Energy Efficiency, Taxonomic Overview

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Glossary

conversion efficiency The physical ratio of desired output to total input in an energy conversion process, such as converting fuel to electricity or fuel to heat. Undesired or nonuseful outputs are excluded, making the ratio less than unity for most devices (except in such cases such as heat pumps and heat-powered chillers, where it can exceed unity and is called a coefficient of performance). The definition is thus based partly on what each individual finds useful. Synonymous with the thermodynamic concept of First Law efficiency, but counts only the quantity of energy, not also the quality, and hence differs from Second Law efficiency, which counts both.

customer The ultimate recipient of energy services, regardless of intermediate transactions.

delivered energy Secondary energy provided at the place where it is used to provide the desired energy service (e.g., electricity or fuel entering the end-use device that performs that final conversion). Further losses between that device and the customer may or may not be included. Delivered energy is net of distribution efficiency (1) to the end-use device, but may or may not be net of distribution efficiency (2) between end-use device and customer.

distribution efficiency (1) The fraction of centrally supplied energy shipped out (such as electricity from a power station, petroleum products from a refinery, or natural gas from a treatment plant) that is delivered to the end-use device, net of energy “lost” or “consumed” in its delivery. For electricity, this conversion into unwanted forms, chiefly low-temperature heat, comprises transmission as well as distribution losses, and is conventionally measured from the generator’s busbar to the customer’s meter. (2) The fraction of energy services produced by the end-use device that reaches the customer (e.g., the fraction of the heat produced by a furnace that provides warmth in a room, net of nonuseful heat escaping from pipes or ducts).

end use (1) The category of desired physical function provided by an energy service, such as heating, cooling, light, mechanical work, electrolysis, or electronic signal processing. (2) The physical quantity of such end use delivered to the customer, whether or not it is useful energy.

end-use device Equipment converting delivered energy into energy service.

end-use efficiency The physical ratio of end use (2) provided to delivered energy converted in the end-use device.

energy conservation An ambiguous term best avoided; considered by some as synonymous with increased energy efficiency but to many others connoting the opposite: privation, curtailment, and discomfort, i.e., getting fewer or lower quality energy services. The degree of confusion between these meanings varies widely by individual, culture, historic period, and language spoken. Some analysts, chiefly outside the United States, embrace energy conservation as an umbrella term for energy efficiency plus changes in personal habits plus changes in system design (such as spatial planning or design for product longevity and materials recovery/reuse).

energy efficiency Broadly, any ratio of function, service, or value provided to the energy converted to provide it. Herein, energy efficiency and its components all use (a) physical rather than economic metrics and (b) engineering, not economic, definitions (this physical convention can, however, become awkward with multiple inputs or outputs). Energy efficiency may or may not count thermodynamic quality of energy (ability to do work); see the distinction between First Law and Second Law efficiency.

energy intensity Energy (primary, delivered, or otherwise defined) “used” per unit of service or value provided.

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Intensity can be expressed in economic or in physical terms (e.g., the very crude and aggregated metric of primary energy consumption per dollar of real gross domestic product).

energy service The desired function provided by converting energy in an end-use device (e.g., comfort, mobility, fresh air, visibility, electrochemical reaction, or entertainment). These functions, which together contribute to a material standard of living, are generally measured in physical units, not by energy used or money spent. Because diverse services are incommensurable, they cannot be readily added to express a meaningful "total end-use efficiency" for a person, firm, or society. Economic surrogates for such totals are seldom satisfactory.

extractive efficiency The fraction of a fuel deposit that is recovered and sent out for processing and use, net of energy employed to conduct those extractive processes.

hedonic (functional) efficiency How much human happiness or satisfaction (equivalent to economists' welfare metrics) is achieved per unit of energy service delivered. Some analysts similarly distinguish the task (such as delivering heat into a house) from the goal it seeks to achieve (such as the human sensation of indoor comfort in winter).

primary energy (1) Fossil fuel extracted and then converted, typically at a central facility, into a secondary form (e.g., crude oil into refined products or coal into electricity) for delivery to end-use devices. (2) Nuclear, hydroelectric, and renewable energy captured for such delivery; if electric, conventionally expressed as the imputed amount of fossil fuel used to produce that much electricity in a typical thermal power station. (3) The quantity of energy described in (1) or (2). Most analysts exclude from primary energy consumption the metabolic energy in human food, but include the nonsolar energy needed to grow, process, deliver, and prepare it.

secondary energy Any processed, refined, or high-quality form of useful energy converted from primary energy, such as electricity, refined petroleum products, dry natural gas, or district heat. Excludes undesired and nonuseful conversion products.

Second Law efficiency The ratio of First Law thermodynamic efficiency to its maximum theoretically possible value; equivalently, the ratio of the least available work that could have done the job to the actual available work used to do the job. For a device that produces useful work or heat (not both), such as a motor, heat pump, or power plant, Second Law efficiency is the amount of output heat or work usefully transferred, divided by the maximum possible heat or work usefully transferable for the same function by any device or system using the same energy input. This maximum is defined by the task, not the device: to maximize how much heat is delivered from fuel into a building, an ideal fuel cell and an ideal heat pump would be used. Second Law efficiency thus measures the effectiveness of a device in approaching the constraints of the First and Second Laws of thermodynamics. First and Second Law efficiencies are nearly equal for a power plant, but are very different when high-quality energy is converted into a low-energy useful form: a 60%-efficient (First Law) furnace delivering 43°C heat into a house in a 0°C environment has a Second Law efficiency of only 8.2%.

service substitution Providing a desired energy service by a different means (e.g., providing illumination by opening the curtain in the daytime rather than turning on an electric light).

useful energy The portion of an energy service that is actually, not just potentially, desired and used by customers (e.g., lighting an empty room, or overheating an occupied room to the point of discomfort, is seldom useful).

Efficient use of energy is in all countries the most important, economical, prompt, underused, overlooked, and misunderstood way to provide future energy services. It is rapidly becoming even larger, faster, and cheaper as technologies, delivery methods, and integrative design improve. Whole-system design can indeed make very large energy savings cost less than small ones. But capturing energy efficiency's remarkable potential requires careful terminology, prioritization, attention to engineering details and to market failures, and willingness to accept measured physical realities even if they conflict with economic theories. If well done, such energy efficiency can displace costly and disagreeable energy supplies, enhance security and prosperity, speed global development, and protect Earth's climate—not at cost but at a profit.

1. DEFINITION AND IMPORTANCE OF ENERGY EFFICIENCY

Energy efficiency is generally the largest, least expensive, most benign, most quickly deployable, least visible, least understood, and most neglected way to provide energy services. The 39% drop in U.S. energy intensity (primary energy consumption per dollar of real gross domestic product) from 1975 to 2000 represented, by 2000, an effective energy "source" 1.7 times as big as U.S. oil consumption, three times net oil imports, five times domestic oil output, six times net oil imports from Organization of Petroleum Exporting Countries (OPEC) members, and 13 times net imports from Persian Gulf countries. It has lately increased by 3% per year, outpacing the growth of any source of supply (except minor renewables). Yet energy efficiency has gained little attention or respect for its achievements, let alone its far larger untapped potential. Physical scientists, unlike engineers or economists, find that despite energy efficiency's leading role in providing energy services today, its profitable potential has barely begun to be tapped. In contrast, many engineers tend to be limited by adherence to past practice, and most economists are constrained by their assumption that any profitable savings must already have occurred.

The potential of energy efficiency is increasing faster through innovative designs, technologies, policies, and marketing methods than it is being used up through gradual implementation. The uncaptured "efficiency resource" is becoming bigger and cheaper even faster than oil reserves have lately done through stunning advances in exploration and production. The expansion of the "efficiency resource" is also accelerating, as designers realize that whole-system design integration (see Section 4) can often make very large (one or two order-of-magnitude) energy savings cost less than small or no savings, and as energy-saving technologies evolve discontinuously rather than incrementally. Similarly rapid evolution and enormous potential apply to ways to market and deliver energy-saving technologies and designs; research and development can accelerate both.

1.1 Terminology

Efficiency unfortunately means completely different things to the two professions most engaged in achieving it. To engineers, efficiency means a physical output/input ratio. To economists, efficiency means a monetary output/input ratio, though for practical purposes many economists use a monetary output/physical input ratio. Only physical output/input ratios are used here, but the common use of monetary ratios causes vast confusion, especially to policymakers using economic jargon.

