

Negawatts for Fabs

Advanced Energy Productivity for Fun and Profit

Teleconference Presentation by Amory B. Lovins

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Advanced energy efficiency's value

- Profit: retrofit ~\$1–2+ M/fab-y with aftertax ROI >50%/y (esp. nice as prices and margins plunge)
- Competitive advantage over inattentive rivals
- Improved yield, uptime, throughput, flexibility
- Lower construction time, cost, complexity
- Faster setup, potential for shorter product cycles
- Stretched infrastructure capacity
- Profitable environmental and climate protection
- Enhanced ergonomics, excitement, performance
- –3/5 kWh/in² since '83 just scratches the surface!

If fabs were as well designed as chips...

- **Retrofits:** save 50+% on HVAC/facilities (half of fab electricity), probably a lot on tools too; the deeper the design integration, the bigger the savings, but average paybacks may become *shorter*
- **New fabs** can cut kWh/standard wafer* 3x, probably more, but will take *less* time and money to build; most plant becomes far smaller & simpler
- Saving energy improves vital **operational** parameters in both retrofits and new construction
- Can **back-end** plants save as much as front-end?

*150 mm, 10 mask levels

Three pillars of energy efficiency

- 1. New design mentality:** whole-system engineering often makes big savings free (or better)
- 2. Technical improvements:** new *and* retrofit
- 3. Management** (like financial cost controls)
 - Must be strong, systemic, and systematic, because...
 - TQM principles applied to making chips are being ignored in making chilled water, clean air,...
 - Tech. efficiency (kW/t, W/cfm,...) seldom measured
 - Aggregated metrics (kWh/in² std. wafer) inadequate
 - Design errors are repeated, not found and fixed

New design mentality: an example

- Redesigning a standard, supposedly optimized industrial pumping loop cut power from 95 to 7 hp (−92%), cost less to build, and worked better
- No new technologies—just two design changes
 - Big pipes, small pumps (not the opposite)
 - Lay out pipes first, then equipment (not the reverse)
- Optimize the *whole system*, not just each part in isolation (which pessimizes the system), and optimize for multiple benefits, not just one
- “Just stop having an old idea” —irreversibly

A culture ripe for energy inefficiency

- Fast parallel design means “infectitious repetitis”
- “Copy exactly” *forbids* continuous improvement
- Focus is on speed and yield, not on “small” costs
- Many assume efficiency adds cost, risk, and delay
- Indeed, *any* change in habits is feared as “risky”
- Investment is biased toward expanding production
- Easy to fund oversized eqt., hard to fund efficiency
- Toolmakers focus on first cost, not full energy cost
- TQM culture typically stops at the cleanroom wall
- Nobody owns the waste, even if it’s measured

The design process is deficient

- Insufficient attention, competition, and integration
- Perverse incentives reward expenditure, not saving
- Formulaic—rarely optimized to local climate
- Pervasive overdesign: most HVAC is ~3x too big
- Little reliable measurement, even less design accountability: a chilled-water plant designed with no place to put an accurate flowmeter obviously has no design intention of improving efficiency, ever
- “Value engineering” is neither
- Design is linear, not circular. It should be: require, design, build, *measure, analyze, improve*, repeat

Two empirical examples

(both advised by Supersymmetry Services Pte Ltd)

- Big Asian back-end: 1997 retrofit, mainly HVAC
 - Cut energy use 56% (69% per chip) in 11 months with 14-month av. payback; further projects will save more
- STMicroelectronics' world-class Singapore fab
 - '94–7 retrofits saved US\$2.2M/y w/0.95-y av. payback
 - '91–7 improvements saved \$30M; kWh/6" std. wafer –60%, from ~226 to 91 (1998 target = 86 & falling)—providing 80% of energy capacity for a 3.5x expansion
 - all retrofits were performed during continuous operation via cryogenic freeze-plugs and hot-taps (>20 each)

Actual efficiencies do vary

- Two '96 Asian hard-drive plants had a 54x range of kWh/drive (the high one went broke in '97)
- One chipmaker's *rated* chilled-water-plant COP* varied so widely that the worst fab's was 42% below the best despite a better climate. Even that best was >20% below the state of the art (6.54 or 0.54 kW/t** in tropics), which costs *less* to build
- Those fabs' owner was losing well over \$1M/y just by not sharing its own best practice among its fabs

*Only one was measured; it averaged 21% worse than its rating

**Including pumps & towers; 7.5 (0.47 kW/t) w/ 5.5°C & 15°C CHW

Losses multiply

- Facility designers typically assume that tools will use ~2–5x more energy than they actually use
- Typical tool duty ~0.3, but load diversity ignored
- Phantom loads mean hundreds of extra tons (\$2k/t capital cost) and incur HVAC part-load penalties
- Inflated loads mean deep coils, big pressure drops, oversized fans (heating air as much as tools do!)
- This inflates capital costs too: bigger fans, coils, silencers, chillers, towers, pipes, valves, ducts, motors, electricals, land, fndns., UPS & losses,....
- More filters, resins, O&M, noise, insurance,....

