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Science and Technology for Sustainable Well-Being

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The American Association for the Advancement of Science (AAAS) is not about the advancement of science just for science's sake. Rather, as indicated by the Association's motto, "Advancing Science, Serving Society," it is about advancing science in the context of a desire to improve the human condition. This mission necessarily entails attention to the social as well as natural sciences; attention to the embodiment of science in technology through engineering; and attention to the processes by which understandings from the natural sciences, the social sciences, and engineering influence—or fail to influence—public policy. All of these long-standing preoccupations of the AAAS are integral to the theme of the 2007 Annual Meeting and of this essay, "Science and Technology for Sustainable Well-Being."

I begin my exploration of that theme with some premises and definitions relating to well-being and sustainability, before turning to a taxonomy of shortfalls in sustainable well-being and a rough quantification of those that are reflected in morbidity and mortality. I then address the status of five specific challenges in which science and technology (S&T) have particularly important roles to play: meeting the basic needs of the poor; managing the competition for the land, water, and terrestrial biota of the planet; maintaining the integrity of the oceans; mastering the energy-economy-environment dilemma; and moving toward a nuclear weapon-free world. I close with some thoughts on what more is needed in order to improve the pace of progress, including what the AAAS is doing and can do and what individual scientists and engineers can do.

Well-Being and Sustainability

Human well-being rests on a foundation of three pillars, the preservation and enhancement

of all three of which constitute the core responsibilities of society:

- *Economic conditions and processes*, such as production, employment, income, wealth, markets, trade, and the technologies that facilitate all of these;

- *Sociopolitical conditions and processes*, such as national and personal security, liberty, justice, the rule of law, education, health care, the pursuit of science and the arts, and other aspects of civil society and culture; and

- *Environmental conditions and processes*, including our planet's air, water, soils, mineral resources, biota, and climate, and all of the natural and anthropogenic processes that affect them.

Arguments about which of the three pillars is "most important" are pointless, in part because each of the three is indispensable: Just as a three-legged stool falls down if any leg fails, so is human well-being dependent on the integrity of all three pillars.

The futility of attempts to strengthen any one of the pillars in ways that dangerously weaken one or both of the others is underlined by their interdependence. The economic system cannot function without inputs from the environmental system, nor can it function without elements of societal stability and order provided by the sociopolitical system. And societal stability itself cannot be maintained in the face of environmental disaster, as the effect of Hurricane Katrina on New Orleans demonstrated is true even in the most economically prosperous and technologically capable country in the world.

This understanding about the elements of well-being leads, when combined with the proposition that improvements in well-being are most meaningful if they can be sustained, to a set of definitions that embody the essence of the sustainable-well-being challenge (1):

- *Development* means improving the human condition in all of its aspects, not only economic but also sociopolitical and environmental;

- *Sustainable development* means doing so by means and to end points that are consistent with maintaining the improved conditions indefinitely; and

- *Sustainable well-being*, in my lexicon,

entails pursuing sustainable development to achieve well-being where it is now most conspicuously absent, as well as converting to a sustainable basis the maintenance and expansion of well-being where it already exists but is being provided by unsustainable means.

Shortfalls

Persistent shortfalls in the pursuit of sustainable well-being are evident across a range of dimensions of the human condition, including (2):

- *Poverty*, afflicting not only the 2.5 billion people in the poorest countries who live on less than the equivalent of \$2 per day, but also hundreds of millions in addition who have much more but still cannot afford many of the ingredients of a decent existence in the more prosperous settings in which they live;

- *Preventable disease*, which keeps infant and child mortality high and life expectancy low, especially in Africa but among the very poor everywhere;

- *Impoverishment of the environment*, meaning progressive erosion of the environmental underpinnings of well-being in the qualities of air, water, soil, biota, and climate;

- *Pervasiveness of organized violence*, manifested in the well over 100 instances of armed conflict since World War II (nearly all of them in the South, with a total loss of life in the tens of millions), as well as in the global rise of terrorism;

- *Oppression of human rights* in other ways (for the preceding items are also forms of such oppression), denying human beings their dignity, their liberty, their personal security, and their possibilities for shaping their own destinies; and

- *Wastage of human potential*, resulting from all of the foregoing and the despair and apathy that accompany them, from shortfalls in education, and from the loss of cultural diversity.