Wringing more work from energy via smarter technologies is often, and sometimes deliberately, confused with a pejorative usage of the ambiguous term energy conservation. Energy efficiency means doing more (and often better) with less—the opposite of simply doing less or worse or without. This confusion unfortunately makes the honorable and traditional concept of energy conservation no longer useful in certain societies, notably the United States, and underlies much of the decades-long neglect or suppression of energy efficiency. However, deliberately reducing the amount or quality of energy services remains a legitimate, though completely separate, option for those who prefer it or are forced by emergency to accept it. For example, the 2000–2001 California electricity crisis ended abruptly when customers, exhorted to curtail their use of electricity, cut their peak load per dollar of weather-adjusted real gross domestic product (GDP) by 14% in the first 6 months of 2001. Most of that dramatic reduction, undoing the previous 5–10 years of demand growth, was temporary and behavioral, but by mid-2002, the permanent and technological fraction was heading for dominance. Even absent crises, some people do not consider an ever-growing volume of energy services to be a worthy end in itself, but seek to live more simply—with elegant frugality rather than involuntary penury—and to meet nonmaterial needs by nonmaterial means. Such choices can save even more energy than can technical improvements alone, though they are often considered beyond the scope of energy efficiency.

Several other terminological distinctions are also important. At least five different kinds of energy efficiency can be measured in at least five different stages of energy conversion chains; these are discussed in Section 1.2. Also, technical improvements in energy efficiency can be broadly classified into those applicable only to new buildings and equipment, those installable in existing ones (retrofitted), those addable during minor or routine maintenance (slipstreamed), and those that can be conveniently added when making major renovations or expansions for other reasons (piggybacked).

Efficiency saves energy whenever an energy service is being delivered, whereas "load management" (sometimes called "demand response" to emphasize reliance on customer choice) changes only the time when that energy is used, either by shifting the timing of the service delivery or by, for example, storing heat or coolth so energy consumption and service delivery can occur at different times. In the context chiefly of electricity, demand-side management, a term coined by the Electric Power Research Institute, comprises both of these options, plus others that may even increase the use of electricity. Most efficiency options yield comparable or greater savings in peak loads; both kinds of savings are valuable, and both kinds of value should be counted. They also have important but nonobvious linkages: for example, because most U.S. peak electric loads are met by extremely inefficient simple-cycle gas-fired combustion turbines, saving 5% of peak electric load in 2000 would have saved 9.5% of total natural gas consumption, enough to reequilibrate high 2003 gas prices back to ~$2/GJ lower historic levels.

Conflating three different things—technological improvements in energy efficiency (such as thermal insulation), behavioral changes (such as resetting thermostats), and the price or policy tools used to induce or reward those changes—causes endless misunderstanding. Also, consider that the theoretical potential for efficiency gains (up to the maximum permitted by the laws of physics) exceeds the technical potential, which exceeds the economic potential based on social value, which exceeds the economic potential based on private internal value, which exceeds the actual uptake not blocked by market failures, which exceeds what happens spontaneously if no effort is made to accelerate efficiency gains deliberately; yet these six quantities are often not clearly distinguished.

Finally, energy statistics are traditionally organized by the economic sector of apparent consumption, not by the physical end uses provided or services sought. End uses were first seriously analyzed in 1976, rarely appear in official statistics even a quarter-century later, and can be difficult to estimate accurately. But end-use analysis can be valuable because matching energy supplies in quality and scale, as well as in quantity, to end-use needs can save a great deal of energy and money. Supplying energy of superfluous quality, not just quantity, for the task is wasteful and expensive. For example, the United States now provides about twice as much electricity as the fraction of end uses that economically justify this special, costly, high-quality form of energy, yet from 1975 to 2000, 45% of the total growth in primary energy consumption came from increased conversion and grid losses in the expanding, very costly, and heavily subsidized electricity system. Much of the electric growth, in turn, provided low-temperature heat, a physically and economically wasteful use of electricity.

Many subtleties of defining and measuring energy efficiency merit but seldom get rigorous treatment, such as the following losses, services, or metrics:

- Distribution losses downstream of end-use devices (an efficient furnace feeding leaky ducts yields costlier delivered comfort).
- Undesired or useless services, such as leaving equipment on all the time (as many factories do) even when it serves no useful purpose.
- Misused services, such as space-conditioning rooms that are open to the outdoors.
- Conflicting services, such as heating and cooling the same space simultaneously (wasteful even if both services are provided efficiently).
- Parasitic loads, as when the inefficiencies of a central cooling system reappear as additional fed-back cooling loads that make the whole system less efficient than the sum of its parts.
- Misplaced efficiency, such as applying energy-using equipment, however efficiently, to a task that does not need it—say, cooling with a mechanical chiller when groundwater or ambient conditions can more cheaply do the same thing.
- Incorrect metrics, such as measuring lighting by raw quantity (lux or footcandles) unadjusted for its visual effectiveness, which may actually decrease if greater illuminance is improperly delivered.

To forestall a few other semantic quibbles, physicists (including the author) know energy is not "consumed," as the economists' term "consumption" implies, nor "lost," as engineers refer to unwanted conversions into less useful forms. Energy is only converted from one form to another; yet the normal metaphors are clear, common, and adopted here. Thus an 80%-efficient motor converts its electricity input into 80% torque and 20% heat, noise, vibration, and stray electromagnetic fields; the total equals 100% of the electricity input, or roughly 30% of the fuel input at a classical thermal power station. (Note that this definition of efficiency combines engineering metrics with human preference. The motor's efficiency may change, with no change in the motor, if changing intention alters which of the outputs are desired and which are unwanted: the definition of "waste" is as much social or contextual as physical. A floodlamp used to keep plates of food warm in a restaurant may be rather effective for that purpose even though it is an inefficient source of visible light).

More productive use of energy is not, strictly speaking, a physical "source" of energy but rather a way to displace physical sources. Yet this distinction is rhetorical, because the displacement or substitution is real and makes supply fully fungible with efficiency. Also, energy/GDP ratios are a very rough, aggregated, and sometimes misleading metric, because they combine changes in technical efficiency, human behavior, and the composition of GDP (a metric that problematically conflates goods and services with "bads" and nuisances, counts only monetized activities, and is an increasingly perverse measure of well being). Yet the two-fifths drop in U.S. energy intensity and the one-half drop in oil intensity during the period 1975–2001 reflect mainly better technical efficiency. Joseph Romm has also shown that an important compositional shift of U.S. GDP—the information economy emerging in the late 1990s—has significantly decreased energy and probably electrical energy intensity, as bytes substituted for (or increased the capacity utilization of) travel, freight transport, lit and conditioned floorspace, paper, and other energy-intensive goods and services.

The aim here is not to get mired in word games, but to offer a clear overview of what kinds of energy efficiency are available, what they can do, and how best to consider and adopt them.

1.2 Efficiency along Energy Conversion Chains

The technical efficiency of using energy is the product of five efficiencies successively applied along the chain of energy conversions: (1) the conversion efficiency of primary into secondary energy, times (2) the distribution efficiency of delivering that secondary energy from the point of conversion to the point of end use, times (3) the end-use efficiency of converting the delivered secondary energy into such desired energy services as hot showers and cold beer. Some analysts add another term at the upstream end, (4) the extractive efficiency of converting fuel in the ground or power from wind or from sun in the atmosphere, etc. into the primary energy fed into the initial conversion device, and another term at the downstream end, (5) the hedonic efficiency of converting delivered energy services into human welfare. (Delivering junk mail with high technical efficiency is futile if the recipients did not want it.) Counting all five efficiencies permits comparing ultimate means, the primary energy tapped, with ultimate ends, the happiness or economic welfare created. Focusing only on intermediate means and ends loses sight of what human purposes an energy system is to serve. Most societies pay attention to only three kinds of energy efficiency: extraction (because of its cost, not because the extracted fuels are assigned any intrinsic or depletion value), conversion, and perhaps distribution. End-use and hedonic efficiency are left to customers, are least exploited, and hence hold the biggest potential gains.

They also offer the greatest potential leverage. Because successive efficiencies along the conversion chain all multiply, they are often assumed to be equally important. Yet downstream savings—those nearest the customer—are the most important. Figure 1 shows schematically the successive energy conversions and losses that require about 10 units of fuel to be fed into a conventional thermal power station in order to deliver one unit of flow in a pipe. But conversely, every unit of flow (or friction) saved in the pipe will save approximately 10 units of fuel, cost, and pollution at the power station. It will also make the pump's motor (for example) nearly two and a half units smaller, hence cheaper. To save the most primary energy and the most capital cost, therefore, efficiency efforts should start all the way downstream (see Section 4.2), by asking: How little flow can actually deliver the desired service? How small can the piping friction become? How small, well matched to the flow regime, and efficient can the pump be made? Its coupling? Its motor? Its controls and electrical supplies?

