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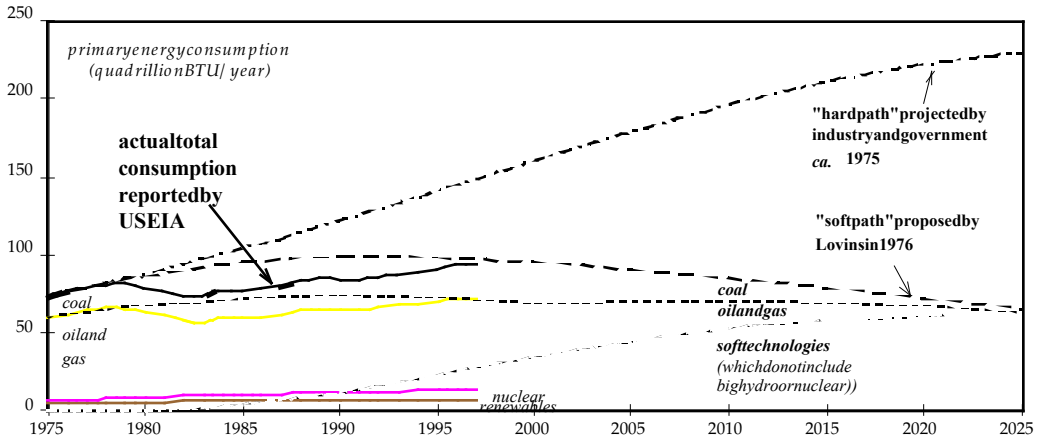
Energy Surprises for the 21st Century

By Amory Lovins and Chris Lotspeich

Twenty-three years ago, Amory Lovins was heavily criticized as wildly optimistic for predicting that energy efficiency would play a major role in shifting United States energy use patterns, thus reducing overall consumption far below official forecasts.[1] He argued that energy would shift in more economically and environmentally benign directions, while energy intensity (primary energy consumed per real dollar of gross domestic product [GDP]) would markedly decrease without threatening continued economic growth. Today, total U.S. energy use is slightly *below* the level suggested in that 1976 "soft energy path"[2] graph (see figure below), and in all but five of the intervening years the amount of energy consumed per dollar of GDP has fallen—for a total drop of more than 35 percent since 1973. Renewable energy sources were delayed a decade by federal hostility—exemplified by reductions of more than 90 percent in research and development budgets and suppression of public information—and are only now slowly regaining momentum.[3] Improvements in technology and integrated whole-systems design techniques, and greater attention focused by competitive pressures, are increasing the potential for a "third wave"[4] of energy efficiency, reversing the period of stagnation from 1986 to 1996.



In addition to such oft-discussed trends as fuel price deregulation and electricity restructuring—and in many other countries, privatization of state-owned industries—other, less-recognized forces of change are afoot. This article provides an overview of some of the issues and innovations that are likely to alter the global energy

sector in the early 21st century. From superefficient energy use to the emergence of hydrogen as a viable energy carrier, from climate concerns to security dilemmas, the relationships between these important concepts and the energy industries are as intricate as they are full of potential to promote growth, profits and opportunity.

Energy Efficiency and Electricity Restructuring

Historically, energy resource discussions have focused on supply. But people don't want barrels of oil or kilowatt-hours of electricity per se; they want the services that energy ultimately provides, such as hot showers, cold beer, comfortable buildings, light, torque and mobility. Focusing on these desired services, delivered by the end-use application of energy, allows consideration of a broader range of options than simply the energy supplied by the local grid or pipeline. Considered from the demand as well as the supply side of the equation, what is the cheapest, cleanest way to deliver each of these services? Often the better, more cost-effective way is using less energy more productively, with smarter technologies. Efficient end-use can thus compete with new supply as an energy resource.

Today, harnessing market forces and using widely demonstrated synergistic design, technology and management techniques can deliver the high quality of life available in Western economies at much lower financial and environmental cost. Industry surveys of utility-directed "demand side management" efforts to save electricity show saved watts—or "negawatts"—typically costing society in the range of 0.5 to 2.5 cents per saved kilowatt-hour, with well-run industrial and commercial programs usually falling toward the low end of that range.[5] While scores of specific market and regulatory barriers prevent fuller realization of efficiency's potential, clever firms are finding ways to turn these obstacles into business opportunities.[6] They could do so far faster and more thoroughly if simple, high-leverage reforms in public policy rewarded least-cost results—*e.g.*, rewarding electric distribution utilities for minimizing the cost of energy services rather than the price of kilowatt-hours.[7]