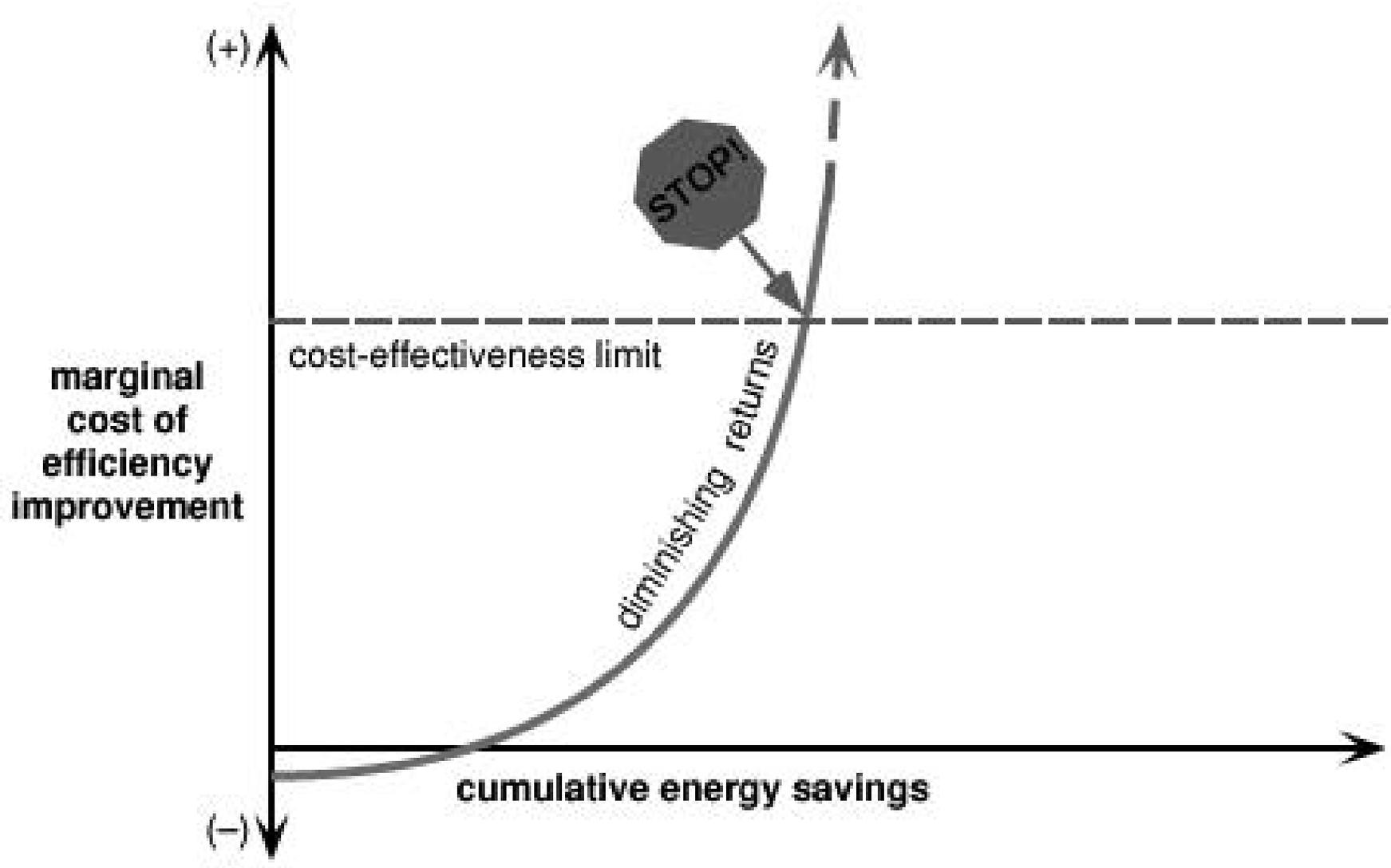
If Boeing built aircraft the way most designers build fabs...

