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Profitable Solutions to Climate, Oil, and Proliferation

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Abstract Protecting the climate is not costly but profitable (even if avoided climate change is worth zero), mainly because saving fuel costs less than buying fuel. The two biggest opportunities, both sufficiently fast, are oil and electricity. The US, for example, can eliminate its oil use by the 2040s at an average cost of $15 per barrel (2000$), half by redoubled efficiency and half by alternative supplies, and can save three-fourths of its electricity more cheaply than operating a thermal power station. Integrative design permits this by making big energy savings cheaper than small ones, turning traditionally assumed diminishing returns into empirically observed expanding returns. Such efficiency choices accelerate climate-safe, inexhaustible, and resilient energy supply—notably the "micropower" now delivering about a sixth of the world's electricity and 90% of its new electricity. These cheap, fast, market-financeable, globally applicable options offer the most effective, yet most underestimated and overlooked, solutions for climate, proliferation, and poverty.

Keywords Energy · Climate · Oil · Proliferation · Efficiency · Renewables · Integrative design

The energy choices commonly offered to citizens would, if clearly stated, amount to this unhappy multiple-choice test: "Would you rather die of (a) climate change, (b) oil wars, or (c) nuclear holocaust?" Seldom offered is a fourth way: "(d) None of the above." We can make this better choice real, simply by using energy in a way that saves money.

Another quiz: "How is climate protection like the Hubble Space Telescope?" Answer: Both were spoiled by a sign error—a confusion between a plus sign and a minus sign.[1] Just as this mixup caused the telescope's mirror to be ground in the wrong shape, so the world's climate conversation has been severely distorted by confusing theory with observations. The debate is difficult because it is all about cost, burden, and sacrifice—what will climate protection cost, is it worth it, and who should pay? Somehow the economic theorists forgot that efficiency is cheaper than fuel, so they omitted the money saved by substituting efficiency for fuel. (Instead they assumed that efficiency must cost more than the fuel it saves, or it would have been bought already in their assumed nearly perfect and universal markets.) This incorrect assumption, contrary to all empirical evidence from practitioners, is the biggest obstacle to climate protection. Once more leaders and pundits understand that saving fuel costs less than buying fuel, any remaining resistance to climate protection will melt faster than the glaciers.

INTRODUCTION

Fortunately, many companies understand this and are investing in energy efficiency, whether or not they are concerned about climate. IBM and STMicroelectronics have long cut their carbon emissions 6% year^{-1} with 2- to 3-year paybacks from making their factories more energy efficient. DuPont said it would cut its 2010 global greenhouse emissions to 60% below 1990's; by 2006, it had achieved an 80% reduction at a $3,000-million profit.

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[1] Lovins 2005, Sep 2005, RMI Publ. #C05-05, www.sciam.com/media/pdf/Lovinsforweb.pdf or www.rmi.org/rmi/Library/C05-05_MoreProfitLessCarbon.

Dow's $1,000-million investment in energy efficiency has so far returned $9,000 million in savings. BP met its operational carbon reduction goals 8 years early at a $2,000-million profit. United Technologies cut its energy use per dollar 45% during 2003–07. GE is cutting its energy intensity 30% during 2005–2012 to build shareholder value. Interface may hold the record with 1996–2008 reductions of 71% in absolute greenhouse-gas emissions while offsetting the rest, growing the company two-thirds, and doubling profits. Even these achievements just scratch the surface of what is possible and worthwhile: McKinsey&Company showed (McKinsey&Company 2009) how to cut forecast 2030 global greenhouse-gas emissions by 70% at an average cost of just $6 per tonne of CO_2 equivalent. Including the newer technologies and integrative designs described below would have made that potential bigger and much cheaper (less than zero).

If global energy intensity—primary energy used per dollar of real GDP—continued to drift down by just 1% year^{-1} under canonical long-term trends of population and economic growth and of decarbonizing fuels, then global CO_2 emission rates would about triple by 2100, so we would all be toast. However, can we *make* toast, not *be* toast? If energy intensity fell not by 1% but by 2% year^{-1}, emissions would stabilize, and if intensity fell by 3–4% year^{-1}, climate could stabilize (to the extent irreversible changes aren't already underway). Is this conceivable? Yes: the US has spontaneously cut its energy intensity by 2–4% year^{-1} for most of the past few decades, under both high and low energy prices. Denmark in 1980–2006 shrank its carbon intensity 2.7% year^{-1}. China cut its energy intensity over 5% year^{-1} for a quarter century through 2001.[2] Attentive Western firms are profitably cutting their energy intensity 6–16% year^{-1}. Therefore, why should 3–4% year^{-1} be difficult—especially since most of the forecast growth is in countries like China and India that are building their infrastructure from scratch, and can more easily build it right than fix it later? And since virtually everyone who does energy efficiency makes money, why should this be costly?

Detailed analyses cited below show how the US, for example, can save about half its oil and gas use at about one-fifth of their current price, and about three-fourths of its electricity use at about one-eighth the electricity's price. Even Japan, with 2- to 3-fold lower energy intensity, has found ways to save two-thirds of the remaining energy (National Institute for Environmental Studies 2009). These opportunities are best described in two main themes: burning oil and producing electricity. These, respectively, cause 43 and 41% of US, and roughly 45 and 30% of global, fossil-fuel carbon emissions. Electricity generation is ~50% coal fired in the US, 42% in the world, so each unit of electricity saved displaces 3–4 units of especially carbon-intensive fuel—huge climate leverage.

