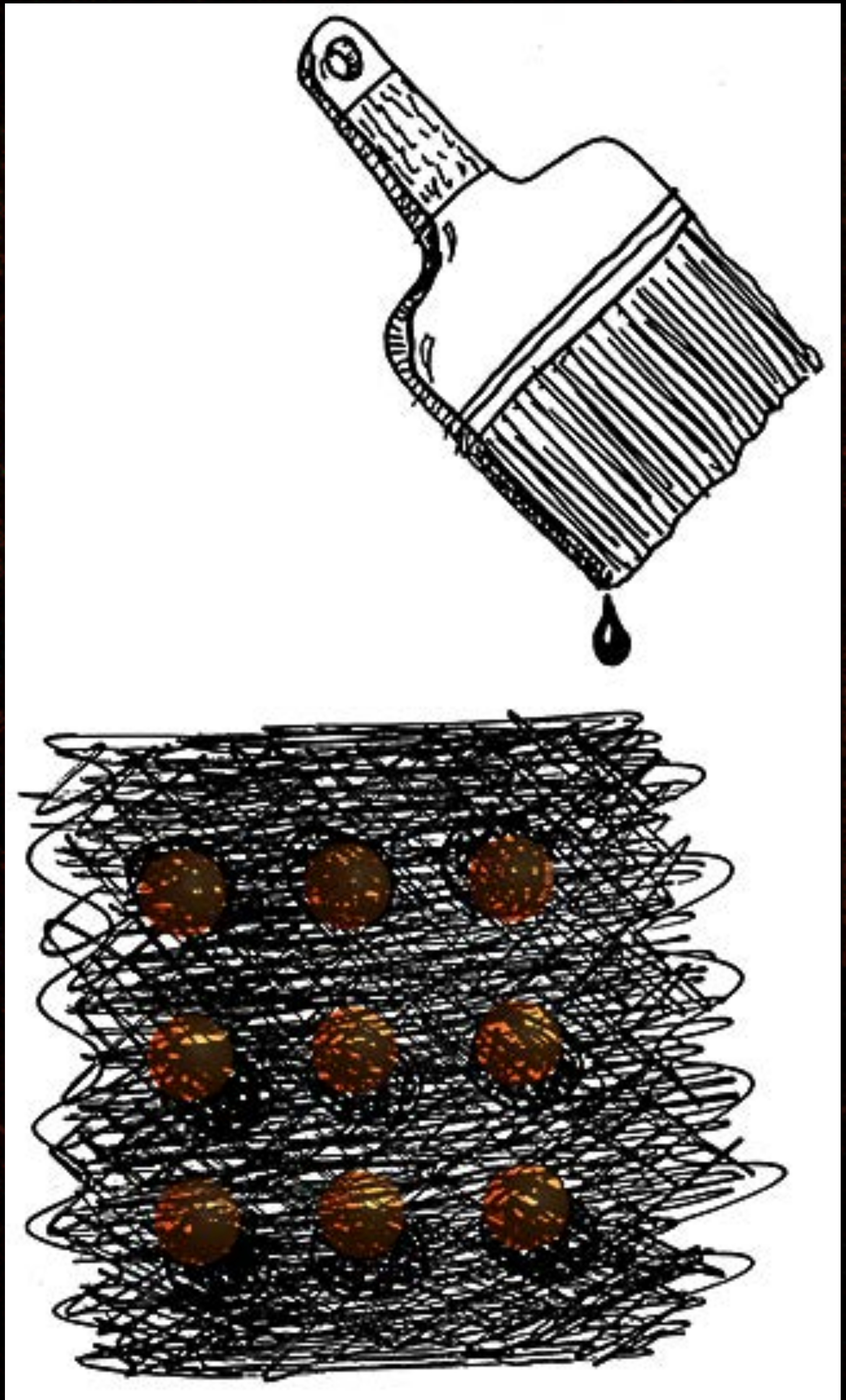
geographer's
solution



mechanical
engineer's
solution



statistician's
solution



“wide line”
solution

Lovins House, Old Snowmass, Colorado (1983)






US office buildings: 2–5× 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

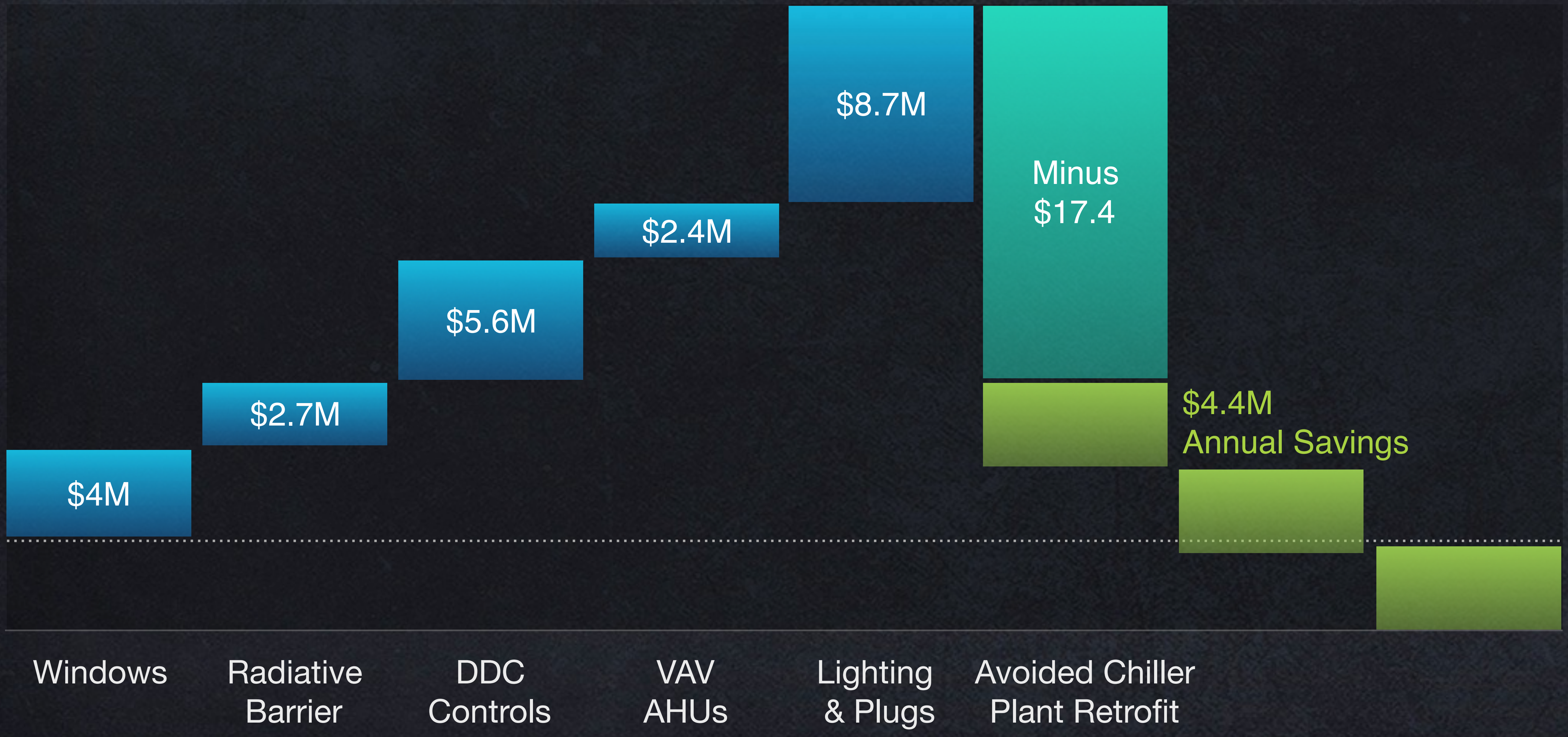
…51 (–83%)
2015 new

…21 (–93%)
…and in Germany,
2013 new
(office, gallery, apt.)

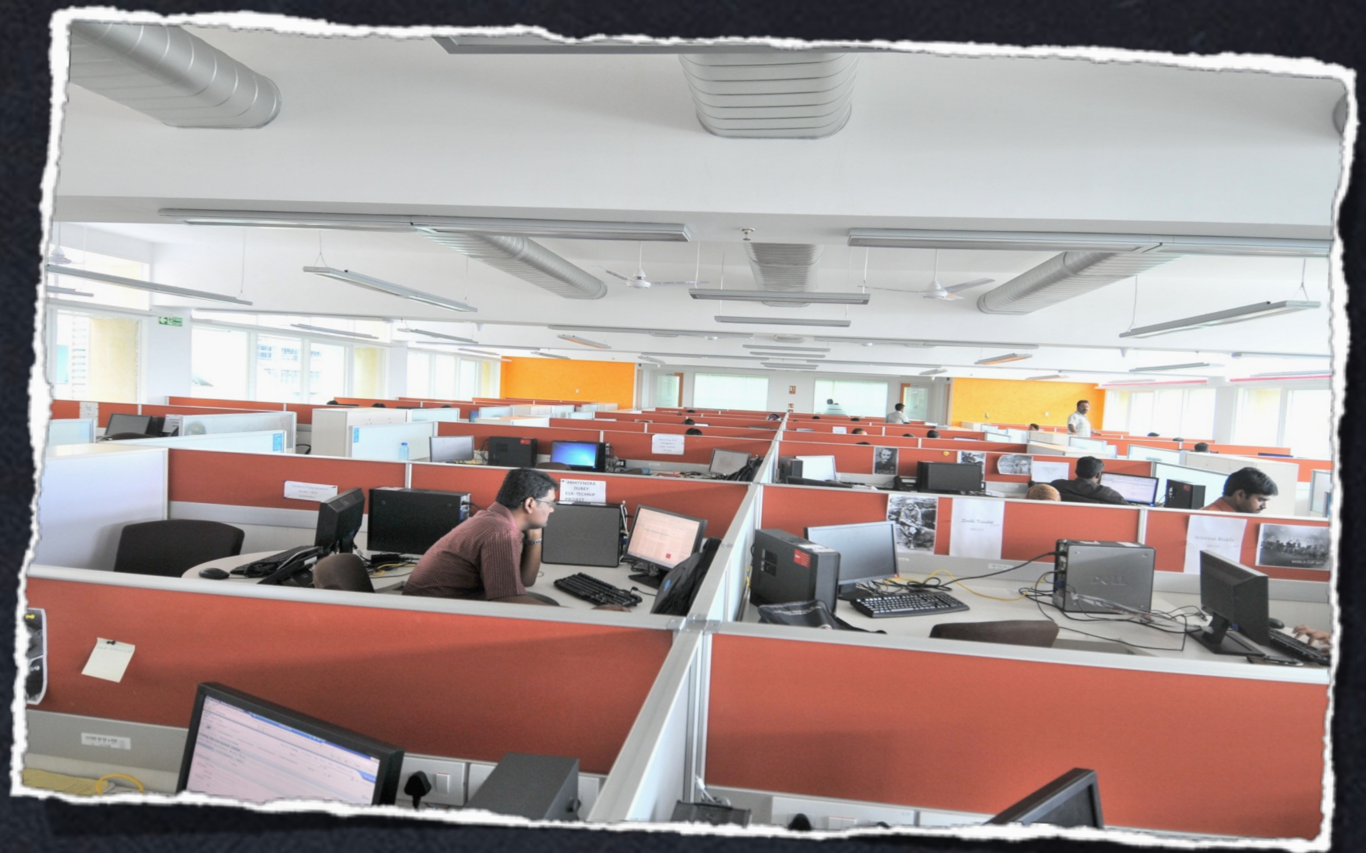
Yet all the technologies in the 2015 example existed well before 2005!

Integrative Design in Retrofitting the Empire State Building

Empire State Building retrofit sequence



5x-more-efficient new Indian commercial buildings



Infosys's 1.5 million m^2 of 22k-m^2 office blocks (2009–14) in six cities:

Energy Performance Index fell 80%, to 66 kWh/m^2-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)

Eat the lobster!

Homarus americanus

李永禄
LEE Eng Lock
Lǐ Yǒnglù

Why systems?

The Right Steps in the Right Order

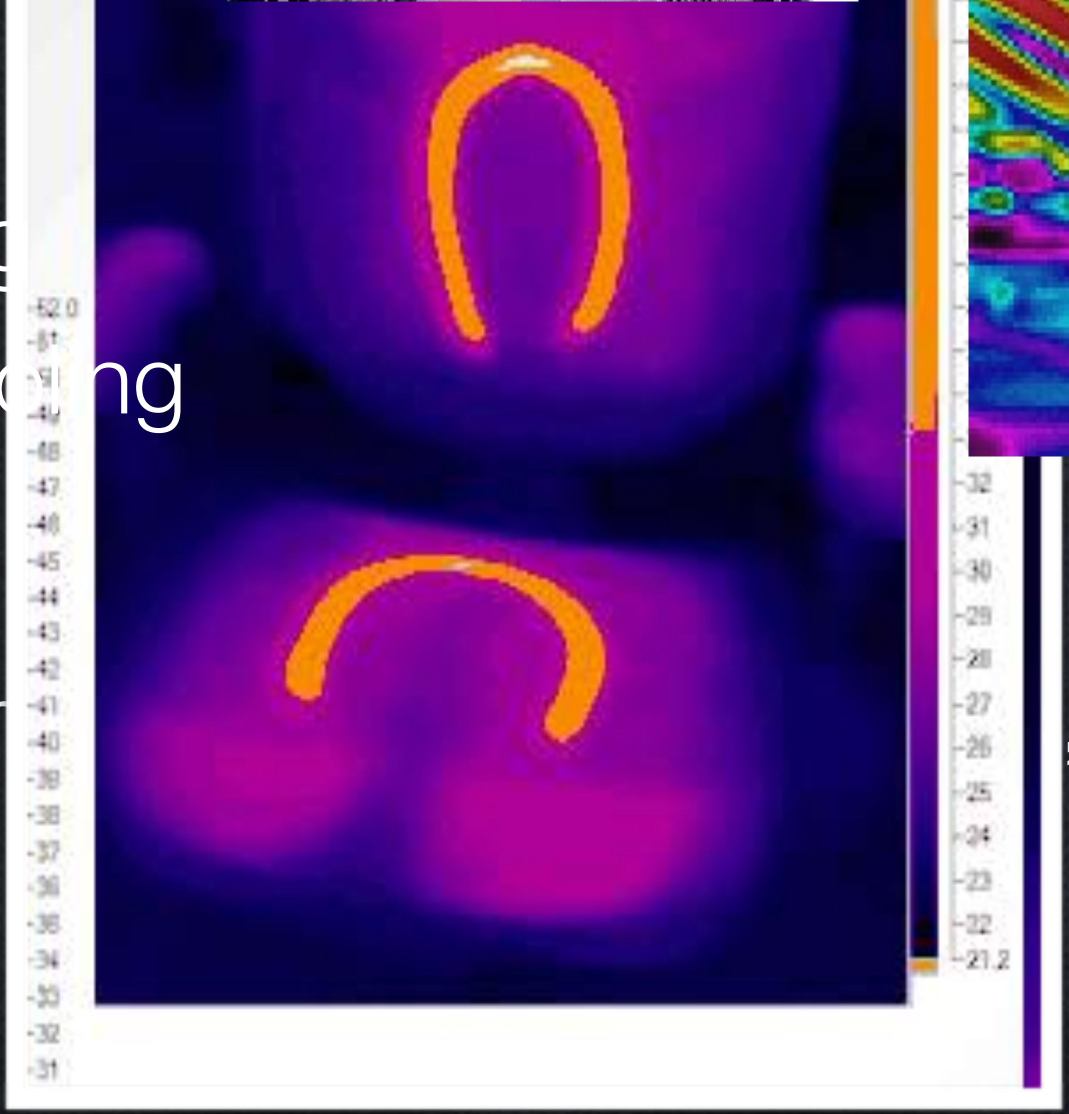
The right steps in the right order: lighting

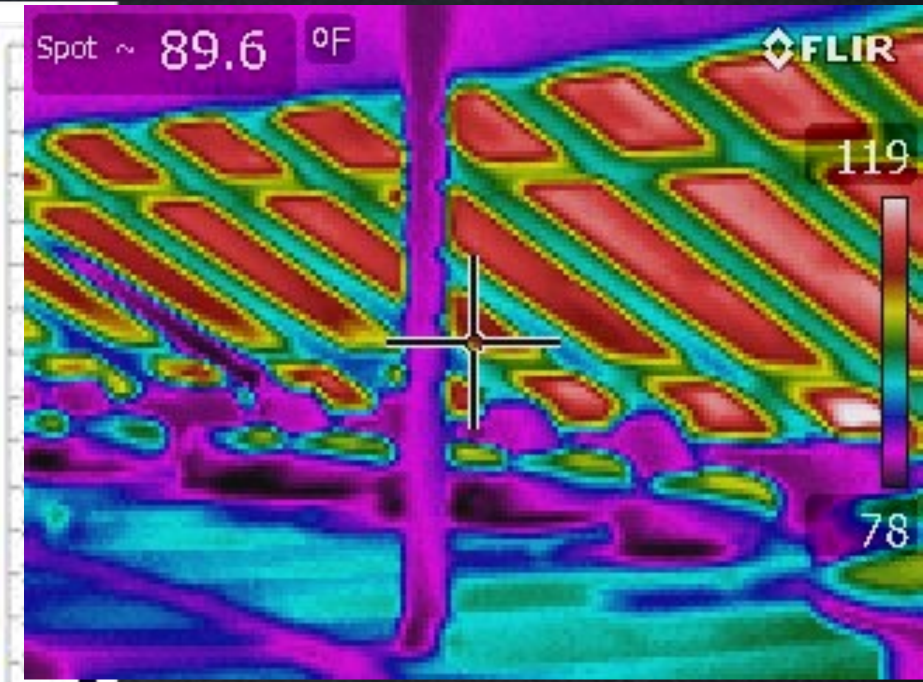
1. Improve visual quality of task
2. Improve geometry of space, cavity reflectance
3. Improve lighting quality (cut veiling reflections and discomfort glare)
4. Optimize lighting quantity
5. Harvest/distribute natural light
6. Optimize luminaires
7. Controls, maintenance, training

The right steps in the right order: space cooling

0. Cool the people, not the building

1. Expand comfort envelope
2. Minimize unwanted heat gains
3. Passive cooling
4. Active nonrefrigerative cooling
5. Superefficient refrigerative cooling
6. Cooling storage and controls





Res y, m , higher uptime

Sequence 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 get rewarded for excelling in these achievements, via Integrated Project Delivery and Performance-Based Design Fees!

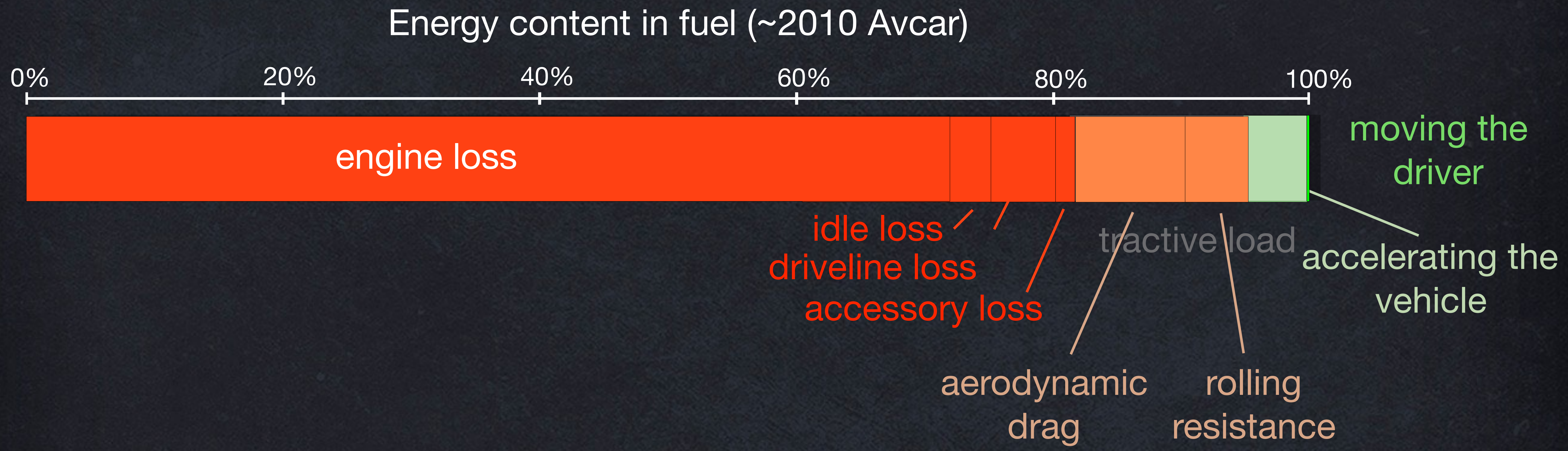
Oak Brook Tower retrofit design (1992)

19,000 m^2, 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 similar 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 m^2 of glass
  - Add deep daylighting, plus very efficient lights (3 W/m^2) and office equipment (2 W/m^2)
- 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

Oak Brook Regency Tower West, 1415 W. 22nd St., Oak Brook, Illinois, http://www.rejournals.com/wp-content/uploads/2013/07/OBRTExterior1.jpg

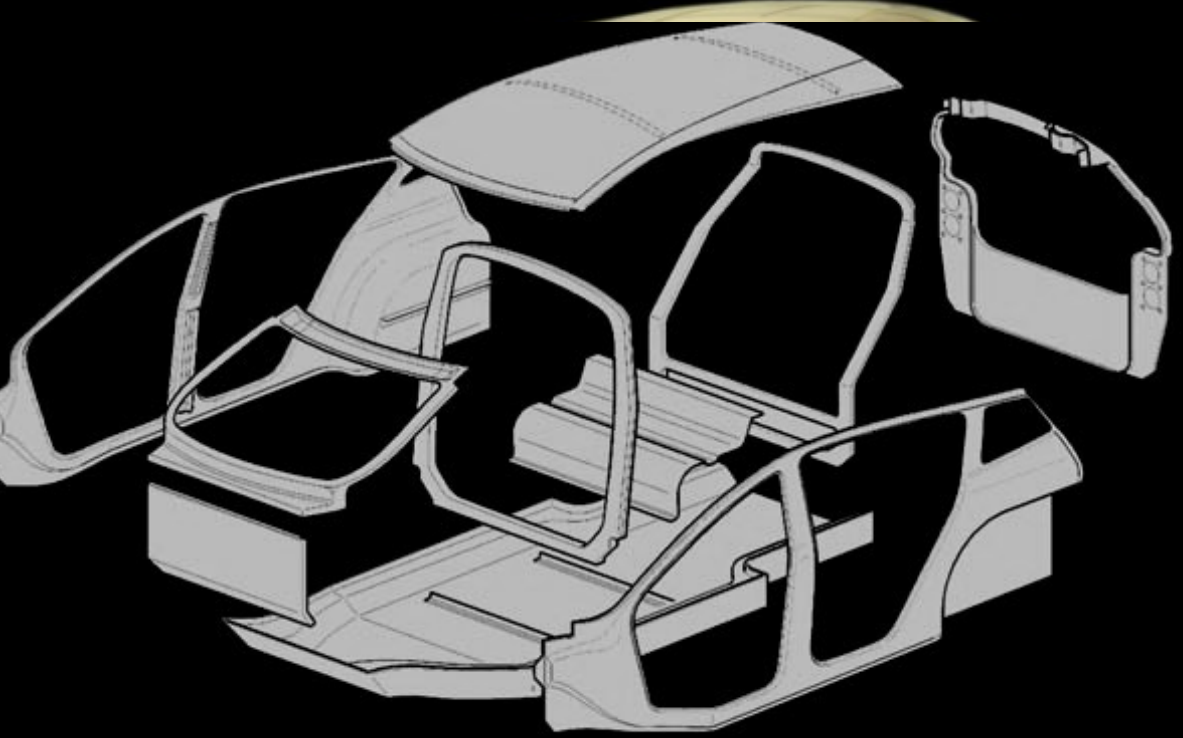
Start with tractive load, not powertrain



