Population and the Energy Problem

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ABSTRACT: When energy is scarce or expensive, people can suffer material deprivation and economic hardship. When it is obtained in ways that fail to minimize environmental and political costs, these too can threaten human wellbeing in fundamental and pervasive ways. The energy problem today combines these syndromes: much of the world's population has too little energy to meet basic human needs; the monetary costs of energy are rising nearly everywhere; the environmental impacts of energy supply are growing and already dominant contributors to local, regional, and global environmental problems (including air pollution, water pollution, ocean pollution, and climate change); and the sociopolitical risks of energy supply (above all the danger of conflict over oil and the links between nuclear energy and nuclear weapons) are growing too. This predicament has many causes, but predominant among them are the nearly 20-fold increase in world energy use since 1850 and the cumulative depletion of the most convenient oil and gas deposits that this growth has entailed, resulting in increasing resort to costlier and/or environmentally more disruptive energy sources. The growth of world population in this period was responsible for 52% of the energy growth, while growth in per capita energy use was responsible for 48% (excluding causal connections between population and energy use per capita). In the United States in the same period, population growth accounted for 66% of the 36-fold increase in energy use. In the late 1980s, population growth was still accounting for a third of energy growth both in the United States and worldwide. Coping with global energy problems will require greatly increased investment in improving the efficiency of energy enduse and in reducing the environmental impacts of contemporary energy technologies, and it will require financing a transition over the next several decades to a set of more sustainable (but probably also more expensive) energy sources. The difficulty of implementing these measures will be greatest by far in the developing countries, not least because of their high rates of population growth and the attendant extra pressures on economic and managerial resources. If efficiency improvements permit delivering the high standard of living to which the world aspires based on a per capita rate of energy use as low as 3 kilowatts—about a quarter of the current U.S. figure—then a world population stabilized at 10 billion people would be using energy at a rate of 30 terawatts, and a population of 14 billion would imply 42 terawatts (compare 13.2 terawatts in 1990). Deliv-

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ering even the lower figure at tolerable monetary and environmental costs will be difficult; each additional billion people added to the world population will compound these difficulties and increase energy's costs, making everyone poorer.

INTRODUCTION

Energy is an indispensible ingredient of material prosperity and a source of many of the largest impacts of human beings on their environment. Where and when energy is in short supply or too expensive, people suffer from lack of direct energy services (such as cooking, heating, lighting, and transport) and from inflation, unemployment, and reduced economic output. But when and where energy supply is expanded without regard for the environmental and sociopolitical costs of doing so, there arises the danger of damages to the environmental and social fabric exceeding the energy's economic benefits.

The sizes, growth rates, and geographic distribution of human populations influence the demands for energy and the means chosen to meet those demands in ways both obvious and subtle. Conversely, the availability, costs, and impacts of energy—and the efficiency with which energy is used—are and will remain important determinants of how many people can be supported (in different regions and on the planet as a whole) with what quality of life. The multifaceted interactions of energy and population are addressed here in three steps: a summary of the nature of contemporary energy problems; an exposition of the ways in which demographic factors have influenced the development of these problems and are influencing the immediate prospects for solutions; and a discussion of alternative scenarios for population and energy supply in the 21st century.

THE NATURE OF THE ENERGY PROBLEM

The problem is not that we are running out of energy. It's that we have nearly run out of the *low-cost* energy that has fueled the industrial development of today's rich countries and has shaped the expectations of the poor ones (Holdren, 1986; Holdren, 1990).

This is partly a matter of monetary costs, where the unsurprising reality is that industrializing and industrialized societies found and used the most convenient and least expensive energy resources first: the biggest, richest, shallowest, nearest deposits of oil and natural gas, and the closest and most cost-effective hydroelectricity sites. Cumulative depletion and rising de-

TABLE 1.

World Energy Supply in 1970 and 1990.

	1970		1990	
	Terawatts	Share	Terawatts	Share
"Industrial" Energy Forms	7.3	88.0%	11.7	88.6%
Petroleum	3.3	39.7%	4.5	34.1%
Coal	2.2	26.8%	3.2	24.2%
Natural Gas	1.4	16.4%	2.5	18.9%
Hydropower	0.4	4.7%	0.8	6.1%
Nuclear Fission	0.03	0.4%	0.7	5.3%
"Traditional" Energy Forms	1.0	12.0%	1.5	11.4%
Fuelwood	0.6	7.2%	0.9	6.8%
Crop Wastes and Dung	0.4	4.8%	0.6	4.5%
TOTAL	8.3	100%	13.2	100%

A terawatt (TW) is 10^{12} watts and is equal to 31.5×10^{18} joules/year (31.5 exajoules/year); this is equivalent to about 1 billion tonnes of coal or 5 billion barrels of oil per year. Hydropower contribution is calculated as the quantity of fossil-fuel energy that would be required to generate the same amount of electricity. Note that fossil fuels constituted 83% of the total in 1970 and 78% in 1990. Industrial energy figures for 1970 are based on British Petroleum (1990); the 1990 figures are the author's extrapolations from data in British Petroleum (1990), Energy Information Administration (1989), and Energy Information Administration (1990). Figures for traditional energy forms are the author's estimates based on a variety of sources; see, e.g., Hughart (1970), World Bank (1983), Hall et al. (1982), Goldemberg et al. (1987).

mand now require resorting to smaller, leaner, more distant, more difficult—and hence more expensive—resources of these kinds, or to more abundant resources, such as coal and uranium and solar energy, which are more capital intensive to convert into the fluid fuels and electricity that industrialized societies require.

