Integrative Design: A Disruptive Source of Expanding Returns to Investments in Energy Efficiency

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Energy end-use efficiency's potential is large[1] and little-tapped. Yet all official studies substantially understate its potential and overstate its cost, because they focus on individual *technologies* without also counting integrative *design* that optimally *combines* those technologies. The efficiency resource keeps getting bigger and cheaper as innovation, competition, and volume make energy-saving technologies more effective and less costly—both faster than they're being applied.[2] But even more important complementary advances in integrative *design* remain nearly invisible, unrecognized, untaught, and practiced only by a small subset of exceptional designers.

Examples below for buildings, industry, and vehicles show that optimizing whole systems for multiple benefits, not disjunct components for single benefits, often makes gains in end-use efficiency much bigger and cheaper than conventionally supposed. Indeed, integrative design can often yield *expanding* rather than the normal diminishing returns to investments in energy efficiency, making very large (even order-of-magnitude) energy savings cost *less* than small or no savings. Yet dis-integrated design prevails, because:

- R&D is structured to develop efficiency technologies, not design methods (probably no DOE R&D program develops, spreads, or values integrative design);
- design pedagogy was integrated in Victorian times, but for more than a century has been getting sliced into ever more specialized subdisciplines, so synergies are lost;
- there are almost no curricular materials or trainings for teaching integrative design, nor is it expected or evaluated in licensing designers or accrediting design schools;
- force of habit, and fear of liability for deviating from standard practice, make both designers and clients wary of fundamental design innovation;

[1] *E.g.*, in 2009, the NAS/NRC's *America's Energy Future* conservatively found that U.S. buildings can profitably save more electricity (35%) than projected growth in all sectors through 2030, while McKinsey & Company found profitable potential savings by 2020 totaling 23% of U.S. energy, worth over $1.2 trillion but costing less than half that ("Unlocking Energy Efficiency in the U.S. Economy," www.mckinsey.com/clientservice/electricpowernaturalgas/downloads/us_energy_efficiency_full_report.pdf).
[2] Some technological improvements are transformational: *e.g.*, biomimetic Fibonacci rotors (Pax Scientific, 2008–), LED-optimized luminaires saving up to 98% of ASHRAE lighting power density (like Kim Lighting's 2009 outdoor "Warp9"), and adaptive-emissivity glazings (Serious Materials, ~2012).

- most software design tools optimize parts, not wholes, and cannot support integrative design, nor is there a readily identifiable and skilled integrative design practice from which tool-builders can extract the necessary insights;
- design practice has become commoditized, so most clients expect, reward, and get minor adaptations of previous drawings, not clean-sheet whole-system optimization.

These mutually reinforcing causes create a vicious circle reinforcing the status quo. Reversal requires a concerted effort to replace disciplinary fragmentation with a clear whole-system design methodology; new teaching materials (including practical case-studies) and teacher training; collaboration between design clients, firms, and schools to create "demand pull"; rewarding designers for what they save, not what they spend; early-adopter clients' offering liability waivers or risk-sharing to overcome hesitancy; wide dissemination of results to build broad acceptance; and rapid feedback from field results to keep improving pedagogy and practice.

Integrative design

Integrative design rigorously applies orthodox engineering principles, but achieves radically more energy- and resource-efficient results by asking different questions that change the design logic. Scattered but encouraging examples have lately emerged in hundreds of buildings as well as in several vehicle designs and diverse industrial facilities, both new and retrofit. Integrative design was validated by an $18-million 1990–97 Pacific Gas and Electric Company experiment[3] and taught at Stanford Engineering School in 2007.[4] Yet it remains rarely practiced or recognized:[5] the National Academies' *America's Energy Future* mentions its potential value for buildings but ignores its effect, and ignores it altogether for vehicles and industry. Such omissions of integrative design, perhaps due to relative unfamiliarity, make energy efficiency's potential seem smaller and costlier than it really is, so huge investments are misallocated to supply.

To be sure, integrative design isn't easy at first: it requires designers with diverse backgrounds and synthetic as well as analytic talents, a transdisciplinary team, a demanding client, and meticulous attention to detail. But experience demonstrates that it can be done, it can be taught, with practice it becomes as easy as dis-integrated design is now, and in the long run, it may become a key determinant of competitive success.