Analyses of energy use should start with the desired services or changes in well being, then work back upstream to primary supplies. This maximizes the extra value of downstream efficiency gains and

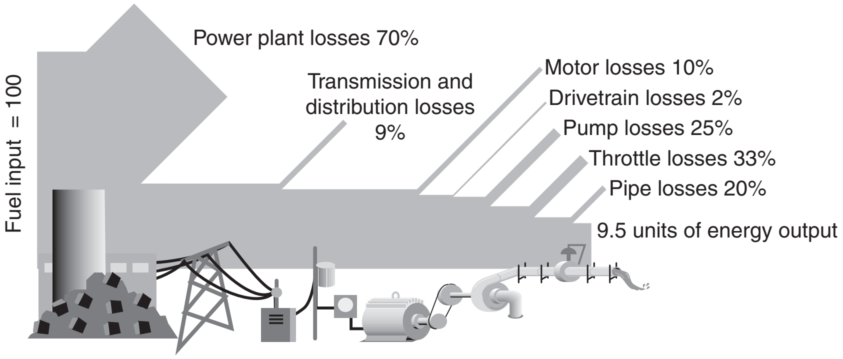

FIGURE 1 To deliver one unit of flow in the pipe requires about 10 units of fuel at the power plant, thus those 10-fold compounding losses can be turned around backward, yielding 10-fold compounding savings of fuel for each unit of reduced friction or flow in the pipe. From the E SOURCE "Drivepower Technology Atlas," courtesy of Platts Research & Consulting.

the capital-cost savings from smaller, simpler, cheaper upstream equipment. Yet it is rarely done. Similarly, most energy policy analysts analyze how much energy could be supplied before asking how much is optimally needed and at what quality and scale it could be optimally provided. This wrong direction (upstream to downstream) and supply orientation lie at the root of many if not most energy policy problems.

Even modest improvements in efficiency at each step of the conversion chain can multiply to large collective values. For example, suppose that during the years 2000–2050, world population and economic growth increased economic activity by six- to eightfold, in line with conventional projections. But meanwhile, the carbon intensity of primary fuel, following a two-century trend, is likely to fall by at least two- to fourfold as coal gives way to gas, renewables, and carbon offsets or sequestration. Conversion efficiency is likely to increase by at least 1.5-fold with modernized, better-run, combined-cycle, and cogenerating power stations. Distribution efficiency should improve modestly. End-use efficiency could improve by four- to sixfold if the intensity reductions sustained by many industrial countries, when they were paying attention, were sustained for 50 years (e.g., the United States decreased its primary energy/GDP intensity at an average rate of 3.4%/year from 1979 to 1986 and 3.0%/year from 1996 to 2001). And the least understood term, hedonic efficiency, might remain constant or might perhaps double as better business models and customer choice systematically improve the quality of services delivered and their match to what customers want. On these plausible assumptions, global carbon emissions from burning fossil fuel could decrease by 1.5- to 12-fold despite the assumed six- to eightfold grosser world product. The most important assumption is sustained success with end-use efficiency, but the decarbonization and conversion-efficiency terms appear able to take up some slack if needed.

1.3 Service Redefinition

Some major opportunities to save energy redefine the service being provided. This is often a cultural variable. A Japanese person, asked why the house is not heated in winter, might reply, "Why should I? Is the house cold?" In Japanese culture, the traditional goal is to keep the person comfortable, not to heat empty space. Thus a modern Japanese room air conditioner may contain a sensor array and moveable fans that detect and blow air toward people's locations in the room, rather than wastefully cooling the entire space. Western office workers, too, can save energy (and can often see better, feel less tired, and improve esthetics) by properly adjusting venetian blinds, bouncing glare-free daylight up onto the ceiling, and turning off the lights. As Jørgen Nørgård remarks, "energy-efficient lamps save the most energy when they are turned off"; yet many people automatically turn on every light when entering a room. This example also illustrates that energy efficiency may be hard to distinguish from energy supply that comes from natural energy flows. All houses are already ~98% solar-heated, because if there were no Sun (which provides 99.8% of Earth's heat), the temperature of Earth's surface would average approximately −272.6°C rather than +15°C. Thus, strictly speaking, engineered heating systems provide only the last 1–2% of the total heating required.

Service redefinition becomes complex in personal transport. Its efficiency is not just about vehicular fuel economy, people per car, or public transport alternatives. Rather, the underlying service should often be defined as access, not mobility. Typically, the best way to gain access to a place is to be there already; this is the realm of land-use management—no novelty in the United States, where spatial planning is officially shunned, yet zoning laws mandate dispersion of location and function, real-estate practices segregate housing by income, and other market distortions maximize unneeded and often unwanted travel. Another way to gain access is virtually, moving just the electrons while leaving the heavy nuclei behind, via telecommunications, soon including realistic "virtual presence." This is sometimes an effective alternative to physically moving human bodies. And if such movement is really necessary, then it merits real competition, at honest prices, between all modes—personal or collective, motorized or human-powered, conventional or innovative. Creative policy tools can enhance that choice in ways that enhance real-estate value, saved time, quality of life, and public amenity and security. Efficient cars can be an important part of efficient personal mobility, but also reducing the need to drive can save even more energy and yield greater total benefit.

1.4 Historic Summaries of Potential

People have been saving energy for centuries, even millennia; this is the essence of engineering. Most savings were initially in conversion and end use:

preindustrial households often used more primary energy than modern ones do, because fuelwood-to-charcoal conversion, inefficient open fires, and crude stoves burned much fuel to deliver sparse cooking and warmth. Lighting, materials processing, and transport end uses were also very inefficient. Billions of human beings still suffer such conditions today. The primary energy/GDP intensities in developing countries average about three times those in industrialized countries. But even the most energy-efficient societies still have enormous, and steadily expanding, room for further efficiency gains. Less than one-fourth of the energy delivered to a typical European cookstove ends up in food, less than 1% of the fuel delivered to a standard car actually moves the driver, U.S. power plants discard waste heat equivalent to 1.2 times Japan's total energy use, and even Japan's economy does not approach one-tenth the efficiency that the laws of physics permit.

Detailed and exhaustively documented engineering analyses of the scope for improving energy efficiency, especially in end-use devices, have been published for many industrial and some developing countries. By the early 1980s, those analyses had compellingly shown that most of the energy currently used was being wasted—i.e., that the same or better services could be provided using severalfold less primary energy by fully installing, wherever practical and profitable, the most efficient conversion and end-use technologies then available. Such impressive efficiency gains cost considerably less than the long-run, and often even the short-run, marginal private internal cost of supplying more energy. Most policy-makers ignore both these analyses, well known to specialists, and less well-known findings show even bigger and cheaper savings from whole-system design integration (see Section 4).

Many published engineering analyses show a smaller saving potential because of major conservatisms, often deliberate (because the real figures seem too good to be true), or because they assume only partial adoption over a short period rather than examining the ultimate potential for complete practical adoption. For example, the American Council for an Energy-Efficient Economy estimates that just reasonable adoption of the top five conventional U.S. opportunities—industrial improvements, 40-mile per gallon (U.S. gallons; = 4.88 liters/100 km) light-vehicle standards, cogeneration, better building codes, and a 30% better central-air-conditioning standard—could save 530 million T/year of oil equivalent—respectively equivalent to the total 2000 primary energy use of Australia, Mexico, Spain, Austria, and Ireland. But the full long-term efficiency potential is far larger, and much of it resides in innumerable small terms. Saving energy is like eating an Atlantic lobster: there are big, obvious chunks of meat in the tail and the front claws, but a similar total quantity of tasty morsels is hidden in crevices and requires some skill and persistence to extract.

The whole-lobster potential is best, though still not fully, seen in bottom-up technological analyses comparing the quantity of potential energy savings with their marginal cost. That cost is typically calculated using the Lawrence Berkeley National Laboratory methodology, which divides the marginal cost of buying, installing, and maintaining the more efficient device by its discounted stream of lifetime energy savings. The levelized cost in dollars of saving, say, 1 kWh, then equals $Ci/S[1-(1+i)^{-n}]$, where C is installed capital cost (dollars), i is annual real discount rate (assumed here to be 0.05), S is energy saved by the device (kilowatt-hours/year), and n is operating life (years). Thus a \$10 device that saved 100 kWh/year and lasted 20 years would have a levelized "cost of saved energy" (CSE) of 0.8¢/kWh. Against a 5¢/kWh electricity price, a 20-year device with a 1-year simple payback would have CSE = 0.4¢/kWh. It is conventional for engineering-oriented analysts to represent efficiency "resources" as a supply curve, rather than as shifts along a demand curve (the convention among economists). CSE is methodologically equivalent to the cost of supplied energy (e.g., from a power station and grid): the price of the energy saved is not part of the calculation. Whether the saving is cost-effective depends on comparing the cost of achieving it with the avoided cost of the energy saved. (As noted in Section 2, this conventional engineering–economic approach actually understates the benefits of energy efficiency.)