In the short run, the restructuring of segments of the U.S. electricity sector could unfortunately shift the focus away from efficient outcomes and back toward the sale of bulk electricity as a cheap commodity. Such restructuring is often intended simply to replace the equitable sharing of the cheapest power with a "big dogs eat first" principle. But it will yield surprisingly small benefits even to those major customers unless retail distributors are rewarded for cutting all customers' bills rather than for selling them more energy.[8] Otherwise, the modest benefit of more competitive generation is achieved in a way that sacrifices the much larger benefit of efficient end-use. Moreover, regardless of restructuring outcomes, utilities too are discovering that they can't compete unless they help their customers wring more work from each kilowatt-hour, because that's the only important way to deliver better service and lower bills. The more competition is

introduced, the truer this becomes, because efficient end-use becomes the key to differentiating among different suppliers' almost identically priced kilowatt-hours.

Much of the currently fashionable restructuring is even harming efforts to harness energy efficiency, renewable sources and the distributed utility (described below). End-use efficiency is the most important source of cost-effective displacement of central thermal power stations. Demonstrated and widely applicable efficiency improvements usually cost less than just *operating* a thermal power station, even if its construction and delivering its power were to cost nothing.[9] Efficient use becomes even more powerful when synergistically combined with decentralized, modular electricity production at a scale of kilowatts and megawatts, renewable resources in particular, and local energy storage. These approaches should rebound as competitive restructuring progresses if its design fosters competition rather than reinforcing incumbents. Energy efficiency and distributed power generation will increasingly be bought for reasons other than saving commodity costs—respectively to yield qualitatively superior services and distributed benefits—and will therefore become increasingly unpredictable using economic tools and experience. For example, the 6 to 16 percent labor productivity gains in efficient buildings—due to their superior visual, acoustic and thermal comfort—are typically worth at least ten times more than the energy savings themselves, but are absent from all economic models of whether building proprietors will improve their energy efficiency.[10]

The ability to respond to price is more important than price itself. Price matters, but its policy importance has been much overrated. High energy prices are neither necessary nor sufficient for very efficient use of energy. Seattle pays roughly half the electricity prices of Chicago, yet in the 1990s it has been saving electricity twice as fast as Chicago. Seattle's City Light municipal utility helps its customers and utilities to save energy by making an efficient, effective, informed market in negawatts, while Chicago's Commonwealth Edison has historically tended to discourage such savings—by tariff structures, direct promotion and other means—more than it has encouraged them. If, as preliminary data suggests, the U.S. has resumed since 1997—with record-low energy prices—the rapid pace of energy savings that it last enjoyed at record-high energy prices, this would further confirm that price is not the only way to focus attention or influence choice.

Whole-System Design for Efficiency

Large, quick-payback energy savings can often yield after-tax returns of more than 100 percent per year, even at or below today's low U.S. energy prices. These energy-saving opportunities are getting bigger and cheaper all the time. After saving $150 to $200 billion worth of U.S. energy use per year (compared with 1973 efficiency levels), the United States is still wasting upwards of $300 billion a year, and that waste is climbing.[11] The result is a growing reservoir of energy available for other uses, but not yet freed up

by more efficient use. End-use efficiency is a rapidly expanding resource, as we are learning new ways to achieve such efficiency faster than the resource is being tapped.

Whole-system design techniques offer some of the most significant savings opportunities. Inventor Edwin Land once remarked that "people who seem to have had a new idea have often simply stopped having an old idea." This is particularly true when designing systems for resource savings. The old idea is one of diminishing returns—that the greater the resource saving, the higher the cost. But that old idea is giving way to the new idea that bigger savings can cost less: that saving a large fraction of resources can actually cost less than saving a small fraction of resources (or saving nothing).

Interface Corporation, the leading maker of materials for commercial interiors, applied such an approach to a standard "pumping loop" (a common feature in many factories and most large buildings) in its new Shanghai carpet factory. A top European company had designed the system to use pumps requiring a total of 95 horsepower. But before construction began, Jan Schilham, a Dutch engineer at Interface, realized that two embarrassingly simple design changes would cut that power requirement to only 7 horsepower—a 92 percent reduction. The redesigned system cost less to build, involved no new technology and worked better in all respects.