GETTING OFF OIL

In 2004, a comprehensive Pentagon-consponsored study (Lovins et al. 2004) showed how to eliminate US oil use by the 2040s, led by business for profit, using only 2004 technologies. Half the oil can be saved by redoubling its end-use efficiency at an average cost of $12 per saved barrel (bbl) (2000$, 5% year^{-1} real discount rate). The rest can be displaced by a mix of new supply: three-fifths saved natural gas, two-fifths advanced biofuels unrelated to the food system. Saving half of US natural gas is so cheap, averaging <$1 GJ^{-1}, that these supply substitutions cost an average of only $18 bbl^{-1} (and even the costliest increment beats $26 bbl^{-1} oil), so the cost of eliminating US oil use is only $15 bbl^{-1}—clearly profitable even if, as the study assumes, climate change and all other externalities were worth zero. The assumed implementation rate is substantially slower than in 1977–1985, when the US last paid attention to oil: in those 8 years, GDP grew 27%, oil use fell 17%, oil imports fell 50%, and oil imports from the Persian Gulf fell 87%. Unlike previous, policy-driven oil studies, the transition is driven by business logic: a $180,000 million investment, half to retool the vehicle-making industries and half to build a modern biofuel industry, would annually return $155,000 million gross or $70,000 million net against a $26 bbl^{-1} oil price while cutting US CO_2 emissions 26%, adding a million jobs, and potentially saving a million at-risk jobs, chiefly in auto-making. Innovative public policies could speed and reinforce the business logic, but without requiring new energy taxes, subsidies, mandates, or national laws. This strategy is actually being implemented via "institutional acupuncture,"[3] and signs of "peak oil on the demand side" are rapidly emerging (Gold and Campoy 2009; Cambridge Energy Research Associates 2009).[4]

[2] China raised its energy intensity a total of 2% during 2000–2005 by binging on energy-intensive basic materials industries, but looks back on track for a ~4.0% year^{-1} reduction during 2005–2010, intends legally binding cuts of 3.4–4.0% year^{-1} during 2005–2020, and just announced attainment of its 5-year industrial efficiency goal in 3 years: Seligsohn (2009).

[3] Lovins (2008a), e.g., Boeing's *787 Dreamliner* has turned an efficiency leapfrog (most importantly including a half-carbon-fiber airframe) into a breakthrough competitive strategy now starting to be emulated in the automotive sector; Wal-Mart saved 38% of its truck fleet's 1 ton^{-1} km^{-1} during 2005–2008 and aims for 50% by 2015 (http://walmartstores.com/Sustainability/9071.aspx); and the Pentagon is now leading the US Government off oil to minimize the cost, in blood and treasure, of delivering fuel to the battlefield (Lovins 2010a).

[4] A Deutsche Bank study (Sankey et al. 2009) even projects world oil demand will peak around 2016, then fall by 2030 to ~40% below the

This transition beyond oil is driven most strongly by tripling the efficiency of uncompromised but safer cars, trucks,[5] and planes, via a common recipe: lightweighting, low drag in moving through the air and along the road, and advanced propulsion. Design integration makes the tripled efficiency's cost equivalent to buying a liter of gasoline, diesel fuel, or Jet A at respective 2000 prices of \$0.15, \$0.07, and ≤\$0.12, often with better performance—e.g., Opel's 2002 diesel-hybrid *Eco-Speedster* concept car can do 250 km h^{-1} *and* 40 km l^{-1} (though not at the same instant). Surprisingly, ultralighting can double cars' efficiency using the costliest materials (carbon-fiber-reinforced composites) without increasing their mass-production cost, because simpler manufacturing and a two-thirds-smaller powertrain offset the costlier materials.

For example, a 3.56-l 100 km^{-1} (28.1 km l^{-1}, emitting 86 gC km^{-1}) midsize gasoline-hybrid SUV was virtually designed (Lovins and Cramer 2004) in 2000 by Hypercar, Inc. and two European Tier One automotive partners (Fig. 1), then costed based on supply chain offers to produce a 499-line-item Bill of Materials at midvolume (50,000 units $year^{-1}$). The results implied[6] a retail price just \$2,511 higher than the equivalent steel model (Audi's 2000 *Allroad 2.7T*)—about a 1-year payback at US fuel prices—and the extra price was only because the car was hybrid electric; its ultralighting, saving 53% of its curb weight with comparable or better crashworthiness, was free, for two reasons. First, radically simplified manufacturing: just 14 body parts, each made with one low-pressure dieset (implying ~99% lower tooling cost than for a typical steel SUV with ~10- to 20-fold more parts, each with an average of four progressive steel-stamping diesets); each part liftable with one hand and no hoist; the parts' snapping together with self-fixturing clevis joints precisely aligned for bonding, eliminating the usual robotized body shop for assembly and welding; and optional elimination of the paint shop too if color is laid in the mold. Since traditional steel-car tooling costs many hundreds of millions of dollars, and the body shop and paint shop are the hardest and costliest parts of automaking, total capital intensity would undercut the industry's leanest plant by at least two-fifths. Second, the propulsion system would shrink by two-thirds. Together, the cheaper manufacturing and powertrain would approximately pay for the costlier ultralight materials.

Fig. 1 A full-scale nondriving model of the complete virtual design for Hypercar, Inc.'s *Revolution* (World Technology Award, 2003). This uncompromised, ultralight, carbon-fiber midsize sport-utility vehicle (SUV) would seat 5 adults in comfort, carry up to 2 m^3 of cargo, weigh 857 kg, haul a half-ton up a 44% grade, accelerate 0–100 km h^{-1} in 7.2 s, improve efficiency by 3.6-fold to 3.56 l 100 km^{-1}, and in midvolume production, have a retail price \$2,511 (2000\$) higher than its steel equivalent. Simulated frontal crashes caused no damage to the passenger compartment when hitting a fixed barrier at 56 km h^{-1}, and protected occupants from serious injury in a head-on collision with a steel SUV twice its weight at a combined speed of 96 km h^{-1}. The hydrogen fuel-cell version would accelerate 0–100 km h^{-1} in 8.3 s, improve efficiency 6.3-fold to 2.06 l 100 km^{-1}, and drive 530 km on 3.4 kg of 350-bar H_2. Capital to mass-produce this design was not available because the capital market collapsed just when funding was sought in November 2000. However, many of this design's innovations are finding their way into the marketplace, and Hypercar, Inc., now Fiberforge Corporation, is commercializing a manufacturing technology to produce such automotive structures from advanced composites at attractive costs with less than one-minute cycle times—a vital ingredient not available when the car was designed in 2000. Photo © and courtesy of Rocky Mountain Institute

Fig. 2 Toyota's *1/X* concept car, first shown 26 October 2007 at the Tokyo Motor Show, achieves the interior volume of a *Prius* with half its fuel use and one-third its weight, via carbon-fiber structure, exceptional design integration, and ingenious packaging. Its curb mass is only 420 kg, 20 kg of which is extra batteries to make it a plug-in hybrid supplemented by a 0.5-l engine under the rear seat, as shown in the cutaway. The day before Toyota's announcement, Toray, the world's largest maker of carbon fiber, announced a factory to mass-produce carbon-fiber car parts for Toyota—an oblique but unmistakable expression of strategic intent by both firms. Honda and Nissan announced similar deals with Toray in July 2008

Footnote 4 continued
consensus forecast or ~8% below current levels, due to electrification of light vehicles. However, it assumes Chinese new cars will be 26% electric in 2020 versus China's latest target of 80%; overlooks improvements in light-vehicle physics; and ignores non-routine truck and plane improvements and other oil savings. Its startling findings may thus be conservative.