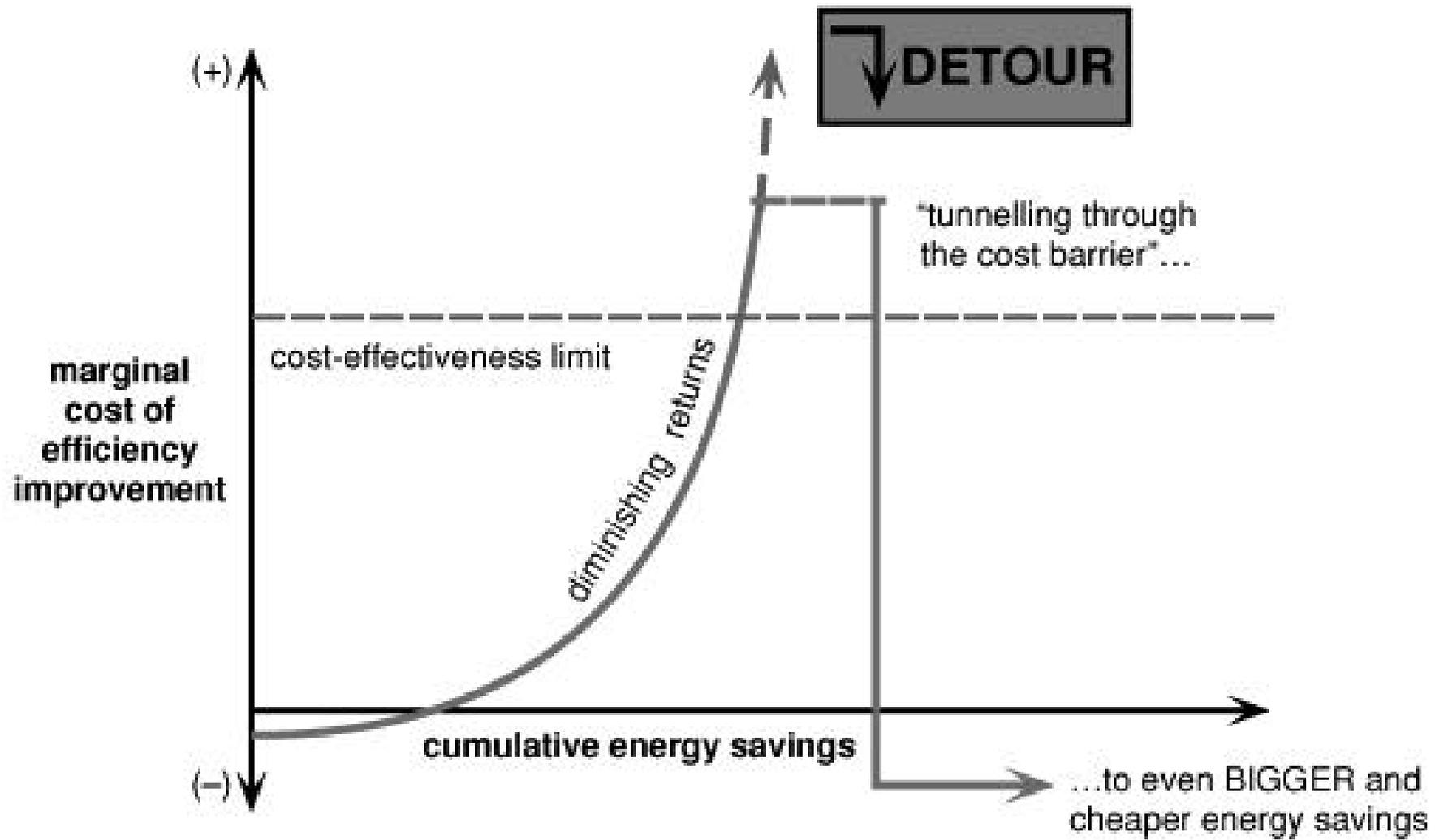
- Each jumbo jet would carry ~12 passengers
- The rest of the plane would be carrying extra fuel, engines, structure, landing gear,...
- Actual jumbo jets can carry their payloads only because their design is based on carefully *measured* requirements, not arbitrary assumptions
- Chip fabs should do no less: who'd dream of installing 3x the needed robot, conveyor, ... capacity?
- In God we trust; all others bring data

What's efficiency worth over 20 y?

Eyes on the prize (5¢/kWh, no HVAC capital cost):

- 1 watt of cleanroom heat = \$0.6/y operating cost, or ~\$8–9 in 20-y present value (PV) including filters—twice the cost of 1 peak watt of solar cells
- Fan towers (humid climate): 0.1" w.g. (25 Pa) of avoided pressure drop = \$18,000/y = \$230,000 PV
- 1 cfm (1.7 m³/h) cleanrm exhaust = \$4/y = \$53 PV
- Each percentage point's efficiency gain in a 1-hp continuous-duty motor = \$6/y = \$71 present value





1. Use whole-system design to “tunnel through the cost barrier”

- Achieve multiple benefits from single expenditures: save energy *and* capital *and* other costs
 - Superwindows have 10 distinct benefits, premium motors 16, dimmable ballasts 18,...
 - The key is whole-system optimization
 - Transdisciplinary, integrative design (charrettes...)
- And/or piggyback on other planned changes
 - Upgrades, renovations, retrofits, expansions,...
- Proven in numerous technical systems

