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Least-Cost Climatic Stabilization

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This paper is a 31 July 1991 revision of a version originally prepared 15 October 1990 for the Mitchell Prize competition. That earlier version is also to be published in the *Proceedings* of the November 1990 IBM/Japan (Gotemba) and of the December 1990 Dahlem Conference (Berlin) global-warming symposia, and a further revision will appear in 1992 in book form. The research and logistical support of the RMI staff, especially Rick Heede and Catherine Henze, valuable comments by Robert Socolow and Howard Geller, and the essential contributions of many colleagues around the world are gratefully acknowledged.

Introduction: stabilizing global climate saves money

The threat of serious, unpredictable, and probably irreversible changes in the earth's climate has moved from conjecture to suspicion to near-certainty (IPCC 1990). Denial is now confined to the uninformed (Brookes 1989). Yet the threat's cause continues to be widely misunderstood even by many experts on its mechanisms.

Global warming is not a natural result of normal, optimal economic activity. Rather, it is an artifact of the economically inefficient use of resources, especially energy. Advanced technologies for resource efficiency, and proven ways to implement them, can now support present or greatly expanded worldwide economic activity while stabilizing global climate *and saving money*. New resource-saving techniques -- chiefly in energy, farming, and forestry -- generally work better *and cost less* than present methods that destabilize the earth's climate.

In short, even based on energy-efficiency assessments by such organizations as the Electric Power Research Institute (the utility industry's think-tank) and leading U.S. National Laboratories, most of the best ways known today to abate climatic change ("stabilize" the climate) are

- *not costly but profitable;*
- *not hostile but vital to global equity, development, prosperity, and security; and*
- *reliant not on dirigiste regulatory intervention but on the intelligent application of market forces.*

Newer analyses summarized here reveal even bigger and cheaper energy-saving potential, as well as innovative ways to abate other sources of global warming at unexpectedly low costs. These findings imply that most global warming can be abated not at roughly zero net cost, as two government-sponsored analyses have recently found, but at *negative* net cost -- without ascribing any value to the abatement itself.

However, technical and implementation options, obstacles, and strategies vary widely with culture and geography. This paper therefore identifies opportunities to use resources more efficiently, describes concrete successes in capturing those opportunities, and outlines an agenda for systematically harnessing them. This is discussed for three main types of societies: the industrialized OECD countries, the USSR and its former satellites, and developing countries. The discussion highlights needed interactions (*e.g.*, issues of trade, technology transfer, and emulation) and possible synergisms between these three regions.

Major abatement terms

Over a century's time horizon, about half of global warming in the 1980s[1] was caused (IPCC 1990) by burning fossil fuel, which produces carbon dioxide (CO_2) and monoxide (CO), nitrous oxide (N_2O), fugitive methane (CH_4), and ozone (O_3). Another one-fourth or more was driven by unsustainable farming and forestry practices, which produce biotic CO_2 and CH_4 and nitrogen-cycle N_2O. Virtually all the rest was driven by the release of halons and chlorofluorocarbons (CFCs), whose production (but not use) will be phased out during the 1990s to protect the stratospheric ozone layer. Among the ~57% of current worldwide contributions to global warming estimated by EPA to arise directly from energy use (1989, p. VII-28), 20% is ascribed to transportation, 22% to industry, and 15% to buildings. The sizeable uncertainties in all these figures are immaterial for the purposes of this paper, since, as will be shown, major abatements are available and cost-effective for each gas and in each application.

Stabilizing atmospheric concentrations of heat-trapping gases at current levels will require that their present rates of emission be reduced by different amounts, because different gases remain in the air for different periods and react to form different products. These reductions are believed (IPCC 1990) to be more than 60%[2] for CO_2, 15-20% for CH_4, 70-80% for N_2O, 70-85% for the most important CFCs[3], and 40-50% for HCFC-22. These required reductions, too, are not as interchangeable in practice as they might seem mathematically (Krause *et al.* 1989, Ch. 2). Yet reductions generally larger than these -- large enough to return the atmosphere to a composition likely to entail no climatic change (*id.*) -- will be shown below to be very cheap, free, or better than free.[4]

Specifically, this paper will show that demonstrated technologies and implementation methods can

- save most of the fossil fuel now burned, at a cost below that of the fuel itself, making the abatement cost less than zero;
- change soil from a carbon source to a carbon sink (and incidentally reduce related emissions of CH_4 and N_2O too) at a net cost around zero or less; and
- displace CFCs (and often their proposed hydrohalocarbon substitutes) at a net cost close to zero -- though this cost is irrelevant, since the substitution is already required by international treaty to abate stratospheric ozone depletion.

The cost of the main global-warming abatements therefore ranges, broadly speaking, from strongly negative to roughly zero to irrelevant -- with policy implications discussed in the Conclusions.

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[1]Counting contributions by gases projected to be released in 2025 rather than in the 1980s (IPCC 1990a, Figs. 2 & 3), or integrating their effects over a longer period (Lashof & Ahuja 1990), would strengthen this paper's conclusions, which are most detailed for energy efficiency. These conclusions hold independently of such assumptions, since they rest on the demonstrated potential to reduce dramatically *all three* source terms (energy, agroforestry, and CFCs).

[2]Simulations suggest 50-80% (EPA 1989).

[3]EPA (1989) gives 75-100% for CFC-11 and -12.

[4]This paper does not consider several recently proposed innovations that could allegedly capture and sequester CO_2 from electric generation and other combustion processes at relatively low costs (Hendriks *et al.* 1990, Wolsky & Brooks 1989). If such processes turn out to work, that is "icing on the cake." Early data suggest, however, that these processes, while probably cheaper than global warming, abate CO_2 at a cost several to many times that of the proven energy-efficiency options described below.

Technological and economic options

Methodological note

Throughout this paper, unless otherwise noted, costs of saved energy are expressed in 1986 U.S. dollars, levelized at a 5%/y real discount rate using the Lawrence Berkeley Laboratory methodology (Lovins 1988, pp. 11ff; Lovins & Sardinsky 1988, "Conventions"), whereby the marginal cost of buying, installing, and maintaining the efficient device is divided by its discounted stream of lifetime energy savings. Specifically, the levelized cost ($) of saving, say, 1 kW-h equals $Ci/S[1-(1+i)^{-n})]$, where C is installed capital cost ($), i is the annual real discount rate (in this case 0.05), S is the energy saved by the device (kW-h/y), and n is its operating life (y). Thus a $10 device which saved 100 kW-h/y and lasted 20 y would have a cost of saved energy of 0.80¢/kW-h. Against a 5¢/kW-h electricity price, a 20-y device with a one-year simple payback saves energy at a cost of 0.4¢/kW-h. Similar accounting is used for the cost of saving direct fuel. Cost of saved energy is methodologically equivalent to cost of supplied energy (*e.g.*, from a power plant): the price of the energy saved is not part of the calculation, and whether the saving is cost-effective depends on comparing the cost of achieving it with the avoided cost of the energy saved.

The installed capital cost C is marginal cost for devices installed in the course of new construction or routine replacement -- usually assumed for devices, like household appliances or commercial chillers, that are normally replaced anyhow every 10-20 years and can simply be replaced by better models. C is total cost for immediate retrofit -- usually assumed for options whose life is relatively short, like lights or motors, or many decades, like building shells. Unless otherwise noted, *costs and savings used in this paper are empirical,* based on purchasing and operating conditions typical of the application described. Financing costs are not normally included (because devices with paybacks of about a year, like most of those described, should normally be expensed rather than capitalized), but could be with a minor effect on the results.

If the new device has a different lifetime, required population, or maintenance cost than the original device, then C is corrected for the change in present-valued capital and operating cost to achieve the same cycle life. In some cases -- as with the compact fluorescent lamp mentioned below, which lasts ~13x as long as the incandescent lamp it replaces -- the saved present-valued maintenance cost can exceed the total cost of the device, resulting in a negative value for both C and the cost of saved energy. Naturally, this means that the present-valued dollar cost of the efficient device (lifetime kW-h saving times ¢/kW-h cost of that saving) is negative and can be used to offset the positive costs of other kinds of savings.

In general, this paper does not explicitly count the transaction costs of implementing the technologies described, since these are highly sensitive to implementation methods and marketing skill. In mature utility programs, however, transaction costs (program design, marketing, physical delivery, monitoring, evaluation, research, regulatory support, etc.) are very small. For example, Southern California Edison Company in ~1983-85 reported total transaction costs totalling hundredths of a cent per kW-h.[5]

This paper does not try to assess the macroeconomic consequences of energy efficiency (nor, similarly, of other global warming abatements such as changes in farming and forestry practices). In general, saving energy and

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[5]Details are in (Lovins 1988, pp. 105-106). The 1984 transaction costs reported to the California PUC (SCE 1985) were of two kinds. Those directly allocated to programs included outreach, research, evaluation, and technical and regulatory support; levelized over the annualized savings during an assumed 20-y average measure life, they cost 0.0051¢/kW-h in the commercial, industrial, and agricultural sectors and 0.039¢/kW-h in the residential sector, or respectively 3.5% and 2.0% of direct program costs. In addition, general demand-side overheads for administration, public awareness and education, advertising, measurement, and evaluation -- reduced 25% *pro rata* on the direct-cost share of non-efficiency programs (solar, independent power production, and load management) -- cost 0.026¢/kW-h. These latter costs may have been partly or wholly offset by the avoidance of similar costs to support the supply-side resources displaced. As noted by Nadel (1990), however, transaction costs can be one or two orders of magnitude higher in less mature or less well-designed programs, especially those on a small scale, in startup, or with heavy residential emphasis.

capital should lower their prices and hence increase the net dollar saving to society. At the levels of savings described here, this indirect benefit might exceed the direct dollar savings. The cheaper energy and capital would also be expected to boost economic output, and this too would conventionally be considered a benefit. Whether the increased output in turn decreased the net energy savings would depend on the composition of the marginal output, and on whether, for example, people used their extra income to buy snowmobiles and motorboats, symphony tickets, or additional energy-saving measures. Such differences between the engineering-economics approach used here and the econometric approach are discussed elsewhere (Evans *et al.* 1991, Cherfas 1991, Lovins 1991, 1991a); perhaps the most important difference is that econometric models generally omit any potential for negative-cost savings (*i.e.*, saving fuel more cheaply than buying and burning it) because, in the economic paradigm, such cost-effective savings are assumed to have been achieved already.

Energy efficiency

Removing a 75-watt incandescent lamp and screwing into the same socket a 15-watt compact fluorescent lamp[6] will provide the same amount of light for 13 times as long, yet save enough coal-fired electricity over its lifetime to keep about a ton[7] of CO_2 out of the air (plus 8 kg of SO_x and various other pollutants). If the quintupled-efficiency lamp saves oil-fired electricity, as it would in many developing countries, it can save more than enough oil to drive a standard 20-mi/gal car for a thousand miles, or to drive the most efficient prototype car across the United States and back. If it saves nuclear electricity, it avoids making a half-curie of long-lived wastes and two-fifths of a ton-TNT-equivalent of plutonium. Yet far from costing extra, the lamp generates tens of dollars' net wealth -- it saves tens of dollars more than it costs -- because it displaces replacement lamps, installation labor, and utility fuel. It also defers hundreds of dollars' utility investment (Lovins 1990).[8]

This is an example -- one of the costlier ones that could be given -- of the proposition that today *it is generally cheaper to save than to burn fuel.* The CO_2 and the other pollution avoided by substituting efficiency for fuel are thus avoided *not at a cost but at a profit.*

Most of the best energy-saving technologies -- especially the superefficient lights, motors, appliances, and other end-use devices that save electricity -- are supplanted by still better models approximately annually.[9] Saving electricity gives the most climatic leverage, because it takes 3-4 units of fuel (in socialist and developing countries, often 5-6 units) to generate and deliver a single unit of electricity, so saving that unit displaces many units of fuel, mainly coal, at the power plant. Power plants burn a third of the world's fuel and emit a third of the resulting CO_2, as well as a third of the NO_x and two-thirds of the SO_x, both of which also contribute to global warming (Krause *et al.* 1989, Ch. 2) -- a little directly, and more by degrading forests and other ecosystems that otherwise store carbon. Electricity is also by far the costliest form of energy[10], so it is the most lucrative kind of energy to save. Saving electricity saves much capital: the U.S. in the mid-1980s spent as much private capital and public subsidy (Heede *et al.* 1985) expanding its electric supply, about \$60 billion per year, as it invested in all durable-goods manufacturing industries. Moreover, a fourth of the world's development capital goes to

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[6]An "integral" model, in which the adapter base, ballast, lamp, and envelope (if any) are a single throwaway unit, may replace a 75-W incandescent lamp with 14-18 W using an electronic or 16-20 W using an electromagnetic ballast. With a reflector-equipped "modular" model, lower wattages (down to ~8 W) may deliver adequately equivalent light in a directional beam.

[7]All tons (t) in this paper are metric; all miles (mi) and gallons (gal) are U.S.; and standard metric prefixes are used ($M = 10^6$, $G = 10^9$, $T = 10^{12}$, $P = 10^{15}$, $E = 10^{18}$), along with mostly metric units (*e.g.*, 1 ha = 2.4 acre).

[8]These calculations (Lovins 1990) assume that each kW-h saved directly by the lamp also saves 0.36 kW-h of net space-conditioning energy, as it would in a typical U.S. commercial-sector building (Lovins & Sardinsky 1988, Shepard *et al.* 1990).

[9]However, this is no reason to wait, as the lass from deferring the benefit usually exceeds the benefit of the new model's often modest incremental improvement.

[10]Average 1989 U.S. retail electricity at 6.44¢/kW-h (1989 \$) is equivalent in heat content to oil at \$110/bbl.

electrification, and about five times as much such capital is projected to be needed in the 1990s as is likely to be available. This ~$80 billion annual shortfall (Churchill 1989, Reddy & Goldemberg 1990) may imperil proposed development. For these reasons, this discussion emphasizes the frequently undervalued opportunities to save electricity.

Electricity

Many utilities still think that only ~10-20% of the electricity used can be cost-effectively saved. However, a recent reassessment by the Electric Power Research Institute found a potential, mainly cost-effective, to save 24-44% of U.S. electricity within this decade, not counting a further 8.6% already expected to occur spontaneously or another 6.5% likely to be saved by utilities' planned efficiency programs (EPRI 1990, Fickett *et al.* 1990). The California Energy Commission has similarly identified a potential to save electricity 2.5%/y faster than projected load growth (CEC 1990, Figs. 3-1 and C-4). As will be shown below, such electrical savings, and analogous non-electrical energy savings, can save enough money to pay for most *non*-energy kinds of global-warming abatement. Most of this electricity-saving potential is untapped: for the non-Communist world during 1973-87, oil intensity fell by 32%, but non-oil intensity by only 1%.

Analyzing technologies even a few years old, however, can make potential savings seem much smaller and costlier than they now are (Lovins 1980). Today's best electricity-saving technologies can save twice as much as five years ago, but at only a third the real cost. Still more detailed assessments[11] of these new opportunities, based on *measured* cost and performance data, thus reveal that full retrofit of U.S. buildings and equipment with today's most efficient commercially available end-use technologies would deliver unchanged or improved services while saving far more electricity, and at far lower cost, than previously supposed. This makes it possible to abate a large fraction of global warming -- enough, it appears, to stabilize the earth's climate (*i.e.*, stop perturbing it) -- at negative net cost.

The modern U.S. electric-efficiency potential, compared to "frozen" 1986 efficiency levels, includes saving

- half of motor-system (or a fourth of total) electricity through 35 motor, control, drivetrain, and electric-supply improvements collectively paying back in ~16 months against 5¢/kW-h electricity (Lovins *et al.* 1989, Fickett *et al.* 1990)[12] -- a key opportunity in reindustrializing countries like the USSR, whose motors already use 61% of all its electricity (Orlov 1988, Makarov *et al.* 1988);
- 80-92% of lighting electricity (or a fourth of total electricity including net space-conditioning effects) at a net cost less than zero, because much of the lighting equipment more than pays for itself by costing less to maintain (Lovins & Sardinsky 1988, Piette *et al.* 1989);
- a sixth of total electricity through numerous design improvements to household appliances, commercial refrigeration and cooking, and office equipment -- where the potential saving exceeds 90% at roughly zero or negative cost (Shepard *et al.* 1990);
- two-thirds of water-heating electricity through eight simple improvements (insulation, high-performance showerheads, etc.) (Lovins 1986);

[11]These are presented chiefly in the COMPETITEK[SM] Hardware Reports cited below. The first three (Lovins & Sardinsky 1988, Lovins *et al.* 1989, Shepard *et al.* 1990) total 1,268 single-spaced pages documented with more than 3,000 notes, chiefly citing primary sources. The findings of the three remaining Hardware Reports are already known in sufficient detail through earlier analyses (*e.g.*, Lovins 1986, 1986a, 1988) and from many other authors' studies, some of the most important of which are cited below.

[12]Improvements to or beyond the machine driven by the motor are not included here, but can often save about half the remaining energy (*e.g.*, Johansson *et al.* 1983, Larson *et al.* 1989a) -- and each unit of energy saved downstream, *e.g.*, by reducing friction in pipes exiting a pump, can save nine units of fuel at the power plant.

- most of the electricity used for space-heating and -cooling, through both mechanical-equipment retrofits and improved building shells[13] -- including "superwindows" that can now insulate 2-4 times as well as triple glazing but cost about the same (Rosenfeld & Hafemeister 1989, Bevington & Rosenfeld 1990, Lovins 1986a & 1988);
- three-fourths of all electricity used in typical U.S. houses and commercial buildings at respective retrofit costs of 1.6¢/kW-h and -0.3¢/kW-h (Lovins 1988);
- about three-fourths of total U.S. electricity at a net cost averaging about 0.6¢/kW-h (**Figure One**) -- several times cheaper than just *operating* a typical coal or nuclear power plant, even if building it cost nothing. Of course, considerably more could be saved at less than long-run marginal cost, which is at least tenfold higher, and higher still when externalities are included.[14]

Two examples -- industrial drivepower (Lovins *et al.* 1989, Nadel *et al.* 1991) and commercial fluorescent lighting (Lovins & Sardinsky 1988) -- illustrate how such large, cheap savings can be achieved by, and only by, whole-system engineering with meticulous attention to detail.

Most analysts emphasize only two drivesystem improvements: high-efficiency induction (asynchronous) motors, and adjustable-speed drives (ASDs) using variable-frequency electronic inverters. The motors gain several percentage points' efficiency by using more and lower-loss materials plus better design and manufacturing. This is worthwhile because a large motor typically consumes electricity worth its entire capital cost every few weeks. Further, the output of many pumps, blowers, and fans is controlled by running them at full speed against a mechanical obstruction. Yet their power consumption varies roughly as the cube of their flow rate, so if only half the full flow were needed, seven-eighths of the full input power (less minor ASD circuit losses) could be saved by removing the obstruction and halving the speed. ASDs' full use could thus save ~20% (EPRI 1990) or ~14-27% (Lovins *et al.* 1989) of all U.S. motor energy, with typical paybacks estimated at ~1 to ~2½ y respectively.

So far so good. But adding 33 further drivesystem improvements -- in the choice, sizing, maintenance, and life of motors, in control systems of three further kinds, and in upstream electrical supplies and downstream mechanical drivetrains -- can at least double the savings from these two measures. It can also cut total retrofit cost by perhaps fivefold (Fickett *et al.* 1990), because of the 35 combined measures, 28 are free by-products of the seven that must be paid for, yielding greater savings at no extra cost.

For example, immediately retrofitting an in-service standard induction motor to a high-efficiency model, without waiting for it to burn out, is commonly assumed to incur an unattractively long (~10-20 y) payback. Yet many U.S. motors are so grossly oversized that probably half never exceed 60%, and a third never exceed 50%, of their rated load. This oversizing often makes actual at-load efficiency lower than the nameplate rating implies, and may enable the replacement motor to be smaller, hence cheaper. Making the new motor the right size reduces the payback of immediate retrofit to ~3 y. Also counting the new motor's longer life (because it runs cooler and has higher-quality bearings) makes the immediate-retrofit cost negative, averaging about -$13/kW.

In addition, the new motor automatically eliminates any increased magnetic losses that may have been caused by improper repair of the old motor. This plus proper motor sizing yields direct electrical savings roughly twice as big as would be expected from the new motor's better nameplate efficiency alone. The high-efficiency motor

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[13] And through lighter-colored paving and building surfaces and smarter landscaping, especially urban forestry: direct shading, evapotranspiration, and reduction in the mesoscale urban "heat island" effect will enable a half-million trees in Sacramento, for example, to save 15 peak MW and 35 GW-h/y in the tenth year of a program costing 2¢/kW-h (SMUD 1990; Akbari *et al.* 1988). In Sacramento, simulations show savings up to 14% in peak and 19% in annual cooling energy just from whitewashing buildings, and up to 35% and 62% from all measures to modify urban albedo (to average values of 40% overall and 90% for houses) (Taha *et al.* 1988).

[14] An exhaustive compilation (Ottinger *et al.* 1990) found that external costs due mainly to SO_x, NO_x, CO_2, and particulate emissions total about 5.8¢ for coal-fired generation, 2.7¢ oil-fired, 1.0¢ gas-fired, and 2.5¢ nuclear, all per busbar kW-h.

also has better power factor and greater harmonic tolerance (hence better ASD operation). Thus it provides a half-dozen important operational advantages -- but need be paid for only once.

Many of these savings, however, depend on others. For example, not only efficiency but also motor life depends on other energy-saving improvements: reducing voltage imbalance between the phases, improving shaft alignment and lubrication practice, reducing overhung loads (sideways pulls) on the shaft (*e.g.*, by substituting toothed, non-stretch, low-tension "synchronous" belts for V-belts), and improving housekeeping -- not siting motors in the sun or next to steam pipes, not smothering them beneath multiple coats of paint, etc. Motor choice, life, sizing, controls, maintenance, and associated electrical and mechanical elements all interact intricately. A few interactions are unfavorable, but most make the savings of the whole drivepower package far larger and cheaper than would appear from considering just a few fragmented measures, as most analyses do.

Or consider commercial fluorescent lighting: say, four 40-W lamps driven by two 16-W electromagnetic ballasts in a ~65%-efficient enclosed luminaire.[15] An imaging specular reflector -- a very shiny, computer-designed, specially shaped piece of sheet-metal -- inserted above the lamps nearly doubles optical efficiency, because each exit ray bounces barely more than once rather than nearly three times, yielding almost the cube of the reflectance benefit. Half the lamps can then be removed, the rest relocated, and approximately the same delivered light obtained as before. (The removed lamps appear to be still there, but they are only virtual images, and virtual lamps require no electricity or maintenance. The avoided maintenance costs end up paying for half the retrofit package.) While being relocated, the lamps can also be replaced with new ones whose "tristimulus" phosphors -- tuned to red, green, and blue retinal cones -- emit up to 18% more light per watt, with more pleasant and accurate color.

The two two-lamp ballasts can then be replaced with one four-lamp high-frequency electronic ballast shared between two adjacent luminaires. The ballast and its control systems save electricity in at least 15 ways. These include lower ballast dissipation and higher lamp output at ~20 kHz than at line frequency (together boosting system lumen/W by >40%); reduced sensitivity to abnormal supply voltage or lampwall temperature (cutting design margins by an eighth); continuous dimming of the lamps to match available daylight (often saving >50% in perimeter zones); brightening the lamps as they dim with age and dirt, so they need not be too bright when young, fresh, and clean in order to provide enough light when old, tired, and dirty (saving a seventh of the energy over each group relamping cycle); and facilitating automatic control by occupancy sensors and timers. Together, these ballast and control mechanisms typically save about half the energy per unit of delivered light in the center of a large building, and 70-80+% in a typical mix of core and perimeter zones. The better lamp phosphors and reflector optics cut W/lux by a further ~15% and ~35+% respectively -- a cumulative total saving of ~83-91%.

Such large savings are not unusual even in awkward cases, because further opportunities are available too: reducing endemic overlighting, concentrating local light on the visual task, making the light more visually effective (*e.g.*, by radial polarizers that reduce veiling glare), using lighter-colored surfaces to bounce light around better, bouncing daylight several times as far into the room (via lightshelves, top-silvered blinds, glass-topped partitions, etc.), and improving maintenance. In all, 70-90+% savings on electricity used for lighting are typically available at a cost of ~0.6¢/kW-h (or twice that if the maintenance costs saved by the customer were ignored), with no reduction in illuminance and with greatly improved lighting quality.

As with motors, however, achieving both such large savings and higher-quality service depends on harnessing complex interactions -- thermal, optical, and electrical -- between all the components. It requires including all

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[15] Surprisingly, starting with three 34-W lamps, two "high-efficiency" electromagnetic ballasts, and a modern louvered parabolic troffer yields the same percentage savings within a few percent, partly because of more favorable thermal interactions within the luminaire. Either way, there are ~1½ billion such fixtures in U.S. service.

the right parts, and combining them into something greater than their sum. This demands not just new technology but also new thinking, and new ways to deliver integrated packages of modern hardware plus managerial and cultural changes.[16] That is not easy; but neither is expanding electric supplies.

Illustrating the power of properly combined packages of technologies, five engineering firms' conceptual designs recently found (ACT[2] 1991) a cost-effective retrofit energy-saving potential of 67-87% in a 1,900-m^2 Pacific Gas & Electric Company research office that was one-third more efficient than a typical U.S. office to start with. One firm found 86% potential retrofit electrical savings, at ~27% of PG&E's long-run marginal supply cost, by combining daylighting, advanced lighting components and controls (delivering 500 lux with 3.1 W/m^2), ~20 W/workstation office equipment, ~0.7 W/m^2K superwindows with spectral response "tuned" to each elevation of the building, and a ~65%-downsized, system-COP->10 mechanical system.

Potential savings appear to be only slightly smaller and costlier in the most efficient countries than in the United States. Detailed studies have found a potential to save half of Swedish electricity at an average cost of 1.3¢/kW-h (Bodlund *et al.* 1989); half the electricity in Danish buildings at 0.6¢/kW-h or three-fourths at 1.3¢/kW-h (Nørgård 1989), and 80% (including fuel-switching) in West German households with a 2.6-year payback (Feist 1987). To be sure, Europeans do (for example) light their offices less intensively, and turn the lights off more, than Americans do, but that does not affect the *percentage* savings available in the lighting energy that *is* used -- a function only of the lighting technology itself, which is quite similar in both places.

Abundant observational evidence confirms that the potential savings in socialist and developing countries (Goldemberg *et al.* 1988) are much larger and (at world equipment prices) cheaper than in OECD. Differences in what electricity is used for between industrialized and developing or capitalist and socialist countries are surprisingly small (*id.*; Reddy & Goldemberg 1990; Lovins 1979), and major savings are available in essentially every significant application. The feasibility of major electric savings is confirmed by comparisons at all scales: the micro-scale of individual technologies (*e.g.*, Shepard *et al.* 1990), sectoral intensities[17], and aggregate intensities.[18] It therefore seems reasonable, and probably conservative, to treat the U.S. values as a surrogate for the global average of potential electrical savings' fractional quantity and average cost.

A recent comparison (Hirst 1991) of the Rocky Mountain Institute (RMI) electric-efficiency supply curve in Figure One with the Electric Power Research Institute's version (Fickett *et al.* 1990) shows substantial similarities (Figure Two). But nearly all the remaining difference is from the EPRI curve's showing a drivepower saving three times smaller and five times costlier than EPRI agreed to in the same article (*id.*), and from methodological differences:

- the EPRI supply curve shows only potential savings *by the year 2000*, *excluding* a further 9-15% saving that EPRI believes will occur by then automatically (through price response, government standards, and present utility programs), while the RMI supply curve shows full long-term savings potential, and
- EPRI excludes but RMI includes credit for maintenance costs saved by customers, so commercial lighting savings cost 1.2¢/kW-h in the EPRI but -1.4¢/kW-h in the RMI supply curve.

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[16]With motors, for example, an important cultural need is to change lubrication from a low-caste, dirty-hands occupation to a high-caste, white-lab-coat occupation.

[17]For example, Kahane (1986) found that in the car, paper, and cement industries, electricity per ton of product was falling in Japan but rising in the U.S.

[18]For example, International Energy Agency statistics show that the Japanese GNP in 1986 was 36% less electricity-intensive than the American, and this gap was projected by those governments to widen to 45% in 2000.

