
ROCKY MOUNTAIN
INSTITUTE

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CEE 173L/273L: Advanced Energy End-Use Efficiency

Public Lectures in Advanced Energy Efficiency:

2. Industry

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American industry

- The mightiest transformative force in history
- Extracts raw materials, processes them into primary and secondary forms, makes those into artifacts that may be used for varying lengths of time (or none), and recycles a bit
- Uses essentially all physical materials, >18% of freshwater withdrawals* (>60% including agriculture, a primary industry), ~31% of electricity, 35% of directly used natural gas, 96% of directly used coal, 24% of oil (nearly half for feedstocks), and 32% of total energy

  *USGS doesn't report how much of the public water supply goes to industry, so it's not included here, but I've prorated power stations' water withdrawals, 48% of the U.S. total, on industry's 31% share of electricity consumption.
- Emits 29% of U.S. fossil-fuel CO_2

First Industrial Revolution:

People are scarce
and nature
is abundant —
increase labor
productivity

Next Industrial Revolution:

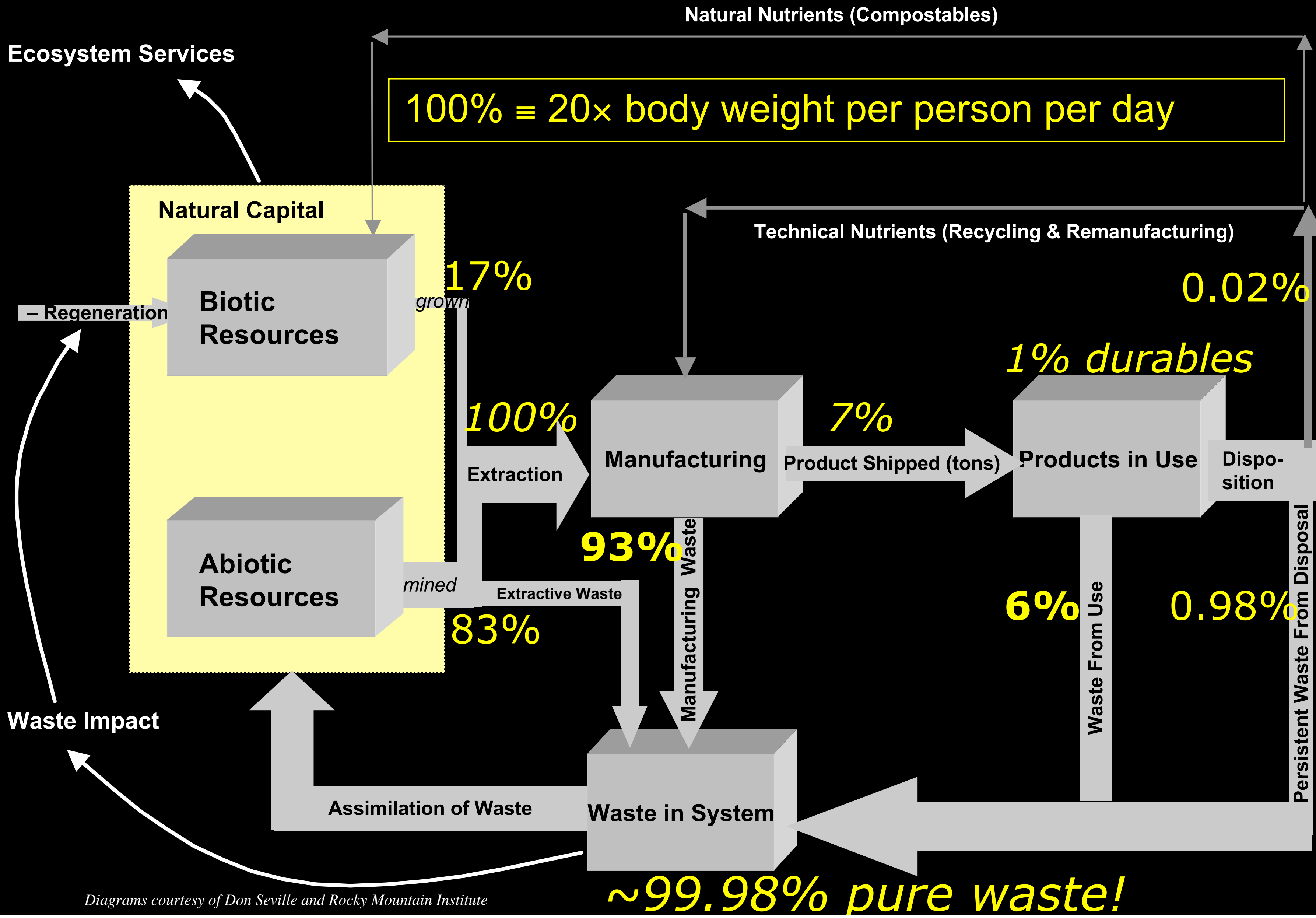
People are abundant
and nature
is scarce —
increase resource
productivity

Natural Capitalism (www.natcap.org, 1999)

- Design principles for a world that makes sense *and* money
- Productively use and reinvest in *all four* forms of capital
- Two design principles about processes/products
  1. Radical resource productivity (tunnel through the cost barrier)
  2. Biomimetic production (closed loops, no waste, no toxicity)
- Plus two design principles about business strategy
  3. Reward these shifts by a "solutions economy" business model
  4. Reinvest resulting profits back into scarcest (natural) capital
- Result: stunning competitive advantage; do well by doing good; biggest business win is often in recruiting, retaining, and motivating the best people
- Book and *Harvard Business Review* summary are free at www.natcap.org; numerous translations are available
- Most of Rocky Mountain Institute's revenue comes from private-sector consultancy applying these principles, chiefly in industry

The resource cycle: a massflow perspective

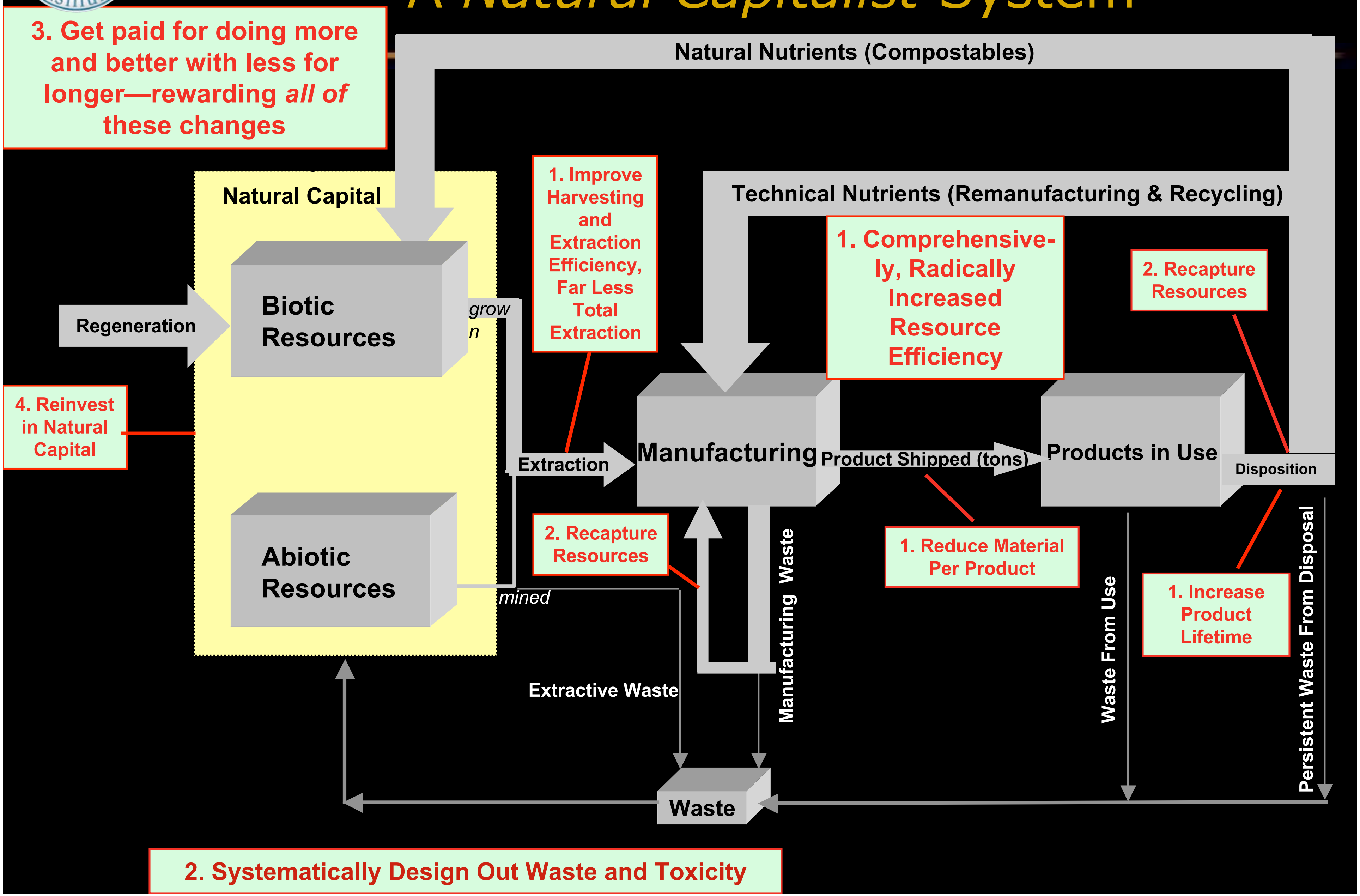
The current system (U.S. numbers to illustrate)



Diagrams courtesy of Don Seville and Rocky Mountain Institute

The resource cycle: a massflow perspective

A *Natural Capitalist* System

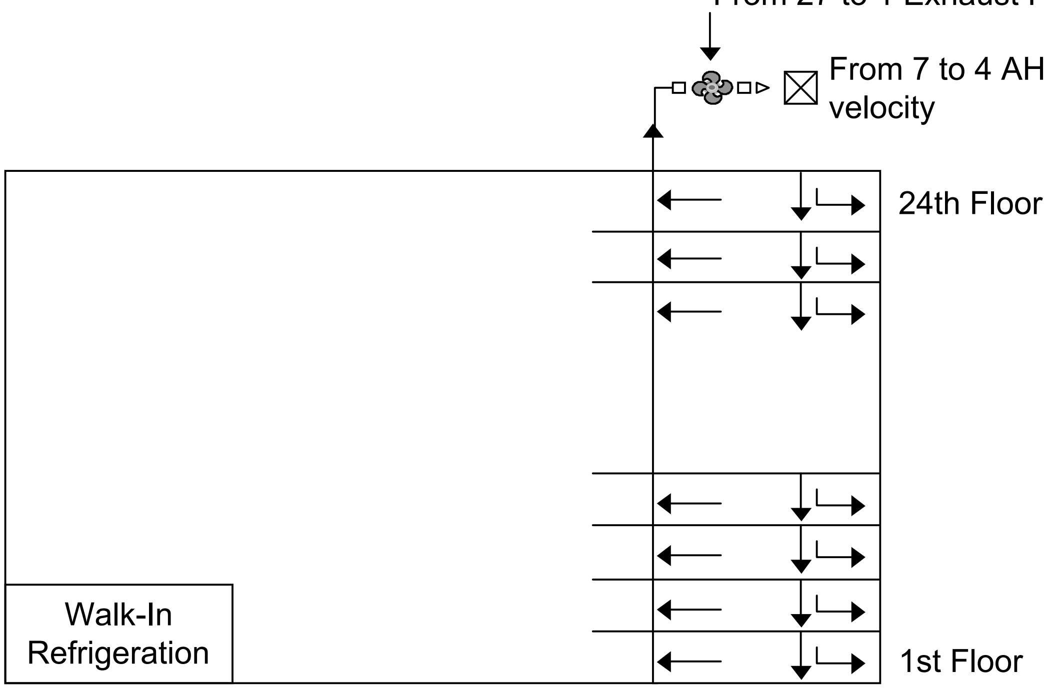


Lots of luscious low-hanging fruit: two Asian fab retrofit examples

by RMI Senior Fellow LEE Eng Lock, Singapore

- Big Asian back-end fab: 1997 retrofit, mainly HVAC
  - Cut energy use 56% (69%/chip) in 11 months with 14-month average payback; further projects then saved even more
- STMicroelectronics's world-class Singapore fab
  - '94–97 retrofits saved US$2.2M/y with 0.95-y av. payback
  - '91–97 improvements saved $30M; kWh/150mm std. wafer fell 60%—providing 80% of energy capacity for a 3.5× expansion; 80% paid back within 18 months
  - All retrofits were performed during continuous operation via cryogenic freeze-plugs and hot-taps (>20 each)!
- This low-hanging fruit already fell down and is mushing up around the ankles—and the tree keeps pelting our heads with more fruit
- If these fabs had been properly designed, none of this would be possible—but they used infectious repetitis

Or consider LEE Eng Lock's 92% retrofit reduction in electric power used for fluid movement: cold-room water pumps, air-handling-unit fans, and rooftop toilet stack exhaust fans (Hyatt Hotel, Singapore)



	kW Original	kW Retrofit	% Δ
Exhaust	25	1.6	-94%
AHU Fans	45	2.6	-94%
CRWP	22	3.1	-86%
Total	**92**	**7.3**	**-92%**

- CRWP
  - Eliminate valves
  - Bigger pipes
  - No elbows
  - Much simpler pipe layout

(22 kW → 3.1 kW)

92→7.3 kW, a 92% saving

Typical areas for big industrial savings

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

We'll focus here mainly on *one* example—pumping systems. The basic tools are well understood…

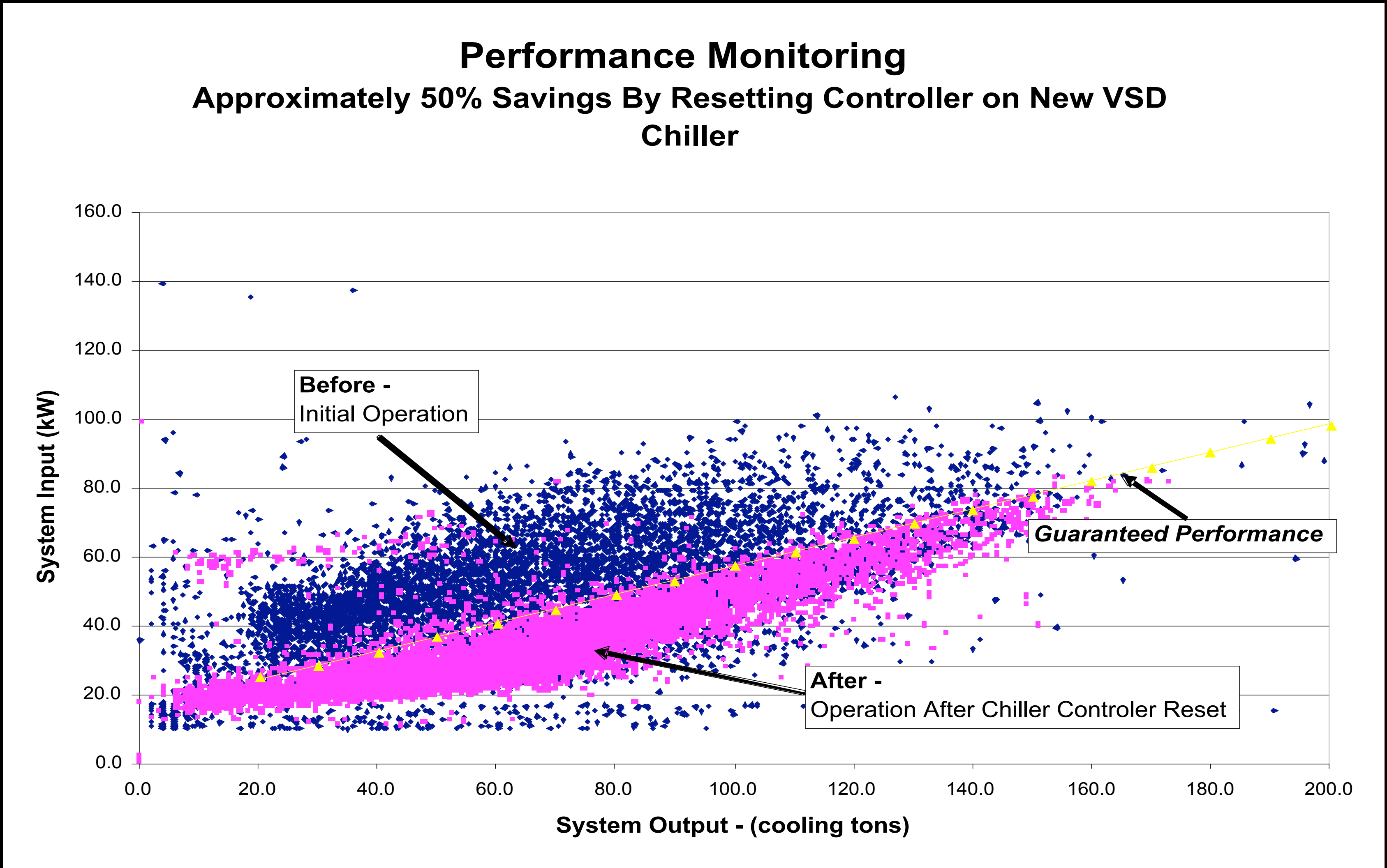
What is efficiency worth? (you'd better know up front)

- For example, consider the 25-y present value (10%/y real discount rate for a high-tech industry) of saving electricity in a chip fab at $0.08/kWh levelized, *zero* HVAC capex, nominal 1 kW/t HVAC + 10% parasitics
  - 1 watt of cleanroom power use and heat release = *$9 opex…or ~$10–11 including filters*
  - 250 Pa (1"w.g.) of makeup/exhaust ΔP = $4.2 per L/s or $8.4/cfm (with standard fan efficiencies)
  - Each percentage point's efficiency gain in an 8,766 h/y motor in conditioned space = $152/kW = $113/hp
- Without such metrics to know what efficiency is worth, you and your suppliers can't invest in it wisely

