Energy in Transition

The era of cheap and convenient sources of energy is coming to an end. A transition to more expensive but less polluting sources must now be managed

by John P. Holdren

As the foregoing articles make clear, civilization is not running out of energy resources in an absolute sense, nor is it running out of technological options for transforming these resources into the particular forms that our patterns of energy use require. We are, however, running out of the cheap oil and natural gas that powered much of the growth of modern industrialized societies, out of environmental capacity to absorb the impacts of burning coal, and out of public tolerance for the risks of nuclear fission. We seem to be lacking as well the commitment to make coal cleaner and fission safer, the money and endurance needed to develop long-term alternatives, the astuteness to embrace energy efficiency on the scale demanded and the consensus needed to fashion any coherent strategy at all.

These deficiencies suggest that civilization has entered a fundamental transition in the nature of the energy-society interaction without any collective recognition of the transition's character or its implications for human well-being. The transition is from convenient but ultimately scarce energy resources to less convenient but more abundant ones, from a direct and positive connection between energy and economic well-being to a complicated and multidimensional one, and from localized pockets of pollution and hazard to impacts that are regional and even global in scope.

The subject is also being transformed from one of limited political interest within nations to a focus of major political contention between them, from an issue dominated by decisions and concerns of the Western world to one in which the problems and prospects of all regions are inextricably linked, and from one of concern to only a small group of technologists and managers to one where the values and actions of every citizen matter.

Understanding this transition requires a look at the two-sided connection between energy and human well-being. Energy contributes positively to well-being by providing such consumer services as heating, lighting and cooking as well as serving as a necessary input to economic production. But the costs of energy—including not only the money and other resources devoted to obtaining and exploiting it but also the environmental and sociopolitical impacts—detract from well-being.

For most of human history, the dominant concerns about energy have centered on the benefit side of the energy-well-being equation. Inadequacy of energy resources or (more often) of the technologies and organizations for harvesting, converting and distributing those resources has meant insufficient energy benefits and hence inconvenience, deprivation and constraints on growth. Energy problems in this category remain the principal preoccupation of the least developed countries, where energy for basic human needs is the main issue; they are also an important concern in the intermediate and newly industrializing countries, where the issue is energy for production and growth.

Aside from having too little energy, it is possible to suffer by paying too much for it. The price may be paid in excessive diversion of capital, labor and income from nonenergy needs (thereby producing inflation and reducing living standards), or it may be paid in excessive environmental and sociopolitical impacts. For most of the past 100 years, however, the problems of excessive energy costs have seemed less threatening than the problems of insufficient supply. Between 1890 and 1970 the monetary costs of supplying energy and the prices paid by consumers stayed more or less constant or declined, and the environmental and sociopolitical costs were regarded more as local nuisances or temporary inconveniences than as pervasive and persistent liabilities.

All this changed in the 1970's. The oil-price shocks of 1973-1974 and 1979 doubled and then quadrupled the real price of oil on the world market. In 1973 oil constituted nearly half of the world's annual use of industrial energy forms (oil, natural gas, coal, nuclear energy and hydropower as opposed to the traditional energy forms of fuelwood, crop wastes and dung). Inevitably, the rise in oil prices pulled the prices of the other industrial energy forms upward. The results illustrate vividly the perils of excessive monetary costs of energy: worldwide recession, spiraling debt, a punishing blow to the development

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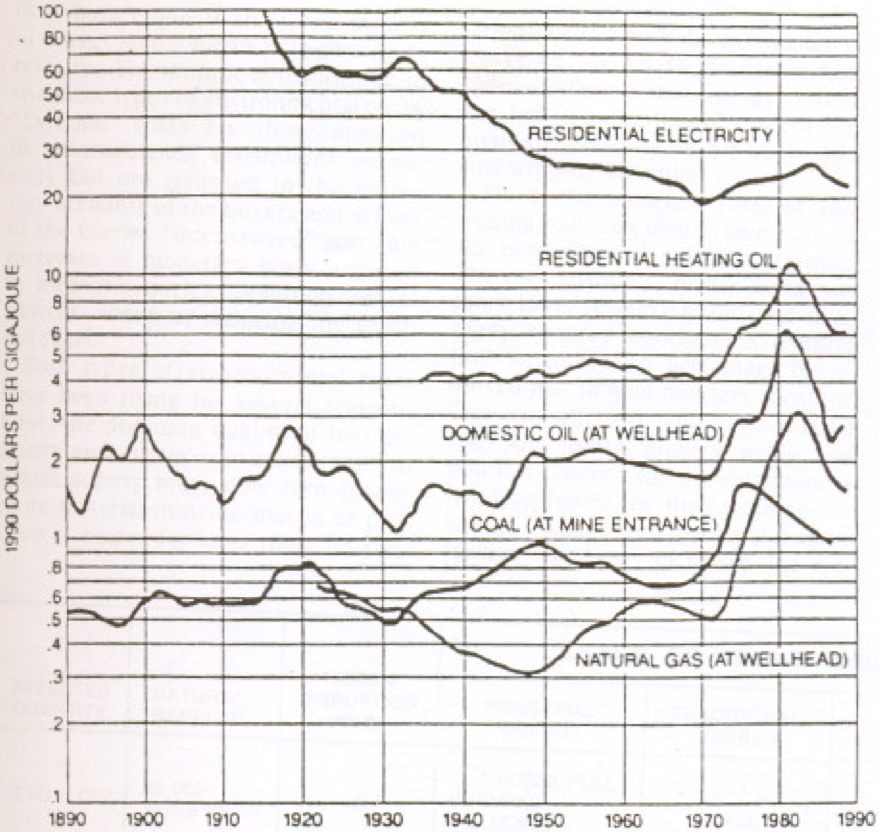
STREET FAIR in New York City brings together large numbers of people from a high-technology segment of the world population of 5.3 billion. If the rest of the world's people used energy at the same rate as citizens of the U.S. do, global energy use in 1990 would be more than four times as large as it is.