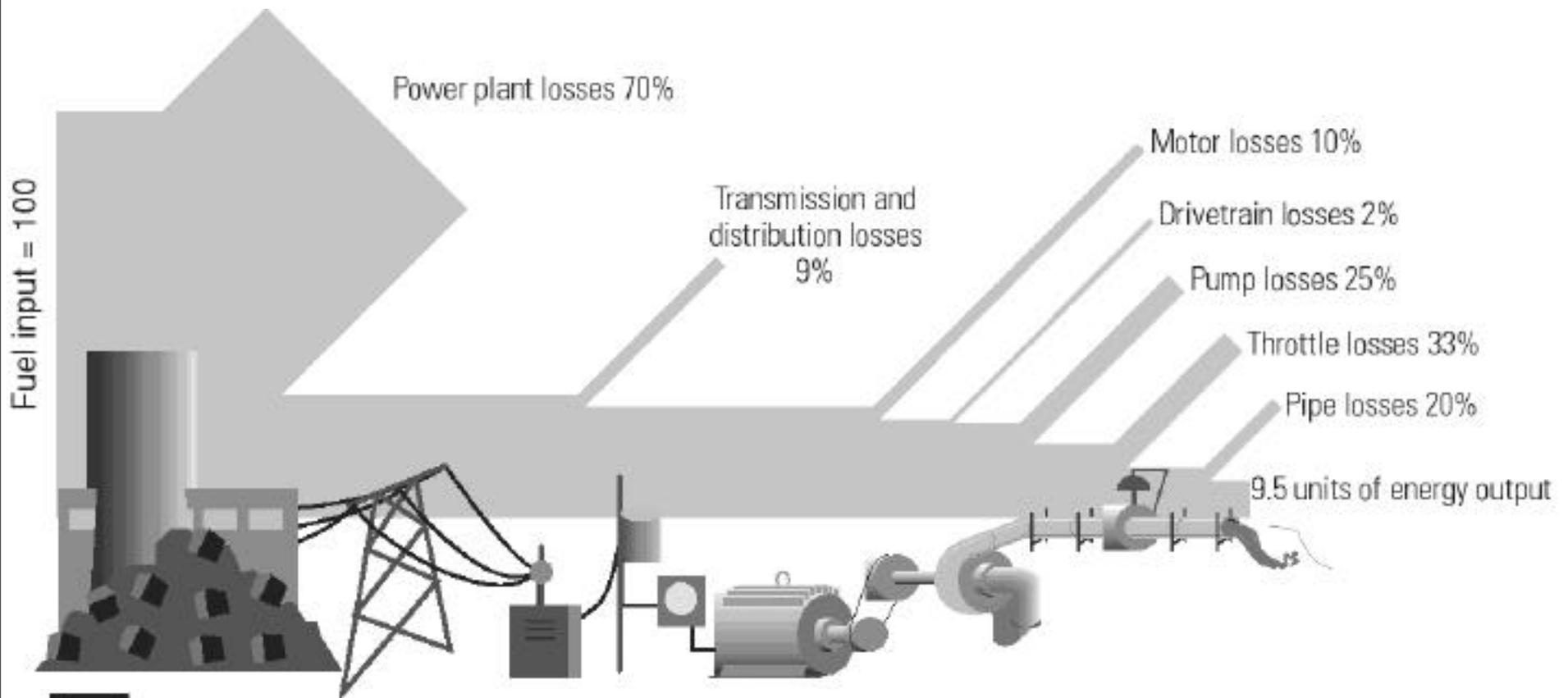
Some principles of efficient design

- Start downstream so savings compound: minimize native (*e.g.*, tools) loads and parasitic loads
- Reduce friction, resistance, flow, and velocity
- Use whole-system design integration to make big energy savings cost less than small ones
- Credit savings from reduced infrastructure
- Simplify, *e.g.*, no balancing valves
- Retrofit during renovations already planned

Start at the end-use to capture compounding savings

- Compounding losses require ~10 units of fuel at the power plant to deliver 1 unit of flow in the pipe
- Turn those compounding losses around backwards into compounding *savings*
- Saving 1 unit of flow or friction in the pipe can then save ~10 units of fuel, cost, and pollution at the power plant
- Downsize in-plant equipment: 1 unit of saved flow or friction saves ~2.4 units of motor sizing, etc.

Compounding losses...