Information is cheap, powerful, but viscous

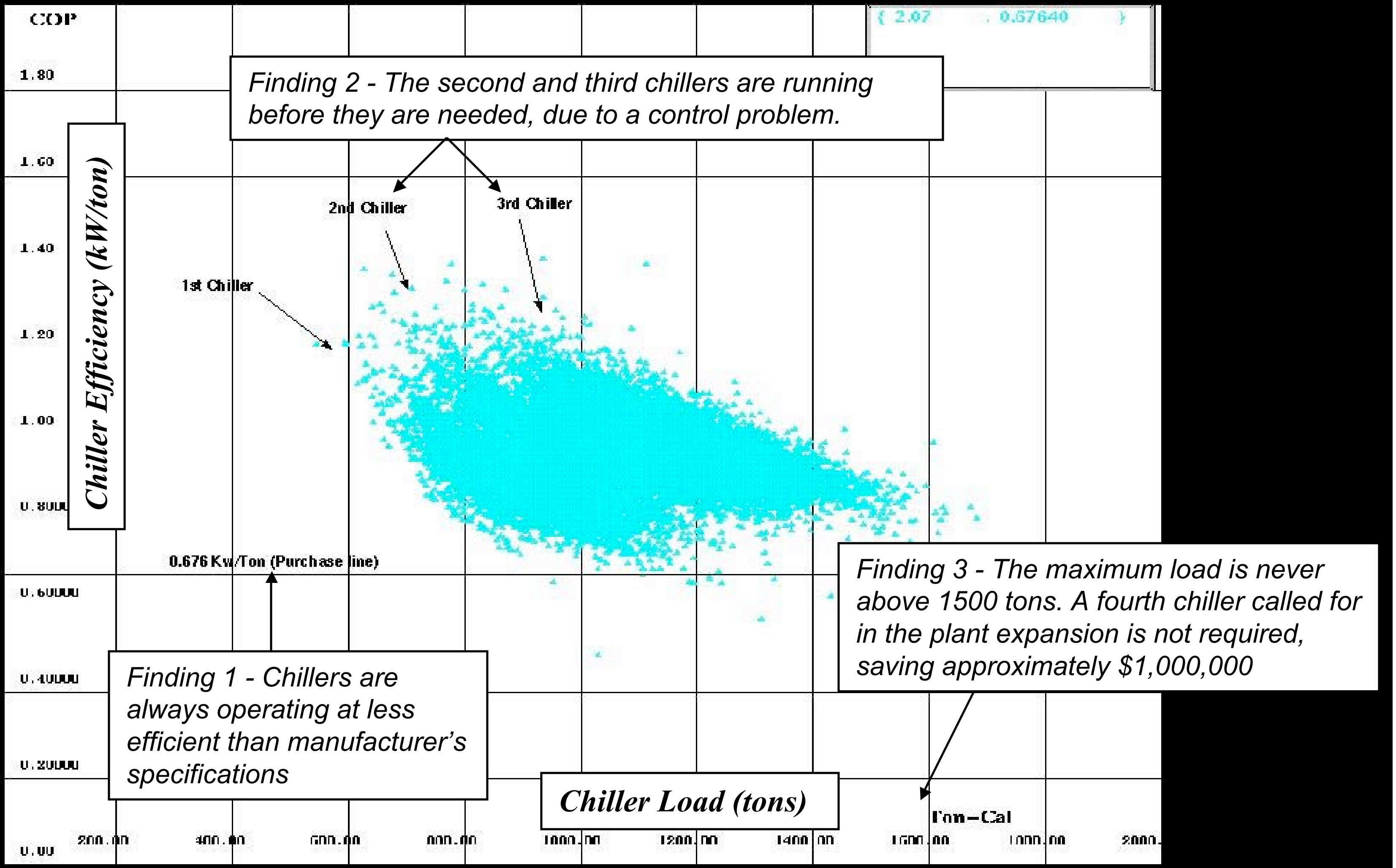
- One factory saved $30,000 the first year by… labeling the light switches
- A hard-drive factory saved a great deal of money by properly labeling the red/green-zone "idiot gauge" showing pressure drop in its big filter banks
  - "Cents per drive" and "Million $ profit per year" (nonlinear)
- Innumerable facilities have saved untold energy and maintenance costs by measuring
- But many more use poor or uncalibrated sensors
- Few plants are designed to measure what's needed
- And very few present key efficiency metrics to the operator, real-time, in effective *graphics*

Measuring performance is the beginning of wisdom



Courtesy Rumsey Engineers

Benefits of monitoring with good graphic display



Courtesy Rumsey Engineers

But 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

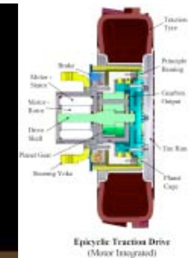
  Thanks to Jim Rogers PE for most of these examples, which we've converted to constant dollars

  - 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!

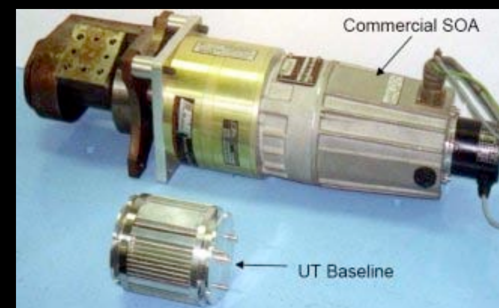
It's not mainly about the hardware anyway!

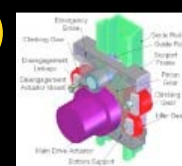
- To be sure, energy-saving technologies get not only cheaper but also more powerful
- Not just the wizardry of nanotech & catalysis, of microprocessor controls and new materials
- Even more importantly, the mundane (next two slides) and the unexpectedly basic (3rd)
- But *most* importantly, the *design* revolution that artfully combines well-known technologies to turn diminishing returns into expanding returns—making *very* large energy savings cost *less* than small or no savings
- Add *that* to new tech and the mind boggles…

1. Electromechanical actuators (rotary and linear, all sizes)



- Prof. Delbert Tesar, UT/Austin, is doing for EM actuators what Gordon Moore did for chips
- Equipping an aircraft carrier with modern electric actuators, replacing hydraulics in 12 main applications, would save:
  - 1.4 million pounds (weight reduced 3.2×)
  - 500 billets (personnel reduced 2.9×)
  - 61,000 square feet (space reduced 9.2×)
  - Maintenance (reduced 2.7×, complexity 2.2×)
  - $20–25 million/y of operating cost

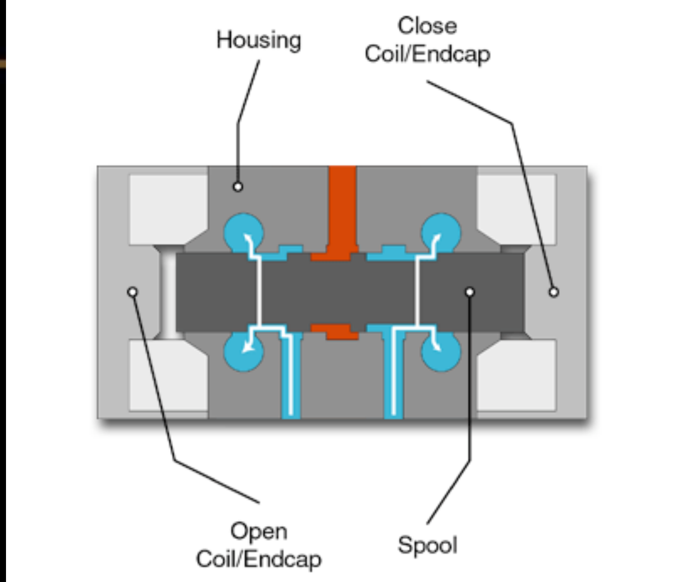




- Order-of-magnitude improvements in power density, reliability, and precision; same/less cost
- Most if not all of what's now done with hydraulics is better done with electrics

2. Basic hydraulic innovations

www.sturmanindustries.com



Leader in hydraulics, magnetic valve/actuators

Digital Hydraulic Operating System

- Digital Valves—high speed, precise control
- Hydraulics—high power density
- Intelligent Electronic Control

Technology benefits

- High switching speed—180 μs @ 0.15-mm stroke
- Small size, low mass—3-mm-dia. spool @ 0.5 gram
- Low electrical power usage—0.125 W @ 10 Hz
- Two stable low- or zero-energy states (no "hold" energy)
- Integrated position feedback for fast closed-loop control
- Fail-safe designs

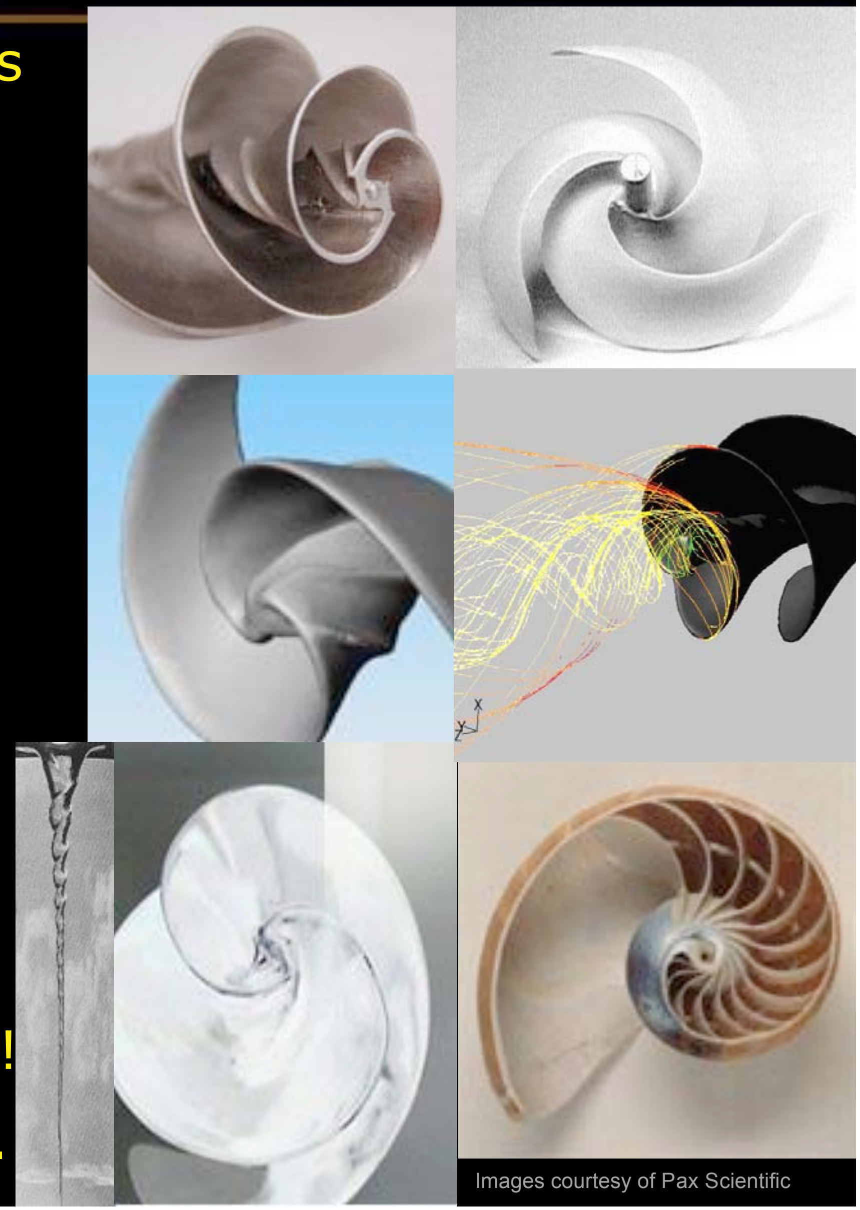
Hydraulic valves, actuators, pneumatic valves

Applications: Mobile hydraulics, pick & place machines (robots), engine controls, pump controls,…

Superior motion controls (real-time closed-loop) permit enormous efficiency gains, *e.g.*, starting with a brief "kick" to overcome deadweight inertia, then using only low-energy traverse motion

3. Not just steady technological evolution but "punctuated equilibrium," even in fundamental and mature applications like fluid flow

- Biomimetic rotor from Jay Harman's firm Pax Scientific, San Rafael, CA (www.paxscientific.com)
- Fibonacci spiral shape matches the pattern of minimum-drag *laminar vortex flow* found throughout nature
- In pumps, fans, stirrers, turbines, turboexpanders, etc., such overlooked novel rotor forms can significantly raise efficiency and reduce noise
  - *E.g.*, computer muffin fans get +30% flow/W or –10 dBa
- Commercialization is now starting
- Nearly unlimited applications: surprisingly, the phenomena don't depend on scale or Reynolds number!
- May ultimately save >10% of all el.



Images courtesy of Pax Scientific

Designing for breakthrough industrial energy efficiency: the eightfold way

1. Business vision, model, strategy, & 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 makes it possible to:

Capture multiple benefits

Make them compound

Free up the most capacity

Avoid the most capex

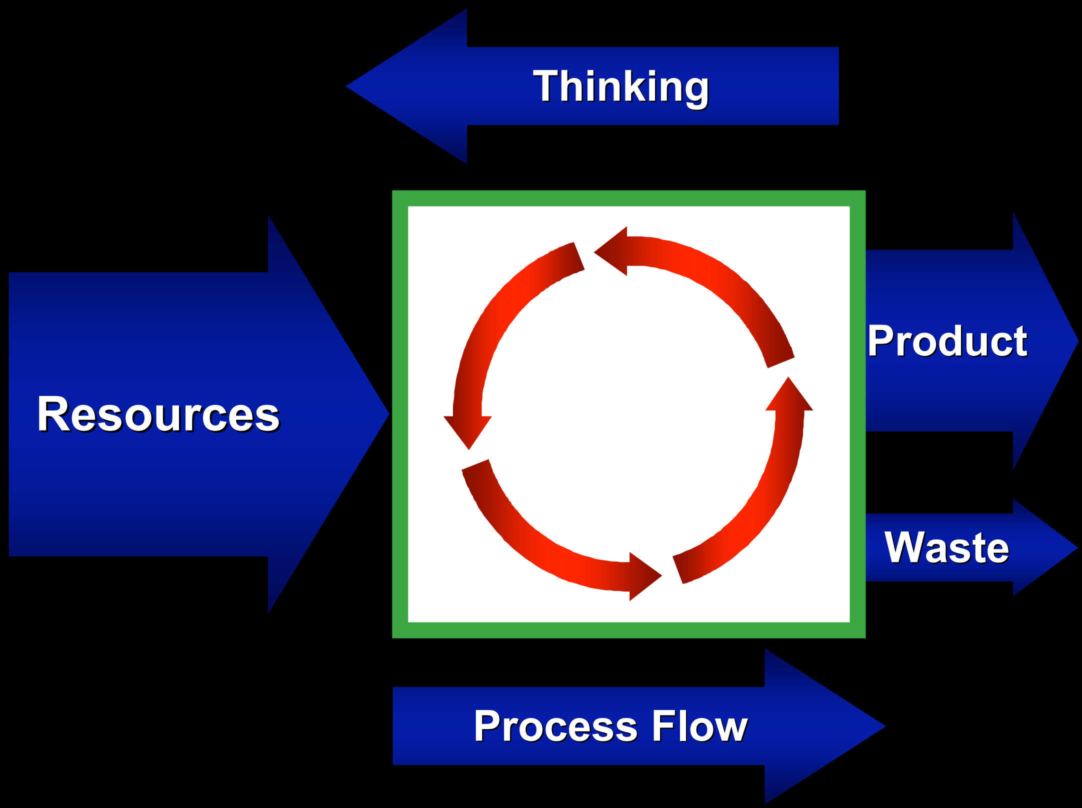
Eliminate the most waste & harm

Make the most profit

Do the most good

Have the most fun

But whole-system designers must think in the *opposite* direction to the process flow



- Save capex, not just opex, by making equipment unnecessary, smaller, or simpler
- Consider the whole system all together
- Optimize it for multiple benefits
- Reduce waste:
  - Can wastes be reduced or eliminated—designed out?
  - Can wastes be recycled as inputs?
  - Can wastes be made into other products?
- Capacity used to make waste can now make value instead—winning more capacity at zero capex:
  - Debottlenecking
  - Throughput gains

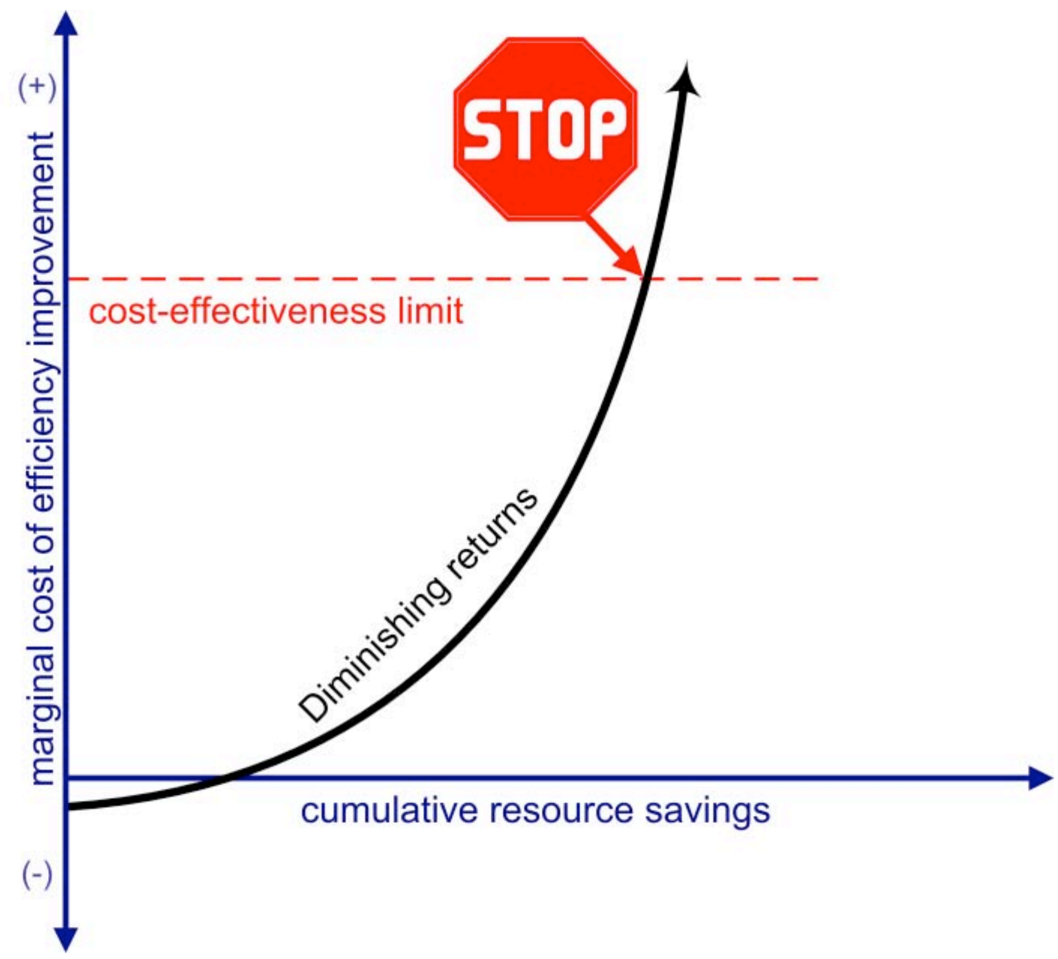
Design for *whole*-system performance, not sub-system performance!

