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Environmental Change and the Human Condition

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Introduction by Carl Kaysen

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John Holdren has been a colleague of mine for many years. He is the Teresa and John Heinz Professor of Environmental Policy and director of the Program in Science, Technology, and Public Policy at Harvard University's Kennedy School, as well as professor of environmental science and public policy in the department of earth and planetary science at Harvard University.

Since receiving his B.S. and M.S. in aeronautics and astronautics at MIT and his Ph.D. in aeronautics/astronautics and plasma physics from Stanford, he has had two extraordinary careers, one as an academic and one as a public figure. After brief stints at the Lockheed Corporation, the Lawrence Livermore Laboratory, and Caltech, he went to UC Berkeley in 1973. There he cofounded and codirected a campuswide interdisciplinary program in energy and resources for twenty-three years, before assuming his position at Harvard in 1996. His bibliography includes some three hundred articles and reports, and he has edited, coedited, written, and contributed to fourteen books on energy, environmental problems, nuclear weapons, and arms control.

In 1981, John was one of the earliest recipients of the MacArthur Prize Fellowship. He is chair of the Committee on International Security and Arms Control of the National Academy of Sciences and was a member of President Clinton's Committee of Advisors on Science and Technology (PCAST), where he led studies for the White House on protection of nuclear bomb materials, the U.S. fusion-energy R&D program, and energy R&D strategies for meeting the climate change challenge.

I've worked with John on the Academy's Committee on International Security Studies and in the Pugwash movement for many years, so I can add a few personal observations to his long public record. When Pugwash won the Nobel Peace Prize in 1995, jointly with Joseph Rotblat, John, as chair of the Pugwash Executive Committee, addressed the Norwegian Nobel Committee in Oslo. His combination of great energy, intellectual acuity, focus on the task at hand, a calm and easy manner, and a smile often hidden in the thickets of his facial adornments make him an invaluable colleague in any joint enterprise. The speed with which he can put together a comprehensive and balanced record of long and complicated discussions never ceases to astonish all who work with him.

John P. Holdren

Environment and Well-Being

I think it is useful to consider the determinants of human well-being as falling into three broad categories: economic conditions and processes (such as markets, productive technologies, employment, income, wealth, and so on); sociopolitical conditions and processes (such as self-determination, governance, personal and national security, justice, education, health care, science, culture, and so on); and environmental conditions and processes (such as soils, the biota, nutrient cycles, mineral resources, climate, and so on).

A key understanding in relation to these three categories is that major failures in any one may undermine the human enterprise. The conditions and processes in each of the three categories are indispensable to human well-being. While some trade-offs around the edges are inevitable, it is a mistake to imagine that one or the other of the categories is primary and the others secondary. Human activities need to be managed in a way that preserves and enhances the ingredients of well-being under all three headings. A second important point is that the threats to human well-being arising from the environmental category remain less well understood (by publics, policymakers, and professors alike) and therefore less comprehensively addressed in politics and policy than are the threats in the other two categories.

What are the threats in the environmental category? As shown in Table 1, they can be divided into two groups: those arising from human activities and those generated by natural processes. Of course, there is an interaction between natural hazards and human activities: human indirection and inattention often lead to the magnification of natural hazards and to the general lack of priority we give to protecting ourselves and our property from these natural hazards.

The problems we know best and fear most may not be the most dangerous ones. Direct health impacts from pollution – dirty air, toxic contamination of ground and surface water, carcinogens in food, radioactivity from nuclear accidents, and mismanagement of nuclear wastes – have historically received most of the attention, for reasons of the measurability and visibility of harm, and the ready understandability of the mechanism. The "indirect" threats – impacts of climate change, stratospheric ozone depletion, biodiversity loss, and alteration of geographic distribution and of population dynamics between beneficial and destructive organisms – are harder to predict and quantify, but they may prove to be more dangerous and less easily remedied.

The problems we know best and fear most may not be the most dangerous ones.

An important reason for the persistent underestimation of threats in this "indirect" category is the widespread misimpression about the extent to which modern technology and medicine have reduced the dependence of human well-being on environmental conditions and processes – above all on climate, which affects all the others. Notwithstanding the remarkable accomplishments of biomedical, agricultural, and environmental engineering technologies, the fact is that civilization remains dependent on nature for most of the cycling of nutrients on which food production depends, for most of the regulation of crop pests and agents and vectors of human disease, for most of the detoxification and disposal of wastes, and for the maintenance of climatic conditions within limits conducive to all these other environmental services and to the human enterprise more generally.