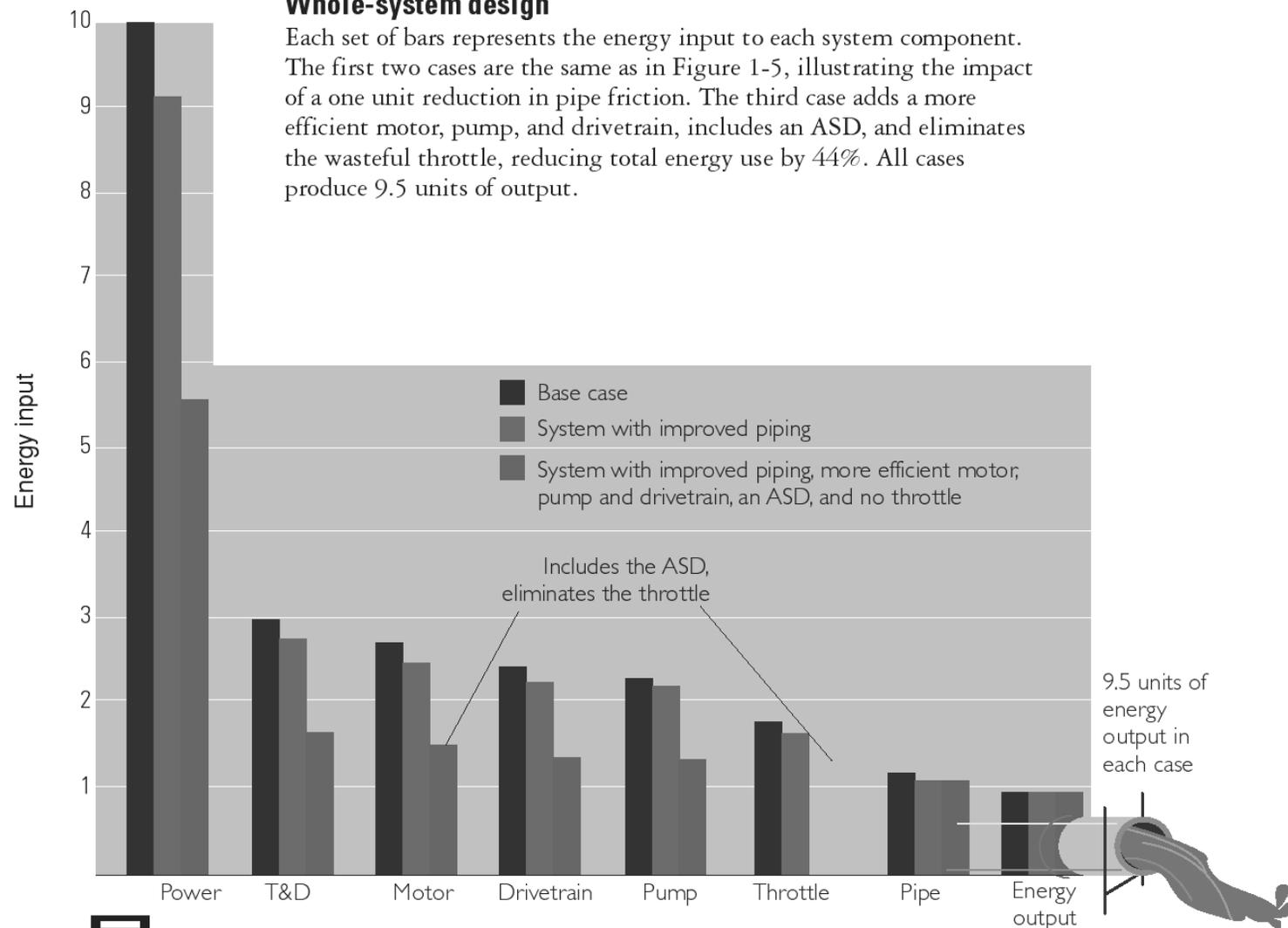


From the *Drivepower Technology Atlas*.
Courtesy of E SOURCE, www.esource.com.

...if turned around backwards, become compounding *savings*

Whole-system design

Each set of bars represents the energy input to each system component. The first two cases are the same as in Figure 1-5, illustrating the impact of a one unit reduction in pipe friction. The third case adds a more efficient motor, pump, and drivetrain, includes an ASD, and eliminates the wasteful throttle, reducing total energy use by 44%. All cases produce 9.5 units of output.



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

Whole-system design: drivepower

- $\sim 3/4$ of industrial, $\sim 2/3$ of all, el. runs motors—more total primary energy than highway vehicles
- Motors use $\sim 85\%$ of *total* fab electricity*—nearly all applications but lights, electronics, & thermal
- A big motor at 100% duty uses its own capital cost's worth of electricity every few *weeks*
- Almost all (except rarely run) motors in most fabs are good candidates for immediate retrofit, and many for retrofit to variable-speed inverter drive

*counting UPS losses as part of the total usage

Whole-system design: drivepower (2)

- In the U.S. market, induction motors' price and efficiency are *uncorrelated* up to 100+ hp (also true of industrial pumps and much else)
- Buying a “high-efficiency” motor is a bad idea: use Motor Master™ software to buy *the best*
- But first, make it the right size (half of U.S. industrial motors run at <60%, 1/3 at <50%, of their rated loads; many fabs may be worse)
- Before that, make the right size really small.
- Then make it even smaller: shrink loads first!

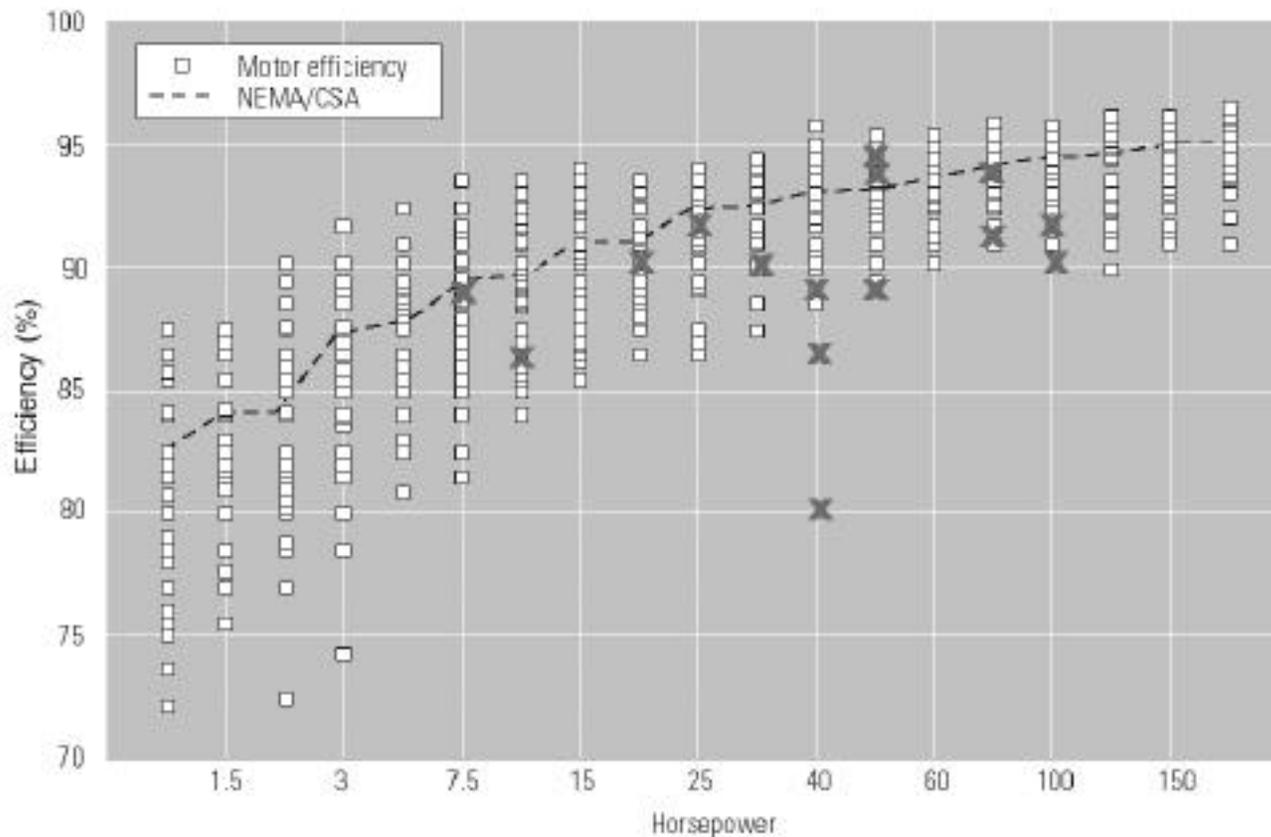
Not buying the best motors costs...