ENERGY COSTS in the U.S. over the past century are charted, in constant U.S. dollars. The fuel-price shocks of the 1970's were precipitated by the Organization of Petroleum Exporting Countries (OPEC) but reflect an underlying reality: cheap (easily recoverable) oil and natural gas are already gone in most of the world. Although fuel substitution and conservation brought the price of OPEC oil down in the early 1980's, prices are not likely ever to reach their preshock lows. Electricity was less affected by the price shocks because of the limited role of oil in generating electricity and the modest contribution of fuel costs to the total cost of supplying electricity.

prospects of the oil-poor countries of the Southern Hemisphere and the imposition in the industrialized nations of disproportionate economic burdens on the poor.

The early 1970's also marked a transition in coming to grips with the environmental and sociopolitical costs of energy. Problems of air and water pollution, many of them associated with energy supply and use, were coming to be recognized as pervasive threats to human health, economic well-being and environmental stability. Consciousness of the sociopolitical costs of energy grew when overdependence on oil from the Middle East created foreign-policy dilemmas and even a chance of war, and when India's detonation of a nuclear bomb in 1974 emphasized that spreading competence in nuclear energy can provide weapons as well as electricity.

The 1970's, then, represented a turning point. After decades of constancy or decline in monetary costs—and of relegation of environmental and sociopolitical costs to secondary status—energy was seen to be getting costlier in all respects. It began to be plausible that excessive energy costs could pose threats on a par with those of insufficient supply. It also became possible to think that expanding some forms of energy supply could create costs exceeding the benefits.

The crucial question at the beginning of the 1990's is whether the trend that began in the 1970's will prove to be temporary or permanent. Is the era of cheap energy really over, or will a combination of new resources, new technologies and changing geopolitics bring it back? One key determinant of the answer is the staggering scale of energy demand brought forth by 100 years of unprecedented population growth, coupled with an equally remarkable growth in per capita demand for industrial energy forms. Supplying energy at rates in the range of 10 terawatts (one terawatt is one billion watts), first achieved in the late 1960's, is an enterprise of enormous scale. The way it was done in 1970 required the harvesting, processing and combustion of some three billion metric tons of coal and lignite, some 17 billion barrels of oil, more than a trillion cubic meters of natural gas and perhaps two billion cubic meters of fuelwood. It entailed the use of dirty coal as well as clean; undersea oil as well as terrestrial; deep gas as well as shallow; mediocre hydroelectric sites as well as good ones; and deforestation as well as sustainable fuelwood harvesting.

The greatest part of the past century's growth in industrial energy forms was supplied by oil and natural gas—the most accessible, versatile, transportable and inexpensive chemical fuels on the planet. The century's cumulative consumption of some 200 terawatt-years of oil and gas represented perhaps 20 percent of the ultimately recoverable portion of the earth's endowment of these fuels. If the cumulative consumption of oil and gas continues to double every 15 to 20 years, as it has done for a century, the initial stock will be 80 percent depleted in another 30 or 40 years.

Except for the huge pool of oil underlying the Middle East, the cheapest oil and gas are already gone. The trends that once held costs at bay against cumulative depletion, that is, new discoveries and economies of scale in processing and transport, have played themselves out. Even if a few more giant oil fields are discovered, they will make little difference against consumption on today's scale. Oil and gas will have to come increasingly, for most countries, from smaller and more dispersed fields, from offshore and Arctic environments, from deeper in the earth and from imports whose reliability and affordability cannot be guaranteed.