Table 1.
Classification of Environmental Threats

Environmental threats from human activities

- Direct loss of life, health, property, or income from routine, accidental, or malicious emissions:
  - toxic
  - carcinogenic
  - mutagenic
  - teratogenic
  - corrosive
- Loss of life, health, property, income, pleasure, or security as a result of a disruption of biological or geophysical resources or processes, including those of:
  - soils
  - vegetation
  - nutrient cycles
  - hydrology
  - climate
  - the stratospheric ozone shield
  - population dynamics of valued or destructive organisms

Natural hazards

- Weather/climate: storms, floods, droughts, avalanches, ice ages
- Geology: earthquakes, landslides, tsunamis, volcanoes
- Biology: die-offs, outbreaks of valued or destructive organisms

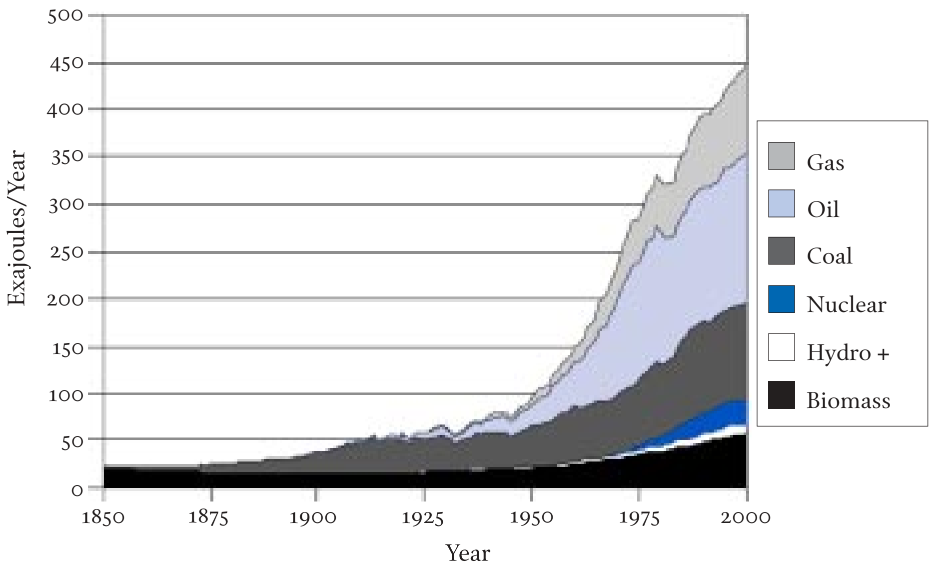
Environment and Development

Different types of environmental problems are associated with different phases of the societal trajectory between poverty and wealth. In the poorest developing countries, where infrastructure is largely absent and rapidly growing populations using primitive technologies must meet their basic needs with renewable resources in their immediate surroundings, the biggest problems are (a) degradation of those resources (e.g., deforestation, desertification, erosion); (b) bacterial contamination of waste-saturated water supplies; and (c) acute indoor air pollution from inefficiently burning biomass fuels in badly ventilated dwellings.

In the high-growth phase of economic development – with medium rates of population growth and rapid growth of gross domestic product (GDP) per capita, fed by a rapidly rising use of energy and materials in manufacturing, transport, and construction of buildings and infrastructure, with a low priority given to efficiency and the environment – the characteristic environmental problems include (a) massive urban and regional air pollution; (b) acid precipitation; (c) industrial pollution of surface and ground water with hydrocarbons and metals; and (d) filling and pollution of estuaries by ports, freight terminals, and oil refineries.

The richest countries – where population growth rates are low, per capita economic growth is moderate, and substantial investments in pollution control have begun to curb emissions to air, water, and soil of some of the more easily captured pollutants – are responsible for (a) continuing high emissions to the atmosphere of pollutants resistant to control (notably greenhouse gases, nitrogen oxides, very fine particles, and some toxic metals) resulting from high levels of material consumption and personal mobility; (b) cleanup challenges of daunting magnitude from the accumulated burden of past pollution of ground water, soil, and riverine and estuarine

Figure 1. World Primary Energy Supply, 1850 – 2000



sediments; (c) luxury levels of consumption of meat, fish and shellfish, and tropical fruits and hardwoods, leading to deforestation by lumbering, grazing, and plantation operations; to overharvesting of estuarine, open-ocean, and coral reef environments; and to conversion of mangrove swamps into aquaculture ponds (mostly beyond the borders of the consuming countries).