Examples from RMI’s industrial practice (~$30b of facilities)

- Save half of motor-system electricity; retrofit payback typically <1 y
- Similar w/ 30–50+% retrofit savings of chip-fab HVAC power
- Retrofit very efficient oil refinery, save 42%, ~3-y payback
- Retrofit North Sea oil platform, save half the electricity, get the rest from wasted energy streams
- Retrofit USNavy *Aegis* cruiser’s hotel loads, save ~50%, few-y paybacks
- Retrofit big LNG plant, ≥40% energy savings; ~60%? new, cost less
- Redesign $5b gas-to-liquids plant, –$1b capex, save >50% energy
- Redesign giant platinum mine, 43% energy savings, 2–3-y paybacks
- Redesign new data center, save 89%, cut capex & time, improve uptime
- Redesign new chip fab, save ~67%, eliminate chillers, reduce capex
- Redesign supermarket, save 70–90%, better sales, ?lower capex
- Redesign new chemical plant, save ~3/4 of electricity just in auxiliaries, cut construction time and cost by ~10%
- Redesign new 58m yacht, save 96% potable H_2O & 50% el., lower capex
- “Tunneling through the cost barrier” now observed in 29 sectors
- Needs engineering pedadogy/practice reforms; see www.10xE.org

10xE FACTOR 10 ENGINEERING

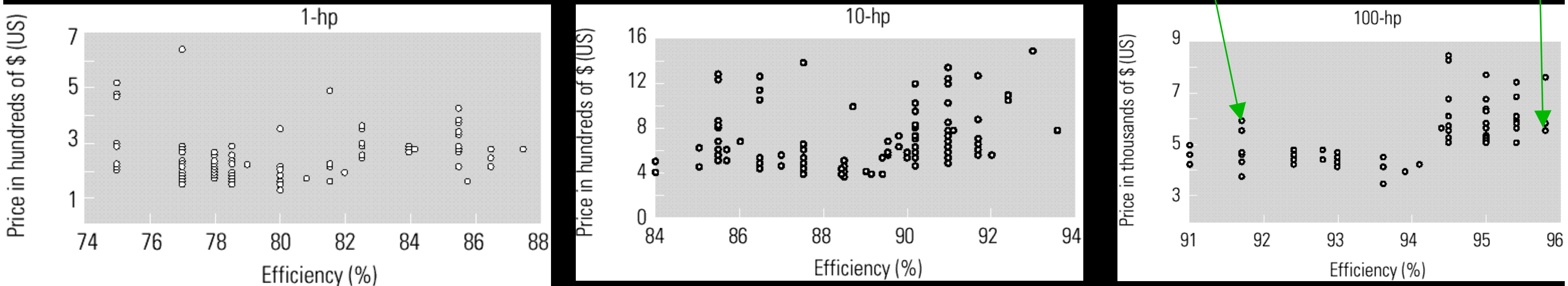
Old design mentality: always diminishing returns…



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

Buying this motor instead of this motor can cost you >$20,000 present value

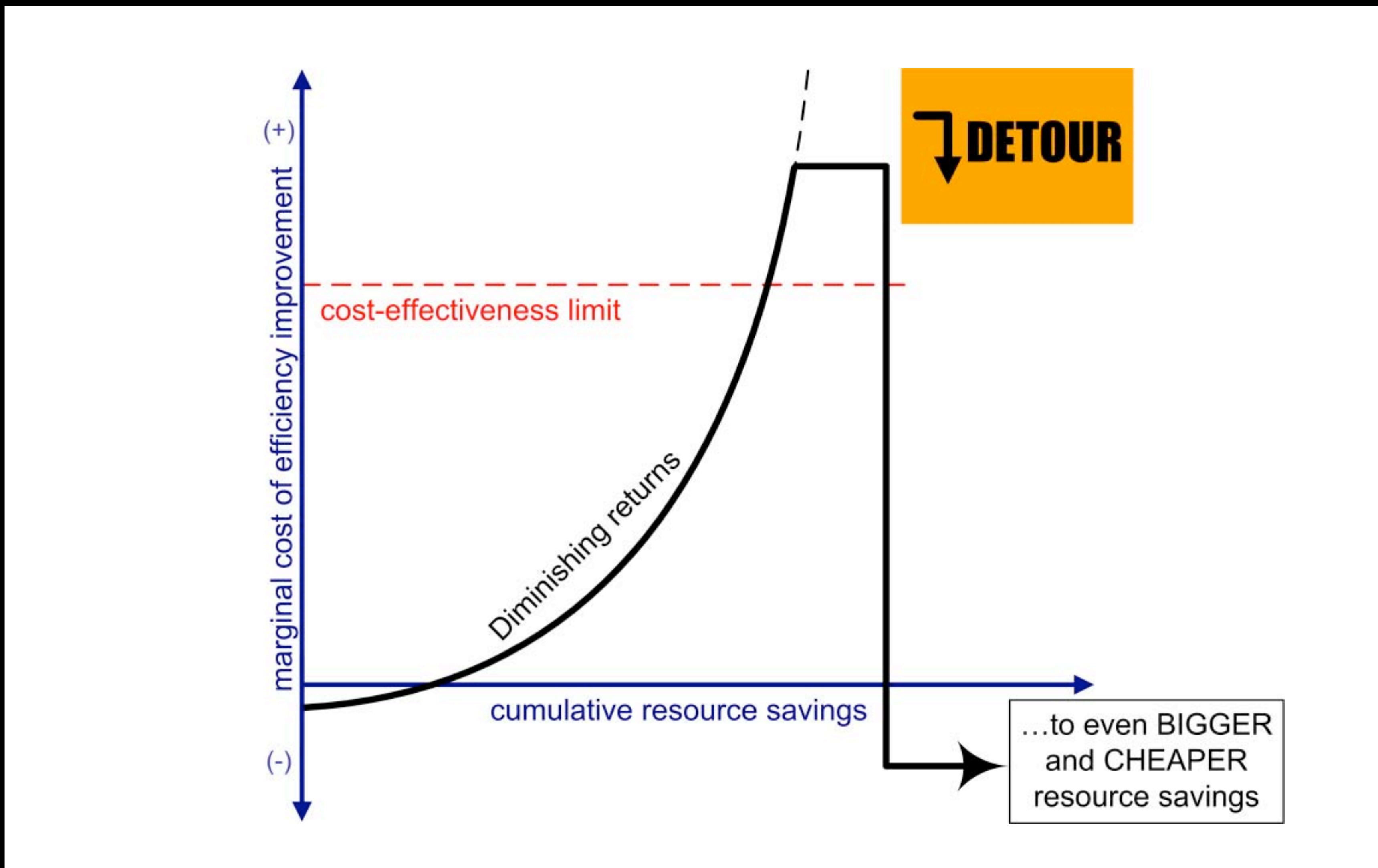


E SOURCE (www.esource.com)* Drivepower Technology Atlas*, 1999, p. 143, by permission

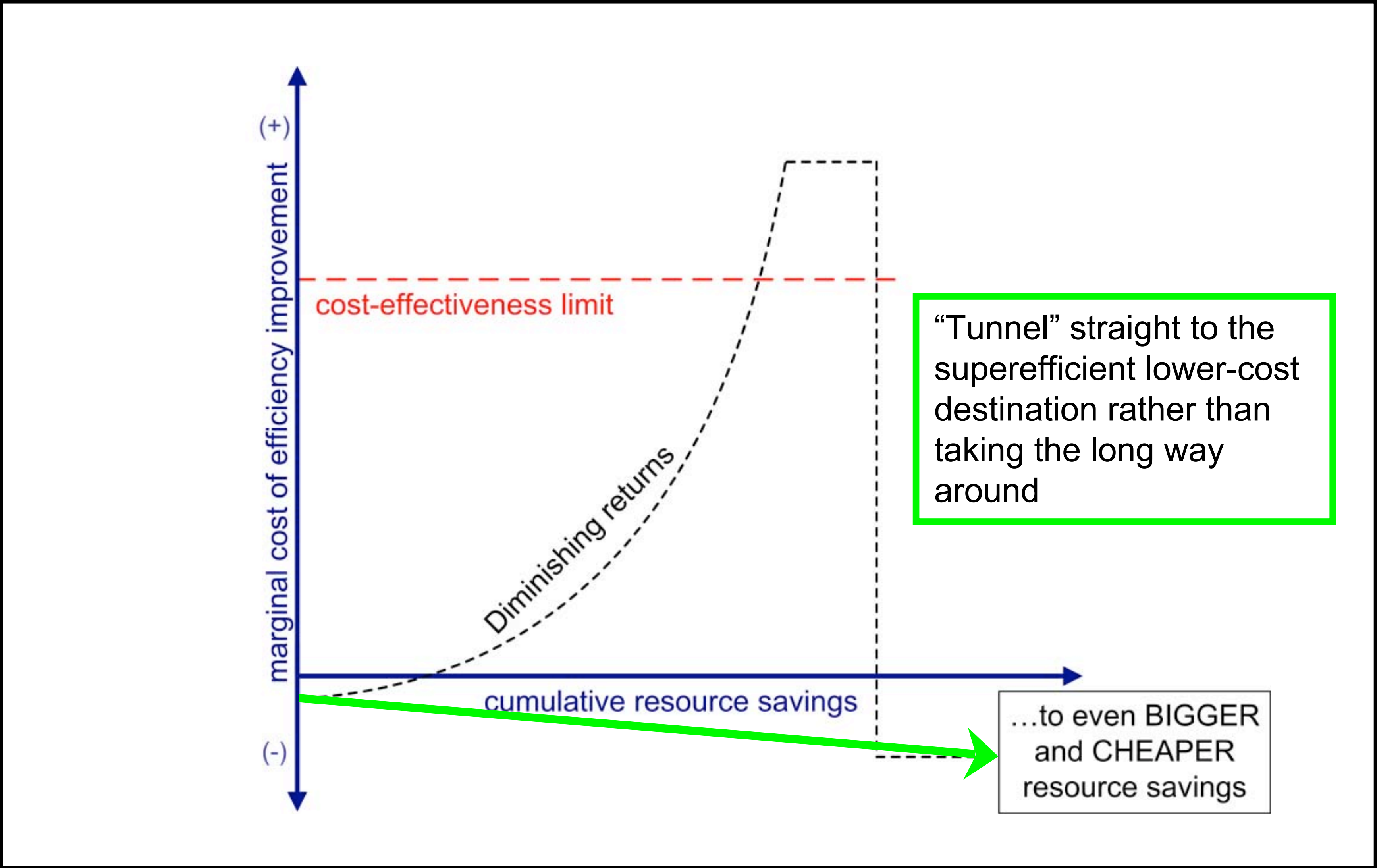
◇ Same for industrial pumps, most rooftop chillers, refrigerators, televisions,…

◇ "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"



Edwin Land

"Invention is just a sudden cessation of stupidity"

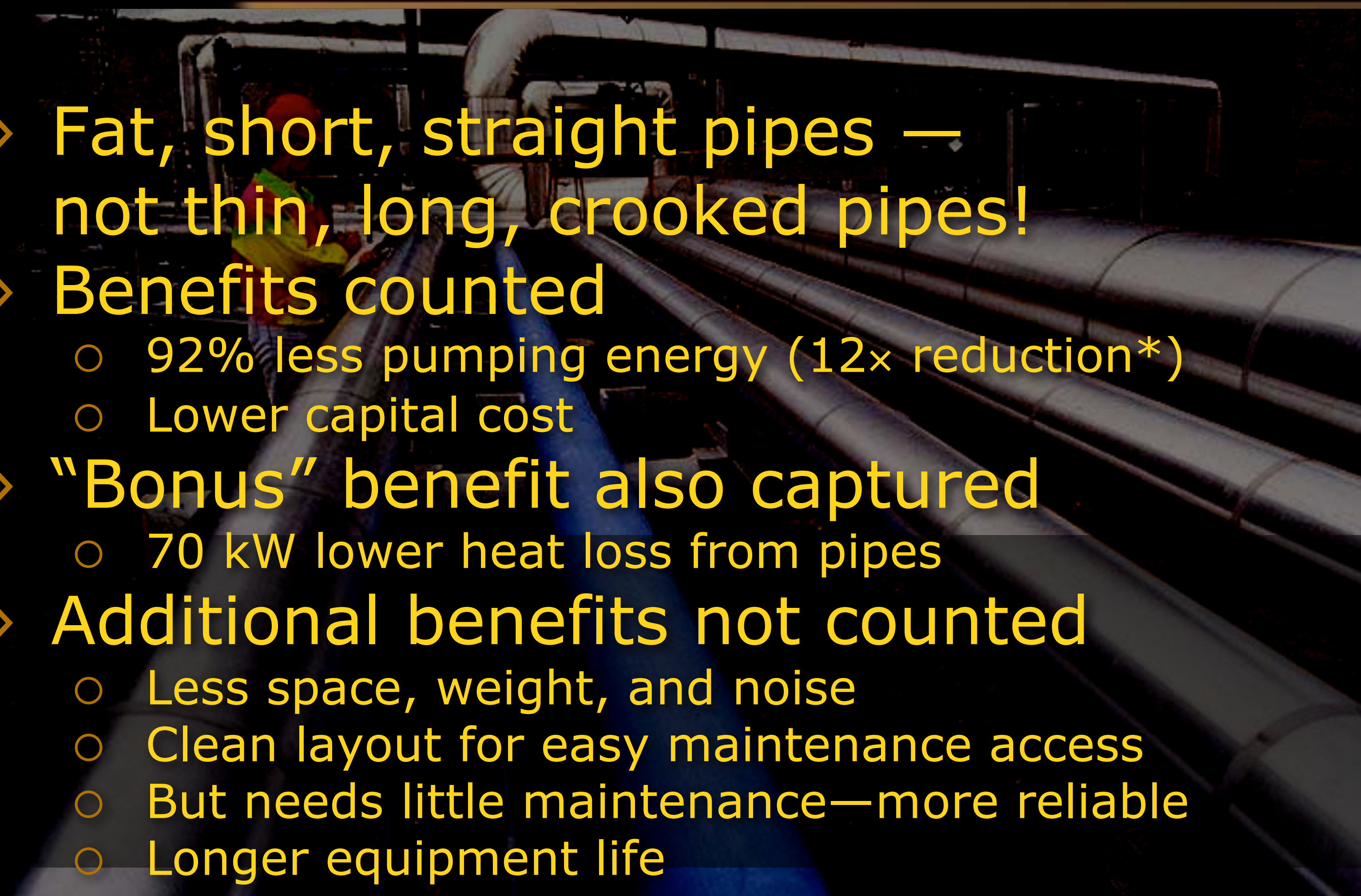
New design mentality

- Redesigning a standard (supposedly optimized) industrial runaround pumping loop cut its 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

No new technologies, just two design changes

No new technologies, just two design changes



- Fat, short, straight pipes — not thin, long, crooked pipes!
- Benefits counted
  - 92% less pumping energy (12× reduction*)
  - 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 too and save…~98%?

*Designer, Ing. Jan Schilham, says this was measured, but spreadsheet predicted 84% savings; we’re tracking down this discrepancy

This case is archetypical

- Most technical systems are designed to optimize isolated components for single benefits
- Designing them instead to optimize the whole system for multiple benefits typically yields ~3–10x energy & resource savings, usually costs less to build, yet improves performance
- We need a pedagogic casebook of diverse examples…for the nonviolent overthrow of bad engineering—RMI's *10xE* ("Factor Ten Engineering") project at www.10xE.org—partners welcome

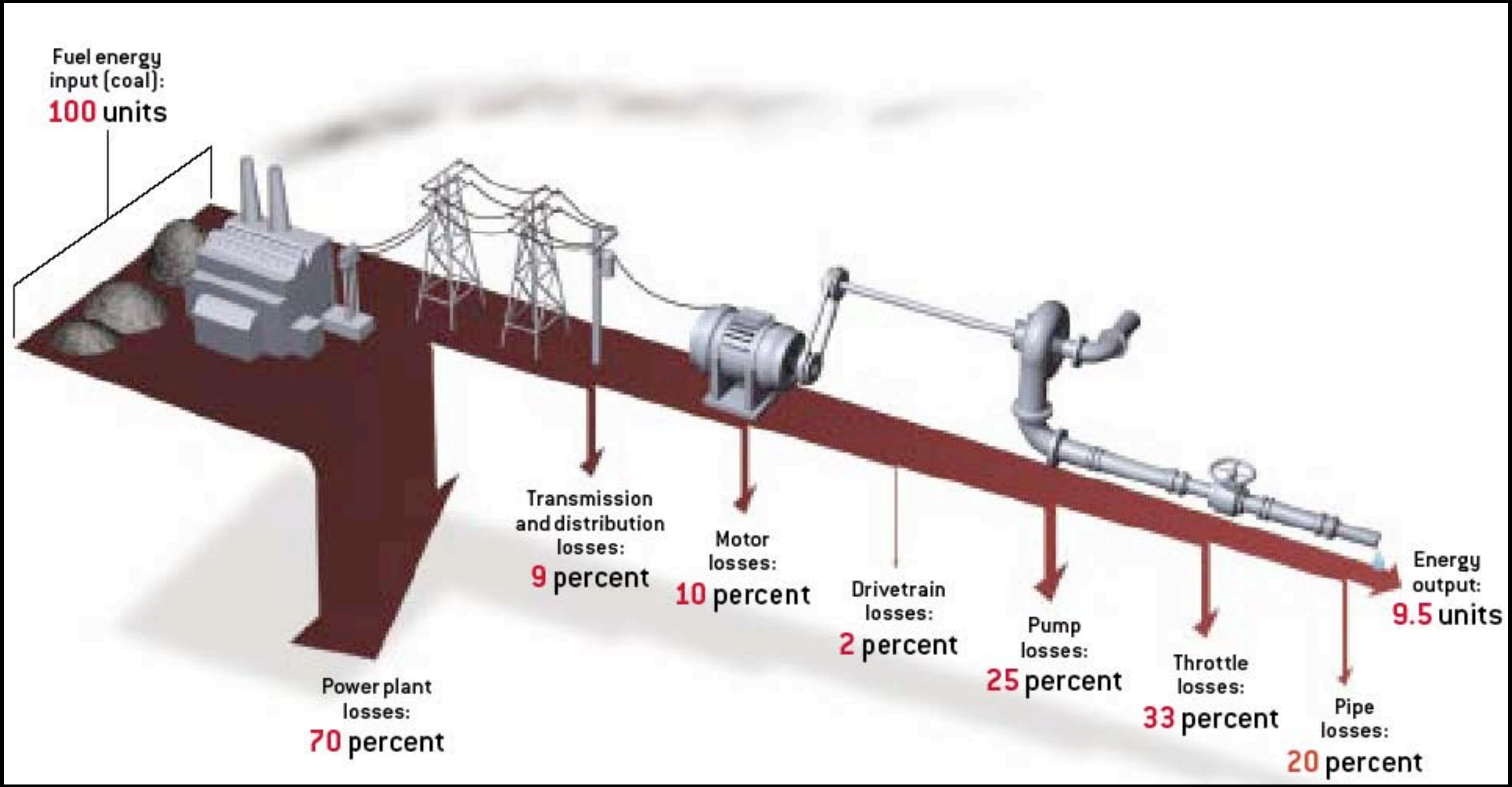
A peculiar pedagogic error

- An RMI PhD engineer's review of all main U.S. engineering textbooks found none that correctly presents two basic design cases
  - They say to optimize pipe diameter against saved friction, ignoring the capital cost of the *pumping equipment*
  - They say to optimize thermal insulation against saved heat cost, ignoring the capital cost of the *heating equipment*
  - Instructions for designing a wall or a window by itself are no substitute for a way to design a whole house combining them
  - America's ~$9 trillion worth of houses reflect this design error
- It's common for businesses to ignore lifecycle costing by counting *only capex, not opex*
- But this is the *opposite* error—it counts only *opex, not capex* (beyond that of one narrowly defined component—the insulation or the pipe)

Why focus on pumping examples?