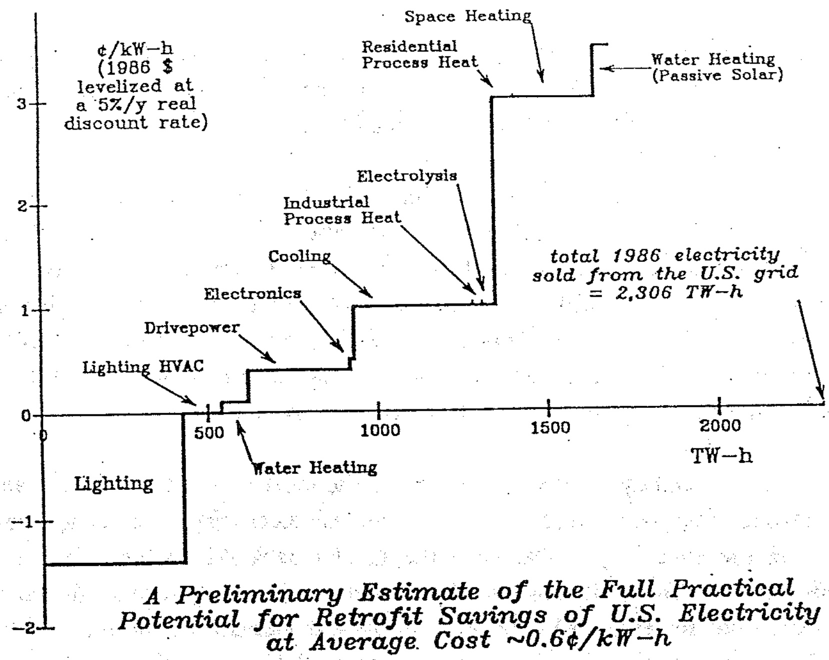

Figure One: Supply curve of the full technical potential to save U.S. electricity by retrofitting the best commercially available 1989 end-use technologies wherever they fit in the 1986 stock of buildings and equipment. The vertical axis is levelized marginal cost (1986 ¢/kW-h delivered, 5%/y real discount rate). Costs are negative if the efficient equipment's saved maintenance costs exceed its installed capital costs. The horizontal axis is cumulative potential saving corrected for interactions. Measured cost and performance data are summarized for about a thousand technologies, condensed into end-use blocks. Fuel-switching, lifestyle changes, load management, further technological progress, and some technical options are excluded. How much of the potential shown is actually captured is a policy variable, but many utilities have in fact captured 70-90+% of particular efficiency markets in a few months or years through skillful marketing, suggesting that most of the potential shown could actually be captured over a few decades. Note that savings totalling around 50% have a net internal average cost of zero, and that new-construction savings would be larger and much cheaper (often negative-cost) than the retrofit savings shown. For comparison, utilities such as Bonneville Power Administration and Wisconsin Power & Light Co. report empirical total costs of 0.5¢/kW-h for saving business customers' electricity. The "electronics" saving has turned out in more recent analyses to be larger and cheaper than shown (Shepard *et al.* 1990, Ch. 6), and the drivepower saving, to be probably twice as large as shown (Lovins *et al.* 1989, Fickett *et al.* 1990), although saving more drivepower energy leaves less cooling energy available to be saved.

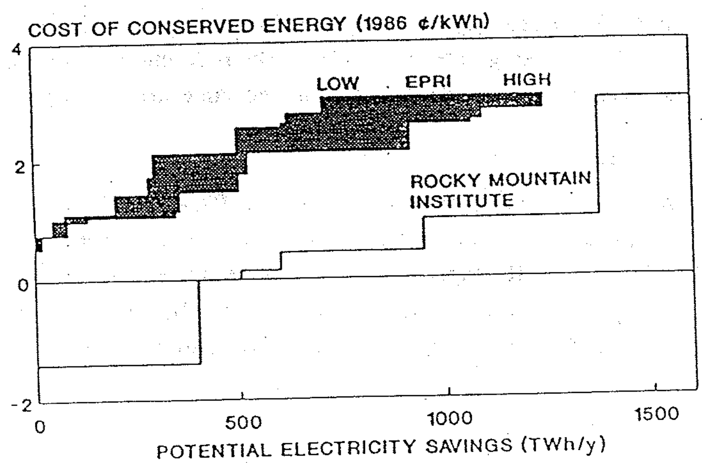

Figure Two: Supply curves for potential U.S. savings of electricity, compared with ~1986-88 frozen efficiencies, from analyses by EPRI (1990) and RMI (Fickett *et al.* 1990). This comparison, slightly modified from Fig. 12 of Hirst (1991), shows EPRI's uncertainty range; the RMI curve is a midcase. Important methodological differences between the two curves are summarized in the following paragraph. The RMI curve is now considered by the author to be technically conservative, and will be updated in early 1992.

Normalizing for these non-substantive differences would make the two curves nearly identical. The remaining differences -- believed to be due to the modernity, thoroughness of characterization, and disaggregation[19] of the measures analyzed -- are less important than the EPRI/RMI consensus that cost-effective potential savings are many times larger than utilities currently plan to capture.

Oil

The potential for saving oil with today's best demonstrated technologies is also large and cheap. Unlike electricity, about half of the needed technologies are not yet on the market, though they could be within a few years. There are large potential savings in transportation (~44% of world oil use), industrial heat (~12%), building heat (~14%), electric generation (~10%), and feedstocks (~14%). The rest of the oil is used or lost in refineries (G. Davis 1990).

Transportation

Personal mobility, the most familiar and pervasive use of oil, accounts for about two-thirds of OECD transportation energy use (EPA 1989, p. VII-37) and offers some of the most dramatic savings. To start with, a US-DOE study (Difiglio *et al.* 1989) describes 15 proven, readily available improvements in car design. These, plus two more equally straightforward ones (Ledbetter & Ross 1990), can maintain average 1987 U.S. new-car size, ride, and acceleration at 33.6 actual mi/gal (7.0 l/100 km). That is 35% less fuel-intensive than the average new 1987 U.S. car. The measures' average cost is 53¢/gal saved (14¢/l). This result is conservative:[20] at least seven attractive cars with actual performance over 42 mi/gal (55 EPA-rated mi/gal), albeit with non-1987-average size or acceleration, are already on the U.S. market. Savings ~72% as large are achievable in light trucks at about half the unit cost (Ledbetter & Ross 1989, Table 10). Contrary to widespread belief, such improvements need not entail downsizing: only 4% of the improvement (by twofold) in new U.S.-made cars' fuel economy during 1976-87 came from making them smaller, while the other 96% came from making them smarter (Patterson 1987).

A further doubling or tripling of car efficiency has been demonstrated by ten automakers[21] whose prototypes have achieved average on-road efficiencies of 67-120 mi/gal (2.0-3.5 l/100 km) -- ~4-6 times the present OECD fleet or ~2½-4 times the low-powered USSR/Eastern European fleet (Chandler *et al.* 1990). The Toyota AXV, for example, carries 4-5 passengers at EPA ratings of 89 mi/gal city and 110 highway, while Renault's 4-passenger Vesta 2 prototype was tested in 1987 at 64 and 138 mi/gal. Two prototypes -- a 71-mpg Volvo and a 92-mpg Peugeot -- should cost about the *same* to mass-produce as ordinarily inefficient cars of comparable size.[22] Thus

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[19]Disaggregation alone -- counting many small savings as well as a few big ones -- can roughly double the quantity of savings.

[20]*E.g.*, a drag coefficient of 0.3 is assumed, but <0.1 is readily achievable and consistent with attractive appearance (0.15 for vans); the Ford Sable and several other models already get 0.3, Renault's Vesta 2 prototype, 0.186, and the experimental Ford Probe V, 0.137. A curb weight of 2,800 lb (1,273 kg), only 12% below the 1991 U.S. average of ~3,180 lb, is also assumed, but is ~2.0-2.7 times as heavy as some 4- to 5-passenger prototypes. Indeed, a U.S. car fleet averaging 2,000 lb and hence 50 mi/gal could be achieved by materials substitution *alone* (Flemings *et al.* 1980); each 200 lb reduction improves fuel economy by ~5% (Bleviss & Walzer 1990).

[21]Ten examples from eight companies are discussed by Bleviss 1988 & 1988a and by Goldemberg *et al.* 1988. More recent varieties reported in the trade press, from Audi, Citroen, GM, Fiat, Honda, Nissan, Volkswagen, and others, support the same conclusions.

[22]This is largely because their ~1200-1555 lb curb weight (~550-707 kg) requires extensive use of plastics and composites, so large, complex assembles can then be molded as a unit and snapped together. Not having to make and assemble many small parts, cheaper tooling, and being better able to design for easier assembly save more money than the more exotic materials cost. The leftover money pays for better aerodynamics, smarter chip controls, etc., and the total net marginal cost is about zero. This negative cost of weight reduction is consistent with consultancy data recently provided to Mark Ledbetter (personal communication, 8 October 1990), and with Chrysler's finding (*Automotive News* 1986) that a largely plastic/composite car could cut a steel car's part count by 75% and plant cost by up to 60%. Earlier incremental calculations (*e.g.*, von Hippel & Levi 1983) of a $500 marginal cost to achieve 71 mpg have therefore proven, as

such radical efficiency improvements appear to be far cheaper than paper studies had predicted by simply extrapolating the cost of far smaller incremental savings. Though each prototype has individual design peculiarities, collectively they prove that cars more than three times as efficient as the world fleet can be at least as comfortable, peppy, safe[23], and low in emissions as today's typical new OECD cars. Comparable opportunities apply also to light trucks (Bleviss & Walzer 1990).

Even this dramatic efficiency gain results only from incremental progress, not basic redesign. For example, one could choose crushable-metal-foam bodies (which would be extremely crashworthy at a curb weight of ~750 lb [~340 kg]), series-hybrid drives, switched-reluctance motors integrated into wheel hubs at zero marginal weight, power-electronic regenerative braking (eliminating the hydraulic system), variable-selectivity windows, miniature sodium headlamps, and other innovations. Systematically combined, such features appear to be able (Lovins 1991b) to yield a very safe, peppy station wagon averaging around 150 mi/gal (1.6 l/100 km). Other major innovations show additional promise, *e.g.*, membrane oxygen enrichment of air intake, variable-geometry turbochargers, direct-injection diesels, ceramic engines, new two-stroke engines, monolithic solid-oxide fuel cells, etc. (Bleviss 1988a).

There is also the option of a more diverse mix of car sizes. Minicars (no more than 4½x10½' [1.4x3.2 m] and 0.55 l displacement) recently held a fifth of the Japanese domestic car market. General Motors, too, has invested over $50 million in successfully developing a 1- or 2-passenger, ~0.75-liter "Lean Machine" rated at ~150-200 mi/gal (1.2-1.6 l/100 km). Said to be safer than a normal car (because of its "bouncy" composite materials and its maneuverability), and occupying less than half the driving or parking width of a normal car (Sobey 1988), it is licensed to Opel and Suzuki but stalled by regulatory ambiguities.

Similarly, the minivehicles popular in many developing countries can be much improved. Taiwan is now doing this with motorcycles and scooters. An unwelcome development, in contrast, is the widespread improvisation of carrying passengers on adapted tractors, especially in China and India: a typical Chinese tractor carrying 1 ton is estimated by the World Bank to use 75% more fuel per km than a fully loaded 4-ton truck, and such tractors used 27% of China's diesel fuel around the mid-1980s (EPA 1989, p. VII-58). Efficient alternatives are clearly important.

The world's half-billion motor vehicles -- twelve times the 1945 fleet, and now consuming nearly half the world's oil -- has grown by about 5%/y for two decades (Bleviss & Walzer 1990). If this growth continues, we'll run out of land and air long before we run out of oil. **Transportation system alternatives** are thus essential to supplement light-vehicle efficiency, because urban highway congestion handicaps even the most efficient cars. California's congestion, for example, is frequently severe on the urban roads that carry 40% of traffic. It costs $17 billion/y in wasted fuel and lost time (360 million person-h/y), and is expected to triple in the 1990s (CEC 1990, p. 7-13). Congestion is even worse in many developing countries. The main technical options for alleviating it include:

- **Improved road design, signalling, signage, and controls** (nearside turn on red, computer-controlled traffic lights, freeway entry-ramp flow controls, etc.). In-car computers linked to computer-driven transmitters that suggest time-minimizing route changes are already under test in Berlin. Automatic proximity-

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hoped, to be overly conservative. Moreover, plastics and composites can improve safety and cut maintenance costs, although they require careful design for recyclability.

[23]Today, some light cars are among the safest and some heavy ones are among the most dangerous. This proves that for safe momentum transfer in a crash, design and materials are far more important than mass. Some of the prototypes, such as the Volvo LCP, are designed for survival in a 35-mph head-on crash -- a 36% higher energy-dissipation capability than the U.S. 30-mph standard. Energy-absorbing materials and body designs can thus ensure that ultralight cars are safer than today's -- without taking credit for their greater maneuverability, faster acceleration (because they are so light, despite their ~25-50 hp engines), and shorter stopping distance.

control systems could safely pack 2-3 times as many cars per lane-mile and "save up to 20% of the fuel consumed" (Bleviss & Walzer 1990).

- **Symmetrical treatment of competing transportation modes.** A thorough study of 32 cities on four continents (Newman & Kenworthy 1989) found that after controlling for per-capita income and other variables, vehicle-miles travelled per capita in Australian and Western European cities and in Tokyo are respectively 85%, ~45%, and ~25% of the U.S. average -- correlated with mass-transit shares of 8%, 32%, 63%, and 4% respectively. The American cities' high gasoline intensity was fundamentally due to their overprovision of roads and of downtown parking as apparently free goods, while other modes had to pay far more of their own costs. In California, for example, cars pay only ~10% of their full costs through taxes and tolls, while mass transit pays ~20-25% through fares (CEC 1990, p. 7-9).
- **Coordinated land-use/transport development.** A mile of travel by mass transit is commonly assumed to displace a mile of travel by car, implying that mass transit has limited effect and uninviting economics (though almost always severalfold cheaper than roadbuilding: Goldstein *et al.* 1990, App. B). Recent studies, however, indicate that the one-for-one assumption is misleading, because "the availability and usage of transit services also changes the location of trip origins and destinations in a way that reduces the need to travel by car, and reduces the distance of travel required by [most]...people who will continue to drive their cars" (Goldstein *et al.* 1990).[24] That study found a nearly twofold difference in vehicle-miles per comparable, income-normalized household in two nearby California communities, one with and one without light-rail service. Each mile of mass-transit travel displaced *ten* miles of car travel. Less thorough studies elsewhere have found a 1:4-5 ratio, essentially independent of cultural factors (Newman & Kenworthy 1989, pp. 77-100). These results are empirical, reflecting *actual* transit ridership, not market potential. Because doubling residential density reduces vehicle-miles per household by 25-30% (Newman & Kenworthy 1989), doubling a region's population through infill would increase car travel by only 40-50%, rather than the 100% expected from sprawl. The effect of transit corridors on commercial density, too, is even greater than on residential density, enabling many more errands to be done per trip. Capturing these benefits requires zoning that encourages infill and highly mixed land-use but discourages sprawl.[25] It also requires careful coordination of land-use and of parking with transport planning, and frequent, fast, safe transit. Such variables are far more important to per-capita gasoline use than gasoline prices, incomes, and vehicle efficiencies (*id.*).
- **Ridesharing** in private vehicles, and **vanpooling**, long organized by employers but paid for by riders, work well in some U.S. cities, encouraged by dedicated carpool lanes and other incentives. In the U.S., where the average car carries only 1.7 people, full 4-passenger carpooling would save 45% of all gasoline (Bleviss & Walzer 1990). During 1973-88 alone, California's vanpool and rideshare programs saved 2.5 billion vehicle-miles and 156 million gallons of fuel, or over 5 million tons of carbon (CEC 1988). Another option, voluntary **carsharing** among 4-6 households, is proving quite successful in West Germany. And a Belgian innovation -- a **national hitchhikers' club** with a variety of cost- and risk-reducing features -- could be widely emulated.
- **Telecommuting** via electronic media (Shepard *et al.* 1990, pp. 432-436) is now the main workstyle of some ten million Americans and growing rapidly. It saves money, time, stress, unhappiness, and pollution (Washington State Energy Office 1990). A related Swedish experiment is fitting one car per subway train with computers, modems, FAXes, etc. to make commuting time more productive.

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[24]This should come as no surprise, since the U.S. Interstate Highway System has proven to be the most important determinant of land-use in this century: as night satellite photographs reveal, an estimated ~95% of Americans live in counties on or adjacent to interstates. Of course, the roads were built between cities and through or near towns to start with, but they have since accreted most new "greenfield" developments too.

[25]Newman & Kenworthy (1989) found that fuel use rises steeply and nonlinearly as density drops too low to support satisfactory transit service. Urban per-capita gasoline use worldwide falls into roughly three classes (Newman & Hogan 1987): car cities (<30 persons/ha, typically North American), public transport cities (30-130, typically European), and walking/cycling cities (>130, typically Asian). Australian residents have claimed to be as satisfied with their lifestyle in high- as in low-density suburbs even if they might not originally have preferred the former (Duxbury *et al.* 1988).

- Offering safe and convenient **bicycle** (and **pedestrian**) lanes or paths, and coordinating with public transit (so bikes can be taken on trains and buses or rented at stations), enables bikes to carry 9% of all Dutch commuter traffic, and "in some cities, they account for more than 40% of all passenger trips" (Bleviss & Walzer 1990). In contrast, although 54% of working Americans work within five miles of home, only 3% bike to work. The scope for overcoming obstacles to biking is enormous: all U.S. biking is currently estimated to displace more than 14 billion car trips per year, saving the marginal portion of ~$6 billion in differential costs, but the gasoline displaced is currently less than 1% of total usage (Calwell *et al.* 1990, p. 26).
- Some capital-short developing countries have devised **cheap, highly effective transit designs.** Jaime Lerner, for example, developed unsubsidized, 10¢/ride commuter bus systems in Rio de Janeiro and Curitiba, Brazil, some with one-minute intervals. His onstreet "boarding pods" and special door designs nearly trebled density to 12-18,000 passengers per corridor-hour (Lerner 1987). Coordinated land-use policy and a three-tier bus system (including dedicated radial express lines) gave Curitiba "one of the highest rates of motor vehicle ownership and one of the lowest rates of fuel consumption per vehicle in Brazil" -- because most car-owners prefer mass transit for routine city travel (Bleviss & Walzer 1990).

Heavy transportation can save considerable energy too. For example, **commercial jet aircraft efficiency** is about twice as high in today's 757/767/MD9-80 aircraft as in the older aircraft in U.S. fleet (Lovins & Lovins 1981), and that fleet in turn is about twice as efficient as that of, say, Aeroflot. Further savings of ~50% have been demonstrated in the Boeing 7J7 and of ~40% in the McDonnell Douglas MD-91/92.[26] New methods of drag reduction (Vaughan 1988) can save 20-40% of fuel. By such methods, Boeing's recently released 777 achieves almost twice the fuel efficiency of a 727 -- ~94.5 seat-mile/gal, *vs.* the 727-200's 50 -- and 35% less fuel per seat-mile than a typical DC-10: ~185 lb/2000 mi, *vs.* 285 for a DC-10-30, 210 for a 747-400, or 205 for a 767-300ER (Mikov & Cole 1990).

Yet this 10%-better-than-767 performance is being achieved in today's most efficient commercial airliner *without* using (at least initially) GE's unducted propfan engine, with a bypass ratio of 36[27]. That engine uses 40% less fuel than the 727's JD8D-17 engines (Kavanagh 1990), at a 25% ($1 million/engine) price premium. Against its nearest competitor, its saved energy[28] costs only 19¢/gal or 5¢/l (a 14-21%/y rate of return @ $1/gal); against the fleet, it looks about twice that good. It is therefore slightly too costly for cash-strapped airlines, but extremely attractive at social discount rates, or at long-run replacement fuel costs, or counting externalities like global warming.[29]

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[26]The latter, described by Henne (1989), meets or exceeds all current or anticipated noise rules, sharply reduces pollution, and has less interior noise than any other commercial airliner. Both aircraft were fully developed but shelved in 1989 for lack of a market in those cheap-fuel, cash-short days. The 777, brought to market in November 1990, combines some of their features with conventional engines.

[27]*Vs.* ~6 for conventional engines and 10 for GE's latest large conventional engine, the GE90.

[28]Levelized at 5%/y real over a 15-y operating life, assuming a 16.8% weighted saving from initial fuel consumption of 1.424 million gal/engine-y, typical of a narrowbody two-engine aircraft flying 3,200 h/y (Kavanaugh 1990, p. 8). Unfortunately, the >40% drop in fuel use per passenger-mile in the U.S. during 1970-80 and the >50% decline in real jet-fuel price during 1980-87 greatly reduced airlines' economic incentive to save more fuel (EPA 1988, p. VII-52). The 1990-91 Mideast crisis's doubling of fuel prices increased U.S. airlines' average fuel share of total costs from ~15% to nearly 25%, but that price spike proved short-lived.

[29]The contribution to Ottinger *et al.* (1990) by P. Chernick & E. Caverhill found the local and regional CO_2 externality alone to be worth 1.1¢/lb, equivalent to about an eighth of 1989 jet-fuel prices; adding SO_x, NO_x, and particulates increased this by fivefold. Soviet estimates *excluding* CO_2 are even higher, at over 60% of the 1989 U.S. jet-fuel price (Chizhov & Styrekovich 1985). Chernick & Caverhill further estimate the external cost of U.S. oil imports at $2.26/million BTU, or 52% of the 1989 jet-fuel price. Thus counting the externalities would more than double the price, making new aircraft like the 7J7 or MD91/92, or engines like GE's unducted fan, immediately attractive even at the airlines' high discount rates.

Aircraft can also benefit from further improvements (still not begun in many countries) in computerized operations management, fuel-load minimization, idle reduction, flightpath optimization with improved weather monitoring, more frequent aircraft washing, weight paring[30], etc. In all, EPA (1989, p. VII-52, emphasis added) has identified improvements that "could reduce fuel use per passenger mile *to less than one-third of the current [U.S.] average....*"

Even in the U.S. with its relatively modern **railway** equipment, potential energy savings of ~25% were estimated (Ephraim 1984) before Caterpillar introduced a diesel locomotive with doubled efficiency (*Fortune* 1986). Substituting Japanese- or French-style (or more advanced) high-speed trains for long car or short air trips could likewise save ~80% and ~87% of travel energy, respectively, at current European efficiencies (Parson 1990), and similar fractions of travel cost. New proprietary developments in simple and cost-effective magnetic-levitation trains show particular promise. Just electrifying main rail lines, in countries with efficient utility systems, can save tens of percent of primary fuel compared with typical OECD diesels (EPA 1989, p. VII-61).

Freight-energy savings estimated at ~80% (NRC 1990, p. 73; Sobey 1988) are also available by substituting rail for long freight hauls by truck, using *e.g.* GM's **Roadrailer**, which converts in seconds between a semitrailer and a railcar, and pays back in a few years from lower demurrage and enabling just-in-time inventorying.

Heavy trucks can directly save ~60% of their energy, with paybacks of probably a few years, through turbocharged and adiabatic (uncooled) low-friction engines, improved controls and transmissions, better tires and aerodynamics, exhaust heat recovery, regenerative braking, improved payloads and payload-to-capacity matching, and reduced empty backhauls through better shipping management (Lovins *et al.* 1981, Samuels 1981). Savings of 40% have already been prototyped (*Automotive News* 1983), and savings of 50% have been found to have reasonable cost with present technology (Goldemberg *et al.* 1988). Most of these techniques also apply to **buses**, and many apply to **agricultural traction**, the need for which can be further reduced by improved cultural practices (*infra*).

Even after the doubling of **ships'** energy efficiency per ton-mile during 1973-83, considerable further savings remain available (Spyrou 1988) from improved propellers, engines, and hydrodynamics, antifouling paints, heat recovery, and (in some cases) modern versions of sails. The same engine innovations identified for trucks may, by themselves, achieve 30-40% savings (EPA 1989, p. VII-50).

Transportation equipment stays efficient only with proper **maintenance and operation**. Much of China's truck energy intensity (twice that of the U.S. [Chandler *et al.* 1990]), and that of many developing countries, is due to poor maintenance. Nor is OECD adequate in this respect: about 1 mi/gal, or ~5% of the fuel used by the U.S. car fleet, could be saved simply by proper tire inflation. Road quality, too, is a key determinant of vehicle efficiency and life, especially in the USSR and Eastern Europe. Poor roads, while not discouraging vehicle ownership (EPA 1989, p. VII-59), subtly nudge designers toward tank-like designs -- in effect, substituting extra fuel (to haul around the extra weight, drive more slowly, and stop often) for pothole repairs.

Low-temperature heat

Buildings can use the same improvements that save electricity in water- and space-heating to save oil (or gas fungible for oil[31]). New options include furnaces up to 97% efficient (while also saving >90% of fan energy),

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[30]At mid-October 1990 prices, according to a 12-13 October 1990 CNN Headline News "Dollars and Cents" feature, it cost the average U.S. airline ~$22.50/y in fuel to carry one extra can of soda onboard.

[31]This discussion assumes such fungibility. This is reasonable on a timescale of several decades – sufficient to achieve flexibility in refinery product-slate allocation – but in the short term, saved gas may mainly displace residual oil currently in surplus, rather than scarcer light products.

superwindows that gain net winter heat even facing away from the Equator, ventilation heat recovery, and cost-effective ways to insulate or "outsulate" a wide range of existing buildings. A major government study found that even with 1979 technologies, careful retrofits could save 50% or 75% of U.S. space heat at average costs of \$10/bbl and \$20/bbl respectively -- severalfold cheaper than heating oil (SERI 1981). Technological progress since (Rosenfeld & Hafemeister 1988, Bevington & Rosenfeld 1990, Shepard *et al.* 1990) has cut these costs by probably half.[32] EPA considers a 75% reduction in households' total energy intensity achievable by 2025 (EPA 1989, p. VII-6).

A compilation (Rosenfeld *et al.* 1990) prepared for a National Academy of Sciences study, which is discussed below, adopted a midrange finding that presently commercial technologies could save 45% of the electricity (EPRI 1990) and 50% of the direct fuel used by U.S. buildings in 1989. Those savings would respectively save \$37 billion and \$20 billion a year more than they would cost. An additional \$4.3 billion per year could be saved by cost-effective fuel-switching. The carbon avoided would thus total 232 million tons a year, or a sixth of total U.S. emissions, at a net cost of *minus* \$61 billion per year (or -\$263 per ton of carbon). The paper also summarized eight other studies, several of which documented much larger and cheaper savings than those agreed upon by the Academy subpanel.

High-temperature heat

Most of the oil used for **industrial process heat**, being fungible for gas, could be replaced by less carbon-intensive natural gas saved in buildings -- and by far less of it. U.S. industry reduced its primary energy intensity, nearly all by saving process heat, by 30% during 1977-1985. Similar savings continue today, chiefly through improved insulation, heat recovery, controls, and process design (Ross & Steinmeyer 1990): computerized process simulation and controls, and substitution of membrane and other nonthermal processes for distillation, offer especially important opportunities still largely untapped. (Process redesign for waste minimization often provides an apt opportunity.)

Numerous conversations with industrial energy managers confirm that many tens of percent more industrial energy remain to be saved. The typical paybacks are often around two years, even in the most efficient countries, where many firms have already cut energy intensity in half since 1973. Swedish industry in the mid-1970s, for example, was a third more energy-efficient than U.S. industry despite having a more energy-intensive product mix (Schipper & Lichtenberg 1976). Even so, ~50% of its 1975 energy intensity could still be cost-effectively saved by using the best ~1980 technologies, or ~60-65% by using the best technologies entering the market around 1982 (Johansson *et al.* 1983). Both opportunities continue to expand: some leading European chemical firms that have already halved their fuel intensity since 1973 are reporting *typical additional* savings around 70% from pinch technology (thermodynamic process-design optimization) and better catalysts, with two-year paybacks.

Further large savings are available from **long-term redesign and coordination of industrial systems** to cascade industrial process heat through successively lower temperatures on a regional scale. Using heat pumps, cogeneration (with heat transmission up to 50 km), and heat exchangers (up to 25 km), ~25% of industrial energy could thereby be saved in West Germany, 30% in the U.S., and 45% in The Netherlands and Japan. Much of this potential appears cost-effective. Probably all of it is attractive at long-run marginal social cost (Groscurth & Kümmel 1989).

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[32]Even against low gas prices, and with a relatively new building stock much of which was built under modern standards, the California Energy Commission has found it cost-effective to save half of the natural gas used in existing households (CEC 1990, Fig. 3-1).

These are technical improvements only. But the rapid "**dematerialization**" of the industrial economies (Larson *et al.* 1986, Herman *et al.* 1989) has reduced industrial energy intensity in the U.S. and Western Europe nearly as much as improved energy efficiency has (Lovins *et al.* 1981). U.S. steel consumption per real dollar of GNP, for example, is now below its *1860* level and falling. Worldwide, raw-material use per unit of industrial output has fallen by at least 60% since 1900, and this decline is accelerating so quickly that Japan's intensity fell by 40% just during 1973-84 (Colombo 1988). As will be noted below, the scope for future compositional energy savings is especially large in the USSR and similar economies distorted by excessive output of primary materials that are largely wasted (Chandler *et al.* 1990).