- 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

Reinventing the wheels

Hypercar *Revolution* midsize concept SUV (2000)
3.6 L/100 km on-road (gasoline) or 2.1_{equiv} (H_2)
carbon-fiber structure, ≤2-y retail payback



Toyota *1/X* carbon-fiber concept PHEV sedan (2007)
***Prius* size, 1/2 fuel use (1.8 L/100 km), 1/3 weight**

Bright *IDEA* 1-T 5-m^3 aluminum fleet van (2009)
~2.4 L_{equiv}/100 km PHEV, 3–12×-eff., needs no subsidy

BMW *i3* 4-seat electric, carbon-fiber passenger cell
2013– mass-production, >150k sold for ~$41–45k
1.7 L/100 km, MY2019 247-km range (≥370 w/REx)

A competitive carbon-fiber electric car, 2013–

sglcarbon.com

2013 BMW *i3*, http://www.superstreetonline.com/features/news/epcp-1303-bmw-i3-concept-coupe/

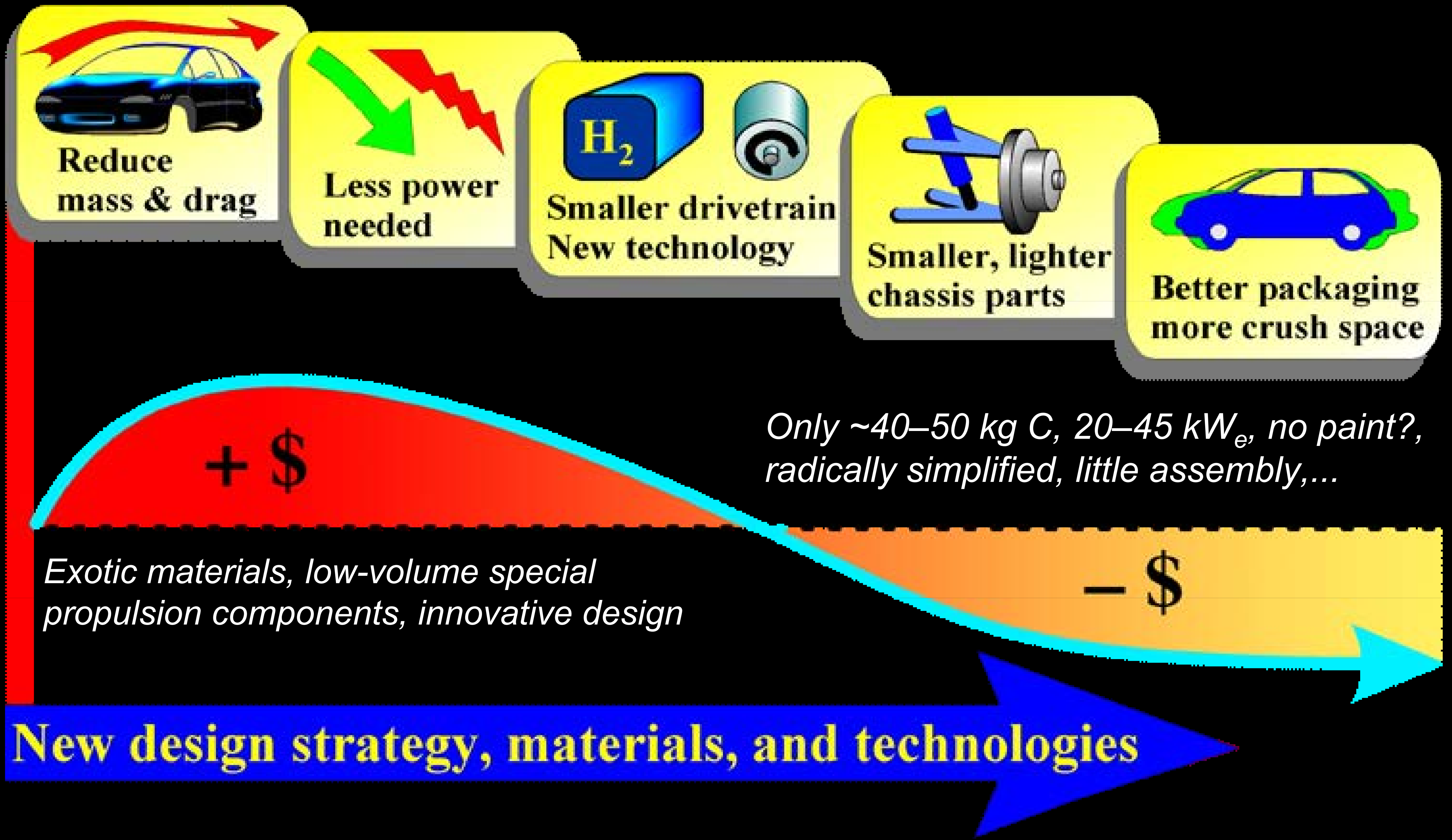
BMW MY2013's ~120–150-kg carbon-fiber-composite passenger cell; m_c 1,250 kg

https://www.autocar.co.uk/car-news/industry/bmw-set-make-more-extensive-use-carbon-fibre

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

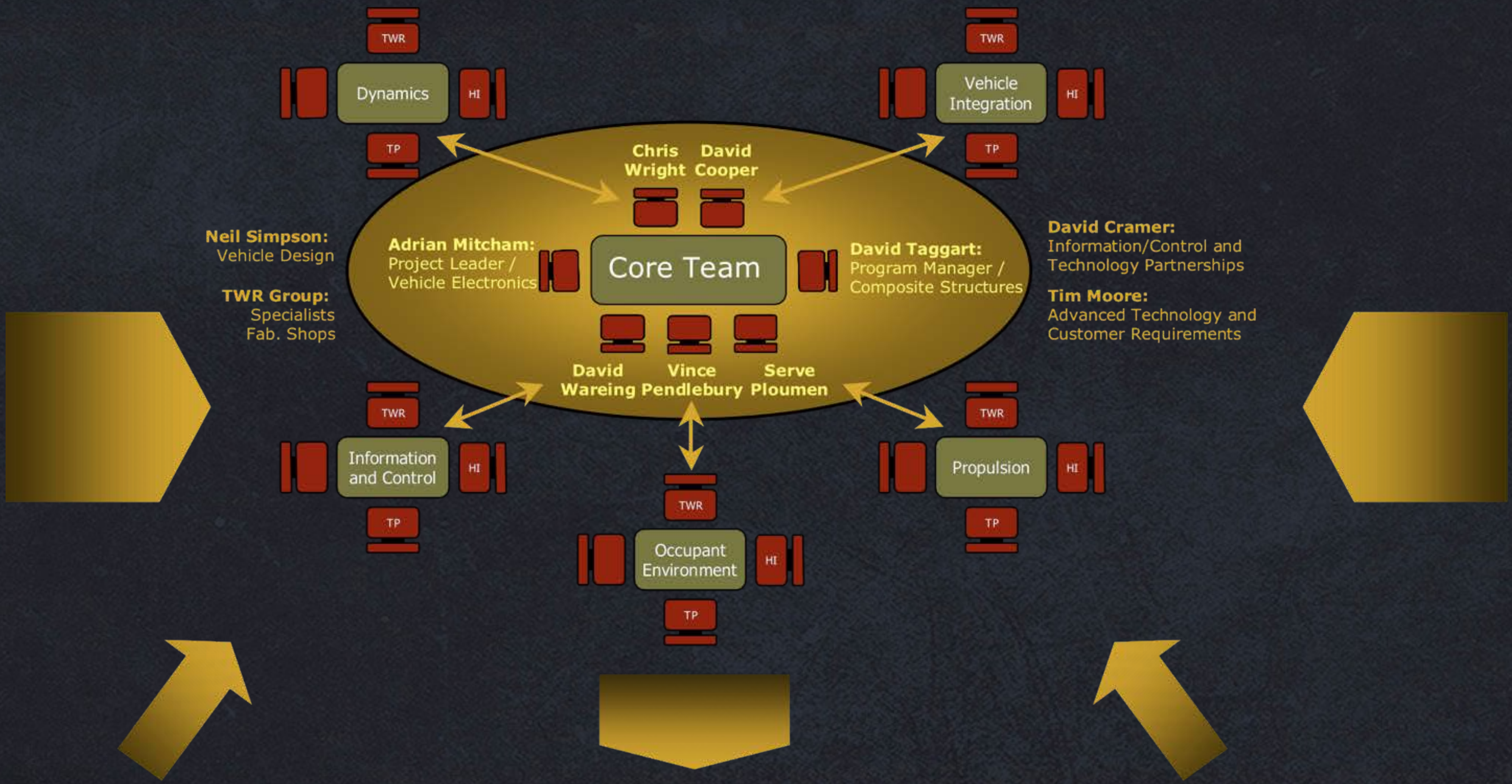
- pays for the carbon fiber by needing fewer batteries (which recharge faster)
- saves ~2.5–3.5 kg total for each kg of direct mass saved (Detroit says <1.3–1.5)
- needs two-thirds less capital, ~70% less water, ~50% less energy, space, time
- requires no conventional body shop or paint shop
- provides clean, quiet, superior working conditions
- delivers 1.9 L_{equiv}/100 km (124 mpge) on US 5-cycle test, 1.7 Ger., ~1.6 old US cycle
- provides exceptional visibility, agility, traction, and crash safety

Decompounding mass and complexity also decompounds cost



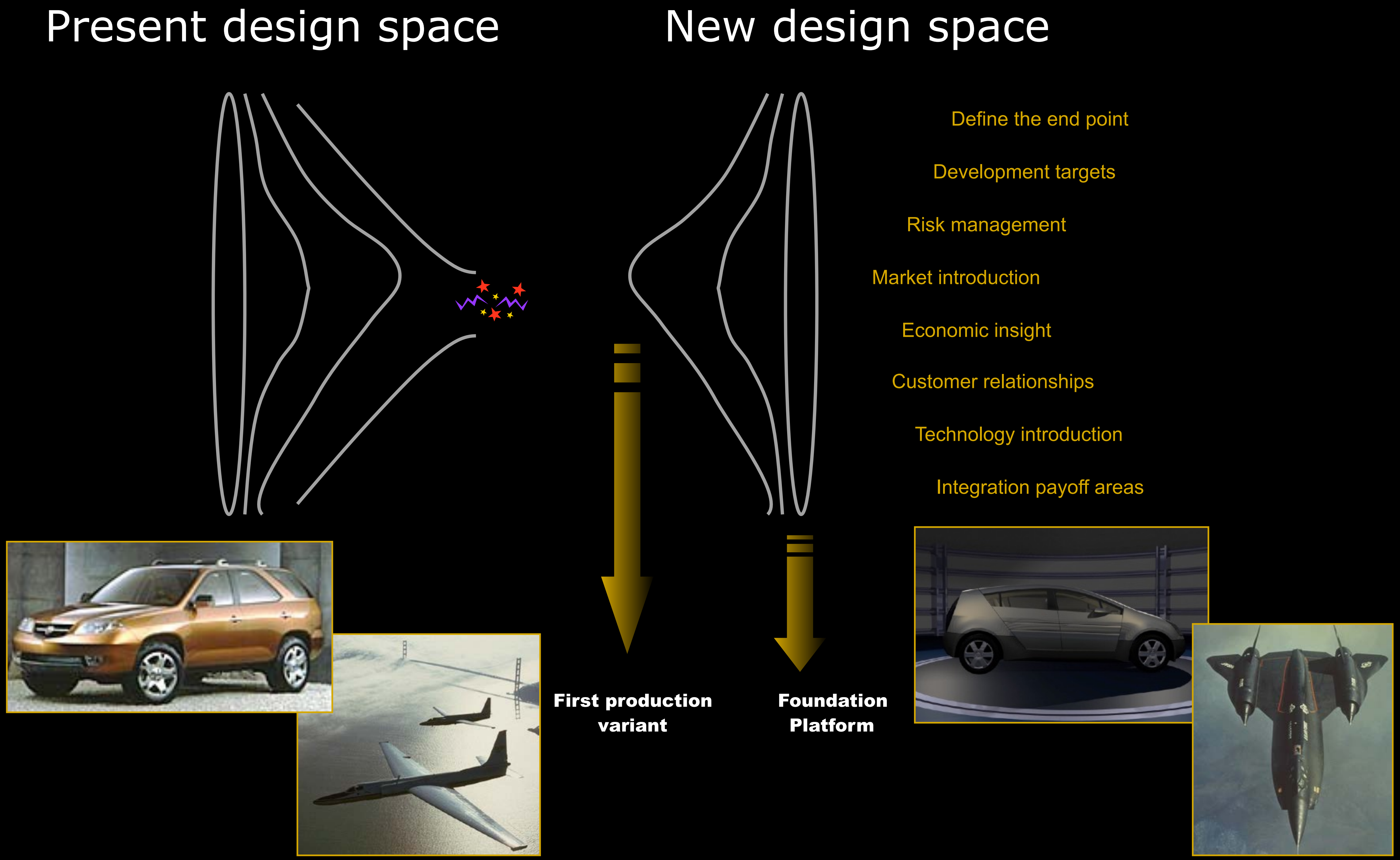
Hypercar®

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

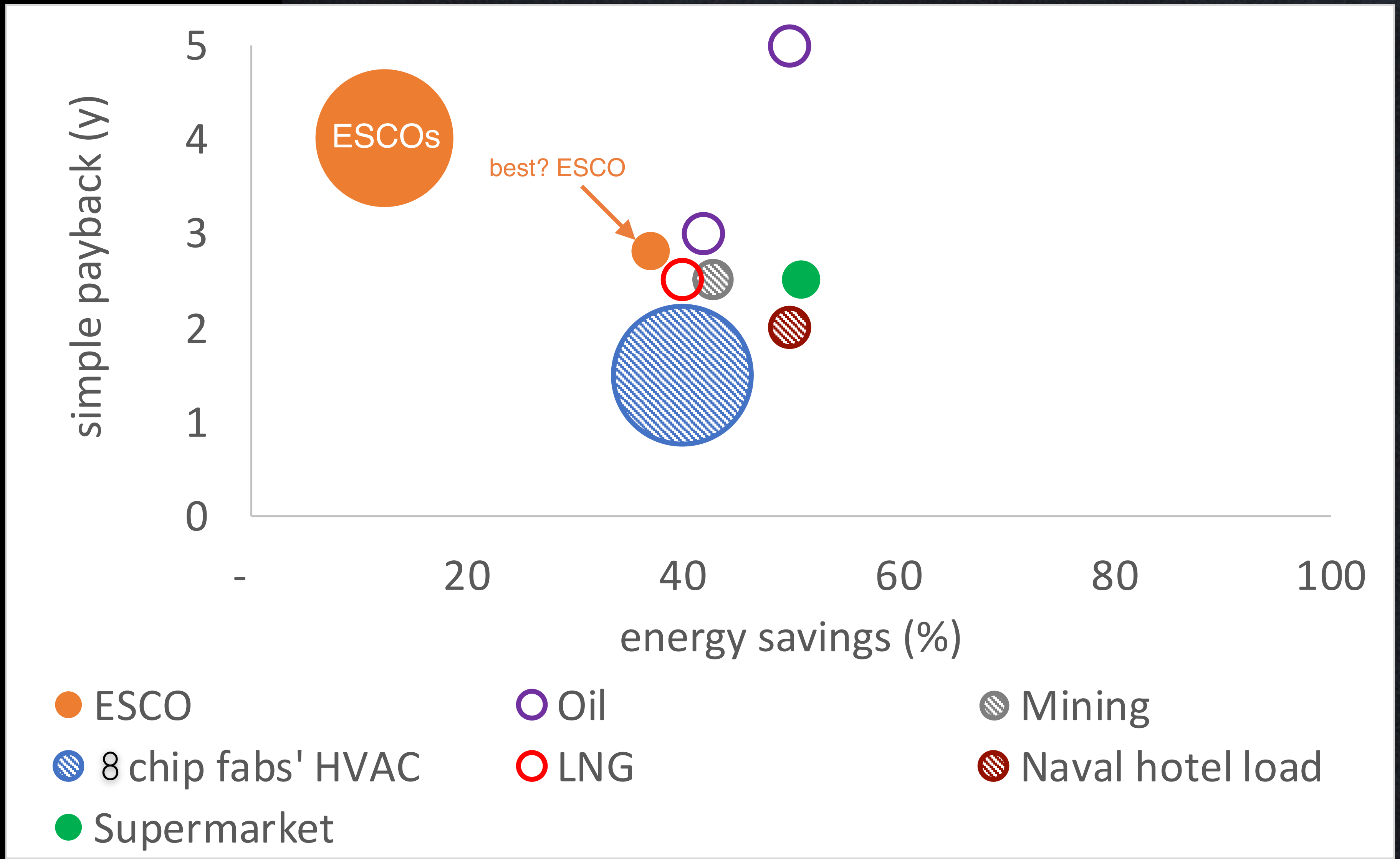
Design to win the future, not perpetuate the past

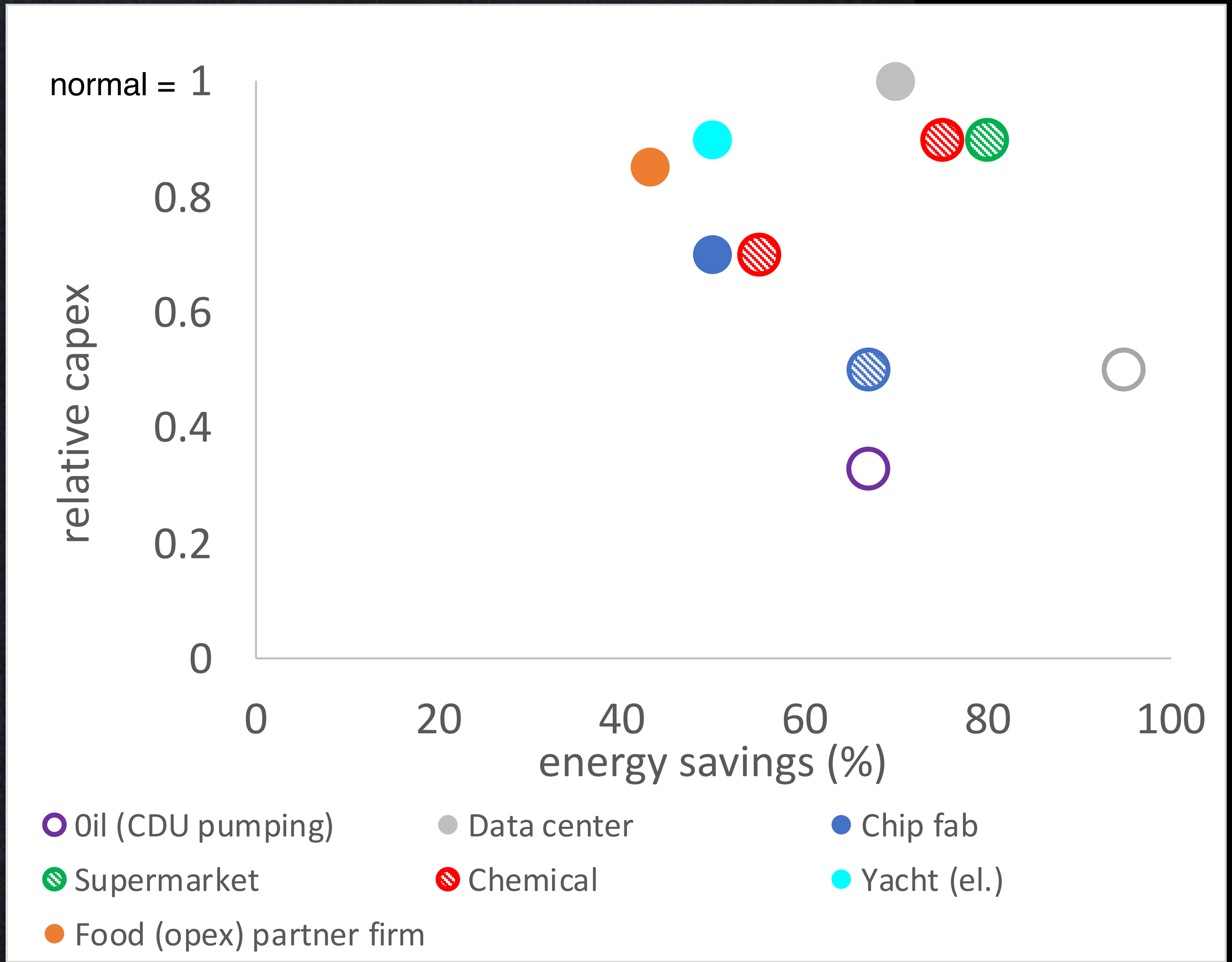


Design “in the future”

RMI’s latest >$40b worth of integrative design in diverse industrial projects—retrofits and newbuilds

(solid = built, shaded = incomplete data, circle = not yet built)





Retrofits

Newbuilds

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

thin, long, crooked

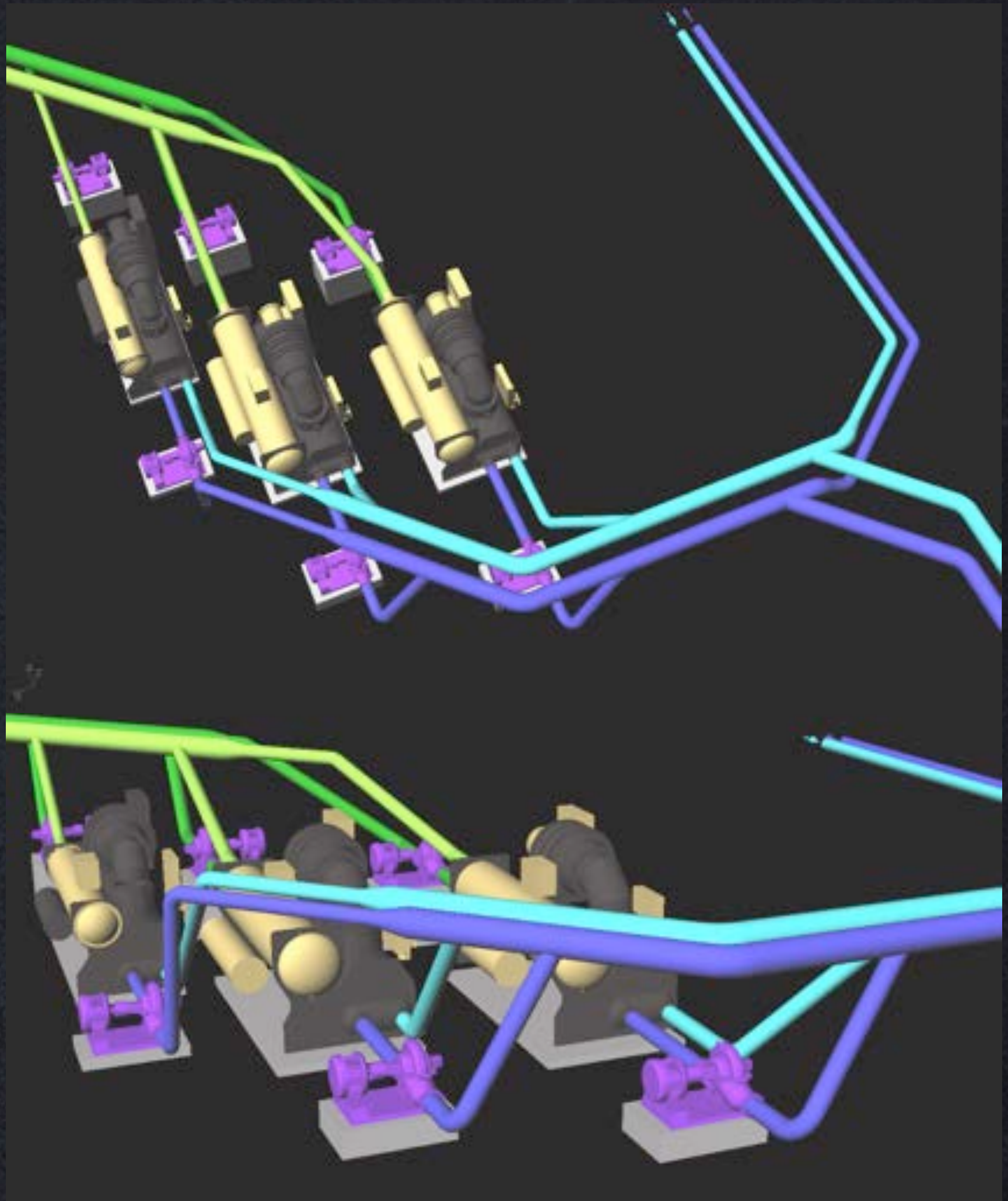
fat, short, straight

Typical paybacks ≤1 y retrofit, ≤0 new-build

But not yet in any official study, industry forecast, or climate model

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

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)

No new technologies, just two design changes

Fat, short, straight pipes — not thin, long, crooked pipes!