Underlying these shortfalls is an array of driving forces and aggravating factors, among them:

- *Non-use, ineffective use, and misuse of S&T*, including misuses both intentional (as in the development and deployment of weapons of mass destruction) and inadvertent (as manifested in the side effects of broad-spectrum herbicides, pesticides, and antibiotics);

- *Maldistribution of consumption and investment*, where the maldistribution is of three kinds: between rich and poor as the beneficiaries of both consumption and investment; between military and civilian forms of consumption and investment ["too much for warfare, too little for welfare" (3)]; and between the two activities themselves; i.e., between too

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much consumption and too little investment;

•*Incompetence, mismanagement, and corruption*, which although sometimes attributed to developing countries particularly are in fact pervasive in industrialized and developing countries alike;

•*Continuing population growth*, which, while not the sole cause of any of the shortfalls listed, makes the remedy of all of them more difficult (4); and

•*Ignorance, apathy, and denial*, the first consisting of lack of exposure to information and the second and third of having the information but lacking the conviction or optimism or understanding to act on it.

The magnitudes of the contributions to premature mortality of a number of the shortfalls and their respective contributing factors are shown in Table 1, which is adapted from a remarkable compilation of the underlying causes of premature death produced by the World Health Organization (WHO) (5–7).

How Can S&T Help?

Table 1 underlines the role, in global mortality, of shortfalls in the deployment if not always the development of adequate technologies for food production, clean water and sanitation, and clean and efficient energy supply. I would characterize the roles of S&T in addressing the challenges of sustainable well-being in broader terms as follows:

•Advances in science improve our understanding of shortfalls, dangers, and possibilities and enable advances in technology.

•Advances in technology help meet basic human needs and drive economic growth through increased productivity, reduced costs, reduced resource use and environmental impact, and new or improved products and services.

•S&T together provide the basis for integrated assessment of challenges and opportunities, advice to decision-makers and the public about these, and formal and informal education toward a more S&T-literate (and therefore more informed and capable) society.

The need to do better with S&T applied to the goal of sustainable well-being is particularly compelling in relation to the five specific

challenges mentioned above, and I turn to these now.

Meeting the Basic Needs of the Poor

The contemporary effort to address this most fundamental of sustainable-development needs is cataloged and chronicled in the Millennium Development Goals (MDG) project of the United Nations (UN). The MDGs, consisting of eight overarching goals and specific targets for the pace of progress to be made on them, were officially adopted in 2000. The goals, targets,

the targets, they are really very modest when viewed in terms of the immense shortfalls in well-being that would persist into 2015 and beyond even if the targets were met. Where the targets do seem likely to be met for the world as a whole, moreover, as is the case for access to safe drinking water, regional shortfalls still loom large (8).

The considerable progress that has been made in some important respects (such as in life expectancy, which has been improving virtually everywhere other than sub-Saharan Africa and the former Soviet Union) has been the result of a combination of economic and social factors, but improvements in technology appear to have been the most important (9). Among other advances, widespread gains in the productivity of agriculture, which played a crucial role in improving nutrition and health in the developing world, were driven above all by investments in agricultural S&T that yielded, in strictly economic terms, enormous rates of return; and export-led economic growth, providing the means with which the public and private sectors in many developing countries have contributed to lifting portions of their populations out of poverty, has likewise been driven strongly by technology (9).

Relatively simple and inexpensive technologies can have large positive impacts on the most fundamental aspects of well-being, such as public health, as was initially demonstrated in today's industrialized countries when they first introduced simple water-treatment technologies (8) and has been shown more recently in developing countries with such simple innovations as oral rehydration therapy for diarrheal diseases, which has sharply lowered death rates even in circumstances where incomes were not rising (9). A current example of large "bang for the buck" in the

public health domain is the rapid expansion in the use of insecticide-treated bed nets to combat malaria, particularly in Africa, funded by a combination of private, governmental, and multilateral initiatives (10).

These insights and examples only serve to underline how much better we could be doing with the application of S&T to meeting basic

1 CONTRIBUTORS TO GLOBAL MORTALITY IN 2000

| Fundamental cause | Primary shortfalls and drivers | Millions of years of life lost |
|---|-------------------------------------|--------------------------------|
| Childhood and maternal malnutrition | Poverty, technology, apathy | 200 |
| High blood pressure, cholesterol, overweight, low physical activity | Consumption, denial | 150 |
| Unsafe sex | Ignorance, denial | 80 |
| Tobacco | Denial | 50 |
| Unsafe water | Poverty, technology, apathy | 50 |
| War and revolution (20th-century average) | Violence | 40 |
| Indoor smoke from solid fuels | Poverty, technology | 35 |
| Alcohol | Wasted potential, ignorance, denial | 30 |
| Urban air pollution | Consumption, technology | 6 |
| Global climate change | Consumption, technology, denial | 5 |