Furthermore, reductions in the throughput of resources needed to maintain a given stock of material goods represent an additional revolution just beginning (Lovins *et al.* 1981). These reductions involve recycling, reuse, remanufacture, scrap recovery, minimum-materials design (often by computer), near-net-shape processing, increased product lifetime, and substituting elegantly frugal materials (such as optical fibers for copper cables, reducing their tonnage by 97½% and their manufacturing energy by 95% [Colombo 1988]) or processes (such as ambient-temperature biological enzymatic catalysis for chemical-engineering pressure-cookers[33]). Recycling alone typically saves about half of materials-processing energy, so "[t]he potential energy savings are staggering" (Ross & Steinmeyer 1990, p. 96). This is especially true in a garbage-rich, landfill-poor country like the United States, which, for example, throws away enough aluminum to rebuild its commercial aircraft fleet every three months, even though recycling aluminum takes only ~5% as much energy as making it from virgin ore. Collectively, these **materials-policy options** can probably reduce long-run industrial energy intensity per unit of maintained stock (not throughput) *by an order of magnitude*. If this were combined with technical gains in process efficiency, surprisingly little industrial energy use would remain: industrial energy use smaller than today's could support a worldwide Western European material standard of living (Lovins *et al.* 1981, Goldemberg *et al.* 1988).

Electric-utility hydrocarbon fuels

Another kind of oil saving comes via **electricity**.[34] The potential to save electric utilities' small remaining oil input by substituting other forms of generation has been exaggerated (Lovins & Lovins 1989, pp. 108-110). Yet that oil and the larger amount of gas still used in thermal power plants were together equivalent to 13% of all oil burned in the U.S. in 1989. Nearly twice that much electricity could be saved by lighting retrofits alone, at negative net cost (Piette *et al.* 1989, Lovins & Sardinsky 1988). Globally, oil-and-gas use in power plants is equivalent to ~22% of total oil use (G. Davis 1990), but lighting retrofits plus other cheap electrical savings can clearly displace far more than 22% of electricity at negative net cost (Figure One).

Miscellaneous oil uses

The oil and gas used as **feedstocks** (10% and 3% of their respective total U.S. consumption in 1986, 14% and 7% globally) are subject to unknown but probably substantial savings. These mainly involve more efficient petrochemical processes (Ross & Steinmeyer 1990), internalization of solid-waste disposal costs (leading, as in Europe, to high plastics recycling rates, improved product design and longevity, agricultural reform [*infra*], and lower use of disposable packaging), and reduced but more durable highway construction leading to lower asphalt requirements (and less fuel burned to make cement). In addition, at least half of the ~2% of oil used to propel the other 98% through **pipelines** would be saved by the above measures, and analogously for refinery fuel and losses (~6%) and for gas compressor energy (~3%).

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[33]For example, if we were as smart as chickens (as Ernie Robertson points out), we would know how to make eggshell at ambient temperature, rather than calcining limestone at ~1250°C into Portland cement that's several times weaker.

[34]Besides the scope for saving power-plant fuel by saving electricity, small but useful amounts of oil and gas can be directly replaced by electrotechnologies that are cheaper and/or better in certain applications, but they will increase industrial electric use only a few percent as much as improved electric efficiency decreases it (EPRI 1990).

Total oil-saving potential

The combined potential to save oil by these means in the United States, shown in Figure Three, is ~80% at an average cost below $3/bbl (plus a further 20% of leftover saved gas at ~$10/bbl-equivalent). Qualitative evidence that potential oil savings and costs are comparable in other OECD countries includes:

- the similar efficiencies of new light vehicles (nearly 30 mi/gal for cars) throughout OECD[35];
- the cost-effectiveness of large additional industrial and building heat savings even in such efficient-in-aggregate countries as Sweden (Johansson *et al.* 1983; Bodlund *et al.* 1989), West Germany (Lovins *et al.* 1981, Feist 1987), and Denmark (Nørgård 1979), and hence even more so in less efficient countries; and
- the virtual irrelevance of differences in oil end-use structure, because such large savings are available in each end-use.

These considerations apply *a fortiori* in the other two world regions, since they are even less efficient than OECD.

Aggregate energy intensities per unit of economic output are typically 2-3 times as high in socialist and developing countries as in OECD (Chandler *et al.* 1990, Goldemberg *et al.* 1988). Both this fact and the field observations reported universally in the literature suggest that if all countries became as energy-efficient as OECD countries should be, the potential percentage savings would be even larger in socialist[36] and developing countries than in OECD, and the costs correspondingly lower (Goldemberg *et al.* 1988). If such countries rapidly build or rebuild their infrastructure, too, the opportunities will arise more in new construction than in retrofit, as would be the case in most OECD countries. This will further increase savings and reduce costs. One can therefore conclude that most of the oil now used in the world can be saved at an average cost far below mid-1991 world oil prices -- perhaps an order of magnitude below.

Other energy

Natural gas, natural-gas liquids (NGL), and coal used for process or building heat or for feedstocks are subject to the same categories of savings just described, and can be saved with similar effectiveness and cost. This is especially true in heating applications, where oil, gas, and NGL are used essentially interchangeably and in nearly identical technologies. In broad outline, therefore, no additional treatment of these other fuels is necessary. There are two exceptions: (1) Seven-eighths of Chinese household energy comes from coal, nominally for cooking. Although its use is officially forbidden for space-heating, despite indoor winter temperatures often below freezing in many provinces (Chandler *et al.* 1990), cooking coal nonetheless contributes precious heat. Better-insulated houses would thus improve comfort more than they would save coal in that instance: only in combination with gas (*e.g.*, biogas) cooking will they displace much coal. (2) Much Soviet and Eastern European steel is still produced in open hearths, which are half as efficient as basic-oxygen plants that are themselves no longer state-of-the-art. The USSR is by far the world's largest steelmaker but consumes at least two-thirds

[35]New cars were until recently a few mi/gal less efficient in the U.S. than in Western Europe and Japan, but in the past few years new German and Japanese cars sold in those countries have been *less* efficient than new U.S.-made cars sold in the U.S. In any case, such differences are immaterial compared with the potential improvements, partly because only half as much of Europe's and Japan's oil use is for transportation as in the U.S.; rather, they use more oil in industry and buildings. The thermal efficiency of buildings in such countries as Germany, Britain, and Japan is particularly low: German houses, for example, have worse average shell thermal integrity than American houses.

[36]Their efficiency analyses so far (*e.g.*, Chandler *et al.* 1990) show savings of only about a sixth for the Soviet Union by 2030 (or a third including changes in output structure). Extensive discussions there support our and other observers' belief that this is not because of a lower actual potential -- quite the contrary -- but only because Soviet analysts have not yet become familiar enough with disaggregated analyses, modern Western technology, and market mechanisms to apply these opportunities to their own difficult situation.

more energy than Japan to make each ton of steel (EPA 1989, p. VII-107). It can thus save large amounts of coal by this improvement alone. Continuous casting and more advanced processes can save even more (Eketorp 1989).

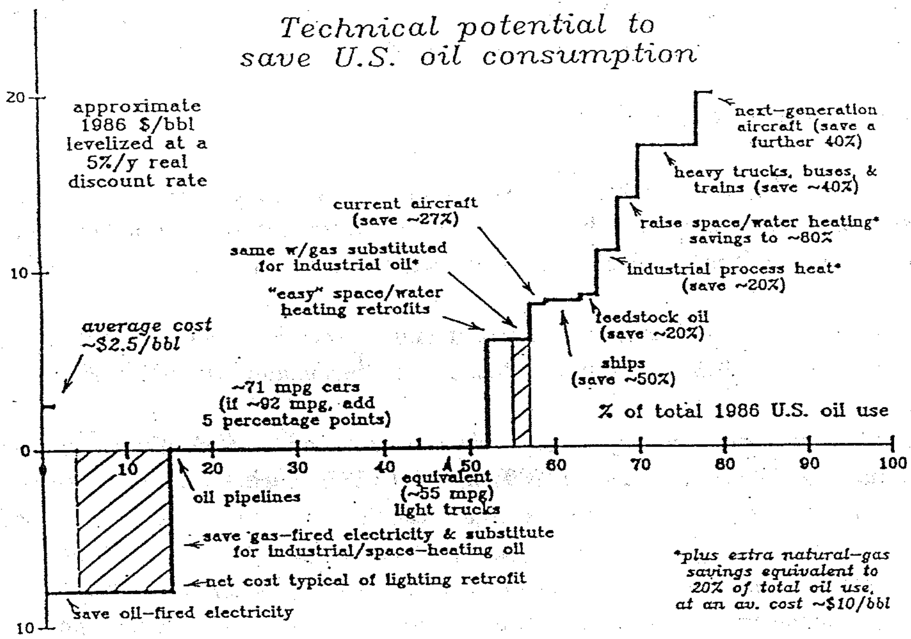

Figure Three: Supply curve of the full technical potential to save U.S. oil use by retrofitting or substituting the best demonstrated 1988 end-use technologies, at least half of which are on the 1991 U.S. market. The vertical axis is levelized marginal cost (1986 $/barrel delivered, 5%/y real discount rate). The horizontal axis is cumulative potential saving (% of total 1986 U.S. end-use) corrected for interactions. Shaded areas represent savings of natural gas that then displaces oil used to heat buildings or industrial processes. The cost and performance data are empirical (Lovins & Lovins 1989); costs above $10/bbl are quite uncertain, but this has little effect on the result. No lifestyle changes or intermodal transport shifts are assumed. The curve reflects many conservatisms: *e.g.*, omission of any light-vehicle improvements (Lovins 1991b) whose marginal cost exceeds zero, omitting new industrial and aircraft developments, and translating the negative-cost lighting retrofits (which save the oil- and gas-fired electricity) directly into equivalent $/bbl without taking credit for the value of the fuel displaced. The overall uncertainty appears to be ~10 percentage points in total quantity and <2x in average cost.

For some two billion people, most fuels are noncommercial, but that does not mean they are renewable. Unsustainably harvested wood and dung burned for fuel release biotic carbon from soil to air: in effect, they mine carbon fixed in soil organisms by reducing their populations and diversity. This contributes ~23% of global CO_2 emissions and hence increases poor countries' 1987 share of those emissions from 19% (from fossil fuels) to 42% (Reddy & Goldemberg 1990). The use of such fuels also causes erosion, deforestation, loss of soil fertility, blindness among women and children, and many other social ills. A combination of energy efficiency[37], reforestation, cascaded fuel-switching, and social changes (chiefly related to the role of women) is needed to address this complex problem (Goldemberg *et al.* 1988). Among the desirable fuel-switching measures is exchanging the use of LPG and biogas for electric and kerosene lighting and cooking (*id.*); a good gas stove can also be 5-8 times as efficient as a traditional <10%-efficient woodstove (Goldemberg *et al.* 1988). Similarly, a compact fluorescent lamp driven by a 25%-efficient electric generator and grid is some 200 times as fuel-efficient as the kerosene lamps used in ~80% of Indian households (*id.*).

Such substitutions are only part of a complex chain of successive fuel-switching (Goldemberg *et al.* 1988, pp. 255-273) needed to address simultaneously the fuelwood *and* oil problems of countries like India. The main

[37]Comprising not only efficient stoves (Baldwin *et al.* 1985, Baldwin 1987) but probably also efficient pots, perhaps with double walls and lids, enhanced heat transfer, and internal hot-gas paths -- a concept that has as yet received no serious engineering attention for developing-country use.

steps, devised by A.K.N. Reddy, are: replace household kerosene, wood, and dung with biogas (which also produces more and better fertilizer); use sustainably grown gasified fuelwood and a little biogas to run old diesel pumpsets, new pumpsets (if not photovoltaic), and short-haul freight; use the electricity saved from pumpsets to electrify all homes and replace kerosene for lighting; desubsidize kerosene and diesel fuel; and shift long-haul freight from trucks back to revitalized railways. End-use efficiency is the key throughout.

Conversion and distribution efficiency

More efficient use of delivered energy is only part of the energy savings available. Major savings are also available in converting and distributing primary fuels. Some salient opportunities from around the world that could reduce global fossil-carbon emissions by a third or more at negative net cost include:

- improving maintenance and operational techniques at most developing countries' thermal power plants, where efficiencies below 20%, output several times lower than nameplate ratings, and poor availability are endemic;
- substituting 42+%-efficient combined-cycle gas turbines, or better still, >50%-efficient intercooled steam-injected gas turbines (Williams & Larson 1989), for 25- to 35%-efficient classical thermal power plants (a ~50+% CO_2 reduction), at a fourth the marginal capital cost and lead time of scrubbed coal plants -- an especially attractive opportunity in the gas-rich Soviet Union (Chandler *et al.* 1990) and when integrated with efficient biomass gasifiers (Larson & Williams 1988, Larson *et al.* 1989);
- substituting low- for high-carbon fuels (*e.g.*, natural gas emits half as much carbon per unit energy as coal);
- expanding economic power wheeling (transmitting bulk power from areas with higher to those with lower generating costs) by using Japanese advances in power electronics and mainly Soviet advances in control theory to raise grid capacity;
- saving several percent of electric energy in OECD and up to ten times that in socialist and developing countries through advanced distribution management and metering at negative cost;
- reducing the major losses of natural gas (~8%, Arbatov 1990[38]) and district heating energy (half to two-thirds, Demirchian 1989) in the Soviet grids, and the even more dismaying loss of much of the *delivered* Soviet district-heating energy (which heats about three-fourths of all buildings) owing to the lack of operable controls, let alone meters, for each office or apartment, making open windows serve as thermostats[39];
- extending advanced Scandinavian district-heating technology to cold countries not yet taking advantage of it (*i.e.*, most of them) wherever superinsulation retrofits aren't cheaper;
- displacing electric space and water heating with gas or passive-solar techniques, as some North American electric utilities already pay customers to do;
- recovering gas-pipeline compression energy with a city-gate turboexpander/generator (a U.S. opportunity in the multi-GW range);
- eliminating gas flaring, which accounted for nearly 1% of 1986 fossil carbon releases (Marland *et al.* 1989), by using the gas as a feedstock or to fuel steam-injected gas turbines;

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[38]Makarov & Bashmakov (1990) put the losses at ~2%, but Arbatov's higher estimate, or something close to it, has been informally confirmed by other knowledgeable Soviet experts. Arbatov found 50 Gm^3/y of losses (mostly CH_4) due to leakage and ruptures, excluding 17 Gm^3/y lost in extraction, out of 800 Gm^3/y of total production, 80 burned for compression, and 30 of associated gas burned (not vented). The losses are very nonuniform in time and space. In contrast (Abrahamson 1989), U.S. production losses are ~0.13%, ~0.54% is "lost and unaccounted for" in interstate pipelines, and corresponding losses in retail distribution are a highly variable 1-6%, averaging 2-3%. These figures are all too high, and should be greatly reduced to save both money and fire-danger, as well as to reduce global warming. Abrahamson (1990) further cites direct CH_4 measurements in ambient urban air consistent with urban leakage of ~2.9-5.9% of U.S. natural gas consumption, some perhaps from storing and using coal.

[39]Similarly, Makarov (Chandler *et al.* 1990) states that "metering and individual control of residential heating and hot-water systems, coupled with repairs and improved management of district heating systems, could permit [Polish] housing space to double with only 15% growth in energy consumption." This implies a 43% efficiency gain. Jászay (1990) estimates a corresponding 30% sectoral saving potential in Hungarian buildings.

- making industrial cogeneration -- a common and lucrative practice in West Germany -- the universal practice in all countries that can use both the electricity and its process-heat coproduct (examples are cited below); and
- using simple kiln improvements to double, or more, the efficiency of traditional charcoal-making in developing countries (EPA 1989, p. VII-140).

Renewable energy sources

Many renewable energy sources are already, or are rapidly becoming, competitive without subsidy. Those sources that do not quite compete yet usually have a smaller margin of disadvantage than their pollution reduction would justify if counted (Ottinger *et al.* 1990, SERI 1990). The speed of progress and the variety of options showing great promise of further improvement are both most encouraging (Weinberg & Williams 1990, SERI 1990).[40] Integrating different types of renewable power sources, in different places, tends to provide needed storage automatically (*id.*), or at least more cheaply than with nonrenewable central stations (Lovins & Lovins 1982, pp. 268-270 & Apps. 1-3; Lovins 1978). Even the costlier electric technologies, such as photovoltaics, are already competitive in remote sites (Weinberg & Williams 1990), for certain substations' support, or in uses requiring high power quality and reliability.[41] Progress is similarly rapid in bringing down the costs and raising the conversion efficiency of both thermal and biochemical processes for converting biomass to liquid fuels (*id.*, SERI 1990). And new developments in solar process heat[42] promise to provide it economically even in unfavorable climates.

The menu of renewable sources is very large and rich (*id.*) and many sources have the potential to grow rapidly. A contrary impression can be created by dividing renewable energy into many small pieces and discussing only one at a time. However, in the most detailed official study to date in the U.S., five National Laboratories (SERI 1990) found that either fair competition plus restored RD&D priority[43], or proper counting of avoided environmental costs, could increase competitive renewable electric output from 363 TW-h/y (363 billion kilowatt-hours per year) in 1988[44] to ~1,573-1,895 TW-h/y in 2020, or ~60-72% of all 1989 U.S. electricity sold. Renewable generation at that level could run an expanded but efficient economy without fossil-fueled or nuclear power stations. All the technologies assumed would compete with assumed 2030 prices of 6¢/kW-h baseload (1988 $), 9¢ intermediate, and 15¢ peaking.

The same study also found that in 2030 -- about the retirement date of a standard power station ordered today -- cost-effective electric *and* nonelectric renewable sources could together supply 44-60 EJ/y (41-57 quadrillion BTU/y) with R&D restoration, equivalent to 48-67% of present total U.S. energy demand, including 72-148% as

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[40]For example, apparently competitive solar-thermal-electric technologies now include not only the Luz trough-concentrator technology mentioned by Weinberg & Williams 1990, but also the Sunpower/Cummins combination of an Ericsson engine with a solar dish, now believed to cost ~5¢/busbar kW-h with cheap dishes (Beale 1990) and perhaps less with very cheap ones like Solar Steam's. Yet only a few years ago, solar-thermal-electric technologies looked unpromising.

[41]The Federal Aviation Administration, for example, is converting hundreds of ground avionics stations to PV power even where there is already grid power to the site, because cleaning up and backing up the grid power costs more than starting with an isolated source.

[42]Especially David Mills's development, at the University of Sydney, of semiconductor-sandwich surfaces which should soon be able to absorb visible light at least 85-90 times as well as they emit infrared (personal communications, December 1989 & October 1990). Such a surface in a hard vacuum, if it is sufficiently heat-resistant, can be calculated to yield heat at high enough temperatures for most industrial processes, even on cloudy winter days at high latitudes. More recently (personal communications, April 1991), even higher selectivity ratios have been achieved, although the applications curently envisaged are at only a few hundred °C.

[43]Real Federal renewable-energy RD&D funding fell by 89% during 1979-89. SERI assumed an increase equivalent to a total of $3 billion over the next 20 years -- about the cost of one 1-GW nuclear plant. This is assumed in the following paragraph.

[44]Excluding nonelectric sources, such as at least 3.3 EJ/y of direct biofuels: renewable supply of all kinds was probably not the cited ~8% but rather ~10-12% of total U.S. primary supply, and the fastest-growing part, outpaced only by savings (Lovins & Lovins 1989).

much electricity as the U.S. uses today.[45] A vibrant and much expanded economy, if it used energy in a way that saves money, would need no more than that.[46] Even these impressive renewable outputs are conservative: they are based on midrange expectations of economic performance, and do not represent "an upper limit on the potential contribution of renewables" (*id.*, p. ix).

Electric generation is not the only role where renewables plus efficiency can do the job. Studies a decade ago showed that a combination of renewables (including sustainably grown biofuels[47]) with efficiency (chiefly doubled light-vehicle efficiency) could cost-effectively *eliminate* the need for fossil fuels both for light vehicles[48] and for power plants in each region of the globe. Indeed, one such study, done for the German government, found that such sources could provide essentially all the energy needed, at levels of end-use and energy-system efficiency available and cost-effective in 1980, to sustain a 1975 West German standard of living *throughout* a long-run world with a population of 8 billion (Lovins *et al.* 1981). Another study, though twofold more conservative, reached broadly similar conclusions about the combined potential of efficiency and renewables (Goldemberg *et al.* 1988), consistent with a decade's shorter-term analyses for the U.S. (SERI 1981, 1990).

Four further investigations of efficiency-plus-renewables strategies also merit emphasis:

- A detailed analysis by the Swedish State Power Board (Bodlund *et al.* 1989) found that doubled electric end-use efficiency (costing 78% less than marginal supply), plus fuel-switching to natural gas and wood, plus environmental dispatch[49], could together support 54% growth in Swedish real GNP during 1987-2010 and handle the voter-mandated phaseout by 2010 of the nuclear half of the country's electric generation, yet at the same time *reduce* the heat and power sector's CO_2 output by one-third and *reduce* the cost of electrical services by nearly $1 billion per year. (This reduction arises because efficiency would save more money than fuel-switching and environmental dispatch would cost.) This result is especially striking because Sweden is arguably the world's most energy-efficient country (in aggregate or in many details: *e.g.*, Schipper & Lichtenberg 1976) to start with, with a heavily industrialized economy and a severe climate. Any other country should therefore be able to do better.
- At the same time, a study for the Indian state of Karnataka analyzed the combination of several end-use efficiency measures with small hydro dams, bagasse cogeneration, biogas/producer gas, a small amount of natural gas, and solar water heaters. This far from comprehensive combination would achieve far greater and earlier development progress than the a fossil-fueled plan advanced by the state utility (but later rejected by the government). The efficiency-plus-renewables combination would also have used three-fifths less electricity, cost a third as much, and emitted only 1/200th as much fossil-fuel CO_2 (Reddy & Goldemberg 1990). This is encouraging too, since India already emits ~5% of global carbon

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[45] The lower figures, here and in the previous paragraph, assume that intermittent renewable electricity is artificially constrained not to exceed 20% of regional generation. Circumstances requiring this now appear rare (Lovins & Lovins 1982, Sørensen 1979).

[46] *E.g.*, improving energy productivity 1%/y faster than GNP growth would cut total energy use in 2030 to 68% of 1991 use -- similar to the 64-70% of unconstrained renewable supply projected to be cost-effectively available in 2030.

[47] *I.e.*, those whose production can be indefinitely repeated because it depletes nothing. If such biomass were not burned, it would rot or be eaten by respiring animals and release its carbon anyhow; the issue is only whether that carbon release is taken up again, promptly and in equal measure, by new photosynthesis.

[48] Pure-electric cars are not considered here. They appear unlikely in principle to compete in cost, range, and performance with efficient fueled cars (including those which convert the fuel to electricity with an onboard motor-generator or fuel cell [Lovins 1991b], the "series hybrid" concept). They also do not reduce global warming if powered by anything like the present utility fuel mix (DeLuchi *et al.* 1988). For the same reasons of economics and an actual worsening of global warming, coal synfuels are not considered either (*id.*). Compressed or liquefied natural gas can modestly reduce CO_2/vehicle-mile, but far less than efficiency and biofuel options, and with some drawbacks, so they are best considered a transitional niche fuel.

[49] *I.e.*, operating most the power stations that emit the least carbon, and vice versa, by including externalities in economic dispatch.

(*id.*) and projects that this fraction, assuming the traditional coal-based strategy, will increase enormously.

These two analyses are especially interesting when considered together, because between them they span essentially the full global range of energy intensity and efficiency, technology, climate, wealth, income distribution disparities, and social conditions. Yet both find that the money saved by efficiency more than pays for the renewables, yielding a net profit on the whole carbon-displacement package in the energy sector. In addition:

- **An analysis of British, Dutch, German, French, and Italian potential for carbon reduction from 1985 to ~2015 (Krause *et al.* 1991) found that if electric demand grew 82%, as officially forecast, then optimizing the electric supply system -- by emphasizing gas cogeneration and renewables -- could nonetheless cut its carbon emissions by 54%, from 293 to 135 MtC/y, at zero net cost, despite the higher gas prices that the increased gas demand was assumed to cause. Such optimization *plus* end-use efficiency (assumed to keep demand constant and, generously, to cost just as much as the coal and nuclear plants it displaced) could cut emissions to 50-75 MtC/y -- a 75-83% reduction from the base case -- while *reducing* electric service costs by 10%.**
- **A similar Lawrence Berkeley Laboratory analysis for the New England power sector (Krause *et al.* 1991a)** found that by using 75% of the identified cost-effective potential for each of three resource groups -- efficiency (including a little fuel-switching), wind and biomass, and gas and biomass cogeneration -- the region could meet 67% of the forecast 160 TW-h/y of electric demand in 2005. This would halve carbon emissions from a sector that is already one-third nuclear. Yet even though this falls well short of long-term potential, using 75% of each option set's potential is not least-cost, and all plants were assumed to retire at the end of original book life (thereby removing 3.2 GW or 44% of the 7.4 GW of regional nuclear capacity), production-cost redispatch modelling found only a 4.3% rise in the cost of electrical services. A least-cost resource mix would instead decrease this cost.

National analyses commissioned by the governments of Australia (Greene 1990) and Canada (DPA Group 1989) similarly found that national CO_2 emission reductions of ~20% via energy efficiency would be highly profitable. A 36% Australian energy saving from projected 2005 levels, reducing forecast fossil-fuel CO_2 emissions by 19%, would produce net internal-cost savings, in today's Australian dollars, of $6.5 billion *per year* by 2005. Each $5 invested in efficiency could save $15 worth of new energy supplies and 1 ton of CO_2 -- an average abatement cost of -A$37/t. Similarly, the Canadian report found a cumulative net saving of $100 billion through 2005 (present-valued Canadian dollars) from a 20% CO_2 cut compared to present emissions. And a private analysis for California detailed potential CO_2 emission reductions of 26% from projected levels in 2000 and of 54% in 2010, both at negative net cost (Calwell *et al.* 1990). In 1991, indeed, Southern California Edison Co. and the Los Angeles Department of Water & Power pledged to cut their CO_2 emissions by 20% from current levels -- with half the reduction to occur in the first decade.

Farming and forestry

As noted earlier, nearly all greenhouse gas emissions not related to energy use or CFCs arise from unsustainable farming and forestry practices. These emissions include:

- ~46% of anthropogenic CH_4, which comes from livestock-gut fermentation and rice-paddies, rising to 68% if biomass burning[50] is included;

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[50]Much biomass is burned, often unsustainably, for fuelwood, slash-and-burn shifting cultivation, disposing of crop residues, and clearing forests to extend cultivation. The last three of these terms probably release ~1.4-2.9 GtC/y, *vs.* ~1.6 from burning wood and dung for fuel (Krause *et al. 1989*, p. I.3-15n8). Burning inevitably emits *non*-CO_2 trace gases whether the carbon is recycled or not -- *i.e.*, independently of whether the carbon release is compensated by re- or afforestation or by other biotic carbon sinks. How the carbon is harvested will of course affect the ecosystem's ability to sustain such compensation (*id.*, p. I.3-15).

- ~57% of CO, from forest clearing, chiefly for agriculture (Newell *et al.* 1989) and fuelwood;
- ~52% of anthropogenic NO_x and ~15% of anthropogenic N_2O, emitted by biomass burning;
- a further ~33% and ~18% of anthropogenic N_2O, derived from cultivating and fertilizing natural soils[51], respectively; and
- about a fourth of all CO_2, from deforestation, desertification, and simplification of terrestrial ecosystems including farmland (Krause *et al.* 1989, Ch. 3).

Ecological simplification in its myriad forms is less visible, but no less important to global warming, than the clearcutting of American forests or the burning of Brazilian forests. Just the loss of *above*-ground biomass and diversity, assuming no loss of soil carbon, means that replacing an old-growth Pacific Northwest forest with a young one reduces its total carbon inventory by two- to threefold (Harmon *et al.* 1990).[52] But typically at least as much terrestrial biomass is belowground as aboveground -- and in temperate farmland, some *20-30 times* as much is in the soil as in the plants above it (Krause *et al.* 1989, p. I.3-32[53]). This invisible but enormous carbon stock, typically upwards of 100 metric tons of carbon per hectare (tC/ha), is at risk of mobilization into the air if insensitive practices defeat living systems' ability to fix carbon into soil biota. In essence, turning (for example) prairie into corn and beans, and substituting synthetic for natural nutrient cycles, puts a huge standing biomass of soil bacteria, fungi, and other biota out of work. They then tend to lose interest, die, oxidize or rot, and return their carbon to the air.

At the same time, soil erosion, still endemic throughout most farmlands, transports soil organisms and other soil organic constituents ("finely pulverized young coal") into riverbeds and deltas, where they decay into CH_4 -- a greenhouse gas many times as potent as CO_2 (IPCC 1990). Reduced soil fertility from erosion, biotic simplification, compaction, or the use of poisons requires ever greater inputs of agrichemicals, notably nitrogen fertilizers, whose production consumes ~2% of industrial energy (Ross & Steinmeyer 1990) and whose use increases N_2O emissions from the soil. Other well-known agricultural problems include:

- burgeoning pest resistance -- the world loses more of its crops to pests now than before the pesticide revolution -- and pesticide-caused health problems, especially among fieldworkers;
- rapidly growing OECD demand for food free of chemical contamination (*Wall St. J.* 1989)[54];
- crops' narrowing genetic base as diverse native stocks are inexorably lost to habitat destruction and seedbank neglect;
- problems of water quality and quantity;
- many farmers' marginal profitability as their revenues immediately flow back to input suppliers; and
- the distressing spectacle of simultaneous food surpluses and famines.