- Pumping is the world's biggest use of motors
- Motors use 3/5 of all electricity
- 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 paying back in 16 months at a $0.05/kWh tariff; but though lucrative, that's not the *first* thing to do!
- Downstream savings are often bigger and cheaper—so *minimize flow and friction first*

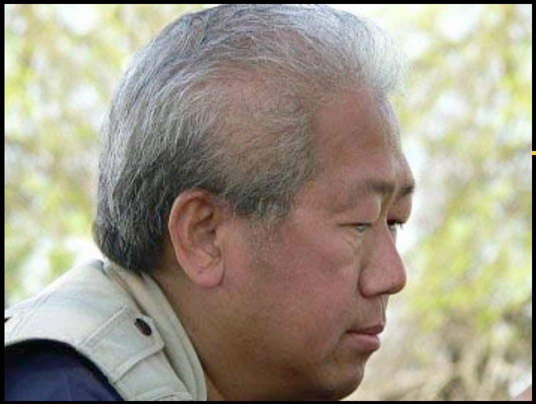
Compounding losses…or savings…so start saving at the *downstream* end to save ten times as much energy at the power plant



Also makes upstream equipment smaller, simpler, cheaper

So how do we do this magic?

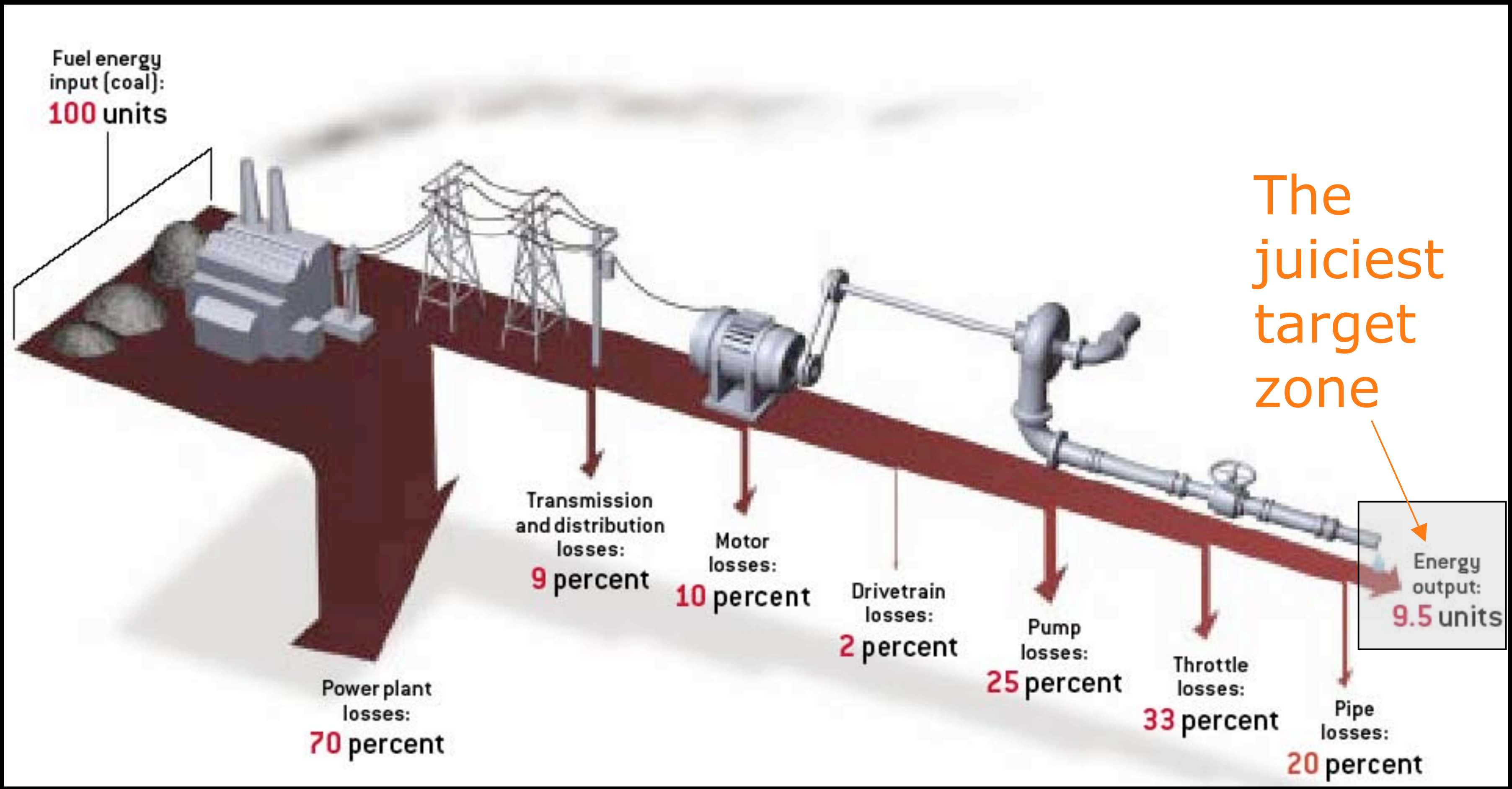
"Like Chinese cooking. Use everything. Eat the feet."



– LEE Eng Lock, Singapore efficiency engineer

Chinese food is world-famous for using every part and wasting nothing—by following a good recipe, with meticulous attention to detail

Let's start all the way downstream, asking why we really need all that flow



First seek to eliminate part or all of the flow: zero flow uses zero resources

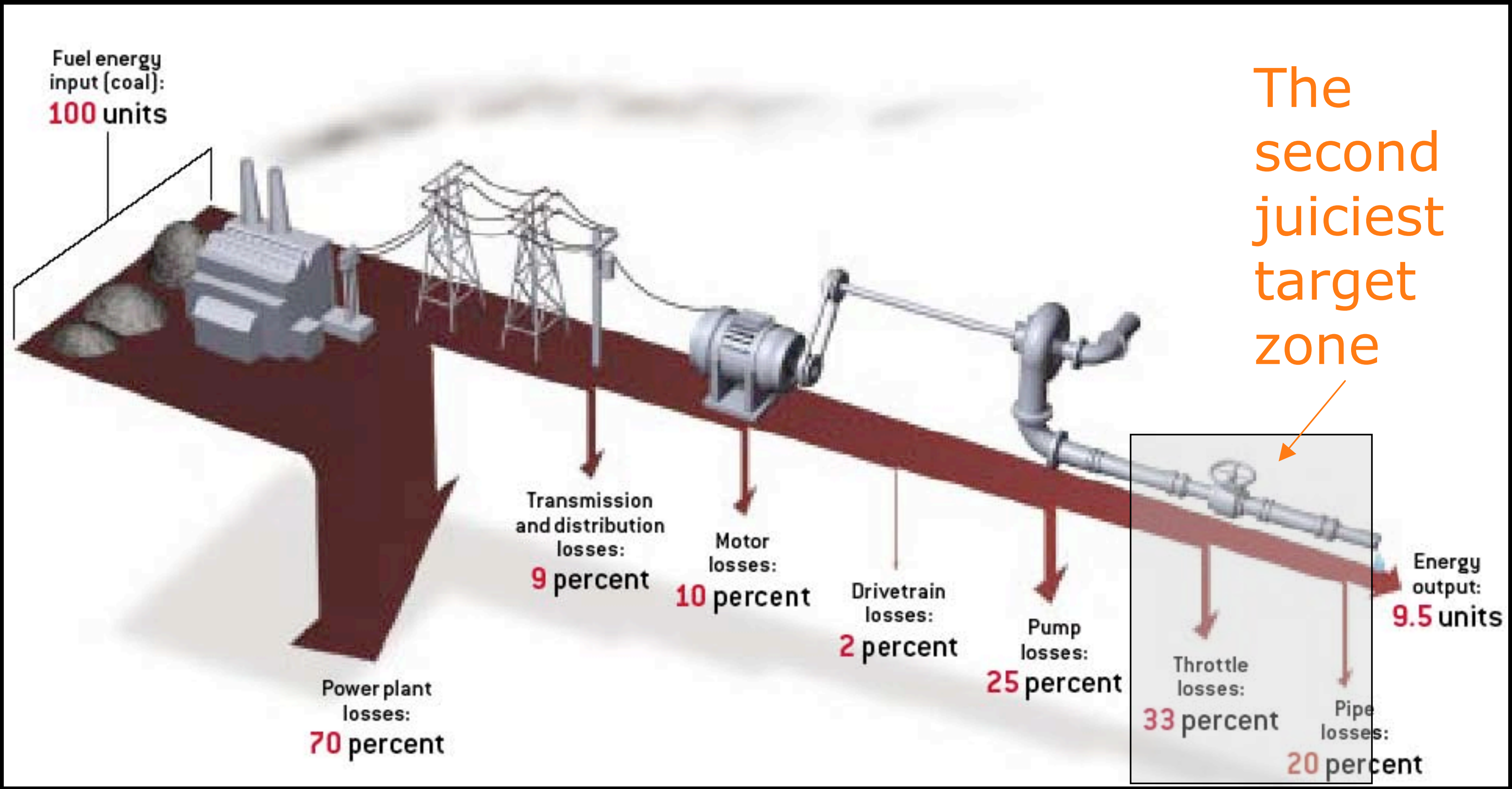
- LNG plant (−161˚C) in a +54˚C desert
  - Each 1 C˚ by which the site is cooled by raising albedo (white sand, crushed shells, etc. instead of grey concrete and black asphalt) saves $59 million (in present value) via lower chiller load and cooler air
  - Sun-rejecting pavings may save *10–20 C˚* ≈ $0.6–1.2b
  - Further potential with better pipe sheathing (what gets hotter than black?)
- Ice-cream plant, best-in-class equipment
  - Insulated box contains pipes to freeze the cream
  - The same box also contains the compressors and motors!
  - Taking them out of the box uses fewer kWh to freeze the same flow of cream
- Pump no cold water in building that stays cooler
- No refrigerative cooling (nor much of its pumping) needed because other cooling methods were substituted for chillers—how?

Highly reliable process cooling below condensing temp. *without* chillers

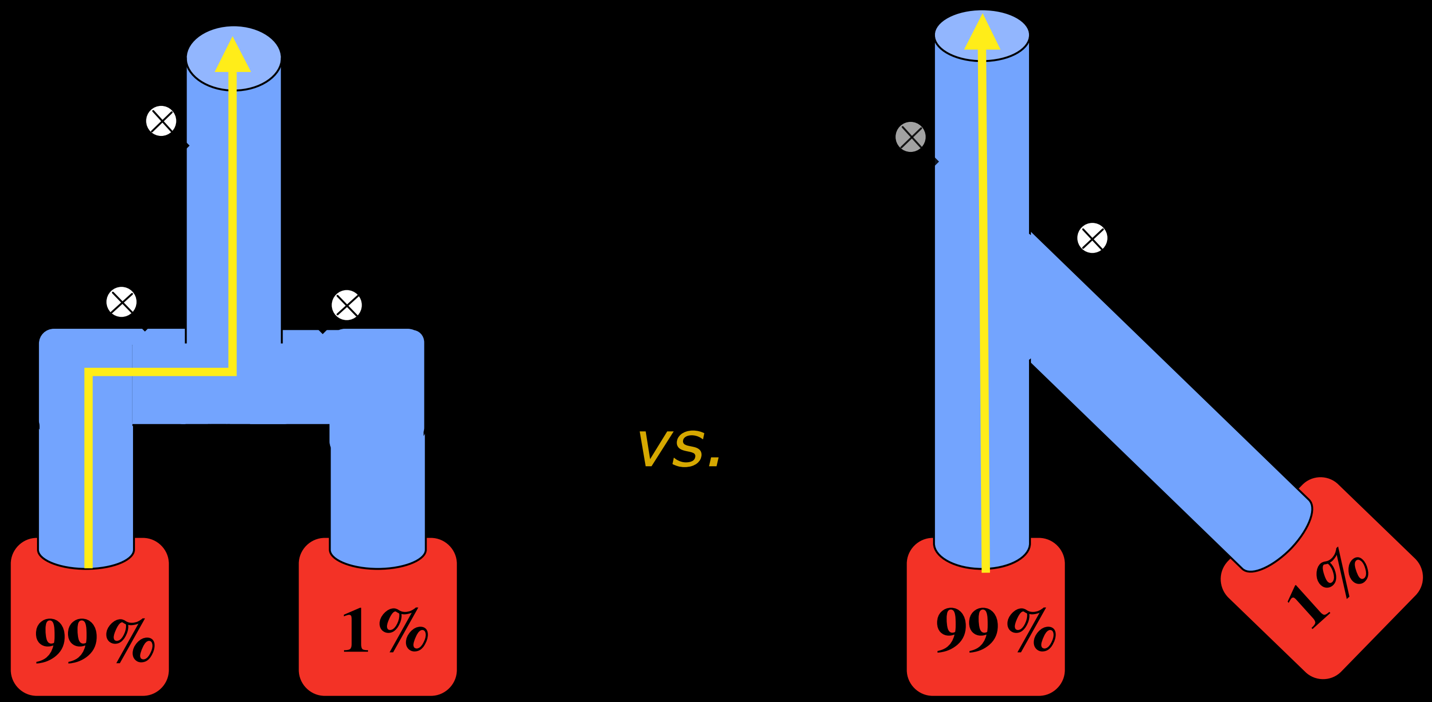
(COP = Coefficient of Performance = cooling out / electricity in)

- First meet most of the load with airside or waterside economizers (CT @0.010 kW/t + ChW pump @0.018 kW/t = COP 125, $100/t)
- Dig a hole, ?insulate it, line it, use auto-snowmaking machines (COP hundreds, 50 t/unit-h) to spray slush on subfreezing nights
  - Optionally, cover “Mt. Sherbet” with foil bubblepack, foam, or straw
  - Cool with the 0˚C meltwater off the bottom, spray return water back on top
  - Be sure to make it big enough (this method assumes cheap land)
  - Each hectare (2.47 acres), if solid ice 10 m thick or slush ~15 m thick, yields 3 million ton-h of refrigeration at 12C˚ΔT
  - Most temperate zones have over twice the needed ~500 subfreezing h/y (slushmaking works decently below –2˚C, very well below about –5˚C)
  - A big slushpond should cost less up front than a chiller system and have >10 × better system COP—≥100 *vs.* <10
- Or if it’s too hot for an icepond, it’s probably fine for solar or wasted process heat to run triple-effect absorption + [low-temp desiccant + direct/indirect evap = Pennington cycle]; COP ~100

Next, let's minimize the piping system and its friction



Bends cause friction

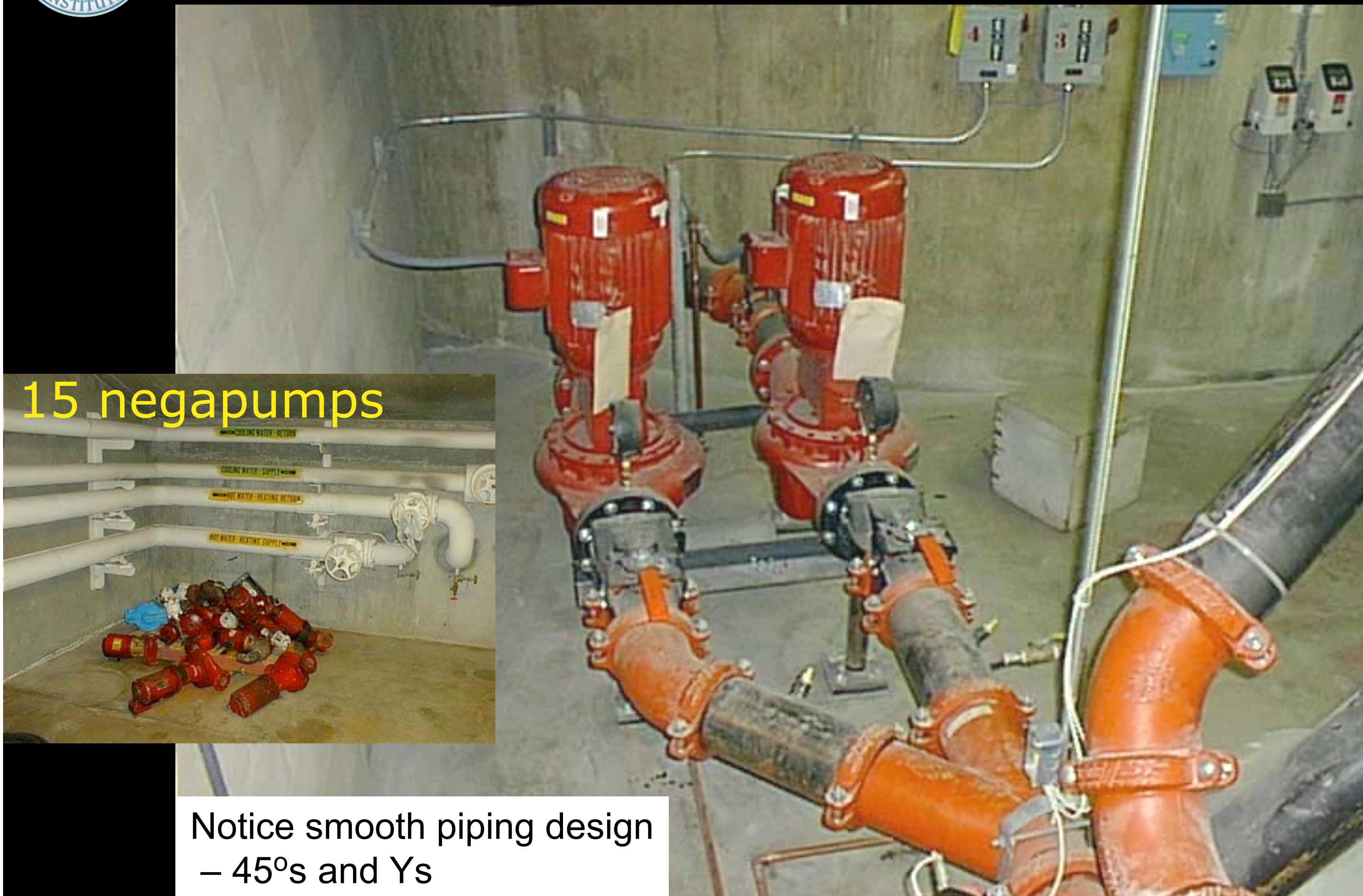


Boolean pipe layout

hydraulic pipe layout

High-efficiency pumping / piping retrofit

(Rumsey Engineers, Oakland Museum)



Notice smooth piping design – 45°s and Ys

downsized CW pumps, ~75% pumping energy saving

Find and untangle the pipe spaghetti

Minimizing piping friction

- Surface finish: *e.g.*, drawn metal tubing is about as smooth as plastic pipe, which can have ~30× less friction than normal metal pipe; and metal pipe has lately become smoother than assumed
- Abrupt bends can have 2× friction of sweet bends
- Segmented bends can have 50% more friction than continuous smooth bends
- One 90° elbow adds the same friction as straight pipe ~35× its hydraulic length*
- Typical industrial piping is so overfitted that it has ~3–6× the friction it should

*Defined as four times the cross-sectional area of the pipe, divided by the length of its wetted perimeter

Pipe fittings: none are best

- Equivalent-length / pipe-diameter loss coefficients:
  - ~2 for a pipe coupling or union
  - ~17 for a 45° elbow
  - ~75 for a 180° return bend
  - Typically ~300 for a *wide-open* or ~475 for a half-open globe valve (!)
- Pipe layout needs to be simple, even ugly, without "pretty" right angles
- *Avoid constrained entering/leaving conditions* that kill pump efficiency: there's generally space to do it right, and if there isn't, make some more