On this basis, the author's analyses in the late 1980s found, from measured cost and performance data for more than 1000 electricity-saving end-use technologies, that their full practical retrofit could save about three-fourths of U.S. electricity at an average CSE ~ 0.6¢/kWh (1986 dollars)—roughly consistent with a 1990 Electric Power Research Institute analysis in which the differences were mainly methodological rather than substantive. Similarly, the author's analysis for Royal Dutch/Shell Group found that full use of the best 1987–1988 oil-saving end-use technologies, assuming turnover of vehicle stocks, could save about 80% of U.S. oil use at an average levelized CSE below \$2.5/barrel (1986 dollars). Both analyses have proven systematically conservative: today's potential is even larger and cheaper. (The analyses explicitly excluded financing and transaction costs, but those would only slightly affect the results. There is also a huge literature accurately predicting and rigorously measuring the empirical size, speed, and cost of efficiency improvements delivered by actual utility and government programs.) Such findings are broadly consistent with equally or more detailed ones by European analysts: for example, late-1980s technologies could save three-fourths of Danish buildings' electricity or half of all Swedish electricity at \$0.016/kWh (1986 dollars), or four-fifths of German home electricity (including minor fuel switching) with a ~40%/year aftertax return on investment. Such findings with ever greater sophistication have been published worldwide since 1979, but have been rejected by nontechnological economic theorists, who argue that if such cost-effective opportunities existed, they would already have been captured in the marketplace, even in planned economies with no marketplace or mixed economies with a distorted one. This mental model—"don't bother to bend over and pick up that banknote lying on the ground, because if it were real, someone would have picked it up already"—often dominates government policy. It seems ever less defensible as more is learned about the reality of pervasive market failures (see Section 5) and the astonishing size and cheapness of the energy savings empirically achieved by diverse enterprises (discussed in Section 3). But by now, the debate is theological—about whether existing markets are essentially perfect, as most economic modelers assume for comfort and convenience, or whether market failures are at least as important as market function and lie at the heart of business and policy opportunity. To technologists and physical scientists, this seems a testable empirical question.

1.5 Discontinuous Technological Progress

This engineering/economics divergence about the potential to save energy also reflects a tacit assumption that technological evolution is smooth and incremental, as mathematical modelers prefer. In fact, although much progress is as incremental as technology diffusion, discontinuous technological leaps, more like "punctuated equilibrium" in evolutionary biology, can propel innovation and speed its adoption, as with 5×-efficiency light vehicles (see Section 4.1).

Technological discontinuities can even burst the conventional boundaries of possibility by redefining the design space. Generations of engineers learned that big supercritical-steam power plants were as efficient as possible (~40% from fuel in to electricity out). But through sloppy learning or teaching, these engineers overlooked the possibility of stacking two Carnot cycles atop each other. Such combined-cycle (gas-then-steam) turbines, based on mass-produced jet engines, can exceed 60% efficiency and are cheaper and faster to build, so in the 1990s, they quickly displaced the big steam plants. Fuel cells, the next innovation, avoid Carnot limits altogether by being an electrochemical device, not a heat engine. Combining both may soon achieve 80–90% fuel-to-electric efficiency. Even inefficient distributed generators can already exceed 90% system efficiency by artfully using recaptured heat.

As another example, most authors today state that the theoretical efficiency limit for converting sunlight into electricity using single-layer photovoltaic (PV) cells is 31% (~50% using multicolor stacked layers; the best practical values so far are around 25 and 30%). This is because semiconductor bandgaps have been believed too big to capture any but the high-energy wavelengths of sunlight. But those standard data are wrong. A Russian-based team suspected in 2001, and Lawrence Berkeley National Laboratory proved in 2002, that indium nitride's bandgap is only 0.7 eV, matching near-infrared (1.77 μm) light and hence able to harvest almost the whole solar spectrum. This may raise the theoretical limit to 50% for two-layer and to ~70% for many-layer thin-film PVs.

Caution is likewise vital when interpreting Second Law efficiency. In the macroscopic world, the laws of thermodynamics are normally considered ineluctable, but the definition of the desired change of state can be finessed. Ernie Robertson notes that when turning limestone into a structural material, one is not confined to just the conventional possibilities of cutting it into blocks or calcining it at ~1250°C into Portland cement. It is possible instead grind it up and feed it to chickens, in which ambient-temperature "technology" turns it into eggshell stronger than Portland cement. Were we as smart as chickens, we would have mastered this life-friendly technology. Extraordinary new opportunities to harness 3.8 billion years of biological design experience, as described by Janine Benyus in *Biomimicry*, can often make heat-beat-and-treat industrial processes unnecessary. So, in principle, can the emerging techniques of nanotechnology using molecular-scale self-assembly, as pioneered by Eric Drexler.

More conventional innovations can also bypass energy-intensive industrial processes. Making artifacts that last longer, use materials more frugally, and are designed and deployed to be repaired, reused, remanufactured, and recycled can save much or most of the energy traditionally needed to produce and assemble their materials (and can increase welfare while reducing GDP, which swells when ephemeral goods are quickly discarded and replaced). Microfluidics can even reduce a large chemical plant to the size of a watermelon: millimeter-scale flow in channels etched into silicon wafers can control time, temperature, pressure, stoichiometry, and catalysis so exactly that a very narrow product spectrum is produced, without the side-reactions that normally require most of the chemical plant to separate undesired from desired products. Such "end-run" solutions (rather like the previous example of substituting sensible land-use for better vehicles, or better still, combining both) can greatly expand the range of possibilities beyond simply improving the narrowly defined efficiency of industrial equipment, processes, and controls. By combining many such options, it is now realistic to contemplate a long-run advanced industrial society that provides unprecedented levels of material prosperity with far less energy, cost, and impact than today's best practice. The discussion in Section 4.1, drawn from Paul Hawken *et al.*'s synthesis in *Natural Capitalism* and Ernst von Weizsäcker *et al.*'s earlier *Factor Four*, further illustrates recent breakthroughs in integrative design that can make very large energy savings cost less than small ones; and similarly important discontinuities in policy innovation are summarized in Section 6.

In light of all these possibilities, why does energy efficiency, in most countries and at most times, command so little attention and such lackadaisical pursuit? Several explanations come to mind. Saved energy is invisible. Energy-saving technologies may look and outwardly act exactly like inefficient ones, so they are invisible too. They are also highly dispersed, unlike central supply technologies that are among the most impressive human creations, inspiring pride and attracting ribbon-cutters and rent- and bribe-seekers. Many users believe energy efficiency is binary—you either have it or lack it—and that they already did it in the 1970s. Energy efficiency has relatively weak and scattered constituencies, and major energy efficiency opportunities are disdained or disbelieved by policymakers indoctrinated in a theoretical economic paradigm that claims they cannot exist (see Section 3).

2. *BENEFITS OF ENERGY EFFICIENCY*

Energy efficiency avoids the direct economic costs and the direct environmental, security, and other costs of the energy supply and delivery that it displaces. Yet the literature often overlooks several key side-benefits (economists call them "joint products") of saving energy.

2.1 Indirect Benefits from Qualitatively Superior Services

Improved energy efficiency, especially end-use efficiency, often delivers better services. Efficient houses are more comfortable; efficient lighting systems can look better and help you see better; efficient motors can be more quiet, reliable, and controllable; efficient refrigerators can keep food fresher for longer; efficient cleanrooms can improve the yield, flexibility, throughput, and setup time of microchip fabrication plants; efficient fume hoods can improve safety; efficient supermarkets can improve food safety and merchandising; retail sales pressure can rise 40% in well-daylit stores; and students' test scores suggest 20–26% faster learning in well-daylit schools. Such side-benefits can be one or even two more orders of magnitude more valuable than the energy directly saved. For example, careful measurements show that in efficient buildings, where workers can see what they are doing, hear themselves think, breathe cleaner air, and feel more comfortable, labor productivity typically rises by about 6–16%. Because office workers in industrialized countries cost about 100 times more than office energy, a 1% increase in labor productivity has the same bottom-line effect as eliminating the energy bill, and the actual gain in labor productivity is about 6–16 times bigger than that. Practitioners can market these attributes without ever mentioning lower energy bills.

2.2 Leverage in Global Fuel Markets

Much has been written about the increasing pricing power of major oil-exporting countries, especially Saudi Arabia, with its important swing production capacity. Yet the market power of the United States—the Saudi Arabia of energy waste—is even greater on the demand side. The United States can raise its oil productivity more and faster than any oil exporter can adjust to reducing its oil output. This was illustrated from 1977 to 1985, when U.S. GDP rose 27% while total U.S. oil imports fell by 42%, or 3.74 million barrels (bbl)/day. This was largely due to a 52% gain in oil productivity, causing U.S. oil consumption to fall by 17% and oil imports from the Persian Gulf to fall by 91%. That took away an eighth of OPEC's market. The entire world oil market shrank by a tenth; OPEC's share was slashed from 52 to 30%, and its output fell by 48%. The United States accounted for one-fourth of that reduction. More efficient cars, each driving 1% fewer miles on 20% less gasoline—a 7-mile per (U.S.) gallon gain in 6 years for new American-made cars—were the most important single cause; 96% of those savings came from smarter design, with only 4% deriving from smaller size.