Equally fundamental to the problem are energy's environmental and sociopolitical costs. On the environmental side, all fossil-fuel combustion contributes to the world's pervasive problems of air pollution, acid precipitation, and the potential for global climatic change (Brown et al., 1980; World Resources Institute, 1990); and the biomass fuels that rank next in importance behind fossil fuels as contributors to world energy supply (see Table 1) are themselves significant air polluters as well as contributors, in many circumstances, to deforestation and impoverishment or erosion of soils (Holdren, 1987; Smith, 1987). Overall, as indicated in Table 2, energy supply is rivalled only by agriculture as a source of environmental

TABLE 2.

Magnitudes and Origins of Global Environmental Impacts

Indicator of Impact	Natural Baseline	Human Disruption Index	Share of Human Disruption Caused By: Industrial Energy Supply	Traditional Energy Supply	Agriculture	Nonfuel Materials, Manufact., Other
Lead emissions to atmosphere	25,000 tonnes/yr	15	63% (fossil-fuel burning, incl additives)	small	small	37% (metals processing, manufact., refuse burning)
Oil added to oceans	500,000 tonnes/yr	10	60% (oil harvesting, processing, transport)	negligible	negligible	40% (disposal of oil wastes)
Cadmium emissions to atmosphere	1,000 tonnes/yr	8	13% (fossil-fuel burning)	5% (burning traditional fuels)	12% (agricultural burning)	70% (metals processing, manufact., refuse burning)
Sulfur dioxide emissions to atmosphere	50 million tonnes/yr (S content)	1.4	85% (fossil fuel burning)	0.5% (burning traditional fuels)	1% (agricultural burning)	13% (smelting, refuse burning)
Methane stock in atmosphere	800 parts per billion	1.1	20% (fossil fuel harvesting & processing)	3% (burning traditional fuels)	62% (rice paddies, domestic animals, land clearing)	15% (landfills)
Mercury emissions to atmosphere	25,000 tonnes/yr	0.7	20% (fossil-fuel burning)	1% (burning traditional fuels)	2% (agricultural burning)	77% (metals processing, manufact., refuse burning)
Land use or conversion	135 million km^2 ice-free land	0.5	0.2% (occupied by energy facilities)	6% (to supply fuelwood use sustainably)	88% (grazing, cultivation, cumulative desertification)	6% (lumbering, towns, transport systems)

Indicator of Impact	Natural Baseline	Human Disruption Index	Share of Human Disruption Caused By: Industrial Energy Supply	Traditional Energy Supply	Agriculture	Nonfuel Materials, Manufact., Other
Nitrogen fixation (as NOx, NH4)	200 million tonnes/yr	0.5	30% (fossil fuel burning)	2% (burning traditional fuels	67% (fertilizer, agricultural burning)	1% (refuse burning)
Nitrous oxide flows to atmosphere	7 million tonnes/yr (N content)	0.4	12% (fossil fuel burning)	4% (burning traditional fuels)	84% (fertilizer, land clearing, aquifer disruption	small
Carbon dioxide stock in atmosphere	280 parts per million	0.25	75% (fossil fuel burning)	3% (net deforestation for fuelwood)	15% (net deforestation for land clearing)	7% (net deforestation for lumber, cement mfg)
Particulate emissions to atmosphere	500 million tonnes/yr	0.25	35% (fossil fuel burning)	10% (burning traditional fuels)	40% (agricultural burning, wheat handling)	15% (smelting, non-agric land clearing, refuse burning.
Ionizing radiation dose to humans	800 million person-rem per year	0.20	1% (half from nuclear energy, half from radon in coal)	unquantified extra radon release from soil disturbance	unquantified extra radon from soil disturbance	99% (medical X-rays, fallout, air travel)
Nonmethane hydrocarbon emissions to atmosphere	800 million tonnes/yr	0.13	35% (fossil fuel processing & burning)	5% (burning traditional fuels)	35% (agricultural burning)	20% (nonagric land clearing, refuse burning)

Some impacts are most appropriately characterized as alterations of natural inventories, or stocks, others as alterations of natural flows. The human disruption index is the ratio of the size of the human alteration to the size of the undisturbed stock or flow, denoted the "natural baseline." The figures for the shares of human disruption accounted for by different classes of activities are based on current conditions. Estimates are the author's based on a variety of sources and are very approximate; see, e.g., Holdren (1987); Lashof and Tirpak (1989), Graedel and Crutzen (1989), Intergovernmental Panel on Climate Change (1990), and World Resources Institute (1990).

disruption at global scale (see also Study of Critical Environmental Problems, 1970).

Environmental costs include "external" and "internalized" components—the former being the costs of environmental damage and the latter the costs of measures imposed to try to reduce such damage. Both these types of environmental cost have been increasing (Hall et al., 1986; UN Environment Programme, 1987; Holdren, 1987; Brown et al., 1990; World Resources Institute, 1990). The reasons include the increasing scale of energy use; growing reliance on lower-grade and/or more remote resources whose harvesting, processing, and transport entails greater effort and larger impacts; saturation of the capacities of local, regional, and global environments to absorb the effluents and other impacts of energy supply without serious disruption of environmental function; and the necessity of tighter and therefore (usually) costlier environmental controls to try to offset the first two phenomena.

Prominent among the sociopolitical costs of energy supply is dependence on imported energy supplies from regions whose volatile politics may threaten the reliability of supply or impose unpalatable conditions for access (Yergin, 1988); the stakes in this connection include the possibility of military conflict if access to imports that are deemed indispensible is threatened (Deese and Nye, 1981; Farinelli and Valent, 1990). Another important conflict-related sociopolitical cost is the spread of nuclear-weapons capabilities attendant on the spread of nuclear energy technology (Sweet, 1984; Holdren, 1989); still another is the potential for increased international tension and conflict arising from energy-generated global environmental change, including especially the consequences of altered climate (Gleick, 1989; Lipschutz and Holdren, 1990; Gleick, 1990). The sociopolitical costs and risks of energy supply have been increasing along with the environmental ones, as the rising scale of energy use and depletion of local resources have led to increasing import dependence, growing transboundary pollution, and continuing spread of nuclear energy facilities.