Table 1. Contributors to global mortality in 2000, categorized by fundamental causes. Units in column three are millions of years of life lost to premature deaths in the year 2000 (= numbers of premature deaths in 2000 from the indicated cause \times average loss of life expectancy per death from that cause). The categorization of fundamental causes and associated lost-life estimates are from WHO (5), except for "war and revolution"; that figure is the author's estimate for the 20th-century annual average, based on a UN figure of about 100 million conflict-related deaths in the 20th century (6) and the author's guess of 40 years of lost life expectancy per conflict-related death. Attributions of relevant "shortfalls and drivers" are the author's (7).

and some indicators of the extent of progress on them are summarized in Table 2. The MDG picture is clearly mixed. Many regions are on track to meet many of the targets, but other regions—and above all sub-Saharan Africa—are projected to fall short on most of them. What is worse, while the MDGs appear ambitious in terms of the pace of improvement embodied in

human needs if a more respectable effort were being devoted to this aim. The dimension of the shortfall is suggested by the figures for official development assistance (ODA) from the Organization for Economic Cooperation and Development (OECD): A recent upturn in ODA has brought the total back only to the 1990 level of 0.33% of the gross national income of the donor countries (this despite long-standing international agreement on a target of 1%, which itself seems pathetically small in relation to both the needs and the opportunities) (11). The United States, by far the richest country in the world in gross national income, is the stingiest among all the OECD countries in the fraction of it, 0.2%, devoted to ODA. [Americans spend 3.5 times more on tobacco and 20 times more on defense (12).]

Land, Water, and Terrestrial Biota

Turning to the environmental dimension of sustainable well-being, a central challenge is how to manage the intensifying competition among human uses for the land, water, and biota of the planet. Those uses fall mainly into three categories:

- Land and water for housing, commerce, industry, and infrastructure (energy, transport, and communications).

- Land, water, and net primary productivity (NPP) for the production of food, feed for domestic animals, fiber, biofuels, and chemical feedstocks.

- Land, water, and biota (plants, animals, and microorganisms) for recreation, beauty, the solace of unspoiled nature, and other “ecosystem services.”

The term “ecosystem services” refers to functions of ecosystems that underpin human well-being, including, besides those already separately mentioned, regulation of water flows; detoxification and purification of soil, water, and air; nutrient cycling; soil formation and maintenance; controls on the populations and distribution of pests and pathogens; pollination of

flowers and crops; maintenance of biodiversity; and regulation of climate (through, e.g., evapotranspiration, reflectivity, and carbon sequestration) (13, 14).

The competition among these uses for the limited supplies of land and water and the biota that these can support is being intensified by rising population and affluence, with affluence providing a particularly powerful multiplier in the demand for land and water for agriculture and pasture as rising incomes translate into higher consumption of meat. Also contributing to the intensification of the competition is global climate change (about which more will be said below), which is

sharply increasing the demand for both biofuels and carbon sequestration in intact forests (15) at the same time as it stresses farms and forests in many parts of the world with increased heat, drought, and wildfires (16).

A number of other factors complicate the challenge of managing the competing uses of land, water, and biota. One is the rising tide of toxic spillovers from energy supply, industry, and agriculture, which reduce the usability of water and otherwise directly stress managed and unmanaged ecosystems alike (more about this below, too). Another is the prevalence of haphazard, unintegrated, and short-range planning in relation to society’s uses of land and

water. A third—and one of the primary causes of the preceding two—is the frequent failure to charge a reasonable price (or any price at all) for the use of environmental resources or the degradation of environmental conditions and services.

A quantitative picture of world water supply and demand is presented in Table 3 (17). A key point is that only about a quarter of total runoff and recharge is actually available for human use (after uncaptured storm runoff and remote areas are subtracted), and nearly 40% of the globally available amount is already being used. (Irrigated agriculture is by far the largest user, and it is the fastest-growing—driven above all by rising demand for grain to feed to animals and now, in the United States especially, for corn to convert to ethanol.) There is a difference of a factor of 40 in current annual water withdrawals per person between the poorest and richest countries, which bodes ill for future water demand in relation to supply as incomes and populations continue to rise.