Benefits counted

- 7–12× less pumping

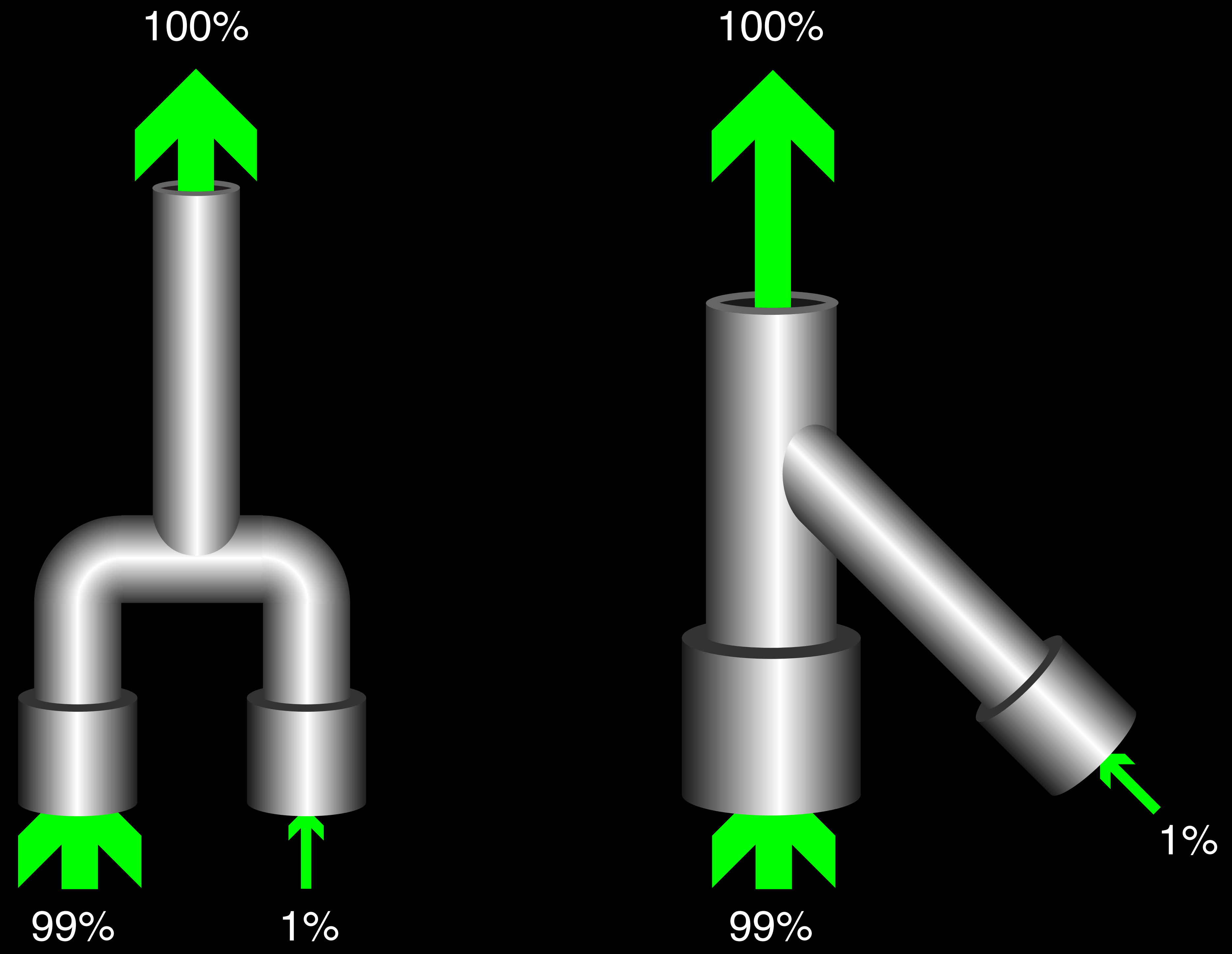
“Bonus” benefit also captured

- 70 kW lower heat loss from pipes

Additional benefits not counted

- Less space, weight, and noise
- Clean layout for easy maintenance access
- Needs little maintenance, yet better uptime and longer life
- More flexibility for later debottlenecking

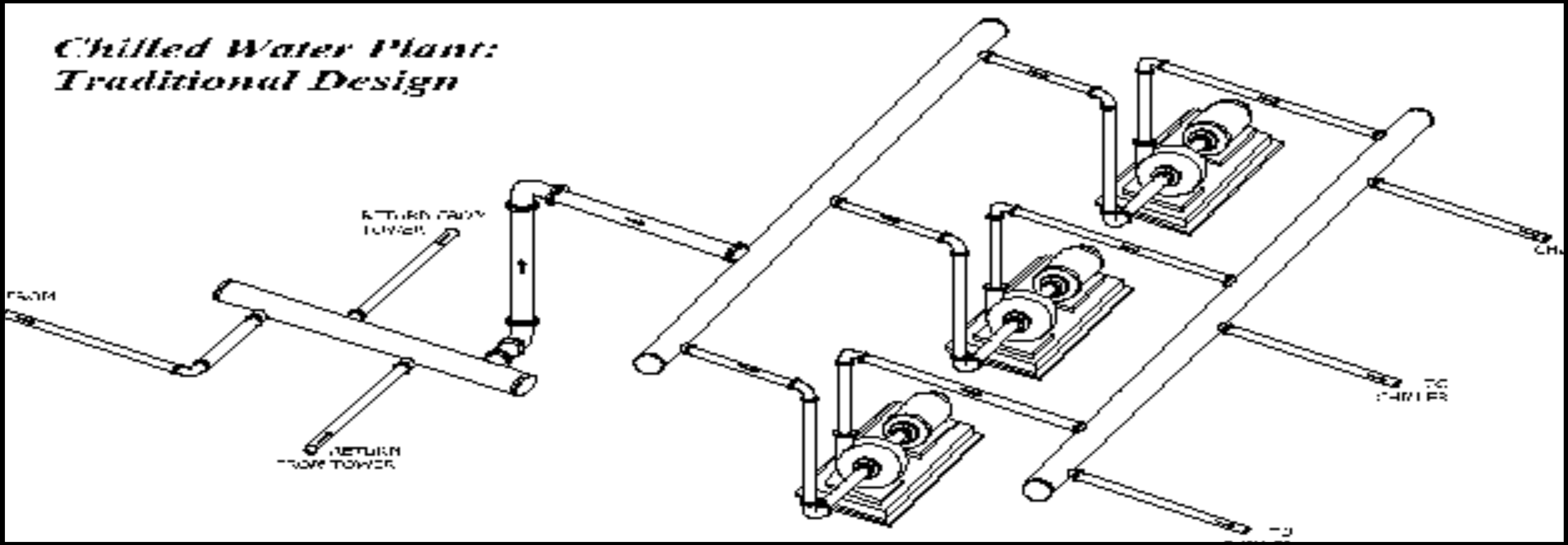
Count these too and save…~98%?

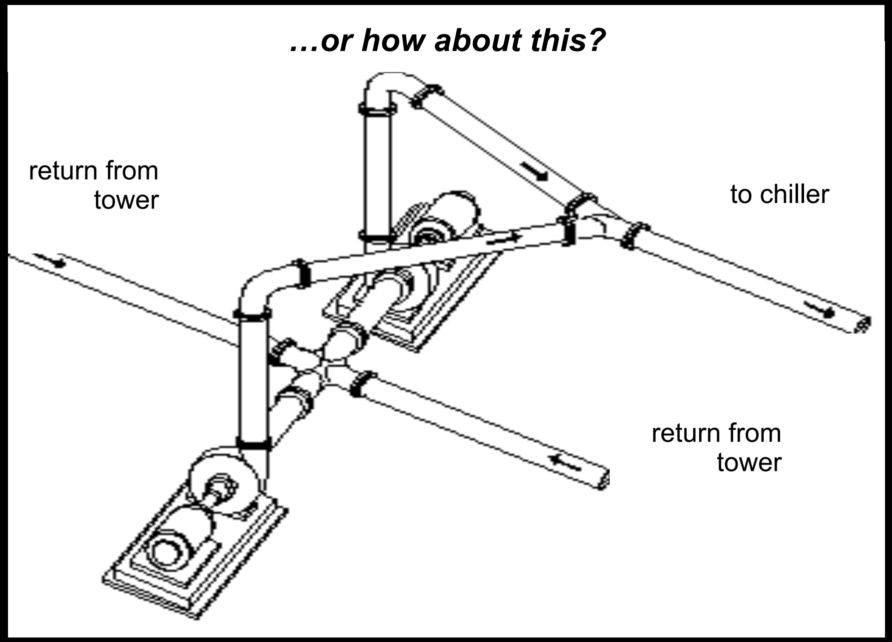

100%
99%
1%
100%
99%
1%

Retrofitted Low-Friction Piping Layout

Images courtesy of
Peter Rumsey, PE,
FASHRAE,
Senior Fellow, RMI

Which of these layouts uses less capital and energy?



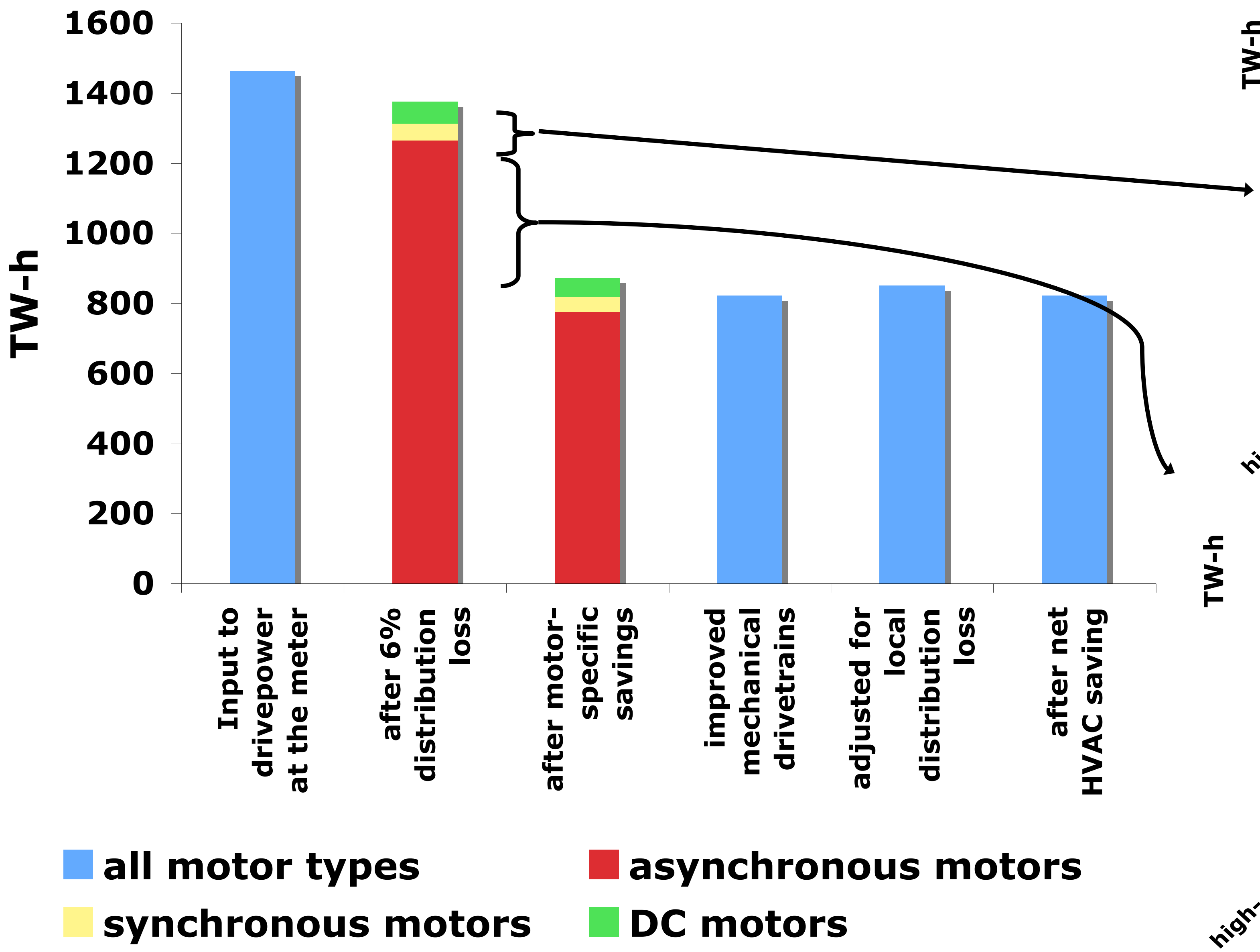


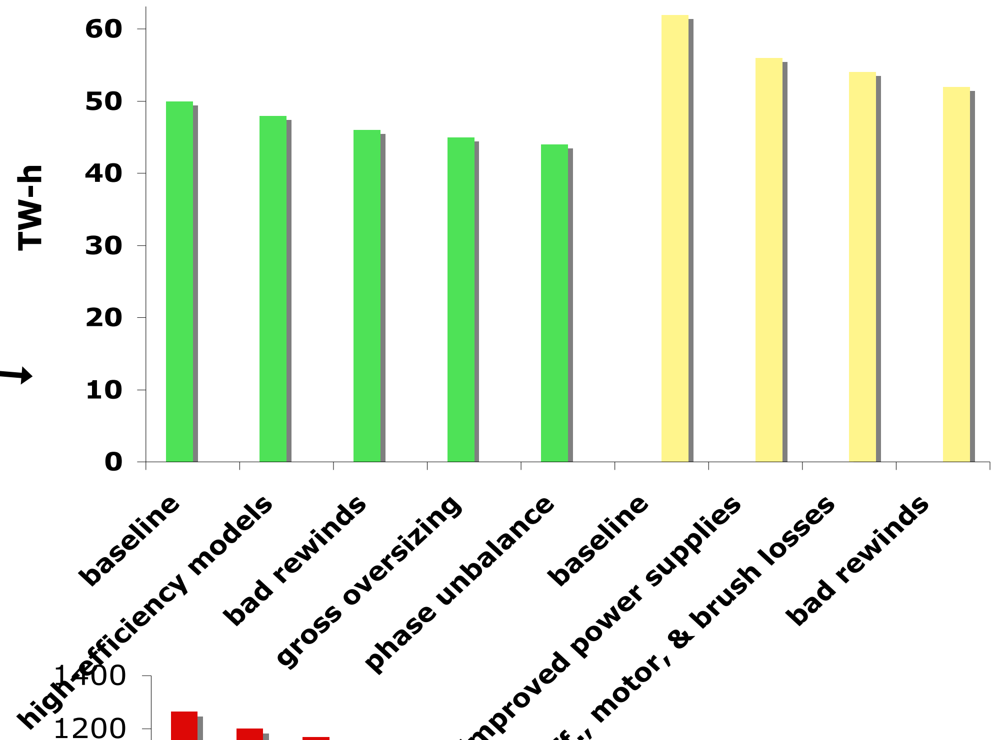
- Less space, weight, friction, energy
- Fewer parts, smaller pumps and motors, less installation labor
- Less O&M, higher uptime

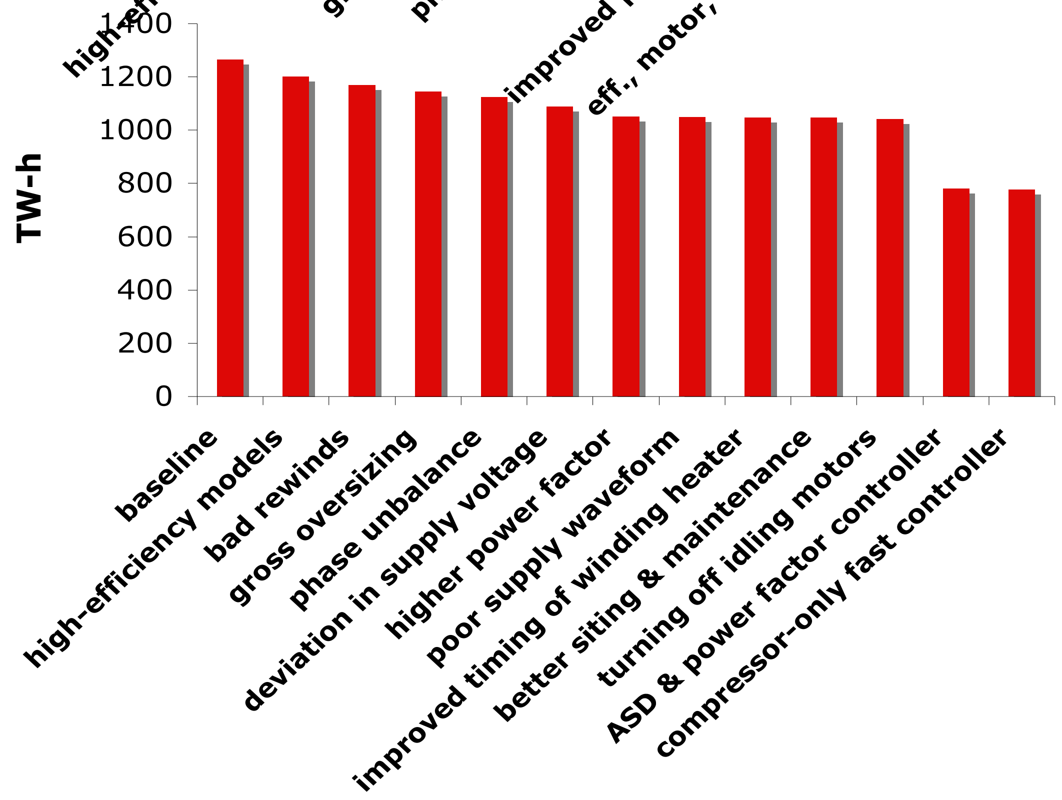
100
Energy units
-70%
Power Plant
-9%
Power Grid
-12%
Motor/Drivetrain
-55%
Pump/Throttle
-20%
Pipe
10%
Delivered flow


100
Energy units
-70%
Power Plant
-9%
Power Grid
-12%
Motor/Drivetrain
-55%
Pump/Throttle
-20%
Pipe
5%
Delivered flow

U.S. drivesystems' 1986 retrofit potential, assuming the same flow delivered with the same friction—no downstream savings

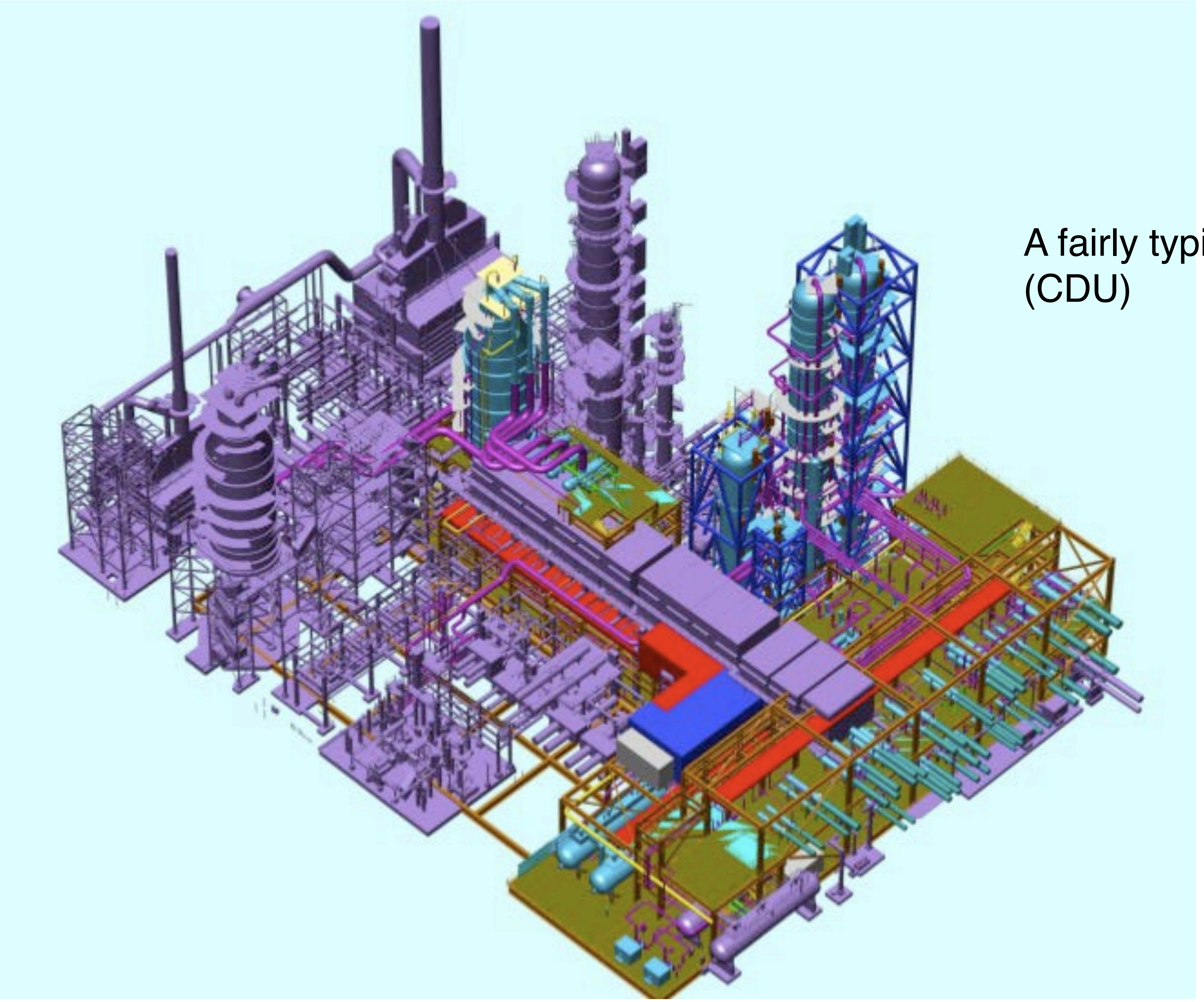






Source: *The State of the Art: Drivepower*, RMI/COMPETITEK, 1989

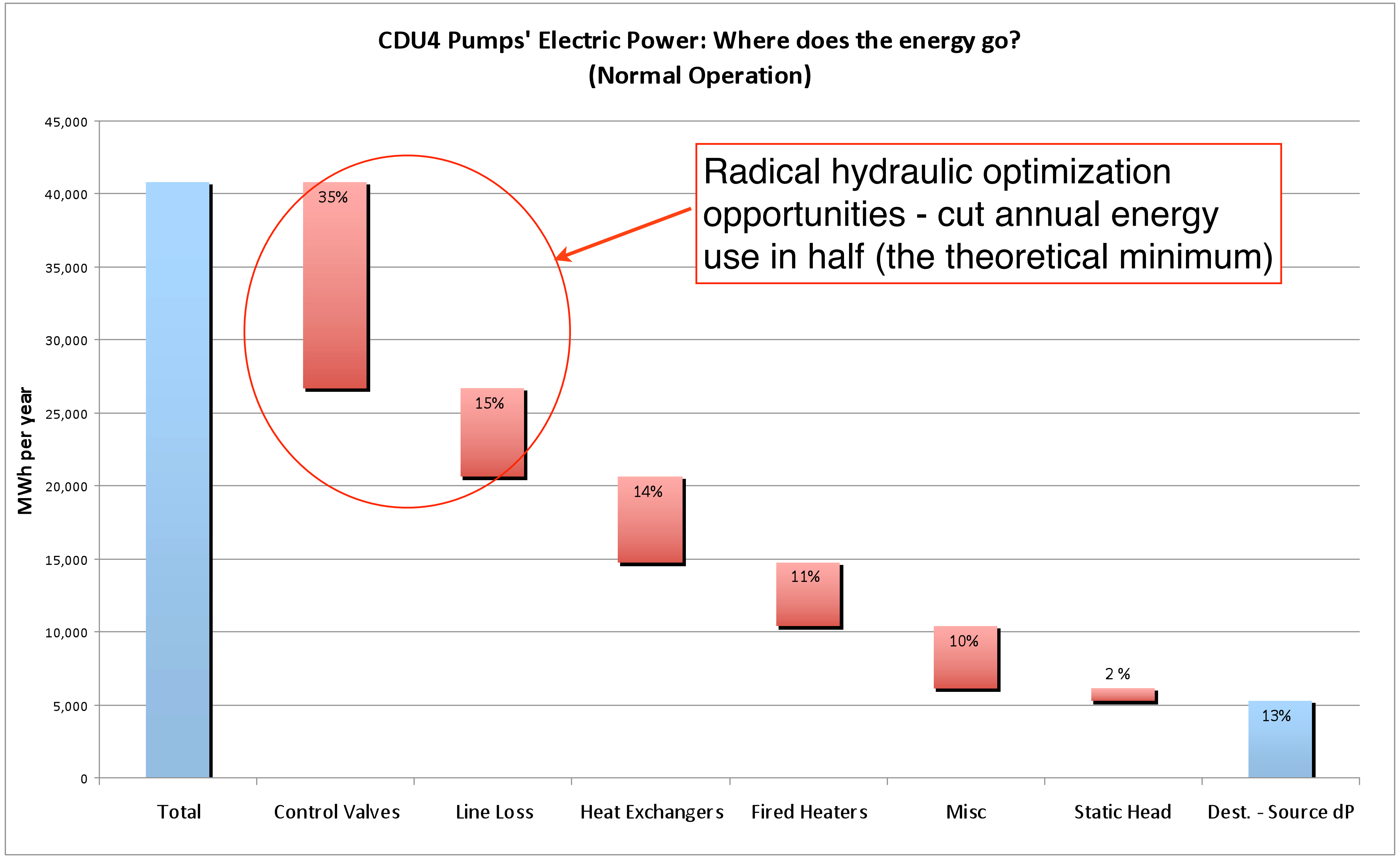
Designing a refinery using an efficiency lens