The responses to this predicament must include measures to adjust to costlier energy as well as measures to limit further increases in costs. Adjustment to costlier energy means, above all, increasing the efficiency with which energy is used in producing the goods and services that people want. People do not after all want liters of fuel, megajoules of heat, or kilowatthours of electricity *per se*, but rather convenient transportation, comfortable living spaces, cold beer, rewarding employment, and other amenities producible with greater or lesser energy inputs depending on the technology at hand. The logical response to more expensive energy is to modify energy-using technologies to deliver the amenities we want with less energy, substituting for it other resources that are cheaper (including, for example, insulation for buildings and refrigerators, lightweight materials for automobiles and airplanes, and greater ingenuity in the design of lightbulbs, heating and cooling systems, electric motors, and industrial processes).

It is clear that the potential for improvements in energy efficiency is large (Goldemberg et al., 1987; Lashof and Tirpak, 1989; Carlsmith et al., 1990). This is suggested by the nearly 40-percent increase in the energy efficiency of the U.S. economy in the 16 years following the initial oil-price shock of 1973 (Energy Information Administration, 1990; Schipper et al., in press), and by dozens of detailed engineering-economic studies of the energy-efficiency potential in particular sectors of human activity such as transportation, agriculture, manufacturing, housing, and commerce (see, e.g., National Research Council, 1980; Solar Energy Research Institute, 1981; Office of Technology Assessment, 1983; Hirst et al., 1986; Williams and Larson, 1987; Bleviss, 1988; Lovins and Sardinsky, 1988; Rosenfeld and Hafemeister, 1988; Ross, 1989; International Energy Agency, 1989).

It is quite plausible that, using known technologies that would be cost-effective at today's energy prices, the current U.S. standard of living could be provided with about half the current U.S. energy use per capita. Indeed, such a living standard probably can be managed with even less energy—perhaps a quarter to a third of the current U.S. figure—given a modicum of further technical innovation and the sort of increase in energy prices that seems inevitable over the next few decades in any case, accompanied by some structural and lifestyle changes that the combination of these price increases and environmental concerns could bring about (for example, increased durability of goods, shorter commutes, more attractive public transportation systems, reduced materials use in packaging). The potential for increases in energy efficiency in other countries varies in detail—some are already much more energy-efficient than the United States, others much less so—but nowhere is the potential small (Goldemberg et al., 1987; Lashof and Tirpak, 1989).

Actually achieving this potential is being impeded, however, by difficulties with education, financing, and economic restructuring (Hirst, 1990; Schipper and Ketoff, 1989). Education is a problem because much of the energy-efficiency potential depends on billions of consumers knowing what options are available and how to make rational choices among them. Financing is a problem because even where the payback time of efficiency improvements is very short, the requisite investments will not be made if people have no money. Economic restructuring is a problem because most of the world's economies are structured today around low-cost energy;

some of the changes required to cope with costly energy will entail economic dislocations and transitions that will be resisted by many who are doing well under the status quo (or, in the less-developed countries, by those who believe the modes of industrial development that worked in the past remain the best hope for them). Because of these difficulties, realizing the potential of energy efficiency around the world will be an arduous and time-consuming task.

In parallel with this effort to adjust to costly energy through increased energy efficiency, we will need to modify our energy-supply systems in order to put a ceiling on the further cost escalation—above all the escalation of environmental costs—to which continuing reliance on today's approaches would commit us. In the short term (the next 10 years) such modifications should include tighter controls on emissions of sulfur and nitrogen oxides from fossil-fuel combustion, tighter controls on emissions of hydrocarbons and particulate matter from fossil and biomass fuels alike, more effective measures to minimize the leakage associated with ocean drilling and transport of petroleum, efforts to put fuelwood harvesting onto a sustainable basis, and implementation of steps to reduce the dangers of accidents and weapons proliferation posed by contemporary nuclear energy systems.

We should begin preparing, at the same time, for a shift over a period of several decades to new energy-supply technologies that will reduce drastically the tremendous carbon dioxide emissions of today's pattern of energy supply. Global warming, to which carbon dioxide release from fossil-fuel burning is the largest single contributor, is arguably the most dangerous and intractable of all of the environmental impacts of human activity (Schneider and Londer, 1986; Schneider, 1989; Lashof and Tirpak, 1989; Brown et al., 1990). It is the most dangerous because climate affects—and climate change can drastically disrupt—most of the other environmental conditions and processes on which the wellbeing of 5.3 billion people critically depends: magnitude and timing of runoff, frequency and severity of storms, sea level and ocean currents, soil conditions, vegetation patterns, and distribution of pests and pathogens, among others. It is the most intractable because the "greenhouse" gases mainly responsible for the danger of rapid climate change over the next few decades are being released largely by human activities too massive, widespread, and central to the functioning of our societies to be readily altered: carbon dioxide from fossil-fuel combustion and deforestation, methane from rice paddies and cattle guts and the harvesting and transport of oil and natural gas, nitrous oxides from land clearing and fertilizer use and fuel combination (Table 3).

Because we remain dependent, in 1990, on fossil fuels for nearly 80%

TABLE 3.

Sources of Principal Greenhouse Gases, Late 1980s

Gas	Share of Total Warming Potential of All Late 1980s Emissions	Sources of Emissions
Carbon Dioxide	66%	Coal-burning 32%, oil burning 31%, net deforestation 22% (of which about 1/6 for fuelwood), gas-burning 13%, cement manufacturing 2%. About 3/4 of fossil fuel and 1/4 of fuelwood are burned in industrialized nations by 23% of world's population.
Methane	17%	Rice cultivation 25%, domestic animals 22%, fossil fuels 20%, biomass burning 18% (1/6 for fuelwood), landfills 15%.
Chlorofluorocarbons	12%	Refrigeration and air conditioning, plastic foams, solvents, aerosol cans
Nitrous Oxide	5%	Land transformations and fertilizer use 64%, biomass burning 24% (1/6 for fuelwood), fossil-fuel burning 12%.