motor rating, <i>hp</i> / kW	eff. rating, U.S. code minimum	<i>best</i> eff. on U.S. mkt. '96	20-y PV of gross savings*
<i>10</i> / 7.5	87.5%	93.6%	\$6.2k
<i>25</i> / 19	89.5%	94.1%	\$11.4k
<i>40</i> / 30	91.0%	95.8%	\$18.5k
<i>75</i> / 56	92.5%	95.4%	\$20.6k
<i>100</i> / 75	93.0%	95.8%	\$26.3k
<i>200</i> / 149	94.1%	96.5%	\$44.3k

*5¢/kWh, 8,766 h/y, 4% internal losses from meter to load terminals, 5%/y real discount rate, 40% added for extra HVAC energy (COP 3, 5% parasitics), marginal HVAC costs \$2,500/ton. Analysis uses Motor Master database for all 60-Hz 480-V 4-pole TEFC NEMA Type B motors.

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.

Whole-system design: drivepower (3)

- Best-efficiency, right-sized motors are a first step
- RMI (1989) and EPRI (1990) found ~50% of typical industrial motor-system energy could be saved by retrofits costing $< \$0.005/\text{kWh}$, equivalent to a ~16-month max. payback at $5\text{¢}/\text{kWh}$
- This takes *comprehensive drivesystem* retrofits in between the meter and the input shaft of the driven machine: buy 7 savings, get 28 more for free
- Motor management & maintenance important too
- Downstream savings are often bigger & cheaper

Minimize friction first

- Meticulously reduce pressure drop/static head
- Lay out pipes/ducts first, *then* equipment
- Smooth, short, optimally sized pipes/ducts
- Few, short, sweet bends; turning vanes
- Few, low-pressure-drop valves/dampers
- Careful detailing to minimize turbulence
- First minimize flow, effectively upsizing existing pipes/ducts, then downsize pumps/fans
- Low-face-velocity (<200 fpm) filters & coils
- Analogously for all power wiring: make it fatter

Integrate design for multiple benefits

- Operational benefits—higher yield, throughput, & uptime, faster first-silicon-out & product cycles—can be worth more than energy and capital savings
 - Examples: cleanroom LCD displays and lightpipes
 - Both improve ergonomics and labor productivity
- Multiply savings by reversing losses
 - Low-pressure-drop, low-face-velocity air systems
 - Low parasitic loads, fewer tons, better optimization
 - Small equipment, less electrical capacity, piping, space, structural loading,...

Indirect operational benefits (1)

- Retrofit tool CRT display in cleanroom to flat-panel liquid-crystal display
 - Present-valued energy saving (~\$1k+ @ \$9/W) approximates total, and exceeds marginal, LCD cost
 - LCD lasts longer, doesn't drift, and is more reliable
 - LCD is easier to read (less fatigue, fewer errors)
 - Lightweight, small footprint, less UPS/HVAC sizing
 - Better laminar flow (no “thermal chimney”)
 - No static charge or outgas to compromise cleanroom
 - Sealed, no slots with airflow to gather/stir dust
 - No implosion, high-voltage, or EMI risks

Indirect operational benefits (2)

- Convert cleanroom fluorescent tubes to light-pipes fed by halide/sulfur lamp plus daylight
 - Severalfold heat reduction, worth ~\$9/W
 - No disturbance to laminar flow, no EMI or static
 - No lamps to replace in cleanroom: less traffic, no breakage risk, no particle shedding from contacts
 - No ballasts to fail or outgas
 - Easily reconfigured (tint, location, lux, better source)
 - Indirect light: same/better visibility w/5x fewer lux
 - Delivers attractive light with no flicker or hum
 - Less fatigue, better visibility and productivity

2. Beyond HVAC and motors (1)

- Progressive Technologies' Sentry™ control cuts tool exhaust 2–5x (hundreds in use to boost *yield*)
- Two ways to save ~70+% of fume-hood exhaust flow (worth >\$50/cfm) while improving safety
- Particle-counter real-time airflow control
- Applied Materials' "Green Tools" —*key initiative*
 - Reduced pressure drops, increased thermal insulation
 - Power supplies, motors, chillers, vacuum pumps,...
- Dual compressed-air pressure (2 & 7 bar)
- Rinse optimization (saves ~30+% UPW)
- Compact site layout (cut ST/AMK energy ~6.5%)

Beyond HVAC and motors (2)

- Thermal and liquid-gas-plant integration
 - Hook up the unconnected heat and coolth flows
 - Double benefits: *e.g.*, city-water summer precool of OSA saves its chiller energy *and* DI boiler energy
- Fuel cells w/no UPS, cascaded process heat
- Next frontiers: deep-UV-laser cleaning, optimizing tools' environmental requirements, aerogel capacitive DI, fast compressor/pump controls, scroll vacuum pumps (5x), process improvements (*e.g.*, Legacy's H₂O/O₃ photoresist-strip eliminates H₂SO₄, greatly reduces UPW & exhaust,...)

Cut CO₂/chip by 10–100x...at a profit!