Those 8 years around the second oil shock (1979) demonstrated an effective new source of energy security and a potent weapon against high oil prices and supply manipulations. The United States showed that a major consuming nation could respond effectively to supply disruptions by focusing on the demand side and boosting oil productivity at will. It could thereby exercise more market power than suppliers, beat down their prices (breaking OPEC's pricing power for a decade), and enhance the relative importance of less vulnerable, more diversified sources of supply. Had the United States simply continued its 1979–1985 rate of improvement of oil productivity, it would not have needed a drop of oil from the Persian Gulf after 1985. That is not what happened, but it could be if the United States chose to repeat and expand its previous oil savings.

2.3 Buying Time

Energy efficiency buys time. Time is the most precious asset in energy policy, because it permits the fullest and most graceful development and deployment of still better techniques for energy efficiency and supply. This pushes supply curves downward (larger quantities at lower prices), postpones economic depletion, and buys even more time. The more time is available, the more information will emerge to support wiser and more robust choices, and the more fruitfully new technologies and policy options can meld and breed new ones. Conversely, hasty choices driven by supply exigencies almost always turn out badly, waste resources, and foreclose important options. Of course, once bought, time should be used wisely. Instead, the decade of respite bought by the U.S. efficiency spurt of 1979–1985 was almost entirely wasted as attention waned, efficiency and alternative-supply efforts stalled, research and development teams were disbanded, and underlying political problems festered. From the perspective of 2004, that decade of stagnation looked like a blunder of historic proportions.

2.4 Integrating Efficiency with Supply

To the first order, energy efficiency makes supply cheaper. But second-order effects reinforce this first-order benefit, most obviously when efficiency is combined with onsite renewable supplies, making them nonlinearly smaller, simpler, and cheaper. Consider the following examples:

- A hot-water-saving house can achieve a very high solar-water-heat fraction (e.g., 99% in the author's home high in the Rocky Mountains) with only a small collector, so it needs little or no backup, partly because collector efficiency increases as stratified-tank storage temperature decreases.
- An electricity-saving house needs only a few square meters of PVs and a simple balance-of-system setup (storage, inverter, etc.). This can cost less than connecting to the grid a few meters away.
- A passive-solar, daylit building needs little electricity, and can pay for even costly forms of onsite generation (such as PVs) using money saved by eliminating or downsizing mechanical systems.
- Such mutually reinforcing options can be bundled: e.g., 1.18 peak MW of photovoltaics retrofitted onto the Santa Rita Jail in Alameda County, California, was combined with efficiency and load management, so at peak periods, when the power was most valuable, less was used by the jail and more was sold back to the grid. This bundling yielded a internal rate of return of over 10% including state subsidies, and a customer present-valued benefit/cost ratio of 1.7 without or 3.8 with those subsidies.

2.5 Gaps in Engineering Economics

Both engineers and economists conventionally calculate the cost of supplying or saving energy using a rough-and-ready tool kit called "engineering economics." Its methods are easy to use but flawed, ignoring such basic tenets of financial economics as risk-adjusted discount rates. Indeed, engineering economics omits 207 economic and engineering considerations that together increase the value of decentralized electrical resources by typically an order of magnitude. Many of these "distributed benefits," compiled in the author's *Small Is Profitable*, apply as much to decentralized efficiency as to generation. Most of the literature on the cost of energy alternatives is based solely on accounting costs and engineering economics that greatly understate efficiency's value. Properly counting its benefits will yield far sounder investments.

Efficient end use is also the most effective way to make energy supply systems more resilient against mishap or malice, because it increases the duration of buffer stocks, buying time to mend damage or arrange new supplies, and it increases the share of service that curtailed or improvised supplies can deliver. Efficiency's high "bounce per buck" makes it the cornerstone of any energy system designed for secure service provision in a dangerous world.

3. ENGINEERING VS. ECONOMIC PERSPECTIVES

Engineering practitioners and economic theorists view energy efficiency through profoundly different lenses, yet both disciplines are hard pressed to explain the following phenomena:

1. During the period 1996–2001, U.S. aggregate energy intensity fell at a near-record pace despite record low and falling energy prices. (It fell faster only once in modern history, during the record high and rising energy prices of 1979–1985.) Apparently, something other than price was getting Americans' attention.
2. During the period 1990–1996, when a kilowatt-hour of electricity cost only half as much in Seattle as in Chicago, people in Seattle, on average, reduced their peak electric load 12 times as fast, and their use of electricity about 3640 times as fast, as did people in Chicago—perhaps because Seattle City Light encouraged savings while Commonwealth Edison Co. discouraged them.
3. In the 1990s, DuPont found that its European chemical plants were no more energy efficient than its corresponding U.S. plants, despite long having paid twice the energy price—perhaps because all the plants were designed by the same people in the same ways with the same equipment; there is little room for behavioral change in a chemical plant.
4. In Dow Chemical Company's Louisiana Division during the period 1981–1993, nearly 1000 projects to save energy and reduce waste added $110 million/year to the bottom line and yielded returns on investment averaging over 200%/year, yet in the latter years, both the returns and the savings were trending upward as the engineers discovered new tricks faster than they used up the old ones. (Economic theory would deny the possibility of so much "low-hanging fruit" that has fallen down and is mushing up around the ankles: such enormous returns, if real, would long ago have been captured. This belief was the main obstacle to engineers' seeking such savings, then persisting after their discovery.)
5. Only about 25–35% of apartment dwellers, when told that their air conditioner and electricity are free, behave as economists would predict—turning on the air conditioner when they feel hot and setting the thermostat at a temperature at which they feel comfortable. The rest of the apartment dwellers show no correlation between air-conditioning usage and comfort; instead, their cooling behavior is determined by at least six other variables: household schedules, folk theories about air conditioners (such as that the thermostat is a valve that makes the cold come out faster), general strategies for dealing with machines, complex belief systems about health and physiology, noise aversion, and wanting white noise to mask outside sounds that might wake the baby. Energy anthropology reveals that both the economic and the engineering models of air-conditioning behavior are not just incomplete but seriously misleading.
6. The United States has misallocated $1 trillion of investments to about 200 million refrigerative tons of air conditioners, and 200 peak GW (two-fifths of total peak load) of power supply to run them, that would not have been bought if the buildings had been optimally designed to produce best comfort at least cost. This seems explicable by the perfectly perverse incentives seen by each of the 20-odd actors in the commercial real-estate value chain, each systematically rewarded for inefficiency and penalized for efficiency.
7. Not just individuals but also most firms, even large and sophisticated ones, routinely fail to make essentially riskless efficiency investments yielding many times their normal business returns: most require energy efficiency investments to yield roughly six times their marginal cost of capital, which typically applies to far riskier investments.

Many economists would posit some unknown error or omission in these descriptions, not in their theories. Indeed, energy engineers and energy economists seem not to agree about what is a hypothesis and what is a fact. Engineers take their facts from tools of physical observation. Three decades of conversations with noted energy economists suggest to the author that most think facts come only from observed flows of dollars, interpreted through indisputable theoretical constructs, and consider any contrary physical observations aberrant. This divergence makes most energy economists suppose that buying energy efficiency faster than the "spontaneous" rate of observed intensity reduction (for 1997–2001, 2.7%/year in the United States, 1.4%/year in the European Union, 1.3%/year worldwide, and 5.3%/year in China) would require considerably higher energy prices, because if greater savings were profitable at today's prices, they would already have been bought; thus the engineers' bottom-up analyses of potential energy savings must be unrealistically high. Economists' estimates of potential savings at current prices are "top-down" and very small, based on historic price elasticities that confine potential interventions to changing prices and savings to modest size and diminishing returns (otherwise the economists' simulation models would inconveniently explode). Engineers retort that high energy prices are not necessary for very large energy savings (because they are so lucrative even at present prices) but are not sufficient either (because higher prices do little without enlarged ability to respond to them).

Of course, engineering-based practitioners agree that human behavior is influenced by price, as well as by convenience, familiarity, fashion, transparency, competing claims on attention, and many other marketing and social-science factors—missing from any purely technological perspective but central to day-to-day fieldwork. The main difference is that they think these obstacles are "market failures" and dominate behavior in buying energy efficiency. Most economists deny this, and say the relatively slow adoption of efficiency must be due to gross errors in the engineers' claims of how large, cheap, and available its potential really is. This theological deadlock underlies the debate about climate protection. Robert Repetto and Duncan Austin showed in 1997 that all mainstream climate-economics models' outputs are hard-wired to the input assumptions, and that realistic inputs, conforming to the actual content of the Kyoto Protocol and its rules, show that climate protection increases GDP. Florentin Krause has shown that the main official U.S. government analyses, taken together, concur. Yet the official U.S. position at the end of 2003 was still that climate protection, even if desirable, cannot be mandated because it is too costly.