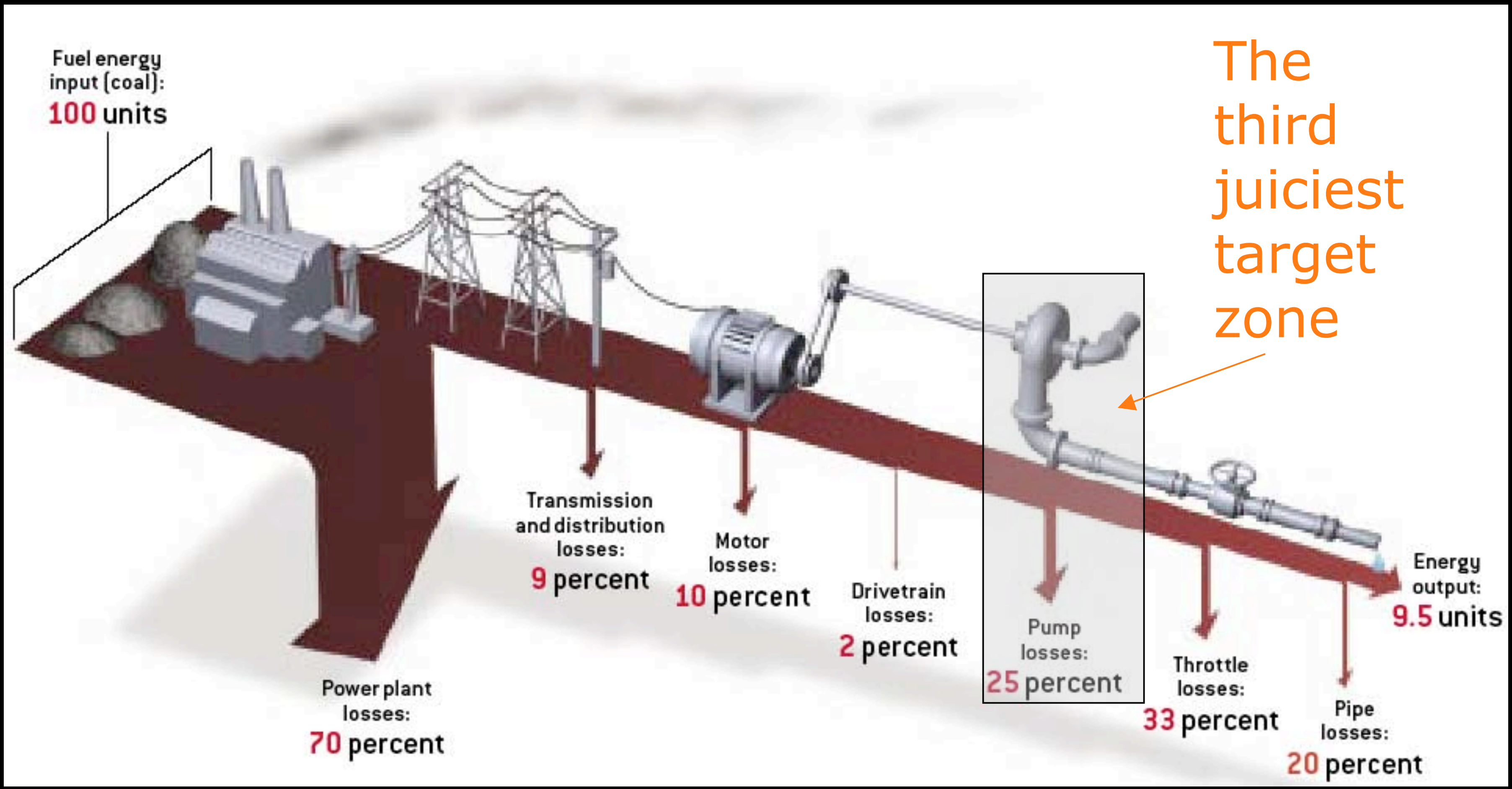
Choice of valves

- Wide-open full-port ball valve (90° turn = full range): friction is about identical to straight pipe, but is significant for gate valves
- Wide-open friction is ~25–35× larger for globe valves (widely used in throttling) than in ball or gate valves
- Yet ball valves cost ~3× *less* than globe valves, without counting capital credit for downsizing pumps, etc.
- Ball valves give good control, but ASDs are even better—we shouldn't throttle the flow at all
- Three-way valves are generally worth taking out

Number of valves

- Many valves are unnecessary—Department of Redundancy Department
- Balancing valves, like primary-secondary pumping, are typically an artifact of excessive pipe friction
- If you think you need balancing valves, first reduce pipe friction: would you use balancing rheostats in home wiring?
- If there's too much friction in one place, reduce it —don't "balance" it by adding more friction (this is the approved ASHRAE method for duct balancing!)

Next, let's optimize the pump



Rightsizing pumping systems: a small but ubiquitous example

- Tommerup & Nørgård (Technical U. of Denmark) analyzed & measured circulating pumps for space-heating water in typical Danish houses; hydraulic power *need* typically <1–2 W (6.346 *Procs. ECEEE 2007 Summer Study*)
- New pumps (~5–8 W_e) amply displace old pumps using 5–10× more power, via proper sizing, pump efficiency 5–10→40%, and proper controls
- New EU building-efficiency standards count such pumps (120 million, ~13-y life) in energy budget; they now use ~15% of a typical home's electricity
- If replacements were rightsized and efficient, they'd save EU ~50 TWh/y (in continuous duty, common in DK) = 8.5 GW baseload power plants = 50 MTC/y = 1/6 of EU's Kyoto CO_2 reduction target

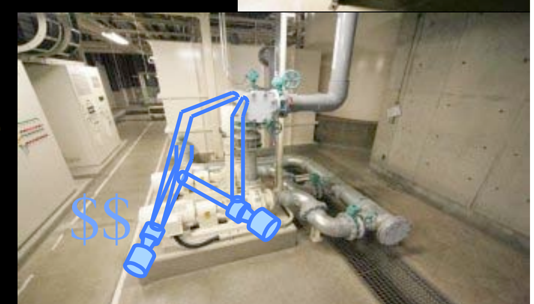
Optimize for the operating conditions actually *measured*

- Rules of thumb & piled-up margins destroy pump efficiency
- If you specify the pump within 10% of its Best Efficiency Point, does it really *run* there?
  - Use adjustable-speed drives to run in the bull's-eye, then recheck later to make sure you're still there
- If there's much variation, specify pumps with a big bull's-eye
  - Consider multiple pumps, each optimized for a piece of the load curve
  - Use ASDs to avoid having to trim impellers of loads decrease
- 4–6, even 8, percentage points' efficiency often costs no more (when specifying European industrial pumps)
- Superefficient pumps are usually very cost-effective
  - *E.g.*, a major oil company sought a subsidy for a 25-m-head, 64-m^3/h, 64%-efficient Sulzer pump instead of a 38%-efficient Turo…but it should have been close to 80% efficient!
  - Emerging Pax-rotor pumps should be even better

Common pump errors

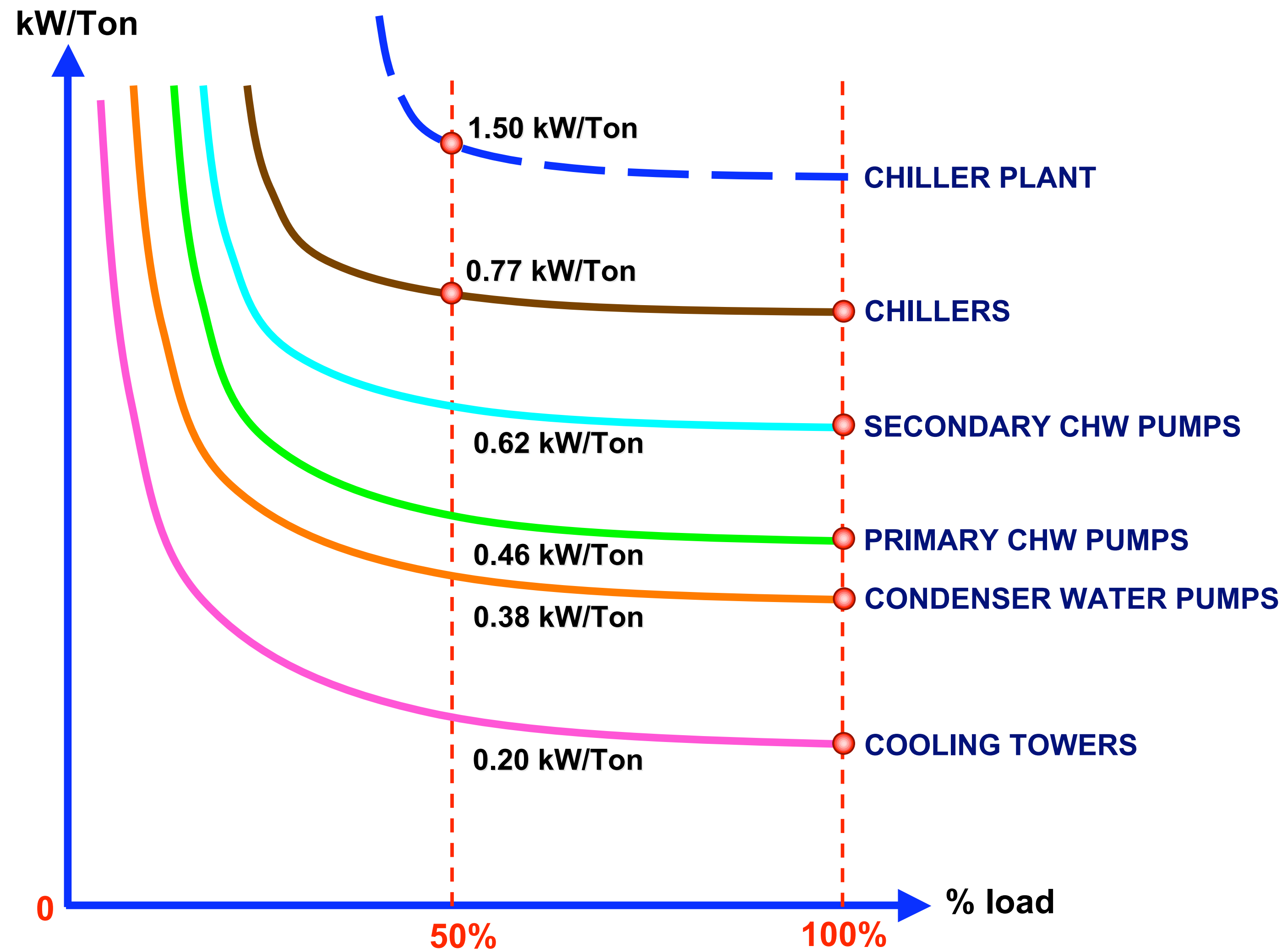
- Oversized pumps for "flexibility": better to specify the right size now, but design for changes later
  - Specify pad and geometry to accommodate other sizes
- Constrained entering and leaving conditions

  - Pipe bends & fittings cause turbulence, miss bull's-eye
  - Use ≥5 diameters' clear pipe run on inlet, ≥3 outlet
- Unnecessary friction-causing fittings
  - Bends, end suction diffuser, triple-duty valve
- If pipes *look* neat, they'll lose money



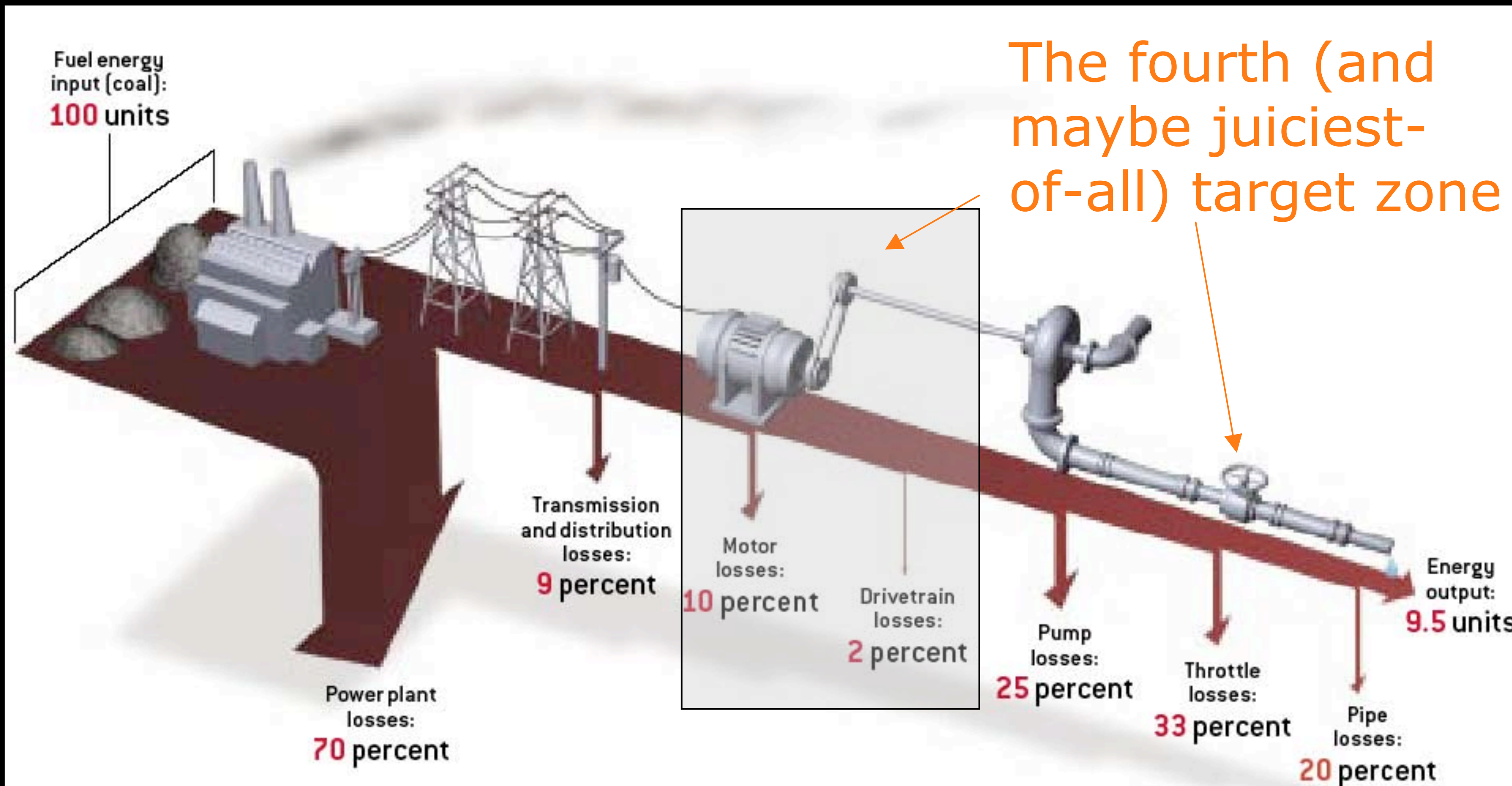
NB: If you can retrofit a system to reduce the *flow* through the *same* pipe, this effectively oversizes the pipe, greatly reducing friction (nearly $\propto d^{-4.8}$)—and energy use falls roughly as flow^3 × friction!

Chiller *system* efficiency (not just chiller efficiency) varies substantially with load: what if your car had only one gear? Lesson: multiplex-unequal staging + ASDs



Courtesy of LEE Eng Lock

Next, let's optimize the drivesystem and its [often missing] controls



By now the motor is probably much smaller

Most induction-motor retrofits…

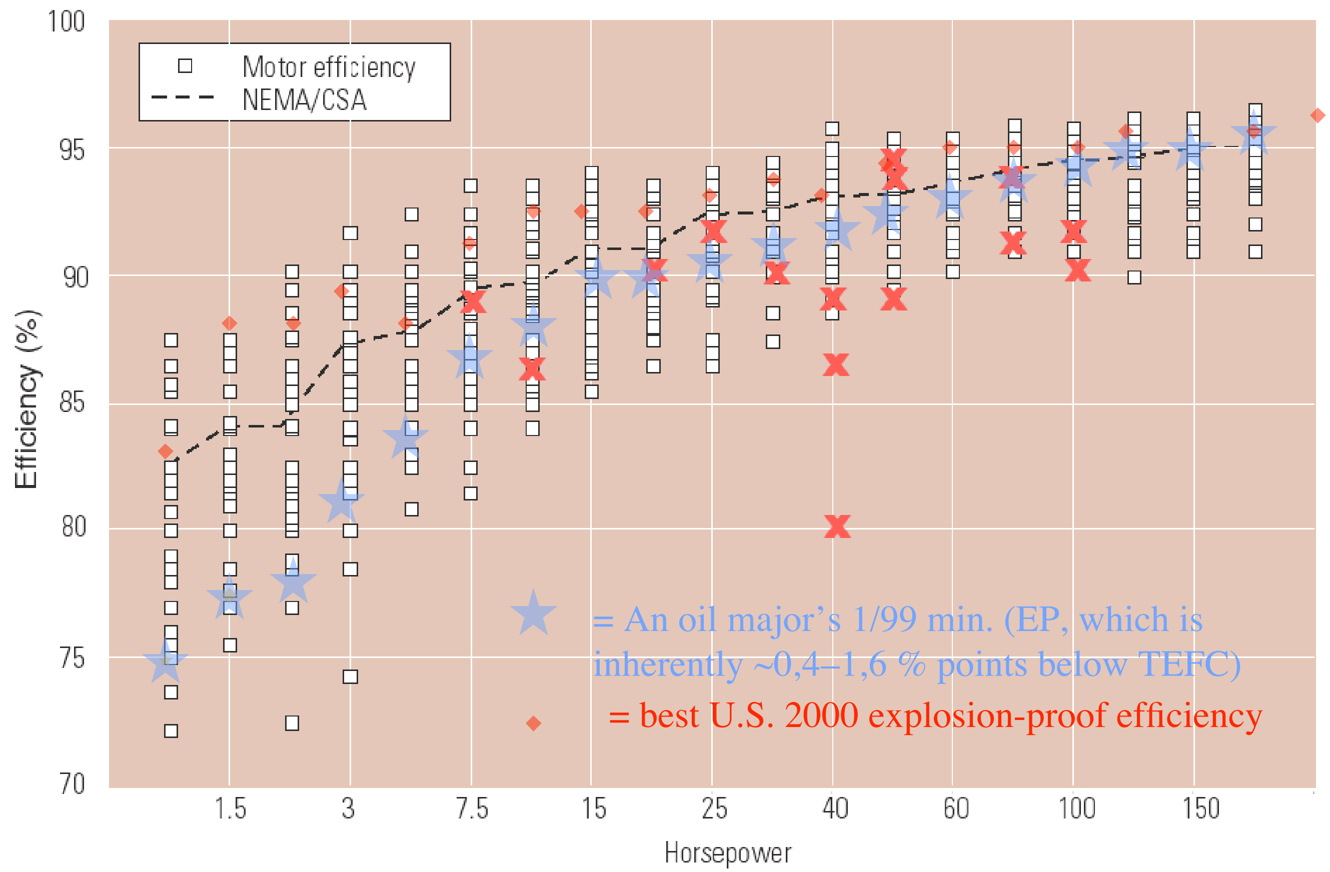
- Use only two kinds of improvements
  - **"High-efficiency" motors** instead of less efficient ones (but "high" efficiency isn't good enough—only best-in-class efficiency is optimal, with very rare exceptions)
  - **Adjustable-speed drives** (ASDs = VFDs = VSDs = inverter drives) in appropriate applications, which are more numerous than commonly supposed: ASDs can optimally trim pumps to run in their efficiency bull's-eye as process needs shift, thus eliminating throttling valves—generally a good idea
    - Would you drive your car with the accelerator floored and control speed with the brake? What if the car were a cube-law device?
- Both these measures are often worthwhile
- They typically save ~15–20% of drive electricity, at costs of several ¢/saved kWh

Value of motor efficiency

- Each percentage point improvement in a continuous-duty induction motor has a present value of $70/kW ($47/hp)
  - 5%/y real discount rate for 20 y
  - 5¢/kWh tariff including any demand charge
  - unconditioned space
  - 5% distribution losses back to site meter
  - no reactive losses, heating, or demand charges counted
  - all other savings mechanisms omitted

Efficiency of 1800-rpm induction motors on the U.S. market in 1996 vs NEMA and CSA standards

A wide range of efficiencies is available in each size class, including models that exceed the definition of "energy efficient" by a wide margin. (480V, 4-pole, TEFC).