Figures shown are for anthropogenic emissions only; for relation of anthropogenic to natural emissions or stocks, see Table 2. Share of warming potential depends on time horizon: figures shown here are based on warming potential over the next 100 years. It has been assumed that half of land-clearing and fuelwood use represents net deforestation. Combining figures in the table reveals that fossil fuels are contributing 53% of the warming potential and fuelwood another 3%. Data are from Intergovernmental Panel on Climate Change (1990), Lashof and Tirpak (1989), British Petroleum (1990), and author's calculations based on these.

of the world's energy use, the task of modifying or replacing fossil-fuel technologies in order to reduce emissions of greenhouse gases will be a massive undertaking. Some progress is possible for a time by substituting natural gas for coal, since the former emits only 60% as much CO_2 per gigajoule as the latter; but this is at best a temporary expedient since world resources of gas are less than a tenth the size of those of coal (Haefele, 1981; World Energy Conference, 1983). Another approach is to modify the largest CO_2 emitting facilities, such as coal-burning electric power plants, so that the carbon dioxide can be captured from the stack gases for sequestering in depleted natural gas wells or in deep ocean waters (Okken et al., 1989). This will be difficult and expensive because the volume and mass of CO_2 involved are so large—about 3 tonnes of CO_2 for every tonne of coal burned, nearly 10 million tonnes of CO_2 from a 1-million-kilowatt coal-burning power plant in a year.

Still more difficult will be reducing CO_2 emissions from the dispersed uses of fossil fuels in vehicles, homes, commercial buildings, and industry. Some of these uses can be replaced by electricity, which can be generated by nonfossil means or by burning fossil fuels in centralized facilities with sequestering of the CO_2. (In 1990, about 60% of the world's electricity generation was still based on fossil fuels.) The rest of the dispersed uses of fossil fuel could be replaced, in principle, by converting the relevant devices to burn hydrogen and alcohol fuels instead of petroleum products, coal, and natural gas. As long as the hydrogen and alcohol were made from nonfossil sources—or, in the case of hydrogen, if it were made from fossil fuels in a way that permitted capturing and sequestering the associated CO_2—there would be no net CO_2 addition to the atmosphere from their use (Ogden and Williams, 1989; Williams, 1990).

The principal nonfossil energy sources that could be used in the coming decades to make electricity, hydrogen, or alcohols to reduce civilization's reliance on fossil fuels are solar energy (harnessed directly as sunlight or indirectly in the form of biomass, hydropower, wind, and ocean heat), geothermal energy, nuclear fission, and nuclear fusion. The magnitudes of these sources are summarized and compared to those of the fossil fuels in Table 4. All of these options have promise, but all of them have liabilities as well—high costs of solar collectors, competing uses for biomass and rivers, safety and proliferation hazards of fission, uncertain technology and economics for fusion and dry-rock geothermal (see, e.g., National Research Council, 1980; Lashof and Tirpak, 1989; Solar Energy Research Institute, 1989; Brower, 1990).

Some of the liabilities of these long-term energy options will prove to be reducible with time and effort; others will prove resistant. We will not know which is which unless the research effort is made. It is safe to say already, however, that there is no panacea among these energy options. None offers good prospects of making energy abundant, cheap, and free of significant environmental impacts. And those with the greatest promise of abundance and low impact seem likely to be the most expensive.

The energy circumstances and prospects summarized here represent a formidable challenge even for the richest, most industrialized countries. Restructuring our economies around costlier energy, cleaning up our fossil-fuel technologies as quickly as possible, and beginning a transition away

TABLE 4.

Estimates of World Energy Resources

Stock Resources ("Nonrenewables")	Probable Remaining Recoverable Resources (terawatt-years): United States	World
Petroleum	40	600
Natural Gas (conventional)	40	400
Coal	1,000	5,000
Heavy oils, tar sands, unconventional gas	200?	1,000??
Oil shale	5,000	30,000
Uranium (in conventional reactors)	200	2,500
Uranium (in breeder reactors)	200,000	3,000,000
Lithium (for 1st generation fusion)	140,000,000 (oceans)	
Deuterium (for 2nd generation fusion)	250,000,000,000 (oceans)	

Flow Resources ("Renewables")	Total Flow	Plausibly Harnessable Flow
Sunlight	88,000 TW at Earth's surface, 26,000 TW on land	Converting insolation on 1% of land area at 20% efficiency yields 52 TW (electric)
Biomass	100 TW global net primary productivity, 65 TW on land	Biomass fuels from 10% of land area at 1% efficiency yields 26 TW (chemical)
Ocean heat	22,000 TW absorption of sunlight in oceans	Converting 1% of absorption at 2% efficiency yields 4 TW (electric)
Hydropower	13 TW potential energy in runoff	Using all feasible sites yields 2-3 TW peak, 1-1.5 TW average (electric)
Wind	1,000-2,000 TW driving winds worldwide	Using all cost-effective terrestrial sites may yield 1-2 TW (electric)

Stock resources are measured in terawatt-years (TWy). 1 TWy = 31.5×10^{18} joules. Flow resources are measured in terawatts (or terawatt-years per year). Compare 1990 world energy use of 13.2 TW = 13.2 TWy/y. Estimates are the author's based on a wide variety of sources; see, e.g., Hubbert (1969), Brobst and Pratt (1973), Hughart (1980), Haefele and Sassin (1981), World Energy Conference (1983), British Petroleum (1990).

from fossil fuels to more sustainable options are difficult tasks at best. But a look at the distribution of world energy use by national income reveals that the problems are even more daunting. About 85% of the world's economic product and 72% of the use of industrial energy forms are accounted for by the 23% of the world's population living in "rich" countries (Gross National Product per person over $4000 per year), while the 77% of the people living in "poor" and "middle income" countries must divide up only 15% of the economic product and 28% of the industrial energy use. Even when traditional energy forms—of which the greatest consumption occurs in the less developed countries—are taken into account, one sees that two thirds of the world's total energy use is accounted for by less than a quarter of the population.