In fact, climate protection is not costly but profitable; its critics may have the amount about right, but they got the sign wrong. The clearest proof is in the behavior and achievements of the smart companies that are behaving as if the United States had ratified the Kyoto Protocol, because energy efficiency is cheaper than the energy it saves. For example, large firms such as DuPont, IBM, and STMicroelectronics (ST; one of the world's largest chipmakers) have lately been raising their energy productivity by 6%/year with simple paybacks of a few years. DuPont expects by 2010 to cut its greenhouse gas emissions by 65% below the 1990 level; ST expects to achieve zero emissions (despite making 40 times more chips). British Petroleum announced that its 10% reduction by 2010 had been achieved 8 years early at zero net cost; actually, the 10-year net-present-valued saving was $650 million. Other examples abound; the Web sites www.cool-companies.org and www.pewclimate.org contain examples of the achievements of actively engaged businesses. The companies involved, many of them well known in the business world, are hardly naïve or deluded. Anyone ignoring this market reality is mistaking the econometric rearview mirror for a windshield. Econometrics measures how human populations behaved under past conditions that no longer exist and that it is often a goal of energy policy to change. Where price is the only important explanatory variable, econometrics can be a useful tool for extrapolating history into how price may influence near-term, small, incremental changes in behavior. But limiting our horizons to this cramped view of technical possibilities and human complexity rules out innovations in policies, institutions, preferences, and technologies—treating the future like fate, not choice, and thus making it so.

4. DIMINISHING VS. EXPANDING RETURNS TO INVESTMENTS IN ENERGY EFFICIENCY

Among the most basic, yet simply resolved, economic/engineering disagreements is whether investing in end-use efficiency yields expanding or diminishing returns. Economic theory says diminishing: the more efficiency we buy, the more steeply the marginal cost of the next increment of savings rises, until it becomes too expensive (Fig. 2). But engineering practice often says expanding: big savings can cost less than small or no savings (Fig. 3) if the engineering is done unconventionally but properly.

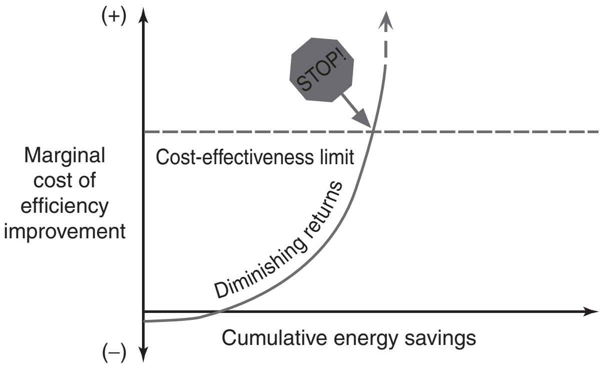

FIGURE 2 Diminishing returns (greater energy savings incur greater marginal cost) can be true for some (not all) components, but need not be true for most systems.

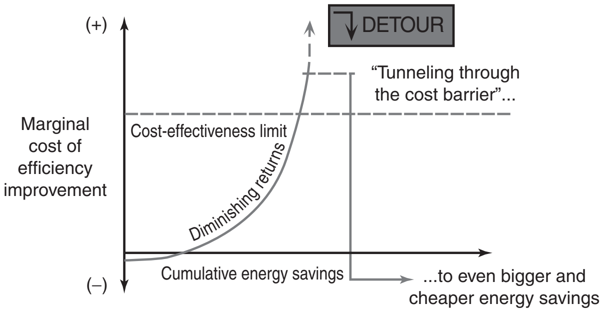

FIGURE 3 Optimizing whole systems for multiple benefits, rather than isolated components for single benefits, can often "tunnel through the cost barrier" directly to the lower-right-corner destination, making very large energy savings cost less than small or no savings. This has been empirically demonstrated in a wide range of technical systems.

4.1 Empirical Examples

Consider, for example, how much thermal insulation should surround a house in a cold climate. Conventional design specifies just the amount of insulation that will repay its marginal cost out of the present value of the saved marginal energy. But this is methodologically wrong, because the comparison omits the capital cost of the heating system: furnace, ducts, fans, pipes, pumps, wires, controls, and fuel source. The author's house illustrates that in outdoor temperatures down to –44°C, it is feasible to grow bananas (28 crops at this writing) at 2200 m elevation in the Rocky Mountains with no heating system, yet with reduced construction cost, because the superwindows, superinsulation, air-to-air heat exchangers, and other investments needed to eliminate the heating system cost less to install than the heating system would have cost to install. The resulting ~99% reduction in heating energy cost is an extra benefit.

Similarly, Pacific Gas and Electric Company's Advanced Customer Technology Test for Maximum Energy Efficiency (ACT^2) demonstrated in seven new and old buildings that the "supply curve" of energy efficiency generally bent downward, as shown schematically in Fig. 3. For example, an ordinary-looking new tract house was designed to save 82% of the energy allowed by the strictest U.S. standard of the time (1992 California Title 24); if this design were widely implemented rather than restricted to a single experiment, it was estimated by PG&E that it would cost about $1800 less than normal to build and $1600 less (in present value) to maintain. It provided comfort with no cooling system in a climate that can reach 45°C; a similar house later did the same in a 46°C-peak climate. Another example, the 350-m^2 Bangkok home of architecture professor Suntoorn Boonyatikarn, provided normal comfort, with 10% the normal air-conditioning capacity, at no extra construction cost. These examples illustrate how optimizing a house as a system rather than optimizing a component in isolation, and optimizing for life-cycle cost (capital plus operating cost, and preferably also maintenance cost), can make a superefficient house cheaper to build, not just to run, by eliminating costly heating and cooling systems. Similarly, a retrofit design for a 19,000-m^2 curtainwall office building near Chicago found 75% energy-saving potential at no more cost than the normal 20-year renovation that saves nothing, because the $200,000 capital saving from making the cooling system four times smaller (yet four times more efficient), rather than renovating the big old system, would pay for the other improvements.

In a striking industrial example, a pumping loop for heat transfer originally designed to use 70.8 kW of pumping power was redesigned to use 5.3 kW, 92% less, with lower capital cost and better performance. No new technologies were used, but only two changes in the design mentality:

1. Use big pipes and small pumps rather than small pipes and big pumps. The friction in a pipe falls as nearly the fifth power (roughly –4.84) of its diameter. Engineers normally make the pipe just fat enough to repay its greater cost from the saved pumping energy. This calculation improperly omits the capital cost of the pumping equipment—the pump, motor, inverter, and electricals that must overcome the pipe friction. Yet the size and roughly the cost of that equipment will fall as nearly the fifth power of pipe diameter, while the cost of the fatter pipe will rise as only about the second power of

diameter. Thus conventionally optimizing the pipe as an isolated component actually pessimizes the system! Optimizing the whole system together will clearly yield fat pipes and tiny pumps, so total capital cost falls slightly and operating cost falls dramatically.

2. Lay out the pipes first, then the equipment. Normal practice is the opposite, so the connected equipment is typically far apart, obstructed by other objects, at the wrong height, and facing the wrong way. The resulting pipes have about three to six times as much friction as they would have with a straight shot, to the delight of the pipefitters, who are paid by the hour, who mark up a profit on the extra pipes and fittings, and who do not pay for the extra electricity or equipment sizing. But the owner would do better to have short, straight pipes than long, crooked pipes.

Together, these two design changes cut the measured pumping power by 12-fold, with lower capital cost and better performance. They also saved 70 kW of heat loss with a 2-month payback, because it was easier to insulate short, straight pipes. In hindsight, however, the design was still suboptimal, because it omitted seven additional benefits: less space, weight, and noise; better maintenance access; lower maintenance cost; higher reliability and uptime; and longer life (because the removed pipe elbows will not be eroded by fluid turning the corner). Properly counting these seven benefits would have saved not 92% but nearer 98% of the energy, and cost even less, so about a factor-four potential saving was left uncaptured.