These trends indicate the need for "a major overhaul of current agricultural production methods" (Krause *et al.* 1989, p. I.3-14). Such an overhaul appears necessary to achieve *adequate, acceptable, and sustainable* food and fiber output even if global warming were not of concern. Achieving it may be difficult because of the rapid loss of rural culture and traditional ecological knowledge as farmers vanish into cities (Jackson 1980): every year's

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[51]Forcing the nitrogen cycle boosts the yield from side-reactions whereby denitrifying bacteria in the soil produce N_2O from nitrate and nitrifying bacteria produce N_2O from ammonium. Cultivation also appears to increase microbial N_2O emissions even without fertilizer, and nitrate runoff into surface- and groundwaters appears to result in increased N_2O emissions (Krause *et al.* 1989, p. I.3-20).

[52]Hence Oregon has estimated that cutting of old-growth forest is responsible for ~17% of the state's total carbon emissions (Oregon Department of Energy 1990).

[53]Contrary to the conservative assumption made by Harmon *et al.* (1990), the data cited by Krause *et al.* (1990) do show a 10% soil-carbon loss when the natural forest becomes managed.

[54]For example, a 1986 National Institutes of Health study found that *every* U.S.-registered fungicide is a known carcinogen (Davies 1990). The Dutch Parliament is shortly expected to pass a law requiring 25% biocide reductions by 1993 and 50% by 2000 (*id.*).

delay adds to the loss of those irreplaceable human resources. However, as with the changes to the energy system described above, changes in the agricultural system needed to reduce global warming will increasingly be seen as attractive for a wide range of other reasons, including economics. And off these changes, those with the highest climatic leverage involve livestock.

Livestock

Just as saving electricity reduces CO_2 emissions disproportionately by displacing severalfold or manyfold more fuel, so affecting the numbers and rearing of livestock -- which convert ~3-20+ units of grain to one unit of meat -- can disproportionately help to protect existing forest-, farm-, and rangeland while reducing emissions of CO_2, N_2O, and CH_4. High-priority actions include (Krause *et al.* 1989, EPA 1989):

- reducing OECD dairy output to match demand[55];
- desubsidizing livestock production, especially for cattle, which emit ~72% of all livestock CH_4 (Crutzen *et al.* 1986): many dairy and beef cattle would not be grown without large subsidies, especially in OECD (Soden 1988);
- reforming beef grading and distribution, particularly in the U.S., to reduce the inefficient conversion of costly, topsoil-intensive grains to produce fat that is then largely discarded (Browning 1990);
- regulating or taxing methane emissions from manure so as to encourage its conversion to biogas for useful combustion;
- improving livestock breeding[56], especially in developing countries, to increase meat or milk output per animal, consistent with other important qualities and with humane practices;
- shifting meat consumption to less feed- and methane-intensive animals[57] and to aquaculture (preferably integrated with agriculture, a highly flexible and productive approach that may also help cut rice-paddy CH_4); and
- developing, if possible, alternative feed, fodder, and rumen flora that minimize CH_4 output[58].

Many of these livestock options would have important side-benefits. For example, many OECD cattle herds are fed, at conversion ratios of 8:1 or worse, with grain from developing countries. The Western European herd consumes two-thirds of the domestic grain crop, yet still imports >40% of its feed grain from developing countries (Krause *et al.* 1989, p. I.3-19). OECD consumption of this large amount of feedlot beef is thus "directly related to starvation in the poor countries of the world." If OECD countries replaced part of their feedlot beef consumption with range beef and lamb, white meats, aquaculture, marine fish, or vegetable proteins, then Central America might feel less pressure to convert rainforest to pasture. Many developing countries could free up arable land. There could be less displacement of the rural poor onto marginal land, and renewed emphasis on traditional food crops rather than on export cash crops. Above all, this one action could save enough grain, if properly distributed, to feed the world's half-billion hungry people (*id.*).

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55 Dairy cows produce extra methane because they are fed at about three times maintenance level (Krause *et al.*, p. I.3-16).

56 This does not mean using such biotechnological innovations as bovine growth hormone, which is not an improvement in the herds but rather an artificial way to make existing cows produce, probably briefly, much more milk than they were meant to.

57 For example, shifting half of beef consumption to pork and poultry would maintain dairy output and total meat consumption while reducing methane emissions by ~40% -- about twice the stabilizing CH_4 reduction (Krause *et al.* 1989, p. I.3-18). In OECD, the market is already shifting in this way, largely because of health concerns. Ultralean, organic range beef (which grazes only on natural grasslands and is not grain-fed), which alleviates those concerns and can cost less, may also produce less methane than equivalent feedlot beef (EPA 1989, p. VII-270).

58 EPA is encouraged about this option and believes that the resulting productivity increases would often yield a significant net profit: as J.S. Hoffman of EPA put it, "This creates a very economic picture for methane [abatement]" (Stevens 1990). IPCC (1990a) apparently concurs. Validating field experiments are now underway.

Low-input sustainable agriculture

Organic farming techniques that are already rapidly spreading in OECD for economic, health, and environmental reasons (*Wall St. J.* 1989) can simultaneously reduce biotic CO_2, N_2O, and CH_4 emissions directly from farmland, and indeed may *reverse* the CO_2 emissions. These techniques can and often do use standard farm machinery, but require it less often[59], and can work well on any scale. They substitute natural for synthetic nutrients (*e.g.*, legumes for synthetic nitrogen), mulches and cover crops for bare ground, natural predators and rotations in a polyculture for biocides in a monoculture, and nature's wisdom for humans' cleverness. They integrate livestock with crops, and garden and tree crops (*infra*) with field crops. They maintain often tens and sometimes hundreds of cultivars instead of just one or a few. In Asia, they draw on a particularly rich tradition of integrating many kinds of production -- vegetables, fish, rice, pigs, ducks, etc. -- in a sophisticated quasi-ecosystem that efficiently recycles its own nutrients.

Green Revolution seeds and artificial fertilizers are often assumed to be essential to grow enough food in land-short developing countries. Yet diverse African field studies have demonstrated that "ecoagriculture," which substitutes good husbandry and local seed for otherwise purchased inputs, yields nearly as much maize, sorghum, etc. in the short term. The small yield difference probably narrows with time "[i]n view of the accelerated degradation of soils that usually accompanies chemical agriculture." Such results "suggest that regenerative farming could be greatly expanded both in industrialized and developing countries without negative consequences for the goal of increasing Third World agricultural yields. On the contrary, without [such] a conversion...the loss of arable land, notably in the tropics, threatens to accelerate out of control..." (Krause *et al.* 1989, pp. I.3-23 & -24).

In both OECD and developing countries, ordinary organic farming practices modelled on complex ecosystems generally produce comparable or slightly lower yields than chemical farming but at much lower costs. They therefore produce *comparable or higher farm profits* (NRC 1989) -- without counting the considerable premium many buyers are willing to pay for food free of unwelcome biocide, hormone, and antibiotic residues (*Wall St. J.* 1989). The organic practices' economic advantage has been demonstrated in large commercial operations over a wide range of crops, climates, and soil types (NRC 1989). That advantage tends to increase at family-farm scale, which brings further social benefits (Jackson *et al.* 1984). Similar economic benefits have been found in many hundreds of diverse U.S. and West German farms (Brody 1985, Bechmann 1987, Bossel *et al.* 1986).

Little is yet known about CH_4 and N_2O cycles, so it is only a plausible hypothesis, not yet a certainty, that the reduced tillage and fertilization that accompany profitable organic farming, together with reductions in the burning of biomass and fossil fuels, will suffice to eliminate most of the ~35% of total N_2O that is released by human activity. Yet even if N_2O reductions from organic fertilizers turned out to be less than hoped, the CO_2 benefits would still be large, because CO_2 can be absorbed by building up organic matter in soil humus through the gradual accumulation of a richly diverse soil biota. Today, in both OECD and developing countries, and reportedly in Eastern Europe and the USSR too, soil loss, and especially the physical loss or biological impoverishment (hence carbon depletion) of humus, is far outpacing soil and humus formation and enrichment. But successful conversions to organic practices, chiefly in the U.S. and West Germany, have demonstrated that after a few year's reequilibration, these carbon losses can be not only eliminated but reversed.

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[59]In California (CEC 1990), ~3% of energy is used directly in agriculture. Of the one-third of that used for irrigation, ~40% can readily be saved through simple and highly cost-effective water-efficiency measures -- thereby saving electricity (coal-fired on the margin), since pumping water is the largest single use of electricity in the state. The further ~22% of agricultural energy use for synthetic pesticides and fertilizers would be virtually eliminated by organic techniques, while the ~24% for traction could be cut about in half (*id.*) through the reduced need for field operations. In all, therefore, organic farming would save nearly half of California's agricultural energy use (Calwell *et al.*, p. vi). To the extent it were less centralized, it would also reduce transportation needs for both inputs and outputs.

Not just forests, then, but also farmland can be changed from carbon sources to carbon sinks. For example, an ordinarily impoverished soil in the U.S. cornbelt could plausibly start at 2% organic content or ~1% C. A decade of organic practices -- rotating corn with alfalfa or clover, using manure and green manure, and integrated pest management -- could raise the organic content by a conservative 0.02%/y[60], thereby adding ~4.8 tC/ha over the decade (Holmberg 1988). Doing this on the United States' 50 million hectares (Mha) of farmland would offset the annual combustion of ~10% of current U.S. gasoline use per year. Thus a very efficient U.S. car fleet (~5-7 times as efficient as now), getting a substantial part of its fuel from sustainably grown biomass, would emit only as much fossil carbon as the farmland would reabsorb into soil humus (*id.*). Based on organic-farming comparisons by the National Research Council (1989) and others (*e.g.*, McKinney 1987), this carbon sink could be achieved at zero or negative net internal cost. Specifically, each hectare of sustainably grown corn or other fuel feedstock could, for example, produce 600 gal of anhydrous ethanol, fix enough soil carbon to offset the combustion of 200 gal of gasoline (Holmberg 1988)[61], and increase the farmer's profits.

There are also many techniques for substantially reducing the use of nitrogen fertilizer (Krause *et al.* 1989, p. I.3-20) within the context of conventional OECD farming practice or of lower-input but still not truly organic modifications. Most of these techniques are cost-effective because they reduce chemical and application costs and nitrate-runoff pollution without cutting yields. In many developing countries, too, additional measures to reduce CH_4 emissions are available and desirable: *e.g.*, biogas-digester preconditioning of rice-paddy fertilizer, improved dryland rice options, and reducing in-paddy anerobic fermentation of rice residues.[62] Substantial reductions in N_2O and CH_4 releases can undoubtedly be obtained by the simpler of these management techniques at costs on the order of $3-30 per ton of carbon-in-CO_2-equivalent. On closer examination, side-benefits, such as saving fertilizer and reducing runoff through more precise application, may well turn out to pay for some important abatement measures.

Sustainable forestry

The needs and opportunities in forestry are strikingly analogous to those in farming. Often the two are directly linked, chiefly by ways to reduce agriculture's pressure on forests and by opportunities for agroforestry -- applying agricultural traditions to tree crops. The former options include (EPA 1989, Krause *et al.* 1989):

- reducing the area and increasing the fallow period of slash-and-burn to sustainable levels;
- replacing slash-and-burn with sustainable techniques (often proven by indigenous cultures), including agroforestry using native or cultivated tree-crops or both;
- using trees felled during land-clearing for timber and biofuel;
- using crop wastes not as direct fuel but rather for composting and mulch, and for efficiently burned, low-leakage biogas or gasification to run steam-injected-gas-turbine cogeneration (Larson *et al.* 1989);
- controlling artificial burns;
- adopting low-input/organic farming and forestry techniques (the former because they reduce pressure for land-clearing);

[60]For example, Holmberg (1988) cites Herman Warsaw, a successful (370 bu/acre in 1985) organic corn farmer who in the past 30 y increased the organic content of his soil from ~3½% to ~8% in the top 3" and from 1% to 3% at 1' depth. The average increase in the top foot of topsoil was ~4% (~2% in carbon terms). He believed he learned how to achieve the same improvement in five years. We assume half that speed. This is probably quite conservative: for example, Holmberg also cites Steve Pavich's 1% carbon gain profitably achieved in 12 y and probably reproducible in half the time in dry Arizona and California soils, and USDA/Beltsville test plots' achievement of 0.2-0.6%/y carbon gains through light (40 t/ha-y) applications of compost and manure. The carbon uptake assumed here is 45x slower than Beltsville's two-year achievement at a 160 t/ha-y manure application rate.

[61]This is not to say that corn is necessarily the best feedstock nor ethanol the best biofuel, but the conclusion holds for other examples too.

[62]Perhaps by frequent pond-switching between rice and aquaculture, a phenomenally productive traditional Asian technique in which fish graze the rice stubble, or by using the rice straw more widely for roofing or as a biogas feedstock.

- improving developing countries' farm productivity in order to reduce land needs per person; and
- reducing feedlot if not total beef consumption (*supra*).

Agroforestry (Leach & Mearns 1988) is especially applicable to developing countries. Projects in many African conditions have demonstrated profitable 40-90% crop-yield gains while providing surplus woodfuel (*id.*). Such practices can also permit the beneficial substitution of organic for artificial fertilizer and other agrichemicals (Krause *et al.* 1989, p. I.3-23ff). Some tree crops can yield not only wood and food but also oils, resins, or terpenes (*id.*, p. I.3-41) that are directly usable as fuel, especially in diesel tractors and pumpsets. The oils can also be combined with dirty, wet alcohols in a simple solar catalytic reactor to yield superior diesel fuels such as methyl and ethyl esters.

Nonagricultural ways to relieve pressure on existing forests (Krause *et al.* 1989, p. I.3-40) involve energy and materials policy. This includes recycling forest products[63] and "stretching" their effect (as by using honeycomb structures, *infra*), substituting electric efficiency for tropical-forest hydroelectric projects, designing frame structures so as to minimize the waste of timber, improving the protection and hence the lifetime of outdoor structural wood, and wringing far more work from biofuels (*e.g.*, Baldwin *et al.* 1985, Larson *et al.* 1989, Goldemberg *et al.* 1988).

Additional forest-protection measures include taking better care of existing forests, harvesting more thoughtfully, planting shelterbelts, excluding livestock (*e.g.*, with photovoltaic-powered electric fences), regenerating degraded forests, and promoting recreation and ecotourism to create a supportive constituency. These actions should supplement silvi/agri/aquacultural integration, the reforestation of surplus OECD farmland and degraded drylands, the planting of fuelwood around developing-country cities and along roads, and urban forestry. Together, such forestry practices could probably sequester a maximum of ~1.3 billion tons of carbon per year (GtC/y) -- enough, with the concomitant stabilization of existing carbon pools, to offset one-fourth of worldwide 1985 fossil carbon releases (Krause *et al.* 1989, p. I.3-49). This broader menu of options *nearly doubles* the 0.7 GtC/y net carbon sink calculated by EPA for conventional forestry (1990, p. VII-7). Yet much of the extra carbon capture comes from practices like agroforestry that are generally profitable without counting their environmental benefits.

Some of the most promising and profitable new forests, too, can be in cities. Urban tree-planting programs are an especially cheap carbon sink because one tree planted in a typical U.S. city sequesters or avoids *~10-14 times* as much carbon release as if it were planted in a forest where it could not also save space-cooling energy (Akbari *et al.* 1988). Urban forests and woodbelts can go far to relieve developing countries' fuelwood shortages and urban sprawl. The biomass produced by urban trees, even if not systematically and densely planted, can be substantial: Los Angeles County alone sends ~3,600-7,300 t/d of pure, separated tree material to landfills, not counting mixed truckloads. That ~1 GW of currently wasted (and costly-to-dispose-of) thermal energy is equivalent, at 70% conversion efficiency, to 0.5 million gal/d of gasoline -- enough to drive a 60-mi/gal car >10 mi/d for every household in the County.

Urban forestry is also consistent with urban agriculture -- long practiced in Western Europe and in China, where it provides 85+% of urban vegetables (100% in Beijing and Shanghai), plus large amounts of meat and treecrops (Wade 1981). Urban farming in turn further reduces greenhouse-gas emissions from centralized agriculture, saves energy otherwise needed to process and transport food, and improves nutrition, esthetics, community structure, and urban culture. Even the most crowded cities can farm on rooftops. With superwindows and air-to-air heat exchangers, climate is no obstacle: Rocky Mountain Institute's 99+%-passive-solar

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[63] "The average OECD person consumes about as much wood in the form of paper as the average Third World person consumes in the form of fuelwood" (Krause *et al.* 1989, p. I.3-43). Producing a ton of paper takes ~3/4 ton oil-equivalent of energy (Herman *et al.* 1989). If that energy were biomass, as the majority of it is in the U.S. forest products industry, it could still be used instead to make liquid biofuels for sale to replace oil.

headquarters grows bananas with no heating system despite outdoor temperatures as low as -44°C (-47°F).[64]

In considering these supplements to conventional forestry, however, it could be overly sanguine to suppose that forestry in its present form will be able to sustain its vital carbon-sequestering role. Most discussions of CO_2 abatement through fiber-production forestry emphasize *planting trees*, often of specific, fast-growing, genetically engineered kinds. But planting trees is very different -- often by severalfold in carbon inventory (Harmon *et al.* 1990) -- from maintaining a diverse forest that changes at its own pace. Much "modern" forestry repeats the ecological errors of monocultural, chemical-driven agriculture, treating trees like rows of giant corn -- short-rotation (annual) monoculture instead of long-rotation (perennial) polyculture (Jackson *et al.* 1984). This is as true with *Pinus radiata* in New Zealand or southern pine in the U.S. as with eucalyptus in developing countries, where >40% of all new hardwood plantings are now eucalypts (Krause *et al. 1989*, p. I.3-46).

Much modern forestry rests on mechanistic assumptions that appear from historic evidence to be ecologically unsound and unsustainable (Plochmann 1968; Cramer 1984; Maser 1988). Clearly what is needed is to sustain and increase both the quantity *and* the ecological quality (diversity, health, cycle time, resilience) of existing and new forests. This will require forest managers -- just like farmers -- to think like ecologists, not accountants.

Currently, forestry economics is being questioned chiefly on an accounting basis (the U.S. Forest Service, for example, is the world's largest socialized roadbuilder), not on fundamental grounds. But new questions are emerging, and new answers will follow. In this decade, researchers may discover whether in forestry, as in farming, ecologically sound practices are also the most profitable kind, and whether, as some forest scientists are starting to suspect (Maser 1988), a forest is worth more as a going (growing) concern than in liquidation. Unfortunately, the kinds of re- and afforestation that might prove not to be very productive or sustainable in the long run are the kinds currently considered in global-warming economic analyses. By normal forestry-economics standards, the fast-rotation plantings now dominating forestry practice appear profitable: that is why they are so widely practiced. But they could be increasing carbon inventories aboveground at the expense of the larger, invisible inventories belowground.

However it is practiced, planting trees is certainly a cheap way to sequester carbon (at least aboveground). Massive tree-planting programs have been found in several analyses, including a U.S. Forest Service / ex-Council of Economic Advisors report to EPA, to sequester carbon at low costs, typically on the order of \$10/tC (ICF 1990, p. 39), despite taking no credit for the discounted revenues from ultimate timber harvest, nor for other benefits meanwhile.[65] Cost estimates used by a National Academy of Sciences study (discussed below) are in a similar range. A study for Pacific Power suggests that timber revenues could in fact repay the cost of the reforestation about twice over (Reichmuth & Robison 1989). If this proves true, as the apparent profitability of current forestry activities suggests, then these canonical ~\$10/tC abatement costs are too high: profitable tree planting abates global warming at *negative* cost.

Consistent with this, EPA (1989, p. VII-7) considers reforestation "one of the most cost-effective technical options for reducing CO_2 and other gases." If the planting programs are based on agroforestry, urban forestry, and other ecologically sensitive techniques, then the average cost of sequestering carbon in trees should be even lower.

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[64]The 372-m^2 building, at 2,165 m in a 4,900 C°-d/y climate, also saves half of normal water use, 99-100% of water-heating energy, and 90+% of household electricity (reducing the lights-and-appliances bill to \$5 a month @ 7¢/kW-h). Its marginal cost for all these savings, \$16/m^2, paid back in 10 months with 1983 technology, and would pay back faster today, mainly because windows can now insulate twice as well (<0.5 W/m^2K or >R-11) at nearly the same cost.

[65]These include, *e.g.*, erosion and flood control, groundwater recharge, runoff holdup (stretching reservoir capacity), fish and wildlife enhancement, esthetic value, and recreation.

CFC substitution

The projected cost of the CFC/halon production phaseout now required by the London Amendments to the Montréal Protocol has declined by roughly half over the past two years through closer scrutiny and ingenious technological innovations. In some instances, including refrigeration with reoptimized design, the substitute may actually *improve* performance (Shepard *et al.* 1990, p. 62). In others, notably the cleaning of printed-circuit boards with terpene derived from orange peels, or new low-flux soldering techniques using aqueous or no cleaning, the substitute works better and costs *less*. Although ~$135 billion worth of equipment in the U.S. alone uses CFCs, the need is expected to be met by a combination of ~29% efficiency/maintenance/recovery/recycling/reclamation, 39% "drop-in" replacements (those that directly replace CFCs with little or no modification of equipment), and 32% substitution by replacements requiring different or redesigned equipment (Manzer 1990).

According to EPA analyses (EPA 1989a, ICF 1990), late-1989 data indicated that a U.S. phaseout of CFCs by 2000 would cost ~$1.3 billion, or ~$2.4/tC-equivalent, at a 6%/y real discount rate. This figure is the sum of many disparate terms, all subject to technological change that tends to reduce costs. New technologies, like the advanced thermal insulation mentioned next, are reducing the total cost quickly enough that it may before long become slightly negative.

There is no obvious reason why abatement should cost more in other countries, given access to OECD technologies: quite the contrary, since a third of global CFC use (Krause *et al.* 1989, p. I.3-3) is for aerosol propellants long ago cheaply displaced in the U.S. The U.S. accounts for ~29% of global CFC consumption (Turiel & Levine 1989). The global abatement cost appears, therefore, to be ~$4½ billion, and is continuing to decline with further technological development. Since CFCs in the 1980s accounted for ~24% of global warming (IPCC 1900), $4½ billion is equivalent to <$2 per ton of carbon-equivalent in CO_2.

Multigas abatements

There are important opportunities to abate two or more greenhouse gas emissions simultaneously, both at a net profit. A few examples illustrate the diversity of such options:

- Five advanced classes of thermal insulation now under development or in early commercialization, along with other design refinements, can save 90+% of the electricity used by refrigerators and freezers (Shepard *et al.* 1990, pp. 44-60) -- the biggest users of electricity in households lacking electric space and water heating, in countries as diverse as the U.S. and Brazil (Reddy & Goldemberg 1990). This saving alone can avoid burning roughly enough coal each year to fill up the refrigerator. (Savings >80% are also available with conventional insulation.) The emerging insulations also substitute a vacuum for the CFCs normally used to fill plastic foam; eliminate most of the refrigerant inventory (currently CFCs); and can accommodate the modest efficiency losses, if any, caused by switching to non-CFC refrigerants. Best of all, certain advanced insulations can make the appliance's walls thinner, because they insulate up to twelve times as well as CFC-filled plastic foam. The resulting increase in interior volume may be worth about enough to pay for the insulation (Shepard *et al.* 1990, pp. 59-60).
- Landfills emit ~30-70 Mt/y of uncontrolled methane, about a sixth of total methane from human activities (Krause *et al.* 1989, p. I.3-11). Capturing this gas and using it as fuel -- ideally for cogeneration -- both prevents its emission *and* displaces a larger amount of CO_2 otherwise emitted by a coal- or oil-fired power plant or boiler. ICF (1990, pp. 43-45) calculates that 75% recovery just from U.S. landfills holding >0.9 million tons of waste would burn ~55% of U.S. landfill methane at a cost roughly half the market value of the electricity. At least 123 U.S. landfills already recover methane as fuel (EPA 1989, p. VII-191), but far more do not yet. Capturing and burning coal-bed methane (*id.*, p. VII-131) looks

similarly profitable (or at least breakeven) and makes mines safer. Converting livestock or human manure into biogas, whether on a commercial or a village scale, and using the biogas to displace fossil fuels or unsustainably grown firewood (Goldemberg *et al.* 1988), also appears economic with modern technologies available at many scales. Interestingly, since ~20% of U.S. methane emissions can be captured just from landfill, coal, and natural-gas leakage, and there are apparently attractive agricultural abatement options too, there is a growing consensus that the ~15-20% CH_4 abatement needed to stabilize this gas's heat-trapping will prove costless or profitable.

- Recycling paper, or composting food and garden wastes, reduces landfill CH_4 output; saves the CO_2 and NO_x otherwise emitted when fuel is burned to produce and transport those materials; and saves money. Compost can also displace synthetic fertilizer, whose manufacture releases CO_2 and whose use releases N_2O. By improving tilth, compost can also help the soil to retain water, saving irrigation pumping energy and hence CO_2. If part of a locally based agriculture, compost can further help to substitute fresh food for perishable food refrigerated with CFCs and fossil-fueled power plants (~9 GW in the U.S.: Shepard *et al.* 1990, p. 115). Local agriculture can also save oil otherwise burned to transport food; the average molecule of American food has been estimated to travel ~1,200 miles before it's eaten.
- Native building materials such as adobe, caliche, mudbricks, rammed earth, etc. can displace CO_2-intensive production and transportation of cement. Sustainably grown timber or bamboo incorporated into buildings can also temporarily sequester carbon (Krause *et al. 1989*, p. I.3-14). Where timber is scarce, however, pressed-wood/paper-honeycomb materials can reduce tree use per building by up to ~90% at negative net cost, incidentally increasing the building's energy efficiency too (Hartwell 1990). Improved energy infrastructure, especially for more efficient use of fuelwood, can also divert large amounts of wood from fuel to fiber use (Leach & Mearns 1988, Goldemberg *et al.* 1988, Baldwin *et al.* 1985).
- Efficient motor vehicles can cost-effectively and simultaneously reduce emissions of CO_2, CO, O_3, N_2O, NO_x, SO_x, hydrocarbons, and other radiatively active gases or photochemical products such as peroxyacetyl nitrate (Krause *et al.* 1989). The reduced air pollution, especially O_3 (Newell *et al.* 1989), can also reduce forest death and other vegetative damage, maintaining more and healthier trees as carbon sinks. On a microdesign scale, more efficient car air conditioners, or reduced cooling loads due to such improvements as lighter-colored paint or spectrally selective glass, can reduce the inventories and leakage of CFCs, save compressor operating energy (hence CO_2), and save CO_2 in all driving by transporting a smaller, lighter compressor (Lovins 1991b).
- Electrical savings that displace new hydroelectric dams can achieve their fuel-saving goal but preserve the carbon inventories in the impoundment area's above- and below-ground biota, rather than emitting them both as CO_2 when the area is cleared and, even worse, as CH_4 after flooding converts it to an anerobic swamp. Since the electric savings are cost-effective (cheaper than the dam or a thermal power station), both these abatements cost less than zero.

Though not thoroughly catalogued or characterized, such multigas abatements will generally reduce the total cost of abating global warming by providing multiple benefits for single expenditures. Omitting them from supply-curve analyses is thus a conservatism. It may well be a significant one.

Supply curves for abatement

In 1989, the Amsterdam office of McKinsey & Co. prepared for the Dutch government one of the first attempts at a supply curve for global-warming abatements (Six 1990). It was explicitly illustrative and incomplete, but heuristically valuable. Since then, an increasing body of ever more detailed and empirically grounded evidence has taught two lessons: that using supply curves to relate the marginal quantities and marginal costs of abatement is a useful way to gain understanding of policy options, and that closer scrutiny tends to raise the quantities and lower the costs. For example, the data from one such compilation (ICF 1990) of diverse government and industry studies of the U.S. potential for abating emissions of CO_2, nonbiotic CH_4, and CFCs in 2010 are plotted in **Figure Four:**

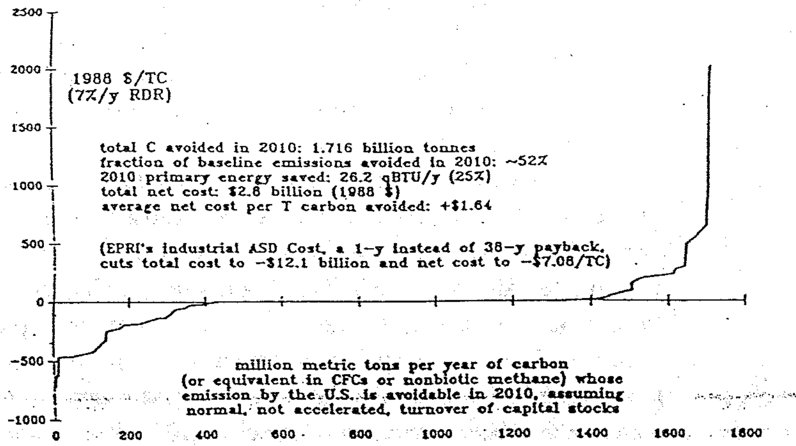

Figure Four: Supply curve, from data prepared by a USEPA contractor, of potential abatements of U.S. emissions of CO_2, nonbiotic CH_4, and CFCs in 2010 (ICF 1990[66]).