There are, as the preceding articles have shown, a variety of other energy resources that are more abundant than oil and gas. Coal, solar energy and fission and fusion fuels are the most important ones. But they all require elaborate and expensive transformation into electricity or liquid fuels in order to meet society's needs. None has very good prospects for delivering large quantities of fuel at costs comparable to those of oil and gas prior to 1973 or large quantities of electricity at costs comparable to those of the cheap coal-fired and hydropower plants of the 1960's. It appears, then, that expensive energy is a permanent condition, even without allowing for its environmental costs.

The capacity of the environment to

absorb the effluents and other impacts of energy technologies is itself a finite resource. The finitude is manifested in two basic types of environmental costs. "External" costs are those imposed by environmental disruptions on society but not reflected in the monetary accounts of the buyers and sellers of the energy. "Internalized" costs are increases in monetary costs imposed by measures, such as pollution-control devices, aimed at reducing the external costs.

Both types of environmental costs have been rising for several reasons. First, the declining quality of fuel deposits and energy-conversion sites to which society must now turn means more material must be moved or processed, bigger facilities must be constructed and longer distances must be traversed. Second, the growing magnitude of effluents from energy systems has led to saturation of the environment's capacity to absorb such effluents without disruption.

Third, the monetary costs of controlling pollution tend to increase with the percentage of pollutant removed. The combination of higher energy-use rates, lower resource quality and an already stressed environment requires that an increasing percentage be removed just to hold damages constant. Consequently, internalized costs must rise. And fourth, growing public and political concern for the environment has lengthened the time required for siting, building and licensing energy facilities, and has increased the frequency of mid-project changes in design and specifications, forcing costs still further upward.

It is difficult to quantify the total contribution of all these factors to the monetary costs of energy supply, in part because factors not related to the environment are often entwined with environmental ones. For example, construction delays have been caused not just by regulatory constraints but also by problems of engineering, management and quality control. Nevertheless, it seems likely that in the U.S. actual or attempted internalization of environmental impacts has increased the monetary costs of supplying petroleum products by at least 25 percent during the past 20 years and the costs of generating electricity from

AFFECTED QUANTITY	NATURAL BASELINE	HUMAN DISRUPTION INDEX	SHARE OF HUMAN DISRUPTION CAUSED BY:			
			INDUSTRIAL ENERGY	TRADITIONAL ENERGY	AGRICULTURE	MANUFACTURING, OTHER
LEAD FLOW	25,000 TONS/YEAR	15	FOSSIL-FUEL BURNING, INCLUDING ADDITIVES	SMALL	SMALL	METALS PROCESSING, MANUFACTURING, REFUSE BURNING
OIL FLOW TO OCEANS	500,000 TONS/YEAR	10	OIL HARVESTING, PROCESSING, TRANSPORT	SMALL	SMALL	DISPOSAL OF OIL WASTES
CADMIUM FLOW	1,000 TONS/YEAR	8	FOSSIL-FUEL BURNING	BURNING TRADITIONAL FUELS	AGRICULTURAL BURNING	METALS PROCESSING, MANUFACTURING, REFUSE BURNING
SO_2 FLOW	50 MILLION TONS/YEAR	1.4	FOSSIL-FUEL BURNING	BURNING TRADITIONAL FUELS	AGRICULTURAL BURNING	SMELTING, REFUSE BURNING
METHANE STOCK	800 PARTS PER BILLION	1.1	FOSSIL-FUEL HARVESTING AND PROCESSING	BURNING TRADITIONAL FUELS	RICE PADDIES, DOMESTIC ANIMALS, LAND CLEARING	LANDFILLS
MERCURY FLOW	25,000 TONS/YEAR	.7	FOSSIL-FUEL BURNING	BURNING TRADITIONAL FUELS	AGRICULTURAL BURNING	METALS PROCESSING, MANUFACTURING, REFUSE BURNING
NITROUS OXIDE FLOW	10 MILLION TONS/YEAR	.4	FOSSIL-FUEL BURNING	BURNING TRADITIONAL FUELS	FERTILIZER, LAND CLEARING, AQUIFER DISRUPTION	SMALL
PARTICLE FLOW	500 MILLION TONS/YEAR	.25	FOSSIL-FUEL BURNING	BURNING TRADITIONAL FUELS	AGRICULTURAL BURNING, WHEAT HANDLING	SMELTING, NONAGRICULTURAL LAND CLEARING, REFUSE BURNING
CO_2 STOCK	280 PARTS PER MILLION	.25	FOSSIL-FUEL BURNING	NET DEFORESTATION FOR FUELWOOD	NET DEFORESTATION FOR LAND CLEARING	NET DEFORESTATION FOR LUMBER, CEMENT MANUFACTURING

ENERGY SUPPLY accounts for a major share of human impact on the global environment. Most impacts can be characterized as alterations to preindustrial flows or to stocks of environmentally active substances (natural baselines). The human disruption index is the magnitude of the human-generated alteration divided by the baseline. Impacts shown here, except oil flows, all involve flows to or stocks in the atmosphere. The estimates are based on several sources and are approximate.

coal and nuclear power by 40 percent or more.