The red Xs are nameplate ratings for 75 representative pump and fan motors totaling 3,347 hp (2.5 MW) in a 15-year-old chip fab. (A further 10 motors had no or illegible nameplates. Some motors were ODP, not TEFC.) Many Xs represent multiple motors; the upper and middle 40-hp points represent 14 and 37 motors, respectively. The size-weighted rated efficiency averaged 6.81 percentage points below the best 1996 motors shown. For all 75 motors, at 5¢/kWh and 90% duty factor, the 20-year present value of this shortfall is $1.4 million, excluding an avoidable HVAC capital cost of $0.6 million.

From the *Drivepower Technology Atlas*.
Courtesy of E SOURCE, www.esource.com.

Partial motor survey in a typical chip fab found a $1.4 million potential PV saving just from using premium-efficiency motors to replace 75 typically inefficient motors (2.5 MW)—1/3 of the plant's total motors

But adding 33 more kinds of improvements…

- About doubles the savings
- Cuts the cost of the saved energy by about fivefold (because paying for 7 measures yields 28 more as free byproducts)
- This "tunnels through the cost barrier," making very large savings (~50% between the retail meter and the input shaft of the driven machine) cost *less* than small savings
- Probably conservative: in *every* USDOE Motor Challenge project analyzed*, ancillary system benefits (longer life, less wear & tear, lower capital and labor costs, etc.) were worth more than the energy savings normally counted

*Pye & McKane, *Procs. ACEEE Summer Study on Energy Efficiency in Industry*, 1999, pp. 326–336

Prompt retrofits of induction motors…

- Usually assumed not to save enough to justify the *entire* cost of a new motor (*vs.* just the marginal cost, if any, of a more efficient replacement when the old one burns out)
- Often assumed to need ~10–20 years to repay a new motor’s cost
- But this view counts just one benefit—electricity directly saved by the new motor’s higher nameplate efficiency

But that omits ~17 other benefits

- Making the new motor the right *size*—often 1–2, sometimes 3, frames smaller
  - Half of US industrial motors never exceed 60% of their rated load; one-third never exceed 50%
  - Simple equipment can quickly measure the needed size
  - Oversized motors (<3/4 of full load) become less efficient and have worse power factor
  - Underloaded motors also run faster, wasting more energy (flow) in cube-law machines
  - Right-sized new motors will thus *save more and cost less* than expected from nameplate ratings that consider only efficiency, not also size
    - Rarely, upsizing is worthwhile, often to speed processes (Greenville Tube Co.: 150→200 hp + eddy-current→vector drive saved 30%, productivity +15%, scrap –15%, cost –$77k/y, 5-month payback)

Premium-efficiency motors aren’t just more efficient, but also…

- Have efficiency curves flatter across the load range, hence over integrated varying loads
- Typically have higher power factor (also flatter across the load range), reducing distribution losses and capacity needs
- Run cooler for lower resistive losses and longer life (each 10 C° roughly doubles expected life)
- Cooler operation also extends grease life for longer lubrication intervals or less downtime

Premium-efficiency motors…

- Come with more durable bearings
  - 3/4 of midsized motor failures are caused by bearing failures
- Automatically correct any iron damage from poor (most) past rewinds w/ stator burnout ovens
  - Such damage wastes ~$1–3b/y in U.S. motors per GE (EASA notwithstanding)
- Are less susceptible to such iron damage (though it's better to use the nondestructive Thumm method→)
  - Avoided iron loss plus sizing effects typically about doubles the savings compared with efficiency ratings alone

Stators after Dreisilker (Thumm) stripping method

Dreisilker (Thumm) stripping equipment

Photos courtesy Dreisilker Electric Motors, Inc.

Premium-efficiency motors also…

- Become less heated by harmonics
- Are more tolerant of phase unbalance and improper supply voltage
- Reduce distribution losses (as I^2) via all these loss reduction mechanisms
- Reduce cooling and air-handling loads in conditioned space
- Altogether ~18 benefits, not one—but paid for only once!

Savings depend on other improvements too

- Efficiency and motor life depend on…
  - reducing voltage unbalance and harmonics
  - improving shaft alignment and lubrication practice
  - reducing overhung loads (sideways pulls) on the shaft that can cut bearing life by at least 5- to 10-fold, *e.g.* in belt-drive fans
  - improving housekeeping—not siting motors in the sun or next to steam pipes, not smothering them beneath multiple coats of paint, etc.

Capture system synergies

- For example, with a V-belt-drive fan…
  - Cut belt losses from 10–15+% to 1–2% with a good synchronous belt
    - Doesn’t stretch or slip; very long life; very low maintenance (no tension adjustments)
    - Costs about –$1/kWh due to saved maint.
  - But must use a soft-start device (or flat Habasit-class belt) for high-inertia loads like big centrifugal fans—which otherwise strip the teeth off a cogged belt

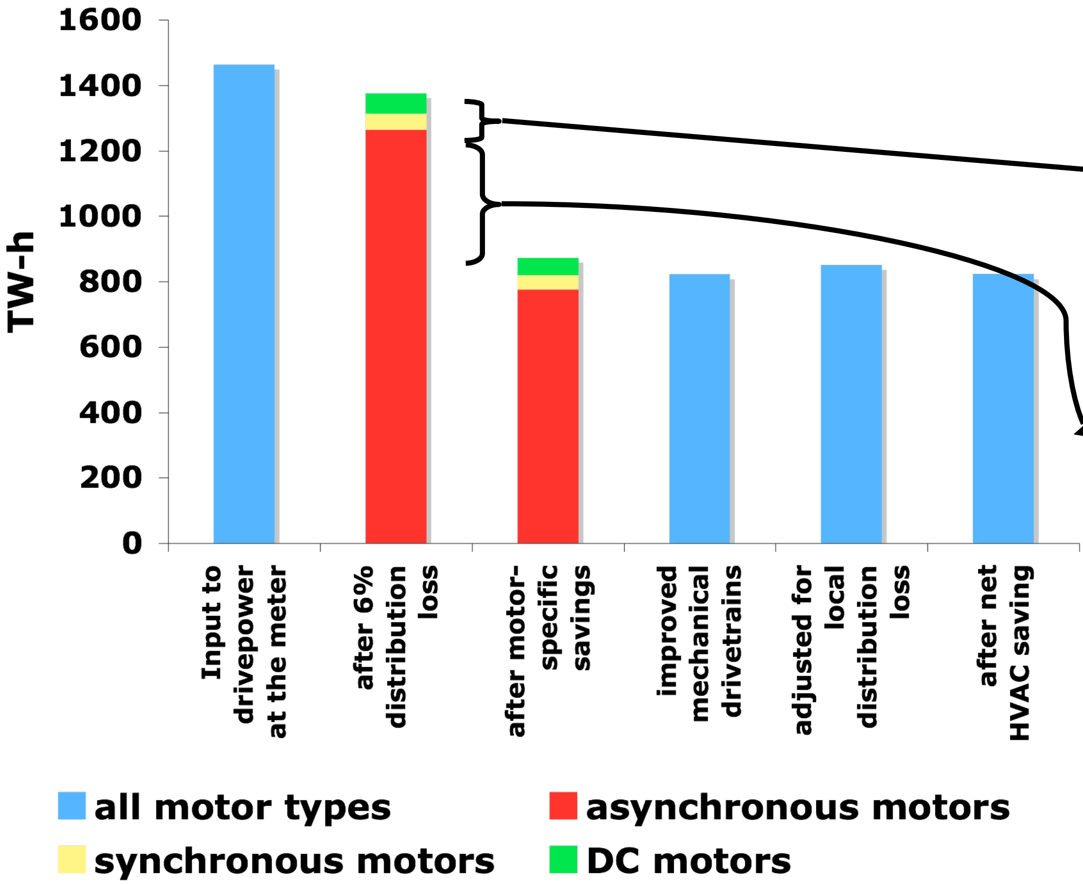
But beware of changed motor "slip" (actual *vs.* synchronous speed)

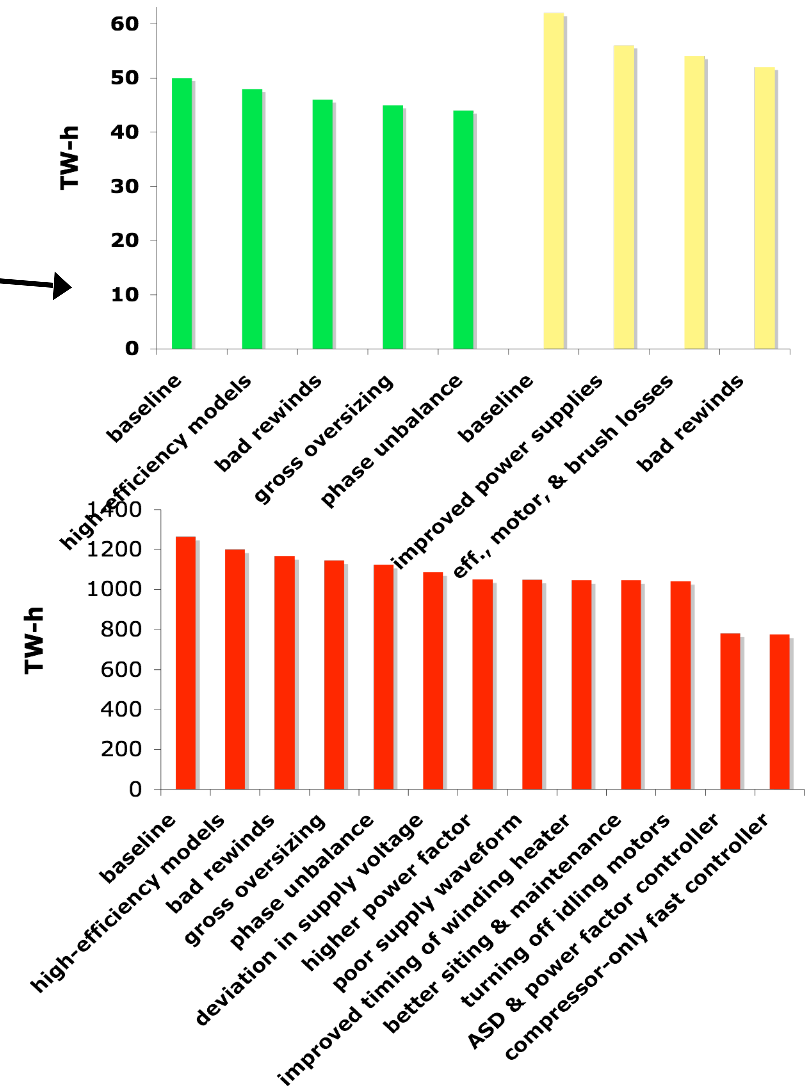
- If not carefully selected, premium-efficiency motor may run faster than the original one
- This could waste more energy on excess speed and flow than it saves through greater efficiency
- So you'll need to readjust ASD frequency, choose sprocket size, or trim impeller
- Best: no belt; perhaps no fan or pump; perhaps even no waste heat to remove!

Motor procurement, installation, maintenance

- What's the job? (the *actual* load regime)
- Buy *the most* efficient motor for the job
  - Shop with Motor Master or equivalent software
- Install meticulously (laser alignment)
- Eliminate overhung loads (belt drives)
- Lubes: clean, not too much, up-to-date
- Keep motors clean, dry, cool, quiet
- Measure performance, track w/barcodes
- Nondestructive rewinds—or none

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

Putting it all together: the pattern that connects

- Even if we can't replace existing pipes, we can greatly reduce pumping energy anyway by
  - Replacing throttling valves with ASDs
  - Replacing globe valves with ball/gate valves
  - Reoptimizing pumps and motor systems
- But ASDs also improve flow control
  - Better yield, throughput, product quality
  - Link with direct digital controls for smarter process
- This, plus more reliable motors and fewer valves, will improve uptime and save maintenance
- Leverage maintenance *time* into more projects
- Do all this as a whole-system package

A similarly detailed systems analysis is rewarding, and many have already been done, for other major end-uses

…lighting, space heating, water heating, space cooling, pumps, fans, residential appliances, office equipment, commercial cooking and refrigeration—all significant uses of electricity *except* process heat, electrochemistry, and electrometallurgy

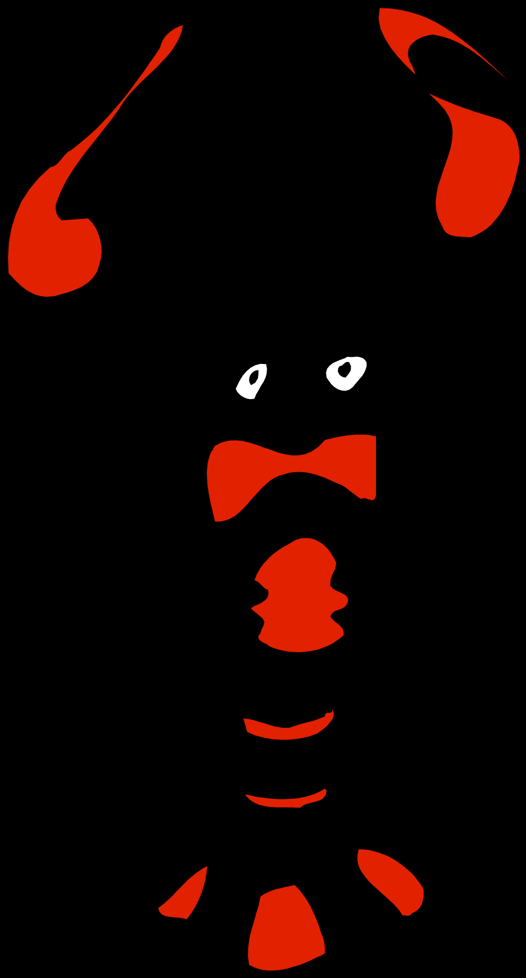
Technology Atlases & updates, www.esource.com

NOW, FOR SPECIFICITY…
A BRIEF INDUSTRIAL RETROFIT CASE-STUDY

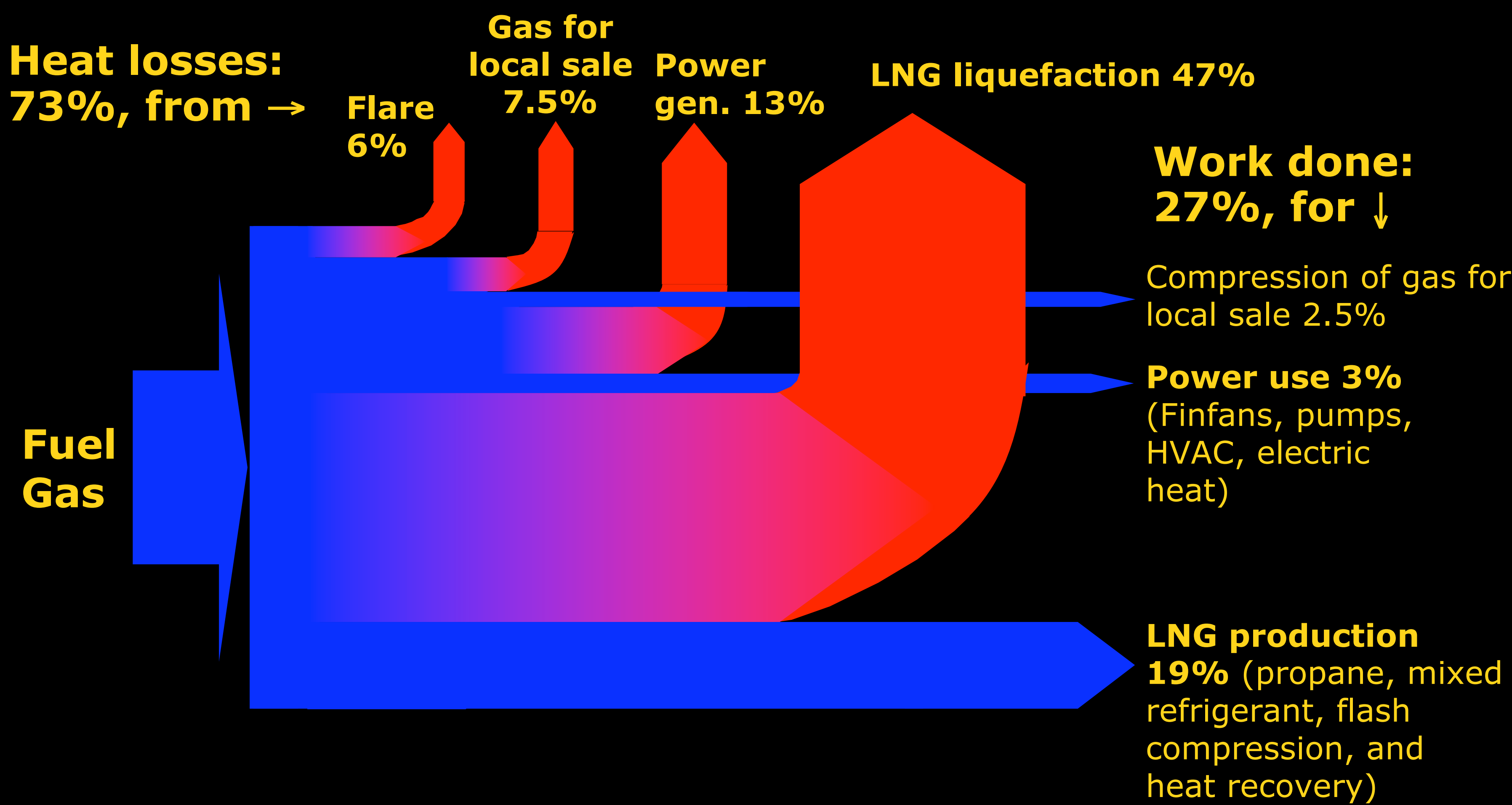
A giant liquefied-natural-gas liquefaction plant

Eating the Atlantic lobster

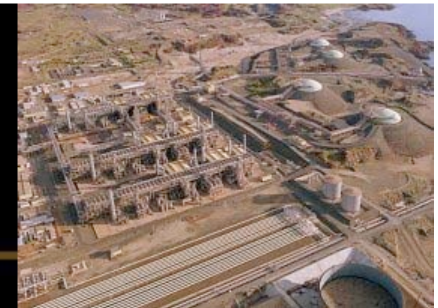
- Big, obvious chunks of meat in the tail and the front claws
- A roughly equal quantity of tasty morsels hidden in crevices, requiring skill and persistence to recover
- Go for both
- Mmmmm!