This curve's basic structure is arrestingly simple: a long flat section in the middle at roughly zero cost (the cheap CFC abatements, landfill and coalbed methane capture, and reforestation), plus "tails" of essentially equal area at both ends. These "tails" comprise chiefly ~25% energy savings at negative net cost on the left, and the costlier kinds of renewable energy and industrial fuel-switching at positive cost on the right (*i.e.*, costing respectively less and more than competing fossil fuels). The calculated potential reduction from this quite incomplete list of measures[67] totals 1.72 billion metric tons of carbon per year (GtC/y), or ~52% of the base-case emissions projected for that year. This large abatement is significant for two reasons:

- some major options, such as sustainable farming, forestry other than standard reforestation, most industrial and heavy-transport savings, and other trace gases, were not counted; yet
- the net private internal cost of halving the U.S. contribution to global warming is roughly zero.

A similarly conservative linear-programming optimization for The Netherlands (Okken *et al.* 1991) found a very similarly shaped supply curve (**Figure Five**). It counted only reductions in fossil-fuel CO_2, not other gases, and hence is akin to combining the left- and right-hand ends of the ICF supply curve. But this Dutch analysis found a 35% CO_2-saving potential in 2000 from measures *all* costing less than zero, whereas for the ICF study the corresponding figure was roughly 20%. The Dutch study found a net cost of ~$90/tC for CO_2 reductions totalling up to ~65%. As can be seen by comparison with Figure Four, this is a relatively modest cost for such a large fossil-fuel saving in a comparatively efficient country. The quantity of potential savings would of course be even larger if any credit were taken for the essentially free *non*-fossil-fuel abatements included in the middle portion of the ICF curve.

These large, approximately costless potential savings are qualitatively consistent with the findings of the Mitigation Subpanel of a 1991 National Academy of Sciences study (Evans *et al.* 1991).[68] The Subpanel analyzed, on

[66]Plotted from Tables 10-15; some utility-sector data in Table 14 differ from those in Appendix H, although their total differs little.

[67]As a small example, only half of the industrial motor-system retrofit potential was considered, and that half -- all from adjustable-speed drives (ASDs) -- was assigned a cost ~38 times EPRI's value (Fickett *et al.* 1990) or ~15x RMI's (Lovins *et al.* 1989). Correcting this apparent error changes the net cost of abating a ton of carbon-equivalent emission from +$1.6 to -$7.

[68]The Panel on Policy Implications of Greenhouse Warming of the Academy's Committee on Science, Engineering, and Public Policy, whose Synthesis Panel report was published 10 April 1991. The Chairman was Governor Dan Evans, a distinguished engineer and former

very conservative assumptions[69], a much wider range of technical measures (some of which the Subpanel felt might entail modest lifestyle changes). The Subpanel therefore found a larger abatement potential. The measures on which the Subpanel reached consensus could, if fully implemented, collectively abate ~61-64%[70] of 1988 U.S. contributions to global warming at an average net cost of -$6/tC -- again, slightly profitable rather than costly. (The range of average costs found was -$24 to +$9/tC.) The mean net cost would thus equal zero at a global-warming abatement somewhat larger than 61-64%. The report, citing IPCC (1990a), states that at least a 60% abatement is likely to be needed to stabilize the climate.

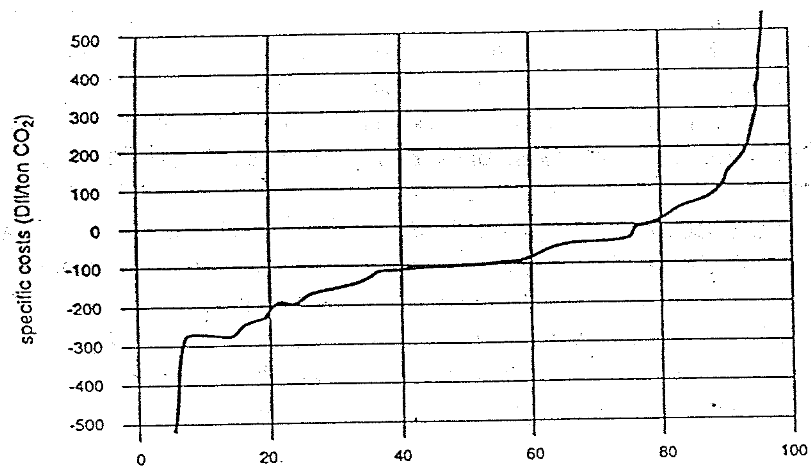

Figure Five: Supply curve (Okken *et al.* 1991, Fig. 3.13, reproduced by authors' kind permission) of Dutch fossil-fuel-CO_2 abatements from saving fossil fuel through end-use efficiency, small-scale cogeneration, and renewables, compared with a midcase projected emission of 224 million tons of CO_2 (excluding feedstock uses) in the year 2000. Of the 97 $MtCO_2$/y reduction potential shown, 80% is from end-use efficiency, of which 80% was found to be cheaper than the fuel it saved. Most of the latter measures were therefore included in the base-case projection. The list of measures considered was less complete than that evaluated in this paper, and was technically conservative (*cf.* Krause *et al.* 1991).

The point is not whether any of these three sets of figures is exactly right -- they all inevitably reflect many uncertainties -- but rather that sound public policy requires an open process to identify all the parts of such supply curves and harness the public's imagination and ingenuity in refining and achieving each. It should be possible to reach near-agreement about the numbers, or at least to understand the origins of residual disagreements.

Chair of the Northwest Power Planning Council. The report will be a valuable contribution to public policy formation. Its main shortcomings include outdated energy-efficiency potential, inadequate attention to less conventional forestry options and to organic agriculture, omission of multigas abatements, and an excessively restrictive and short-term view of renewable energy potential (SERI 1990). Improving the analysis in any of these respects would raise the calculated abatement and lower its cost (*infra*).

[69]The mean potential savings assumed included 20% in household refrigerators and dishwashers (compared to a cost-effective potential with best present technology -- see citations in the first part of this paper -- of >90% in prototypes *vs.* the present stock), zero in other household appliances (typically two-thirds or more in models entering production), 25% in commercial cooking and commercial/industrial space-heating (>50% and ~100% in conventional equipment), "up to 30%" for all industrial electricity and fuel (>50%), 40% for commercial ventilation (>70%), 45% for commercial lighting (~70-90+%), 50% for residential space-heating and commercial water-heating (~100%) and for commercial space-cooling (~80+%), and 55% for residential water-heating (~65-100%). Light vehicles were taken only to 25 on-road mi/gal without, or 36 with, reductions in size or performance, and similarly with other transportation modes. The Subpanel did not examine the RMI/COMPETITEK analyses cited earlier.

[70]The quantities of savings cited add up, corrected for interactions, to 61%; their cited percentage savings, to 64%. It is not clear which set of figures is more accurate.

As a small initial contribution to that goal, how might the additional opportunities described earlier in this paper change the conclusions of the ICF or NAS analyses? Qualitatively, these extra options would clearly have two effects: reducing global warming even more, and converting those studies' low net cost to a substantially negative net cost, whether for the United States or worldwide. The rough magnitude of some of these changes can be estimated as follows:

- The Academy apparently assumed industrial electricity-saving potential equivalent to about one-third of the savings that RMI has demonstrated (Lovins *et al.* 1989) and EPRI concurred with (Fickett *et al.* 1990) for motor systems *alone*. The RMI/EPRI-agreed cost of such savings is also an order of magnitude lower. Ignoring the substantial non-motor electricity-saving possibilities, just substituting the RMI/EPRI motor findings would therefore triple the saving and cut its cost (*i.e.*, increase its net present-valued financial saving) by about $60 billion. Considering industrial fuel savings more fully, and taking full credit for industrial energy savings from the leaner materials flows described earlier, would also yield major gains. So would substituting the gas saved in industrial and building heat for more carbon-intensive fuels.
- EPRI's assumed potential for electricity savings in buildings was presented to the NAS panel as 45% at an average cost of 2.5¢/kW-h. Yet detailed, empirically based retrofit analyses for Arkansas, which has a slightly more difficult climate than the U.S. average, found a retrofit potential to save 77% in houses at 1.6¢/kW-h and 74% in commercial buildings at -0.3¢/kW-h (Lovins 1989).[71] More recent developments (Shepard *et al.* 1990) would support even more favorable results, but just the Arkansas results would raise the EPRI/NAS building-electricity carbon saving by two-thirds and nearly double its net financial saving.
- The 50% fuel saving assumed in buildings is smaller and costlier than the potential found by a major Federal study a decade ago (SERI 1981), and improvements in the building stock meanwhile do not seem to account fully for the difference. Such key developments as superwindows, whose simpler versions have captured a large share of the U.S. insulated-glass market in the past few years, were not considered. Interestingly, the Arkansas house-retrofit analysis just cited found that gas savings of 60% would result at *no* extra cost as a free byproduct of the 77% electric savings -- or far more, at modest cost, if the gas appliances were also made more efficient. In an era when skilled practitioners can retrofit superinsulation that saves most, or in some cases nearly all, space-heating, and retrofit savings of two-thirds of water-heating fuel are straightforward, a 50% fuel-saving potential is clearly outdated.
- U.S. cars and trucks alone released ~0.32 GtC in 1988 (Rowberg 1990), or 14% of the U.S. contribution to global warming (ICF 1990); all transport modes, 20%. Since most of that consumption can be saved at negative cost, as was documented earlier, today's most efficient transportation technologies (Lovins 1991b) (let alone further system-design improvements) could probably increase the total abatement potential by ~15+ percentage points -- several times the assumption in the Academy's less complete survey.
- The renewable energy potential considered economically competitive in the recent Interlaboratory White Paper (SERI 1990) -- *i.e.*, cheaper than the internal cost of carbon-emitting alternatives -- is officially

[71]The residential retrofit, costing ~$5.5k in a typical 127-$m^2$ frame house, includes improved insulation, superwindows added over the existing single glazing, reduced infiltration, light-colored wall paint, lights and appliances comparable to the best European models, a hot-water-saving package, and an air conditioner whose more than doubled efficiency (to COP = 4.54) was nearly paid for by making it two-thirds smaller. The resulting package -- carefully chosen after rejecting nearly 100 other options -- was simulated to save 77% of annual and 83% of peak electric use (and, fortuitously, 60% of the gas without improving the gas appliances) with a 2.9-year retrofit payback at measure prices determined from local quotations, Arkansas Energy Office field experience, and standard R.S. Means construction-cost data. The commercial-sector retrofit included ~100 measures: the lighting package discussed earlier, standard improvements to space-cooling and air-handling systems, some shell improvements (anti-gain window films, lighter roof color, etc.), and better internal equipment (refrigeration, computers, etc.) and building controls. Interactions were explicitly accounted for. The cost of nearly doubling the efficiency of replacement chillers was negative because it was less than the cost saved by downsizing to accommodate the reduced cooling loads. The ~76% calculated electric savings cost slightly less than zero because the savings in lighting maintenance costs (chiefly from replacing incandescent with modular compact fluorescent lamps) paid for the lighting equipment with more than enough money left over to pay for all the non-lighting improvements too.

projected to be adequate, in concert with even cheaper energy efficiency, to displace most or all of the U.S. fossil-fueled power stations now operating or planned for the next few decades, plus much direct fuel.[72] Since most of the world, especially the most populous parts, has a renewable energy potential broadly comparable or superior to that of the United States (Sørensen 1979, Lovins *et al.* 1981), the same conclusion should hold generally. Any serious long-term energy scenario must therefore consider carefully the opportunity to squeeze down fossil-fuel use between efficiency and renewables.[73]

- It is not clear that zero- or negative-cost forestry options, such as urban forestry and maintenance of old-growth forests, have been properly taken into account. Similarly, using organic agriculture to change 50 million hectares of American farmland to a carbon sink, on the assumptions described earlier, would reduce U.S. contribution to global warming by 1%[74], nearly as large as the Academy's assumed savings of oil and gas in commercial buildings. The cost of this extra 1% abatement would be negative, because such practices are probably more profitable for the farmer (NRC 1989, Brody 1985, Bossel *et al.* 1986, Bechmann 1987, McKinney 1987). But as noted above, Holmberg's (1988) assumptions about carbon uptake may well be conservative by at least severalfold.
- Adding synergisms between measures, described earlier as "multigas abatements," should further improve the total abatement potential and its economics.
- Like most such analyses, the Academy study assumed that saving electricity would displace the *average* kW-h generated. However, "environmental dispatch" in which the most carbon-intensive (or otherwise polluting) power stations were backed out first would save ~59% more carbon per kW-h (Rosenfeld & Meier 1990). This would be a natural consequence of internalizing external costs, such as the 5.8¢/kW-h authoritatively estimated for coal-fired electricity in the United States (Ottinger *et al.* 1990). Since ~17 state utility regulators across the U.S. have already adopted this practice for planning in some degree, another 20+ are currently doing so, and all OECD member nations officially accept the principle of internalization, it is probably only a matter of time before economic dispatch of power stations starts taking avoided pollution-, including carbon-, abatement costs fully into account.

A simple thought-experiment illustrates the importance of giving the energy-efficiency potential the most searching and up-to-date possible scrutiny:

- In 1989, Americans paid $453 billion at retail for commercial fuels and power (Rosenfeld *et al.* 1990, 1989 $).
- The U.S. energy system is quite competitive in most respects.[75] Competitively providing the world's commercial energy would therefore probably cost, shorn of taxes and subsidies, not far from the same amount per joule.
- Scaling up for consumption yields an internal shadow expenditure for global retail energy on the order of one and two-thirds trillion dollars per year. (We use this very rough estimate because actually quoted prices often do not reflect actual costs.)
- Just the potential described earlier for directly saving electricity and oil would save upwards of three-fourths of that energy, and at typical late-1980s energy prices, would repay the savings' cost in a few years.

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[72] The total cost-effective renewable energy output in 2030 was projected to be 37-67% as large as current U.S. total primary energy use.

[73] Assistant Secretary of Energy J.M. Davis has recently presented such a "jaws" scenario -- conceptually an updated version of a "soft path" scenario published 14 years earlier (Lovins 1976), and driven by identical economic logic.

[74] Its global significance would be far greater -- on the order of 0.7 GtC/y if successfully applied throughout the world's 1.5 billion hectares of cultivated land (Krause *et al.* 1989, p. I.3-33).

[75] Direct Federal subsidies reduced the apparent total energy bill by ~10% in FY1984 (Heede *et al.* 1985), but became smaller in 1986, so the overall distortion is probably lower now, though it may be more unevenly allocated between competing options.

- The savings would be slightly smaller and costlier in the most efficient OECD countries, but substantially bigger and cheaper in other countries. The U.S. potential would thus be a reasonable-to-conservative global average.
- The present-valued cost of such large savings was shown above to be on the order of a tenth of present energy prices.
- Subtracting that tenth from the gross savings leaves a potential long-run net monetary saving[76] of at least $1 trillion a year from fully implementing the efficiency opportunities described.

That is about as big as the global military budget. The money now wasted on inefficiently used energy is certainly needed for more productive purposes than wasting energy. But more importantly for the purposes of this paper, the negative-cost energy savings that yield this ~$1-trillion-a-year of net wealth creation represent probably the cheapest increment of global-warming abatement. Cheap energy efficiency can reduce global warming by about a third -- *and free about a trillion saved energy dollars per year to pay for other abatements, with money left over.* Recent official assessments show abatements in the ~50-64% range at roughly zero net cost despite assuming energy savings several times smaller and costlier than those demonstrated above. But those studies slighted the modern energy-efficiency potential (and some other opportunities too). Properly counting that potential is thus bound to abate even more global warming, and to change the total net internal cost of abating global warming from about zero to a value robustly less than zero.

It is also important to note that a trillion saved dollars per year is so much money that it can buy a great deal of additional abatement even at relatively high unit costs. For example, many of the costlier ways to achieve the last pieces of abatement required for climatic stabilization might cost (say) $165 per ton of carbon. If so, then the net money saved by the energy efficiency program could buy six billion tons of carbon abatement per year -- about equivalent to today's entire global output of CO_2 from all combustion processes. Since most of that fossil-fuel CO_2 would already have been abated by the energy efficiency itself, and since most other kinds of abatement (biotic carbon, CFCs, and most CH_4 and N_2O) appear, as noted above, to be relatively inexpensive, it is not easy to construct an optimized menu of abatements that could stabilize the climate *without* having a considerable amount of money left over. In other words, although the amount of money that energy efficiency can save is not precisely known, it is clearly large enough to ensure a financial surplus despite the considerable uncertainties about how much the non-energy abatements may cost.

Opportunity cost requires "best buys first"

There is, however, one caveat requiring emphasis. To abate global warming promptly with finite resources, *it is vital to choose the best buys first.* This is because of "opportunity cost" -- the impossibility of using the same money to buy two different things at the same time.

If, for example, you spend a dollar on a costly source of electricity, such as nuclear power or photovoltaics, then you'll get relatively little electricity for that dollar -- that's what "expensive" means. You'll therefore be able by such means to displace little coal-burning in power stations. But if you use the dollar to buy a very cheap option instead, such as superefficient lights or motors, then the resulting bounty of electricity could displace a lot of coal. Therefore, whenever you spend the dollar on a costly option *instead of* on a cheap one, you'll unnecessarily release into the air the extra carbon that would not have been released had you bought the cheapest option first. That is why, for example, nuclear power makes global warming worse:[77] it emits less carbon per dollar

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[76]Long-run because the sunk capital costs of the energy system cannot be saved in the short run, but re-incurring those costs -- rolling over retiring capacity into replacement capacity -- can still be avoided by achieving durable, reliable, long-term efficiency gains.

[77]Algebraically, if K is the carbon intensity of existing coal-fired plants (in tC/kW-h), C_n is the levelized cost of a marginal nuclear kW-h, and C_e is the levelized cost of a marginal saved kW-h (both in $/kW-h), then $K([C_n/C_e] - 1)$ tons of extra carbon are released per kW-h made in a new nuclear plant instead of saved by improved end-use efficiency. This assumes simple fungibility of dollars between the two investments. Recent experience of the U.S. utility industry, however, suggests that matters are actually worse: when utilities overinvested

than coal-fired plants, but in this opportunity-cost sense, many times more than efficiency (Keepin & Kats 1988 & 1988a; Lovins 1989c).

This is not an academic point; it is at the crux of essential policy choices. Investors must understand which options are cheapest, hence most profitable, and policymakers must avoid or amend regulatory structures that divorce these two attributes. Even in societies where capital is allocated by planning rather than by markets, the planners must be able and eager to determine the best buys and then buy them. *Any other sequence of investments prolongs and enlarges climatic risk.* We therefore turn next to how the least-cost investment sequence can actually be discovered, bought, and successfully marketed and delivered in diverse societies.

Implementation techniques

The foregoing discussion has highlighted both commonalities and differences among the technical options available to the world's three main regions. In all regions, for example, energy efficiency is an urgent priority, though for somewhat different reasons: for example, high energy efficiency in industrialized countries is vital to global climatic protection and is economically valuable for those countries, while high efficiency in the other two regions is currently less important for the world but economically vital to their own development (which would in turn raise their CO_2 output to the majority of the global total). Moreover, non-OECD countries now building infrastructure and stocks of consumer goods have a chance to build in efficiency from scratch, often as a natural and inexpensive feature of investments they are making anyhow, whereas OECD faces the daunting task of retrofitting trillions of dollars' worth of obsolete buildings and equipment.

Most instructive, however, are the differences in and synergisms between implementation strategy in the different regions. Many of these have been extensively treated in a huge literature, so we seek here only to summarize main points that may previously have been overlooked or underrated.

OECD countries

The OECD countries emitted nearly three-fifths of 1950-86 fossil CO_2 (Krause *et al.* 1989, p. I.1-9) and cause the lion's share of global warming today. They have such large economies largely because they have vigorous markets[78] with high innovation rates and rapid discovery, application, learning, and corrective feedback in most sectors. Most OECD countries also have a powerful public consensus for environmental protection. That is why, for example, government policy is committed to major CO_2 reductions in West Germany, Denmark, and the

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in capacity by ~$200 billion, many, seeking to recover sunk costs, turned their efficiency departments into surplus-power marketers, making power-plant dollars not just a neutral complement to but a direct enemy of efficiency dollars. Thus EPRI estimated a few years ago (1986) that today's "strategic marketing" programs will directly result, by 2000, in some 35 GW of new *on*peak demand -- about two-thirds of the savings projected from the industry's efficiency programs. Whenever nuclear investments, therefore, mean not only foregoing an efficiency investment but deliberately seeking to boost electric demand, more carbon will be released than C_n/C_e would indicate.

[78]Centrally planned exceptions, such as the French electric sector, are likely to prove short-lived when 1992 European economic integration unleashes new competitive pressures and transparent-pricing requirements. Increasing North American integration under Canadian and (soon) Mexican free-trade agreements will similarly hone competition. Some economies, such as Sweden's and Japan's, and in some respects the EEC itself, are more properly regarded as mixed, with an overlay of sophisticated public-sector planning and coordinating apparatus. Yet the vitality of the market sector, the diversity of the public institutions within OECD, and the forces of market and political accountability in most OECD countries have permitted as impressive a range of initiatives to flower in the mixed as in the most *laissez-faire* economies.

Australian State of Victoria[79], to CO_2 stabilization (variously defined) in Britain, Sweden, Canada, and Japan, and to stabilization followed by reduction in The Netherlands and Norway.[80]

This region is ideal for adopting and adapting the best worldwide experience of market mechanisms for capturing profitable global-warming abatements. Favorable conditions include widespread acceptance of the polluter-pays principle[81]; availability of generally sound statistical data and reporting systems; widespread sophistication in industrial organization to meet financial objectives; a large population of skilled entrepreneurs; and the world's highest mobility of labor, capital, and (most importantly) information.

Although most Western European "Greens" traditionally distrust markets and the private sector, there are clear signs that many are starting to appreciate the power of properly structured and informed markets[82], hence the importance of ***making markets in avoided depletion and abated pollution*** (Lovins 1989). The basic concept is simple: economic *glasnost* -- prices that tell the truth -- can scarcely achieve efficient behavior without a market where the buyers and sellers of technological solutions can meet and do business. My potential loss from a carbon tax must be convertible to your potential profit from selling me a more efficient lamp. If I can't buy that lamp, my only response is a behavioral change (using a dimmer lamp or using it less often), which is relatively weak and impermanent.

Ways to make markets in saved energy and water, developed at Rocky Mountain Institute and elsewhere, are now entering widespread use both in the United States and abroad. Based on successful early experience, they show promise of accelerating energy efficiency and appear applicable also to other key ways to abate global warming, as described next.

Energy

Electric utilities

More than half of Americans can already get financing from electric utilities for electricity-saving equipment, in the form of concessionary loans, gifts[83], rebates, or leases (Fickett *et al.* 1990, Lovins & Shepard 1988). Such financing is essential because customers typically want to get their energy-saving investments back within a couple of years, whereas if they don't become efficient and the utility builds a power station instead, *its* technical and financial strengths enable it to accept a payback period closer to 20 years (*id.*). This roughly tenfold "payback gap" is rational to both parties, but societally, it causes a severe misallocation (~\$60 billion a year in the U.S. in the mid-1980s) by effectively diluting price signals tenfold. Utility financing -- ~\$2 billion in 1991 -- helps to close this gap by reducing customers' implicit >60%/y real discount rate approximately to utilities' ~5-6%/y (*id.*).

[79] The German proposal, whose implementation is being worked out, is to reduce CO_2 emissions by 25% of 1987 levels by 2005. A stricter proposal, with very large long-term reduction targets, was overwhelmingly recommended by the Enquête-Kommission of the Bundestag, which has produced two excellent reports on the subject. Victoria has also adopted the 25%-reduction Toronto goal. Denmark's plan calls for 20% reductions by 2005 and 50% by 2030.

[80] There is no analogous U.S. policy, apart from some commendable state initiatives (Calwell *et al.* 1990, p. 12); on the contrary, in both global warming and ozone protection, a strong consensus in the rest of OECD was openly thwarted by U.S. representatives during 1989-90. At this writing, the US and Turkey are the only OECD countries lacking CO_2 targets.

[81] Finland and The Netherlands introduced carbon taxes in early 1990, Sweden will do so in January 1991, and Germany is weighing one.

[82] Acknowledging this trend, in Royal Dutch/Shell's latest Group Planning scenarios, the "Sustainable World" scenario was somewhat *dirigiste* as first drafted, but was changed to rely far more on market forces -- logically enough, since its options cost less.

[83] Southern California Edison Company, for example, has given away more than a million compact fluorescent lamps, because that was cheaper than operating the company's existing power plants.

Utility financing of efficiency enables all supply- and demand-side options to compete on a "level playing field." Such competition, through either a planning or a market process, is now mandatory (to varying practical degrees) in the ~43 states with a "least-cost utility planning," or best-buys-first, policy (Moskovitz 1989). Such financing works so well that if all Americans saved electricity at the same speed and cost at which the ~10 million people served by Southern California Edison Company *did* save electricity during 1983-85, chiefly financed by SCE's rebates, then national forecast needs for power supplies a decade ahead would decrease by ~40 GW/y, at a total cost to the utility of ~1% of the cost of new power stations (Lovins 1988 [p. 171] & 1985 [pp. 180-183], Fickett *et al.* 1990, SCE 1985).

This sort of service-delivery, engineering-driven model of how utilities promote customers' efficiency gains retains an important place in dealing with specific market failures, such as the split incentives between builders and buyers or landlords and tenants. (Government performance standards and labels are also a key part of the policy toolkit in such situations.[84]) But a complementary approach is now starting to supplement and might ultimately supplant the "we-will-wrap-your-water-heater" philosophy. Rather than merely marketing "negawatts," many utilities are also starting to make markets *in* negawatts: to make saved electricity into a fungible commodity subject to competitive bidding, arbitrage, derivative instruments, secondary markets, etc. For example, some utilities are

- buying back savings from customers by paying "generic rebates" per kW-h or peak kW saved -- including rebates for beating government standards or for scrapping old equipment;
- in eight states, operating "all-source bidding" in which all ways to make or save electricity compete in open auction and the utility takes the low bids, which are generally for efficiency[85];
- starting to buy saved electricity from other utilities -- a form of arbitrage on the difference between the cost of supply and efficiency;
- considering making spot, futures, and options markets in saved electricity (an electricity futures market was in fact launched in Britain in spring 1991);
- exploring ways to broker saved electricity between customers, rewarding any customers who goes "bounty-hunting" by correcting inefficiencies anywhere in the system[86];
- selling electric efficiency in *other* utilities' territories (Puget Power Company, for example, sells electricity in one state and efficiency in nine states); and
- in seven states, considering or experimenting with sliding-scale hookup fees for new buildings -- "feebates" whereby the builder either pays a fee or gets a rebate when the building is connected to the grid (which and how big depends on the building's efficiency).[87] Feebates can offer major economic advantages to all the parties, can generate tens of thousands of dollars' net wealth per U.S. house so built, and are readily coupled with efficiency labelling.

In addition, gas utilities can make money selling *electric* efficiency, thereby changing the behavior of buildings in ways that also help them open up new gas markets (Lovins 1988). Electric utilities can also sell gas efficiency,

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[84]California's Title 24 building standards alone, now saving the state's citizens ~$1 billion worth of electricity every year, are a good model of how to combine performance standards with prescriptive options to reduce hassle to the builder.

[85]Maine, largely through such bidding, also raised its private, mainly renewable, share of power generation from 2% in 1984 to 20% in 1989 to ~37% in 1991, according to former Maine Public Utilities Commission Chairman David Moskovitz.

[86]This has already been done with saved water (Menke & Woodwell 1990, p. 21). All the other mechanisms described here are also being applied to water efficiency, and many appear useful for other resources or for services such as transport (Lovins 1989).

[87]Formally, the "feebate" should satisfy three boundary conditions: revenue-neutrality (the fees pay for the rebates); fees for inefficient buildings are based on long-run marginal costs including externalities; and rebates exceed the builder's marginal cost of achieving the efficiency. The slopes and intercepts can be adjusted annually as needed to maintain these conditions. When construction of inefficient buildings has been driven off the market, one can declare victory and stop.

and both should be rewarded for selling either. Wisconsin's utility regulators are even considering ordering that state's utilities to help customers switch to any competing energy form that costs less.