Not only, then, is the current level of world energy use supported by energy sources and technologies that are environmentally unsustainable even on today's scale, but the extremely uneven distribution of this use represents a virtual commitment to very substantial growth of energy use among the three quarters of the world's population least able to pay for cleaner energy options. If the energy growth that these countries deem essential to their development actually materializes, and if it comes largely from fossil fuels (as such countries as China and India, with nearly 2 billion people between them, now plan), it will generate huge quantities of carbon dioxide and other pollutants with devastating consequences locally, regionally, and globally. If there is to be an alternative for the poor countries based on increased efficiency and more sustainable (but more expensive) energy-supply options, it can only come about with the help of technological and financial assistance from the industrialized nations on a scale scarcely contemplated up to now—and of which there is still almost no sign.

This global energy-environment predicament would be frightening enough even if the population of the world could be frozen at the current 5.3 billion people. But the population cannot be frozen. Indeed, short of castastrophe, it can hardly be levelled off below 9 billion, and without a global effort at population limitation far exceeding anything that has materialized so far, it might soar to 14 billion or more (Ehrlich and Ehrlich, 1990; Population Reference Bureau, 1990). With these sobering figures in mind, let us take a closer look at the population-energy-environment interaction.

THE POPULATION DIMENSION

The most obvious connections among population, energy, and environment reside in simple (but sometimes misunderstood) algebraic relations. A society's total energy use, E, is the product of its population, P, and its energy use per capita, e

$$E = P \times e \,. \tag{1}$$

The environmental impact, I, associated with a society's enegy use is the product of total energy use times a technology-dependent factor, i, that measures the impact per unit of energy supplied:

$$I = E \times i \,, \tag{2}$$

or

$$I = P \times e \times i \,. \tag{3}$$

[A generalization of Eq. (3) is sometimes called the I = PAT equation: impact equals population times affluence (consumption per person) times technology (damage per unit of consumption). See, e.g., Ehrlich and Holdren (1971), Holdren and Ehrlich (1974), Ehrlich et al. (1977), and Ehrlich and Ehrlich (1990).]

Given a multiplicative relation of this sort, it is unwise as a rule to consider any of the contributing factors to be unimportant, for the consequences of growth in each factor are amplified in proportion to the size and rate of growth of the others. Rising energy use per person has a bigger impact in a large population than in a small one, and a greater impact in a growing population than in a stationary one. And a given environmentally disruptive technology (say, the internal combustion engine) is more damaging in a large, rich population (many people own cars and drive a lot) than in a small poor one (few own cars, and those who do drive little).

If one wants to estimate quantitatively the contribution of population growth to the growth of consumption or of environmental disruption, it is necessary to proceed with some care. [For a celebrated example of the pitfalls, see Commoner (1971) and the refutation in Holdren and Ehrlich (1972).] Consider, as an example of particular relevance to the present paper, the case of energy growth. If in a period of time Δt the population grows by an increment ΔP and the per-capita energy use grows by an increment Δe, then the increment in total energy use is given by

$$E + \Delta E = (P + \Delta P) \times (e + \Delta e) \,, \tag{4}$$

$$\Delta E/E = \Delta P/P + \Delta e/e + (\Delta P/P)(\Delta e/e) \,. \tag{5}$$

It should be apparent from (5) that the percentage growth in total energy use ($100 \times \Delta E/E$) is equal to the sum of the percentage growth in population and the percentage growth in energy use per capita only if the increments are small enough that the second-order term can be neglected. Thus, if population grows 1% and energy use per capita grows 1%, the increase in total energy use is about 2%; but if population grows 100% and energy use per capita grows 100%, the increase in total energy use is not 200% but 300%.

To keep track of the contributions to the growth of a multiplicative product over a long period of time, therefore, one should either use logarithms of the ratios of final to initial values of the contributing terms (see the unabridged version of this paper in the Conference Proceedings) or else convert the percentages to annual averages (to keep them small enough to be approximately additive). Using the latter approach, which is quite accurate for growth rates in the ranges exhibited by population and energy, gives

$$\text{population share of growth} = \frac{\text{annual average population growth rate}}{\text{annual average energy growth rate}} \qquad (6)$$

Table 5 shows the global growth of population and energy from 1850 to 1990, a period in which the use of industrial energy forms increased more than 100-fold, the use of industrial and traditional energy forms combined increased nearly 20-fold, and civilization—largely by and through this increase in energy use—evolved from a modest to an overwhelming global ecological force. The increase in population in this period was a factor of 4.7. The average rate of increase of energy in this 140-year period was 2.1% per year, and that of population was 1.1% per year. The rate of increase of industrial energy forms was 3.4% per year. (See Table 6.).

The power of this last growth rate is particularly evident in the rightmost column of Table 5, showing the cumulative consumption of industrial energy forms. One sees that this cumulative consumption, of which some 90% came from fossil fuels—has been doubling roughly every twenty years; and 40% of the responsibility for this growth in the last 100 years, from 1890 to 1990, belongs to population (Table 6). The part of the cumulative consumption to 1990 that was oil and gas, more than 200 terawatt-years, represented perhaps 20% of the ultimately recoverable portion of the Earth's initial endowment of these fuels in their conventional forms (that is, excluding heavy oils, oil shales, tar sands, and unconventional gas resources).