Despite these expenditures, the remaining uninternalized environmental costs have been substantial and in many cases are growing. Those of greatest concern are the risk of death or disease as a result of emissions or accidents at energy facilities and the impact of energy supplies on the global ecosystem and on international relations.

The impacts of energy technologies on public health and safety are difficult to pin down with much confidence. In the case of air pollution from fossil fuels, in which the dominant threat to public health is thought to be particulates formed from sulfur dioxide emissions, a consensus on the number of deaths caused by exposure has proved impossible. Widely differing estimates result from different assumptions about fuel composition, air-pollution control technology, power-plant siting in relation to population distribution, meteorological conditions affecting sulfate formation and, above all, the relation between sulfate concentrations and disease.

Large uncertainties also apply to the health and safety impacts of nuclear fission. In this case, differing estimates result in part from differences among sites and reactor types, in part from uncertainties about emissions from fuel-cycle steps that are not yet fully operational (especially fuel reprocessing and management of uranium-mill tailings) and in part from different assumptions about the effects of exposure to low-dose radiation. The biggest uncertainties, however, relate to the probabilities and consequences of large accidents at reactors, at reprocessing plants and in the transport of wastes.

Altogether the ranges of estimated hazards to public health from both coal-fired and nuclear-power plants are so wide as to extend from negligible to substantial in comparison with other risks to the population. There is little basis, in these ranges, for preferring one of these energy sources over the other. For both, the very size of the uncertainty is itself a significant liability.

Often neglected, but no less important, is the public health menace from traditional fuels widely used for cooking and water heating in the developing world. Perhaps 80 percent of global exposure to particulate air pollution occurs indoors in developing countries, where the smoke from primitive stoves is heavily laden with carcinogenic benzopyrene and other dangerous hydrocarbons. A disproportionate share of this burden is borne, moreover, by women (who do the cooking) and small children (who are indoors with their mothers).

The ecological threats posed by energy supply are even harder to quantify than the threats to human health and safety from effluents and accidents. Nevertheless, enough is known to suggest they portend even larger damage to human well-being. This damage potential arises from the combination of two circumstances.

First, civilization depends heavily on services provided by ecological and geophysical processes such as building and fertilizing soil, regulating water supply, controlling pests and pathogens and maintaining a tolerable climate; yet it lacks the knowledge and the resources to replace nature's services with technology. Second, human activities are now clearly capable of disrupting globally the processes that provide these services. Energy supply, both industrial and traditional, is responsible for a striking share of the environmental impacts of human activity. The environmental transition of the past 100 years—driven above all by a 20-fold increase in fossil-fuel use and augmented by a tripling in the use of traditional energy forms—has amounted to no less than the emergence of civilization as a global ecological and geochemical force.

Of all environmental problems, the most threatening and in many respects the most intractable is global climate change. Climate governs most of the environmental processes on which the well-being of 5.3 billion people critically depends. And the greenhouse gases most responsible for the danger of rapid climate change come largely from human endeavors too massive, widespread and central to the functioning of our societies to be easily altered: carbon dioxide (CO_2) from deforestation and the combustion of fossil fuels; methane from rice paddies, cattle guts and the exploitation of oil and natural gas; and nitrous oxides from fuel combustion and fertilizer use.

The only other external energy cost that might match the devastating impact of global climate change is the risk of causing or aggravating large-scale military conflict. One such threat is the potential for conflict over access to petroleum resources. The danger is thought to have declined since the end of the 1970's, but circumstances are easily imagined in which it could reassert itself—particularly given the current resurgence of U.S. dependence on foreign oil. Another threat is the link between nuclear energy and the spread of nuclear weapons. The issue is hardly less complex and controversial than the link between carbon dioxide and climate; many analysts, including me, think it is threatening indeed.

What are the prospects for abating these impacts? Clearly, the choices are to fix the present energy sources or to replace them with others having lower external costs.