Rapid experimentation in these and other market-making methods has been facilitated by the great diversity of the U.S. electric utility system: ~3,500 utilities of all shapes and sizes in ~50 major and hundreds of minor regulatory jurisdictions. Although learning is often painfully slow, with many utilities still reporting relatively small, slow, and costly savings (Nadel 1990), new results are encouraging. A few years ago, some utilities had captured ~70-90+% of particular efficiency micromarkets, mainly difficult ones (residential shell retrofits), in only one or two years[88]. In 1990, greater marketing experience (Lovins & Shepard 1988a) has enabled, for example, New England Electric System to capture 90% of a small-commercial pilot retrofit market in two months, and Pacific Gas & Electric Company to capture 25% of its entire new-commercial-construction market -- 150% of the year's target -- in three months, (PG&E then raised its 1991 target, and captured all of it in the first nine days of January.)

Such entrepreneurship is being encouraged by a nationwide agreement in principle among U.S. utility regulators[89] to change the rules of price formation so as to ensure that utilities' cheapest options are also their most profitable ones. Although many ways to do this are available (Moskovitz 1989), the most common is to decouple utilities' profits from their sales and then let them keep as extra profit part of what they save their customers. Under a new policy approved in summer 1990, for example, Pacific Gas & Electric will be allowed to keep 15% of certain savings -- adding ~$40-50 million to its 1991 profits. But the customers are better off getting 85% of an actual, prompt saving than getting all of nothing. At this writing, five states have approved such reforms and another 20+ are doing so. The previous regulatory scheme rewarded utilities for selling more electricity (or gas) and penalized them for selling less. Similar perverse incentives still exist in many countries, despite the diversity of utility structures, and can be corrected by similar means.

More than a dozen states' least-cost planning comparisons, too, already credit efficiency and renewables, or penalize their competitors, with shadow prices reflecting externalities (Ottinger *et al.* 1990); more than half the states are expected to do so by the end of 1991. The correct externality values are not exactly known, but they certainly exceed zero, so in adopting a nominal figure, the New York Public Service Commission's Chairman, Peter Bradford, notes that it is better to be approximately right than precisely wrong. This approach, too, is attracting considerable interest in Europe.

These regulatory moves toward simulating efficient market outcomes have accelerated the already rapid shift in U.S. utilities' culture and mission, away from selling more kilowatt-hours and toward the profitable production of customer satisfaction (Fickett *et al.* 1990). About a third of U.S. utilities have already made this transition. Selling more efficiency may reduce their electric sales and revenues, but their costs go down more; and under the new rules, they can keep part of the difference, making money on margin instead of volume. Such a utility can indeed make money in six ways: it saves operating, construction, and replacement costs, plus associated risks and externalities; under the new U.S. Clean Air Act its fuel savings will be able to generate tradeable emission rights (currently for acid gas, but extendible by future legislation to fossil carbon); as soon as its regulators reform their ratemaking rules, it will be specifically rewarded for efficient behavior; and it can earn a spread on financing customers' efficiency improvements.[90]

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[88]*E.g.*, the Hood River County experiment in Oregon, and several Iowa municipal utilities' load-management promotions. In at least one case -- water-heating wraps in Osage, Iowa -- reported market capture was 100%.

[89]Unanimously approved by the National Association of Regulatory Utility Commissioners in November 1989.

[90]Arbitrageurs get rich on spreads of a fraction of a percent, but the difference in discount rates between utilities and customers is more like a thousand percent.

Oil efficiency

Analogous concepts are starting to enter the oil-efficiency market. Most importantly, on 30 August 1990, the "Drive+" feebate proposal passed the California Legislature with overwhelming bipartisan support[91] (Levenson & Gordon 1990). This bill would enact a revenue-neutral, open-ended sales-tax adjustment based on both fuel efficiency (measured as CO_2 emissions per mile) and smog-forming emissions. Buyers of dirty, inefficient cars would pay two fees; buyers of clean, efficient cars would get two rebates. By influencing car choice directly, feebates could overcome the ~6:1[92] dilution of gasoline prices by the other costs of owning and running a car. Governor Deukmejian vetoed Drive+ on 30 September 1990, but it seems likely to become law in 1992, perhaps volume-normalized. Drive+ may then launch a national trend. Similar proposals are pending in Iowa and Massachusetts, are being drafted in other states, and have been proposed nationally.

This rapidly spreading idea has gotten several of the makers of superefficient prototype cars seriously interested in entering the U.S. market immediately, in order to maximize their share of the early adopters' market. Interestingly, General Motors did not oppose Drive+ in 1990, reportedly because the company prefers market-oriented feebates to standards or other direct regulations.[93] Nor did the White House's generally anti-efficiency National Energy Strategy (February 1991) explicitly exclude feebates.

A useful early refinement to basic feebates would be "accelerated scrappage": basing rebates for efficient new cars on the *difference* in efficiency between the new car and the old one that is scrapped (if it is worse than a certain level). Drivers who scrapped a functioning car and didn't replace it would get a bounty on presenting a death certificate that it had been duly recycled. By offering a far higher price for scrappage than dealers offer for tradeins, the state would put a premium on getting the least efficient, most polluting cars off the road soonest. This incentive would greatly accelerate the energy and pollution savings. It would also help poor people, to whom the worst cars tend to trickle down[94], to afford to buy a highly efficient new car that they could then afford to run.

Such feebates have wide potential application. They could spread from cars, light trucks, and buildings to appliances, aircraft, heavy road vehicles, etc.[95] In each case, they would transfer wealth from those whose inefficient choices impose large external costs on society (global warming, acid rain, oil-import dependence, etc.) to those who save such costs. Their self-financing makes them politically attractive, as the California Legislature's vote confirms. They entail three straightforward steps: set a target level of efficiency; charge an open-ended variable fee for all new devices that are worse; and rebate the fees (less administrative costs), also on an open-ended variable basis, to all new devices that are better (Rosenfeld *et al.* 1990a).

Feebates could be usefully supplemented by three further policy innovations:[96]

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[91]By 61-11 votes in the Assembly and 31-2 in the Senate.

[92]In the United States at pre- or post-Gulf-crisis prices; typically the ratio is nearer ~3-4:1 in other OECD countries with higher motor-fuel taxes, and 8:1 in some US cases.

[93]The Corporate Average Fuel Economy (CAFE) standards passed by Congress in 1975 were "at least twice as important as market trends in fuel prices, and may have completely replaced fuel price trends as a base for long-range planning about [new-car efficiency]" (Greene 1989), but improved standards would be well complemented by feebates, which reward manufacturers for bringing the best technologies to market soonest and reward buyers for choosing the best from the mix offered.

[94]And whose inefficient cars, despite their fewer miles driven per car, were disproportionately responsible for imports of the same Gulf oil that those same poor people were sent in disproportionate numbers to defend.

[95]Draft recommendations by the California Legislature's Joint Committee on Energy Regulation and the Environment (12 September 1990) include feebates for buildings *and*, on a pilot basis, appliances.

[96]A possible fourth, a novel "pay-as-you-drive" way to charge for car insurance, is starting to receive scrutiny too (El-Gasseir 1990).

- In many EEC countries, and some others like New Zealand, much urban commuting -- often half or more -- is in company-owned cars, provided as a perquisite because this form of compensation is taxed less than equivalent salary (or not at all). This tax dodge is often meant to inflate domestic car sales for the benefit of domestic automakers. It contributes disproportionately, however, to congestion and hence to fuel waste and pollution. Since removing even a small number of cars from a crowded highway can markedly relieve its congestion, eliminating tax breaks for company cars should be a high priority.
- Greater symmetry between modes of transport requires that cars pay more of the cost of providing their infrastructure. Singapore, Oslo, and Bergen, for example, limit traffic by a no-exceptions daily tax on downtown driving. In an even more interesting system being introduced in Stockholm, downtown residents who wish to drive their cars during a given month must buy a permit which also serves as their free pass to the regional public transit system for that month. Then they have it, so they might as well use it.
- "Golden carrot" rebates are designed to elicit the production of specific energy-saving products that are cost-effective but are not yet brought to market because cautious or undercapitalized manufacturers are unwilling to risk retooling costs for uncertain sales. This concept could be adapted to saving oil from its current uses in saving electricity. For example, utilities from San Diego to Vancouver may soon join together to pay, say, a $300 rebate for each of the first 10,000 or 100,000 refrigerators sold in their territories that beat the 1993 Federal efficiency standard by at least 50%.[97] Such incremental efficiency would require one or more of the advanced insulating materials mentioned above to be put into mass production. If the refrigerators are not sold, no rebate is paid, so the utility is at no risk of not getting the desired savings; and once that many *are* sold, the manufacturing hurdle has been leapt, the special rebates can be discontinued, and continuing sales will then yield far larger savings. A larger "platinum carrot" can then be offered for the next incremental advance, and so on until cost-effective opportunities are exhausted. This proposal was originally developed for North American electric utilities and appliances, and has in fact been successfully applied by the Swedish National Energy Commission (Statens Energiverket) to refrigerator design. It is now being considered by other European and South Pacific electric utilities. There is no obvious reason why it could not be offered by governments and applied to other products such as light vehicles, in addition to or in lieu of feebates.

So far, less progress has been made in fundamentally changing mission and culture in free-market oil companies than in regulated, franchise-monopoly utility companies. But there are strong reasons for private oil companies, too, to promote customers' energy efficiency (Lovins & Lovins 1989):

- Under long-run competitive equilibrium conditions (ignoring fluctuations as war or peace breaks out in the Middle East), the major oil companies expect fairly flat long-term real prices, implying little prospect for large upstream or downstream rents. The major rent still largely uncaptured is the spread between the cost of extracting and of saving barrels.
- With long-run real oil prices fluctuating between, say, ~$12/bbl and ~$25/bbl, it is easier to make one's margins selling "negabarrels" that cost $5 to produce than barrels costing $15.
- Selling a variable mixture of fuel and efficiency can be used to hedge risks in supply-side markets (*id.*).
- Efficiency can fundamentally reduce long-term price volatility (*id.*), benefiting a capital-intensive industry.
- Efficiency promotes global development, which is good for the oil business, and deflects Persian Gulf wars, acid rain, and global warming, which are bad for it.

For these and similar reasons, several major and independent oil companies are starting to express interest in significant commitments of effort and resources to marketing efficiency. Some of these firms are, in essence,

[97] This scheme is promoted by A.H. Rosenfeld (Lawrence Berkeley Laboratory) and R. Cavanagh (Natural Resources Defense Council, San Francisco), and has already been accepted by the main utilities involved.

very large, technically oriented banks, and are starting to realize that they can get better at selling financial products, such as leasing efficient end-use technologies. Indeed, investing in retooling to make superefficient cars could hedge against those cars' successful oil savings.

Generic issues

The main cultural obstacles to this transition in oil companies, as in many utilities, are changes in mindsets: selling services rather than commodities, working on both sides of the customer's meter or the vendor's pump, and getting used to doing fewer big things and more smaller things. This difference of unit scale is perhaps the most uncomfortable, because traditional energy-supply systems are ~5-8 orders of magnitude larger than end-uses. But such large scale is not technically or logically necessary, and often it is not economic either. The well-known economies of scale in engineering and manufacturing certain energy systems can easily be swamped by even a small subset of the dozens of known *dis*economies of scale[98]. There is now abundant empirical evidence that minimizing whole-system cost generally entails matching scale, at least roughly, between supply and end-use. This does not mean that everything should be small: it would be nearly as silly to run a huge smelter with thousands of little wind machines as to heat millions of houses with a fast breeder reactor. But it does mean that making supply systems the right size for the job usually makes them cheaper.

Oil and gas companies are starting to compete in electricity markets by promoting smaller-scale technologies such as packaged gas-fired cogeneration plants, steam-injected gas turbines, and combined-cycle retrofits of classical combustion turbines. By some estimates, private additions to U.S. generating capacity exceeded utility additions starting in 1990 (Borré 1990). The 27 states that recently ran supply-side auctions were offered, on average, eight times as much private generation as they wanted (Blair 1990).[99] Fuel vendors are becoming significant players in this competition. Gas companies diversifying downstream now routinely note that building and running a gas/combined-cycle power plant undercuts just the *running* cost of a typical nuclear plant. As oil and gas companies increasingly bundle both electric and gas efficiency with downstream applications of their fuels, they become involved with customer scale and start to think more like customers.

Another obstacle being slowly overcome is the pervasive asymmetry in public policy, long dominated by special interests subject to scant performance accountability. Public policy in almost all countries has for decades been overwhelmingly biased toward supply over efficiency, depletables over renewables, electricity over heat and liquids, and centralization over appropriate scale. There are reasons for this, but they are certainly not economic reasons. They are the same reasons that efficiency got 2.8% and renewables 3.1% of USDOE's FY1988 proposed civilian RD&D budget, *vs.* 12.4% for fusion, 16.6% for fossil fuels, and 11.1% directly for fission; or that U.S. fission, after decades' devoted effort, continues to receive strong policy support despite having missed its cost target by an order of magnitude, while renewables, which quickly met or bettered *their* cost targets and now deliver twice as much energy (Lovins & Lovins 1989), continue to be dismissed as futuristic or impractical. Too often, the balance of official effort between competing options is like the old recipe for elephant-and-rabbit stew: one elephant, one rabbit. But in the U.S., the EEC, and many developing countries, the pendulum is starting to swing towards economic rationality, if only because there is no longer the capital to misallocate.

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[98]These arise from, *e.g.*, higher distribution costs and losses, reduced unit availability, increased reserve requirements, longer lead times (hence greater risks of cost escalation, technical or political obsolescence, or mistimed demand forecasts), higher ratio of onsite fabrication to factory mass-production, more difficult maintenance, greater awkwardness of using waste heat, etc. — ~50 identified mechanisms in all (Lovins & Lovins 1982, App. 1).

[99]Many, but not all, of these proposals could be relied upon to yield actual, reliable capacity if accepted. Opinions differ on the "real" fraction. Many utilities have also found private cogeneration to be more reliable than their own central plants.

These frustrating, though gradually resolving, problems must not obscure the major gains already made. During 1979-86, for example, the United States got more than seven times as much new energy from savings[100] than from all net expansions of supply, and more new supply from sun, wind, water, and wood than from oil, gas, coal, and uranium (Lovins & Lovins 1989). By 1986, U.S. CO_2 emissions were *one-third lower* than they would have been at 1973 efficiency levels; the average new car alone expelled almost a ton less carbon per year; annual energy bills were ~$150 billion lower; and annual oil-and-gas savings were three-fifths as large as OPEC's capacity (Rosenfeld *et al.* 1990a, p. 4).

During 1977-85, the United States increased its oil productivity four-fifths faster than it had to in order to match both economic growth and declining domestic oil output. By 1986, the annual savings, chiefly in oil and gas, were providing two-fifths more energy than the entire domestic oil industry, which had taken a century to build (Lovins & Lovins 1989). Oil, however, has dwindling reserves, rising costs, and falling output, whereas efficiency has expanding reserves, falling costs, and rising output.

By 1989, the United States was getting 91% as much annual primary energy from post-1973 savings as from *all* oil, domestic and imported. Some other OECD countries have done even better. During 1973-88, while energy intensity declined 26% in the U.S., it fell 30% in Japan. In the 1980s, the countries with the highest energy efficiencies, such as Japan and West Germany, have proven among the toughest economic competitors -- and are now redoubling their efficiency efforts as they start to discover the new technological opportunities.

The task now for OECD is twofold: to accelerate these historic efficiency gains by harnessing today's far more powerful and cost-effective technologies and delivery methods, *e.g.*, by promoting superefficient cars through feebates with accelerated scrappage; and to extend to electricity the rapid, consistent efficiency gains obtained during 1973-86 for direct fuels. In principle, it should be possible to save electricity as least as quickly as oil, because

- far more electricity than oil is used in highly concentrated applications[101] and in standardized commodity-like devices installed in relatively few places[102];
- there is far more economic and environmental incentive to save electricity than oil;
- electric applications do not have psychological complications analogous to those of cars, especially in the United States;
- service quality is more likely to be markedly improved by saving electricity than by saving oil; and
- for electricity, unlike oil, a skilled engineering and financial institution, with a relationship with every customer, stands ready to deliver efficiency programs; and
- existing regulation can easily reward such delivery.

The best utility programs confirm this thesis: Southern California Edison's 1983-85 program mentioned above (plus slightly more important concurrent state actions) reduced the decade-ahead forecast of peak load by the equivalent of 8½% of the then-current peak load *per year*, at average program costs of a few tenths of a cent per kW-h saved (Fickett *et al.* 1990). Taken together, many U.S. and some foreign utilities' experience, especially during 1989-91, now extensively confirms that such rapid, reliable, cost-effective electric savings are possible. As usual, the limiting factor in rapidly propagating such success is the number of skilled practitioners. Major initiatives to expand recruitment, training, cross-pollination, and career development opportunities are there-

[100] As indicated in aggregate by improvements in primary energy consumption per unit real GNP -- a crude and sometimes misleading measure, but useful shorthand in most cases. About 65-75% of that improvement is generally considered to be due to technical gains in energy efficiency, nearly all the rest to changes in composition of output, and only a few percent to behavioral change.

[101] About a million industrial motors >125 hp use ~12% of all U.S. electricity (Lovins *et al.* 1989, pp. 28-29 & 39). Of the ~53-60% of all U.S. electricity used by motors, probably half is used by ~1 million and three-fourths by ~3 million large motors.

[102] For example, the ~1.5 billion 2x4' fluorescent lamp fixtures installed mainly in large U.S. office buildings.

fore emerging, and merit reinforcement. Internal technology transfer, and new tools such as expert systems, also require far greater emphasis if utilities and design professionals are to learn as quickly as computer companies -- a formidable cultural challenge. And few utilities are yet good at maximizing all three elements of efficiency success -- participation, savings per participant, and competition in who saves and how.

One last category of policy initiative requires emphasis: incentives within the public sector. Washington State, for example, splits the money saved by energy efficiency improvements to government buildings into three unequal parts: returns to the General Fund, rewards to everyone responsible for achieving the saving (in the form of supplements to institutional budgets or personal cash bonuses), and further efficiency purchases, which bootstrap successively longer-payback investments without requiring recourse to the capital budget. California already returns half its dollar savings to the institution achieving the efficiency, and proposes to earmark the other half for a revolving loan fund to achieve more savings throughout state government. Such mechanisms, plus careful tracking of energy costs so that responsibility for reducing them can be assigned, are the beginnings of sound energy management. Without such exemplary leadership by governments at all levels, citizens will take calls for efficiency less seriously.

Farming and forestry

More is known about the mechanisms of transition to sustainable energy systems than to sustainable farming and forestry, but the latter seem analogous in principle and seem to offer similar scope for such market mechanisms as feebates. Sweden, for example, has long taxed agrichemicals and rebated the proceeds to help farmers make the transition to organic techniques. Iowa has a similar agrichemical tax to finance groundwater protection. Fees on synthetic nitrogen fertilizers could be rebated to users of manures, green manures, or legumes. Fees on logging could be rebated to tree-planting or (better) to forest protection, especially of old-growth stands.

Many agrichemicals are already costly enough, and engender enough health anxiety among farmers, that little more incentive is needed not to use them. What is lacking is transitional advice, reassurance, risk-sharing, and financing: most farmers do not have practical knowledge of sound alternatives, and have too little financial safety-margin (or lender flexibility) to undertake the perceived risk of trying anything new. But in the U.S., Canada, Germany, Japan, and other OECD countries, lively networks of farmers are emerging to help match successful conversion case-studies with farmers facing similar challenges. Expanding and endorsing such clearinghouse activities should be a high government priority.

Alert agrichemical companies are already starting to plan their own transitions. One of us (ABL) has recently been told by senior planners at three major agrichemical manufacturers that they all plan to get out of the business; the only question is how soon, how gracefully, and what to do instead. Like utilities that have revised their product from electricity to end-use services, these agrichemical firms have revised their mission from selling chemical commodities to helping farmers grow nourishing food. Like utilities, too, such firms often have financial resources, marketing skills, and technical capabilities that will be important for the agricultural transition. They are becoming interested in providing such assets as sophisticated soil-test kits (conveniently testing the health and diversity of soil biota is still in its infancy), mineral amendments, targeted predators and other integrated-pest-management tools, adaptable native seed, technical advice, farm-management software, and transitional financing and risk insurance. Together, such elements could make an attractive package for a harried farmer who wants to change but is deterred by "hassle factor," novelty, and perceived risk.

It is also important to make markets in carbon sequestered or not emitted ("negatons" of carbon). Applied Energy Services, Inc., an Arlington, Virginia, firm, is planting trees in Guatemala to offset the output of its new coal-fired generation plant, and is funding the planting by a voluntary $<5\%$ surcharge on the plant's output. As utilities or private market-makers start to broker such carbon offsets to and from utilities and industrial fuel users, farmers and foresters should be able to bid to provide carbon-absorbing services. For example, it should be straightforward to make a market in forest- or prairie-preservation rights, which would certify that at least a certain carbon inventory or density will be maintained for a given period. Such a market would, for example, add value to farmers' decisions to enhance humus through organic practices, or to foresters' decisions to lengthen cycle times or preserve old-growth forest. Analogies already exist: in Southern California, cogeneration deals were made in 1989 in which one of the partners' in-kind equity contributions was reduced smog formation, assessed at the day's market value as quoted by the local pollution-reduction broker (a new profession created by EPA's "bubble concept" for air-pollution offsets). And in 1991, the Chicago Board of Trade launched a "negasulfur" market.

In fact, a market in carbon offsets could in effect transfer some of the large amounts of money saved by electric efficiency into financing the transition to sustainable farming and forestry. Electric utilities, especially those burning coal, would have to reduce their carbon emissions, or purchase "offset rights" representing extra carbon sequestered in trees or soil biota. (Utilities in the parts of the U.S., Germany, and Britain that burn the most coal tend to be the least interested in energy efficiency, so they would need to buy the most offsets.) Until the utilities got tired of this income transfer, it would provide a timely injection of capital to help launch a broad farming and forestry transition -- and thereafter, a spur to the utilities to get serious about their own demand-side opportunities. Such a capital flow could easily exceed $10 billion per year in the United States alone. That is not large compared with the $175-billion-a-year electric bill, but would be a godsend to cash-short farmers and small-scale foresters unable to finance fundamental changes through traditional lenders.

It is hard to estimate the attainable speed of reforms to make farming and forestry more sustainable and carbon-conserving. It is not even known how quickly organic farming is spreading in the United States. Anecdotal evidence suggests it is far faster than anyone had expected (*Wall St. J.* 1989), and informal reports from many regions in 1989-1990 have indicated that demand for organic produce is often tens of times larger than supply. Now that organic farming has finally received an official economic endorsement (NRC 1989), formal definitions and standards are emerging, and most areas and types of operations can find a successful example of conversion relatively close by, many previously skeptical farmers are starting to consider a transition as a more serious near-term option. Extension agents from many parts of the United States report overwhelming demand for transitional counsel. In time, the supply of the needed information and risk capital will catch up. Bundling the global-warming benefits with the other, more familiar benefits of sustainable practices will tend to attract more capital, reduce perceived risk, and hence speed the transition.

Some encouragement may be drawn from the speed with which other farming changes have lately been adopted: low- or no-till herbicide-based cultivation, land set-aside programs, and hedging in commodity futures markets. U.S. farmers responded eagerly enough to financial set-aside incentives to cause spot shortages of some crops. Similar incentives for conversion -- analogous to electric utilities' loans, gifts, rebates, and leases for efficiency -- could bear similar fruit.[103] If government agricultural departments assigned a tenth as high a priority to helping free farms of their chemical dependence as law-enforcement departments do for citizens, and mounted a major campaign to renew the old arts of soil conservation and tilth improvement, there is every reason to think that the time is ripe and many farmers could make surprisingly rapid changes.

CFC substitution

Mandatory production phaseouts and rapidly increasing taxes are already a fact of life for CFCs. Less mature, however, are mechanisms to recover, store, and destroy the large *existing* inventories of CFCs. A few utilities that already pay customers to scrap old, inefficient refrigerators and freezers are starting to integrate CFC re-

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[103] Just the major energy benefits in reducing heat-island effects could motivate utilities to fund urban forestry, including agroforestry, on a large scale, as Sacramento's municipal utility is already starting to do (note 10, *supra*).

covery, usually by hiring specialist appliance-recycling firms (Shepard *et al.* 1990, pp. 95-96). The City of Palo Alto, California, is also considering collecting all CFC-containing products found in local landfills and recovering the CFC for reuse or disposal (Turiel & Levine 1989, p. 197). CFC recovery from air conditioners in both in-service and scrapped cars is also a rapidly growing business.

The recoverable CFC inventories currently in circulation, or sitting in (and leaking from) scrapped cars and appliances, are important for both global warming and ozone depletion. A typical 18-ft^3 U.S. refrigerator/freezer contains ~0.9 kg of CFC-11 in the foam insulation and ~0.23 kg of CFC-12 refrigerant.[104] These CFCs are ~14,000-20,000 as heat-trapping per molecule as CO_2 (Krause *et al.* 1989, p. I.1-10). Their potency, and the high policy priority therefore accorded to their replacement, suggests that "offsets" for CFCs would also be worth marketing -- permitting their continued *use* (even though their production may meanwhile have been phased out) so long as an equally potent quantity of CFCs is removed from the environment (Turiel & Levine 1989, pp. 197-198). Properly done, such "tradeable use rights," analogous to the EPA's "bubble concept" for conventional air pollution, could cap the effective prices of CFC substitutes, reduce energy demand, and smooth the transition to CFC substitutes (*id.*).

Formerly centrally planned economies (FCPES)

The Soviet Union emits 15% of the world's fossil carbon from ~12% of world economic output (calculated by Soviet methodology: Makarov & Bashmakov 1990; actual economic output by OECD definitions appears far lower). The USSR and its former satellites, which are similarly or more carbon-intensive, are engaged in an historic transition of extraordinary dimensions. These countries have great opportunities to help abate global warming. How much they will do so, however, can be neither assessed nor achieved without wrenching structural, political, and economic changes that are only just beginning (Chandler 1989, 1990). These changes include:

- Major reallocation of national resources, especially in the USSR, from military to civilian production within the context of lessening tensions, European partial demilitarization, increased popular control over governmental military adventures (this is needed in the U.S. as well as in the USSR), and a widespread commitment to a global security regime that makes others more secure, not less (Harvey *et al.* 1991).
- Radical economic reform based largely on market principles, truthful prices, and integration into the world economy, including convertible currency and fair opportunities for foreign ownership and joint ventures under reliable legal arrangements.
- Equally radical social and political reform reinvigorating productivity, initiative, and personal responsibility, and hence requiring comprehensive educational renewal.
- Economic restructuring markedly reducing the relative role of primary materials production, enhancing the nascent service sector, favoring smaller enterprises, decentralizing much overcentralized production, introducing competition to monopolies (including electric utilities), and creating a working distribution system that now scarcely exists at all.

This is a tall order; yet there is no way out but through. As the economist P.G. Bunich (now an advisor to President Yeltsin of the Russian Republic) remarked in early 1989,

> Here we are, 280 million Soviets gathered together on a vast beach and wading together into the surf. We're at that awkward point where it's too deep to wade but not yet deep enough to swim, so we're losing our footing -- and anyway, none of us know how to swim. But, by God, some of us will figure out how to swim, and those who figure out first will teach the rest. Of course, we'll have to make some lifejackets, but only a few million, not 280 million.

[104]Technology to recover the former may be available in Germany, but information seems scarce and R&D appears to be a high priority.

That historic transition comes at just the time when the extremely energy-intensive Soviet/Eastern European economies are broken and need fixing. Poland, for example, has about the same per-capita energy use and carbon emissions as Austria, but only a fourth the per-capita GNP (Sitnícki *et al.* 1990). Hungary has about the same per-capita energy use as Japan, but one-fifth to one-fourth the per-capita GDP (Jászay 1990). The Soviet Union is one-third to two-thirds more energy-intensive than the United States, and 2-4 times more than the most efficient countries such as Sweden (with a similar climate) and Japan.

However, significant progress is being made. Hungary got 38% of its 1970-88 increase in energy services from efficiency (31%) and structural change (7%), and can both save much more and considerably expand biomass growth and use (*id.*). Although Poland has so far sustained substantial efficiency gains only in transportation, further cost-effective structural and efficiency improvements could even hold long-term per-capita energy use constant despite 2-3%/y income growth (Sitnícki *et al.* 1990). The Soviet Union's heavy use of natural gas contributed to the 22% drop (about the same as in Western Europe) in its CO_2/primary-energy ratio during 1970-84, far above the 1% drop in the United States (Makarov & Bashmakov 1990).