If the cumulative consumption of these fuels continued to double every 20 years, the initial endowment would be 80% depleted in another 40 years. More probably, as the geophysicist M. King Hubbert had argued

TABLE 5.

Growth of World Population and Energy Use, 1850-1990

	World Population (billions)	Energy Use Per Person (kW)		World Energy Use (TW)			Cumulative Use of Industrial Energy Forms Since 1850 (TWy)
		Industrial Forms	Traditional Forms	Industrial Forms	Traditional Forms	Total	
1850	1.13	0.10	0.50	0.11	0.57	0.68	0.0
1870	1.30	0.16	0.45	0.21	0.59	0.79	3.2
1890	1.49	0.32	0.35	0.48	0.52	1.00	10.1
1910	1.70	0.64	0.30	1.09	0.51	1.60	25.7
1930	2.02	0.85	0.28	1.71	0.56	2.28	53.7
1950	2.51	1.03	0.27	2.58	0.68	3.26	96.6
1970	3.62	2.04	0.27	7.38	0.98	8.36	196.3
1990	5.32	2.19	0.29	11.66	1.54	13.20	386.7

Population figures are from Bogue (1969) and Population Reference Bureau (1990). Energy figures are based on Darmstadter (1968), Hubert (1969), Cook (1973), Hughart (1980), Haefele (1981), British Petroleum (1990), and Energy Information Administration (1990).

TABLE 6.

Population's Share of World Energy Growth, 1850-1990

Time Period	Average Annual Growth in This Period for: Population	Industrial Energy	Total Energy	Share of Population in the Growth of: Industrial Energy	Total Energy
1850-1870	0.70%	3.29%	0.75%	21%	93%
1870-1890	0.68%	4.22%	1.19%	16%	57%
1890-1910	0.66%	4.19%	2.38%	16%	28%
1910-1930	0.87%	2.28%	1.79%	38%	49%
1930-1950	1.01%	2.08%	1.80%	49%	56%
1950-1970	1.85%	5.40%	4.82%	34%	38%
1970-1990	1.94%	2.31%	2.31%	84%	84%
1850-1990	1.11%	3.39%	2.14%	33%	52%
1890-1990	1.28%	3.24%	2.61%	40%	49%

Population share is computed as average annual population growth rate for a given period divided by energy growth rate for the period. This procedure is equivalent, for growth rates in the range encountered here, to the logarithmic procedure mentioned in the text. All data are derived directly from Table 5.

TABLE 7.

Growth of U.S. Population and Energy Use, 1850-1990

	U.S. Population (millions)	Energy Use Per Person (kW)		National Energy Use (TW)			Cumulative Use of Industrial Energy Forms Since 1850 (TWy)
		Industrial Forms	Traditional Forms	Industrial Forms	Traditional Forms	Total	
1850	23.2	0.32	3.09	0.007	0.072	0.079	0.0
1870	39.8	0.89	2.43	0.035	0.097	0.13	0.4
1890	62.9	2.38	1.43	0.15	0.090	0.24	2.2
1910	92.0	5.21	0.64	0.48	0.059	0.54	8.6
1930	122.8	5.93	0.40	0.73	0.049	0.78	20.7
1950	150.7	7.39	0.26	1.11	0.039	1.15	39.1
1970	203.3	10.92	0.30	2.22	0.061	2.28	72.4
1990	251.0	11.00	0.40	2.76	0.10	2.86	122.5

Data are from Bureau of the Census (1972), Bureau of the Census (1989), and Energy Information Administration (1990).

already in the 1950s (see Hubbert, 1969, and references therein), the rate of consumption will peak and begin to decline when cumulative consumption reaches about half the initial endowment—an event that can be expected between 2010 and 2020.

It might be supposed that the global aggregate figures presented in Tables 5 and 6 overstate the role of population in the growth of industrial energy use and the depletion of the fluid fossil fuels, as would be the case if most of the growth in the use of industrial energy forms took place in a different set of countries than those experiencing most of the population growth. Some light is shed on this supposition by investigating the role of population in the growth of energy use in the United States—long the world's largest energy user, and a country which alone has been responsible for more than 30% of the cumulative use of industrial energy forms since 1850. The relevant data are presented in Tables 7 and 8. These figures show that the role of population growth in the growth of energy use is and has been *larger* in the United States than in the world as a whole, accounting for 47% of the country's growth in industrial energy use and 55% of the growth in total energy use between 1890 and 1990.

These strictly numerical analyses do not, of course, tell the whole story of population's role in energy growth, nor would analogous numeri-

TABLE 8.

Population's Share of U.S. Energy Growth, 1850-1990

	Average Annual Growth in This Period for:			Share of Population in the Growth of:	
Time Period	Population	Industrial Energy	Total Energy	Industrial Energy	Total Energy
1850-1870	2.74%	8.38%	2.52%	33%	109%
1870-1890	2.31%	7.52%	3.11%	31%	74%
1890-1910	1.92%	5.99%	4.14%	32%	46%
1910-1930	1.45%	2.12%	1.86%	68%	78%
1930-1950	1.03%	2.12%	1.96%	49%	53%
1950-1970	1.51%	3.53%	3.48%	43%	43%
1970-1990	1.06%	1.09%	1.14%	97%	93%
1850-1990	1.72%	4.32%	2.60%	40%	66%
1890-1990	1.39%	2.96%	2.51%	47%	55%

Population share is computed as average annual population growth rate for a given period divided by energy growth rate for the period. This procedure is equivalent, for growth rates in the range encountered here, to the logarithmic procedure mentioned in the text. All data are derived directly from Table 7.