What two design changes achieved this twelvefold saving in pumping power? Schilham applied techniques pioneered by Singapore engineer Eng Lock Lee of Supersymmetry Services. First, Schilham chose larger-diameter pipes, which generate much less friction than smaller-diameter pipes and therefore need far less pumping energy. The original designer had chosen the smaller pipes because, according to the traditional method, the extra cost of larger ones wouldn't be justified by the pumping energy they would save. While this standard design trade-off optimizes the pipes by themselves, it "pessimizes" the system as a whole. Schilham optimized the whole system by counting not only the higher capital cost of the larger pipes but also the lower capital cost of the smaller pumping equipment that would be needed. The pumps, motors, motor controls and electrical components could all be much smaller because of the reduced friction. Capital cost would fall far more for the smaller equipment than it would rise for the larger pipes. Choosing larger pipes and smaller pumps—rather than smaller pipes and larger pumps—would therefore make the whole system cheaper to build, even without regard to its twelvefold reduction in energy use.

Schilham's second innovation was to reduce the friction even more by making the pipes short and straight rather than long and crooked. He did this by laying out the pipes first, then positioning the various tanks, boilers and other equipment that they connected. Designers normally locate the production equipment in arbitrary positions, and then have a pipefitter connect the components. Awkward placement forces the pipes to make numerous bends that greatly increase friction. In addition to saving on installation, materials and electrical costs, Schilham's short, straight pipes were easier to insulate,

saving an extra 70 kilowatts of heat loss and repaying the insulation's cost in three months.

This small example has important implications for two reasons. First, pumping is the largest application of motors, and motors use three-quarters of all industrial electricity in the United States (or three-fifths of all electricity).[12] Second, the lessons are very widely applicable. Interface's pumping loop shows how simple changes in design mentality can yield huge resource savings and returns on investment. This isn't rocket science; often it's just a rediscovery of good Victorian-era engineering principles, lately overlooked because of specialization.

Capturing savings by such methods is gaining momentum for competitive reasons among many smart companies, but is inhibited by some 60 to 80 specific kinds of market failures, some at the level of the firm and some the result of public policy.[13] Fortunately, proven techniques can turn each of these market failures into a lucrative business opportunity.[14]

Barrier Busting

A common example of breaking down barriers can be found in the behavior of the different parties involved in commercial building construction. Consider four such actors: the owner, the designer, the construction contractor and the tenant. The owner is not likely to specify target levels of energy performance beyond meeting building codes, particularly for a structure intended for lease. The architect probably has not been trained in whole-system, resource-efficient design. If she is familiar with these techniques, she may not wish to struggle with the owner or contractor to explain the benefits of such an approach. In any event, the structure of her compensation typically rewards her for what she spends, not for what she saves. The contractor wishes to capture as much profit as possible from the bid price and has the incentive to install the least expensive components he can find, regardless of how inefficiently they use energy or water. The tenant has no say in the matter and is stuck with the utility bills. All of these people are acting in their economic self-interest, within the bounds of their knowledge; yet the outcome is a relatively inefficient building.

For example, the after-tax return on increasing the diameter of wire by just one size in a standard U.S. office lighting circuit typically approaches 200 percent per year. The wire-size table in the National Electrical Code is meant only to help prevent fires, not save money, and hence specifies wire with half the diameter—with four times the electrical losses due to greater resistance—as would be economically desirable. But an electrician altruistic enough to buy the larger (and more expensive) wire would no longer be the low bidder and wouldn't get the job. This example embodies two barriers: a life-safety minimum-requirement code misinterpreted as an economic optimum, and a split

incentive between the party who chooses the wire size and the party who later pays the electric bills.

There are numerous remedies for these barriers to achieving efficient buildings. Better awareness of demonstrated techniques for more resource-efficient construction would benefit all the above parties.[15] An integrated design workshop where all the parties involved in the building participate in an intensive, multidisciplinary and facilitated meeting to optimize the plans and specifications often radically improves a building's design. Performance-based fees, which reward the architect in part based upon measured savings in energy and water efficiency relative to pre-agreed standards, can provide the incentive for more efficient design.

Public policy can contribute in several ways. For example, building codes can specify more resource-efficient construction. "Feebates" can spur this efficiency: local authorities set targets for water and energy efficiency, then impose fees on substandard buildings while providing rebates for superior designs. The fees pay for the rebates, thus offering a revenue-neutral and technologically dynamic market incentive to design and construct more efficient buildings.

Barrier-busting policies—specific efforts to cure market failures that prevent energy efficiency—should top the public-policy agenda. Most countries ignore them, wrongly assuming that the only steps necessary are proper pricing and fuller commodity competition. Countries making this error will fall further and further behind those that take market economics seriously, and hence seek to purge egregious market failures.