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[3] Brohard, G.J. *et al.* 1998: "Advanced Customer Technology Test for Maximum Energy Efficiency (ACT[2]) Project: The Final Report." *Procs. Summer Study on Energy-Efficient Buildings*, ACEEE, 207.67.203.54/elibsql05_p40007_documents/ACT2/act2fnl.pdf; technical reports at www.pge.com/pec/resourcecenter/, "Related Links."

[4] "Advanced Energy Efficiency"; the five public-lecture podcasts are at itunes.stanford.edu

[5] With minor exceptions, chiefly in DoD, GSA, and the Federal Energy Management Program.

Economic theory generally assumes diminishing returns: the more efficiency we buy, the more steeply the marginal cost of the next increment of savings rises, until it becomes too costly (Fig. 1a). But integrative engineering often yields expanding returns—big savings can cost *less* than small or no savings (Fig. 1b)—if the engineering is done unconventionally but properly.

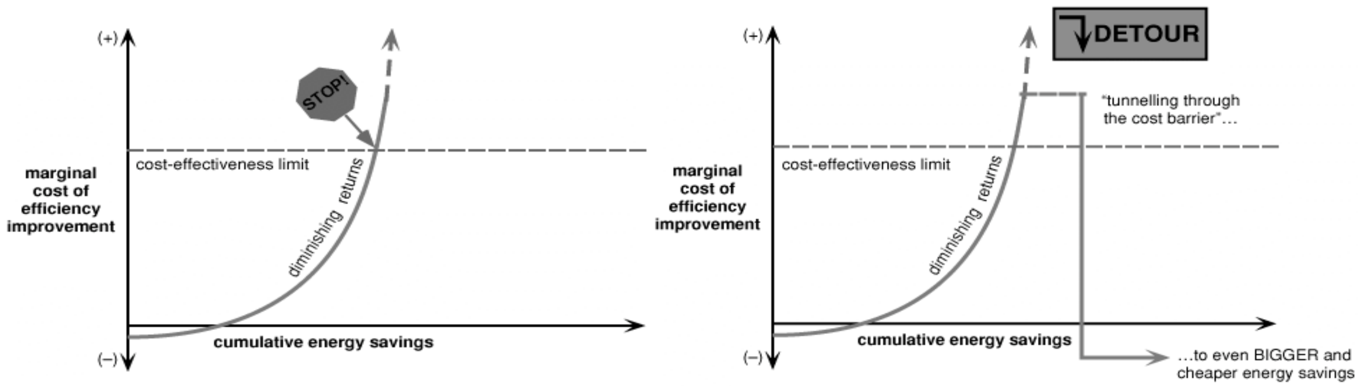

Fig. 1a (left). Diminishing returns are normally assumed for all components but observed only for some, like thermal insulation—and not for others, like refrigerators, TVs, servers, midsize industrial pumps, and motors up to at least 350 hp. Fig. 1b (right) shows how, if we optimize not components for single benefits but whole systems for multiple benefits, we can often make big savings cost less *than small ones, as illustrated on pp. 4–8 below.*

Integrative design applies clear principles that are often ignored and seldom combined:

1. Focusing on the desired end-use places purposes and application before equipment, efficiency before supply, passive before active, simple before complex.
2. Broadening design scope embraces whole systems and sets end-use performance metrics.
3. Designing from scratch, at least initially, creatively harnesses "beginner's mind," spans disciplinary silos, surpasses traditional solutions, and further expands the design space.
4. Analyzing gaps between theoretical minimum requirements and typical usage reveals overlooked opportunities for elegant frugality.
5. Optimizing systems, not isolated parts, lets single expenditures yield multiple benefits.
6. Evidence-based analysis supplants rules of thumb.
7. Measurement and prudence replace mindless oversizing and allow operational risks to be managed explicitly and intelligently.
8. End-use savings multiply upstream energy and capital savings, so efficiency logic is sequenced in the direction opposite to energy flow.
9. Design satisfies rare conditions (making appropriate tradeoffs and engaging end-users), but emphasizes typical conditions to maximize performance integrated over the range.
10. Controls and embedded sensors create intelligence and learning, so design can be optimized in real operation and further improved in future applications.