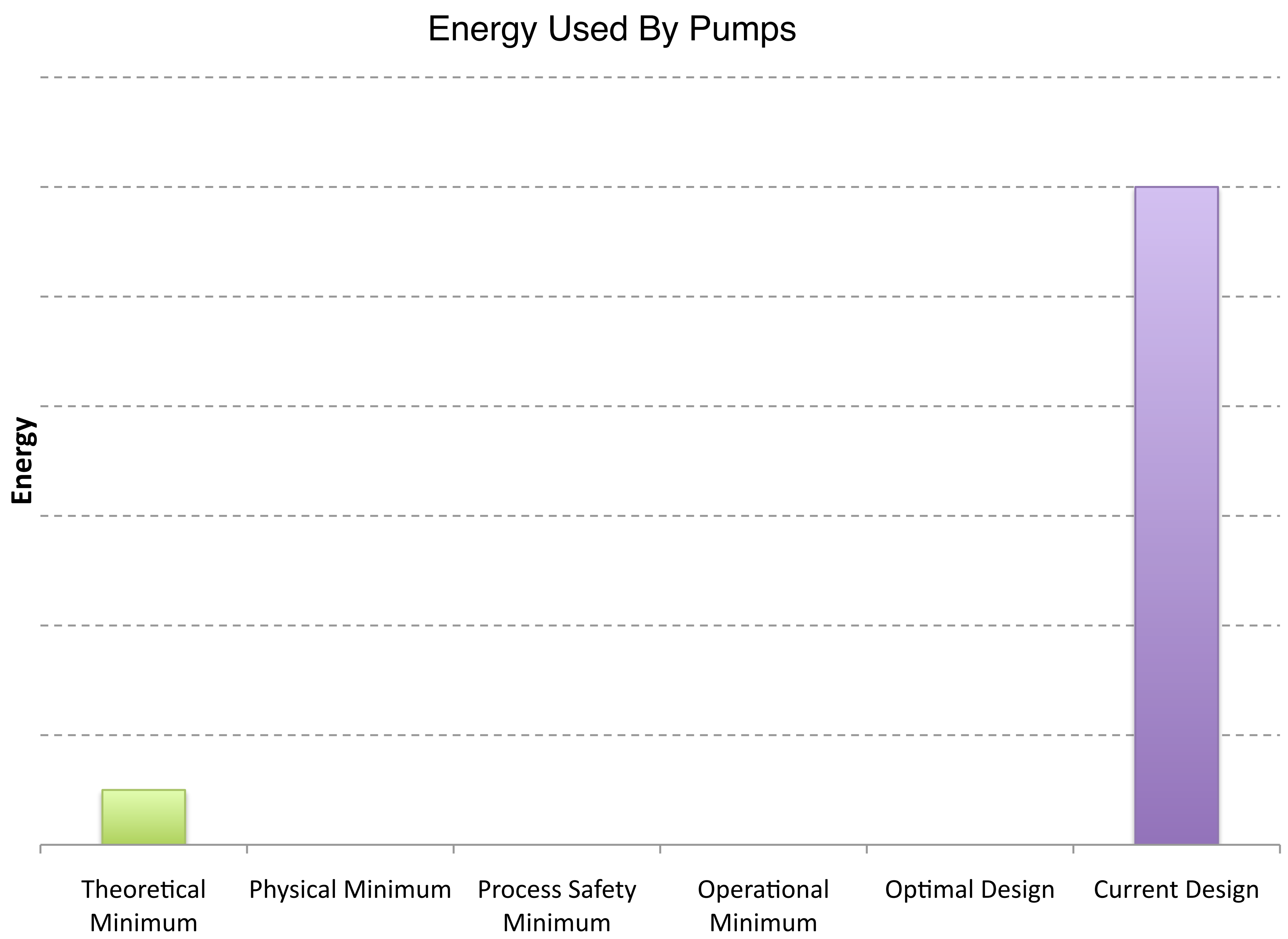
A fairly typical crude distillation unit (CDU)

Stretching the Mind | Generalized Energy System | Hedonic Efficiency | End-Use Efficiency | Resource Chain | Whole System | Up-cycle Waste | Optimize Supply

Start with what's theoretically possible

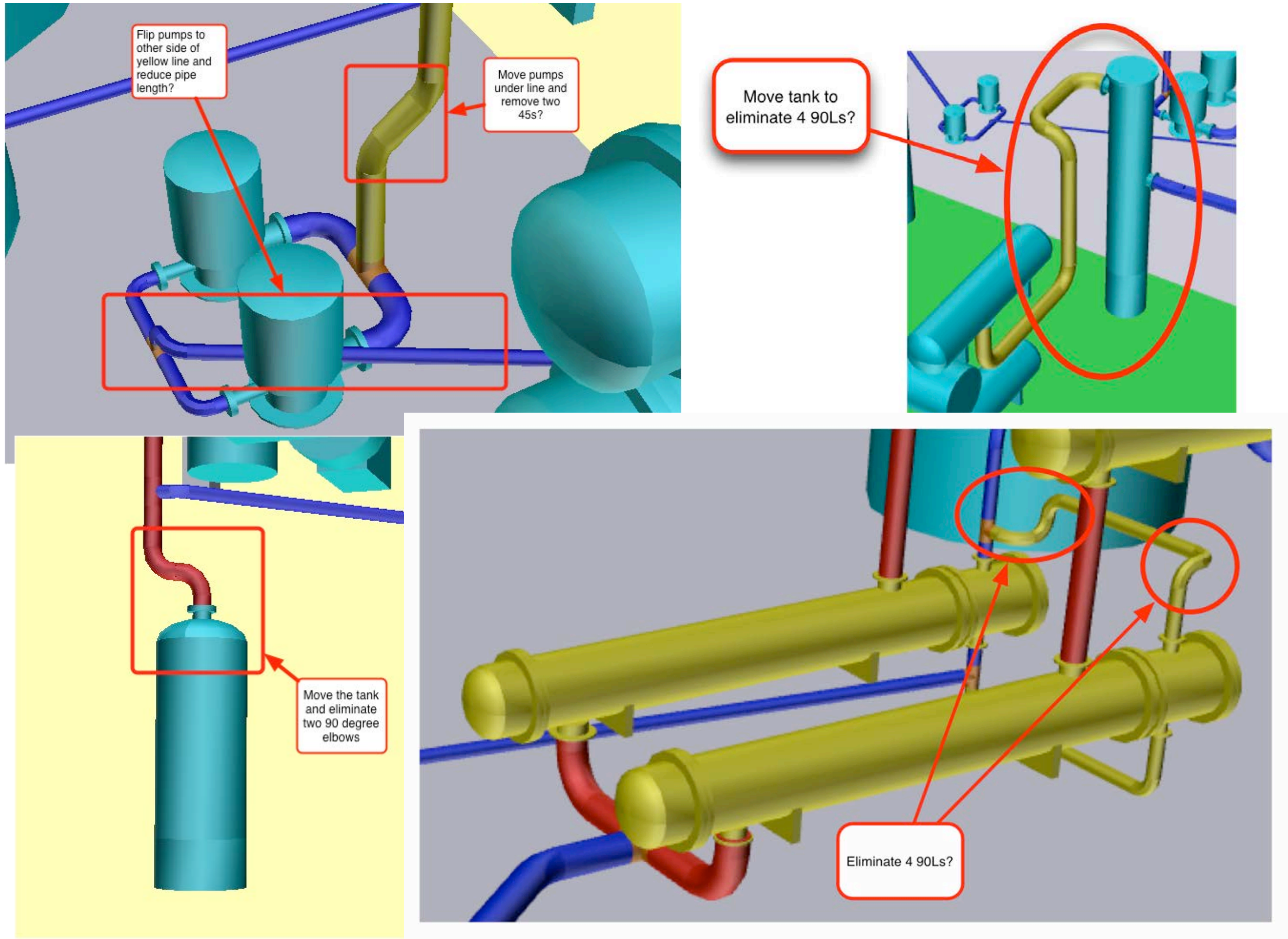


Start with where you want to be—what's theoretically possible?

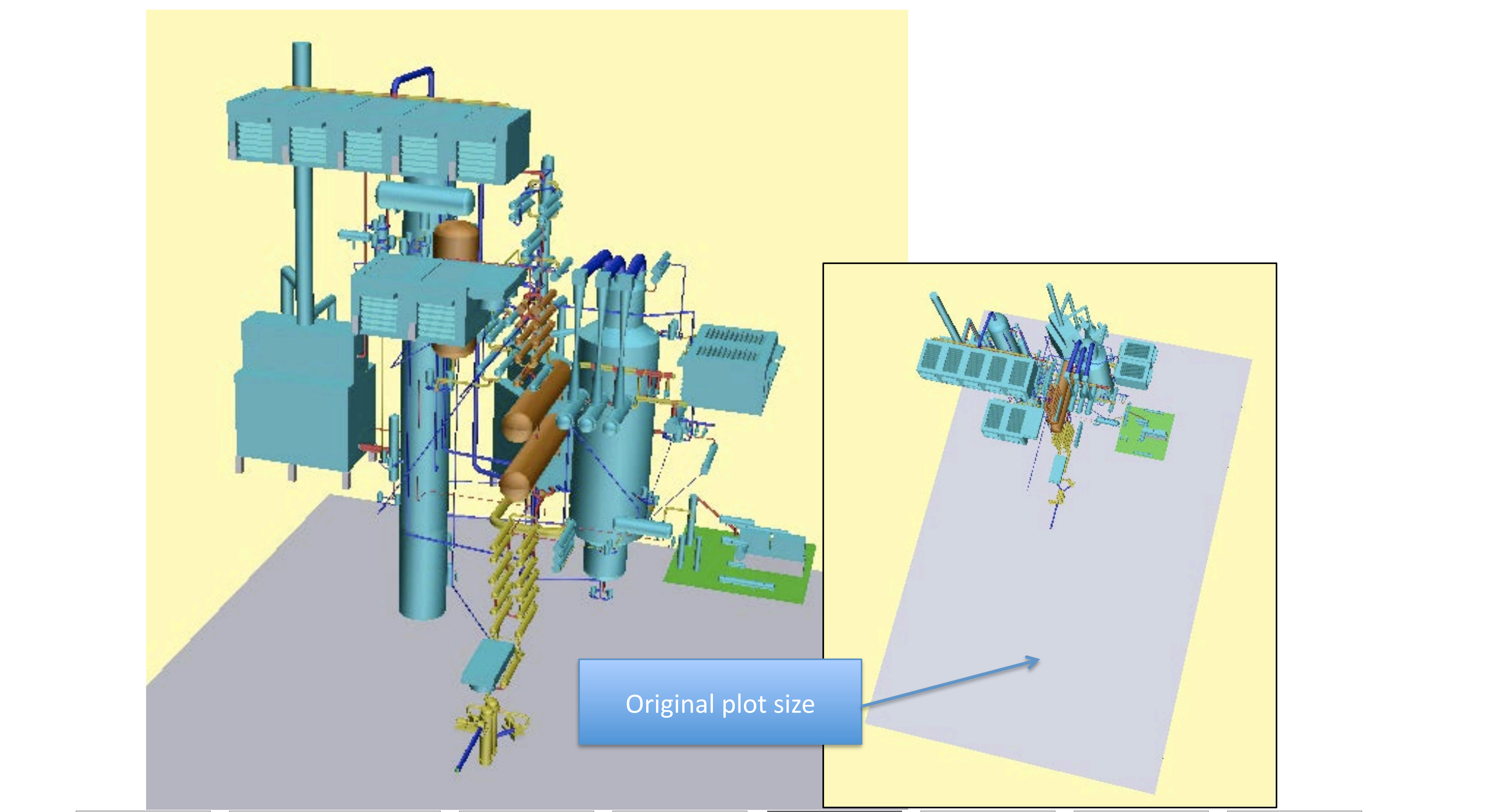


Stretching the Mind | Generalized Energy System | Hedonic Efficiency | End-Use Efficiency | Resource Chain | Whole System | Up-cycle Waste | Optimize Supply

Then question everything you give up during the design...



A draft physical minimum



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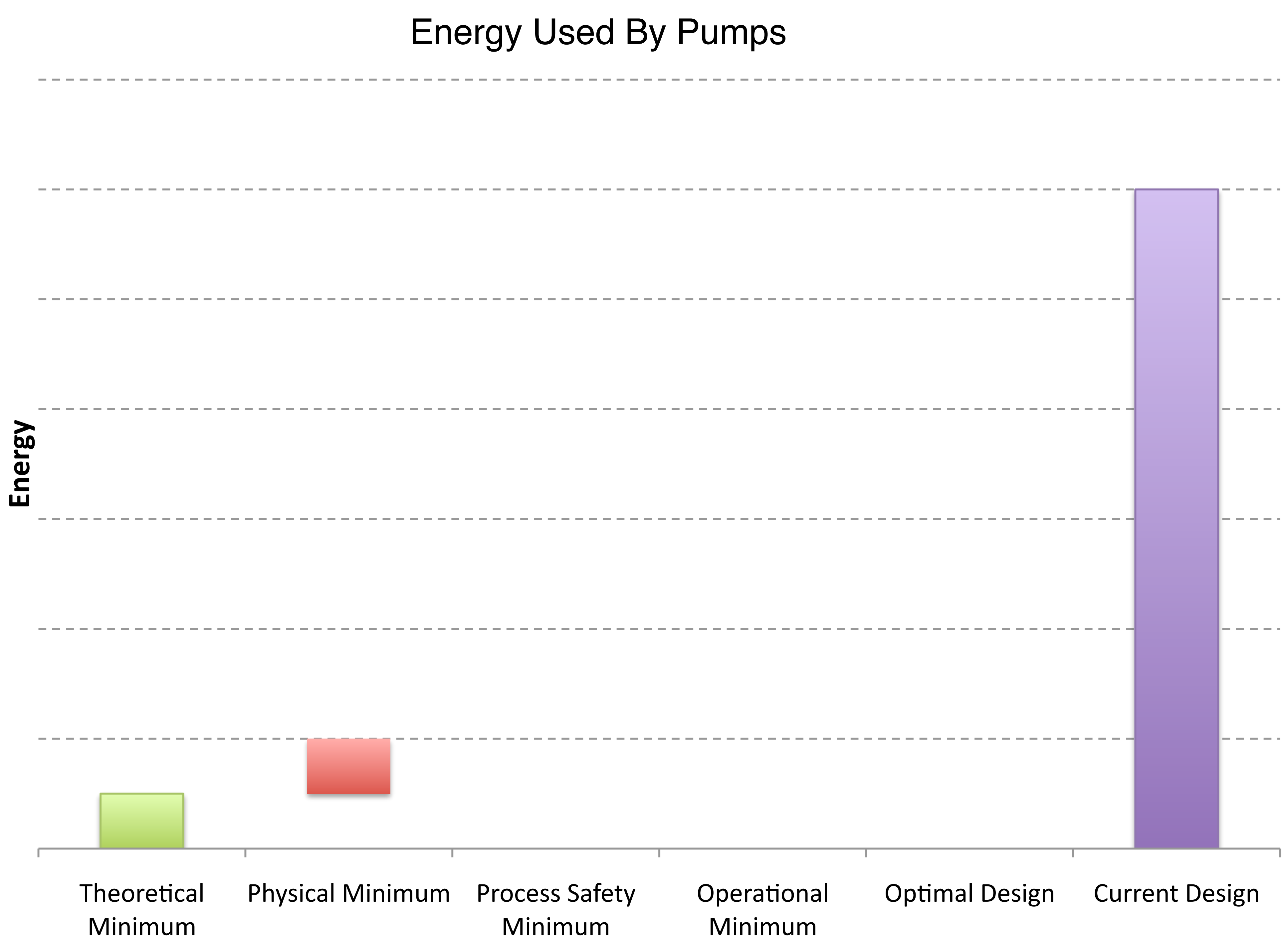
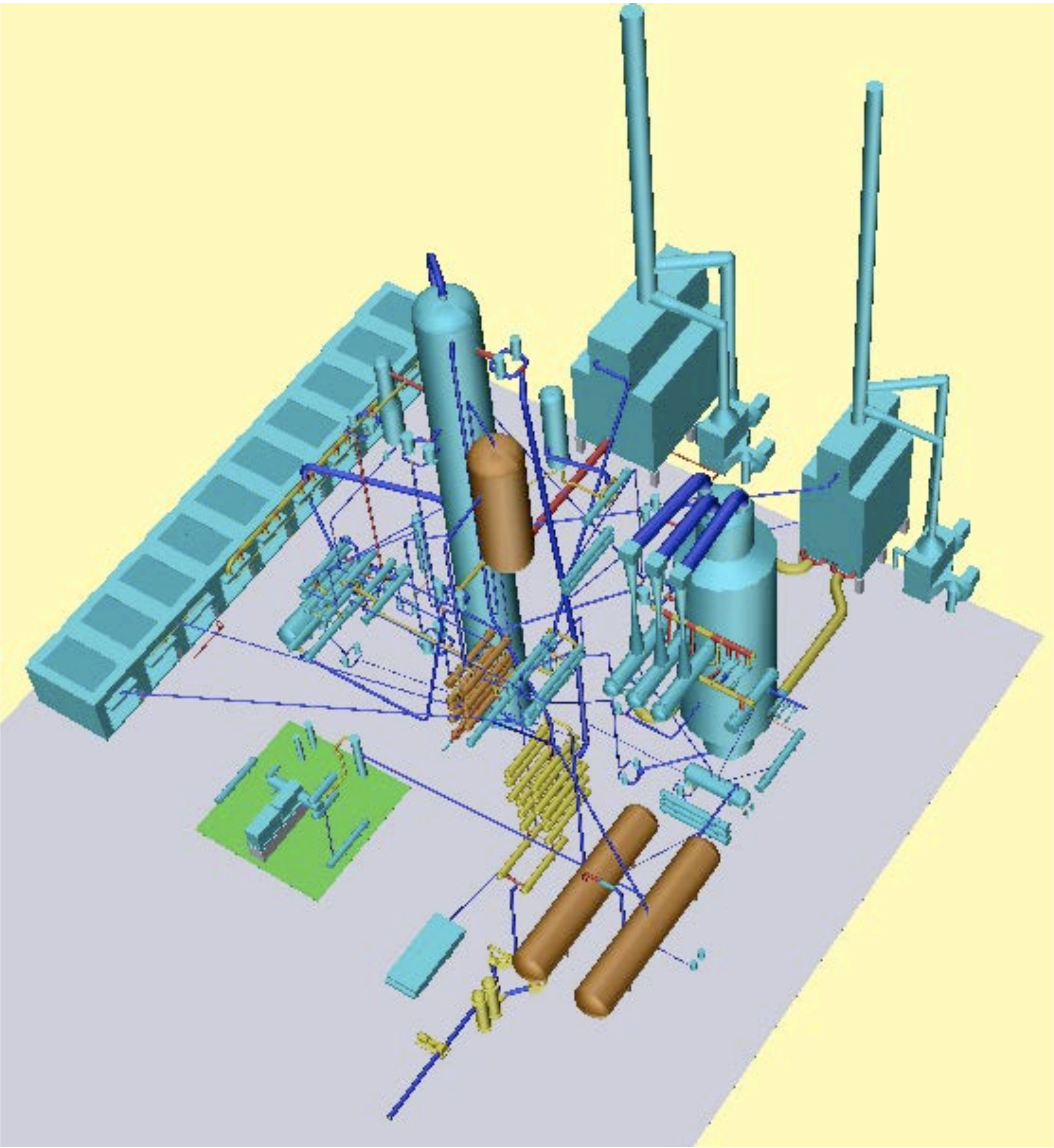