Finally, the kinds of environmental problems that persist and grow at the highest levels of economic development – where population growth rates are low, per capita economic growth is moderate, and substantial investments in pollution control have begun to curb emissions to air, water, and soil of some of the more easily captured pollutants – tend to be those that (a) arise from renewable resource demands driven beyond thresholds of sustainability by the growth of prosperity itself (e.g., decimation of ocean fisheries and overharvesting of tropical hardwoods for high-income diets, homes, and furniture); or (b) are legacies of past carelessness in forms that are very costly to ameliorate after the fact and for which the "polluter pays" principle fails because the polluters have disappeared (e.g., toxic contamination of groundwater); or (c) arise from widely used, hard-to-replace productive technologies in ways that are resistant to inexpensive technological fixes (e.g., CO_2 emissions from fossil-fuel combustion); or (d) tend to export their environmental costs and risks in space and time to an extent that makes difficult their assessment and internalization through price or policy (e.g., CO_2, biodiversity loss, nuclear proliferation and nuclear terrorism risks from nuclear energy).

Energy and the Environment

Many of the most difficult and dangerous environmental problems at each of these levels of economic development – from the damage that the very poor do to the immediate environment, and thus to themselves, to the damage that the very rich do to the global environment, and thus to everybody – arise from the harvesting, transport, processing, and conversion of energy. Energy supply is the source of most indoor and outdoor air pollution, most radioactive waste, and much of the hydrocarbon and trace metal pollution of soil and groundwater. And energy-related operations account for essentially all of the oil that humans have put into the oceans as well as for most of the human-produced gases that are altering the global climate.

But, of course, energy is also an indispensable ingredient of material well-being and of economic development. We cannot do without it. And because the environmental characteristics of the energy resources and technologies on which society depends today can generally be changed only slowly, and at considerable cost, the dilemma embedded in energy's dual roles in economic prosperity and environmental disruption cannot be easily resolved. In light of all of this, it has become increasingly clear that energy is the core of the environment problem; environment is the core of the energy problem; and the energy-environment intersection is the core of the sustainable development problem.

Let me try to clarify the energy situation in quantitative terms. Figure 1 shows world primary energy supply for the period 1850 – 2000, distributed according to fuel source. Note that 150 years ago, in 1850, about 88 percent of the world's energy was coming from the biomass sources – mostly fuelwood and charcoal, augmented by crop waste and dung. The remaining 12 percent came from coal. In the ensuing century, from 1850 to 1950, world use of primary energy grew by a factor of 4.3, and this growth was supported mostly by a tremendous expansion in the use of coal. The growth of oil and natural gas became important only in the latter part of this period; by 1950, oil was supplying just over half as much energy as coal, and natural gas was supplying only a sixth as much as coal.

In the most recent half century, from 1950 to 2000, world energy use grew at a little more than twice the rate that had characterized its growth during the previous one hundred years. The increase in the last half of the twentieth century was 4.7-fold, making the increase over the one hundred fifty years from 1850 to 2000 a factor of 4.3 x 4.7, or 20-fold. As is clear from Figure 1, the great bulk of the growth of world energy in the last half century came from the

Table 2. World, U.S., and Chinese Energy Supply in 2000

		World	United States	China
Primary energy (exajoules)		**450**	**105**	**146**
of which …	oil	35%	38%	22%
	natural gas	21%	25%	2%
	coal	23%	25%	49%
	nuclear energy	6%	8%	0.4%
	biomass	13%	4%	25%
	hydropower and other	2%	1%	2%
Electricity (billion kilowatt-hours, net)		**14,700**	**3,800**	**1,300**
derived from …	fossil fuels	64%	71%	82%
	nuclear energy	17%	20%	1.2%
	hydropower	18%	7%	17%
	wind, geothermal, solar, and biomass	1.6%	2.2%	0.1%

Note: 1 exajoule = 10^{18} joules = 1 billion gigajoules; hydropower is counted as energy content, not as fossil fuel equivalent; net electricity excludes the part of generated electricity that is used within the power plant.