An LNG example:
73% of energy input is lost as heat



Case-study of a huge LNG plant
The tail: power generation



- Just the fuel-gas value (at a very low price) of saving 1 W_e, present-valued over 20 years, is $1.34
- Small electricity savings would let us run 4 well-loaded turbines with true $n+2$ redundancy; given greater savings, just 3 turbines would suffice…
  - Dispatch to minimize part-load penalties
  - Load management; *e.g.*, make LN_2 at night
- "Virtual trailshafting" could optimize each gas turbine's loading so it runs far more efficiently
- Sonic-pulse filter cleaning, not a compressed-air puff
- Water-spray "turbocharge"; indirect evaporative?
- Better: combined-cycle, $\eta \sim 0.55–0.60$ (perhaps ~0.48 at ≥40°C?, *i.e.* ~2×)
- Study windpower better; fuel cells; photovoltaics?

Front claws: thermal integration

~24 PJ/y (770 MW), 496 MW @ **519–537**°C, 274 MW @ **420–461**°C; lost fuel-gas present value = $0.3b

- Use waste heat to make useful heat, coolth, desalinated water, and ?electricity (bottoming cycles)
  - Eliminate furnaces and electric process heat
  - Cascade to successively lower temperatures
  - If we don't fully desalinate, sell *brine* to nearby salt works
- Minimize fin-fans: ~700 units now use 15 MW, worth ~$21M present value worth of electricity
  - Micron-misting of inlet air; motors, belts, ASDs, aerodynamic design
  - Keep them properly clean
- Quick fixes for hot-water system—can also boost turbine η via lower backpressure

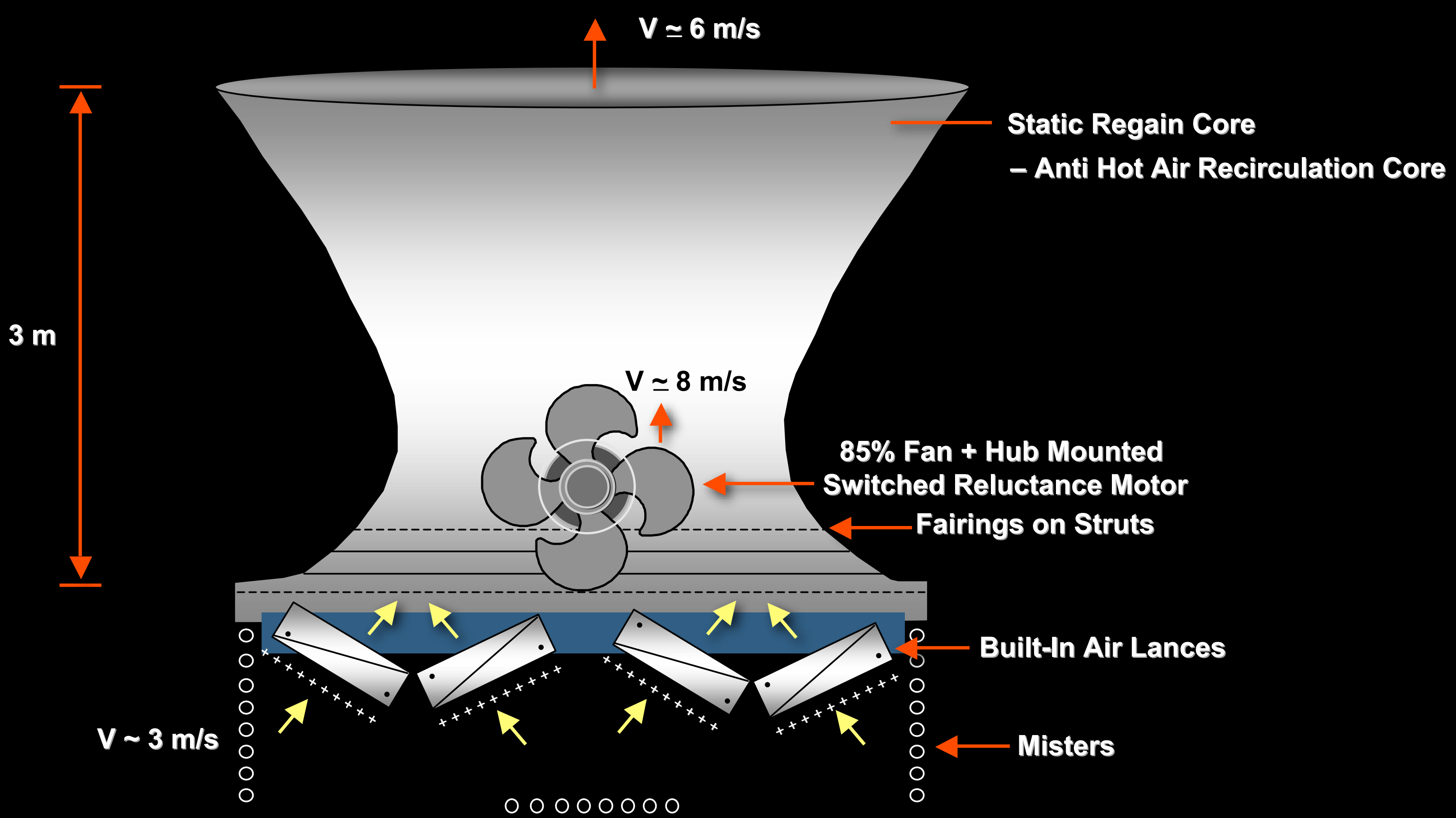
The tasty morsels

- *Systematically* recover pressure let-downs & expansions (cryo…) with turboexpanders
- Motors; especially pumps (16 MW, $21M PV)
  - Compressor Controls Corp. on *all* axial/centrifugal compressors
  - Heat-exchange across trains between C_3 chillers
  - Including throttling→ASDs shift, less piping/valve pressure drop (friction)—especially in submerged units
- 0.87→0.95^+ PF; ø unbalance?; shade/whiten xformers
- Whiten in-sun cryo pipes, vessels, tanks
- Raise landscape albedo, cool site ~10–20 C°?
- Compressors (many recips.), HVAC, buildings
- Optimize (or eliminate) the uses of compressed air

Fin-fans (ubiquitous in big process plants)

- Minimize the generation and discard of waste heat; put it to a cascade of higher-value uses first
- A typical Asian-made fin-fan cell costs ~$18k, needs ~$13k worth of generation and distribution capacity, and uses ~$21k (20-year present value) worth of fuel gas at a cheap ~$29/T
- Micron-mist the inlet air to cool it by ~6–9 C°
- Best, right-sized motors + adjustable-speed drives (e.g., save ~85% of electricity when running at half-speed)
- Numerous aerodynamic improvements (~80% savings, some retrofittable) on the standard ~1940s technology would be feasible & valuable…

Optimized fin fan schematic

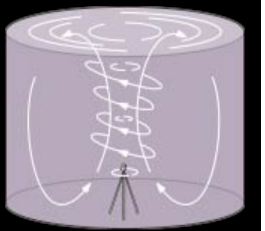


Sketch by Lee Eng Lock, showing IP owned by himself and RMI

Even exotic motors can pay in the right uses

- LNG terminal: spherical load-out storage tanks need continuous circulation
- Now uses 68%-efficient immersed motor/pump system
- Could use 89%-efficient superconducting unit with efficient pump, cutting its boiloff by 2/3…and leveraging upstream savings
- Or maybe ~99% with tiny superconducting motor & Pax rotor (ring vortex flow)
  - 24 W can circulate ~4 million liters of water
  - An aerator replaced 137 kW with 0.56 kW
- Memo: Paint the dark-green LNG tanks white too!

Graphics courtesy of Pax Scientific



Heretical questions

- Is the plant conceivably paying for more uptime than needed? (Sunrayce)
- Might it make sense to swing output up and down more than is now done?
- Or to deliver nonliquefied gas (for local markets) at lower pressure than contract arbitrarily specifies?
- Does the plant have the optimal amount of product storage for price arbitrage?
- Is there an alternative to Sulfinol for CO_2 removal? (add far less water; easy dry?)—perhaps from supercritical CO_2 technology??
- Biggest idea: cascading cryo chillers of several different types (COP $0.1 \rightarrow 0.15$)!

One possible vision of the whole lobster

Think of a five-layered wedding cake…

- Comprehensive end-use efficiency, especially quick wins
- Combined-cycle electricity generation
  - Direct turbine drive plus electricity (with VSDs)
- Off the bottom, ammonia absorption
  - Chill process streams and ?turbine inlets
  - + evap-cooled gas-turbine inlet→no helper motors
- Off the absorption bottom, distill water
  - Make clean water (for use and sale) + salt/brine
- Use the water for cooling towers and for micron-misting of fin-fan inlet air
  - Feed some cooling towers’ cool air to fin-fans

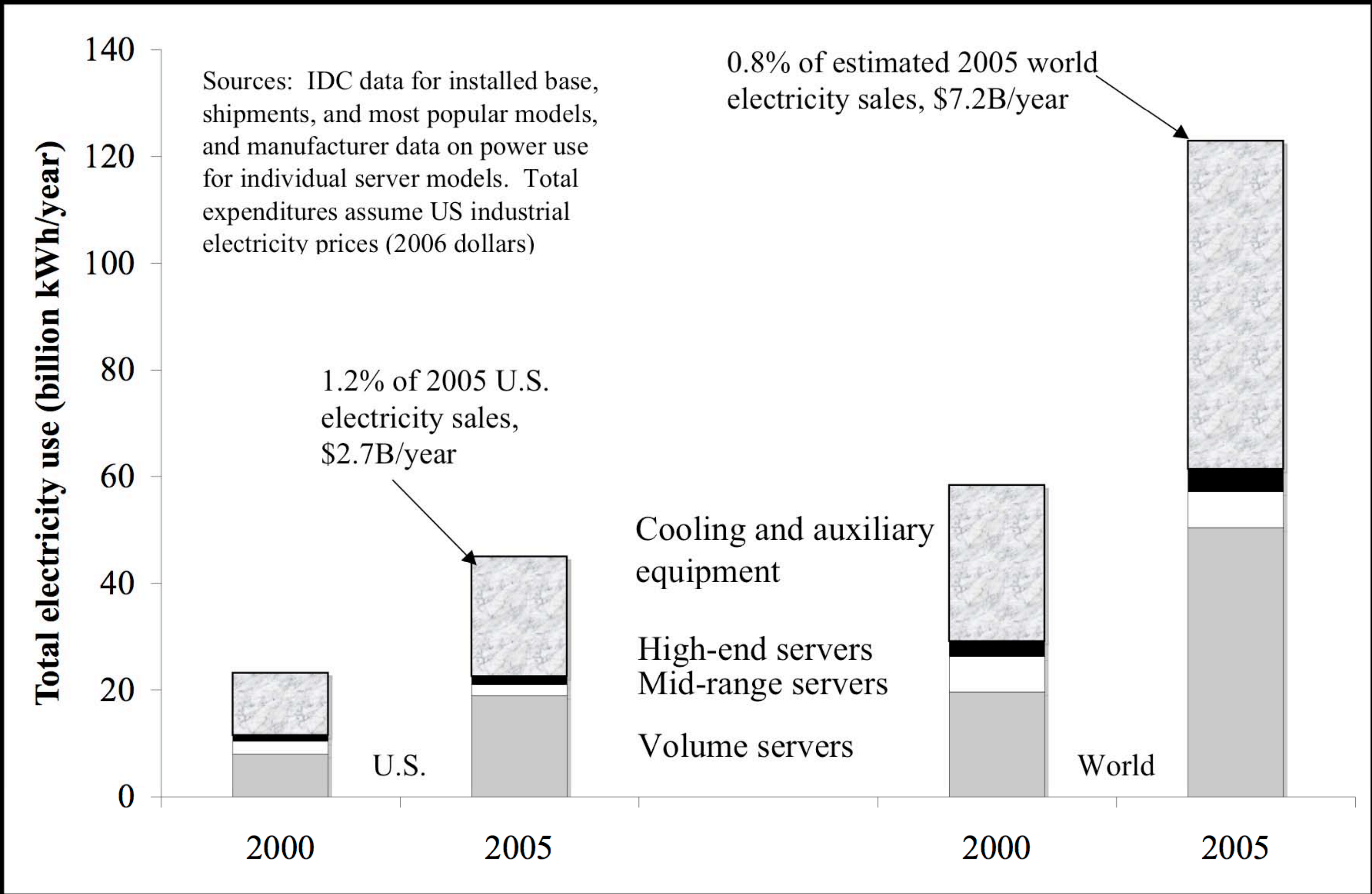
◇ Plus lots more integrations to come!

AND A NONPROPRIETARY NEW-INSTALLATION CASE-STUDY

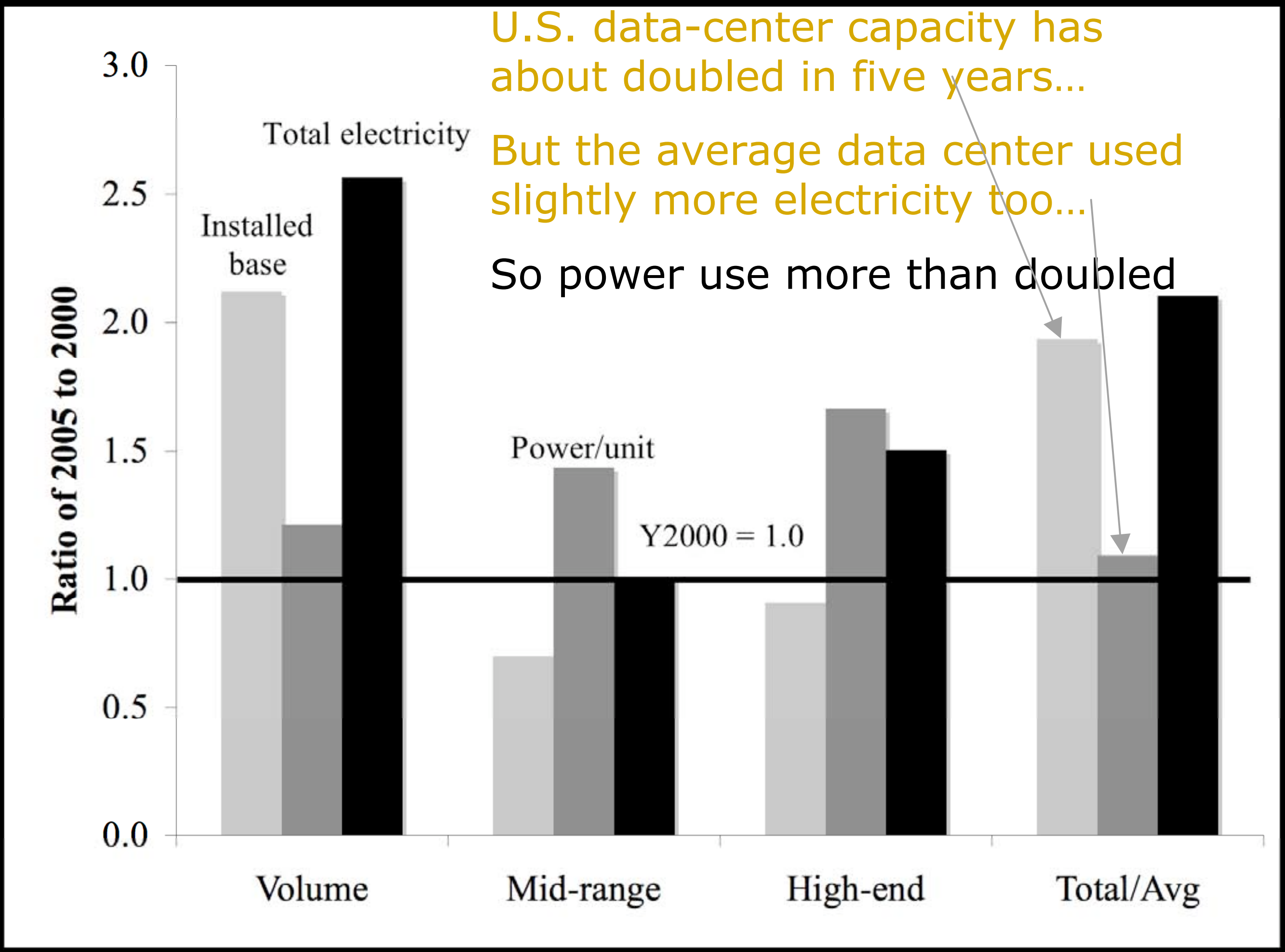
A nominal data center

Data centers use ~1% of all electricity

("Estimating total power consumption by servers in the U.S. and the world," J.G. Koomey, LBNL, jgkoomey@stanford.edu, 15 Feb 07)