The following examples illustrate these principles.

Examples in buildings

How much thermal insulation should surround a house in a cold climate? All engineering texts (at least in English) say to specify just the thickness that will repay its marginal cost from the present value of the saved marginal heating energy. But this omits the *capital cost of the heating system*—furnace, ducts, fans, pipes, pumps, wires, controls, and fuel source. A 1984 sub-arctic-climate house so optimized saved ~99% of its space-heating energy with $1,100 lower construction cost, because superwindows, superinsulation, air-to-air heat exchangers, etc. cost less than the heating system they replaced. This approach has also been adopted in >20,000 EU and US "passive houses," saving 75–95% of US-allowable heating energy with no extra capex.

Similarly, PG&E's "ACT^2" experiment demonstrated in seven new and old buildings in the 1990s[6] that the "supply curve" of energy efficiency generally bent downwards as sketched in Figure 1b. For example, an ordinary-looking new tract house was designed in 1994 to save 82% of the energy allowed by the then-strictest US standard (1992 California Title 24), yet PG&E estimated that if built in quantity, it would cost ~$1,800 less than normal to build and ~$1,600 less in present value to maintain.[7] It provided normal or better comfort with no cooling system in a climate that can reach 113˚F; a similar house later did the same in a 115˚F-peak climate. And the 1996 Bangkok house of architect Prof. Suntoorn Boonyatikarn provided superior comfort, with ~10% of normal air-conditioning energy, at no extra construction cost.[8] This and the cold-climate house example essentially span the range of the Earth's inhabited climates.

A retrofit now underway at the Empire State Building is expected to save ~38% of its energy with a 3-year payback: remaking its 6,500 windows onsite into superwindows (nearly perfect in admitting light without heat), plus lighting retrofits, cut the peak cooling load by one-third, saving $17.4 million capex because the old chillers can be renovated and reduced rather than replaced and expanded.[9] This reveals the opportunity to make deep retrofits cheaper by coordinating with routine renovations like renewing curtainwalls. Such a retrofit design for a 200,200-ft^2 all-glass office tower near Chicago found 75% energy-saving potential at slightly *lower* cost than the normal 20-year reglazing that saves nothing—because the $200,000 capex saved by making the cooling system 4× smaller (yet 4× more efficient), not renovating the big

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[6] Ref. 3, *supra*.

[7] Davis Residential Site Design Report, 1996 (n. 3 above, last reference); "The Super-Efficient Passive Building Frontier," *ASHRAE J*. **37**(6):79–81, June 1995.

[8] www.e2singapore.gov.sg/docs/Seminar_Buildings.pdf.

[9] N. Buhayar, "Old Wine, New Bottles," *Wall St. J.*, 21 Sept. 2009, online.wsj.com/article/NA_WSJ_PUB:SB10001424052970203987204574338684174566044.html (misprinting $17.4 million as $7 million of saved capex).

old system, pays for the other improvements.[10] However, that design wasn't implemented because of a perversely incentivized leasing broker—a reminder of the need for systematic implementation follow-through to overcome obstacles at each stage of the complex value chain.

Digging deeper: a pumping-system example

Motors use ~60% of the world's electricity. Half of motor power runs pumps and fans. Many pumps circulate fluids in factories and buildings. Such a heat-transfer loop originally designed to use 70.8 kW of pumping power was redesigned by Interface Nederland's chief engineer Jan Schilham to use ≤9.7 kW—≥86% less—with lower capital cost and better performance, using no new technologies but only two changes in the design mentality:

- **Use big pipes and small pumps, not small pipes and big pumps.** Pipe friction falls as nearly the fifth power of diameter. Conventional design makes the pipe just fat enough to repay its greater cost from the saved pumping energy over the years. But this omits the *capital* cost of the pumping *equipment*—the pump, motor, inverter, and electricals—that must overcome the pipe friction. Their size and roughly their cost falls as nearly the fifth power of pipe diameter; the cost of the fatter pipe rises as only the second power of diameter. Thus optimizing the pipe as a component pessimizes the system. Optimizing the whole system yields fat pipes and small pumps, with smaller total capex and tiny opex.
- **Lay out the pipes first, then the equipment.** Normal practice is the opposite, making the connected equipment typically far apart, obstructed by other objects, at the wrong height, and facing the wrong way, so the piping has ~3–6× as much friction as it would with a straight shot. The pipefitters like this: they are paid by the hour, mark up a profit on the extra pipes and fittings, and don't pay for the extra electricity or bigger pumping equipment. A smart owner prefers fat, short, straight pipes to thin, long, crooked pipes.