Table 3. World Energy and Economy by GDP per Person, 2000

	Poor Economy	Transition Economy	Rich Economy
Population (billions)	4.1	1.2	0.8
GDP (trillion ppp-corrected 2000 US$)	11	11	23
Industrial energy (terawatts)	2.9	3.2	6.3
Biomass energy (terawatts)	1.4	0.2	0.2
Fossil carbon (billion metric tons of C per year)	1.6	1.7	3.1
per person			
GDP (thousand ppp-corrected 2000 US$)	2.7	9.2	29
Energy – industrial and biomass (kilowatts)	1.0	2.8	8.1
Fossil carbon (metric tons of C per year)	0.4	1.4	3.9

Notes: 1 terawatt = 1 trillion watts = 1 billion kilowatts = 31.5 exajoules per year. 1 metric ton = 1,000 kilograms = 2205 pounds = about 1.1 American tons. One ton of carbon in CO_2 corresponds to 3.67 tons of CO_2. Purchasing-power-parity corrections are from the World Bank.

tremendous expansion in the use of oil and, most recently, natural gas. By 2000, world oil use was 1.6 times greater than coal use, and the energy coming from natural gas was about equal to that coming from coal. Altogether, fossil fuels were accounting for 78 percent of world energy use in 2000, with the remainder coming from biomass fuels (13 percent), nuclear energy (6 percent), and hydropower, geothermal, solar, and wind energy combined (3 percent). (The share attributed to biomass fuels is smaller than this in nearly all official tabulations, because these tabulations leave out the biomass energy forms – gathered fuelwood, crop wastes, and dung – that are not exchanged in organized markets but that constitute the principal energy sources for the poorest third of the world's population.)

Table 2 shows the energy picture in the year 2000 in a bit more detail, comparing sources and magnitudes for the United States and China as well as the world as a whole, and showing electricity generation as well as primary energy. (Electricity is a "secondary" energy form, which, like other secondary energy forms such as gasoline, charcoal, biogas, and hydrogen, comes from one or more of the primary forms.) What is most striking in Table 2 is the high dependence on fossil fuels not only of the whole world but of countries as diverse in their stage of development as the United States and China. What is also striking are the modest percentages of primary energy and electricity supply that are accounted for by nuclear energy and by renewable energy forms other than biomass, notwithstanding the high prominence of these options in national and international energy debates.

In Table 3 the world energy picture in the year 2000 is portrayed in another way – namely, in relation to allocation of energy, economic activity, and emissions of fossil carbon to the atmosphere among poor, transition, and rich economies. The country categories are based on GDP per capita corrected for purchasing power parity (ppp), where countries averaging below US $5,000 ppp per year in 2000 are classified as poor, those between $5,000 and $20,000 as transition, and those above $20,000 as rich. With these definitions, Table 3 shows that the rich countries, with only 13 percent of the world's population in 2000, accounted for 51 percent of the world economic product, 46 percent of the world's energy, and 48 percent of the carbon being added to the atmosphere in CO_2 from fossil fuel combustion. Looking at the per capita numbers underlines the magnitude of the gap: GDP per person in the rich countries is about eleven times higher than in the poor countries, energy use per person is eight times higher, and carbon emissions per person are about ten times higher.

The Business-as-Usual Energy Future

Given these understandings of where we are and where we have been in relation to world energy supply, let us look at where we are going. Table 4 summarizes a middle-of-the-road trajectory through the twenty-first century of the sort often described as a business-as-usual scenario. This means not that nothing changes, but rather that things change in roughly the patterns that have recently been prevailing, with adjustments for demographic and economic shifts that are more or less expected. Thus, in the scenario portrayed in Table 4, population growth rates continue to fall, but the population nonetheless grows until it stabilizes by 2100 at about eleven billion people. Aggregate economic growth averages 2.8 percent per year from 2000 to 2030, but only 2.3 percent per year for the whole century. The energy intensity of the world economy (energy use divided by real GDP) falls throughout the century at the long-term average of 1.0 percent per year, and the carbon intensity of energy supply (carbon emissions divided by primary energy) falls at 0.2 percent per year.

In a simpler division than that of the snapshot for the year 2000, this scenario considers only two country groups: industrialized and developing. One sees from the table that in this business-as-usual energy scenario (a) nearly all of the population growth and most of the energy growth will occur in the developing countries; (b) the industrialized-developing gap in GDP per person will not disappear even by the end of the century, although it will fall from a factor of 6.6 in 2000 to 3.8 in 2050 to 2.4 in 2100; (c) world economic product will increase nearly tenfold over the century, while energy use will quadruple; and (d) carbon emissions from fossil fuel combustion will more than double by 2050, and more than triple by 2100.

What, Us Worry?

The question then arises, is there anything problematic about this? Should we worry about proceeding along the business-as-usual trajectory?