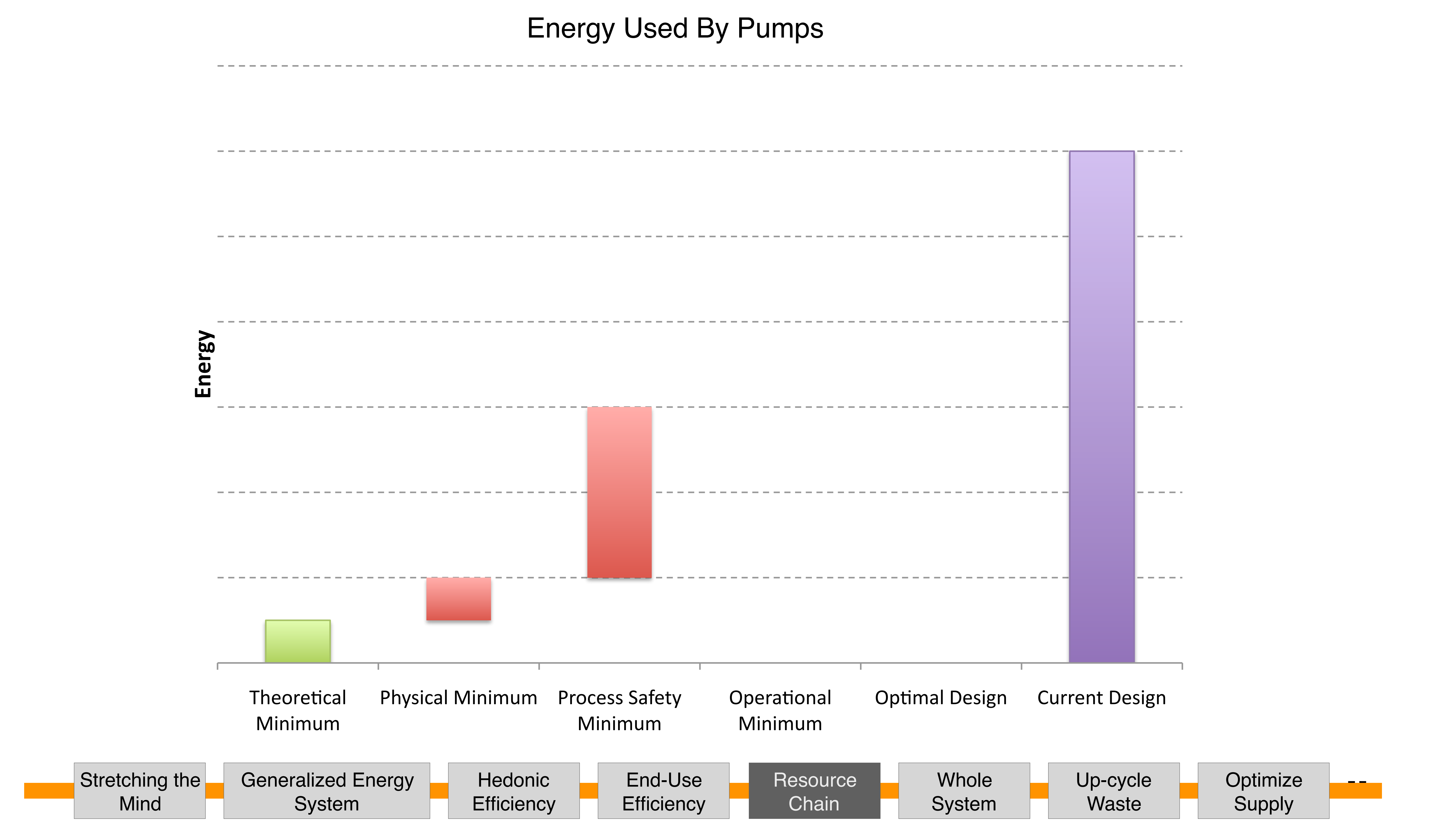
Stretching the Mind | Generalized Energy System | Hedonic Efficiency | End-Use Efficiency | Resource Chain | Whole System | Up-cycle Waste | Optimize Supply

A draft process safety minimum

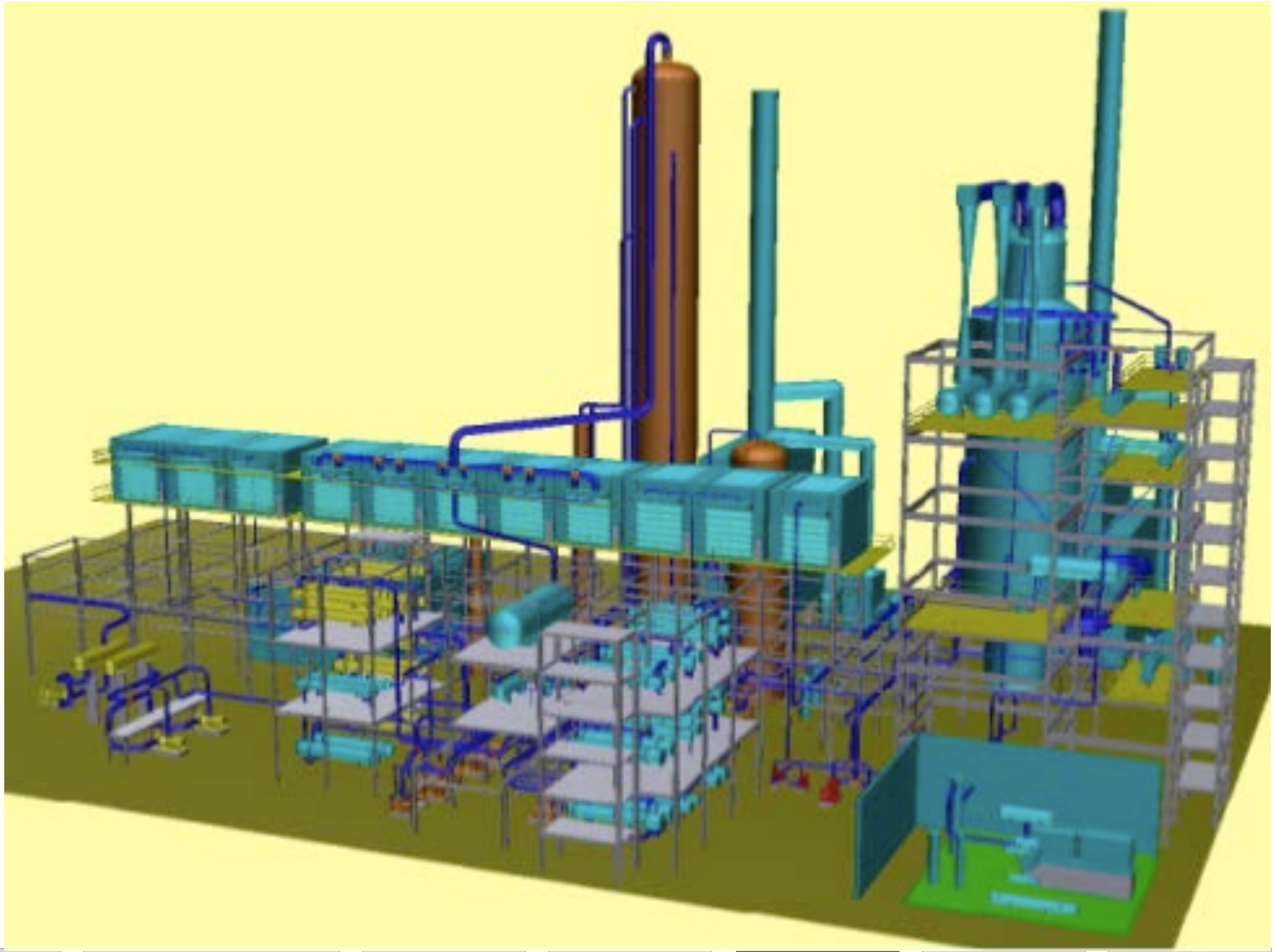


Meets insurance and HSE requirements

A draft process safety minimum



Working toward a safe, operable and maintainable unit



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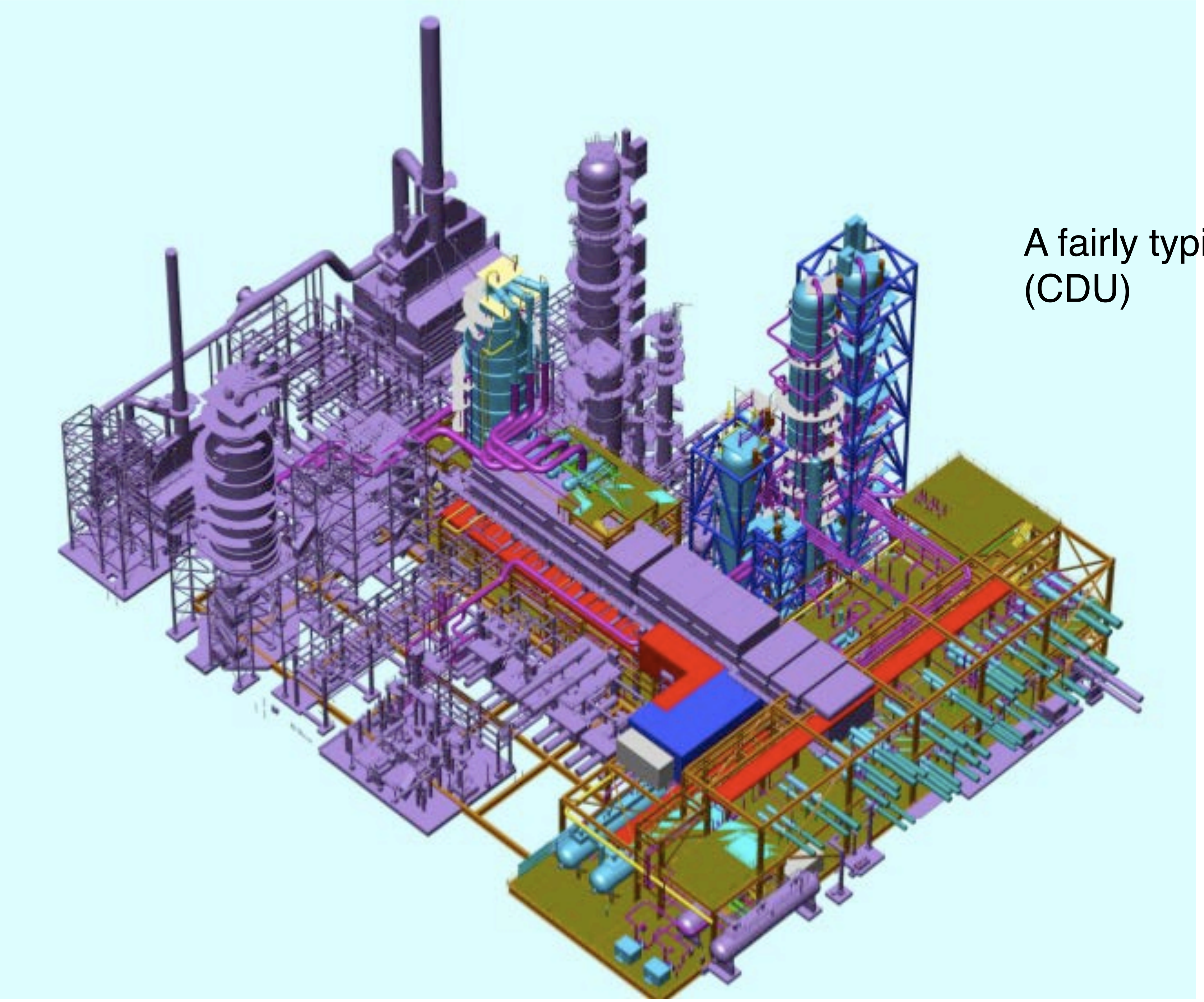
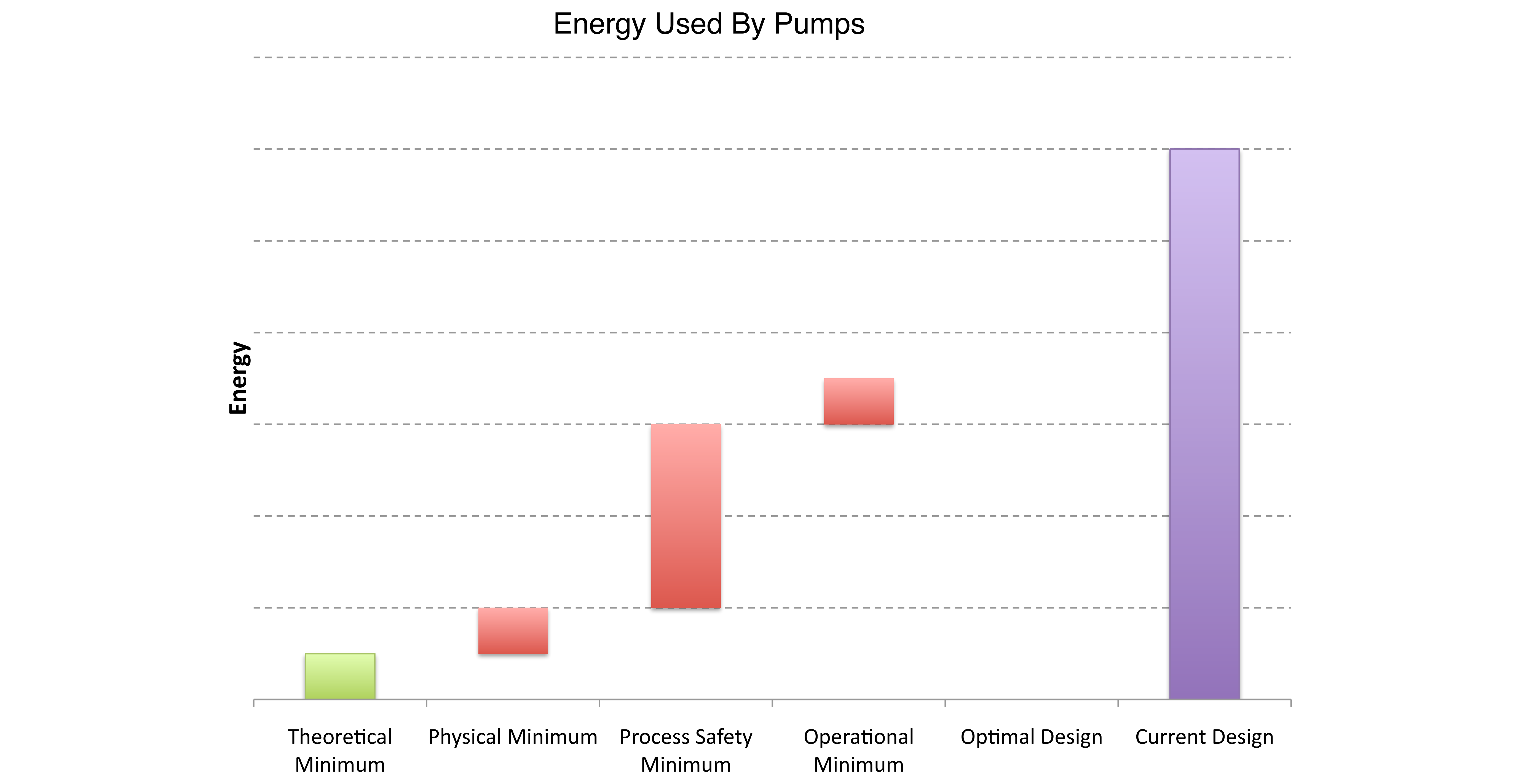


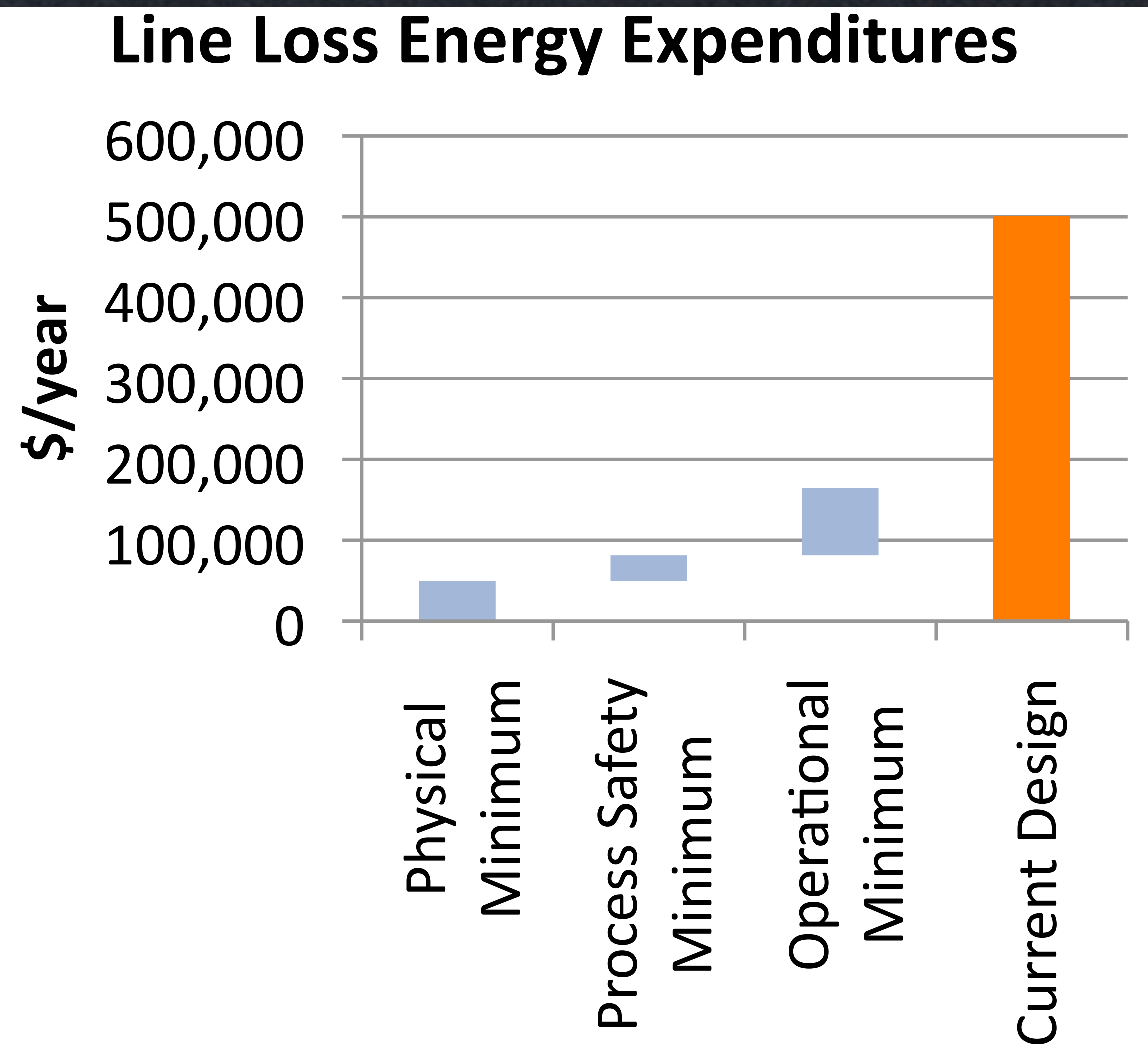
A fairly typical crude distillation unit (CDU)

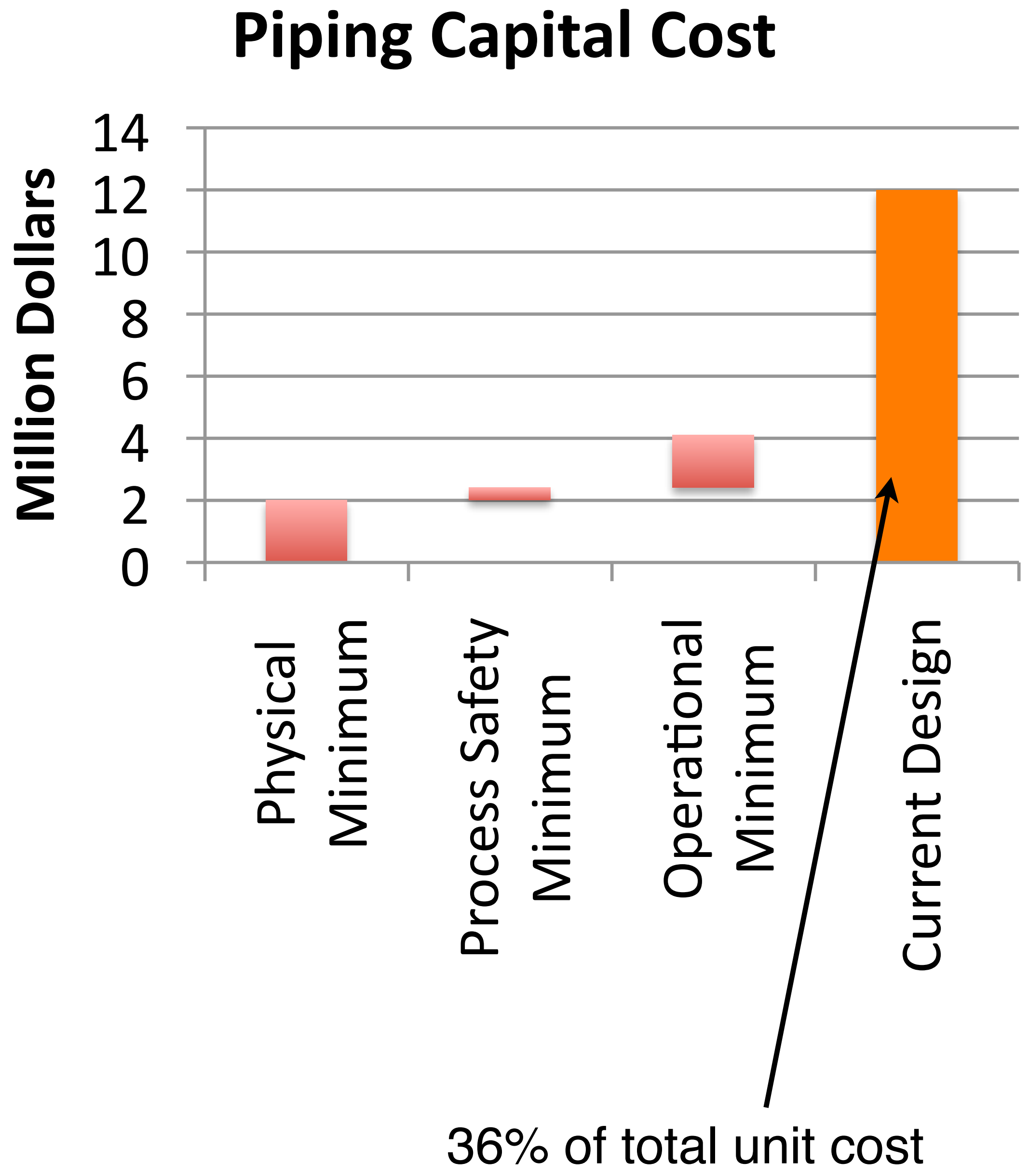
Stretching the Mind | Generalized Energy System | Hedonic Efficiency | End-Use Efficiency | Resource Chain | Whole System | Up-cycle Waste | Optimize Supply | --

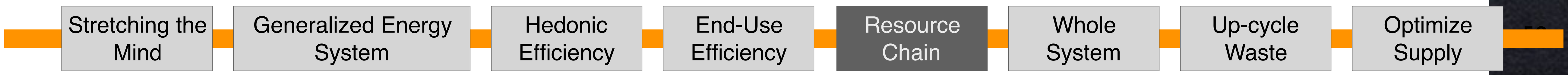
The operational minimum



Operational cost savings due to the new design was small... but the capital savings were significant







1.5 W/GPM

60,000 miles of
blood vessels

7.5 W/GPM

15 W/GPM

Biomimetic hydrodynamics

Images courtesy of Jay Harman and Pax Scientific (San Rafael CA)

Australian sea-captain/ naturalist Jay Harman at paxscientific.com noticed Fibonacci spirals all over nature. Why?