Other recent design examples include a 97% reduction in air-conditioning energy for a California office retrofit, with attractive returns and better comfort; lighting retrofit savings upward of 90% with better visibility and a 1- to 2-year payback; an energy cost reduction >40% with a 3-year payback in retrofitting an already very efficient oil refinery; ~75% electrical savings in a new chemical plant, with ~10% lower construction time and cost; ~89% in a new data center at lower cost; and ~70–90% in a new supermarket at probably lower cost. The obvious lesson is that optimizing whole systems for multiple benefits, not just components for single benefits, typically boosts end-use efficiency by roughly an order of magnitude at negative marginal cost. These enormous savings have not been widely noticed or captured because of deficient engineering pedagogy and practice. Whole-system design integration is not rocket science; rather, it rediscovers the forgotten tradition of Victorian system engineering, before designers became so specialized that they lost sight of how components fit together.

It is not even generally true, as economic theory supposes, that greater end-use efficiency costs more at the level of components. For example, the most common type of industrial motor on the 1996 U.S. market, the 1800-revolution per minute (rpm) totally enclosed fan-cooled (TEFC) motor (National Electrical Manufacturers' Association Design B), exhibited no empirical correlation whatever between efficiency and price up to at least 225 kW. (Premium-efficiency motors should cost more to build because they contain more and better copper and iron, but they are not priced that way.) The same is true for most industrial pumps and rooftop chillers, Swedish refrigerators, American televisions, and many other products. But even if it were true, artfully combining components into systems can definitely yield expanding returns.

Perhaps the most consequential example is in light vehicles. A small private company (see its Web site at www.hypercar.com) completed in 2000 the manufacturable, production-costed virtual design of a midsize sport utility vehicle (SUV) concept car that is uncompromised, cost-competitive, zero emission, and quintupled efficiency. It is so efficient (2.38 liters/100 km, 42 km/liter, 99 mpg, U.S. gallons) not just because its direct-hydrogen fuel cell is about twice as efficient as a gasoline-fueled Otto engine, but also because it is so lightweight (but crashworthy) and so low in aerodynamic drag and rolling resistance that it can cruise at highway speed on no more power to the wheels than a conventional SUV uses on a hot day just for air conditioning. This design suggests that cars, too, can "tunnel through the cost barrier," achieving astonishing fuel economy at no extra cost and with many other customer and manufacturing advantages. With aggressive licensing of existing intellectual property, such vehicles could start ramping up production as early as 2008. All major automakers have parallel development programs underway, totaling ~$10 billion of commitments through 2000, since the basic concept was put into the public domain in 1993 to maximize competition.

A full U.S. fleet of such light vehicles of various shapes and sizes would save about as much oil as Saudi Arabia produces (~8 million bbl/day); a global fleet would save as much oil as OPEC sells. Moreover, such vehicles can be designed to plug into the grid when parked (which the average car is ~96% of the time), acting as a power station on wheels, selling back enough electricity and ancillary services to repay most of its cost. A U.S. fleet of light vehicles doing this would have ~5–10 times as much electric generating capacity as all power companies now own. This is part of a wider strategy that combines hydrogen-ready vehicles with integrated deployment of fuel cells in stationary and mobile applications to make the transition to a climate-safe hydrogen economy profitable at each step, starting now (beginning with ultrareliable combined heat and power in buildings). The resulting displacement of power plants, oil-fueled vehicles, and fossil-fueled boilers and furnaces could decrease net consumption of natural gas, could save about $1 trillion of global vehicle fueling investment over the next 40 years (compared with gasoline-system investment), and could profitably displace up to two-thirds of CO_2 emissions. It could also raise the value of hydrocarbon reserves, in which hydrogen is typically worth more without than with the carbon. It is favored by many leading energy and car companies today, and it is not too far off: over two-thirds of the fossil fuel atoms burned in the world today are already hydrogen, and global hydrogen production (~50 MT/year), if diverted from its present uses, could fuel an entire fleet of superefficient U.S. highway vehicles.

4.2 The Right Steps in the Right Order

Breakthrough energy efficiency results need not just the right technologies but also their application in the right sequence. For example, most practitioners designing lighting retrofits start with more efficient luminaires, improving optics, lamps, and ballasts. But for optimal energy and capital savings, that should be step six, not step one. First come improving the quality of the visual task, optimizing the geometry and cavity reflectance of the space, optimizing lighting quality and quantity, and harvesting daylight. Then, after the luminaire improvements, come better controls, maintenance, management, and training. Likewise, to deliver thermal comfort in a hot climate, most engineers retrofit a more efficient and perhaps variable-speed chiller, variable-speed supply fans, etc. But these should all be step five. The previous four steps are to expand the comfort range (by exploiting such variables as radiant temperature, turbulent air movement, and ventilative chairs); reduce unwanted heat gains within or into the space; exploit passive cooling (ventilative, radiative, ground coupling); and, if needed, harness nonrefrigerative alternative cooling (evaporative, desiccant, absorption, and hybrids of these). These preliminary steps can generally eliminate refrigerative cooling. If refrigerative cooling is still nonetheless desired, it can be made superefficient (e.g., system coefficient of performance 8.6 measured in Singapore), then supplemented by better controls and by coolth storage. Yet most designers pursue these seven steps in reverse order, worst buys first, so they save less energy, pay higher capital costs, yet achieve worse comfort and greater complexity.

Whole-system engineering optimizes for many benefits. There are, for example, 10 benefits of superwindows and 18 benefits of premium-efficiency motors or dimmable electronic lighting ballasts, not just the one benefit normally counted. (The arch that holds up the middle of the author's house has 12 different functions but is paid for only once.) Superwindows cost more per window, but typically make the building cost less because they downsize or eliminate space-conditioning equipment. Similarly, 35 retrofits to a typical industrial motor system, properly counting multiple benefits, can typically save about half its energy (not counting the larger and cheaper savings that should first be captured further downstream, e.g., in pumps and pipes) with a 16-month simple payback against a 5¢/kWh tariff. The saving is so cheap because buying the correct seven improvements first yields 28 more as free by-products. Such motor-system savings alone, if fully implemented, could save about 30% of all electricity worldwide. Such design requires a diverse background, deep curiosity, often a transdisciplinary design team, and meticulous attention to detail. Whole-system design is not what any engineering school appears to be teaching, nor what most customers currently expect, request, reward, or receive. But it represents a key part of the "overhang" of practical, profitable, unbought energy efficiency absent from virtually all official studies so far.

5. MARKET FAILURES AND BUSINESS OPPORTUNITIES

In a typical U.S. office, using one-size-fatter wire to power overhead lights would pay for itself within 20 weeks. Why is that not done? There are several answers: (1) The wire size is specified by the low-bid electrician, who was told to "meet code," and the wire-size table in the National Electrical Code is meant to prevent fires, not to save money. Saving money by optimizing resistive losses requires wire about twice as fat. (2) The office owner or occupant will buy the electricity, but the electrician bought the wire. An electrician altruistic enough to buy fatter wire is not the low bidder and does not win the job. Correcting this specific market failure requires attention both to the split incentive and to the misinterpretation of a life-safety regulation as an economic optimum. This microexample illustrates the range and depth of market failures that any skilled practitioner of energy efficiency encounters daily. A 1997 compendium, *Climate: Making Sense and Making Money*, organizes 60–80 such market failures into eight categories and illustrates the business opportunity each can be turned into. Some arise in public policy, some are at the level of the firm, and some are in individuals' heads. Most are glaringly perverse. For example, in all but two states in the United States, regulated distribution utilities are rewarded for selling more energy and penalized for cutting customers' bills, so naturally they are unenthusiastic about energy efficiency that would hurt their shareholders. Nearly all architects and engineers, too, are paid for what they spend, not for what they save; "performance-based fees" have been shown to yield superior design, but are rarely used. Most firms set discounted-cashflow targets for their financial returns, yet tell their operating engineers to use a simple-payback screen for energy-saving investments (typically less than 2 years), and the disconnect between these two metrics causes and conceals huge misallocations of capital. When markets and bidding systems are established to augment or replace traditional regulation of energy supply industries, negawatts (saved watts) are rarely allowed to compete against megawatts.

In short, scores of market failures—well understood but widely ignored—cause available and profitable energy efficiency to get only a small fraction of the investment it merits. Thus most of the capital invested in the energy system is being misallocated. The most effective remedy would be to put systematic "barrier-busting" atop the policy agenda, turning obstacles into opportunities and stumbling-blocks into stepping-stones, so market mechanisms could work properly, as economic theory correctly prescribes.