Table 4. A Business-as-Usual Economic and Energy Scenario, 2000 – 2100

	2000	2030	2050	2100
Population (billions)				
industrialized countries	1.3	1.4	1.4	1.4
developing countries	4.8	7.1	8.4	9.7
GDP (1,000 ppp-corrected 2000 US$)				
industrialized countries	2.7	9.2	29	29
developing countries	1.0	2.8	8.1	8.1
Energy/person (kilowatts)				
industrialized countries	6.3	7.5	8.0	8.3
developing countries	1.3	2.2	2.9	4.7
GWP (trillion ppp-corrected 2000 US$)	45	105	171	438
Carbon emissions (billion metric tons of C per year)	6.4	10.9	14.3	20.8

Notes: GWP = gross world product. The carbon emissions listed are projected from fossil fuel burning only.

The first concern that most people raise when they are shown a scenario in which energy use quadruples in the twenty-first century is whether the world's energy resources will suffice to support such an increase. Will we simply run out of energy? Table 5, which presents rough estimates for the Earth's endowments of nonrenewable and renewable energy resources, indicates that the answer to this question is no. Particular energy forms may be, or become, scarce in particular places, but the world is far from running out of energy in any absolute sense. The energy for business-as-usual growth throughout this century, and for quite some time beyond that, could be supplied by fossil fuels alone – if we are willing to pay the monetary, environmental, and perhaps also political costs – even without turning in any significant degree to nuclear and renewable energy.

But, while civilization is not running out of energy resources per se, it is running out of a number of things related to energy that ought to concern us.

We are, for example, running out of *cheap oil* much more rapidly than we are running out of energy as a whole. As the world has already learned, spikes in the oil price can be very disruptive economically, and armed conflict over access to the cheap oil that remains may be even more disruptive.

We are running out of *environment*, in the sense that the environment's capacity to absorb, without intolerable consequences, the impacts of energy use and transformation is being severely depleted.

We are running out of *tolerance for inequity* in the energy-economic system – the inequity depicted in Table 3 and destined, according to Table 4, to disappear only slowly under business as usual. It is not just the economic division that is problematic, moreover; it is that the poor are more at risk from the environmental problems than the rich are.

We are running out of *money for better energy options* in two different respects. In the poor countries, the question is where the money will be found to deploy energy systems that are cleaner and more efficient than the less costly ones that are deployed now. In the rich countries, there is more than enough money to pay for these options, but we seem to have run out of the willingness to pay: we are refusing to make respectable investments in energy research and development for better technologies, and we refuse to tolerate even the mention of a carbon tax or other measures to internalize into the cost of energy the environmental damage that is being done.

And we are running out of *time* for a smooth transition to an energy system that is both sufficient to our needs and sustainable in the environmental sense. This matter of timing is perhaps the least-understood dimension of the energy problem. The problem is that energy systems – power plants, oil refineries, pipelines, and so on – tend to last thirty to fifty years. If you want the energy system in 2050 to look very different from today's, you had better start changing now, because the power plants we build over the next decade are still going to be running in 2050. Another way of looking at it is that the capital investment in the world energy system – the amount of money it would take to replace it – is about ten trillion dollars. This huge investment cannot be turned over quickly. If people suddenly decide ten years from now that we've got the wrong energy system, it won't be possible to have a different one ten years after that.

Table 5. World Energy Resources

Nonrenewable		TWy
Conventional oil and gas		1,000
Unconventional oil and gas (excluding methane clathrates)		2,000
Coal		5,000
Methane clathrates		20,000
Oil shale		30,000
Geothermal	– steam and hot water	4,000
	– hot dry rock	1,000,000
Uranium	– in light-water reactors	3,000
	– in breeder reactors	3,000,000
Fusion	– deuterium-tritium, limited by lithium	140,000,000
	– deuterium-deuterium	250,000,000,000
Renewable		**TWy/year**
Hydropower potential		15
Global biomass production		100
Power in the wind		2,000
Sunlight reaching land surface		26,000
	– reaching entire Earth surface	88,000

Note: Nonrenewable resource estimates are for remaining recoverable resources, are highly approximate, and are measured in terawatt-years (1 TWy = 31.5 exajoules). Renewable resources are measured in terawatts of total flow, where 1 TW = 1 TWy/year = 31.5 exajoules per year. Fractions of the renewable flows that could be practically harnessed depend on assumptions, but are generally in the range of 1 – 10 percent. Note that world energy use in 2000 was just under 15 TW or 15 TWy/year, and a quadrupling by 2100 would imply 60 TWy/year.