- x0.44 from 200- to 300-mm shift if same yield
- x0.3 from state-of-the-art fab efficiency*
- x0.4 from onsite trigeneration (net of reformer)
- x0.94 from fuel-cell elimination of UPS losses
- x0.5 fueling with gas, not coal (less carbon/J)
- x0.5 switching energy supply to 50% renewables

*ST has published a path to x0.33, reducing a 1997 15-MW fab to 5 MW. It also considered “doable” a path from ST’s 1997 av. of 5.0 and best of 3.0 kWh/in² std. 6" wafer (vs. the SIA roadmap, 8.0 in 1997) to 1.2 in ~2008 (Murray Duffin, VP, STMicroelectronics, 28 May 1998 talk at 16th Nikkei Microdevices Seminar, Tokyo)

So it's quite easy being green

- These six steps cut CO₂ per chip by ~99%*
- So if chip output rises 30x (40.5%/y for 10 y or 18.5%/y for 20 y), *and* you fuel your growth with these kinds of expansions, your total CO₂ drops by nearly 3x, so you could *sell* carbon permits
- Almost all these steps are profitable now
- The rest (*e.g.*, renewables) soon will be
- All can also bring big operational benefits

*ST published in 5/98 a realistic path to a 92% reduction. We're ignoring here upstream options, *e.g.*, 4–5x Czochralski savings

3. Saving 1–2% of total costs matters

- Saved energy costs, like any saved overhead, drop straight to the bottom line
- Basic energy efficiency retrofits can often add one percentage *point* to total net profit
- If new chip sales earn (say) 10% profit, then saving \$1 worth of energy increases profits by the same as \$10 of new sales—harder and less certain (especially nowadays) than saving energy!
- If you're short of capital, *don't waste it* on oversized and overcomplex utility plant

The Rosetta stone: payback vs. ROI

- Most engineers are told to get <2-y simple paybacks, but lack the magic formula...*aftertax return on investment (ROI, in y) equals:*

$$\frac{1 - \text{marginal tax rate}}{\text{simple payback (y)} - 1}$$

- So if marginal tax rate = 0.36, a 2-y payback is a 64%/y ROI, 18 months is a 128%/y ROI,...
- If your target return is, say, 16%/y, insisting that energy efficiency pay a return ~4–8x higher than that deprives your shareholders of safe profits
- If you lack capital to capture that spread: borrow it, visit www.ipmvp.org, or talk to the RMI team

Measure carefully to manage effectively

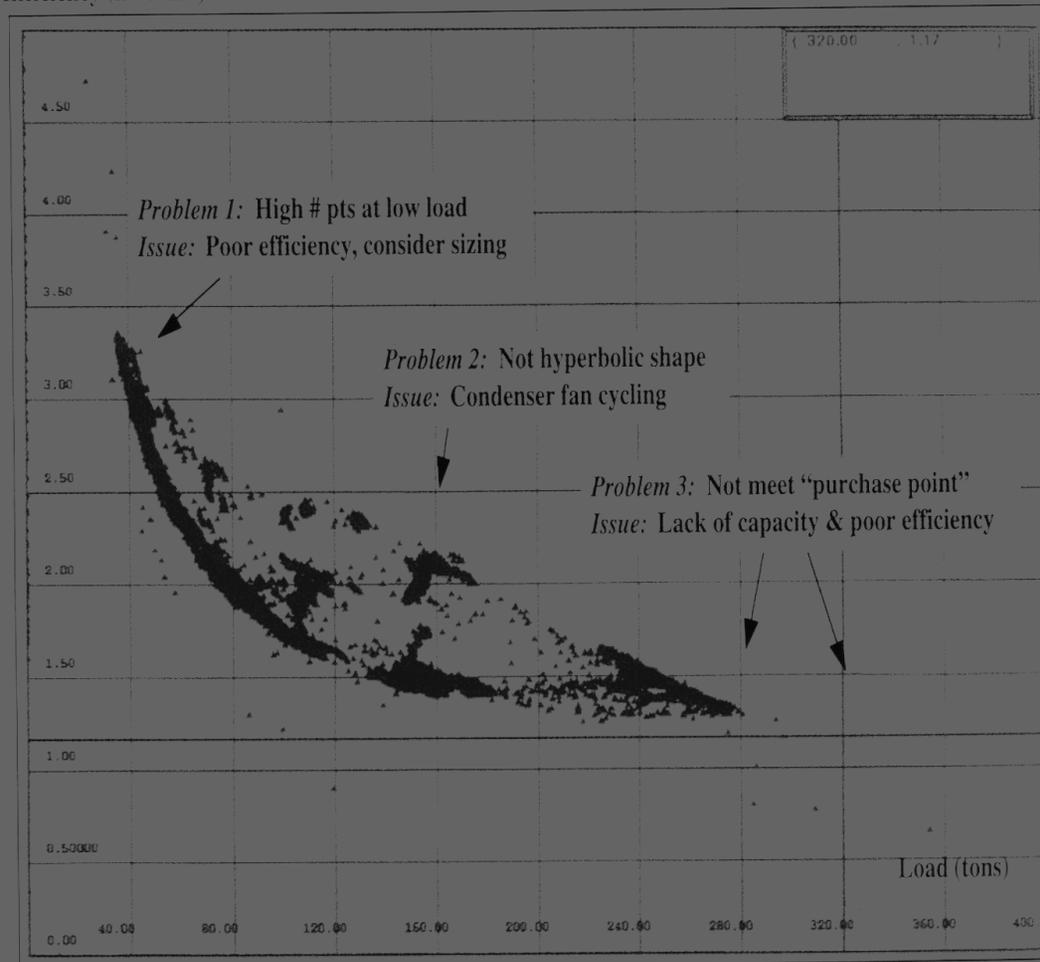
- If you don't measure it, you can't manage it
- You get what (*and* how well) you measure
- Only a handful of fabs now measure precise kW/t
- Determine the economic value of sensor accuracy, precision, and stability, then buy them to that value
- Information must reach the people who need it: systems without feedback are stupid, by definition
- Use sophisticated 3-D graphics software to visualize data; immediate diagnostics; 1-minute archiving; show real-time kW/t always live onscreen

Display to understand: Electric Eye[®]

(This is an unusually simple example. For information: www.supersym.com.sg.)