He began to imitate them.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Trihalomethanes (THMs) are a type of disinfection byproduct (DBP) that form when...
Read More
Vortex mixer utilizes easy, self-install design to provide

Si tion


OPERATIONS
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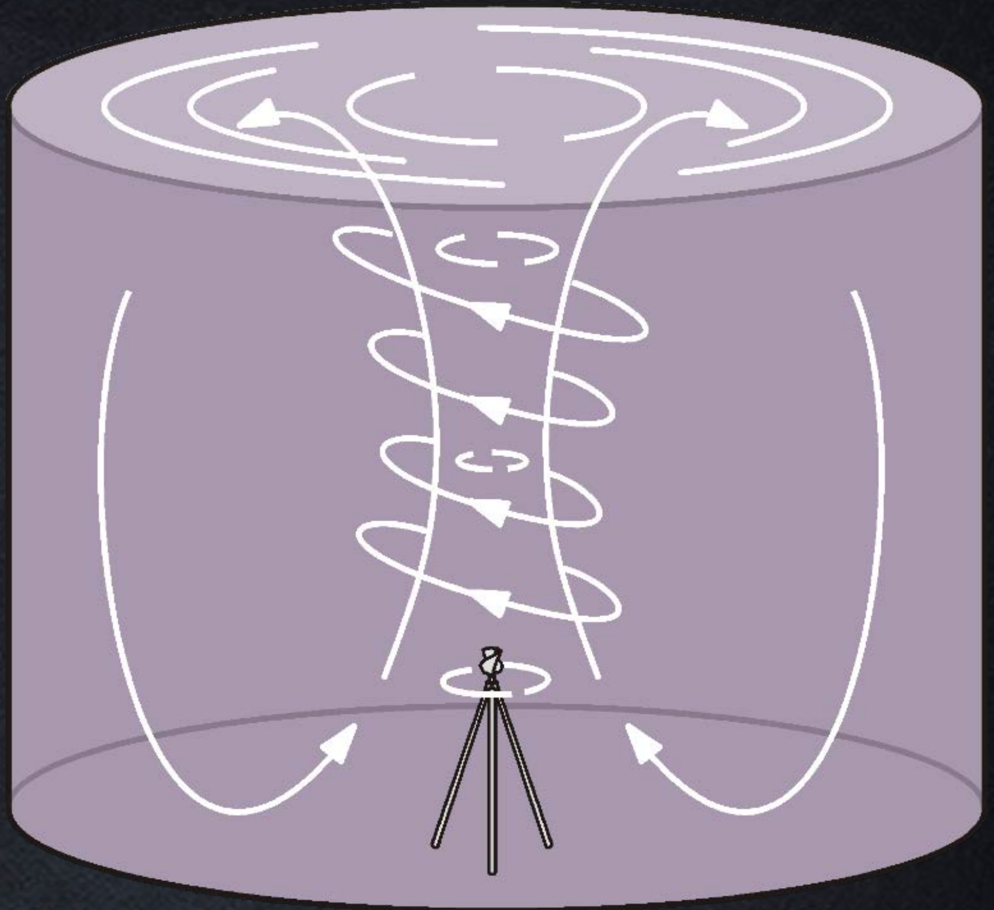
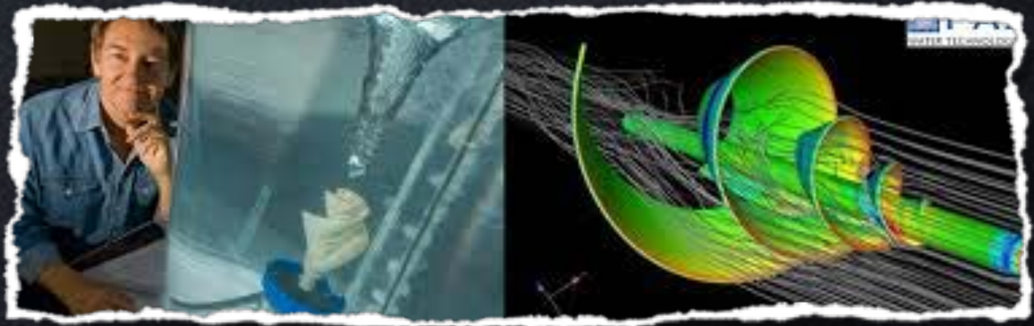
Biomimetic hydrodynamics



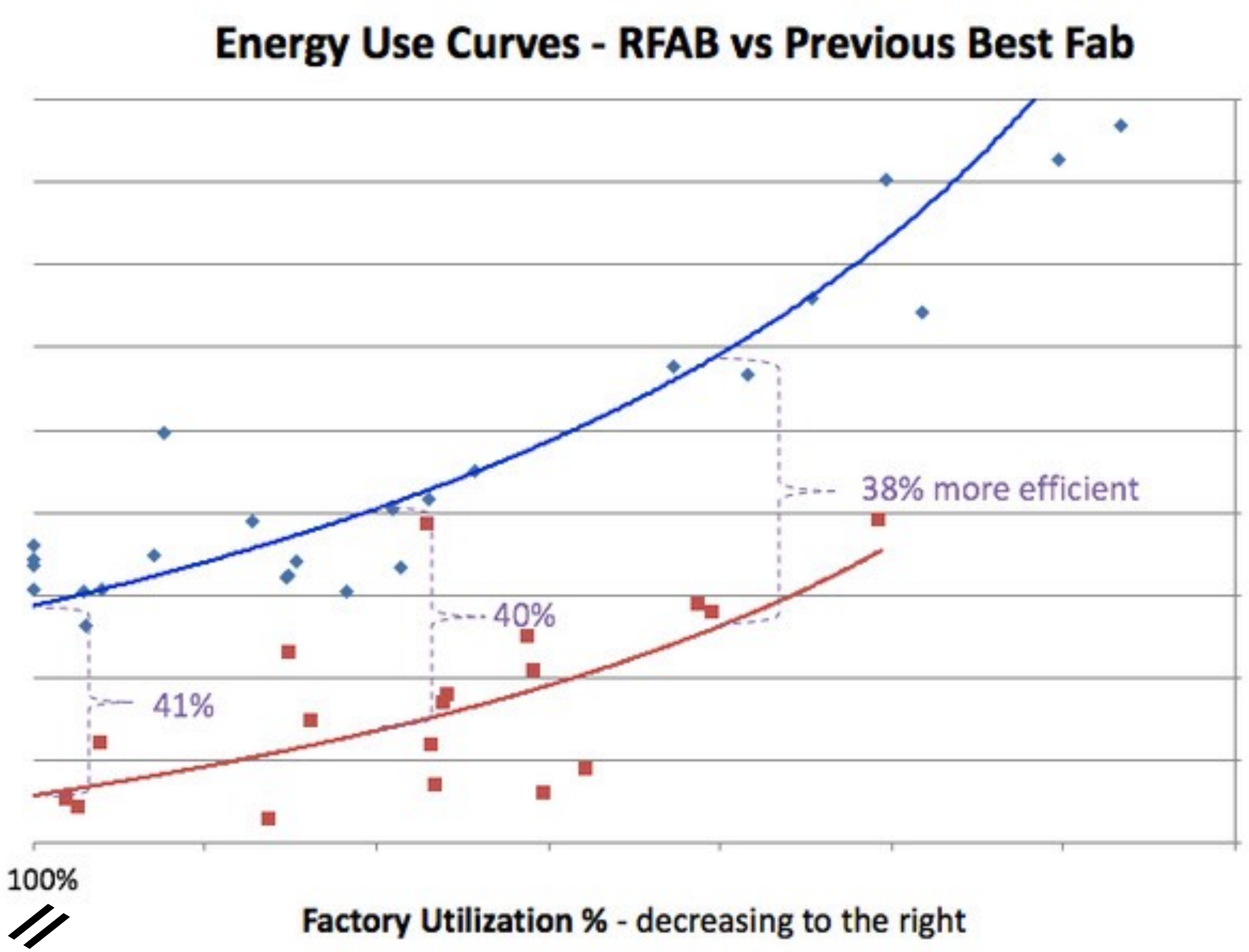


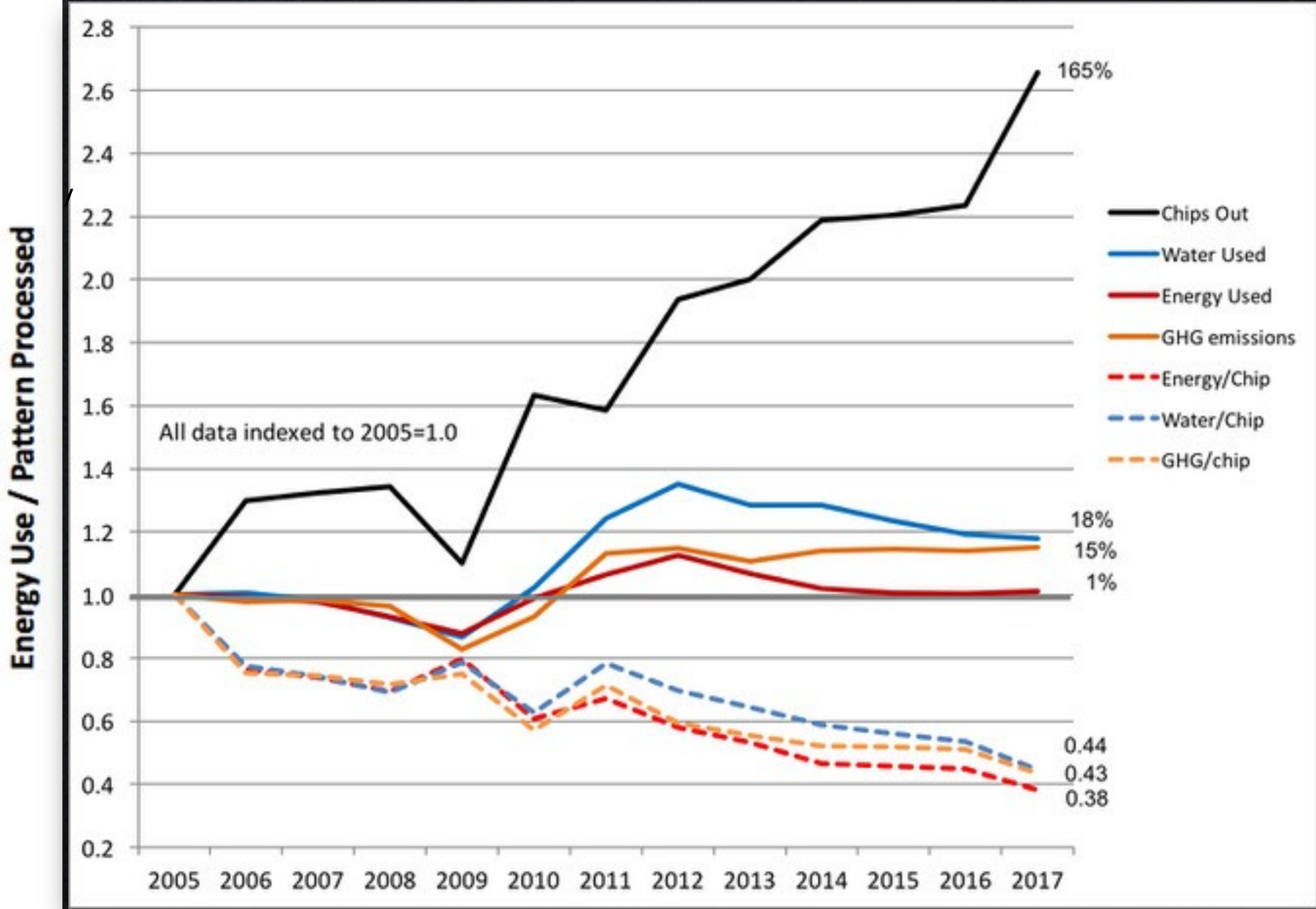
Texas Instruments' RFab (2005)
40% less energy, $230 million cheaper

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%



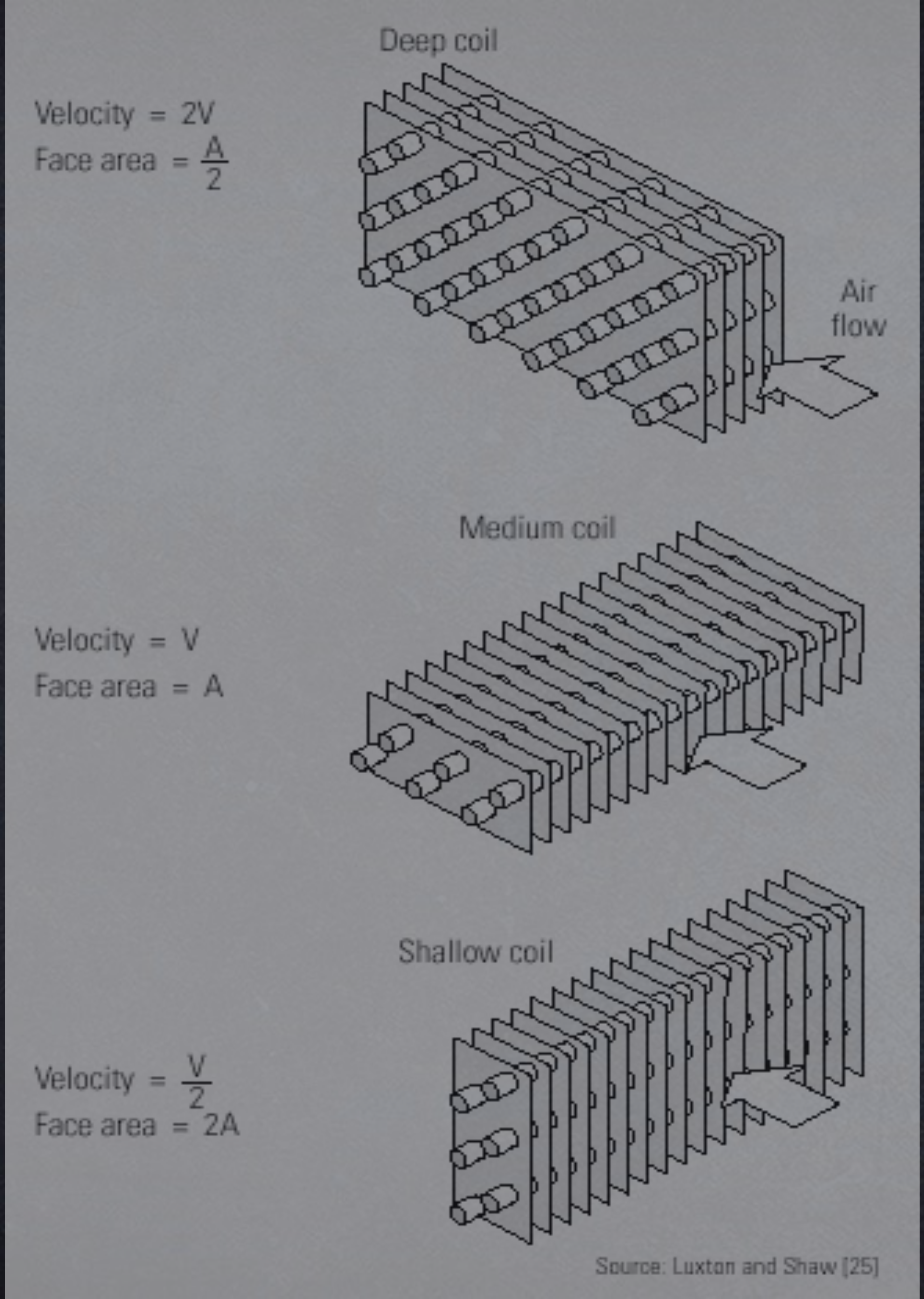


Superefficient big refrigerative HVAC too

(100,000+ ft^2 water-cooled centrifugal, Singapore, turbulent induction air delivery—but underfloor displacement could save even more energy)

Element	Std kW/t	Best kW/t	How
Supply fan	0.6	0.061	Best vaneaxial, ~1.5–3" TSH (less w/UFDV), VAV
ChWP	0.16	0.018	20–40' head, efficient pump/motor, no pri/sec
Chiller	0.75	0.481	1–2F° approaches, optimal impeller speed
CWP	0.14	0.018	20–30' head, efficient pump/motor
CT	0.1	0.01	Big fill area, big slow fan at variable speed
TOTAL	1.75	0.588 (–66%)	*Better uptime & comfort, less capex*

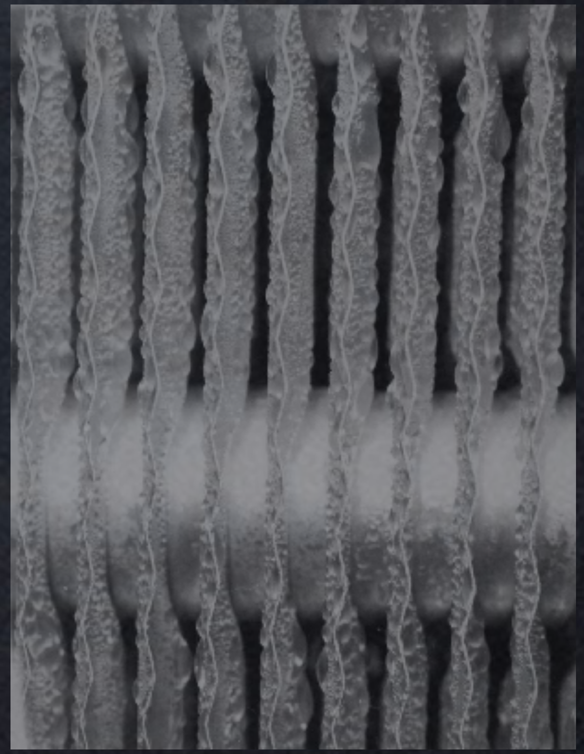
or 0.52 (incl. 0.41 chiller) = COP 6.8 = –70% w/dual ChW temperature



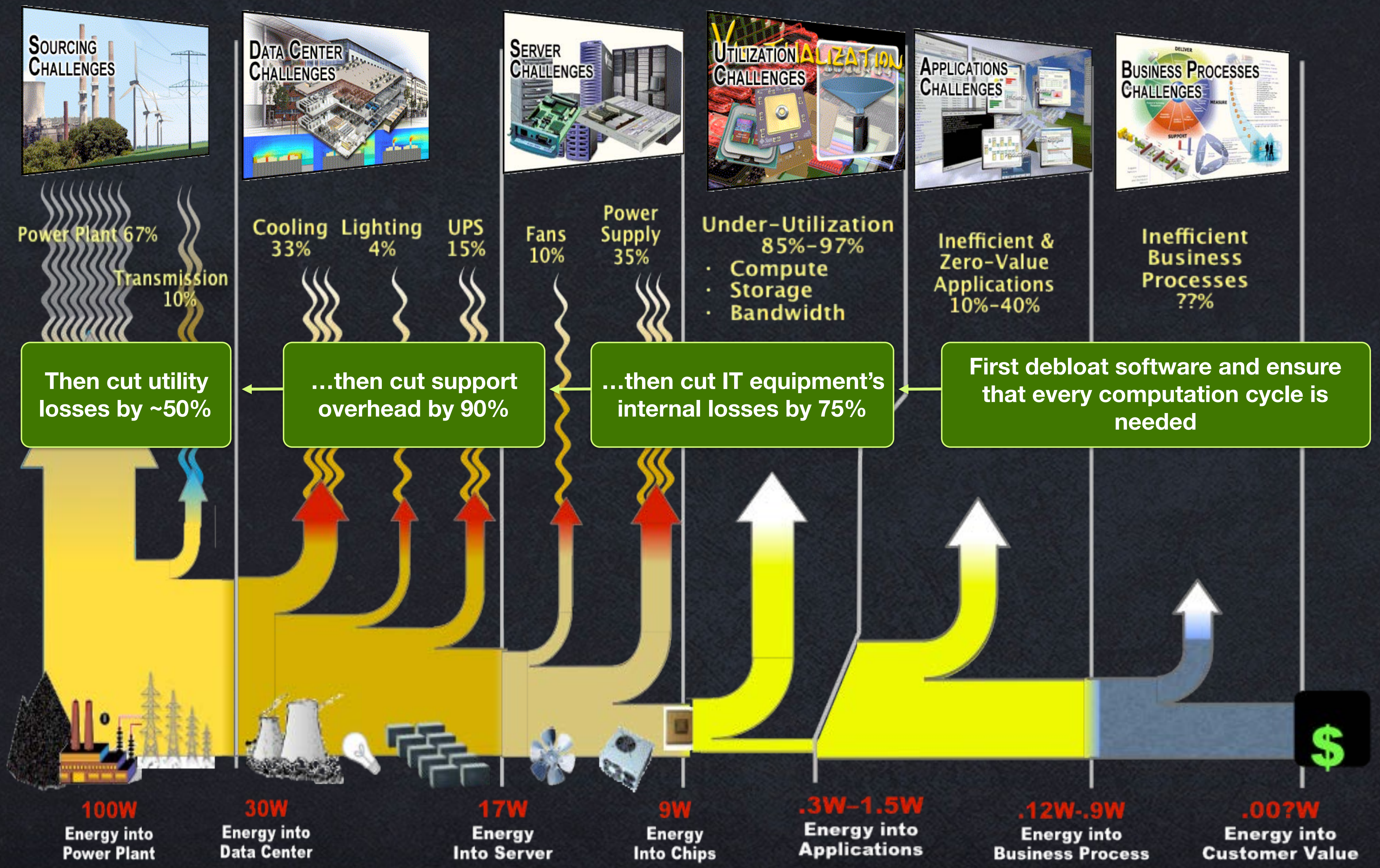
Low-face-velocity, high-coolant-velocity coils

Correct a 1921 mistake about how coils work

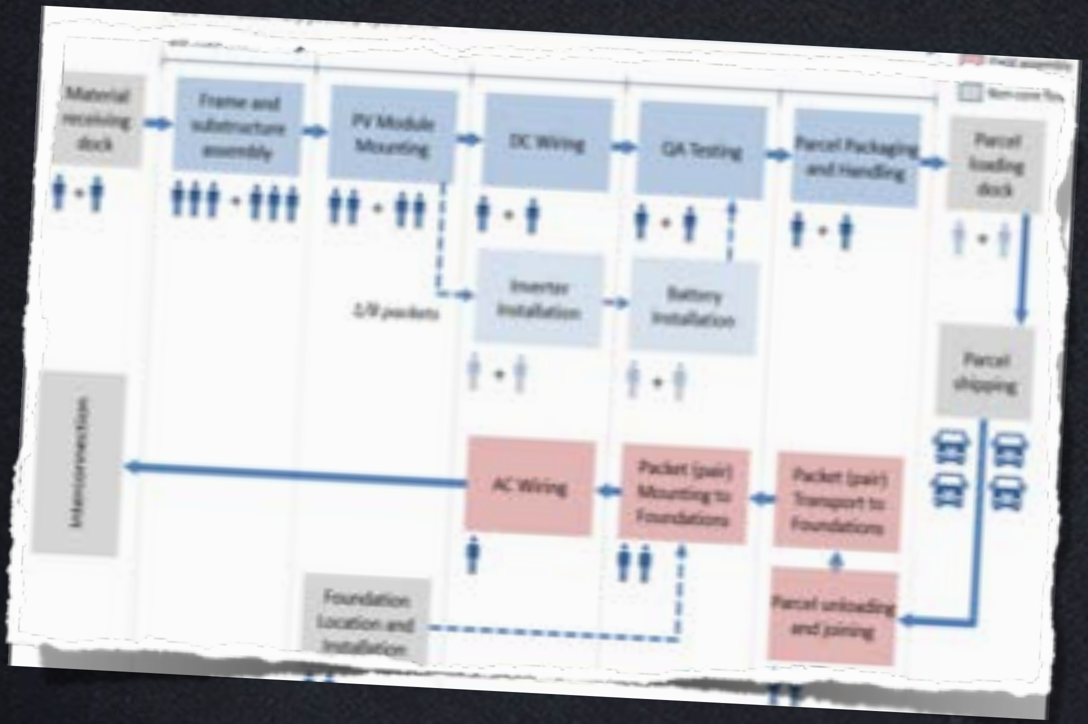
Flow is laminar and condensation is dropwise, so turn the coil around sideways, run at <1 m/s (<200 fpm):
29% better dehumidification,
ΔP –95%; smaller chiller, fan, and parasitic loads