The Climate Change Core of the Energy-Environment Dilemma

The essence of the energy problem is the question of how to meet society's energy needs without undermining the environmental foundations of well-being. And, within the constellation of environmental problems associated with energy, climate change will likely prove to be the most dangerous and intractable in the long run.

It is not the most dangerous today in terms of the number of premature deaths it is causing: indoor air pollution, outdoor air pollution, and bacterial contamination of surface water are killing far more people. But climate change will become the most dangerous over time, because climate profoundly influences all other environmental conditions and processes; it is the envelope within which all other environmental conditions and processes must function. If climate is sufficiently disrupted, therefore, everything else environmental will be disrupted too: the productivity of farms, forests, and fisheries; the geography of disease; the livability of the world's cities in summer; the damages to be expected from storms, droughts, floods, wildfires, and a rising sea level; and much more. And climate change is the most intractable environmental problem because it is so deeply rooted in the characteristics of the world energy supply system that can be changed only slowly and with great difficulty.

There is no longer any serious doubt among informed scientists that the climate is changing, and that it is changing in a way that is unusual compared to the natural patterns of climatic fluctuation. Climate is naturally a fluctuating system. The climate has always changed for a whole variety of natural reasons, but it is now changing more rapidly, and in a pattern that matches what would be expected from the suspected human cause. Indeed, because of this matching "fingerprint," it is virtually certain that the emission of greenhouse gases from human activities – above all, the combustion of fossil fuels – has been responsible for a substantial share of the climatic change that has been experienced in the last hundred years.

There is also a scientific consensus about where we are headed in the way of further climate change under the business-as-usual future. The scientific consensus best estimates,

If climate is sufficiently disrupted, everything else environmental will be disrupted too.

which are those of the Intergovernmental Panel on Climate Change, are that continuation on the business-as-usual emissions trajectory as described in Table 4 will lead to increases in the mean global surface temperature of 2° to 4°C over the current century. By century's end, the Earth will be warmer than it has been at any time in the last one hundred sixty thousand years. The best estimate for the rise of sea level by 2100 is about fifty centimeters. This global average warming will not occur uniformly and will entail major changes in climatic patterns – storm tracks, ocean currents, distribution of precipitation and soil moisture, extremes of hot and cold. And, in part because of the pace of the changes in climatic patterns, the resulting effects on human well-being are far more likely to be negative than positive.

Although most of the detailed analysis and discussion of the impacts of anthropogenic climate change have focused on the consequences of the doubling of the preindustrial concentration of CO_2, this is not because there is any current reason to think that the buildup of the atmospheric burden of CO_2 will stop at that level. It was just for convenience in comparing results that the scientific community settled on a CO_2 doubling as a principal focus of study. On a business-as-usual trajectory like that depicted in Table 4, the concentration of CO_2 would soar past a doubling by around 2060 and would be near a tripling by 2100. And if the trajectory were still the business-as-usual one by that point, it would be practically impossible to stop the further concentration buildup below a quadrupling of the preindustrial concentration. For decades after the concentration stabilized, the temperature would continue to rise, moreover, because of the lag time caused by the thermal inertia of the oceans. And sea level would continue to increase for centuries.

The equilibrium annual average temperature increase in midcontinent North America under a doubling of the preindustrial CO_2 concentration would be around 10°F; under a quadrupling, it would be around 20°F. Now, it is possible to have an interesting argument about whether the climatic and associated ecological consequences of a CO_2 doubling would be manageable without intolerable damage to the human condition – there are enough uncertainties about the details of impacts and adaptation to leave room for both optimistic and pessimistic assessments. But the situation is far less ambiguous for the case of the quadrupled-CO_2 world, which is where we will arrive if we don't do anything about it in the meantime. A quadrupled-CO_2 world would be a roasted world, with weather patterns and extremes of heat unlike anything yet experienced during the tenure of human beings on the planet. It would be a catastrophe for the human condition.

A Thought Experiment on the Magnitude of the Challenge

There has been considerable study of the sizes and shapes of the deflections from the business-as-usual emissions trajectory that would be needed to stabilize the atmospheric concentration of CO_2 at various levels below a quadrupling. Assessing the implications of the results for the character of the energy system is instructive as to the magnitude of the challenge we face. Let me consider here the much-studied case of stabilization at twice the preindustrial concentration, hence at about 550 parts per million by volume (ppmv). While there is nothing magical about this target – and certainly no guarantee that achieving it would avoid severe damages from climate change – it is so difficult to meet (as we will see in a moment) that doing much better seems unlikely.