[5] Ogburn et al. (2008). This article shows 2.3- to 2.7-fold efficiency gains over the road at constant speed. Adding idle reduction, hybridization, refrigeration and further auxiliary/accessory improvements, and optimization of speed and fuel loading could achieve tripled efficiency without the superefficient digital engines now emerging.

[6] Lovins et al. (2004), pp. 68–73 (see also pp. 62–63).

Striking confirmation of ultralighting's potential is Toyota's 2007 *1/X* concept car (Fig. 2)—a four-seat sedan with the interior volume of a *Prius*, half its fuel use, one-third its weight, and a half-liter engine under the rear seat. Without the extra 20 kg of batteries to make it a plug-in hybrid, its curb weight would be just 400 kg—just what I said in the early 1990s a good four-seat carbon-fiber car should weigh (to much mirth from the industry). Most concept cars are dismissed as mere boasts, but one day before Toyota unveiled *1/X*, Toray, the world's leading maker of carbon fiber, announced a $300 million factory to mass-produce carbon-fiber car parts for Toyota (a phrase not previously heard in the industry). This juxtaposition was clearly a statement of strategic intent (as was later confirmed); Honda and Nissan announced similar deals; now the next automotive leapfrog is off and running. Ultralighting will be sped by such gamechanging developments in manufacturing as a lately commercialized competitive manufacturing process for carbon-fiber structures with a cycle time less than 1 min per part.[7]

Nissan, Ford, Audi, and the Chinese auto industry are meanwhile lightweighting their offerings based largely on light metals, which can achieve most of the same fuel savings at broadly comparable cost, though without the simplified manufacturing. For example, a US startup company's aluminum-intensive commercial 1-ton 5-m^3 commercial van,[8] whose driving prototype was first shown in April 2009, achieves ~3–12 times normal fuel efficiencies in urban test cycles. Yet, unlike other plug-in hybrids, it makes a strong business case to fleet buyers with no subsidy, because reducing mass and drag eliminated most of the costly batteries. The way to make batteries affordable is to need far fewer of them, although only a few automakers or national R&D programs have yet adopted this obvious strategy. The first serious inquiry in the US industry into how much lightweighting could be paid for by shrinking powertrain for the same acceleration—a basic level of design integration—was only in the past few years.

The primacy of lightweighting emerges from a typical car's physics. About 87% of the fuel energy never reaches the wheels; it is lost in the engine, idling, driveline, and accessories. Of the 13% that reaches the wheels, just over half is irreversibly lost heating the tires, the road, and the air that the car pushes aside. Only the last 6% accelerates the car and then heats the brakes. Yet, only about one-twentieth of the mass being accelerated is the driver; nineteen-twentieths is the heavy steel car. Thus, just one-twentieth of 6%, or about 0.3%, of the fuel energy actually moves the driver! However, there's good news: more than two-thirds of the "tractive load"—the power needed to move the car—is caused by its mass, and each unit of energy saved at the wheels saves an additional ~7 units that need not be wasted getting it to the wheels. The resulting leverage from wheels to tank makes it immensely fruitful to start by making the car radically lighter-weight. In other words, saving one unit of energy at the wheels saves about eight units of fuel in the tank, whereas saving one unit of energy in the engine saves only one unit of fuel in the tank. Traditionally, automakers have overlooked this platform-physics opportunity, focusing instead on the powertrain because that is where most of the losses are.

Where can this logic lead? Start with a typical car today, make it a good hybrid, drive it properly, and you save about half its fuel (considerably more if new diesels can continue to meet ever-tighter particulate-emissions standards). Now make it ultralight and slippery (which should have been done first) and you save half the remaining fuel. Next, fuel it with advanced and sustainably grown biofuels, and you quadruple oil efficiency again, cutting fuel use to just 6% of the original amount km^{-1}. Next, change the powertrain to a plug-in hybrid (due in major automakers' showrooms in 2010), saving at least half the remaining fuel. (This also creates lucrative opportunities to sell back electricity and ancillary services from parked cars to smart utility grids when and where that's most valuable.[9]) Optionally, the last ~3% of the fuel use, and the biofuel too if desired, could be eliminated by hydrogen fuel cells, which will cost less per km than gasoline and emit 2–6 times less CO_2 km^{-1} using hydrogen from natural gas (or zero with hydrogen from renewables). The ultralight, ultra-low-drag car's 3-fold-smaller tractive load makes 1990s hydrogen storage technologies (350-bar carbon-fiber tanks) attractively compact and cheap. It also makes fuel cells affordable decades sooner: being two-thirds smaller, they can cost three times more per kilowatt, needing ~97% less cumulative production volume to reach competitive cost (Lovins 2003). The same opportunity applies to battery-electrics and plug-in hybrids: a superefficient platform shrinks the powertrain enough to make it far more affordable, so you can sell far more cars far sooner and eliminate oil faster.

[7] Fiberforge Corporation (www.fiberforge.com), Glenwood Springs, CO, USA. (Disclosure: the author is a Director, Chairman Emeritus, and small shareholder of this firm.).

[8] The *IDEA* from Bright Automotive (www.brightautomotive.com), Anderson, IN, USA. (Disclosure: this firm, like Fiberforge, was spun off from the author's nonprofit employer, Rocky Mountain Institute, which maintains a small shareholding in both firms.)