The Distributed Utility: Small Is Profitable

Powerful forces are driving a similarly rapid transition to distributed electric generation, where the power plant shifts from a large remote station to rooftops, basements, backyards or driveways.[16] These incentives include risk reduction through increased system resilience and faster time to market in places and at scales most desired; economies of scale in the production of smaller, modular generation units, such as combined-cycle gas turbines, wind turbines, photovoltaic panels and fuel cells, rather than of electricity from large power plants; and avoided transmission and distribution grid investment. Collectively, about 75 such "distributed benefits" can often make decentralized production, storage, or saving of electricity about tenfold more valuable than today's energy commodity prices reflect.[17] Unable to deliver those benefits, the central power plant, like much bulk electric transmission, will soon become a white elephant, uneconomic to run and difficult to sell. Such plants are unlikely to survive in significant numbers by 2030 in any market economy. Unpleasant vulnerabilities built into the architecture of brittle, highly centralized systems—exemplified by Year 2000 computer problems—could accelerate this trend toward smaller and more localized electricity generation.

Many of the distributed resources will be renewable as those resources' costs inexorably drop and their quality and convenience improve. The Royal Dutch/Shell scenario of a half-renewable world energy supply by 2050 based solely on price competition is not only highly likely but could be surpassed.[18] Yet even if the renewable transition required a couple of centuries, it could be bridged by nearly ubiquitous natural gas. If the carbon dioxide of the natural gas is separated from its hydrogen at the wellhead, and if the hydrogen is shipped as a fuel while the carbon dioxide is reinjected into the gas field, that fossil fuel can be profitably used without harming the climate.

Climate: Making Sense *and* Making Money

Environmental problems due to energy use are unnecessary and only increase business costs. Specifically, meeting and surpassing the Kyoto Protocol climate-protection targets will not be costly but profitable, because saving fuel costs less than buying fuel, let alone burning it. Climate politics will therefore shift from price, pain, penury, bearing burdens and sharing sacrifices, to profit, enterprise, initiative, innovation and competitive advantage. This will make consensus much more straightforward, because no matter how the climate science turns out or who goes first, protecting the climate will be advantageous to its practitioners' bottom line.[19]

New design techniques such as in the aforementioned piping and pumping example can often make big energy savings less expensive to attain than small savings. Such "tunneling through the cost barrier"—contrary to the "law" of diminishing returns commonly assumed—has been empirically and convincingly demonstrated in many kinds of technical systems. But this is absent from all known energy models because they are based on economic theory rather than on engineering practice.[20]

American firms that are starting to discover this are increasingly behaving *as if* the U.S. Senate had already ratified the Kyoto Protocol. The more firms act in this manner, the more likely and less necessary ratification will become. In any event, at least in the United States, leadership on climate protection has already largely passed from the public to the private sector, simply because efficiency costs less than fuel.[21]

Research and development will yield important advances and should be vigorously pursued, but optimal application of old technologies would probably suffice to meet the Kyoto goals while making a profit.[22] Technological research and development must therefore be supplemented by improved design education, re-treading of practicing design professionals, and greater attention to energy anthropology—the emerging science of why people use energy the way they do.

Hypercars™: A Nega-OPEC

A market-driven transformation already irreversibly underway will rapidly increase the fuel efficiency of new light vehicles—including full-sized American cars—above 80 and as high as 200 miles per gallon without compromising safety, performance, comfort or cost.[23] Early models, including fuel-cell-powered cars, will start to enter the market in the next few years and will garner major market shares by 2005 to 2010.[24] Automakers that fail to make this transition to ultralight, ultra-low-drag, hybrid-electric vehicles will risk disappearing. Over the next few decades, such Hypercars and their kin will grow to save as much oil as the Organization of Petroleum Exporting Countries (OPEC) now sells, while providing superior mobility to their drivers and decisive competitive advantages to their manufacturers. Complementary policies designed either to maximize competition among modes of transportation or to eliminate the need for such transportation—for example, eliminating sprawl by not mandating or subsidizing it—can also yield better and fairer access with much less driving.[25]

The existing and emerging competitors for the end-uses now served by petroleum products are so diverse and robust that oil will probably become uncompetitive even at low prices before it becomes unavailable even at high prices. The most intelligent major oil companies already understand that they are in the coal-and-oil endgame; the only internal dilemma is whether to say so, as Arco's Chairman did in February 1999.[26]

The Emerging Hydrogen Economy

Another major competitor—or, as many oil companies are starting to see it, business opportunity—is rapidly emerging. A smooth transitional path to a climatically benign economy based on hydrogen has already been devised. It appears profitable at each step, doesn't need major new infrastructure investments and is already being adopted by very large and capable energy and automotive firms.[27] Much of the energy-carrier role conventionally projected for electricity will instead shift to hydrogen.