I note that a more rigorous consideration of the interaction of anthropogenic greenhouse gases with climate requires looking not only at CO_2 but also at non-CO_2 greenhouse gases, and at both energy-absorbing and energy-reflecting particles in the atmosphere. Coincidentally, however, the warming effects of the non-CO_2 greenhouse gases and absorbing particles are largely cancelled out by the cooling effects of reflective particles. This is likely to remain true during much of this century because increasing control over emissions of the non-CO_2 greenhouse gases and soot will be matched by increasing control over the

A quadrupled-CO_2 world would be a catastrophe for the human condition.

sources of the reflective particles. Because of this and because, under business as usual, the CO_2 becomes increasingly the dominant factor as the century wears on, taking into account the effects of the CO_2 alone gives a decent ap-proximation of the net effects to be expected.

The size of the CO_2 emissions reduction challenge becomes apparent when one recognizes that stabilizing the atmospheric concentration of CO_2 at 550 parts per million requires not just leveling off emissions at a level not too much higher than today's, but also subsequently bringing emissions down, over a period of many decades, to a fraction of today's. There is a variety of trajectories that could meet this goal – some featuring large early departures from business as usual but more gradual declines later, and others deferring early action but requiring very steep declines later. If one wanted to avoid the stabilization trajectories that place too much of the burden of reductions in the early decades of the century, as well as avoid those that involve extremely steep declines later, then one would want to level off emissions at about 11 billion tons of carbon around the year 2035 and then begin gradually to decline them to about 6 to 7 billion tons of carbon per year by 2100 and to 3 to 4 billion tons of carbon per year by 2200.

It is an easy matter to calculate, under some simplifying assumptions, how much the carbon-free part of the world energy supply would need to be expanded in the twenty-first century in order to get on and stay on a not-too-early/not-too-late trajectory for stabilizing CO_2 at 550 ppmv. The carbon-free options are (a) biomass, hydropower, wind, photovoltaics, and other renewable energy sources; (b) nuclear energy (currently nuclear fission and perhaps, after midcentury, nuclear fusion); and (c) advanced fossil fuel technologies that can capture the carbon and sequester it, rather than releasing it into the atmosphere. Assuming middle-of-the-road economic growth and continuation of the recent 1 percent/year world average rate of reduction of the energy intensity of economic activity, the carbon-free contribution would need to increase sixfold (to about 600 exajoules) by 2050 and fifteenfold (to about 1500 exajoules) by 2100 if the world were on the indicated 550-ppmv-stabilization trajectory. Only if the historical world average rate of energy intensity reduction can be doubled to 2 percent per year over the whole world and the whole century can the requirement for carbon-free energy supply be held to a "mere" tripling in the twenty-first century.

To achieve such a rate of energy efficiency improvement worldwide for a century would be a fantastic challenge. Alas, there is as yet little sign of the sorts of policies and commitments that could yield the needed energy intensity reductions and carbon-free energy increases in the years ahead in any combination consistent with stabilizing atmospheric CO_2 at 550 ppmv.

What Should We Be Doing? A Six-Point Program

We should of course be expanding research and the scientific dimensions of the problem. (No talk by a scientist is complete without this recommendation!) We should be doing more research on the science of climate change and its impacts; on the enhancement of terrestrial and oceanic sinks for carbon; on geotechnical engineering to offset the effects of greenhouse gases on the climate; and on adaptation to climate change. And we should be making increasing investments to exploit the opportunities that this research uncovers.

Second, we should have increased national and international support for the education, development, social welfare, and family planning measures known to be most effective in reducing population growth. If the world has, say, eight billion people in 2100 instead of eleven billion, the energy-climate problem will be easier to solve – still not easy, but easier – and so will many other problems.

Third, we should have incentives and other help for firms and consumers to make low-CO_2 and no-CO_2 choices from the menu of energy-supply and energy-end-use-efficiency options available at any given time. These incentives could be as simple as tax breaks for investments in options with the desired characteristics, but it seems unlikely that enough will be done without the stronger medicine of either a carbon tax or an emissions cap enforced through tradable emissions allowances.

Fourth, there should be accelerated research, development, and demonstration to improve the menu of low-CO_2 and no-CO_2 energy options from which incentivized producers and consumers can choose – better solar, wind, and biomass technologies; better nuclear technologies (advanced fission and, I hope, fusion); and very advanced fossil fuel technologies that can capture the carbon and sequester it away from the atmosphere.

The fates of the industrialized and less-developed countries are more interconnected than most people think.