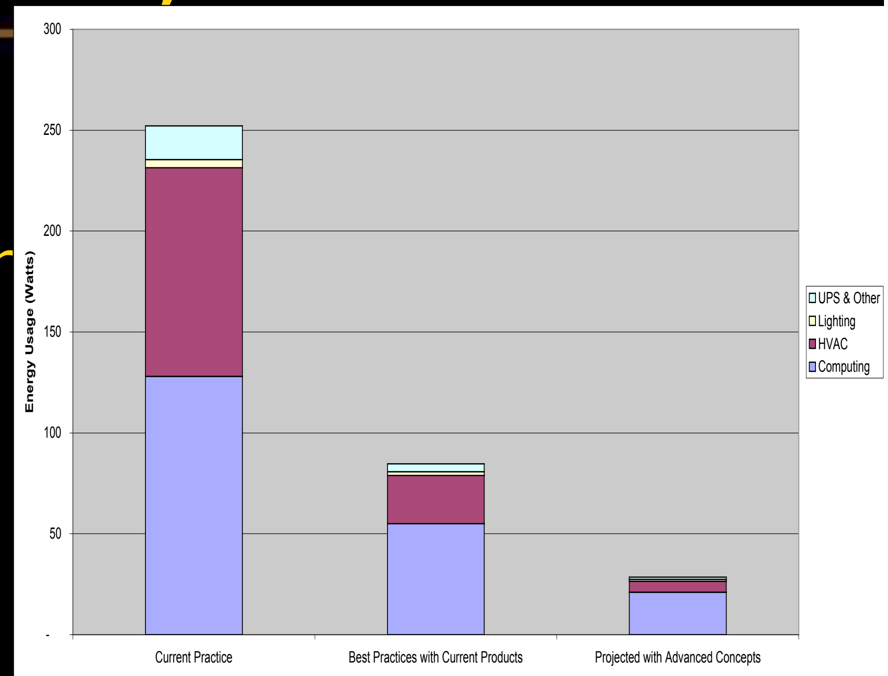


Capability growth is outpacing efficiency gains *(id.)*



RMI’s Energy-efficient Data Center Charrette, San Jose, 2–5 Feb 2003

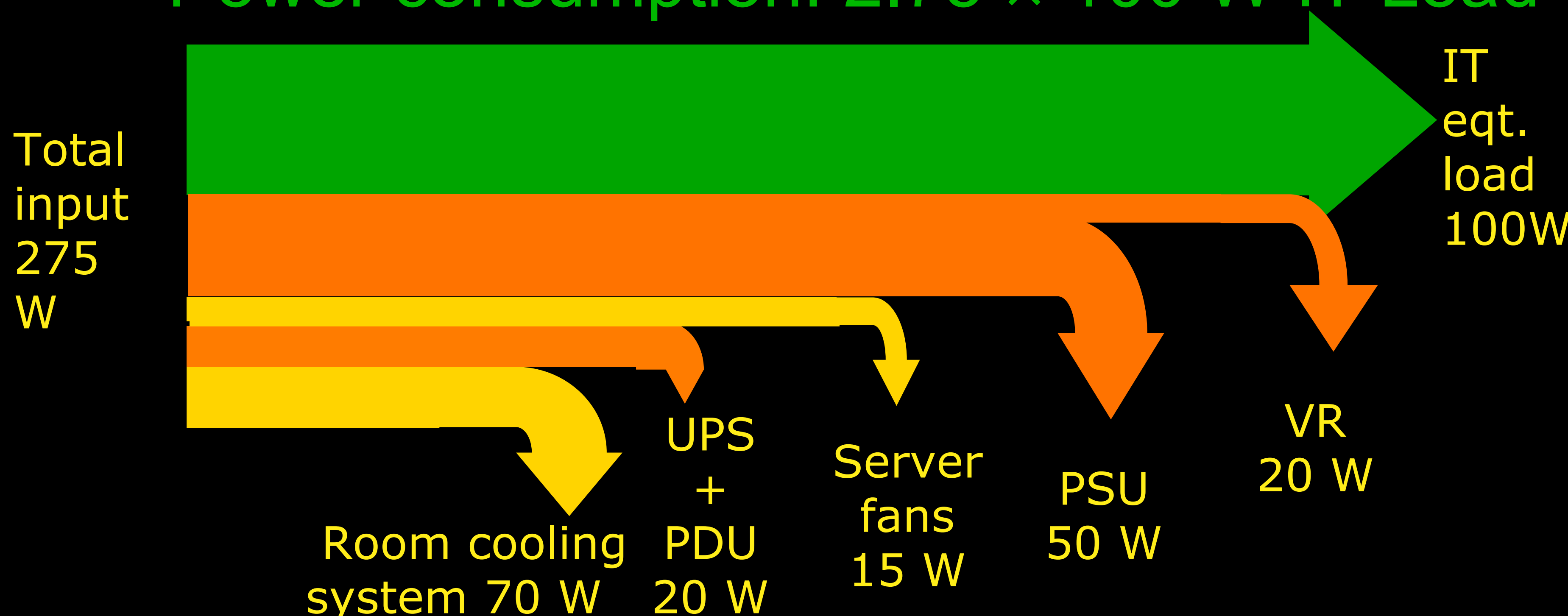
- >90 industry experts found ways to save ~89% of the energy used by a typical data center, probably with *lower* total capital cost, faster construction, and better uptime and throughput
- Ultra-low power consumption at the architecture, software, compiling, and device levels
- Superefficient onsite power-and-cooling system; integrated design *decompounds loads*; very efficient, multi-purpose auxiliaries & sys-tems; can go further, even become a net power *producer*
- Real-estate model also very important: charge by ft^2 *and W*



www.rmi.org/store/p385pid2424.php ($20)

Intel’s nominal data-center power flows (these figures vary greatly between installations!)

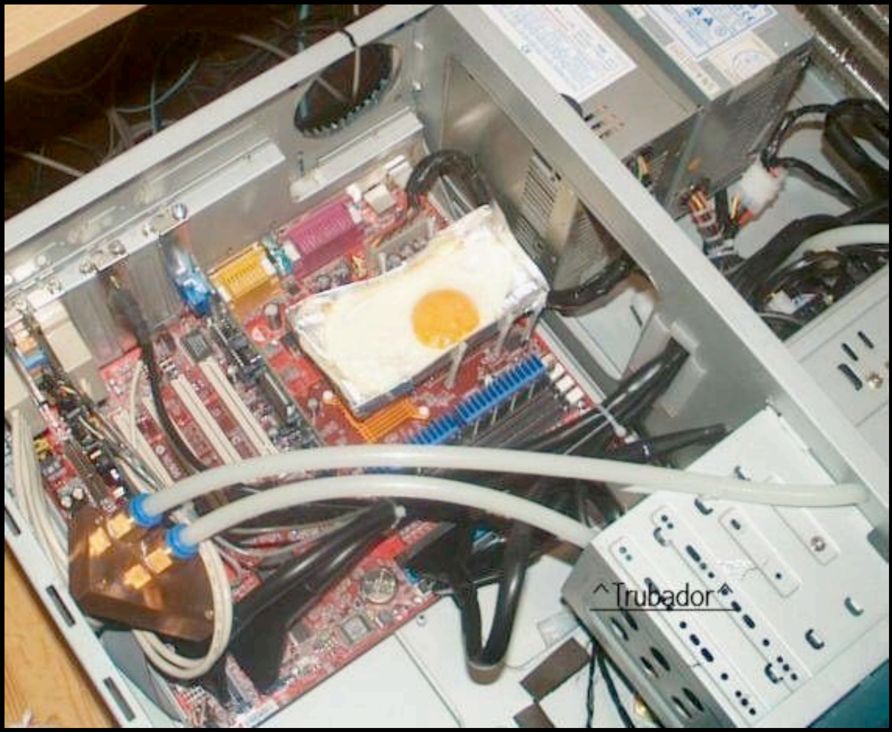
Power consumption: 2.75 × 100 W IT Load



The “overhead” for power and cooling systems is sometimes this big, but LBNL usually measures more like 80–90% overhead, not 175%. But these support systems incur ~75–80% of the facility’s *capital cost.* Time to start at the root of the problem, tracing heat back to its source

Drawing adapted from LBNL; data from Intel Corporation

Frying an egg on an Athlon XP1500+ in 11 minutes



From Trubador, www.handyscripts.co.uk/egg.asp

IBM PS-2E ~5×-efficiency desktop PC (~1992)

- First serious effort at an energy-efficient desktop computer
- Early pizza-box, LCD, PC-card-based
- Superefficient power supply (even at part load), small, high power quality
  - Cost more…but offset by avoided fan
  - Marketers liked the silence (ergonomics)
  - Absence of dust-depositing airpath reduced chip heating and warranty costs
  - Small case, lockable in desk drawer (secure, almost no deskspace)

Simple RMI server substitution

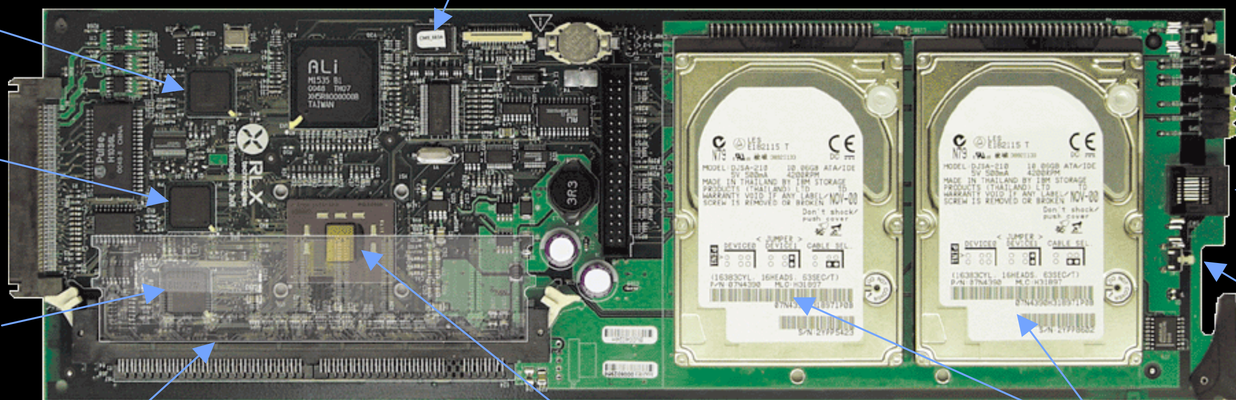
- Several years ago, RMI replaced three (could have replaced four) Windows NT servers with one small NetWinder Linux box (now model 3100)
- Nominal power 14 W, no fan
- Faster and more capable than NTs
- Hardware plus software cost less than NT license fee on replaced NT boxes
- 98–99% energy saving
- Big space saving

1U Wintel Rack Mounted Server, ~2003

- **800 MHz Intel CPU, 19” × 30”**
- **Disk drives, I/O ports, memory**
- **Floppy drive**
- **CD/ROM**
- **Video capabilities**
- **Serial / parallel ports**
- **PCI expansion slots**
- **160 W power supply**
- **9 fans**
- **$2,000+**

This and following slide courtesy of Chris Hipp, ex-RLX

RLX ServerBlade™, ~15.7 W: high density but even higher efficiency



CMS 1 MB

Public NIC
33 MHz PCI

Private NIC
33 MHz PCI

Management NIC
33 MHz PCI

Status LEDs

Serial RJ-45
debug port

Reset Switch

128MB, 256MB, 512MB
DIMM SDRAM
PC-133 (by 11/04, 12 GB)

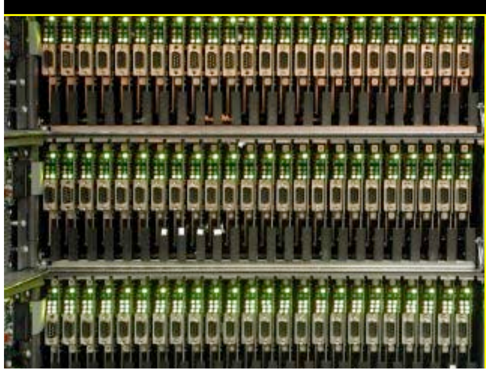
512KB
Flash ROM

Transmeta™
TM5600 633 MHz

Crusoe™

128 kB L1 cache, 512 kB L2 cache
LongRun, Southbridge, x86 compatible
(by 11/04, two 64-bit Intel Xeons)

ATA 66
0, 1 or 2–2.5” HDD
10 or 30 GB each
(later much bigger)



72 blade servers in 9U

Wu-chun Feng's Green Destiny bladed Beowulf cluster, LANL, 4/04

(http://sss.lanl.gov, feng@lanl.gov; thanks to Chris Hipp, ex-RLX)

◇ 240 RLX passively-cooled blade servers, 0.13μm TransMeta Crusoe CPU, **3.2 kW/5 ft²**: 8× denser, 5–8× less power than Wintel

◇ 100% up for 24 months in uncooled, dusty 29˚C (85˚F) hallway at 2250 m elevation

◇ Pay ~50–75% more for the bare hardware (at early blade prices) but ~90% less for power, cooling, space, downtime, system administration

◇ ~7–8× better energy efficiency (in an iterative science application) with ~65–75% lower total cost of ownership

◇ 30 GB DRAM/ft², 960 GB HDD/ft², 11.6 Mflops/ft²

160 peak Gflops; 240 after upgrade to TL5800 @ 1 GHz; 150→276 GB RAM, 4.8→38.4 TB storage

This 2004 supercomputer used the same power as two hairdryers.

Can your data center do that?

Cf. LANL Q supercomputer's cooling towers

Some unexpected lessons

- The tortoise can beat the hare: if MTBF is shorter than computation time, Green Destiny beats Q, just as a Camry eventually beats a blazingly fast but unreliable Formula One
- Actual MTBF is often set not by hardware but by software bugs and by human error in integration, installation, configuration, operation, repair, upgrade, etc.
- 10 C° cooler operation typically doubles equipment life; at 1.6 V, Pentium III-M (500 MHz) *vs.* Transmeta TM5600 (600 MHz) means 122°C *vs.* 64°C, implying ~60× longer hardware MTBF

Some ways to cool a data center

1 refrigerative ton = 3.52 $kW_{thermal}$ = 12,000 BTU/h

	Electric intensity (kW/refrig. ton)	*Marginal capital cost*
Reduce heat loads	0	Generally<0
Air-side economizer	0-?, ~60–80+% of the y in CA	Cheap; needs proper controls & mainten.
Water-side economizer (CT)	0.1–0.2	~$100/ton
	Night Sky: Stanford's Carnegie Inst. for Global Ecology: ≤0.07 kW/t	
Desiccant &/or absorption, waste ht (*e.g.* trigen)	0.1–0.3+	≤$2,000/ton (abs.) or less (Pennington), very low opex
Water-cooled central chiller sys.	<0.4–0.8 dep. on climate	~$1,500–2,000/ ton
Air-cooled central system or CRAC	1.2–1.4+	≤$1,000/ton

How to remove heat? (air is a poor medium for dense loads)

- Water can hold 3,467× as much heat as air per unit volume
- Water requires an order of magnitude less energy to move than air for the same heat flux
- Water can be more precisely/consistently delivered /controlled and efficiently heat-exchanged than air
- Good engineering can make it straightforward and safe to mix electricity and water—many industries have done so for many decades
- So why not conduct or heat-pipe heat to the backplane, then liquid-cool a heat-sink there?
  - Could use dielectric non-water liquid if desired, or heat-pipe straight up
  - If dielectric, could use electrohydrodynamics for tiny, very efficient hxs
- Key: *make the equipment very efficient to start with* (so server doesn't need 30–40% of its energy for fans: 0 is best)
- C. Belady (HP) notes: *radiator* can keep device plate at 75°C!

Simple heat management

- Embalm or bury dead servers—no necrophilia; storage too
- Virtualization—APC estimates 4× savings
- Put hottest, most heat-tolerant, *and* least mission-critical units at the top of mixed racks (failure rates are ~3× higher at the top—guess why!)
- Enable all power-management features (on/off, clock, voltage) to save ~20%+; insist vendors do so by default; if temporarily disabled, restore promptly
- Use science-based DB/RH specs, based on what real eqt likes
- Broaden RH ranges, calibrate RH sensors—no fighting CRACs
- Install ASDs on chilled-water CRACs; turn off unneeded units
- Demand-control ventilation by CO_2 levels
- Use/maintain OSA economizers (81% N CA saving)
- Just proper airflow mgt. can save ~75% of cooling energy

AC *vs.* DC power supplies—so far, determined by cultures, not data

- Swiss data centers in 2001 used about half the kWh for telco switching on a DC bus as for comparable internet apps on an AC bus
- LBNL (06) measured 19%, plausibly 28%, savings from DC supply architecture
- Japanese data centers are mostly designed and built by a telco firm, NTT-F, whose experience with its 48-VDC bus in $>10^4$ installations shows order-of-magnitude higher uptime and far lower losses than AC
    - Most US designers would use hundreds of V to shrink bus
- PS: Why not a "distributed UPS" w/local LVDC batteries, like a bunch of laptops?

IT-equipment-to-total-kW multiplier: how low can we go *vs.* common field observations (Uptime Institute ~2.5, LBNL ~1.8–1.9)?

kW of aux pwr / kW of IT eqt	*UI* *"best possible"*	*LBNL /Rumsey*	*RMI*	*RMI key design elements*
Xformer/el syst loss before UPS	0.1	0.03	0.02	Amorphous-iron transformer, fat wire
UPS/USP/dx wiring to IT eqt	0.1	0.1	0.04 to 0.05	Very eff't DC supply floating on batteries
Chilled water production	0.3	0.04	0.01 to 0.02	Enthalpy-controlled airside economizer + 0.01 kW/t CTs + ice-pond or Pennington
Clg unit blower, OSA handler, de/hum, ltg	0.1	0.02	0.01 to 0.02	Supereff't IT & HVAC, big RH range, ChW cooling, 0.1–0.3 W/sf lighting net of ctrls
TOTAL	**0.6**	**0.19**	**0.08 –0.11**	*NB:* Extra IT savings from DC not shown

(RMI '04: **0.13;** Stanford Carnegie Inst. for Glob. Ecol.: **~0.2**)

The tail: power consumption and efficient conversion

- What's it worth to avoid a watt of power consumption and heat generation in a data center? ~\$10.3$_{PV}$ el + ~\$9.6–16.5 capital*; say \$20–27/W—more than for solar photovoltaic systems!
- Low-V (≤1 V), high-k, voltage islands, VLIW, SiGe, Cu, Si/ins; RLX in 2003 got ~5–8× saving; Intel reports its servers' η rose 6× 2002–07 (30→180 Mflops/W, bracketing Green Destiny's 80 in 2004)
- Dynamic power management like laptops
- Superefficient power supplies; DC-bus architecture
  - Could greatly improve uptime and reduce heat, thus extending life

*At \$0.06/kWh, 90% meter-to-load electric efficiency, COP 2.2 including parasitics, 20-year present value at 5%/y real discount rate, and Ken Brill's 2003 estimate of ~\$9,600–16,500/kW for the kW-related portion (~80–75%) of the total capital cost of the Tier 2–4 facility

Front claws: heat transfer and removal

- Innovative heat transport from devices
  - Negafans, VFD fans, MEMS fans, electrostatic fans (Kronos), inkjets, micro-Stirlings, quantum-tunneling thermal diodes,…and heat pipes!
  - Diamond, carbon fiber, carbon nanotubes,…
- Liquid cooling? (could be dry-chip; liquid at backplane)
- At least thoughtfully designed airflow!
- Extremely efficient air-handling and cooling
  - Passive, then semiactive, then active
  - Economizers, passive latent heat exchangers,…
- Heat-driven HVAC based on onsite trigeneration, system η ~0.90–0.93, ultrareliable, eliminate UPS

Morsels, scraps, broth, aroma

- Building envelope, α, ε, shading, massing, elevators
- Lighting (6–7 connected W/m^2, ~1–3 W/m^2 when occupied, lights-off when only machines are present)
- What temperature and humidity range does the equipment actually require? (*e.g,*. most modern net-working eqt is designed for 20–80%, so 30–70% makes reasonable allowance for sensor errors, etc.; but some data centers strive for 50±5%)
- Load diversity, thermal time constants
- Dynamic time/space matching of cooling to actual instantaneous needs (JCI, HP)
- Perhaps innovative fluid-handling devices
- Lots of little savings multiply: *e.g.*, $0.9^{10} = 0.35$

The whole lobster: a fantasy

- Optimized system architecture/compilation: DARPA PACT aims at ~10–100× savings
- De-bloated code and pared overhead: more *useful* operations per instruction executed
- Optimally share/spread real-time workload, as with multiplexed chillers; why is total data-center electric load constant while its workload varies ≥3×?
- Comprehensive, radical device and system efficiency
- Superefficient heat transfer at each stage
- Onsite trigen (microturbines, engines, fuel cells,…) with heat-driven HVAC (or passive cooling), no UPS
  - Just a simple gas-fired engine-driven single-effect absorption chiller makes a data center into a net *exporter* of electricity

No limits to profitable industrial energy efficiency for a *very* long time to come

- Industry is a materials-processing activity, ~99.98% of the materials are wasted, and most of this waste will ultimately be turned into profit by dematerialization, virtualization, product longevity, closed loops, industrial ecology, desktop mfg., etc.
- Conventional technological innovation continues apace despite appalling private and public underinvestment in energy RD&D
- Important new classes of processes, like microfluidics
- End-use efficiency keeps getting bigger and cheaper, esp. with integrative engineering to "tunnel through the cost barrier"
- Next come two *further* design revolutions
  - Biomimicry: innovation inspired by nature (Janine Benyus)
  - Perhaps nanotechnology (in Eric Drexler's original sense)
    - Caution: nanomaterials look risky, and biomimicry is *not* biotechnology (often unwise): over time, Darwin always beats Descartes
- Plus the options we haven't yet thought of—but could live to do so…if we quickly get the hang of responsibly combining a large forebrain with opposable thumbs!

What is all this but good simple engineering?

“We have met the enemy and they are us.”

—Pogo

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