[9] See Rocky Mountain Institute's 2008 Smart Garage Charrette publications at http://move.rmi.org/innovation-workshop-category/smart-garage.html. A fully electrified light-duty-vehicle fleet in the US or most other industrialized countries could have an order of magnitude more peak electric output capacity when parked (~96% of the time) than all electricity generating companies now own.

GETTING OFF COAL

The second and more challenging part of the energy/climate solution is saving most of our electricity through advanced efficiency techniques, then making electricity without coal (very efficiently burning lower-carbon natural gas[10] to smooth the transition). Almost unnoticed, both these revolutions are now well underway, again driven by compelling economic logic.

Far more work can clearly be wrung from each kilowatt-hour: California, for example, has saved ~$100,000 million of power-system investment and ~65 GW of peak load by holding its per-capita use of electricity flat for three decades—now below the Japanese level. This success owed much to early efficiency standards for buildings and appliances (new California houses use one-fourth the energy they did in the 1970s), and to rewarding utilities for cutting customers' bills rather than for selling more electricity (as ~40 US states, the EU, and nearly all other countries still do). However, even California's accelerating commitment to "negawatts" (saved electricity) still leaves much opportunity ungrasped, for two reasons.

First, even in the late 1980s, the most detailed assessment of electric end-use efficiency's US technical potential—if retrofitted wherever the technologies would fit, make sense, and make money—found ~75% potential savings[11] at an average cost that in today's dollars would be around $0.01 kWh^{-1}—cheaper than *operating* a coal or nuclear plant, even if the plant and grid were free. The North American utilities' think-tank found only a ~40–60% potential saving by 2000 at an average cost 3-fold higher (Fickett et al. 1990), but that is still a very large and very cheap saving, and the differences were nearly all methodological, not substantive (Lovins and Lovins 1991). Other independent researchers found very large and cheap savings potentials in Sweden (Bodlund et al. 1989), Denmark (Nørgård 1979), Germany (Feist 1987), and Britain (Olivier and Miall 1983). To this day, no official study in any of these countries has acknowledged such large opportunities: instead, they still assume 10- to 20-year-old technologies, suboptimally chosen and combined (National Research Council 2009). Yet, in the past two decades, those technologies have become far cheaper and more powerful, thanks mainly to technical improvements, mass production, cheaper electronics, and more streamlined high-volume marketing and delivery. Nobody has yet reassessed the potential using today's technologies, but clearly the late-1980s findings are conservative, because the technologies have improved more than they have been applied.

Second, in the past two decades a new kind of leapfrog has emerged: integrative design.

MAKING VERY LARGE ENERGY SAVINGS COST LESS THAN SMALL ONES

Economists conventionally assume that investments in energy efficiency yield diminishing returns: the more you save, the more steeply the cost of the next unit of savings rises. (Otherwise the economic models would inconveniently explode.) However, a rapidly growing body of design practice has proven that this need not be generally true. Integrative design that captures multiple benefits from single expenditures can often achieve *expanding* returns. This has been demonstrated in thousands of buildings, various vehicle designs, and (just in the author's practice) more than $30,000 million worth of industrial redesigns in 29 sectors. These industrial projects, in diverse applications throughout the industrial world, typically save ~30–60% of energy use in retrofits, paying back in ~2–3 years, and in new facilities, save even more (around 40–90%) with generally *lower* capital cost. These design techniques are well described (Lovins 2005b), have been explained in hundreds of lectures to leading technical organizations worldwide,[12] and are starting to spread rapidly in the private sector, but are not yet reflected in any official study or policy—probably because energy policy in most countries is dominated by economic theorists with little practical knowledge of energy efficiency nor training in the design sciences.

Buildings use ~70% of US electricity and offer the simplest, most intuitively obvious examples of integrative design. The author's house, for example, has produced 35 passive-solar banana crops in the severe climate of the Colorado Rockies (down to −44°C) with no furnace, saving ~99% of space- and water-heating energy and ~90% of household electricity with a 10-month payback using 1983 technologies (Fig. 3).[13] One might suppose that its superinsulation, superwindows, and ventilation heat recovery would markedly increase capital cost, but they added less capital cost than eliminating the heating equipment subtracted. Similarly, Pacific Gas & Electric Co.'s Davis, California test house in 1994 was designed to use 82% less energy than allowed by the strictest US standards (or ~90%

[10] Oil is not mentioned here because <5% of the world's electricity is made from oil and <5% of the world's oil makes electricity—largely, in both cases, gooey "residual" oil unsuited to making distillate products. In industrial countries like the US, the overlap is only 1–2% and shrinking.

[11] Competitek 1986–1992. Largely summarized by E source (Boulder, CO), *Technology Atlas series*, 1992–. www.esource.com.

[12] Five detailed technical lectures summarize the basic concepts, practice, and implications: Lovins (2007).

[13] Lovins (2004), to be updated at www.rmi.org to reflect 2007–2009 renovations and 2010 measurements.

Fig. 3 The author's ~372-m^2 house, indoor farm, and research center at 2200 m elevation in the Rocky Mountains near Aspen, Colorado. It is 99% passively solar-heated despite outdoor temperatures down to −44°C, frost any day of the year, and midwinter cloud as long as 39 days continuously. Initial savings of about 99% in space- and water-heating energy and 90% in household electricity repaid their ~$6,000 extra capital cost in 10 months with 1983 technology, thanks to highly integrative design. Eliminating the conventional heating system saved $1,100 more capital cost than it incurred for k-0.14 wall and k-0.04 roof insulation, k-1.05 (later 0.44 and as little as 0.28) windows, air-to-air heat exchangers, etc. Performance is currently being remeasured after a major renovation to update the technologies by 25 years to 2009 state-of-the-art and to make the house's carbon footprint as negative as possible. Originally built with minor propane use for cooking and ~1% water-heating backup, and with woodstove backup for the last ~1% of space heating, it is now fossil-fuel-free and is expected to remain combustion-free. Photos © and courtesy of Judy Hill Lovins

less than the US norm), yet in reasonable volume would cost ~$1,800 *less* than normal to build; despite some compromises during construction, it provided normal or better comfort with no air conditioner in a site experiencing up to 45°C (46°C with a similar design at another site).[14] In the hot, humid climate of Bangkok, a 1996 house by architect Prof. Suntoorn Boonyatikarn—inspired by the author's house, yet applied to the opposite climate—used ~10% the normal air-conditioning energy to provide superior comfort at

[14] Lovins (1995). This house's and other technical sub-reports of Pacific Gas & Electric Co.'s ACT^2 Project (www.pge.com/mybusiness/edusafety/training/pec/inforesource/act2proj.shtml) are linked to the right-sidebar ACT^2 line at www.pge.com/pec/resourcecenter/.