cal analyses based on Eq. (3) tell the whole story of population's role in the growth of environmental impacts. The reason is that these equations may be, and usually are, nonlinear: the per capita use of energy may depend on population; the choice of technology for energy supply, and thus the environmental impact per unit of energy supplied, is likely to depend on the total rate of energy use and perhaps also on cumulative energy use; and the impact per unit of energy supplied may depend further on the rate of energy use through nonlinearities in the environment's response to energy's disruptions (Brown, 1954; Holdren and Ehrlich, 1974; Holdren, 1987). Thus, in general, one needs to write Eq. (3) as

$$I = P \times e(P) \times i(P,e) \quad (7)$$

Energy use per person may increase with population size if changes in settlement patterns necessitated by population growth result in more transport, per person, of resources, goods, and people; or if population-related growth in material consumption requires resort to lower quality resources whose exploitation entails increases in energy intensity; or if population density and distribution create demands for energy-intensive services not required when population was smaller (such as increased air-conditioning demands attributable to the growth of cities in desert regions, and the multiplication of those demands by the "heat island" effect of high concentrations of heavy energy consumers).

That the choice of energy-supply technologies and the impact per unit of energy supplied depend on the rate of energy use—and, to some extent, on cumulative consumption—should be obvious. Supplying the staggering demand generated by the energy growth of the last century (in which, as we have seen, the growth of population in the United States and worldwide played a major role) has entailed grasping practically every energy resource at hand: low-quality, dirty coal as well as high quality; offshore, Arctic, and imported oil as well as fields close to the point of demand; deep gas as well as shallow; poor hydroelectric sites as well as good ones; deforestation as well as sustainable fuelwood harvesting. This growth of demand has also motivated, arguably, the commercialization of nuclear energy technologies before problems of reactor safety and waste management were under control, as well as promoting the international spread of these technologies before the world political system was ready to cope with the attendant risk of spreading nuclear-weapons capabilities.

It is interesting to note in this connection, given the particular hazards attendant today on the burning of coal and the importing of oil, that if the United States still had the population with which it fought World War 2—135 million people—the 1990 level of per capita energy use for this country could be met from its 1990 array of energy sources *minus* all the imported oil and all the coal. [Imported oil was supplying about 20% of U.S. energy demand in 1990 and coal about 23% (U.S. Energy Information Administration, 1990); the 1943 population of 135 million was 54% of the 1990 population of 250 million.]

The other respect in which impact depends nonlinearly on the magnitude of energy use, and hence nonlinearly on population, arises from the prevalence of nonlinearities in the responses of environmental systems to the stresses imposed on them. These nonlinear "dose-response" relations arise from saturation of the capacity of environmental systems to disperse or neutralize pollutants (depletion of dissolved oxygen in aquatic systems, consumption of acid-buffering capacity in soils and lakes); from thresholds in the sensitivity of organisms to toxic substances (which may result from saturation of internal detoxification mechanisms); from synergisms associated with the combined effects of multiple pollutants; and from the nonlinear dynamics of such critical environmental processes as those that govern climate. (See, e.g., Study of Critical Environmental Problems, 1970; Ehrlich et al., 1977; Myers, 1984; Harte, 1985; Ehrlich, 1986.)

It must be added, finally, that where rates of population growth or redistribution are high, the attendant pressures can swamp the capacities of societies to plan and adapt in ways that could abate or reduce the environmental impacts of energy supply. Countries straining to keep up with feeding, housing, educating, and providing jobs and medical care for populations that are doubling every 20 to 40 years are unlikely to marshal the managerial and technical resources needed to minimize energy's environmental impacts.

I know of no analyses that have even begun to quantify in any comprehensive way the role played by population growth, through these various nonlinearities, in the growth and change of the energy supply system and in the growth of the associated environmental damages. Given the complexity of the phenomena involved and the deficiencies in our understanding of them, in fact, no comprehensive analyses of this sort are likely to be forthcoming soon. But surely the evidence of elementary arithmetic—that population has contributed *at least* 40% of the last century's global growth in the use of industrial energy forms, and *at least* 49% of the global growth in total energy use in the same period—coupled with qualitative understanding of some of the ways that nonlinear effects are likely to have increased population's role and to have magnified the environmental consequences of the overall growth in energy use, makes plain that population growth has been a key causal factor in the genesis of the energy/environment predicament.

POPULATION AND THE ENERGY FUTURE

The mechanisms by which population growth has contributed to and magnified energy/environment problems in the past will continue to operate in the future. A third of current growth in world use of industrial energy forms continues to come directly from population growth; and much of the potential for energy growth in the decades immediately ahead resides in the already huge and still rapidly growing populations of the less developed countries, where energy use per person today is very low and development prospects hinge on its getting larger. The approaches essential to a sensible energy strategy, moreover—investing in energy efficiency, cleaning up contemporary energy options, and fashioning a transition to more sustainable ones—will all be impeded in the LDCs by their very underdevelopment, a condition that itself is all the harder to remedy because of continuing rapid population growth.

The magnitude of world energy use in the future, of course, depends not only on population growth but also on patterns of economic growth

TABLE 9.

An "Optimistic" Scenario for World Energy and Population into the 22nd Century

Year	Income Category	Population (billions)		Energy/person (kilowatt/pers)		Total Energy (terawatts)
1990	Rich	1.2		7.5		9.0
	Poor	4.1		1.0		4.1
		5.3				13.1
2025	Rich	1.4		3.8		5.3
	Poor	6.8		2.0		13.6
		8.2				18.9
2050	(converged)	9.1		3.0		27.3
2100+	(converged)	10.0		3.0		30.0
	Compare:	12.5 billion	×	3 kW	=	37.5 TW
		14 billion	×	3 kW	=	42 TW
		10 billion	×	5 kW	=	50 TW
		14 billion	×	5 kW	=	70 TW

Total energy includes industrial and traditional energy forms. Assumptions are explained in the text.

and on the degree of success or failure in increasing the aggregate energy efficiency of the world economy. It is easy to spin out almost endless scenarios based on varying the trajectories of these three factors—population, economy, and energy efficiency—and previous attempts to do this have produced, unsurprisingly, a wide range of results (see, e.g., Haefele, 1981; World Energy Conference, 1983; and Goldemberg et al., 1987). Just a small subset of such possibilities suffices, however, to make the essential point that limiting population growth to the greatest extent possible will be essential to a manageable energy future even with the best imaginable outcomes for the other variables.