These design changes cut reported pumping power by ≥7×, with lower capital cost and better performance—and saved 70 kW of heat loss with a 2-month payback by facilitating insulation.

The engineer who inspired Schilham's innovations recently designed the pumping system in Fig. 2 (next page). Piping is usually laid out orthogonally—at neat right angles—which is easy to draw but maximizes friction and cost. Nowadays the drawing is usually done by computers, whose CAD software will soon be able to create such non-orthogonal designs. That's unorthodox and less pretty, but far more economical.

[10] *ASHRAE J.*, ref. 7, *supra*.

Fig. 2: A 2009 Singapore piping system by L*EE* *Eng Lock, saving ~69% of normal pumping energy with reduced capex (partly because of the smaller pumps and motors).*

These pumping examples hold another key lesson (Fig. 3 on next page): each unit of friction or flow saved in the piping system saves ~10 units of fuel, emissions, and cost at the power plant, because the ~10× compounding losses from power-plant fuel to pipe flow are turned around backwards into compounding savings. Starting savings downstream also makes the upstream components progressively smaller, simpler, and cheaper, saving the most capital cost too.

Industrial examples

Recent integrative redesigns of diverse industrial plants have typically yielded retrofit energy savings ~30–60% with paybacks of a few years, and new-facility energy savings ~40–90% with generally *lower* capital cost. For example*:*

- a 2009 EDS data center is using 73% less non-IT electricity and 98% less cooling and pumping energy than normal, with 3× the computing/kW, at normal capital cost—but its full potential would have saved ~95% of the electricity and ~50% of the capital cost;[11]

[11] tinyurl.com/yfd95ua; tinyurl.com/ykd5b5s; www.youtube.com/watch?v=QsIyzdva780; search.cdproject.net/responses2/attachedfiles/Responses/53539/9469/EDS_SustainableDC.pdf; EDS staff, personal communications.