The widespread supposition that humans can use all of the “available” runoff is in error, moreover. Enough flow must be left in rivers to meet ecological needs. Taking these ecological flow require-



2 MDG'S, TARGETS, AND PACE OF PROGRESS

| Goal | Target | Progress |
|--|--|---|
| Eradicate extreme poverty and hunger | Proportion of people living on less than \$1 per day to be halved between 1990 and 2015 | Target already met in East and Southeast Asia, but other developing regions are behind pace needed to meet it by 2015 |
| Achieve universal primary education | Full course of primary schooling for boys and girls everywhere by 2005 | Southern Asia, northern Africa, and Latin America on track to meet target; other developing regions behind |
| Promote gender equality and empower women | Eliminate gender disparities at all levels of education by 2015 | Nearly all developing regions far off pace needed to meet target |
| Reduce child mortality | Reduce under-5 mortality rate by 2/3 between 1990 and 2015 | East and Southeast Asia, northern Africa, and Latin America on track to meet target; other developing regions far behind |
| Improve maternal health | Reduce maternal mortality rate by 3/4 between 1990 and 2015 | East and Southeast Asia, northern Africa, and Latin America on track to meet target; other developing regions behind |
| Combat HIV/AIDS, malaria, and other diseases | Have halted and begun to reverse spread of HIV/AIDS and incidence of malaria by 2015 | No. of people with HIV/AIDS may have stabilized in sub-Saharan Africa; is rising in most other developing regions |
| Ensure environmental sustainability | Proportion of people lacking access to safe drinking water and basic sanitation to be halved between 1990 and 2015 | East and Southeast Asia, northern Africa, and Latin America on track to meet sanitation target; other developing regions behind |
| Develop a global partnership for development | No quantitative target; a range of qualitative goals address mechanisms of assistance | If official development assistance is the index, progress is slight; debt and trade measures look better |



Table 2. MDGs, targets, and pace of progress (10, 11).

ments into account reveals that many of the world's river basins are already overexploited: Human withdrawals are leaving less water in rivers than needed to meet ecological requirements. Rising human water demands are also leading, at many locations around the world, to the extraction of groundwater from aquifers at rates exceeding natural recharge, leading to declining water tables, wells running dry, and increased drilling and pumping costs (8).

The current extent of human exploitation of Earth's land surface and vegetation is, similarly, far greater than is generally supposed. Crops, pastures, and grazing now take up about 40% of the planet's 133 million km² of ice-free land (18). Forests, which once covered 50 million km², have shrunk by about 10 million km² in the past 300 years (with half of that loss occurring in the past half century), and desert and near-desert lands have expanded by nearly 10 million km². Cities, towns, roads, and airports now cover about 2% of the land area—approaching 3 million km² (18–20).

Arguably a more informative measure of the scale of human intervention in terrestrial ecosystems than areas transformed is the fraction of the NPP of those ecosystems that human activities have eliminated or appropriated for human purposes; a pioneering study in the mid-1980s estimated that humans appropriate about 25% of terrestrial NPP and have eliminated nearly another 15% through land transformations (21). Subsequent studies using the more extensive remote-sensing information and geographic information systems (GIS) databases that have become available in the meantime have altered the details of the picture but reinforced the basic finding that, depending on the definitions employed, human activities are appropriating between 25 and 40% of terrestrial NPP (22).

Considering the increases in human demands for NPP that are in prospect both for the combination of food and feed and for biofuels, and considering the need to leave large areas of forest substantially intact for purposes of carbon sequestration and other ecosystem functions, these are not encouraging numbers. They become even less so when one considers the loss of biodiversity that has accompanied the level of appropriation of terrestrial NPP already reached.

The Millennium Ecosystem Assessment completed in 2005 developed estimates for contemporary and projected extinction rates compared to past rates suggested by the fossil record: 100 to 1000 times past extinction rates today, another 10 to 100 times higher in the future (13). And already in 2000 it was esti-

mated that 18% of mammal species, 12% of bird species, and 8% of plant species worldwide were threatened with extinction (23); the projected increases in extinction rates, if they materialize, thus portend a biodiversity catastrophe.

The current state of understanding of ecosystem structure and function does not generally allow prediction of what forms and degrees of local or regional biodiversity decline will lead to severe impacts on basic ecosystem functions and the services associated with them. To confuse this ignorance with cause for complacency would be folly, however. The most elementary common sense (embodied in Aldo Leopold's famous dictum from *A Sand County Almanac* that “The first rule of intelligent tinkering is to save all the parts”)—reinforced by a large part of the detailed ecological knowledge accumulated since—tells us that continuing biodiversity loss must eventually exact a large toll in ecosystem performance and resilience against shocks and stresses both natural and anthropogenic (24).