Let me offer, for this purpose, a scenario that I regard as close to the most optimistic that is currently defensible in respect to improvements in energy efficiency and progress in redirecting economic growth toward narrowing the rich-poor gap. The scenario, which is summarized in Table 9, is based on the premise that a standard of living somewhat higher than that of the United States today—presumed high enough to satisfy expectations for a longterm global average—can be delivered by the middle of the next century with a rate of energy use averaging 3 kilowatts per person, just over a quarter of the current U.S. rate. A second premise is a global compact to reduce the rich-poor gap as rapidly as practical. A third is a trajectory of world population growth that corresponds to achieving replacement fertility worldwide by the year 2020 (Population Reference Bureau, 1990).

The scenario is constructed, for simplicity, using just two subpopulations, consisting in 1990 of 1.2 billion "rich" and 4.1 billion "poor." I assume that energy use per person among the population of the rich countries can be reduced by 2% per year between 1990 and 2025, with gains in economic wellbeing to come from increases in energy efficiency exceeding 2% per year. (For example, energy efficiency gains of 3% per year would permit per capita real economic growth of 1% per year combined with a 2% per year decline in energy use per person.) For the poor countries, I assume that the rate of energy use per person *increases* at 2% per year, which together with efficiency improvements would yield a much higher rate of increase in economic wellbeing. The result is a halving of energy use per person in the rich countries between 1990 and 2025 and a doubling in energy use per person in the poor countries. After another 25 years in which rich-country energy use per person falls at around 1% per year and poor-country energy use per person grows at just over 1% per year, the rich-poor distinction has disappeared. Because of the momentum built into the age structure of the world population, the population does not actually stabilize, at around 10 billion people, until after the year 2100. I assume that energy use per person holds constant at 3 kilowatts per person after 2050, with continuing gains in economic wellbeing coming from innovations that further increase energy efficiency.

A few alternative outcomes are summarized at the bottom of Table 9. If replacement fertility is not achieved until 2060, world population stabilizes at 12.5 billion rather than at 10.0 billion; just the *difference* in energy use between these two population figures, at the hypothesized 3 kilowatts per person, is equal to the world's 1970 use rate of all industrial energy forms. If replacement fertility is not reached until 2080, world population stabilizes around 14 billion; at 3 kilowatts per person, this population would generate world energy use more than triple that of 1990. If a satisfactory standard of living in the long run turns out to require closer to half the 1990 U.S. rate of energy use per person, say 5 kilowatts, then a population of 14 billion would use energy at over five times the world's 1990 rate; and just the difference between 10 billion people and 14 billion would account for 1.5 times the total 1990 energy use rate.

What is perhaps most striking in all these figures is that even the most optimistic assumptions about "early" population stabilization, increased energy efficiency, and narrowing the rich-poor gap lead to world energy use more than double that of 1990. Yet, as suggested by the foregoing discussion of the nature of current energy-supply problems and the prospects for alternative sources, to provide such a level of energy use sustainably and at tolerable cost will be a formidable challenge. Every billion people added to the world's population, even at a modest 3 kilowatts per person, adds 3 terawatts to the ultimate rate of energy use and reduces thereby the chances that the total amount can be supplied at bearable economic and environmental cost. Certainly the possibility—appealing to many—that a prosperous world might be run exclusively on solar energy in its least environmentally disruptive forms dwindles rapidly as the scale of energy demand moves beyond 20 or 30 terawatts; at higher use rates, the society of the future is unlikely to have the luxury of foregoing less attractive options.

Whether it will be energy or something else that imposes the strictest physical limit on the eventual size of the human population is of course not yet clear. But certainly it is nonsense to argue, as Commoner does, that no limit could possibly be near because the sunlight reaching the land area of the planet is more than a thousand times the current rate of energy use by civilization (1990, p. 145). In reality, it is far from obvious that civilization could harness more than a few percent of this flow (which, after conversion to electricity and fluid fuels, would represent a much smaller quantity of usable energy) without intolerable disruption of the critical ecological and geophysical processes that are driven by solar energy. It is also far from obvious that the consequences of civilization's *using* energy at such rates—leaving aside the impacts of how the energy is obtained—would be compatible with the continued adequate functioning of biogeophysical processes on which human wellbeing will continue to depend.

It is, of course, conceivable that one or more of the longterm energy options—perhaps solar photovoltaics or fusion or dry-rock geothermal—will eventually emerge in forms that make possible the supply of energy at global rates somewhat exceeding 30 terawatts (but far from the thousand or more that Commoner claims is possible) without encountering disastrously escalating economic and environmental costs. If that proves to be so, and if the consequences of energy end-use at these rates are tolerable, and if none of the other plausibly catastrophic consequences of a human population exceeding 10 billion actually materialize, then perhaps a population of 12 or 14 billion will be manageable after all.

But why try to find out? The overwhelming likelihood is that higher population and the accompanying higher aggregate energy use will make energy costlier in both economic and environmental terms, which will make everyone poorer and the future more perilous. Analogous arguments can be made for the provision of food and water and much else. And whatever the stable or metastable end-state, it is a certainty that it will be costlier and more difficult to get there with high population growth than with low.

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