Fig. 4 Cooling-system supply piping for a Singapore biotechnology facility, designed by Lee Eng Lock. The creative layout (vertically stacked to save costly space), direct diagonal runs, and Y- and "sweet" bends reduce friction 69% compared with normal orthogonal (right-angled) layout, yet decrease capital cost—partly by making the pumps, motors, and electricals smaller. Photos © and courtesy of Lee Eng Lock

normal construction cost.[15] And a very energy-intensive type of small building—the Carnegie Institute for Global Ecology's 2004 wet laboratory at Stanford University—saved about 57% of normal energy use and achieved 50 units of cooling per unit of electricity, with normal construction cost and exceptional occupant satisfaction.[16] In all these super-efficient buildings, spanning nearly the range of the earth's climates, optimizing the whole building as a system—not its components in isolation—saved much construction cost, typically by downsizing or eliminating costly mechanical equipment.

A big-building example is the retrofit, launched in 2009, of the iconic 280,000-m^2 Empire State Building in New York City. The author co-led the design to save 38% of the energy use with a 3-year payback (Buhayar 2009)—several times the savings originally expected to be cost-effective, especially since the building had already been "cream-skimmed" by retrofitting from single to double glazing. Yet, remanufacturing those 6,500 windows onsite into superwindows (whose spectrally selective films and heavy-gas fillings make them nearly perfect in letting in light without heat) will cut winter heat losses by at least two-thirds and summer heat gains by half. That plus better lights and office equipment will cut peak cooling loads by one-third. The old chillers can then be not expanded and replaced but reduced and renovated—saving $17.4 million of investment that helps pay for the other improvements by reducing the net investment to $13.2 million and saving $4.4 million $year^{-1}$ at current energy prices.

Applying similar principles to a Chicago-area all-glass office tower when it needed routine reglazing because of window-seal failures yielded design savings of 77% of the cooling load. This could make the mechanical system 4-fold smaller and 4-fold more efficient at a $200,000 lower capital cost—enough to pay for the other improvements (superwindows, lighting, daylighting, etc.). This combination was found to save 75% of total energy with a *minus*-5-month payback—i.e., slightly *cheaper* than the normal 20-year renovation that must be done anyhow but saves nothing.[17] No official retrofit program has yet been designed to coordinate retrofits with routine renewals of façades and equipment to capture such opportunities.

Similar opportunities abound in industry, which uses the other ~30% of US electricity. Three-fifths of the world's electricity spins motors. Half of motor-system electricity can typically be saved by integrative retrofits paying back within a year because doing the right seven improvements first yields 28 more as free byproducts (Lovins et al. 1989). However, first, the motor-driven systems should be improved to make the motors smaller. Half of global motor torque turns pumps and fans. These can not only be made more efficient, but also *used* more productively by designing friction out of pipes and ducts.

For example, redesigning an archetypical industrial pumping loop cut its pumping energy by about 10-fold, with lower construction cost and better performance, simply by using fat, short, straight pipes rather than thin, long, crooked pipes (Sheikh and Lovins 2008). Even better design could probably have saved about another 4-fold at even lower capital cost. The required piping layout is unconventional but extremely effective: California engineer Peter Rumsey's retrofit of a small pumping loop to use fat, short, straight pipes, Y-joints, and sweet or no bends saved three-fourths of its pumping energy and eliminated 15 pumps. A 2009 industrial example by the Singaporean master engineer Lee Eng Lock (Fig. 4) saves 69% of normal pumping energy, but works better and costs less—partly because the pumps, motors, and electricals become smaller as pipe friction decreases (nearly as the inverse

[15] Lovins 2008b (see three slides near the middle).

[16] The building is described at http://dge.stanford.edu/about/building/.

[17] Lovins (1995), June 1995, RMI Publ. #E95-28, www.rmi.org/rmi/Library/E95-28_SuperEfficientPassiveBuilding.

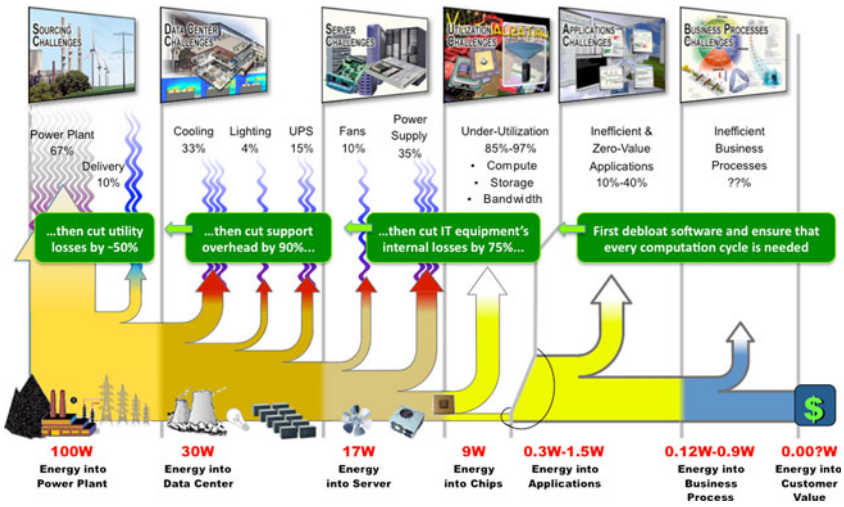

Fig. 5 Schematic diagram of the two-order-of-magnitude leverage in energy savings (and about half in capital savings) available in a new data center by saving downstream first. Diagram © and courtesy of Rocky Mountain Institute and Hewlett-Packard

fifth power of pipe diameter). Most designers ignore those system effects, optimizing pipe diameter only against saved pumping energy without counting capital costs saved by shrinking the pumping *equipment*—just as they optimize thermal insulation in houses only against saved heating energy without counting capital costs saved by shrinking or eliminating the heating *equipment*. These methodological errors, perpetuated by virtually every engineering textbook, are neither necessary nor desirable.