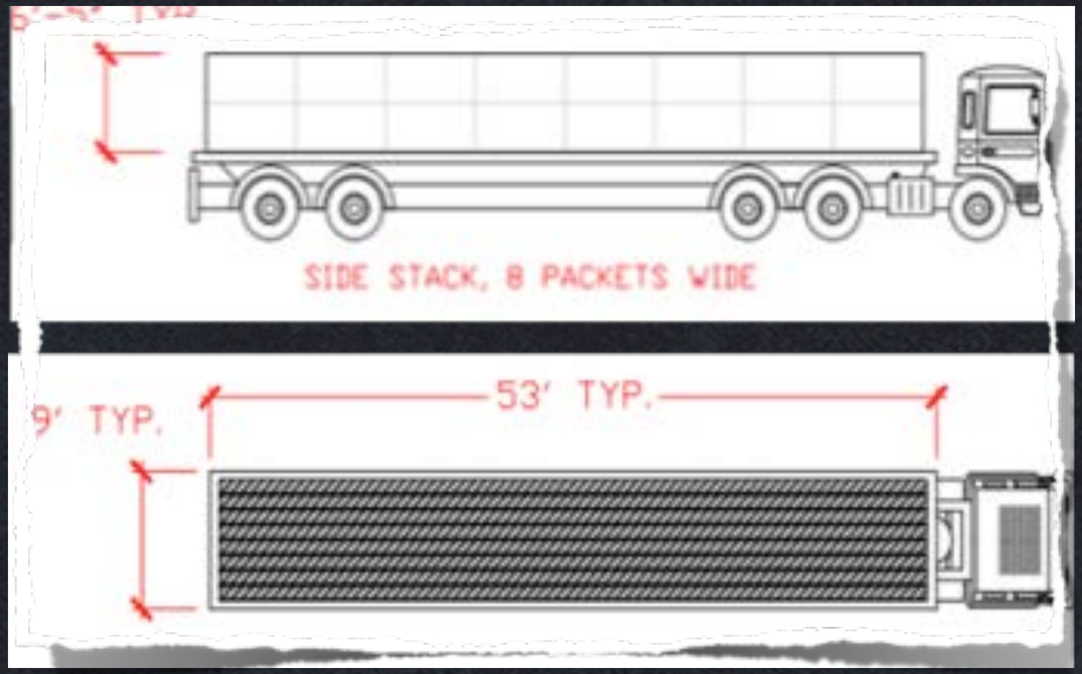
Start saving downstream for data centers



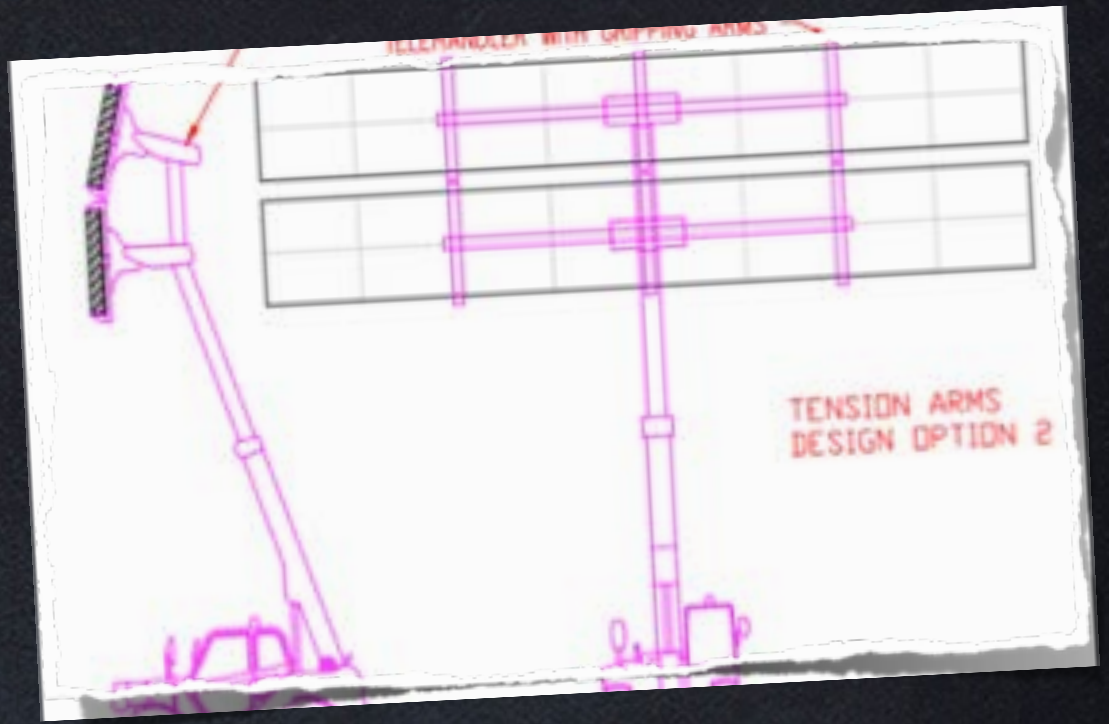
Optimizing solar power plants across the value chain



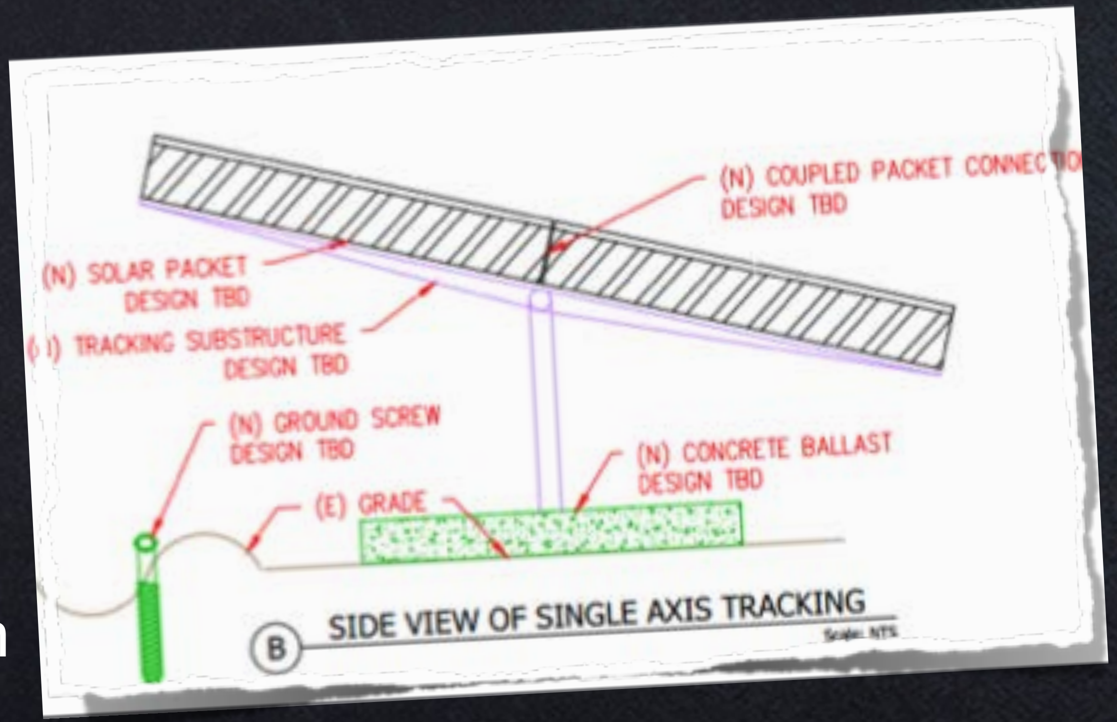
Factory assembly



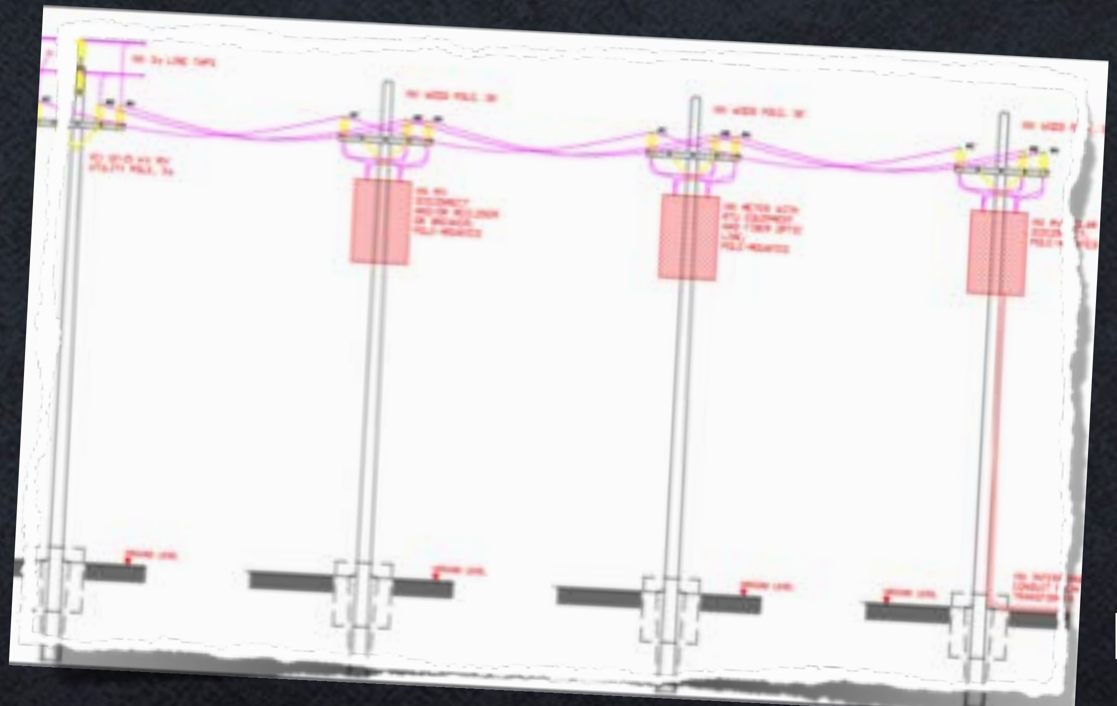
Shipping



Handling

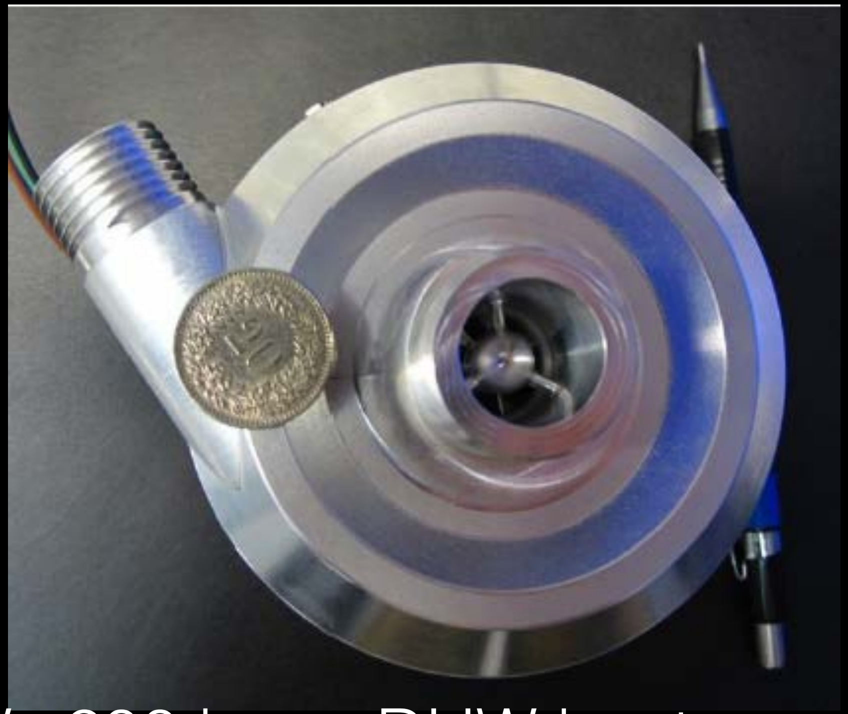


Installation



Interconnection

Heat pumps are getting even more interesting



9–20 kW_t, 200 krpm DHW heat pump
>60% of Carnot efficiency
COP=6–15 for $\triangle T$=13–31K
(www.bs2.ch: COP 12.3 for $\triangle T$=10K)

PV-powered Tesla Gigafactory saved
6–12 months and 98.5% of energy
in a key process by eliminating gas

Negamuda: Safeway ice cream

Old process:

After every flavored batch, clean out all piping to prepare for making the next flavor (“clean in place”).

New process:

After each batch, immediately send next batch through, saving the “mixed batch” as a special new product.

Net New Product Margin =

Average product margin (across all ice-cream product lines)

+ Average raw material cost (previously lost in clean-out)

+ Avoided waste disposal cost (from not having to pay for disposal)

+ Avoided time & materials (from now not cleaning piping frequently)

+ Incremental production achieved at zero capex (from capacity-factor boost)

+ Incremental product margin (from price premium)

– Lost margin on cannibalized products

Now, is that delicious, or what?

Negamuda: an Arctic industrial diamond mine

Old process:

Mine a kimberlite pipe with tens of $b of diamonds conventionally—drill, blast, dig, load, haul, crush, separate (air jets activated by diamonds' X-ray fluorescence flash). Any big diamonds are pretty likely to be broken in blasting or crushing before you even know they're there.

New process:

Eliminate the mine and mill, yet improve recovery and dramatically reduce cost. Probably well worth switching immediately, a third of the way through the surface-then-underground mining plan.

Different questions:

- How does the mine assay diamonds in kimberlite? (Caustic fusion—dissolve the kimberlite in hot NaOH so only diamonds remain.)
- Create a sandworm (*Dune* scifi novels), with hot NaOH in its gut, that burrows around in the carrot-shaped kimberlite pipe and poops out diamonds. Start it up and neutralize behind it with cheap e.g. H_2SO_4.
- Sandworm will need fancy and costly alloys, but even if made of pure unobtainium costing several orders of magnitude more than conventional metals, still much cheaper than the current mining method—even counting zero salvage value for the abandoned mining and milling equipment no longer needed.

Not yet done because the visionary CEO who loved the idea got hired away.

Negamuda: a large platinum-group mine

Conventional improvements:

End-to-end improvements in each step: drill, blast, load, hoist, haul, mill, concentrate, smelt, refine.

Can save ~43% of total energy with a few years' payback.

New question:

Where can improvements yield the greatest leverage for health and safety, resource recovery, capex and opex, and strategic advantage? Answer: ergonomics & info at the face.

Highest-leverage interventions are about the people more than the equipment or process:

Miner ergonomics: 30x-lighter/lux-h cableless headlamps (lithium/LED), phase-change vests (cool the miners, not the air), minimized latent loads, white-painted walls with efficient indirect lighting, continuous hydration + electrolytes, quieter/cleaner/less scary working conditions: light lights, cool heads, cool people

Separately provide coolth and dryness, ventilation and filtration and coolth; no underground diesels; exhaust underground heat not by blowing coal-electric-cooled air several km down and sideways, but by rising heat pipes

Key information to the miner at the face: backpack (or smaller) assay equipment, incentivize hoisting ore not tons

Or get *way* out of the box (there is no box)

- ◇ All-electric mine, but save most of the electricity by very efficient use
- ◇ Get 5 MW by lowering W African iron ore to port with an Austrian reverse-ski-lift, recovering 92–93% of the gravitational energy—capex is similar to railway's, builds faster, easier maintenance
- ◇ Get more power by dewatering and lowering perched water table down to dry port through a hydroelectric turbine
- ◇ No power plant, highly reliable, no grid electricity, no fuel, no emissions
- ◇ Resupply by ski-lift and dirigible—no railway, no road, secure, probably cheaper, easy cleanup

Typical areas for big industrial savings

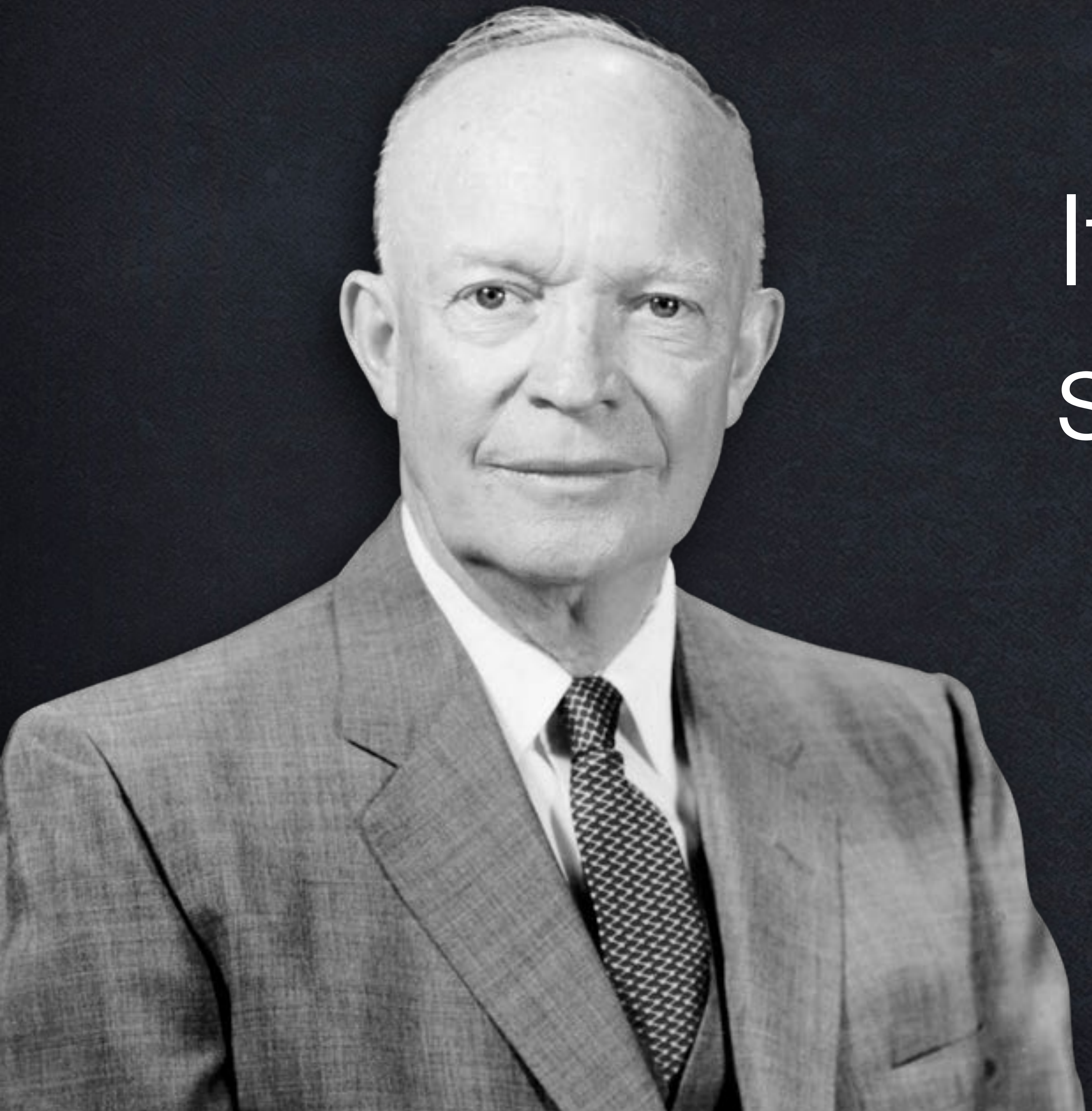
- ◊ Rightsizing everything (if we designed *747*s this way…)
- ◊ Thermal savings and integration
- ◊ Innovative and distributed power systems
- ◊ Designing friction out of fluid-handling systems
- ◊ Superefficient drivesystems
- ◊ Water/energy integration
- ◊ Superefficient and heat-driven refrigeration
- ◊ Advanced controls

Designing for breakthrough industrial energy efficiency: an eightfold way

1. Vision, intent, model, strategy, and culture first: why do it?
2. Task elimination before task
3. Demand before supply
4. Downstream before upstream
5. Application before equipment
6. People before hardware
7. Passive before active
8. Quality before quantity

This approach lets you:

1. Capture multiple benefits
2. Make them compound
3. Free up the most capacity
4. Avoid the most capex
5. Eliminate the most waste & harm
6. Make the most profit
7. Do the most good
8. Have the most fun



If a problem can’t be solved, enlarge it.

—Dwight David Eisenhower

How will we replace fossil fuels for process heat?