Fifth, we should have increased international cooperation to facilitate applying the results of climate research, low-CO_2 and no-CO_2 energy research, and innovations in the ways of implementing these insights and options in the South as well as the North. The problem of global climate change from CO_2 emissions has been mainly caused up until now by the industrialized countries, which have contributed about three-fourths of the fossil fuel carbon added to the atmosphere over the past one hundred fifty years. Now fossil fuel use is growing faster in the developing countries than in the industrialized ones, however, and by 2025 or 2030 these countries will pass the industrialized countries in total emissions (but not in per capita emissions). In this situation, it is perfectly appropriate for the industrialized countries to take the first steps to address the problem, and to pay a large fraction of the costs of action – but there is no solution in the long run unless the developing countries participate in moving off of the business-as-usual trajectory.

This leads finally to the sixth point: We need to construct a global framework of commitments to long-term restraints on greenhouse gas emissions – a framework designed for sufficiency, for equity, and for feasibility. This has not happened yet. The United Nations Framework Convention on Climate Change (which was ratified by the United States in 1992 and which is in force) and the Kyoto Protocol (which the United States has refused to ratify and which may well go into force without this country's participation) were intended as initial steps in the needed direction, but they are not working yet and would not be enough if they were.

Of course, the private sector has a large role to play in the six-point agenda I have laid out here. But the nature of the problem – as one that involves externalities, common property resources, public benefits, and binding agreements among states – dictates that government policy also has to play a major role. The government of the United States – a country with a quarter of the world's fossil fuel use, a quarter of the world's CO_2 emissions, the world's strongest economy, and the world's most capable scientific and technological establishment – ought to be leading and not following in this effort that is so crucial to the prospects for sustainable prosperity for everybody. But we are not leading – we are lagging.

Why the Energy-Climate Problem Is Being Underrated

Why do we underrate this problem so much? I think there are six major reasons that the public, policymakers, and even most scientists continue to be complacent about it.

First, human well-being is more dependent on both energy and climate than most people think. Most people are not at all interested in energy – in BTUs and gigajoules and kilowatt-hours – and it's hard to blame them. People are interested instead in energy *services* – comfortable rooms, cold beer, convenient transportation – and in a strong economy, a livable environment, and a peaceful world. But for the most part they don't understand the connections between energy choices and these elements of personal and societal well-being. They certainly don't understand the multiplicity of ways in which human well-being depends on climate.

Second, existing energy sources are more problematic, and climate change is further along, than most people think. Few people know that nearly 80 percent of the world's energy still comes from fossil fuels. Fewer still know that the disruptions of climate being experienced today, which are already problematic in many respects, do not even reflect the equilibrium consequences of the CO_2 that has already been added to the atmosphere. That is, because of the time lag induced by the thermal inertia of the oceans, further changes in climate could not be avoided even if we could stop the growth of the atmospheric CO_2 concentration overnight.

Third, the energy-climate implications of the expected growth in population and energy use per person are bigger than most people think. Very few people have done the kinds of arithmetic I've presented here, looking at what population, economic activity, energy use, and carbon emissions are likely to be in 2030 or 2050 or 2100.

Fourth, scientific uncertainties are not proper grounds for complacency, as so many people seem to think. There are uncertainties in the climate change picture – big ones, when it comes to the timing and the pattern of impacts of climate change – but uncertainties tend to be symmetric. That is, while things might turn out to be better than your current best estimate, they might also turn out to be worse.

Fifth, the time lags associated with the appearance of the symptoms, diagnosis of the cause, prescription of the remedy, and implementation of the prescription are all longer than most people think. Such time lags make "steering" and "braking" in the energy-climate system very problematic.

Finally, the fates of the industrialized and less-developed countries are more interconnected than most people think. There is a tendency in the industrialized countries to suppose that if the climate change problem does turn out to be as bad as currently advertised, it will mostly be people in the less-developed countries who will suffer. Americans, Europeans, and Japanese think that because we in the North have lots of technology, lots of capital, and lots of infrastructure we will be able to adjust. This view is wrong, in part because the North's assets will not be adequate to protect it against all of the consequences of severe climate change that are in store. But even more importantly, it is wrong because the North will not be able to insulate itself from the misery that climate change generates in the South.

The fact is that the people on this planet live under one global atmosphere, on the shores of one global ocean, our countries linked by flows of people, money, goods, ideas, images, diseases, drugs, weapons, and, perhaps ultimately, nuclear explosives. We cannot keep one end of the boat afloat while the other end sinks. ■

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