Standard textbooks also do not mention the value of starting savings downstream, as noted above for car design. A standard pumping system, for example, starts with coal or other power-plant fuel, two-thirds of whose energy is lost in a classical power station, a bit more in the grid, and still more in a series of compounding losses in the motor, mechanical driveline, pump, and piping/valve system. Only one-tenth of the fuel energy emerges from the pipe as flow. Yet, reducing flow or friction in the pipe turns those compounding losses around backwards into compounding *savings*, leveraging a 10-fold larger fuel saving back at the power plant! Savings in equipment sizing, hence capital cost, also compound from downstream to upstream. Thus, starting one's efficiency efforts at the pipe, not at the power plant, leverages huge energy and capital savings.

Applying these and many other innovative design principles has lately enabled the author's team to design, among many other examples, a chip fab expected to save two-thirds of the energy and half the capital cost of a normal design;[18] a mine that uses no fossil fuels or grid electricity (it runs on gravity); and a 2009 UK data center saving about 67% of total energy, 73% of non-IT energy, and 98% of cooling and pumping energy, with normal capital cost (DatacenterDynamics 2009). (Had the operator's client approved all the designers' recommendations, the energy intensity could have fallen to 1/20th and the capital cost to about half of normal.) Figure 5 shows the two-order-of-magnitude potential energy leverage from starting downstream in a data center.

Of course, none of these or other similar results could be achieved if the original designs had been optimal. Basic reforms are needed in engineering pedagogy and practice. Rocky Mountain Institute is therefore launching a Factor Ten Engineering project[19] to compile a casebook of vivid examples (including many mentioned above) and inject their design lessons vigorously into design teaching and practice worldwide.

BENIGN AND RESILIENT SUPPLY TO MEET REDUCED ELECTRICITY DEMAND

Doubling or quadrupling electric end-use efficiency greatly speeds and eases a parallel revolution now underway in how electricity is supplied. For the power industry's first century, power plants were costlier but less reliable than the grid, so multiple stations backed each other up through the grid. However, in the past few decades, power plants have quietly become cheaper and more reliable than the grid, so ~98–99% of US power failures now originate *in* the grid. It therefore now makes sense to deliver affordable and reliable power by producing it at or near the customers. This facilitates combined-heat-and power (CHP), which saves upwards of half the normal fuel, cost, and emissions by cogenerating electricity and useful heat together in

[18] RMI's previous design, for the recently opened Texas Instruments fab (www.ti.com/corp/docs/rennerroadfab/gdoverview.shtml), saved only 20% of its energy (plus 35% of water) because the two biggest recommendations could not be tested in time for the design deadline, but its 35% capital-cost saving let it be built in Texas, not China.

[19] Described at www.10xE.org. The project needs outstanding cases, teachers, and practitioners; seconded engineers; beta-test sites for draft cases; and money.

buildings. However, even more importantly, it also yields 207 hidden economic benefits—chiefly from financial economics, secondarily from electrical engineering—that typically increase the economic value of distributed electrical resources, especially if they are renewable, by about an order of magnitude—enough to flip almost any investment decision (Lovins et al. 2002). No official assessment yet recognizes these "distributed benefits," but many market actors are starting to: even before the 2008–2009 financial crash, investors were decisively shifting investments from big, slow, lumpy projects to small, fast, modular projects in order to reduce financial risk.

Led by technology and finance, and often supported by national or local policy, the resulting revolution has lately transformed the power market, and continues to accelerate. In 2006, micropower—*The Economist*'s useful term for CHP plus renewables minus big hydroelectric dams (>10 MW)—produced one-sixth of the world's total electricity, one-third of the world's new electricity, and 16–52% of the electricity in a dozen industrial countries (not including the US and UK, which lagged with 7 and 5%, respectively). In 2007, the United States (like China and Spain) added more windpower than the world added nuclear capacity; China beat its 2010 windpower target; and the US added more windpower in 2007 than coal power in the previous 5 years combined. In 2008, for the first time in about a century, the world invested more capital in renewable than in fossil-fueled generating capacity;[20] distributed renewables (those other than big hydro dams) got $100 billion of private capital and added 40 GW, while nuclear got and added zero. In 2009, preliminary data suggest[21] that these trends continued: smaller, faster projects suffered less and recovered faster from the collapse of the capital markets, and in general, renewables continued to get cheaper and more commonplace, central plants costlier and riskier. Growing experience has also confirmed that concerns often voiced about land-use and the cost of reliably integrating variable renewables into the grid are unfounded; indeed, integrating renewables with each other and with end-use efficiency often yields major technical and economic synergies.[22]

This shift toward no- and low-carbon sources of electricity speeds climate protection. Not all such sources are equally effective: a new nuclear plant does save carbon, but ~2–20 times less and ~20–40 times slower than buying micropower instead, so nuclear investment would reduce and retard climate protection (Lovins et al. 2008). Few governments understand this opportunity cost, so some now favor nuclear revival. However, they are finding the private capital markets unwilling to finance new nuclear build,[23] so its financing and risk must generally fall on taxpayers—an approach ranging from politically unattractive to illegal (in the EU)—or on captive customers.[24]

The market-driven and politically popular shift to micropower also speeds global development by freeing up attention and capital for better buys. For example, producing efficient lamps and windows in developing counties takes nearly a thousand times less capital, and repays it about 10-fold faster, than expanding the supply of electricity to provide more lighting and comfort by inefficient methods.[25] The resulting four-orders-of-magnitude reduction in the capital needed by the power sector—the most capital-intensive sector, gobbling roughly one-fourth of the world's development capital—may be the strongest macroeconomic lever for global development, though one not yet recognized by the development and financial communities.