These high intensities have four especially important aspects:

- Energy prices are heavily subsidized (Chandler *et al.* 1990). A senior Soviet colleague who set up a cooperative selling energy-efficiency services in Moscow said, "You might suppose this activity is three times less cost-effective than in the West, because in the Soviet Union we sell energy for about a third of its production cost. But we're also about three times less efficient, so it works out the same." Energy subsidies in Poland in 1987 (before the "big bang" price reforms) were ~49% of the delivered price of coal, 83% of gas, and 27% of electricity (Sitnícki *et al.* 1990). For Eastern Europe as a whole, "Until recently, electricity, coal and natural gas were priced at one fourth, one half and four fifths of world market levels" respectively (Chandler *et al.* 1990). Yet "it is not enough simply to get the prices right: prices must also matter. Making prices matter means not permitting enterprises to pass the cost of energy waste on to consumers" without risking bankruptcy for their uncompetitiveness (*id.*). Absent such fundamental reform, based on understanding that prices are *information*, not a social entitlement, the Eastern economies are simply, as one Soviet scholar put it, "vast machines for eating resources."
- Decades of central planning by empire-building bureaucracies rewarded for setting ever-larger quantitative targets have left the Eastern economies exceptionally overbuilt in primary materials industries. An astonishing 70% of Hungary's energy consumption goes to raw materials production, which provides only 15% of national output (Jászay 1990). Similarly, by producing less unnecessary material and using it more efficiently, market reforms could save a sixth of Soviet energy and half of Czech steel production -- even more in chemicals and nonferrous metals (Chandler *et al.* 1990). This is especially good news because more than two-thirds of Soviet fossil-carbon output is from the industrial and energy sectors (Makarov & Bashmakov 1990).
- Distortions of production, blockage and compartmentalization of information, administered prices, and mandatory allocation of goods and services have led to serious weaknesses in some sectors, notably electronics, that are vital to energy efficiency. That is why "only 25-30% of the cost of [Soviet] energy efficiency...[is the cost of] implementing measures at the point of use. The remaining 70-75% results from the expense and difficulty of expanding domestic production of energy-efficient equipment and materials" (Makarov & Bashmakov 1990). Price distortions make inferior domestic equipment look only half as costly as foreign versions, but those cannot be imported without a convertible ruble, soft credits from abroad, or less restricted and less risky joint ventures.
- As both Western and Soviet analyses independently showed in 1983[105], energy efficiency is by far the most critical technical measure for the success of *perestroika*, because it produces a double benefit: it frees

[105]By Royal Dutch/Shell's Group Planning in London and Corresponding Member V.A. Gelovani *et al.* at the USSR Academy of Sciences' Institute for Systems Studies in Moscow.

scarce resources (capital[106], hard currency, technical skills, etc.) to modernize industry and agriculture, and it frees the saved oil and gas for export to earn hard currency to buy technologies for the same purpose. Because saved energy is fungible for hydrocarbons that can be sold for hard currency, Soviet energy savings are properly denominated not in kopecks per gigajoule but in dollars per barrel. For these reasons, each 1% improvement in aggregate energy productivity (especially in electricity) may increase national output by several percent, and bring even more important qualitative improvements.

These circumstances require a combination of three approaches: *economic reforms, structural shifts in the composition of output, and strong improvement in end-use efficiency.* The alternative, on standard projections, is to double Soviet fossil-carbon output by the 2020s (Makarov & Bashmakov 1990), and Polish a decade earlier (Sitnícki *et al.* 1990). Such projections may be too high because the growth is self-limiting: Makarov & Bashmakov (1990) state flatly that "The Soviet economy can no longer sustain continued growth in energy consumption and the corresponding demand for increasing energy production. If current trends continue, capital and other resources will be required in amounts so large as to preclude the possibility of realizing any but the Pessimistic Variation of the Base Case Scenario." But the prospect conjured up by this kind of involuntary grinding to a halt is not pleasant either.

Besides economic reforms, structural changes, and end-use efficiency, some Eastern European countries would benefit greatly from raising fuel quality by substituting mainly natural gas. This is most true for Poland: the world's fourth largest extractor of coal, 75% coal-fired throughout its economy, and the user of a third of Eastern Europe's 20 EJ/y of primary energy (Chandler *et al.* 1990). Most Eastern European countries have major energy supply problems. Hungary imports half its energy; Soviet fuel reserves are shifting inexorably from high-grade western to remote, costly, and often low-grade Siberian and Far Eastern sites[107], etc. But Poland epitomizes the most acute supply problems. Severe air and water pollution are contributing to economic shrinkage (Chandler *et al.* 1990), coal-mining consumes a fifth of all steel (up >150% since 1978) and nearly a tenth of grid electricity, the average depth of mines is increasing 2-4%/y, more difficult mining conditions are cutting labor productivity in the worst mines to a sixth of the British or West German norm, social and administrative costs are high and rising, and land is so scarce that some mines "transport waste rock and coal washing refuse as far as 80 km for disposal" (Sitnícki *et al.* 1990). Coal exports for hard currency must cease in the 1990s in order to fill domestic needs as coal quality and accessibility decline. In any event, the economic benefits of the exports have been illusory because they greatly speeded the shift from high- to low-quality coal (high sulfur, high ash, high cost, more global warming).

Such conditions offer unusual leverage in abating global warming, because the costs and the environmental impacts of burning such poor fuels are inflated in four ways: more fuel must be burned to yield a given amount of primary energy, and most of that energy is then wasted by inefficient conversion, delivery, and end-use. Conversely, end-use efficiency improvements bring benefits which are amplified manyfold by avoiding system losses. Any such improvements, in a country like Poland, will push the most intractable coal-mining problems further into the future, buying more time to substitute gas which (efficiently used) might bridge to renewables.

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[106] Nearly a fifth of Soviet investment goes to fossil-fuel extraction (not counting the electric sector) (Chandler *et al.* 1990). The same fraction went to Polish coal-mining *alone* in 1980, almost double the 1970 share, while gas and oil extraction's share of investment went from <1% of total industrial investment in 1980 to 39% in 1986. These trends squeezed out non-energy industrial investment, which fell from 74% of total industrial investment in 1970 to 61% in 1986 (Sitnícki *et al.* 1990). That is partly why Sitnícki advocates halting *all* energy-supply investment until the demand side is set in order. In Hungary, likewise, "investment in energy supply grew to 40% of all industrial investment by 1986" (Jászay 1990).

[107] In recent years, Soviet coal-mining's shift to the East has resulted in mining more coal but getting less energy out of it, because grade is falling faster than tonnage rises. Some Eastern coals are of such poor quality that no one has figured out a reliable way to burn them (OTA 1981).

In principle, the Soviet Union has three advantages in promoting energy efficiency. One is its gifted scientists and technologists. Soviet achievements in such areas as control theory, materials coproduction, materials science (diamond films, ceramics, supermagnets, composites, etc.), and mathematical physics can not only help meet domestic needs but also compete in world markets. It is now becoming common, with good reason, for the computer literature to speculate that later in this decade, the combination of Taiwanese hardware and Soviet software may make a strong market showing. Thus the USSR has far more to sell than its unparalleled storehouse of raw materials. So far, however, Soviet technical prowess has not been mobilized to advance energy efficiency in any fundamental way, and indeed no sufficiently detailed and modern (by Western standards) efficiency research or analysis yet exists in the country, though there is plenty of talent to apply to it.

Second, Soviet energy-using hardware is highly standardized. Lighting retrofits in the U.S. or Western Europe are complicated by a fragmented industry distributing thousands of types of fixtures from hundreds of manufacturers. In the Soviet Union, only 10-20 types of fixtures are in general use. For that matter, somewhere in the files of GOSPLAN (if one knows which numbers are real and which are fake) one can ostensibly find a complete record of the entire Soviet capital stock, because its production and shipment were planned. No Western country has a comparable "paper trail": American analysts, for example, know less about their stock of electric motors, which use more primary energy than highway vehicles, than they know about moonrocks.

Third, what is left of the Soviet command economy -- which has been largely retained in the strictly monopolistic utility/electrotechnical sector -- may still be useful in shifting production towards end-use efficiency. The design of every electricity-using device manufactured by the State, for example, must be approved by a single engineer in St. Petersburg -- everything from toasters to giant motors, lamps to computers. He likes efficiency, but his authority is circumscribed. For example, a small lighting institute on the Volga has been trying for years to get permission to pilot-produce some improved compact fluorescent lamps (none are made in the Soviet Union). But the Ministry of Energy and Electrification has never approved the request: the Ministry's job is to build and run power plants, and there is no demand-side institution with any force as a counterweight. There are recent signs that the Ministry is starting to think more about efficiency -- having only 3½-5% more generating capacity than expected 1990 peak load concentrates the mind wonderfully -- but such change of mission will probably be slow. Happily, the view of the leading Soviet climatologist and many of his Academy colleagues -- that global warming would probably, on the whole, be good for the Soviet Union -- is apparently giving way to a realization that the risks of mispredicting are too great (Budyko, Izrael, & Golitsyn 1990). Yet there is still a very limited understanding of energy efficiency within the old Ministries.[108]

The Soviet/Eastern European energy problem is part of a nearly infinite onion containing layer upon layer of challenging social, political, and economic problems. Peeling that onion will be slow and difficult. Soviet experts have suggested, however, some of the specific initiatives that are most needed. Paraphrasing Makarov & Bashmakov (1990), these include:

- International lenders' soft credits for importing energy-saving equipment.
- Joint ventures to make such equipment in the Soviet Union.[109]
- Joint exploration of efficiency opportunities and implementation methods.
- Public education stressing "that energy savings is the principal, and most economically effective, means of solving many global problems of world energy development."

[108]For example, Budyko and Izrael have misinterpreted analyses by Makarov *et al.* as indicating that major gains in Soviet energy efficiency would cost the entire capital investment available. What the studies said was that such gains could accompany a complete, from-the-ground-up reconstruction of the whole Soviet economy and infrastructure -- which of course would cost that much, but would yield far more joint benefits than just reducing global warming.

[109]Poland has introduced now provides a three-year tax holiday for such ventures, along with measures to encourage reinvestment domestically. Those measures include low-interest credits and 50% taxable-income deductibility for investments in modernization -- 100% if they are for environmental protection (Sitnícki *et al.* 1990).

- Collaboration to make nuclear plants safer (a major concern for Western utilities whose operations are hostage to the next Soviet accident) and cheaper. (In our view, and that of many Soviet colleagues, such cooperation may be worthwhile but is very unlikely to lead to a Soviet nuclear revival: as in most other countries, the economic and political obstacles are too daunting and the alternatives too attractive.)
- Systematic reduction of the natural gas system's methane leaks, which increase the Soviet contribution to global warming by anywhere from ~8% (*id.*) to ~26% (Arbatov 1990).
- Expanded cooperation in renewable energy development -- an area of much ingenious Soviet design -- and in trapping and isolating CO_2.

Our own experience suggests the need to add seven major items to that list:

- A high initial priority should be given to superwindows -- the coating technology exists in the Soviet military sector but has not yet been transferred to the civilian sector -- and to superinsulated modular house/apartment construction. It would be silly to try to relieve the housing shortage, let alone meet emergency housing needs in *e.g.* Armenian-earthquake reconstruction, using the same poorly insulated, shoddily built, seismically hazardous technologies whose use is still so widespread.
- Soviet analysts are prone to suppose that building up consumer goods and the service sector will require rapid growth in the electric share of end-use energy, accounting for half the projected rise in CO_2 output (Makarov & Bashmakov 1990, p. 5). Instead, there is good reason to believe that the electricity required could come from larger-than-expected savings both in the new equipment itself and elsewhere, especially in industrial drivepower. But those efficiency opportunities are revealed only by very detailed and up-to-date analysis, so they are not yet well understood by most Soviet experts. A joint USSR Academy of Sciences/RMI book now in preparation may help in this regard.
- As is now starting, it is important that skilled Western and East Asian firms feel able to participate for mutual benefit in major Soviet oil and gas projects. Potentially very large reserves of both will require OECD technology to find and extract. Such new reserves plus high end-use and conversion efficiency could probably "completely cover" Soviet domestic energy needs from high-grade resources -- hydrocarbons could cover ~80% of energy supply -- for many decades to come (Chandler *et al.* 1990). Such new reserves would only be squandered in the USSR, however, and unaffordable to Eastern Europe, without major reforms in price, output structure, conversion efficiency, and end-use efficiency (*id.*).
- To help achieve those reforms, neighboring countries in both Asia and Western Europe could and should provide a massive infusion of capital and technology specifically focused on Soviet and Eastern European end-use efficiency. That is among the cheapest ways in the world to abate global warming, because equipment is so inefficient to start with and the fuel displaced on the margin is mainly low-grade coal (or high-grade, low-carbon gas that can in turn displace more coal). The improved efficiency, preferably using equipment made by joint ventures in the USSR, would free up oil and gas for resale to the efficiency providers. Those fuels, especially the gas, would displace German coal, reducing global warming even more, and earn hard currency to pay for the efficiency technologies and financing. That payback would be very rapid, leaving most of the oil-and-gas revenue stream available to buy other technologies for modernization outside the energy sector. Similarly, Western aeroturbine manufacturers could joint-venture with their Soviet counterparts in producing steam-injected and combined-cycle gas turbines -- a good use of the military aircraft-engine production capacity now being partly demobilized. Those turbines, with their modularity and very short lead times, could help quickly to relieve Soviet and Eastern European power shortages while also yielding major long-term gas and coal savings.
- A formal mechanism to provide up-front, pump-priming credits for Western investments in Eastern energy efficiency would be through the sale of carbon offsets from East to West. Since, for example, West Germany, a carbon-intensive country, is considering introducing a carbon tax, the introduction of German offsets without territorial limits could readily lead to a flow of hard currently eastwards to pay

for carbon savings that can initially be achieved more cheaply in the East than in the West. That hard currency would then be recycled westwards to pay for German or other world-market efficiency technology installed in the East to fulfill the carbon-abatement contract previously sold. Sale of the subsequently saved gas to the West, and its use to offset still more carbon, could be part of the same deal.[110]

- Japanese industry's remarkable training programs for energy-efficiency managers should be exported to the Soviet Union. Those managers' attention to detail is unrivalled elsewhere in OECD, and has much to teach all other countries. In principle, Japanese industry might obtain carbon offsets through fuel savings achieved in Soviet industry, yielding another mutually beneficial currency flow to be coordinated with increasing oil-and-gas collaboration in the Soviet Far East.
- A *sine qua non* for Soviet restructuring is continued cooperation by the NATO countries, especially the United States, in rapid disarmament and demilitarization of both sides' economies (Makarov & Bashmakov 1990). This will require redefining not only military force structures and missions but also strategic doctrine and the whole concept of what security is and how to obtain it at least cost (Harvey *et al.* 1991. Recent U.S.-Soviet cooperation in the Persian Gulf crisis is an encouraging step in this direction. Rapid, effective, comprehensive Western help with Eastern energy efficiency is a critical component of Western security interests: the alternative is not only an unstable meteorological climate but also political instability, stagnation, or worse. NATO has for many years sponsored leading international seminars on technical aspects of energy efficiency, and may be able and willing, given high-level encouragement, to turn its energies in this direction.

In short, the United States and the Soviet Union, which between them release about half the world's fossil carbon, are not only natural technical and financial partners in helping to abate global warming; their intricate security embrace demands such cooperation, mobilizing the best talent in both countries.

This partnership should not stop with energy. Both countries have much to learn from each other's experience of sustainable farming and forestry -- rather than continuing misguided efforts to sell American-style chemical farming to a country whose internal obstacles have so far happily hampered, at least outside Kazakhstan, its efforts at chemical self-contamination of its vast lands. Early citizen-organized farmer-to-farmer exchanges have proven such eye-openers to both sides that they clearly merit expansion: it will be difficult to elicit enough entrepreneurship to break up the state farms unless more Soviet farmers realize what is possible. Further, a large proportion of Soviet vegetables, fruit, meat, and dairy products come from the tiny fraction of farmland privately farmed with some semblance of real economic incentives. Yet the tools used on those plots are often medieval. Important productivity gains could probably be had by as simple a means as transferring to Soviet artisans and cooperatives the technologies of advanced gardening tools (from such firms as Smith & Hawken) that could do so much to ease the work and expand the output of those private plots. Superwindows could in time further provide more fresh winter produce by making indoor microfarming possible in major cities like Moscow.

Carbon offsets are especially important also to preserving the fragile carbon inventories of the Soviet Union's boreal forests, now being plundered by overbuilt pulp-mills at home and in Scandinavia. Similar opportunities exist elsewhere in the parts of Eastern Europe not yet severely damaged by acid rain: Hungary, for example, "possesses rich biomass production potential and could serve as a testbed for new biomass utilization and sequestration technology," involving, *e.g.*, "increasing the humus in soil from 2 to 3 percent and...forest area from 17 to 24%" (Jászay 1990, p. 9). Among the comparative advantages of the Eastern cultures in this context is

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[110]This would be timely, since much German coal will become uncompetitive after 1992 anyway, when its "Kohlepfennig" subsidy becomes legally unsupportable. This could offer an opportunity to make lemons into lemonade. Ideally, such offset arrangements should be brokered in markets that include derivative instruments with a range of maturities, so that rather than locking themselves into contracts lasting far longer than the timescales of installation and technological evolution, the parties would retain some flexibility to keep hunting for better buys as factor costs and gas and carbon values all shift. As noted below, Krause *et al.* (1990) suggest such periodic carbon auctions.

their often intact rural culture and knowledge of how the land works -- assets all but destroyed in the overurbanized West (Jackson *et al.* 1984). There may be more ecological wisdom to be learned from Byelorussian or Bulgarian countrypeople than from Western agronomists.

Developing countries

For all their historic handicaps, most of the peoples of the Soviet Union and Eastern Europe represent industrial cultures with long and distinguished histories of sophisticated technical achievements. Comparable native talents, however, have had a very different historic pattern of expression in developing countries. While their achievements in many arts, sciences, and ways of living have been extraordinary, often predating analogous Western progress by many centuries (Arab and Chinese astronomy, Chinese medicine, Sri Lankan irrigation, and Polynesian navigation come immediately to mind), they have not in general had the opportunity to exploit cheap resources, usually taken from poorer countries or bought at competitively depressed prices, with Western manipulative technologies to produce "modern" infrastructure, sell manufactures at monopoly rents, and create, at least for themselves, widespread material wealth. Therein lies their great opportunity today: ***not to seek to tread that same development path, but to proceed more wisely.***

If developing countries try to repeat the mistakes of OECD, they will never develop. The cheap resources are dwindling; the force-fed monopolistic markets are going fast; the direction of the global economy no longer supports colonists' former ability to buy cheap and sell dear. Rather, one now increasingly buys raw materials at monopoly rents and sells manufactured goods at competitively depressed prices.

The collision between old cultures, new technologies, and perennial aspirations is perilous, both for the little peoples for whom a major mistake may be the end of the line, and for the great peoples whose ultimate weight in the world is so ponderous: a billion Chinese times anything is a big number, and before long, on present trends, India will have more people than China. This is not to say there are no hopeful signs: in the 1980s, the Chinese economy did apparently grow twice as fast as coal consumption (which represents three-fourths of energy use) -- a commendable ~4.7%/y annual decline in aggregate energy intensity (Chandler *et al.* 1990). Yet China is still at least three times as energy-intensive as Japan. A plausible scenario for 1990-2025 (*id.*) is widely assumed to end up with at least 1.4 billion Chinese, with quadrupled per-capita income (rising to a third of the current U.S. level), and with total energy and coal consumption tripling to nearly the present U.S. level. If anything like that actually happens (let alone whatever happens after that), then OECD will need to pursue efficiency very vigorously indeed to help stabilize the earth's climate.

Preventing Chinese energy use from tripling under such a 5%/y-GNP-growth scenario requires far more detailed and comprehensive efficiency efforts. Indeed, without such efforts, the growth may not occur, because under business-as-usual projections, investment in electrification alone will consume approximately the entire economic growth of the developing world.

Consider, for example, the sad story of Chinese refrigerators. When the government decided people should have them, more than a hundred factories were built, and the Beijing households owning a refrigerator rose from 2% to 62% in six years. But through inattention, the refrigerators were built to an inefficient design, and China now needs a billion unavailable dollars' worth of new power plants to run them. An effort to promote development instead created crippling shortages of both power and capital. The officials to whom this was pointed out said the error would not, if they could help it, be repeated: it had taught them that China can afford to develop only by making energy, water, and other kinds of resource efficiency not just an add-on program but *the very cornerstone of the development process*. Otherwise, as is already true even in such a fundamentally wealthy country as the USSR (*supra*), the waste of resources will require so much and so costly supply-side infrastructure that too little money will be left to build the things that were to *use* those resources. As a wise homebuilder once put it, "If you can't afford to do it right the first time, how come you can afford to do it twice?"

Recall, too, that the average poor country[111] derives nearly three times less economic output per unit of primary energy used (commercial and traditional) than the average rich country -- which in turn can cost-effectively at least quadruple *its* energy productivity. These two facts together imply that if poor countries leapfrogged over the mistakes of the rich countries, they could in principle expand their economies *roughly tenfold* without increasing their energy use at all -- while the rich countries could in principle sustain or improve *their* standard of living while using several times less energy than now. (Principle and practice probably differ here. Because of practical constraints in getting organized, the former pace of savings seems less plausible than the latter.) Ultimately, both groups would meet in the middle, and there would be enough energy for all.

Lack of energy or fuel, however, is not the problem. In Reddy & Goldemberg's masterly summary (1990):

> If current trends persist, in about 20 years the developing countries will consume as much energy as the industrialized countries do now. Yet their standard of living will lag even farther behind than it does today. This failure of development is not the result of a simple lack of energy, as is widely supposed.
>
> Rather, the problem is that the energy is neither efficiently nor equitably consumed. If today's most energy-efficient technologies were adopted in developing countries, then only about one kilowatt per capita used continuously -- roughly 10 percent more than is consumed now -- would be sufficient to raise the average standard of living to the level enjoyed by Western Europeans in the 1970s.

This discussion therefore seeks to supplement the large literature on energy and development -- much of it compactly summarized elsewhere (Goldemberg *et al.* 1988, Lovins *et al.* 1981) -- with a few observations on how it may be possible to "do it right the first time" and improve the prospects for a "leapfrog strategy" that largely jumps over both inefficiency and fossil fuels.

Marketing for diversity

First, action requires understanding of choices, and "Consumers who do not obtain their energy efficiently fall into three categories: the ignorant, the poor and the indifferent" (Reddy & Goldemberg 1990). They continue:

> The first [group] consists of people who do not know, for example, that cooking with LPG is more efficient than cooking with kerosene. They can be educated to become more energy efficient.
>
> The second category consists of those who do not have the capital to buy more efficient appliances....An Indian maid may know that her employers spend less money cooking with LPG than she does with kerosene, yet she may not be able to switch because LPG stoves are about 20 times more expensive than kerosene stoves.

This is the position, albeit in a far starker context, of the Western householder who is deterred by the high cost of a compact fluorescent lamp. The remedy is analogous:

> ...utilities or other agencies should help finance the purchase of efficient equipment with a loan that can be recovered through monthly energy payments. Alternatively, a utility can lease energy-efficient equipment. A consumer's savings in energy expenditures can exceed the expenses of loan repayments and new energy bills. In principle, this method of converting initial costs into operating expenses can be extended to commercial and industrial customers as well, thereby improving efficiency and modernizing equipment at the same time.

This is what an RMI-cosponsored pilot project seeks to do with compact fluorescent lamps in Bombay (Gadgil & Sastry 1990). The lamps would be leased with an always-favorable cashflow to the user. The lamps would

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[111] Most poor countries are in fact "'dual societies,' consisting of small islands of affluence in vast oceans of poverty. The elite minorities and the poor masses differ so much in their incomes, needs, aspirations and ways of life that, for all practical purposes, they live in two separate worlds" (Reddy & Goldemberg 1990). For that reason, this discussion focuses mainly on the needs of poor *people* within poor countries.

save the utility at least six times their total cost. There are two bonuses. First, the power saved in the heavily subsidized household sector, where it is sold at a loss, can then be resold to businesses which pay full rates, so the utility converts a loss to a profit. Second, in a city where 37+% of the evening peak load is from lighting, the saving should help to prevent the evening crashing of the grid, as well as improve reliability in some adjacent Western-grid states now short of capacity. Even such simple measures can have a profound economic effect: by one expert estimate, giving away such lamps throughout a very poor country like Haiti might raise the average household's disposable income by as much as one-fifth, because so much of the sparse cash economy goes directly or indirectly for electricity, mainly for lighting.

> The third category of consumers consists of those with little incentive to raise their energy efficiency because their energy costs are so small or because the costs are almost unaffected by efficiency changes....Enticing those customers...will depend on intervention at higher levels[, *e.g.*, via government]...efficiency standards.

Bombay has such people too—especially affluent householders who can afford tubular fluorescent lamps three times as efficient as the poor user's incandescents. Marketing to the affluent group may require emphasizing the compact fluorescent lamp's longer life and esthetic superiority (better color, no flicker, no hum, nicer shape).

Institutional parallels

These three categories and remedies are not unique to developing countries: they have exact parallels in OECD, and for that matter in the USSR and Eastern Europe. Parallel, too, is the problem that most "utilities, financial institutions and governments" lack "methods for converting the initial cost of efficient systems into an operating expense." Further parallel is the issue of scale:

> Spending $2 billion on end-use improvements is much more complicated [than spending $2 billion on a single power plant]. If each efficiency measure costs between $2,000 and $20 million, then between 100 and a million subprojects are involved. Organizing so many diverse activities is difficult....

This is especially true in a nonmarket economy. And equally parallel is the almost universal bad habit of using energy consumption, or (worse) its rate of growth, as a measure of progress rather than as an indicator of inefficiency in meeting social goals with elegant frugality. Until energy planners start by asking what the energy is *for*, and how much of it, of what kind, at what scale, from what source, will do that task in the cheapest way, the outcomes will be far from rational or even affordable. Until energy planners appreciate that it is ten times as important to eliminate the "payback gap" as to get the prices right, their exhortations simply to desubsidize energy prices will continue to prove inadequate.

In developing and ex-socialist countries, while seeking to harness or mimic market forces, it is especially important to remember that markets do not in general produce justice, equity, or sustainability. They were not meant to. Equity requires political and ethical instruments, and an appreciation that, as Reddy's field experience has taught him, "If you look after the needs of the poorest, everything else will look after itself."

Lending institutions

One of the chief obstacles to sound energy-for-development policies is the World Bank's and other multinational lenders' persistent lack of interest and insight (Van Domelen 1989). This is partly because while reorganizing a few years ago, the Bank laid off most of its technical staff and retained chiefly economists who don't understand the engineering and tend toward not-invented-here reflexes.[112] But it's also because the system of rewards within such institutions, as in commercial banks, creates incentives to make bigger loans, not smaller

[112] In spring 1991, however, this began to change, partly through the intervention of the Bank's own Facilities engineers, who became interested in making the Bank's new headquarters building cost-effectively efficient.

ones, and to maximize loan volume in a way that a small, centralized staff can do only in large chunks. The Bank and its peer organizations also lack "templates" for successful Third World energy-efficiency projects. These structural adjustments within the lending organizations will be made only when their major supporters insist that lending follow the same cost-minimizing, all-things-considered rules that their own utilities are already institutionalizing -- *i.e.*, that energy financing be allocated only to the least-cost options (*id.*). The Bank's ~$2 billion a year worth of power-plant investments would practically all fail such a test.

To encourage a major shift of emphasis, the Bank and its regional counterparts may wish to experiment with becoming carbon-offset brokers. For example, American, German, and Japanese coal-fired utilities and industries might choose to fund exceptionally cheap Third World carbon-abatement projects -- agroforestry, lighter-colored buildings and pavements, Curitiba-style bus systems, lighting and motor retrofits, etc. -- *through the Bank* via carbon-offset contracts. (They could even train the relevant Bank and host-country staff in the implementation techniques those modern utilities have developed, and perhaps learn too about the often smarter ideas that resource-short hosts tend to develop out of necessity.) This is at first blush an adventurous financial concept, but in structure it is no odder than a debt-for-nature swap. Another alternative, suggested by Reddy & Goldemberg (1990), is that carbon taxes, collected chiefly from industrialized countries under the OECD "polluter pays" principle, be earmarked for energy- and other carbon-saving projects in developing countries. Certainly OECD's historic responsibility for much of the cause of global warming justifies no less.

It has been argued (Krause *et al.* 1989, pp. I.5-7 & -8) that even if tradeable emission rights have an initial allocation based on an equitable per-capita formula rather than one which "grandfathers" OECD's historically high emissions, such melancholy experiences as the Third World debt crisis suggest "that approaches based mainly on market exchange will not work among nations as structurally different as developing and industrialized countries." In today's political climate, that reservation may be valid (although, as with the Berlin Wall, the unlikely can happen). But as a limited component of a far broader implementation strategy, tradeable rights do make good sense (*id.*). After all, in societal terms they are allocating not costs but benefits, and the only question is how to allocate the benefits to give all parties the necessary incentives to act. Since abating global warming is better than free, *the object is not to figure out how to share sacrifices for the common good, but rather how to help individuals, firms, and nations behave in their economic self-interest.* To this end, Krause *et al.* (*id.*, p. I.5-18ff) have further proposed an ingenious mechanism with some potential advantages -- a Superfund-like international Climate Protection Fund combined with carbon-reduction auctions.