The most important new technology in this transition is the fuel cell, an electrochemical device akin to a battery that can be refilled. There are several designs and fuel alternatives; those most likely to succeed in the marketplace run on pure hydrogen, the most abundant element in the universe. These fuel cells efficiently convert the energy embodied in hydrogen into electricity, producing essentially no pollution or noise but only 170ºF pure drinking water.

A rapid, practical and profitable commercialization path for fuel cells and hydrogen can be executed by coordinating convergent trends in several industries. This strategy, which can be implemented immediately, relies on existing technologies and proceeds in a logical and viable sequence. It has two preconditions. The first is ultralight, ultra-low-drag, hybrid-electric vehicles (such as Hypercars) that are highly fuel-efficient, permitting their fuel cell electricity generators to be fueled by compact onboard tanks of compressed gaseous hydrogen rather than heavy, expensive onboard "reformer" devices

that extract hydrogen from liquid fuels. The second precondition is the integration of hydrogen-powered fuel cell market development between vehicles and buildings.

Capturing and reusing waste heat from fuel cells for other applications such as heating and cooling could allow fuel cells to compete today with traditional forms of energy purchased by most building operators. Such local energy generation could yield even greater economic value wherever electric distribution grids are old or congested, or where other "distributed benefits" are important and rewarded. Hydrogen fuel could be made in the building by a mass-produced "hydrogen appliance," such as an electrolyzer that separates hydrogen from water using electricity at "offpeak" prices—electricity that is cheaper during periods of low demand such as late at night. Another option is a miniature "reformer" that uses heat to convert natural gas into hydrogen and carbon dioxide.

There is a huge fuel-cell market in buildings, which use two-thirds of all U.S. electricity. Supplemented by industrial niche markets, this buildings market would soon cut fuel-cell costs to levels competitive for use in vehicles. Hypercars need severalfold less power to operate than conventional cars, and could thus adopt fuel cells at severalfold higher prices than their normally inefficient counterparts could afford. Those higher prices would be reached several years earlier. The general vehicle market could then be opened to hydrogen by first using the spare, off-peak capacity of buildings' hydrogen fuel sources to serve vehicles too—particularly vehicles whose drivers work or live in or near the same buildings. Furthermore, using those vehicles during the workday as plug-in 20-plus-kilowatt power plants could repay a significant fraction of their lease or purchase cost. This building/vehicle integration could make direct gaseous-hydrogen fueling practical without first constructing a far-flung and costly new infrastructure for bulk hydrogen supply and distribution, since the buildings could make their own hydrogen cost effectively from available electricity or natural gas. It would also work better and cost less than separating hydrogen from liquid fuels, such as gasoline or methanol, using heavy, expensive devices onboard the cars. Ultimately, plug-in Hypercars could provide five to 10 times as much generating capacity as all utilities own—enough in principle to displace essentially all central thermal power stations at a profit.

As both stationary and mobile applications for fuel cells build volume and cut cost for dispersed but stationary reformer and electrolyzer appliances, those hydrogen sources would also start to be installed freestanding outside buildings. Before long, the growing hydrogen market would then justify further competition from upstream bulk supply, especially from climatically benign sources. One option is converting old hydroelectric dams, windfarms or other renewables to "Hydro-Gen" plants that earn far higher profit by shipping each electron with a proton attached—as lucrative hydrogen fuel—instead of selling electricity. Another is Princeton University Professor R.H. Williams's concept of reforming natural gas into hydrogen at the wellhead and reinjecting the carbon dioxide into the gas field (as discussed above). This is generally profitable because it yields as many as

three income streams: sale of hydrogen as a premium fuel, enhanced recovery of methane from repressurizing the gasfield, and potentially trading sequestered carbon under future Kyoto Protocol rules.

Existing natural gas resources—roughly 200 years of supply at current rates of consumption—could also provide a long bridge to a fully renewable energy system, one that would be climatically benign if used as just described. The diverse and dynamic portfolio of hydrogen sources—up- and downstream; renewable and nonrenewable; based on electrolysis, reforming or other methods; and with small to no net climatic effect—would ensure healthy price competition and robust policy choices.

Negawatts, International Development and Security

These advances in the world's most developed countries also fit well with industrializing strategies in the developing world. A synergistic combination of advanced resource productivity, end-use efficiency, renewable energy sources and small-scale distributed power generation offers industrializing countries a development path that can deliver improved quality of life at far lower economic and environmental cost than has been previously considered or demonstrated on a wide scale. Capital requirements can fall by a thousandfold—even ten thousandfold.[28] Long a major sink for investment, the electricity sector can effectively become a net exporter of capital, freeing up resources for other development goals. Integrated urban planning, such as has been pioneered in Curitiba, Brazil,[29] solves many problems at once. It allows growing cities in the developing world to leapfrog the wasteful infrastructure patterns of the West and become leading examples of sustainable development for the rest of the world, including the United States and Western Europe.