As for fixing fossil fuels, it appears that most of their environmental impact (including the hazards of coal mining and most of the emissions responsible for health problems and acid precipitation) could be substantially abated at monetary costs amounting to additions of 30 percent or less to the current U.S. costs of fossil fuels or electricity generated from them. Still, a massive investment in retrofitting or replacing existing facilities and equipment would be needed, representing a particular barrier in parts of the world where capital is scarce and existing facilities and equipment are far below

	1890	1910	1930	1950	1970	1990
WORLD POPULATION (BILLIONS)	1.49	1.70	2.02	2.51	3.62	5.32
TRADITIONAL ENERGY USE PER PERSON (KILOWATTS)	.35	.30	.28	.27	.27	.28
INDUSTRIAL ENERGY USE PER PERSON (KILOWATTS)	.32	.64	.85	1.03	2.04	2.30
TOTAL WORLD ENERGY USE (TERAWATTS)	1.00	1.60	2.28	3.26	8.36	13.73
CUMULATIVE INDUSTRIAL ENERGY USE SINCE 1850 (TERAWATT-YEARS)	10	26	54	97	196	393

TRENDS in population and energy use per person account for the past century's rapid growth of world energy demand. Industrial energy forms are mainly coal, oil and natural gas, with smaller contributions from hydropower and nuclear energy. Traditional fuels are wood, crop wastes and dung. A terawatt is equal to a billion tons of coal or five billion barrels of oil per year. Data were compiled by the author.

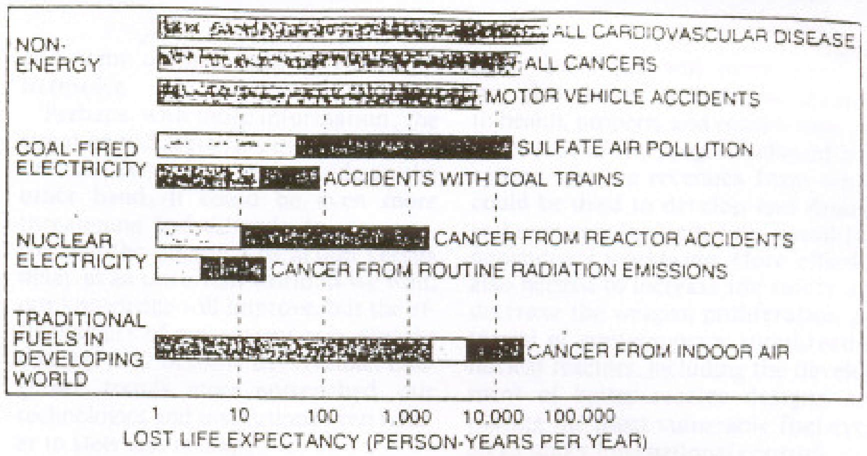
current U.S. standards. The carbon dioxide problem is much harder: replacing coal with natural gas, which releases less CO_2 per gigajoule, is at best a short-term solution, and capturing and sequestering the CO_2 from coal and oil would require revamping much of the world's fuel-burning technology, at huge cost.

Nuclear energy is incomparably less disruptive climatologically and ecologically than fossil fuels are, but its expanded use is unlikely to be accepted unless a new generation of reactors with demonstrably improved safety features is developed, unless radioactive wastes can be shown to be manageable in the real world and not just on paper and unless the proliferation issue is decisively resolved. I believe the first two conditions could be met, at least for nonbreeder reactors, without increasing the already high costs of nuclear electricity by more than another 25 percent. I think the third can be accomplished only by internationalizing a substantial part of the nuclear-energy enterprise, an approach blocked much more by political difficulties than by monetary costs. Fusion can, in principle, reduce the safety, waste and proliferation hazards of fission, but it is not yet clear how soon, by how much and at what monetary cost.

Biomass energy, if replaced continuously by new growth, avoids the problem of net CO_2 production, but the costs of controlling the other environmental impacts of cultivation, harvesting, conversion and combustion of biomass will be substantial. Just bringing the consequences of today's pattern of biomass energy use under control, given its contribution to deforestation and air-pollution problems, will require huge investments of time and money. The tripling or quintupling of biomass supplies foreseen by some would be an even more formidable task, fraught with environmental as well as economic difficulties.

The superabundant long-term option whose external environmental costs are most clearly controllable is direct harnessing of sunlight, but it is now the most expensive of the long-term options and may remain so. The decision to pay the monetary costs of solar energy, if it is made, will represent the ultimate internalization of the environmental costs of the options that solar energy would displace.

There is much reason to think, then, that the energy circumstances of civilization is changing in fundamental rather than superficial ways. The upward trend in energy costs is solidly



RELATIVE MAGNITUDES of some energy and nonenergy risks are shown for a population of one million. Lost life expectancy is measured as the number of deaths per year times the number of years lost per death. Nonenergy data are based on actual U.S. mortality statistics (*blue*). Energy risks are calculated assuming that all electricity use (or household energy use in the developing world) comes from the indicated source. Minimum (*green*) to intermediate (*orange*) to maximum (*red*) estimates of calculated risks are based on various assumptions about sites, dose-response relations and accident probabilities (in the nuclear case).

entrenched, above all because of environmental factors. It is quite plausible, in fact, given existing energy-supply systems, end-use technologies and end-use patterns, that most industrialized nations are near or beyond the point where further energy growth will create greater marginal costs than benefits. "Full speed ahead" is no longer a solution.