What is needed from S&T in relation to the intensifying competition for land, water, and biota? We need, for reasons both purely scientific and as a basis for sensible ecosystem management, a large increase in ecological research focused on the relations linking biodiversity and other aspects of ecosystem condition with ecosystem function and services; and we need a better understanding of what those services do and could deliver in support of human well-being, as well as better ways to quantify their value for incorporation into the market and nonmarket processes shaping the future of ecosystems (25).

We need more studies that combine projected land requirements for food and feed, fiber, biofuels, and infrastructure—rather than pretending that each use can be analyzed separately—and that attempt to reconcile the combined demands with the requirement for enough land covered by intact forests and other native ecosystems to provide the carbon sequestration and other ecosystem services society cannot do without (26). We need more effective use of the capabilities provided by satellite imagery and other remote sensing, and



3 THE WORLD'S WATER

| Stocks | | Cubic kilometers | |
|--|-------|----------------------------------|--|
| Water in the oceans (~35,000 parts per million salt) | | 1,400,000,000 | |
| Water locked up in ice | | 30,000,000 | |
| Groundwater | | 10,000,000 | |
| Water in lakes and rivers | | 100,000 | |
| Water in the atmosphere | | 10,000 | |
| Flows | | Cubic kilometers per year | |
| Precipitation on land | | 120,000 | |
| Evaporation from land | | 70,000 | |
| River runoff and groundwater recharge | | 50,000 | |
| Available river flow and recharge | | 12,000 | |
| Withdrawals for human use | | 5,000 | |
| of which | | | |
| Agriculture | 3,500 | | |
| Industry | 1,000 | | |
| Domestic | 500 | | |
| World desalting capacity | | 13 | |
| Flows per capita | | Cubic meters per person per year | |
| Available river flow and recharge/world population | | 1,800 | |
| Per capita withdrawals, global average | | 800 | |
| Nigeria | | 50 | |
| Israel | | 300 | |
| China | | 500 | |
| Mexico | | 800 | |
| Italy | | 1,000 | |
| United States | | 2,000 | |
| World desalting capacity/world population | | 2 | |



Table 3. Where is the world's water and where is it going? Compiled and rounded from several sources (17). 1 km³ = 10⁹ m³ = 10¹² liters = 264 × 10⁹ gallons. Available river flow and recharge = runoff + recharge – uncaptured storm runoff – remote areas. Withdrawals for human use are estimated for 2007. Per capita withdrawals are data for 2000.

by GIS, both for conducting such studies and for conveying the results to publics and decision-makers in forms they will understand and use (27). And, not least, we need technologies for extracting food, fiber, and fuel from agricultural and forest ecosystems in ways less disruptive of the other services those systems provide than the technologies typically used today (28).

The Oceans

The oceans cover 70% of the surface of the planet, contain 98% of the water, and contribute about half of the NPP. They are a gigantic bal-

ance wheel in Earth's weather and climate. They are an immense reservoir of biodiversity; one even less cataloged and characterized than that of the terrestrial biota. And fisheries derived from them supply 20% or more of the per capita animal-derived protein consumed by 40% of the human population (29).

Although the oceans are perceived by many as being too gigantic and immutable to be much influenced by human activities, they have actually been, like the land, substantially altered by human influences. Human-caused warming of Earth's surface and atmosphere has penetrated the oceans to depths of hundreds of meters; and absorption by the ocean of part of the carbon dioxide (CO₂) added to the atmosphere by human activities has lowered the average pH of seawater by about 0.1 (30). Lead and mercury mobilized by humans move through marine food webs, concentrating at the higher levels, as do synthetic organic compounds such as DDT and PCBs. No part of the oceans is free of traces of oil spills or free of plastic trash.

The most conspicuous of human impacts on the oceans to date has been the decline in the populations of many of the fish and shellfish we harvest for food. Marine fish catches reached a plateau in the mid-1990s and have been maintained there since only by dint of harvesting lower in the food web; continuing expansion of the total supply of protein from fish and shellfish has depended on rapid growth in aquaculture (31). The real magnitude of the human impact, however, is revealed only by looking region by region and species by species at the fish and shellfish stocks on which the catch had depended; it is a picture of devastating decline, brought about not only by unsustainable harvest of target species but also by the extensive bycatch and bottom-habitat destruction brought about by widely used if reprehensible fishing techniques (32).