Decentralized, clean and efficient energy systems can power sustainable development strategies that affordably meet the basic needs of the growing populations of the world's poorer regions. Resource-efficient infrastructure development can yield many social benefits simultaneously, such as stretching limited resources to meet popular needs and aspirations at minimized economic and environmental costs; reducing the vulnerability of key services to disruption; and providing greater local control over resources. This approach can cost-effectively mitigate or prevent many of the challenges to peace and social stability that poverty and hopelessness breed. Countries that are better able to afford to meet their citizens' needs are less likely to make war on each other for control of resources, and will be better able to expand their economies without assuming crushing debt burdens. Nuclear power's market-driven demise—evident today and unlikely to change in the future as alternatives become ever simpler and cheaper—will reduce open or covert traffic in "civil" nuclear technologies (nearly all of which have military applications), reducing the risk of the proliferation of nuclear weapons.[30]

Natural Capitalism[31]

Businesses are the primary engines of resource use, converting materials and energy into wealth, delivering goods and services and creating waste or pollution. This provision of necessities and luxuries is often conducted in ways that systematically degrade the Earth's natural capital—the ecosystems that support all life. Changing the way we do business is an essential aspect of the shift toward a more environmentally, economically and socially sustainable industrial society. Businesses are arguably the only institutions with the resources, agility and motivation—namely, profit—to lead this change.

A chief reason why companies and governments are so prodigal with ecosystem services is that the value of those services does not appear on the business balance sheet. This is a staggering omission. The economy, after all, is embedded in the environment. Recent calculations published in the journal *Nature* conservatively estimate the value of the Earth's ecosystem to be at least $33 trillion a year.[32] That's close to the gross world product, and it implies a capitalized book value on the order of half a quadrillion dollars. What's more, there is no known substitute at any price for most of these resources, and we can't live without them.

The rapidly emerging practice of "natural capitalism,"[33] offers a new approach not only for protecting the biosphere and the future but also for improving profits and competitiveness. Some simple changes to the way we run our businesses, built on advanced techniques for making resources more productive, can yield startling benefits both for today's shareholders and for future generations.

This approach is called natural capitalism because it is what capitalism might become if it behaved as if its largest category of capital—the "natural capital" of ecosystem services—were properly valued. The journey to natural capitalism involves four strongly intertwined and synergistic shifts in business practices.

- **Dramatically increase the productivity of natural capital.** Reducing the wasteful and destructive flow of resources—a half-trillion tons a year moving from depletion to pollution—represents a major business opportunity. Through fundamental changes in both production design and technology, farsighted companies are developing ways to make such natural resources as energy, minerals, water and forests stretch up to 100 times further than they do today. These major resource savings often yield higher profits than small resource savings do, and are not only paid for over time by the saved resources but in many cases may actually reduce initial capital investment. Advanced resource productivity is driven by the same logic as the first Industrial Revolution, which made people 100 times more productive because the relative scarcity of people was limiting progress in exploiting seemingly boundless nature. Today the pattern of scarcity has shifted to just the opposite—abundant people and

scarce resources. This shift changes what we should be making more productive—namely, natural capital.

- **Shift to biologically inspired production models.** Natural capitalism seeks not merely to reduce waste but to eliminate the very concept of waste. In closed-loop production systems modeled on nature's designs, every output either is returned harmlessly to the ecosystem as a nutrient, like compost, or becomes an input to manufacturing another product. Such systems often can be advantageously designed to eliminate the use of toxic materials, which hamper nature's ability to reprocess materials.

- **Move to a solutions-based business model.** The business model of traditional manufacturing rests on the sale of goods. In the new model, value is instead delivered as a continuous flow of services—such as providing illumination rather than selling light bulbs. Services are delivered, too, within a relationship that aligns the interests of providers and customers in ways that reward them for continuous improvement in implementing the first two innovations of natural capitalism—resource productivity and closed-loop manufacturing.

- **Reinvest in natural capital.** As any prudent capitalist would do, business must restore, sustain and expand the planet's ecosystems so that they can produce both vital life-support services and biological resources even more abundantly. Pressures to do so are mounting as human needs expand, the costs engendered by deteriorating ecosystems rise and the environmental awareness of consumers increases. Fortunately, these pressures all create business value.