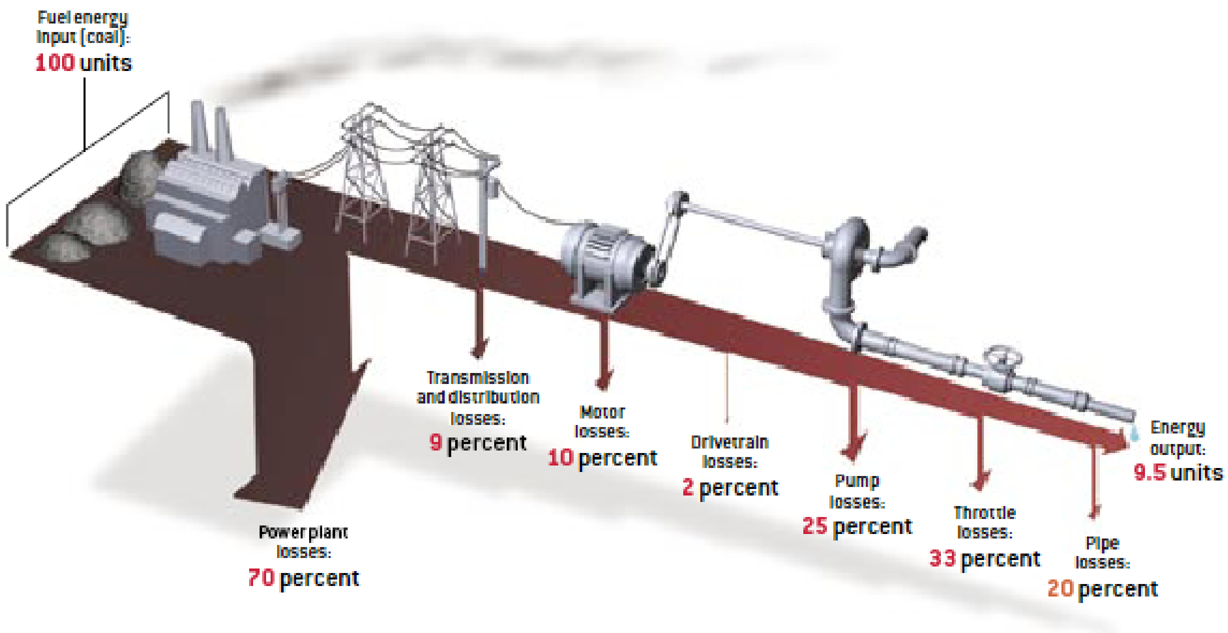

Fig. 3: *Saving downstream energy turns compounding losses into compounding savings of energy and capital.* Reproduced by permission from *Scientific American*, 9/05, pp. 74–83.

- TI's Richardson, Texas chip fab saved 20% of the energy (without using the two biggest recommendations, delayed to later fabs), 35% of water, and \$230M (30%) of capital cost[12]—while the conceptual design for another firm's next fab is expected to save two-thirds of energy and half of capex while eliminating all 22,000 tons of chillers;[13]
- a retrofit underway at the world's #1 platinum mining complex is expected to save ~43% of energy with a 2–3-year payback, while a new-iron-mine conceptual design would use no grid electricity or fossil fuel (it runs on gravity) and considerably reduce net capex;
- retrofit designs for Shell's most efficient refinery, a giant LNG liquefaction plant, and a North Sea platform are respectively expected to save 42%, ≥40%, and ~100% of energy with paybacks of a few years—while a new \$5b Fischer-Tropsch gas-to-liquids-plant design is expected to save >50% of energy and ~20% of capex.

Vehicle examples

Similar design integration yielded a 3.6× increase in the efficiency of a safe, uncompromised, gasoline-hybrid midsize SUV, virtually-designed in 2000 with two European Tier Ones. Its halved mass didn't increase production cost, thanks to the two-thirds-smaller powertrain and the novel carbon-fiber manufacturing technology's savings of ~99% in tooling cost and ~100% by eliminating body and paint shops. At midvolume production, its ~\$2,511 extra sticker

[12] www.ti.com/corp/docs/rennerroadfab/gdoverview.shtml.

price (2000 $) would pay back in one year.[14] OEMs are becoming interested: in 2007, Toyota's *1/X* concept car combined the interior size of a *Prius* with half its fuel use and one-third its weight—and the previous day, Toray announced a factory to mass-produce carbon-fiber car parts for Toyota. Leapfrogs are starting to appear using both advanced-composite and metal solutions.

Such "platform fitness" can greatly accelerate and amplify deployment of any advanced powertrain by making its costly batteries or fuel cells ~3× smaller. For example, a 5-m^3, 1-t plug-in-hybrid-electric commercial van demonstrated in April 2009 requires no subsidy to make a strong business case to fleet buyers, because its low drag and mass (it weighs the same with a ton of payload as its competitors weigh empty) eliminated most of the costly batteries.[15] DOE's automotive strategy, in contrast, appears to fund ~99% powertrain development and ~1% platform fitness. Yet saving one unit of energy in the engine saves just one unit in the tank, while saving one unit at the wheels saves *eight* units in the tank—by eliminating the additional seven units that a conventional powertrain would lose while delivering that one unit to the wheels.

Next steps

Business leaders need to demand radically more efficient design outcomes, and to ask more penetrating questions to ensure that the design process is changed fundamentally, not incrementally. Such "demand pull" can drive basic reforms in engineering pedagogy and practice. Ultimately, this will make profitable integrative design routinely expected—like six-sigma, lean, or safety culture. For now, the potential needs first to be recognized and demanded. Comprehensively applying existing technologies for energy and resource productivity, and developing even better ones, can yield great savings and benefits, but an even bigger prize awaits: There are fewer higher-leverage opportunities to boost energy productivity than "re-minding" designers.

[13] Eight largely completed STMicroelectronics chip-fab retrofits also saved 30–50% of the energy used to make chilled water and clean air, with paybacks typically under one year.
[14] *Intl. J. Veh. Des.* **35**(1/2):50–85 (2004); www.oilendgame.com.
[15] www.brightautomotive.com.