International lending, both bi- and multilateral, badly needs to be restructured "from support for specific projects (such as building dams) to support for goal-oriented programs (such as lighting more homes)" (Reddy & Goldemberg 1990). Another worthy goal would be to support, as in Eastern Europe and the USSR, joint ventures to produce efficient equipment locally. Many utility officials in developing countries, for example, say that their countries have refrigerator factories -- but are unaware that those factories could joint-venture with, or license from, a Danish firm to make refrigerators that look and cost about the same but use ~80-90% less electricity (Shepard *et al.* 1990). It appears that such industrial marriage-brokerage is not on lenders' agenda. It should be. It is indeed extraordinary that some developing countries, like Brazil and Mexico, manufacture for export to rich countries certain appliances more efficient than are available for sale to their own people.

In some instances, it may be possible to package an advantageous three-way swap: *e.g.*, using a Western European compact-fluorescent lamp technology, plus rare-earth phosphors from Soviet minerals, manufactured in an Indian free-trade zone (using rupees as a bridge between guilders and rubles), for sale in both socialist and developing countries if not to the West as well. Currently, however, such high-leverage opportunities apparently are not on lenders' radar screens at all.

Critical to these shifts of emphasis are education, training, and institution-building. Interesting programs are starting to emerge in countries like Brazil, Ghana, India, Thailand, and Tunisia. Their university and government efforts could be nurtured into regional centers of excellence in energy-efficiency technology, field implementation, and policy. A significant private initiative to build such centers' capabilities for regional outreach, research, and training is under serious discussion. Trained people from *within* each culture are essential: only they can understand behavioral issues and novel kinds of mistakes that would baffle a Western expert.[113] A "Negawatt University" network that induced a few smart graduate students to devote their careers to energy efficiency could make a big difference. Today, a few such nascent centers exist (*e.g.*, Bangalore, Bangkok, Berkeley, Genève, Grenoble, Lund, Lyngby, Princeton, Santiago, São Paulo, Sydney), but need support.

Overarching all these issues, even education, is the power of example. Americans, for example, cannot preach that others should protect their forests as we clearcut our own in Alaska, Hawaii, and the other 48 states. We cannot preach the virtues of population control, or energy efficiency, or sustainable rural economies, as we erode their foundations at home. But the power of a positive example can be even stronger than the power of a negative example. Acting from our highest traditions has moved the world before, and can again.

The almost-conventional agenda mentioned so far is essential. But several more steps, seldom discussed, seem warranted too. The central one is a major effort to inventory, then shift, the efficiency of energy-using equipment in international commerce.

Technology transfer -- positive and negative

In Osage, Iowa (population 3,800), the municipal utility has worked with local vendors to make good equipment easy to get and bad equipment hard to get. The hardware stores have a good selection of compact fluorescents, but may keep incandescent lamps out back where you have to ask for them. The lumber yards don't stock 2x4" studs for poorly insulated frame walls, nor ordinary double glazing -- "Sorry, sir, that's obsolete -- special order, it'll take a month" -- but instead sell wider lumber and superwindows, and explain their superiority to help make the sale.[114]

Nobody does that in global commerce. From Bangkok to Cairo, apparently cheap Taiwanese ballasts are being installed in fluorescent lighting fixtures. Those ballasts are often made from unrefined recycled-scrap-copper wire with such high resistivity that its overheating causes most of Taipei's house fires. Seemingly cheap Taiwanese, Czech, and other motors, gearboxes, and the like are also common, and often so inefficient that if run at more than a modest fraction of their rated power, they burn up. Although apparently no one has yet done a formal survey of this component market, nor of the equipment that incorporates such components, many anecdotes leave a strong impression that the world is awash in very inefficient end-use devices marketed to people with limited technical understanding, no independent information sources, and almost infinite discount rates.

Making and selling those devices, however, is not such an innocent pastime. The precious capital, especially foreign exchange, consumed in trying to build and fuel power plants and other energy-supply systems to run such inefficient equipment cannot be used to buy vaccines, to provide clean drinking water and family planning, to plant trees, to teach women to read. The overloaded power supply is unreliable and cannot run a productive

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113 The opposite can also be true. We recently heard of a major tourist hotel, near the Equator, that installed a 250-ton chiller to attract affluent visitors. It never worked: the building seemed to get hotter in the summer and colder in the winter. No expert even from the capital could figure out what was wrong with it. The manager started asking every engineer who came to stay to take a look. Finally, one Dutch engineer instantly spotted the problem: the chiller's chilled-water output was being pumped straight into the cooling tower. Nobody else had thought to check something so obvious.

114 This is a small part of a series of initiatives whereby Osage's residential energy savings have enabled the utility to prepay all its debt, build up a large interest-bearing surplus, cut its rates five times in five years (to half the average Iowa level), thereby attract two big factories to town, and keep recirculating in the local economy more than $1,000 per household per year. This plugging of unnecessary dollar leaks has made the local economy noticeably more prosperous than in neighboring towns. The same principle, elaborated in RMI's Economic Renewal Project, applies to villages, states, and countries.

industry, imposing huge backup-generator costs. Too little electricity is available for such basic needs as lighting (further hampering literacy) and pumping water. Tracing back such interlinked opportunity costs suggests that those inefficient ballasts and motors may ultimately create about as much human misery as the drug traffic. This "negative technology transfer" needs to be put squarely on the international agenda.

We do not know what it would take to get bad equipment off the world market, or at least to stigmatize it as the menace to development that it represents; but some countries have ideas. In Tunisia, for example, the national energy office has achieved an exemplary but little-known decoupling of economic activity from energy use, chiefly by developing nearly two dozen national minimum performance standards for basic appliances, lights, motors, and vehicles. You can buy a variety of cars, but they've all been bid, bought, and imported in bulk by the government on the basis of their fuel efficiency. Inefficient models are deliberately excluded. The saved capital is then available for what people really need -- a prerequisite to the sensible investment approach that has paid off so richly in Costa Rica.[115]

Another possible analogy is the recent UNEP convention on international trade in hazardous wastes, requiring the "informed consent" of the recipient. Recipients of electricity-wasting equipment could surely be better informed -- say, by labelling with life-cycle costs, and a list of alternatives, perhaps put out by the U.N. itself.

An international convention banning trade in energy-guzzlers, as in endangered species, may be too much to hope for, but perhaps Customs authorities, in countries from Bermuda to India where Customs plays a key role in trade regulation[116], could be encouraged to attach tariffs varying inversely with energy efficiency (or even positive-or-negative duties structured like feebates). Devoting to import regulation of energy efficiency a small fraction of the engineering skill that now goes into designing power plants could pay big dividends. One can even imagine multicountry consortia that bulk-buy energy-using commodities (lights, motors, windows, etc.), and maintain a common secretariat that tracks and helps to get the best buys. One way or another, it is important to make it cheaper and more politically attractive for both buyers and sellers to deal in efficient than in inefficient equipment. The industrialized countries, too, have a major but unacknowledged responsibility in this matter: they typically set a bad example in what *they* buy, and they often export their most inefficient and obsolete equipment to boot -- like deregistered pesticides all over again. This occurs even with inefficient motors, etc., removed under present U.S. utility rebate programs: if not scrapped, they may end up being reinstalled down the street or in Mexico.

Another issue meriting exploration -- though its importance is often exaggerated -- is the ways in which intellectual property rights may collide with transfer of energy-saving technology to countries that need them but cannot afford the royalties. Where such problems occur, carbon-tax revenues or carbon-offset sales revenues might be used to pay those royalties -- a sort of *pro bono* fund. It may also be possible to organize a form of nonmonetary recognition, perhaps by UNEP, for inventors and firms who waive royalties in such circumstances. There may be helpful analogies, too, with the ways in which intellectual property rights were handled when Green Revolution crop strains were developed for use by developing countries.

The need for further research, demonstration, development, and outreach -- for there is already much good news to report -- hardly needs further emphasis. But it is important to stress a major hole in most current research agendas: the integrative design of future energy systems that combine efficiency with renewables. This

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[115]Research at Shell and by the late human-rights barrister Paul Sieghart has confirmed the basic premise of basic-human-needs strategies by showing three nearly perfect correlates and predictors of conventionally measured development success: absence of subsidies to basic commodities, adherence to basic human rights, and the health and education of the people ten years earlier. (The Costa Rican electric utility, incidentally, runs a lottery for everyone who uses less electricity this month than last month; but their opportunities to use less are currently limited to behavioral change, since they can't yet buy very efficient equipment and receive no financial help in doing so.)

[116]But often a perverse one, *e.g.*, in India, where they charge far higher duties on energy-saving than on energy-supplying imports.

includes the redesign of industrial processes to match solar heat more conveniently, as those processes were in the past successively redesigned to fit the characteristics of wood, coal, oil, gas, and electricity. It also embraces efforts to anticipate bottlenecks, problems, and technical gaps as renewables and efficiency come to play major roles in energy-service supply in each sector.

Reddy & Goldemberg (1990), asking whether the needed transformation of energy policies can take place in the next few decades, conclude that aside from actions by the international bodies charged with, but largely ignoring, this responsibility, "the best hope for change lies in a convergence of interests." Industrialized countries need to protect the environment and ensure sustainable development; the environmental movement is joining hands worldwide; advocates for the poor, and increasingly the disenfranchised themselves, are crying out for policies that work better and cost less. The realization is spreading around the world that high levels of energy efficiency, and farming and forestry practices that treat nature as model and mentor, are not inimical but vital to a stable climate, a healthful environment, sustainable development, social justice, and a liveable world.

This convergence will be seen and used more clearly for what it is when everyone, especially we in the industrialized world, better understand what so often obscures our view of poor countries' energy and development needs. It is not our regions' differences, important though they are, but their similarities.

Additional benefits

Energy efficiency and sustainable farming and forestry practices, and the other ways described above to abate global warming and make money simultaneously, all have additional benefits which presumably could be expressed as monetary values. Counting those values would make their sources look even cheaper. The following list of omitted joint benefits is illustrative, not exhaustive.

Environmental protection

Energy efficiency and renewable energy sources largely eliminate the environmental impacts of mining, transporting, and burning the fuel they displace. Reduced CO_2 is only one such benefit. Others include avoided SO_x, NO_x, O_3, hydrocarbons, particulates, and other air pollutants; despoiled land; acid mine drainage; oil spills; and impaired esthetic, wilderness, and wildlife values.

A simple example suffices. Rather than raising electric bills to clean up dirty coal-fired power stations, a utility can help its customers to get superefficient lights, motors, appliances, etc., so they need less electricity to do the same tasks. The utility will then burn somewhat less coal and emit less sulfur (ideally backing out the dirtiest plants first), but mainly the utility will save a lot of money, because efficiency costs less than coal. That saved operating cost can then be used partly to clean up the remaining plants, partly to make electricity cheaper, and partly to reward the utility's shareholders. Similar principles permit the negative-cost abatement of urban smog by such measures as superefficient cars (Lovins 1989b). In either case, not only the health of people and other living things (and the longevity of cultural monuments and natural artifacts) will benefit; forests and other ecosystems, being less degraded, will also be better able to sequester carbon.

Sustainable agriculture and forestry, too, do not just reduce biotic CO_2, CH_4, and N_2O emissions; they also help to preserve topsoil, genes (biodiversity), water, fuels, farms, and farmers. They control floods, reducing the siltation of dams and of navigable waterways. (Dams that last longer displace more fossil-fuel CO_2 from thermal power plants.) Sustainable practices increase the habitat and population of land, aquatic, and marine wildlife. They preserve or create diverse and beautiful landscapes. They protect rural culture -- an important cultural "anchor" -- and help to reverse rural depopulation, a key contributor to urban problems. They reduce or eliminate dependence on biocides, whose manufacture accounts for a substantial fraction of all toxic-waste generation, and reduce associated problems ranging from occupational exposure and drift in application to runoff and groundwater contamination after application. They similarly reduce fertilizer contamination of ground- and surface waters, hence eutrophication, nitrate toxicity in drinking water, etc. They also restore the wholesomeness of food now contaminated by biocides, hormones, and antibiotics, probably thereby benefiting public health.

Moreover, such sustainable practices reduce crop losses to pests by rebuilding predator stocks and diversity; may modestly raise net farm or forest income, and make that income stream less vulnerable to weather, pests, crop prices, and other uncontrollable variables; and should reduce dependence on government subsidies. They keep farming, in short, as profitable as now or (in most cases) more so (NRC 1989), and far more consistently so. They thereby reduce strains on the rural banking system, reliance on commodity brokers, and risks arising from commodity speculation. They set a good example for agricultural evolution abroad. They foster a land ethic and the practice of stewardship. And they make farming more diverse, interesting, and appealing to the young.

In sum, informal estimates at EPA's Pollution Prevention Office suggest that most -- perhaps around 90% -- of the problems EPA deals with could be displaced, at negative cost, just by energy efficiency and by sustainable farming and forestry. That is a pleasant byproduct of abating global warming at a profit.

Security

Security -- freedom from fear or privation or attack -- may be achieved by other and cheaper means than armed might and threats of violence (Harvey *et al.* 1991). Security comprises access to reliable and affordable necessities of life (water, food, shelter, health, a healthful environment, a sustainable economy, a legitimate system of government, certain cultural and spiritual assets). It also requires some combination of conflict prevention, conflict resolution, and defense -- preferably nonprovocative -- that is predictably able to defeat aggression (*id.*). Resource efficiency in all its forms is an essential element of both providing needed resources and forestalling conflict over resources.

Energy/security links take many forms, and the list grows with awareness that climatic stability and biotic productivity are essential elements of global security. High on anyone's security list are equitably providing the energy needed for sustainable development; reducing domestic energy vulnerability (Lovins & Lovins 1982); abating the spread of nuclear weapons (Lovins & Lovins 1981); and avoiding conflict over fuel-rich areas like the Persian Gulf.

The United States and other nations recently put their youths in 0.56-mile-per-gallon tanks and 17-feet-per-gallon aircraft carriers in the Middle East because the same youths weren't put in 32-mile-per-gallon cars. A three-mile-per-gallon improvement in the ~20-mi/gal U.S. household vehicle fleet would displace the mid-1990 rate of oil imports from Iraq and Kuwait; a 12 mi/gal improvement would displace all U.S. oil imports from the Persian Gulf. If the military cost of the Gulf war were somehow internalized in the oil price, rather than socialized through taxes and deficits, it would be interesting to how well the oil would sell at more than $100 per barrel (Lovins & Lovins 1990, 1991).

This paper has described cost-effective efficiency improvements in U.S. oil use that could potentially displace the United States' oil imports from the Persian Gulf roughly seven times over. Similar opportunities, differing only in detail, are available to other oil-importing countries, even the most efficient. It is bad enough to pay in dollars the cost of continuing to ignore such opportunities. It is tragic to pay it in blood. Given that the Middle East is uniquely rich in oil, and full of diverse peoples who have fought each other for millenia, there is wisdom in at least making the oil under their disputed territories as irrelevant to the world's continued peace and prosperity as modern technology permits.

Equity

An original and pragmatic treatment of global warming (Krause *et al.* 1989) has proposed that the long-term fossil-fuel "budget" of ~300 billion tons of carbon (GtC) believed to be consistent with a probably tolerable rate of climatic change be split evenly between developing and industrialized countries. This would "push industrialized countries to fully mobilize their technological, financial, and organizational capacities for phasing out fossil fuels without creating infeasible goals" (*id.*, p. I-6.9). It would also leave developing countries more leeway to cope with their presumably lower adaptive capacity, greater needs, and greater population momentum. All regions together, under such a budget, might find it a reasonable milestone to return *global* carbon emissions to ~1985 release rates by ~2005 -- by which time the 20% reduction target set at Toronto should have been achieved by the industrialized countries. This seems a reasonable trajectory, and is certainly fairer than most. But one must also consider the "micro-equity" features of the specific tools proposed. In that respect, the strategy proposed both by Krause *et al.* (1990) and here seems attractive.

One of the best features of the efficiency-and-renewables energy strategy is that many of the technologies are "vernacular," able to be locally made with fairly common skills, and the renewable energy itself is equitably available to all. Sunlight is indeed most abundant where most of the world's poorest people live (Sørensen 1979). In no part of the world between the polar circles is freely delivered renewable energy inadequate to support a good life indefinitely and economically using present technologies (*id.*, Reddy & Goldemberg 1988, Lovins *et al.* 1981).

Much the same is true of sustainable farming and forestry practices. By relying chiefly on natural processes and assets, these practices minimize dependence on inputs that must be bought or brought from afar. In both cases, future generations' rights seem to be far better protected than now.

Resilience

Life is full of surprises. Energy analysts who owe their careers to singular events in 1973 and 1979 cheerfully go on to assume a surprise-free future. It will not be like that at all. There will even be surprises of kinds nobody has thought of yet (just as some people unfamiliar with the history of climatic science suppose global warming is). However, the fundamental principles of resilient design, borrowed chiefly from biology and engineering (Lovins & Lovins 1982), are completely consistent with the energy and agri/silvicultural strategies proposed here. More diverse, dispersed, renewable, and above all efficient energy systems can make major interruptions virtually impossible in principle (*id.*). Growing green things in a way duly respectful of several billion years' design experience is the best way anyone knows to ensure that the earth will keep on handing down that experience.

Buying time

In an earlier analysis of least-cost climatic stabilization (Lovins *et al.* 1981), two colleagues and we noted that if the terrible exponential arithmetic of burning more and more fuel, faster and faster, were simply reversed -- if the amount of carbon released each year steadily *shrank* -- then the "tail" of "global warming commitment" would soon become so slender that its length would be unimportant. A very long period would then be safely available for displacing the last remnants of fossil-fuel use. That simple idea remains valid.[117] In a more subtle

[117]Perhaps by coincidence, the rough and illustrative estimates presented in 1981, at a time when the role of trace gases other than CO_2 was poorly understood, are surprisingly close to those now emerging from today's far more sophisticated analyses. Indeed, Krause *et al.*'s rough timeline for a 300-GtC global carbon budget (1990) -- a 20% reduction in global carbon emissions between about 2005 and 2015, 50% around 2025-2035, and 75% before the middle of the next century -- is "roughly equivalent to the efficiency-plus-renewables scenario of Lovins *et al.* (1981)" (Krause 1990). The 450-GtC budget associated with more sanguine climatological assumptions is close to the Goldemberg *et al.* (1988) scenario, "modified to include significant renewables penetration" (Krause 1990). Krause concludes (*id.*): "The

sense, however, the time-buying value of techniques like energy efficiency is greater than meets the eye. Efficiency buys not just money and avoided pollution but also *time* -- the most precious and least substitutable resource.

An anecdote is useful here. Around 1984, Royal Dutch/Shell Group planners foresaw the 1986 oil-price crash, and warned that a deepwater North Sea oilfield called Kittiwake would have to be brought in at 40% below the planned cost, because by the time the field opened, it would be possible to sell the oil only for $12 a barrel, not $20. The engineers, who had been sweating over one-percent cost cuts, were aghast. But offered the alternative of being fired and leaving the oil where it was, they cut the cost by 40% in about a year.

It turned out they had previously been asked the wrong question: how to bring on fields as fast as possible with cost no object, rather than how to do it cheaply even if it took longer. Asked the new question, they came up with completely different technological answers. (In how many other situations have we gotten the wrong answer by asking that same wrong question?) But the key result was that the new technology made oil that used to cost $30 to extract into oil that costs only ~$18 to extract: the whole oil supply curve therefore flattened out. This in turn postponed depletion, and this in turn bought time in which to develop and deploy still better technologies, on both the demand side and the supply side, which broaden the range of choice and which reinforce each other by buying still more time, together pushing depletion far into the future and facilitating a graceful transition to renewables.

Time-buying is a sound principle worldwide. The startup obstacles to achieving major efficiency gains in the non-OECD regions strengthen the case for strong and rapid efficiency gains in the countries (OECD) best equipped to achieve them. If that might be "overachievement" relative to some theoretical goal of equitable sharing, nobody should mind: on the evidence presented above, maximizing the size and speed of energy savings is likely only to bring larger and earlier economic *benefits*.

Conclusions

This paper has rebutted ten prevalent myths (in italics) about abating global warming:

- *Greater scientific certainty should precede action.* The uncertainties about global warming and its potential consequences are substantial, interesting, and likely to cut both ways. But they are also irrelevant to policy, because virtually all the actions needed to abate global warming (if it does turn out to be a real problem) should be taken anyway to save money. These "no-regrets" actions are about enough to solve the problem if it does exist, and are highly advantageous even if it doesn't. The problem with global warming isn't decision-making under uncertainty; it's realizing that in this instance, uncertainty doesn't matter.
- *The issue is whether to buy a "climatic insurance policy" analogous to fire insurance or to defense expenditures (a major investment mobilizing most of the country's scientific and technological resources, and meant to forestall or respond to unlikely but potentially catastrophic threats to national security).* The "insurance" analogy is partly valid, because delaying action until obvious climatic changes are unambiguously underway makes abatement too little, too late, and too costly -- just like trying to install a sprinkler system in a hotel that's currently on fire, or build military forces while you're already under attack, or buy collision insurance after you've crashed your car. Abating global warming will require significant efforts affecting large numbers of people and stocks of capital over long periods and with long lead times, so waiting too long will certainly raise cost, difficulty, and risk of failure (Schneider 1989). But the analogy breaks down if, as was shown above, the real choice is not balancing uncertain

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former scenario can be seen as representing the limit of practical logistic feasibility, while the latter scenario can be seen as marking the limit of climatic acceptability.***The range of climate-stabilizing energy scenarios is circumscribed by" those two scenarios.

future benefits against daunting present costs, but rather making the investment as wisely and quickly as possible in order to achieve both the uncertain future benefits *and* the guaranteed financial *savings*. Any insurance "premium" is actually negative: the actions that can stabilize global climate will save money anyway, without counting the avoided costs of trying, or failing, to adapt to possible climatic change. This "insurance" is unquestionably a good buy.

- *Abating global warming would be costly.* Distinguished econometricians have claimed that just achieving the Toronto interim target of cutting CO_2 emissions by 20% -- roughly a third of the reduction probably required for climatic stabilization (IPCC 1990) -- would cost the United States alone on the order of $200 billion per year (B. Davis 1990, Nordhaus 1989, Manne & Richels 1990, Passell 1989). Such calculations are wrong by at least an order of magnitude (*e.g.*, Williams 1990; Zimmerman 1990). Worse, their high-cost conclusion is a bald *assumption* masquerading as a fact (Nordhaus 1990). The econometric analysis merely asks how high energy prices would need to be, based on historic price elasticities of demand (typically from decades ago), to reduce fossil-fuel use by *x*%, then counts those higher prices (or their equilibrium econometric effects) as the cost of abatement. This approach ignores the compelling empirical evidence that saving most of the fuel now used is cheaper than even its short-run marginal cost, and hence is profitable rather than costly. The econometricians thus have the amount about right but the sign wrong: using modern energy-efficient techniques to achieve the Toronto target would not cost but *save* the U.S. on the order of $200 billion a year.[118] These techniques did not exist at the time of the behavior described by the historic price elasticities: those elasticities summarize how people used to behave under conditions that no longer hold. Indeed, cost-minimizing energy policy -- if not derailed by the blunder of treating future energy needs as fate instead of choice -- will seek to change those conditions as much as possible.
- *Abating global warming would drastically curtail American and similar lifestyles, and would mean less comfort, mobility, etc.* Nothing could be further from the truth. The fuel-saving technologies that can stabilize global climate while saving money actually provide unchanged services: showers as hot and tingly as now, beer as cold, rooms as brightly lit, torque as strong and reliable, homes as cozy in the winter and cool in the summer, cars as peppy, safe, and comfortable, etc. The quality of these and other services can often be not just sustained but substantially improved by substituting superior engineering for brute force, brains for therms: *e.g.*, efficient lighting equipment provides the same amount of light, but it looks better and you see better. The same is broadly true of sustainable agriculture and silviculture, which provide comparable yields with superior quality, resilience, human health, and (generally) profitability.
- *If such cost-effective abatements were available, they would already have been bought.* This is reminiscent of the econometrician who, asked by his mannerly granddaughter whether she could pick up a $20 bill she'd just noticed lying on the sidewalk, replied, "No, my dear, don't bother: if it were real, someone would have picked it up already" (Gell-Mann 1990). The striking disequilibrium between how much energy efficiency is now available and worth buying and how much has already been bought arises from distinctive, well-understood market failures that leave cheap efficiency seriously underbought at present prices. (For example, consumers have poor access to information and to mature mechanisms for conveniently delivering integrated packages of modern technologies. Discount rates are about tenfold higher for buying efficiency than supply, severely diluting price signals. Many energy utilities misunderstand their business and want to increase their sales -- even though reducing their sales would increase their profits by decreasing their costs even more. Perverse regulatory signals often reward inefficient

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118 Rosenfeld *et al.* (1990) note that commercial direct fuels cost Americans $283 billion and electricity $175 billion in 1989. Saving (for illustration) a fifth of each at average prices would save $92 billion a year, but the costliest sources would in fact be displaced first, and long-run marginal costs generally exceed present prices. Together, these effects probably at least double the value of the savings. A similar result could be obstained by a conservative method using longer-term savings potentials: saving about two-thirds of the direct fuels (an understated and rough composite of the potential for all sectors) and, in the short run, only one-fourth (utilities' average fuel-cost share) of 75% of the electricity, would total ~$221 billion. More sophisticated calculations are of course possible, disaggregated by sector, fuel, region, timing, etc., but not very useful.

and penalize efficient behavior. Markets in saved energy are sparse or absent. And present market signals, omitting externalities that may be as big as the apparent fuel prices, make consumers indifferent to whether they buy, for instance, a 20- or a 60-mile-per-gallon car, since both cost about the same per mile to own and drive.) Solutions exist for each of these market failures. These solutions have been proven in market economies and are rapidly emerging in a wide range of other societies, so there is an ample range of effective policy instruments to choose from. The technical and implementation options -- the everyday work of energy-efficiency practitioners -- are mostly unknown, however, to those econometricians who lie awake nights worrying about whether what works in practice can possibly work in theory.

- *Abatements would be so costly and disagreeable that they could only be achieved by draconian, authoritarian government mandates incompatible with democracy.* On the contrary, the abatements described above are so profitable and attractive that they can be largely if not wholly achieved by existing institutions, within the present framework of free choice and free enterprise. Planners unaware of market-driven alternatives seem anxious to set up new bureaucracies to tell people how to live. Many bizarre schemes have been suggested for substituting dirigisme for markets, penury for development, risks for rewards, and costs for profits. This paper seeks to provide an antidote to this perversion of economic rationality.
- *Combating global warming requires tough tradeoffs -- swapping one kind of pollution or risk for another.* Abating global warming by resource efficiency can simultaneously reduce or eliminate many other hazards too -- oil-security risks, nuclear proliferation, utilities' planning and financial risks, declining farm and forest yields, etc. -- without creating new ones.
- *Available means of abatement, singly or combined, will be too small and too slow, so global warming is inevitable and we must start trying to adapt to it.* This counsel of despair is misguided. To be sure, some significant degree of climatic change or increased climatic volatility in some places may already be unavoidable if the more sensitive models prove valid (IPCC 1990, Krause *et al.* 1989), or if greater climatological or ecological understanding continues to bring unpleasant surprises. A modest degree of adaptation may therefore be prudent if not inevitable (Schneider 1989): *e.g.*, planning coastal developments to accommodate some sea-level rise and water projects to tolerate shifts in rainfall, or reversing the narrowing of crops' and forests' genetic bases. Nonetheless, the techniques described here, if their benefits are properly understood, show promise of such rapid and widespread deployment that most of the harm projected in today's best models could almost certainly be avoided. Many abatement measures also have the valuable side-effect of increasing resilience in the face of whatever climatic change may nonetheless occur.
- *Abating global warming would lock developing countries into abject poverty, or at least prevent their achieving their legitimate aspirations -- even though most global warming so far has been caused by the industrialized countries.* On the contrary, the abatement options discussed above are not merely compatible with but essential to affordable and sustainable global development and increased equity.
- *Policymakers already know what their options are and haven't chosen those described here, so either the policymakers are stupid or the options don't work.* Many policymakers suppose that abatement must be slow, small, costly, inconvenient, and nasty -- not because that's true, but simply because they don't know any better. The difficulty, we suspect, may be the one economist Ken Boulding described: that a hierarchy is "an ordered arrangement of wastebaskets designed to prevent information from reaching the executive." The options described above are available, demonstrated, and often in widespread and successful use. Many, however, are so new that they are not yet widely known even to technical experts, and will take many years to filter up to decisionmakers through normal channels. What is needed, therefore, is better and faster technology transfer to the policymakers. We hope this paper contributes to that effort.

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