A best-buys-first strategy would also improve global security by smoking out the proliferators of nuclear weapons.[26] Taking economics seriously would mean no longer providing, let alone subsidizing, do-it-yourself bomb kits wrapped in innocent-looking civilian disguise. Removing those bomb kits from ordinary commerce would make their ingredients harder, more conspicuous, and politically costlier to get, and would make timely detection more likely because intelligence resources could focus on needles, not haystacks. Politically, the obligation to provide secure and affordable energy under Article IV of the Non-Proliferation Treaty could be satisfied better—in light of modern technical knowledge and market experience—by freely providing the technologies of "negawatts" and

[20] Data from the leading source, New Energy Finance (London), are summarized annually at www.ren21.net, most recently in www.ren21.net/pdf/RE_GSR_2009_update.pdf.

[21] Rocky Mountain Institute maintains a detailed global database of micropower capacity and output, compiled from standard industry and government sources, at www.rmi.org/rmi/Library/E05-04_MicropowerDatabase.

[22] Lovins (2009). See also Lovins et al. (2008), Lovins (2010b) and Rocky Mountain Institute's forthcoming 2010–2011 publications on the theme of *Reinventing Fire*.

[23] Lovins (2010b). A 2008 preliminary draft is posted by kind permission at www.rmi.org/rmi/Library/E08-01_NuclearIllusion.

[24] In the US states (chiefly southeastern) where it is especially powerful, the nuclear industry insists on, and often gets, new state laws that bar or restrict competition by alternatives and make customers pay for new nuclear plants in advance—whether they ever run or not, whatever they cost, no questions asked—plus a return to compensate utilities for the risks they just shed. This approach scraps all four bedrock principles of utility regulation—payment on delivery, only for "used and useful" assets, only if prudently bought, with no Commission able to bind its successors. It also creates in utility investment the same moral hazard that just brought down the US financial system. Curiously, and analogously to recent shifts in nuclear politics in Europe, these changes are most strongly pushed by political conservatives.

[25] A.J. Gadgil et al. (1991) cites ratios somewhat below current estimates.

[26] Lovins et al. (1980a, b), Lovins (2010c).

micropower (before China sells them to everyone) (Lovins 2010c). This is precisely the demand of developing countries expressed in Copenhagen: financial help to get off fossil fuels and protect the climate. Incidental but important benefits of these more granular technologies would be to reduce procurement corruption, increase transparency, advance the role and education of women, strengthen the social periphery vis-à-vis the center, and slow or reverse rural-to-urban migration.

Moreover, global energy security would be greatly enhanced. Imported fuels would be displaced by natural energy flows. The distributed architecture of least-cost energy systems, combined with modern informatics, could make them inherently resilient, so that failures now inevitable by design become essentially impossible by design[27]—a strategy so compelling that the US Department of Defense is moving to adopt it (US Defense Science Board 2008; Lovins 2010a). Just as some developing countries have leapfrogged over wireline to wireless telephony, some are now starting to bypass grid-based electrification and go straight to distributed systems—a revolution in both rural and urban life.

MAKING IT HAPPEN

The technologies outlined here attract investors because they steadily and dramatically reduce cost, lead time, and risk. Users enjoy side-benefits that often make energy efficiency, for example, one or even two orders of magnitude more valuable than its energy savings alone.[28] And the policies that can most help such a shift would not increase but reduce and ultimately eliminate the deliberate price distortions that make fossil fuels look some half-trillion dollars a year cheaper than they actually are (Global Subsidies Initiative 2009).[29] A promising route to a richer, fairer, cooler, safer world would thus be to apply conservative market principles to the energy sector—allowing and requiring all ways to save or produce energy to compete fairly, at honest prices, regardless of their type, technology, location, size, or ownership. It would be interesting to discover who is not in favor of that.

The policies that would best advance this goal are not the usual narrow slate of taxes, subsidies, and mandates, but rather a systematic agenda of "barrier-busting"—turning into a business opportunity each of the scores of market failures in buying efficiency[30] and renewables.[31] For example, when France adopted a "bonus-malus" (feebate, Mims and Hauenstein 2008) system for new cars, just its first year (2008) saw sales decline 42% for inefficient but rise 50% for efficient models (Alliance to Save Energy 2009). About half of the United States, too, have adopted or are considering California-style regulatory reforms ("decoupling and shared savings") (Regulatory Assistance Project 2009) to align utilities' with customers' interests—a method proven to reverse utilities' understandable historic bias toward producing and selling more energy because that is what they got paid for.

One is often asked, "But energy efficiency isn't happening—why not?" Few people realize that, for example, US energy, oil, and coal use all *fell* in 2006, because energy intensity shrank more than the economy grew. That was despite 26 years of stagnant light-vehicle efficiency, despite decades of hostile or indifferent national policy, and despite 48 states' rewarding utilities for selling more energy. Imagine what we could do if we paid attention!

One often hears that solutions must await global agreement in Copenhagen, Cancún, or beyond. Yet, China's 11th Five-Year Plan adopted energy efficiency as its top strategic priority for national development, not because a treaty required this but because leaders like Wen Jiabao understand that otherwise China cannot afford to develop. China's impressive emphasis on energy efficiency is simply enlightened self-interest, and will be further strengthened (with world-leading renewable goals) in the 12th Five-Year Plan for 2010–2015.

Similarly, pricing carbon in the countries that have not yet done so (notably, at the end of 2009, the United States, China, and India) would be appropriate, correct, and helpful. Of course it should be done. Yet it is not actually essential—the returns on efficiency and micropower are

[27] Lovins and Lovins 1981/1982. Reposted by RMI 2001 in OCR .PDF version at www.rmi.org/rmi/Library/S82-03_BrittlePowerEnergyStrategy. The design principles of resilience, synthesized in Chapter 13, can be summarized: "An inherently resilient system should include many relatively small, fine-grained elements, dispersed in space, each having a low cost of failure. These substitutable components should be richly interconnected by short, redundant links…. Failed components or links should be promptly detected, isolated, and repaired. Components need to be so organized that each element can interconnect with the rest at will but stand alone at need, and that each successive level of function is little affected by failures or substitutions at a subordinate level. Systems should be designed so that any failures are slow and graceful. Components, finally, should be understandable, maintainable, reproducible at a variety of scales, capable of rapid evolution, and societally compatible."

[28] E.g., via 6–16% higher labor productivity in offices with better thermal, visual, and acoustic comfort and better air quality; ~40% higher retail sales pressure in well-daylit shops; ~20–26% faster learning in well-daylit schools; higher quality and throughput in efficient factories; and faster healing, less pain, and less readmission in green and efficient hospitals.