Natural capitalism is not motivated by a current scarcity of natural resources. Indeed, although many biological resources, like fish, are becoming scarce, most mined resources, such as copper and oil, seem ever more abundant. Indices of average commodity prices are at 28-year lows, thanks partly to powerful extractive technologies—which are often subsidized and whose damage to natural capital remains unaccounted for. Yet despite their artificially low prices, using resources far more productively can now be so profitable that pioneering companies—large and small—have already embarked on the journey toward natural capitalism. Those who adopt these technologies early are already achieving strong competitive advantage—confirming Edgar Woollard's remark, made when he chaired DuPont, that companies that adopt such principles will do very well, while those that do not won't be a problem, since ultimately they won't be around.

The Biological Century

Energy and resource productivity don't correct excesses in population or consumption—they just buy the time and earn the money needed to address these and

other fundamental problems. There is much more work to be done, including re-examining the social values that allowed such a profoundly and structurally unsustainable industrial economy to come about. New technologies are given meaning within the context of value systems that direct their use as productive tools for humanity, allowing us to live in harmony with each other and the biosphere.

The most fundamental and important energy innovations will come from biological design models. This new metaphor will reshape production and commerce. It hinges on our taking our goals and worldviews not from Bacon and Descartes, but from Darwin and Thoreau, Aldo Leopold and Lewis Thomas, Kevin Kelly[34] and Janine Benyus.[35] Energy is but one of a myriad fields that the biological paradigm will transform.

In sum, past energy surprises pale in comparison with those now certain to occur. This neo-cornucopian vision, however, though in essence market-driven, has vital roles for both public policy and private entrepreneurship, albeit with nontraditional emphases: the cornucopia is the manual model, and one must actually turn the crank!

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[1] See Amory Lovins, "Energy Strategy: The Road Not Taken?" *Foreign Affairs*, 55, no. 1 (Fall 1976) pp. 65–96.

[2] *Ibid*. This article critiqued the then-conventional "hard energy path" for entailing the ever faster and more centralized conversion of depletable fuels into superfluously premium forms, mainly inefficiently used. In contrast, a "soft energy path" would provide the same growing volume of energy services with stabilizing and eventually decreasing consumption by wringing out losses, switching to appropriate renewable sources matched in scale and quality to their tasks, and bridging with efficient, transitional fossil-fuel technologies. The hard path—which was not taken because it was too slow, costly, and disagreeable—assumed the problem was to supply more energy, of any kind, from any source, at any price, while the soft path sought to provide just the amount, quality, scale, and source of energy that would do each desired task in the cheapest way.

[3] For example, in the United States during the Reagan years, the main federal clearinghouses on efficiency and renewables were at times forbidden to publish their phone numbers, and many ideologically incorrect U.S. Government Publishing Office publications on these topics were pulped, such as a USDA Yearbook featuring methods of saving farm energy.

[4] The "first wave" refers to the moderate energy savings after the 1973 first oil shock; the "second wave" refers to the rapid savings after the larger 1979 second oil shock (from 1979 to 1986, GDP rose 19 percent while primary energy consumption fell 6 percent); and there are preliminary indications of a "third wave" of comparably rapid (roughly 3.1 percent per year) savings during 1997 and 1998 despite record-low and falling energy prices.

[5] See Amory Lovins, "Apples, Oranges, and Horned Toads: Is The Joskow & Marron Critique of Electric Efficiency Costs Valid?" *Electricity Journal*, 7, no. 4 (May 1994) pp. 29–49. Available as Rocky Mountain Institute (RMI) Publication #U94-16 (Snowmass, CO: RMI, 1994).

[6] Amory Lovins and Hunter Lovins, "Climate: Making Sense *and* Making Money," RMI Publication #E97-13 (Snowmass, CO: RMI, 1997) especially pp. 11–20, at http://www.rmi.org/catalog/climate.htm.

[7] See Lovins and Lovins (1997); and Amory Lovins and Hunter Lovins, "Least-Cost Climatic Stabilization," *Annual Review of Energy and Environment* **16**:433–531 (1991); available as RMI Publication #ER91-33 (Snowmass, CO: RMI, 1991).

[8] See Amory Lovins, "Negawatts: Twelve Transitions, Eight Improvements, and One Distraction," RMI Publication #U96-11 (Snowmass, CO: RMI, 1996).

[9] See Amory Lovins, "Apples, Oranges, and Horned Toads," RMI Publication #U94-16 (Snowmass, CO: RMI, 1994); see also the technical publications of E SOURCE, Boulder, CO, www.esource.com.