Instead we will need transitions in energy-supply systems and patterns of end use just to maintain current levels of well-being; without such transitions, cumulative consumption of high-grade resources and the diminished capacity of the environment to absorb energy's impacts will lead to rising total costs even at constant rates of use. Providing for economic growth without environmental costs that undermine the gains will require even faster transitions to low-impact energy-supply technologies and higher end-use efficiency.

Although the situation poses formidable challenges, it is likely that the most advanced industrialized nations are rich enough and technologically capable enough to master most of the problems. The richest countries could, if they chose, live with low or even negative energy growth by milking increases in economic well-being from efficiency increases, and they could pay considerably higher energy prices to finance the transition to environmentally less disruptive energy-supply technologies. But so far there is little sign of this actually happening. And whether it could be managed in the Soviet Union and Eastern Europe, even in principle, without massive help from the West is more problematic.

Still more difficult is the situation in the less developed countries (LDC's). They would like to industrialize the way the rich did, on cheap energy, but they see the prospects of doing so undermined by high energy costs—whether imposed by the world oil market or by a transition to cleaner energy options. An acute shortage of capital accentuates their tendency to choose options that are cheapest in terms of monetary costs, and they see the local environmental impacts of cheap, dirty energy as a necessary trade for meeting basic human needs (with traditional energy forms) and generating economic growth (with industrial ones).

Although the LDC share of world energy use is modest today, the demographics and economic aspirations of these countries represent a huge potential for energy growth. If this growth materializes and comes mainly from fossil fuels, as most of these countries now anticipate, it will add tremendously to the atmospheric burdens of CO_2 and other pollutants both locally and globally. And while they resent and resist the go-slow approach to energy growth that global environmental worries have fostered in many industrialized nations, the LDC's are, ironically, more vulnerable to global environmental change: they have smaller food reserves, more marginal diets, poorer health and more limited resources of capital and infrastructure with which to adapt.

Global climate change could have profound consequences for the nations of the Southern Hemisphere: more dry-season droughts, more wet-season floods, more famine and disease, perhaps hundreds of millions of environmental refugees. Even if the North suffered less from the direct effects of climate change because of the greater capacities of industrialized societies to adapt, the world is too interconnected by trade, finance, resource interests, politics, porous borders and possibilities for venting frustrations militarily.

How should society respond to the changing and increasingly alarming interaction between energy and human well-being? How can the energy transition on which civilization has embarked, largely unaware, be steered consciously toward a more supportive and sustainable relation among energy, the economy and the environment?

The first requirement is to develop an improved and shared understanding of where we are, where we are headed and where we would like to go. There needs to be an extended public and indeed international debate on the connections between energy and well-being, supported by a greatly expanded research effort to clarify the evolving pattern of energy benefits and costs. Of course, study and debate will take time. Large uncertainties attend many of the important issues, and some of these will take decades to resolve.

Perhaps, with more information, the situation will seem less threatening and difficult than I have suggested; on the other hand, it could be even more threatening and difficult. In any case, we face the dilemma of action versus delay in an uncertain world: if we wait, our knowledge will improve, but the effectiveness of our actions may shrink; damage may become irreversible, dangerous trends more entrenched, our technologies and institutions even harder to steer and reshape.