[29] Nuclear subsidies tend to be larger than renewable subsidies in percentage terms. Many of the most useful and dispassionate comparisons are compiled by Doug Koplow, www.earthtrack.net.

[30] Lovins and Lovins 1997, RMI Publ. #C97-13, www.rmi.org/rmi/Library/C97-13_ClimateSenseMoney, especially pp. 11–20.

[31] See Lovins et al. (2002), Part 3.

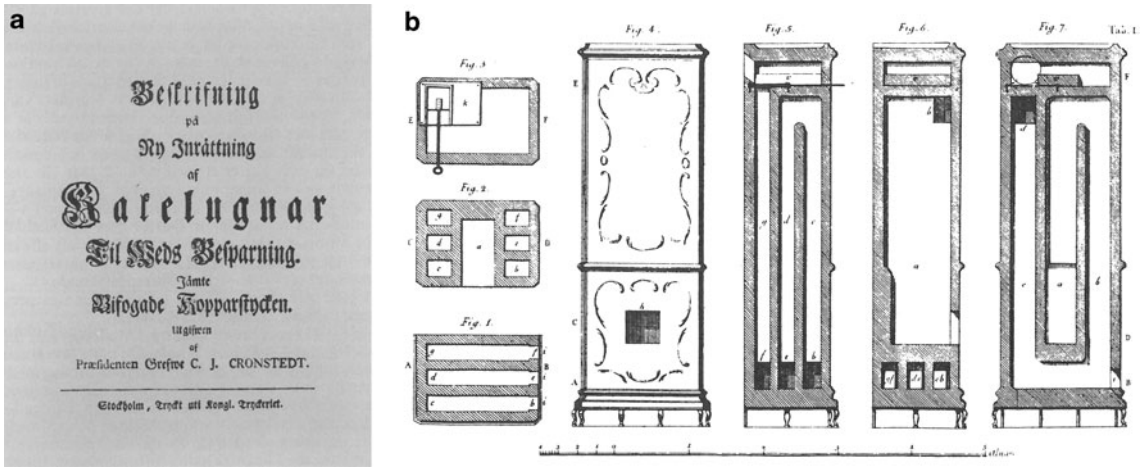

Fig. 6 Count Cronstedt's 50%-efficient stove, commissioned by HM King Gustav III and deployed by order of the Council of State in 1767, cut firewood consumption by ~50–80%, solving Sweden's and northern Europe's firewood crisis. Its five undulating channels absorb heat into the masonry, which slowly reradiates heat into the room. This design, which caused important changes in building design and in daily routines, saved Sweden's forests. It remained the dominant technology for nearly two centuries and is still much valued and used today. See Ref. 60, which reproduces this diagram from Count Cronstedt's 1767 report (cover shown)

juicy even without pricing carbon—and it is certainly not sufficient (little happens if prices are right but barrier-busting is neglected). Ultimately, too, carbon markets will probably clear at low prices because of the huge overhang of unbought cheap efficiency. Strategies that do not depend on carbon pricing are therefore more robust.

Public policy, even if as innovative as it could be, is probably not the only nor the strongest key to the climate, development, and security locks. In most societies, innovation in technology, design, and competitive strategy—driven by the private sector in its coevolution with civil society—is even more dynamic and powerful than public policy. Most governments play catch-up; intergovernmental negotiations are slower still. This natural state of affairs is not an insuperable obstacle to climate protection but a fact to be recognized and worked around by emphasizing the fastest-moving and most creative forces in each society.

Sweden offers an instructive example both of some impressive technical and policy innovations and, in recent years, of a retrograde policy process. In 1989, Vattenfall, then the publicly owned Swedish State Power Board, published a remarkable study (Bodlund et al. 1989) showing how to save half of Sweden's electricity at a cost 78% lower than making more. This plus environmental dispatch (operating most the plants that produce the least carbon) and some fuel-switching could achieve the forecast 54% GDP growth during 1987–2010, shut down the nuclear half of the electricity supply as demanded by most voters in 1980, reduce the heat-and-power sector's CO_2 emissions by one-third, and cut the cost of electricity services by roughly $1,000 million per year. The study was incontrovertible, but so successfully suppressed that a few years later, the Energy Committee of the Parliament had never heard of it. Vattenfall now seems reluctant to acknowledge its origin or message, even though in 1989, the usual disclaimer saying it did not represent the State Power Board's official view had been removed by order of its then CEO. Swedish policy today seems just the opposite of the 1989 least-cost recommendation. Yet, if the 1989 analysis were redone under today's conditions, its conclusion would only strengthen.

A longer historic perspective holds lessons too. In the mid-eighteenth century, much of northern Europe was gripped by a grave energy crisis—a shortage of firewood. HM King Gustav III commissioned a solution from Count Carl Johan Cronstedt (who became a member of the Royal Swedish Academy of Sciences in the year it was founded, 1739). In 1767, Cronstedt showed how to improve the ~10%-efficient open fire, or his colleague Field Marshal Faban Wrede's ~20%-efficient stove, to a ~50%-efficient stove (Fig. 6) that both saved and stored heat, requiring fuel only twice a day. It was deployed nationwide by government order in 1767, cut firewood use by 50–80%, quickly resolved the fuel crisis (Larsson 1979; http://en.wikipedia.org/wiki/Carl_Johan_Cronstedt) and remained the leading competitor until central heating in the late 1940s. Today's best woodstoves using Cronstedt's principles approach 90% efficiency,[32] comparable to the best natural-gas furnaces net of their delivery losses. Yet, the 1767 solution also included end-use efficiency—draft-proofing, insulation, and interior windows (Smeds 2004). Today's best Swedish superinsulated/passive houses need

[32] An English-language source of modern 87% efficient models is www.cronspisen.eu/gb/kakelugnar/; some makers claim efficiencies around 90+%.

no heating (even without superwindows) yet cost no more to build; such performance is even being cost-effectively retrofitted into postwar Swedish apartment buildings. The spirit of Cronstedt remains alive and well, however impermanent the political landscape. And one way or another, whatever the politics of the day, economic reality does have a way of eventually asserting itself.

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