[10] See Joe Romm and W. D. Browning, "Greening the Building and the Bottom Line: Increasing Productivity Through Energy-Efficient Design," RMI Publication #D94-27 (Snowmass, CO: RMI, 1994).
[11] See Amory Lovins, "The Super-Efficient Passive Building Frontier," *ASHRAE Journal*, June 1995, pp. 79–81; available as RMI Publication #E95-28 (Snowmass, CO: RMI, 1995). See also the *Technological Atlas* series and other reports, at http://www.esource.com.
[12] See E SOURCE, *Drivepower Technology Atlas*, E SOURCE Publication #TA-DP-96 (Boulder, CO: E SOURCE, 1996).
[13] See Lovins and Lovins (1997), pp. 11–20.
[14] See Lovins and Lovins (1997).
[15] See Alex Wilson et al., *Green Development: Integrating Ecology and Real Estate*, RMI Publication #D97-11 (Snowmass, CO: RMI, 1997); and the CD-ROM *Green Developments*, RMI Publication #D97-12 (Snowmass, CO: RMI, 1997).
[16] See Amory Lovins, "Putting Central Power Plants Out of Business," RMI Publication #ER98-2 (Snowmass, CO: RMI, 1998).
[17] See Amory Lovins and André Lehmann, *Small is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size* (Snowmass, CO: RMI, forthcoming).
[18] P. Kassler, *Energy for Development*, Shell Selected Paper (London: Shell International Petroleum Co., November 1994). A 1998 Shell newsletter called this outcome highly likely.
[19] See Lovins and Lovins, (1997); and Amory Lovins and Hunter Lovins, "Least-Cost Climatic Stabilization," *Annual Review of Energy and the Environment* 16, pp. 433–531. Available as RMI Publication #ER91-33 (Snowmass, CO: RMI, 1991).
[20] See Paul Hawken, Amory Lovins and Hunter Lovins, *Natural Capitalism* (New York: Little Brown, 1999); and Paul Hawken, Amory Lovins and Hunter Lovins, "A Roadmap for Natural Capitalism," *Harvard Business Review* 77, no. 3 (May–June 1999) pp. 145–158, 211, at http://www.rmi.org/HBR-RMINatCap.pdf.
[21] See Amory Lovins, "The Good News on Climate," *Worldwatch* 12, no. 1 (1999) p. 7. Available as RMI Publication #E96-8 (Snowmass, CO: RMI, 1998).
[22] See Lovins and Lovins (1997).
[23] See Amory Lovins, "Hypercars: The Next Industrial Revolution," Symposium paper (Osaka, Japan: 14 October 1996),at http://www.rmi.org/hypercars/osaka/index.html. Numerous popular and technical publications of RMI's Hypercar Center[SM], some very detailed, are available at http://www.hypercarcenter.org.
[24] See http://www. hypercarcenter.org for a public-source chronology of recent market developments.
[25] Hawken, Lovins and Lovins, *Natural Capitalism*, especially chap. 2.
[26] See http://www.arco.com/news/1999/co0209.html (2 July 1999).
[27] Amory Lovins and B. D. Williams, "A Strategy for the Hydrogen Transition," (Vienna, VA: 10th Annual U.S. Hydrogen Meeting, National Hydrogen Association, 7–9 April 1999), at http://www. hypercarcenter.org /go/whatfgo.html.
[28] Amory Lovins and Ashok Gadgil, "The Negawatt Revolution: Electric Efficiency and Asian Development," RMI Publication #E91-33 (Snowmass, CO: RMI, 1991).
[29] Hawken, Lovins and Lovins, *Natural Capitalism*, chap. 14.
[30] Amory Lovins and Hunter Lovins, "Nuclear Power and Nuclear Bombs," *Foreign Affairs* 58, no. 11, (Summer 1980) pp. 37–77. See also Amory Lovins and Hunter Lovins, "Nonproliferation: Now a Workable Idea," *Christian Science Monitor*, 21 April 1995, op-ed.
[31] This summary draws upon Hawken, Lovins and Lovins, "A Roadmap for Natural Capitalism."
[32] R. Costanza et al., "The Value of the World's Ecosystem Services and Natural Capital," *Nature* 387 (15 May 1997) pp. 253–260.
[33] Paul Hawken's term "natural capitalism" is the title of the aforementioned book, Hawken, Lovins and Lovins, 1999.
[34] See Kevin Kelly, *Out of Control: The Rise of a Neo-Biological Civilization* (Reading, MA: Addison-Wesley, 1994).
[35] See Janine Benyus, *Biomimicry: Innovations Inspired by Nature* (New York: William Morrow & Company, 1997).