Using energy in a way that saves money is not only a perquisite of the rich, it is also arguably the most powerful key to global economic development for the poor. Using quintupled-efficiency compact fluorescent lamps in Bombay or installing superwindows in Bangkok takes about a thousand times less capital compared to expanding the supply of electricity to produce the same light and comfort via inefficient lamps and office/retail air conditioners. The efficiency investment is also repaid about 10 times faster. The resulting ~10,000-fold decrease in capital requirements could turn the power sector, which now uses about one-fourth of global development capital, into a net exporter of capital to fund other development needs. This is also true at the microscale of a rural village: a package of photovoltaics and superefficient end-use devices (lamps, pumps, mobile phone, water purification, vaccine refrigerator, etc.), with normal utility financing and no subsidy, often incurs debt service lower than what the villagers were already paying for lighting kerosene, candles, and radio batteries, so they have a positive cash flow from day one. Conversely, when Chinese authorities imported many assembly lines to make refrigerators more accessible, the saturation of refrigerators in Beijing households rose from 2 to 62% in 6 years, but the refrigerators' inefficient design created unintended shortages of power and of capital to generate it (an extra half-billion dollars' worth). A Chinese Cabinet member said this error must not be repeated: energy and resource efficiency must be the cornerstone of the development process. Otherwise, resource waste will require supply-side investment of the capital meant to buy the devices that were supposed to use those resources. This realization contributed to China's emphasis on energy efficiency (halving primary energy/GDP elasticity in the 1980s and nearly re-halving it since), laying the groundwork for the dramatic 1996 initial shift from coal to gas, renewables, and efficiency. This greatest contribution of any nation so far to reducing carbon emissions was a by-product of two other domestic goals: eliminating the bottleneck in China's development and improving public health.

6. *OLD AND NEW WAYS TO ACCELERATE ENERGY EFFICIENCY*

6.1 Old but Good Methods

In the 1980s and 1990s, practitioners and policymakers greatly expanded their tool kits for implementing energy efficiency. During the period 1973–1986, the United States doubled its new-car efficiency, and from 1977 to 1985, cut its oil use 4.8%/year. From 1983 to 1985, 10 million people served by Southern California Edison Company were cutting the decade-ahead forecast of peak load by

$8\frac{1}{2}$%/year, at ~1% of the long-run marginal cost of supply. In 1990, New England Electric System signed up 90% of a pilot market for small-business retrofits in 2 months. In the same year, Pacific Gas and Electric Company (PG&E) marketers captured a fourth of the new commercial construction market for design improvements in 3 months, so in 1991, PG&E raised the target, and got it all in the first 9 days of January.

Such impressive achievements resulted from nearly two decades of refinement of program structures and marketing methods. At first, utilities and governments wanting to help customers save energy offered general, then targeted, information, and sometimes loans or grants. Demonstration programs proved feasibility and streamlined delivery. Standards knocked the worst equipment off the market. (Congress did this for household appliances without a single dissenting vote, because so many appliances are bought by landlords, developers, or public housing authorities—a manifest split incentive with the householders who will later pay the energy bills.) Refrigerator standards alone cut electricity usage by new U.S. units by fourfold from 1975 to 2001 (5%/year), saving 40 GW of electric supply. In Canada, labeling initially did nearly as well. Utilities began to offer rebates—targeted, then generic—to customers, then to other value-chain participants, for adopting energy-saving equipment, or scrapping inefficient equipment, or both. Some rebate structures proved potent, such as paying a shop assistant a bonus for selling an energy-efficient refrigerator but nothing for selling an inefficient one. So did leasing (20¢ per compact fluorescent lamp per month, so that it is paid for over time), paying for better design, and rewarding buyers for beating minimum standards. Energy-saving companies, independent or utility owned, provided turnkey design and installation to reduce hassle. Sweden aggregated technology procurement to offer "golden carrot" rewards to manufacturers bringing innovations to market; once these new products were introduced, competition quickly eliminated their modest price premia. These engineered-service/delivery models worked well, often spectacularly well. Steve Nadel's 1990 review of 237 programs at 38 U.S. utilities found many costing <1¢/kWh (1988 dollars). From 1991 to 1994, the entire demand-side management portfolio of California's three major investor-owned utilities saved electricity at an average program cost that fell from about 2.8 to 1.9 current ¢/kWh (1.2¢ for the cheapest), saving society over $2 billion more than the program cost.

6.2 New and Better Methods

Since the late 1980s, another model has been emerging that promises even better results: not just marketing negawatts (saved watts), maximizing how many customers save and how much, but making markets in negawatts, i.e., also maximizing competition in who saves and how, so as to drive quantity and quality up and cost down. Competitive bidding processes let saved and produced energy compete fairly. Savings can be made fungible in time and space; transferred between customers, utilities, and jurisdictions; and procured by "bounty hunters." Spot, futures, and options markets can be expanded from just megawatts to embrace negawatts too, permitting arbitrage between them. Property owners can commit never to use more than *x* MW, then trade those commitments in a secondary market that values reduced demand and reduced uncertainty of demand. Efficiency can be cross-marketed between electric and gas distributors, each rewarded for saving either form of energy. Revenue-neutral "feebates" for connecting new buildings to public energy supplies (fees for inefficiency, rebates for efficiency) can reward continuous improvement. Standardized measurement and reporting of energy savings allow savings to be aggregated and securitized like home mortgages, sold promptly into liquid secondary markets, and hence financed easily and cheaply (see the Web site of the nonprofit International Performance Measurement and Verification Protocol, Inc., www.ipmvp.org). Efficiency techniques can be conveniently bundled and translated to "vernacular" forms, which are easily chosen, purchased, and installed. Novel real-estate value propositions emerge from integrating efficiency with on-site renewable supply (part of the revolutionary shift now underway to distributed resources) so as to eliminate all wires and pipes, the trenches carrying them, and the remote infrastructure to which they connect. Performance-based design fees, targeted mass retrofits, greater purchasing aggregation, and systematic barrier busting all show immense promise. Aggressively scrapping inefficient devices, paying bounties to destroy them instead of reselling them, could both solve many domestic problems (e.g., oil, air, and climate in the case of inefficient vehicles) and boost global development by reversing "negative technology transfer."

Altogether, the conventional agendas for promoting energy efficiency—prices and taxes, plus regulation or deregulation—ignore nearly all the most effective, attractive, transideological, and quickly spreadable methods. And they ignore many of the new marketing "hooks" just starting to be exploited: security (national, community, and individual), economic development and balance of trade, protection from disruptive price volatility, avoiding costly supply overshoot, profitable integration and bundling with renewables, and expressing individual values. Consider, for example, a good compact fluorescent lamp. It emits the same light as an incandescent lamp but uses four to five times less electricity and lasts 8–13 times longer, saving tens of dollars more than it costs. It avoids putting a ton of carbon dioxide and other pollutants into the air. But it does far more. In suitable numbers (half a billion are made each year), it can cut by a fifth the evening peak load that causes blackouts in overloaded Mumbai, it can boost profits of poor American chicken farmers by a fourth, or it can raise the household disposable cash income of destitute Haitians by up to a third. As mentioned previously, making the lamp requires 99.97% less capital than does expanding the supply of electricity, thus freeing investment for other tasks. The lamp cuts power needs to levels that make solar-generated power affordable, so girls in rural huts can learn to read at night, advancing the role of women. One light bulb does all that. It can be bought at the supermarket and self-installed. One light bulb at a time, the world can be made safer. "In short," concludes Jørgen Nørgård, by pursuing the entire efficiency potential systematically and comprehensively, "it is possible in the course of half a century to offer everybody on Earth a joyful and materially decent life with a per capita energy consumption of only a small fraction of today's consumption in the industrialized countries."

6.3 Deemphasizing Traditionally Narrow Price-Centric Perspectives

The burgeoning opportunities for adoption of energy efficiency approaches suggest that price may well become the least important barrier. Price remains important and should be correct, but is only one of many ways to get attention and influence choice; ability to respond to price can be far more important. End-use efficiency may increasingly be marketed and bought mainly for its qualitatively improved services, just as distributed and renewable supply-side resources may be marketed and bought mainly for their distributed benefits. Outcomes would then become decreasingly predictable from economic experience or using economic tools. Meanwhile, disruptive technologies and integrative design methods are clearly inducing dramatic shifts of, not just along, demand curves, and are even making them less relevant by driving customer choice through nonprice variables. Ultralight cars, for example, would do a complete end run around two decades of trench warfare in the U.S. Congress (raising efficiency standards vs. gasoline taxes). They would also defy the industry's standard assumption that efficient cars must trade off other desirable attributes (size, performance, price, safety), requiring government intervention to induce customers to buy the compromised vehicles. If advanced cars can achieve not incremental but fivefold fuel savings as a by-product of breakthrough design integration, yet remain uncompromised and competitively priced, then the energy-price-driven paradigm becomes irrelevant. People will prefer such vehicles because they are better, not because they are clean and efficient, much as most people now buy digital media rather than vinyl phonograph records: they are simply a superior product that redefines market expectations. This implies a world in which fuel price and regulation become far less influential than today, displaced by imaginative, holistic, integrative engineering and marketing. In the world of consumer electronics—ever better, faster, smaller, cheaper—that world is already upon us. In the wider world of energy efficiency, the master key to so many of the world's most vexing problems, it is coming rapidly over the horizon. We need only understand it and do it.

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