An analysis of a chiller efficiency reveals three problem areas.

Efficiency (kW/ton)



Use disaggregated physical metrics

- Chilling: for system *and* for each separate subsystem (chiller, ChWP, CWP, CTs), **kW/t**
- Fluid flow and UPW supply: **W/cfm, W/gpm**
- Now rarely measured accurately (if at all)
- 10% flow error = ~30% energy error
- Industry needs a precompetitive consensus system with the accuracy, precision, longevity, and visualization protocols to support transparent, stable cross-facility and time-series comparisons—reliable, cross-checked, with zero ambiguity

Management recommendations (1)

- Establish a serious corporate energy management program: site champions, coaches, accountability, aligned incentives, continuous improvement
- Promote necessary corporate cultural changes, including curiosity and managed risk-taking
- See facilities not as overhead to minimize but as a profit center to optimize by mining valuable waste
- Charge processes the shadow cost of services used
- Review capital allocation rules top-to-bottom so the financial and operating people share the same goal

Management recommendations (2)

- Measure, visualize, and communicate the data
- Convert efficiency metrics into money metrics
- Require whole-system design (*www.esource.com*)
- Set minimum performance benchmarks; reward better. For example, a new Singapore plant should produce 42°F chilled water on the design day at not over 0.54 kW/t: 0.48 chiller* + 0.026 chilled water pump + 0.021 condenser water pump + 0.011 cooling towers. Why settle for worse and costlier?

*ST's *retrofitted* AMK fab averages 0.44 chiller kW/t, producing 59°F (15°C) water at 0.38 kW/t and 42°F (5.5°C) water at 0.58 kW/t

Management recommendations (3)

- As margins slim, we must sweat the details more—and energy efficiency is far more than a detail
- Technology and design are dynamic. Never stop learning. If you've just retrofitted, retrofit again.
- If, as traditional designers may tell you, this stuff (a) doesn't work or (b) is already in their designs, those designs' technical efficiency should compare favorably with the best in the world. Does it?
- Demand and incentivize advanced efficiency from vendors and contractors: reward measured savings, not expenditures. If you keep doing what you've done, you'll keep getting what you've gotten.

A modest prediction

If those responsible for giving you your current levels of efficiency insist it's just fine, kindly remember these two little ideas:

- Companies that take seriously these new opportunities for elegant frugality will gain major competitive advantage.
- Companies that don't won't be a problem... because they won't be around.

* * *

About the author, RMI, and this paper

About the author: Mr. Lovins directs the research and finance of Rocky Mountain Institute (www.rmi.org). A consultant experimental physicist educated at Harvard and Oxford, he has received an Oxford MA (by virtue of being a don), six honorary doctorates, a MacArthur Fellowship, the Heinz Award, and the Nissan, Mitchell, “Alternative Nobel,” and Onassis Prizes; held visiting academic chairs; briefed ten heads of state; published 26 books and several hundred papers; and consulted for scores of industries and governments worldwide. *The Wall Street Journal’s* Centennial Issue named him among 28 people in the world most likely to change the course of business in the 1990s. His work focuses on whole-system engineering and business strategies to transform the car, electricity, semiconductor, chemical, and building sectors toward advanced resource productivity.

About Rocky Mountain Institute: This independent, nonprofit, nonpartisan, market-oriented resource policy center was cofounded in 1982 by Hunter Lovins, its CEO, and her husband Amory Lovins. Its mission is to foster the efficient and sustainable use of resources as a path to global security. RMI’s ~50 staff pursue research and outreach in energy, transportation, climate, water, agriculture, security, community economic development, sustainable corporate practices, and environmentally responsive real-estate development. The Institute’s ~\$3-million annual budget comes 30–50% from programmatic enterprise earnings (mainly private-sector consultancy and proceeds from RMI’s for-profit subsidiary E SOURCE, the premier source of technical and strategic information on advanced energy efficiency, www.esource.com). The rest comes from grants and tax-deductible gifts.

About this paper: These comments are framed largely in a U.S. context for specificity, but apply worldwide, *mutatis mutandis*. Mostly American units have been used for the convenience of the predominantly U.S. audience. Proprietary data have been adapted so as to protect the owners’ interests. This work was supported by the Hewlett, Joyce, MacArthur, and C.S. Mott Foundations. The views expressed are the author’s. Help from Eng Lock Lee, Ron Perkins, and Peter Rumsey (Super-symmetry Services, www.supersym.com.sg), Jay Stein (E SOURCE, www.esource.com), Chris Robertson (Chris Robertson & Associates), Chris Lotspeich (RMI), our collective clients, and others is gratefully acknowledged. Suggestions for improvement will be welcomed.