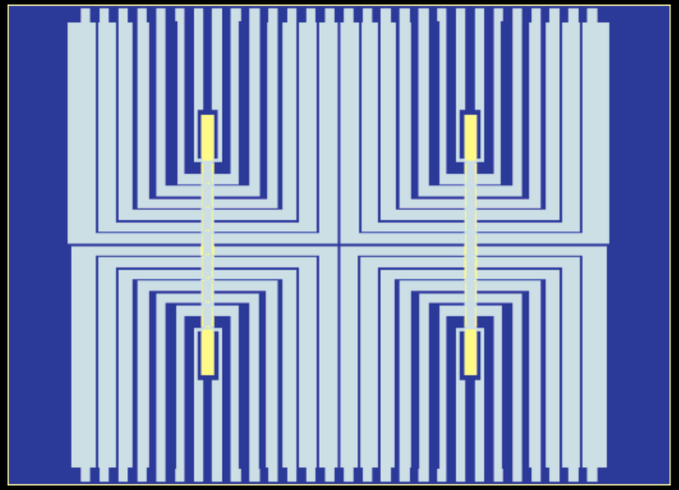
Design out the need
Substitute for the product
Save the product
Reward doing more and better
with less for longer

Then redesign process heat
– less
– cooler
– cleaner

8 neglected *prior* paths to decarbonizing process heat

Design out the *need* for concrete, steel, etc

Chemical microreactor



https://www.researchgate.net/figure/Rendered-top-view-of-the-scale-up-microreactor-die-Metallization-is-shown-in-gray_fig3_277494576

Mobility-as-a-service

estimatefares.com

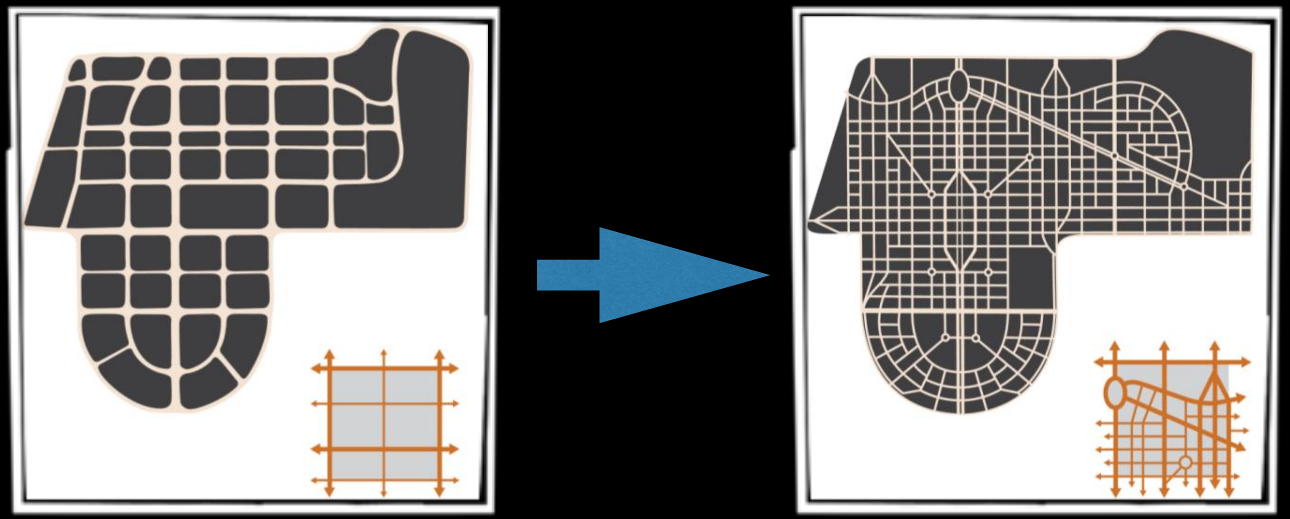
3D printing, local manufacturing

3D-printed metal chairs by John Briscella,"continuum3," from Zach Andrews, designboom.com, 25 Mar 2018

Onsite (not remote) building services

https://www.greentechmedia.com/articles/read/how-much-does-a-rooftop-solar-system-with-batteries-cost#gs.dVVQ0FDG

New Urbanist design



8 neglected *prior* paths to decarbonizing process heat

Solutions-economy business models deliver service, not stuff

8 neglected *prior* paths to decarbonizing process heat

Productive use: frugal structural design

Tension structures—~80–90% less material

Schlaich Bergermann—see the remarkable book Leicht Weit

RPS, IPTC, FabWiki

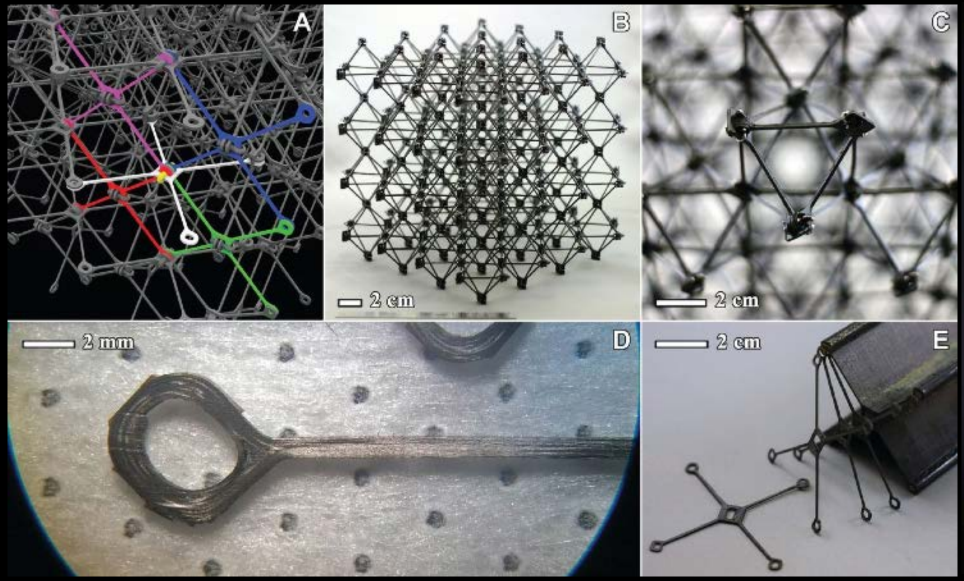
Fabric forms—≥50% less material

Mark West, *The Fabric Formwork Book*, Routledge, 2016; CAST (Centre for Architectural Structures and Technology), University of Manitoba, Winnipeg. See Hawkins *et al*'s 172-reference 2016 review, doi:10.1002/suco.201600117

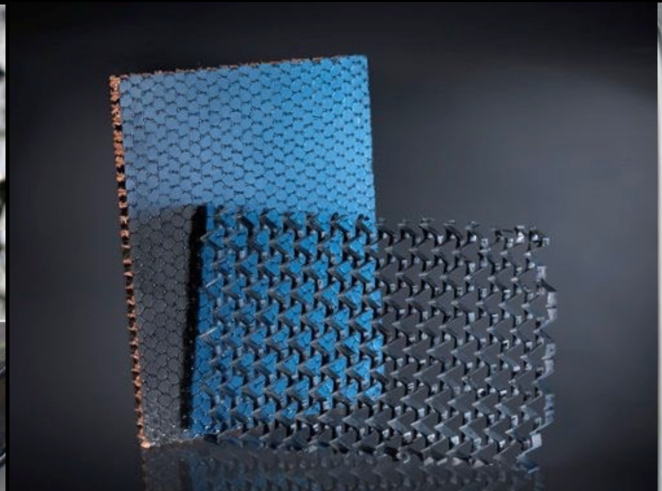
Biomimetic structures—~60–90+% less material

Brennan O'Rear, 2018, from Cooper Hewitt, Smithsonian Design Museum

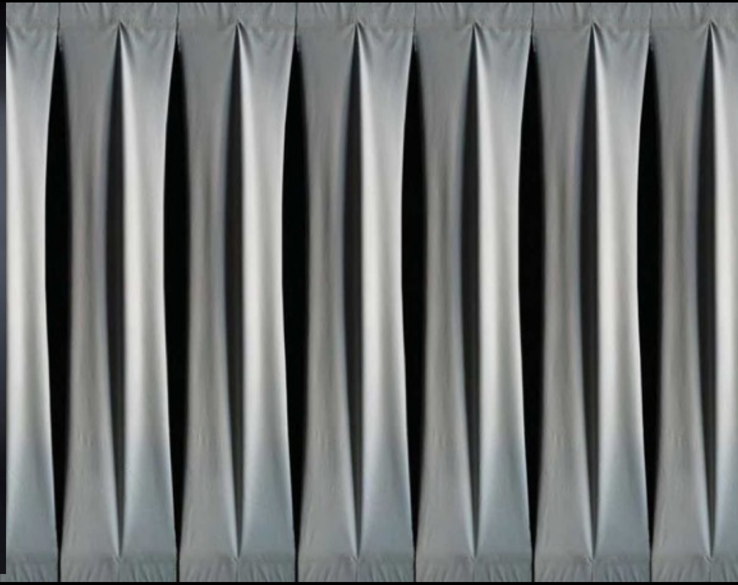
http://animalia-life.club/other/bird-bone-cross-section.html



Cheung et al, *Science*, doi: 10.1126/science.1240889



http://www.miralon.com/how-its-used?hsCtaTracking=0ebe525d-8588-4308-9bef-88516ce9b6ce%7C8601a7f7-555d-48c9-859a-7c44e2156835



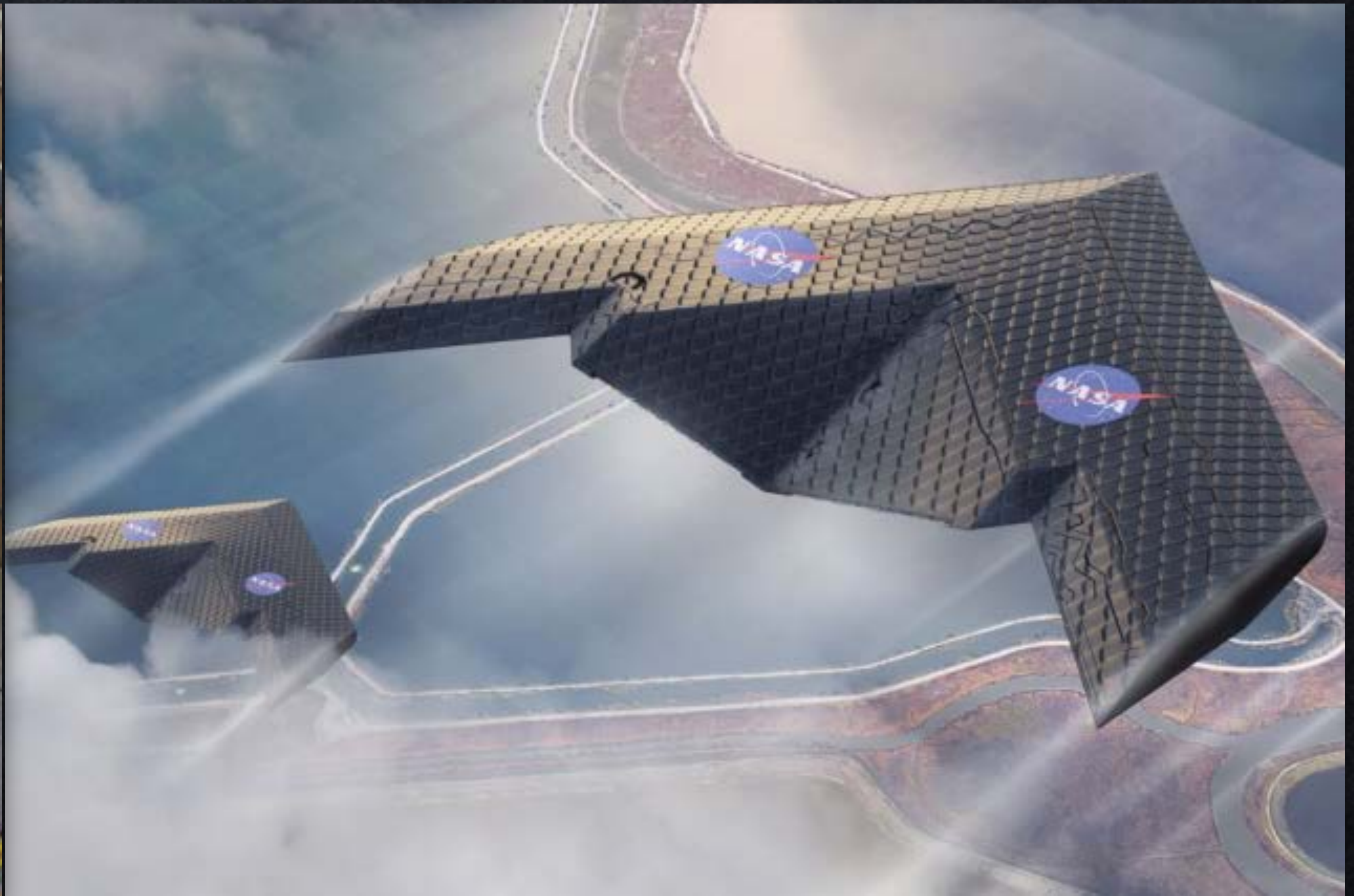
Latest MIT/NASA version—59× lighter than a “dumb” airplane wing

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

N B Cramer et al 2019 Smart Mater. Struct. **28** 055006, 01 April 2019, https://doi.org/10.1088/1361-665X/ab0ea2, http://mit.edu/archive/spotlight/shape-changing-plane-wing/ , http://cba.mit.edu/docs/papers/19.03.MADCAT.pdf



8 neglected *prior* paths to decarbonizing process heat

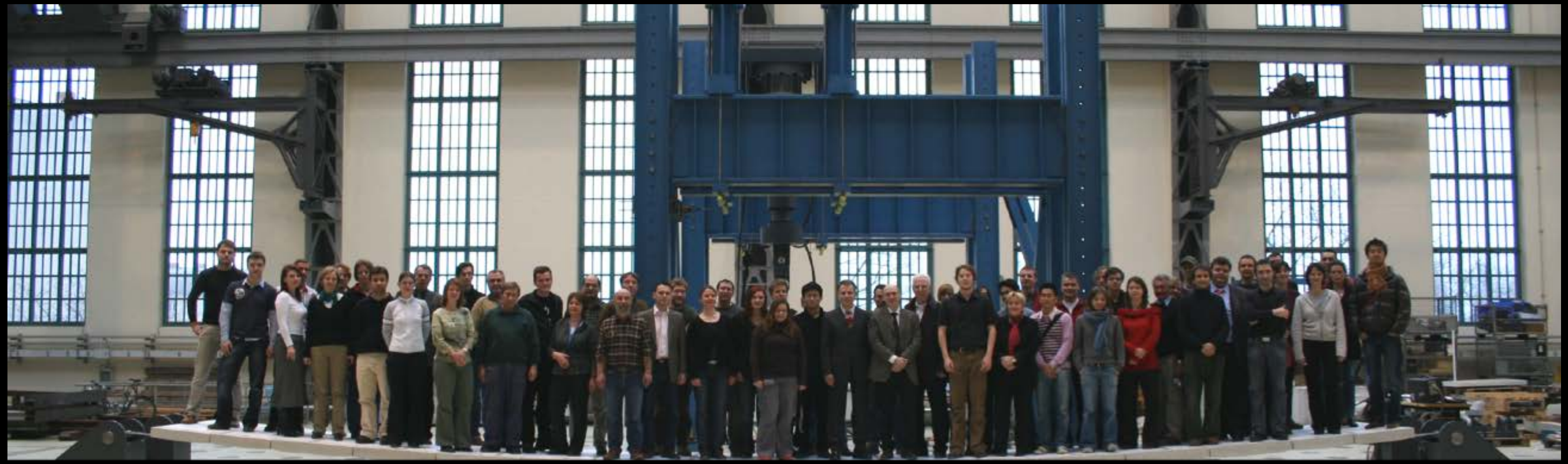
Productive use: material efficiency

A lightweight bridge being 3D-printed

https://www.shapeways.com/blog/archives/35854-3d-printed-bridges-now.html

A 13-m bridge supported only by 1-mm-thick carbon-fiber ribbons

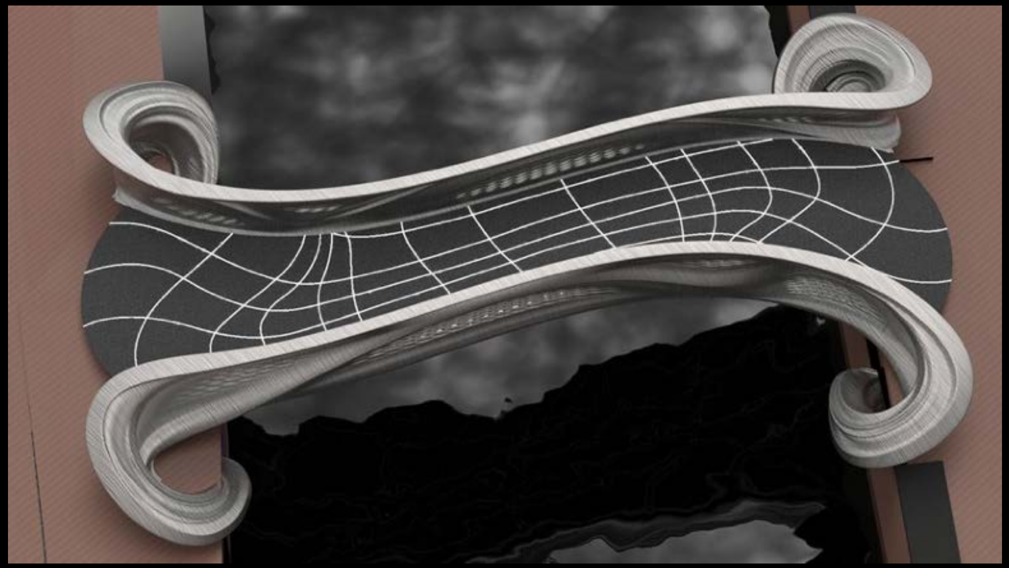
https://www.researchgate.net/publication/275653741_Carbon_fibre_stress-ribbon_bridge



http://chinaplus.cri.cn/photo/china/18/20190112/234804_2.html
https://3dprint.com/184852/bridge-3d-printed-railings-china/

Chinese 3D-printed bridge girder and railing

The artistic 3D-printed 12.5m stainless-steel bridge over Amsterdam's Oudezijds Achterburgwal canal



https://www.designboom.com/technology/mx3d-metal-bridge-3d-print-update-04-03-2018/

8 neglected *prior* paths to decarbonizing process heat

Productive use: other materials

BMW MY2013's ~120–150-kg carbon-fiber-composite passenger cell; m_c 1,250 kg

specifile.co.za

http://tudalit.de/wp-content/uploads/2016/02/TUDALIT13.pdf

8 neglected *prior* paths to decarbonizing process heat

Productive use: quality and design

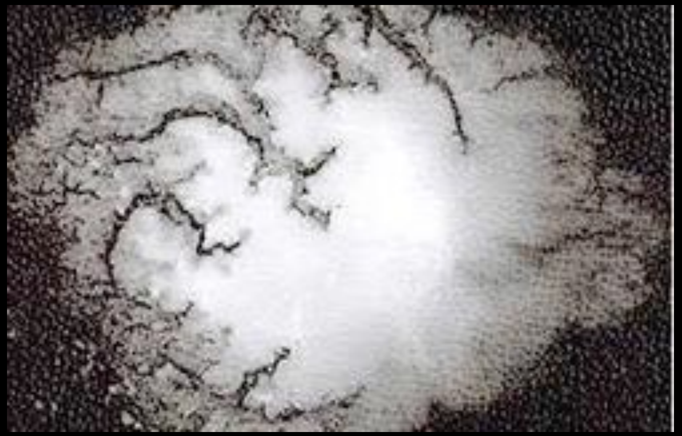
Freedom Tower (541 m)
Rahimian and Eilon, 2012

Shanghai Tower (632 m)
academy.autodesk.com

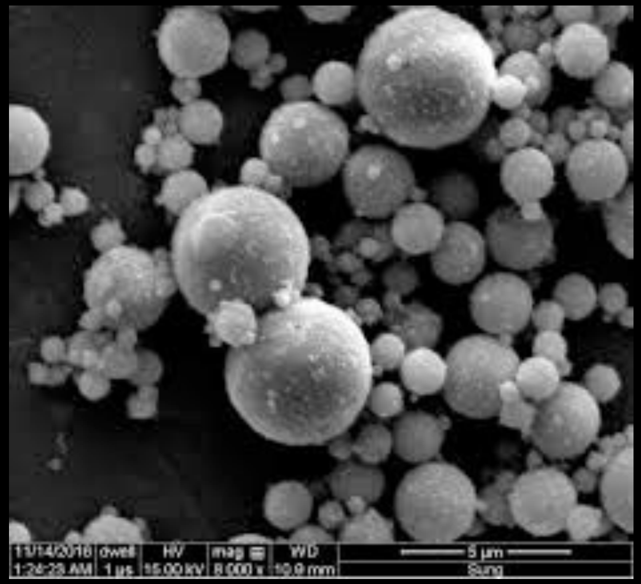
Productive use: substituents

Taiheiyo carbon-neutral bamboo concrete

theconstructor.org

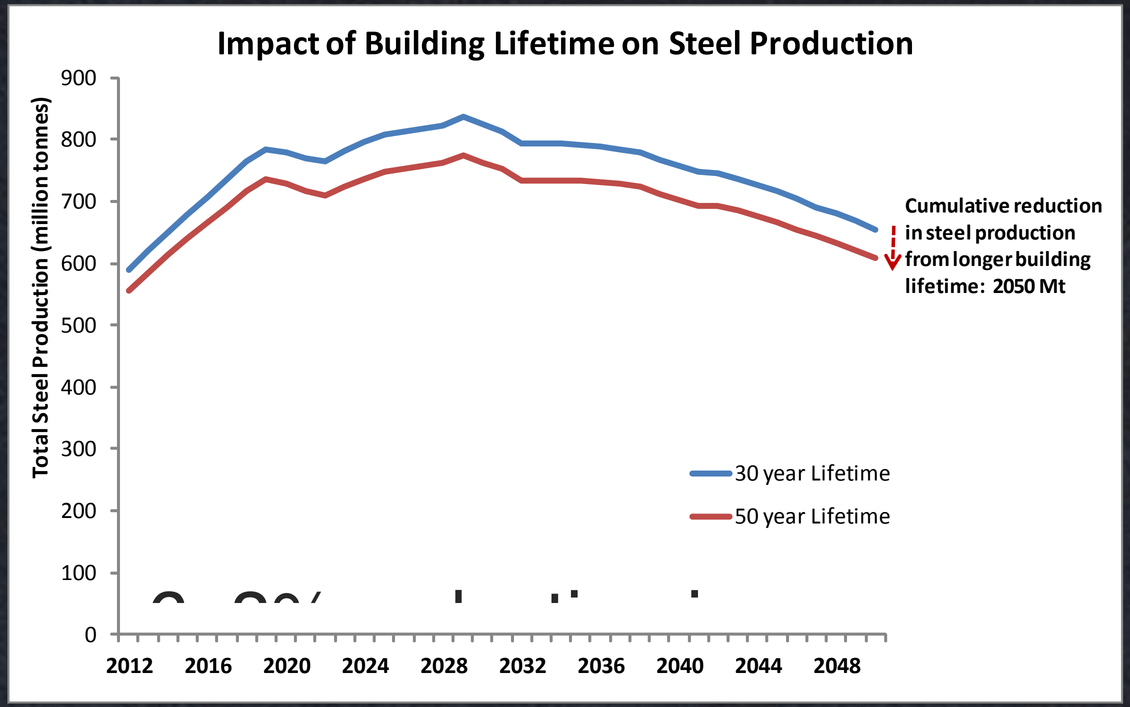


https://www.indiamart.com/proddetail/fumed-silica-8346603562.html



http://news.rice.edu/2018/06/18/cementless-fly-ash-binder-makes-concrete-green-2/

Higher-quality steel and cement in China



Sources: Climate Policy Initiative 2013; Allwood et al., 2011, LBNL 2050

8 neglected *prior* paths to decarbonizing process heat

Productive use:
improve materials quality

https://www.chemistryworld.com/news/sea-urchin-spines-inspire-elastic-concrete/3008390.article

DOI: 10.1126/sciadv.1701216

8 neglected *prior* paths to decarbonizing process heat

Productive use:
closing loops

https://www.slimbreker.nl/why-smartcrushers.html

20 paths to decarbonizing process heat (*e.g.* for cement)

A fuller portfolio

Eliminate need: onsite building services *vs* remote infrastructure, 3D printing/local manufacturing, chemical microreactors, telecoms *vs* roads, shared & connected mobility *vs* parking, urban form *vs* automobility (⅓ less concrete)

Service, not stuff: Solutions-economy business models (structural services not tons of cement, mobility services,…)

Productive use: Elegantly frugal structural design with appropriate safety margins, rewarding civil engineers for quality

Use other materials: *e.g.*, ultralight carbon-fiber cars for heavy metal cars, timber for concrete, adobe/caliche,…

Increase substituents: fly-ash, ground glass, rice-hull derivatives, nano or fume silica,… for clinker, bamboo for rebar

Improve materials-quality uniformity (3× in cement by eliminating Chinese shaft kilns)

Materials efficiency: *e.g.*, fabric concrete forms (≥2×), tension not compression structures (~8×), Girshenfeld, Miralon

Close materials loops: longevity, dematerialization, reuse, remanufacturing, recycling, downcycling,…

Less onsite waste via ontime delivery (Cemex), tighter specs, Smart crushing/unhydrated cement recovery/reuse

Capture significant knock-on effects such as reduced energy to transport cement, build roads & factories,…

Cleaner stuff: Substitute carbon-free or -positive chemistries (Solidia, Calera, Novacem,…)

Processes requiring less or no heat or (biomimetically—abalone shell)

Processes requiring lower temperatures: olivine+steam, ecocement, Bang bacterial cement, geopolymers,…

Make better: More-efficient processes, equipment, and controls

Heat recovery and cascading, cogeneration: *e.g.*, McKay's Hong Kong dioxin-free municipal-solid-waste cogen

Make cleanly: Fuel-switching: biofuels, bioprocessing byproducts, waste solvents, old tires, crop wastes,…

Solar process heat (logical evolution for solar concentrators; can include cogen; feasible even with cloud)

Renewable electricity for heat pumps—now 160˚C, soon >200˚C

Renewable electric process heat or plasma

Renewable hydrogen process heat or reductant

“Only puny secrets need protection.
Big discoveries are protect by public incredulity.”

—Marshall McLuhan

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