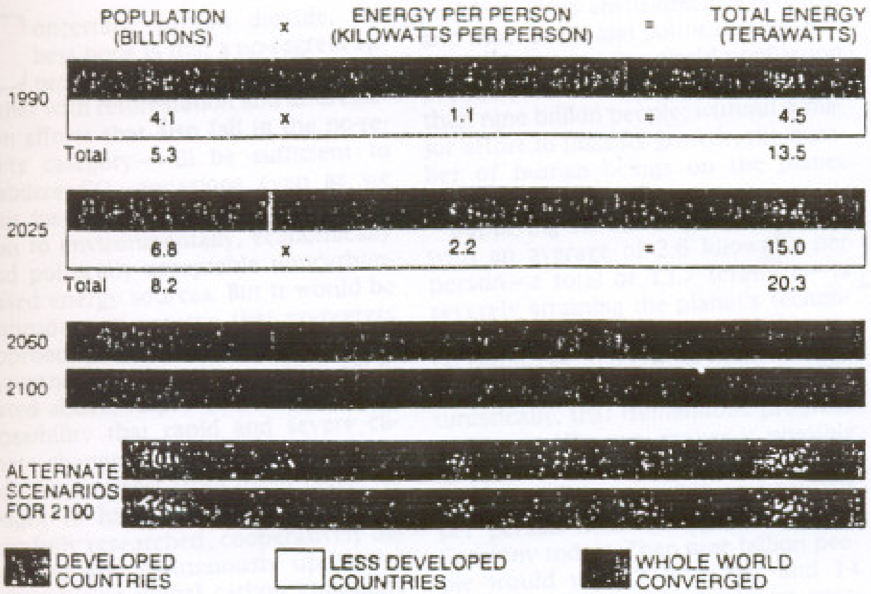
The solution to the dilemma is a two-pronged strategy consisting of "no regrets" and "insurance policy" elements. No-regrets actions are those that provide leverage against the dangers we fear but are beneficial even if the dangers do not fully materialize. In contrast, insurance-policy actions offer high potential leverage against uncertain dangers in exchange for only modest investment, although some of that investment may later turn out to have been unnecessary.

One essential no-regrets program is to internalize and reduce the environmental and sociopolitical costs of existing energy sources. High priority should be given to abating emissions of sulfur and nitrogen oxides from fossil fuels and emissions of hydrocarbons and particles from fossil fuels and traditional fuels alike. Technologies for controlling these emissions exist and will more than repay their costs by reducing damage to health, property and ecosystems. Another part of the program should be a carbon tax, the revenues from which could be used to develop and finance technologies for reducing fossil-fuel dependence worldwide. More effort is also needed to increase the safety and decrease the weapon-proliferation potential of contemporary (nonbreeder) nuclear reactors, including the development of better reactor designs and placing the most vulnerable fuel-cycle steps under international control.

Increasing the efficiency of energy use (another no-regrets approach) is the most effective way of all to abate environmental impacts. Fossil fuels and uranium saved through efficiency generate no emissions and create no fission products or proliferation hazards. (Efficiency, too, can have environmental impacts, but they are usually smaller, or can be made smaller, than those of the energy sources displaced.) Increased efficiency is also the most economical option in monetary terms and the most rapidly expandable, and its ultimate potential is both enormous and sustainable. The main obstacle is educating the vast numbers of individual energy consumers, whose actions hold the key to many of the potential gains, and then providing them with the capital to take advantage of more efficient technologies.

Also crucial to a sensible energy strategy is the acceleration of research and development on long-term energy alternatives: sunlight, wind, ocean heat, and biomass; the geothermal energy that is ubiquitous in the earth's crust at great depth; fission breeder reactors; fusion; and advanced approaches to energy efficiency. The research should emphasize not only the attainment of economical ways to harness these resources but also the prospects for minimizing their environmental costs. Investing in such research qualifies as an insurance approach in that we do not yet know which of the options will be needed or how soon. Some of the money will be wasted, in the sense that some of the options will never be exploited. But the funding required to develop these alternatives to the point that we can choose intelligently between them is modest compared with the potential costs of having too few choices.

Building East-West and North-South cooperation on energy and environmental issues, a no-regrets strategy that will help no matter how the future



"OPTIMISTIC" SCENARIO for world energy use in the next century is based on relatively low population growth, progress in energy efficiency and closing the gap between rich and poor. The scenario assumes a high standard of living can be achieved worldwide at an average rate of energy use of about three kilowatts a person. Nonetheless, energy use in 2060 is double that of 1990.

unfolds, might begin with increased cooperation on energy research. Such collaboration could alleviate the worldwide funding squeeze for such research by eliminating needless duplication, sharing diverse specialized strengths and dividing the costs of large projects. (Until now nuclear fusion has been the only area of energy research that has enjoyed major international cooperation.) It is especially important that cooperation in energy research include North-South collaborations on energy technologies designed for application in developing countries.

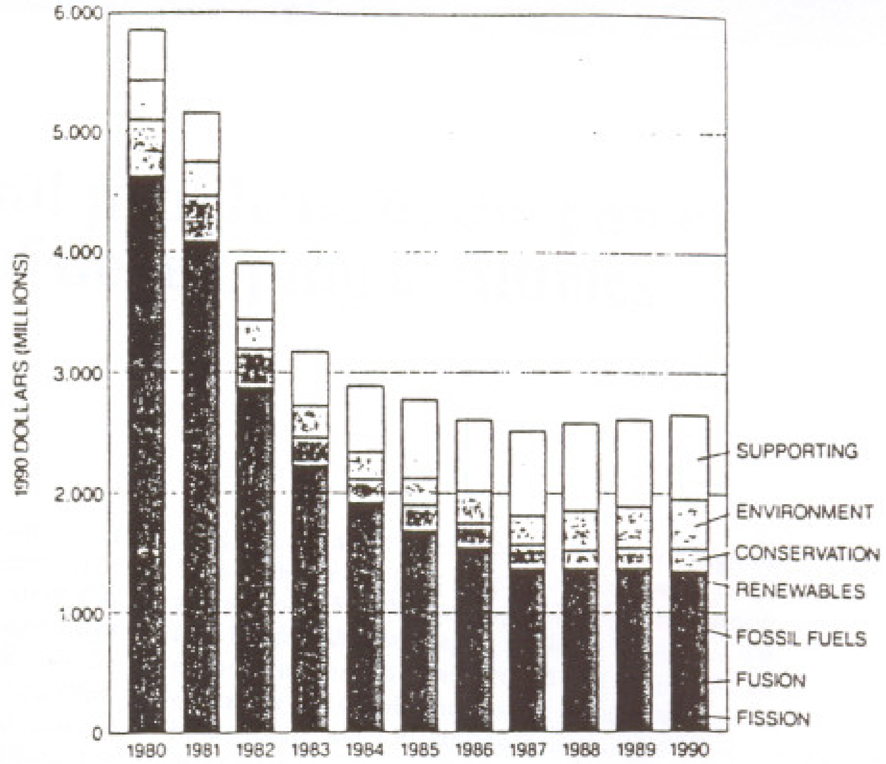
International cooperation on understanding and controlling the environmental impacts of energy supply is also extremely important, because many of the most threatening problems are precisely those that respect no boundaries. Air and water pollution from Eastern Europe and the Soviet Union reach across Western Europe and into the Arctic, and the environmental impacts of energy supply in China and India, locally debilitating at today's levels of energy use, could become globally devastating at tomorrow's. But pleas from the rich countries to solve global environmental problems through global energy restraint will fall on deaf ears in the least developed and economically intermediate countries unless the first group can find ways to help the last two achieve increased economic well-being and environmental protection at the same time.

Concerning carbon dioxide, the best hope is that a no-regrets approach to energy efficiency—together with reforestation and afforestation efforts that also fall in the no-regrets category—will be sufficient to stabilize CO_2 emissions even as we wait for the necessarily slower transition to environmentally, economically and politically acceptable noncarbon-based energy sources. But it would be imprudent to assume that no-regrets approaches will suffice. We need more insurance, beyond the research advocated above, to protect us against the possibility that rapid and severe climate change might necessitate an accelerated retreat from fossil fuels. We ought to have a contingency plan—carefully researched, cooperatively developed and continuously updated—for reducing global carbon emissions at a rate of 20 percent per decade or more if that proves necessary and if the no-regrets strategies already in place are not adequate.

None of the preceding measures, nor all of them together, will be enough to save us from the folly of failing to stabilize world population. The growth of population aggravates every resource problem, every environmental problem and most social and political problems. Short of catastrophe, world population probably cannot be stabilized at less than nine billion people; without a major effort to limit its growth, the number of human beings on the planet could soar to 14 billion or more.

Supplying 5.3 billion people in 1990 with an average of 2.6 kilowatts per person—a total of 13.7 terawatts—is severely straining the planet's technological, managerial and environmental resources, and crucial human needs are going unmet. Let us suppose, optimistically, that tremendous progress in energy efficiency makes it possible to provide an acceptable standard of living at an average of three kilowatts per person (half the figure for West Germany today). Then nine billion people would use 27 terawatts and 14 billion would use 42; the lower energy-use figure is twice today's, the higher one more than triple today's. Can we expect to achieve even the lower one at tolerable costs? As hard as controlling population growth may be, it is likely to be easier than providing increasing numbers of people with energy (and food and water and much else).

The foregoing prescriptions for taking positive control over the energy transition constitute a demanding and ambitious agenda for national and international action. Little of it will happen unless there is widespread consensus about the nature of the problem, the size of the stakes and the possibilities for action. It is hoped that the articles in this special issue of *Scientific American* will make a contribution toward that end.



FUNDING FOR ENERGY RESEARCH in the U.S. has declined sharply since 1980. The bars represent federal budget authority for research, development and technology demonstrations, in 1990 dollars. "Supporting" refers to research in basic energy sciences. Federal energy research could be restored to its 1980 level by raising the gasoline tax a mere three cents a gallon. Note also that the U.S. military spends more than 100 times the total energy-research budget for "insurance" against events that are far less likely to occur than global changes demanding new energy options.

FURTHER READING

BIOFUELS, AIR POLLUTION, AND HEALTH: A GLOBAL REVIEW. Kirk R. Smith. Plenum Press, 1987.

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