Coral reefs, which have the highest density of biodiversity in the oceans, are also increasingly endangered. Originally the risks to reefs

came mainly from subsistence fishing and sediment runoff from agriculture and land development on inhabited islands; to this was later added the stress on reef fish populations from rapidly expanding commercial fishing to supply the aquarium trade in North America and Europe and the live-fish restaurant trade in East and Southeast Asia, as well as physical damage to the reefs from the influx of cruise ships and the reef-walking tourists they carry (33).

Today, coral reefs are being affected throughout their range by two further factors that are independent of local population densities, tourist influxes, and commercial fishing fleets: increasing water temperatures, which can cause bleaching (ejection of the living coral organisms from the calcium carbonate structure) and disease; and declining pH, which hinders the ability of organisms to make the calcium carbonate.

A recent survey concluded that 30% of the world's coral reefs are already severely damaged and that 60% could be lost by 2030 (33).

Another sign of trouble in the oceans is the rapid proliferation of harmful algal

blooms and the oxygen-depleted "dead zones" that are often the ultimate result. This phenomenon is largely driven by overfertilization of coastal zones by river runoff laden with nutrients from sewage and agriculture. The number of regions affected and the scale of the impact in individual regions appear to have been growing recently, with a doubling time on the order of a decade (29, 34).

Scientifically, technologically, and politically, human pressures on the oceans are even more challenging to deal with than the pressures on terrestrial ecosystems discussed above. Difficulties of observation and study in the oceans mean that the marine realm is less well explored and less well understood than terrestrial ecosystems. Technologically, the oceans are a more difficult operating environment than the land for almost any purpose. Politically, the problems of governance and management of ocean resources and the ocean environment are

compounded by the circumstance that most of the world ocean is a commons, not the province of any nation.

Much of what is needed from S&T in relation to the challenge of sustainability for ocean systems and services, however, is similar to what is needed on the terrestrial side: more research on marine ecosystem structure, function, and service; more and better monitoring and reporting, in forms meaningful to and usable by decision-makers; and more integration of analyses relating to multiple interacting uses and stresses, so that limits on what is sustainable can be identified before they are exceeded. Also needed on the marine side is technological change in relation to what we already know is unsustainable: replacement of harvesting technologies that destroy habitat and decimate bycatch with more resource-friendly alternatives, and modification of agricultural and sewage-treatment practices on land in order to drastically reduce the dead zone-inducing impacts of nutrient-laden river runoff (35).

The Energy-Economy-Environment Dilemma

The essence of this dilemma resides in two robust propositions (36–38): First, reliable and affordable energy is essential for meeting basic human needs and fueling economic growth. Second, the harvesting, transport, processing, and conversion of energy using the resources and technologies relied upon today cause a large share of the most difficult and damaging environmental problems society faces.

Contemporary technologies of energy supply are responsible for most indoor and outdoor air pollution exposure, most acid precipitation, most radioactive wastes, much of the hydrocarbon and trace-metal pollution of soil and groundwater, nearly all of the oil added by humans to the oceans, and most of the human-caused emissions of greenhouse gases that are altering the global climate (39).

The study of these environmental impacts of energy has been a major preoccupation of mine for nearly four decades. I have concluded from this study that energy is the hardest part of the environment problem; environment is the hardest part of the energy problem; and resolving the energy-economy-environment dilemma is the hardest part of the challenge of sustainable well-being for industrial and developing countries alike.

Figure 1 shows the composition of world primary energy supply during the bulk of the fossil-fuel era to date, from 1850 to 2000 (40). Energy use increased 20-fold over this period—that number being the product of a somewhat

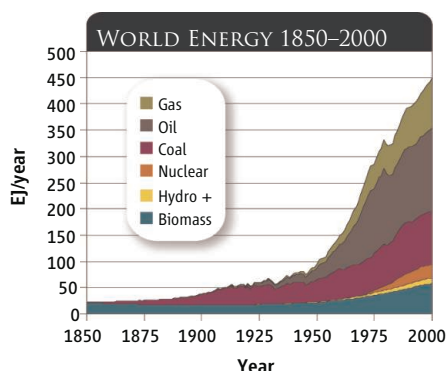


Fig. 1. World supply of primary energy 1850–2000 (40). Primary energy refers to energy forms found in nature (such as fuelwood, crude petroleum, and coal), as opposed to secondary forms (such as charcoal, gasoline, and electricity) produced from the primary ones using technology. "Hydro +" includes hydropower, geothermal, wind, and solar. Fossil fuels are counted at higher heating value and hydropower is counted as energy content, not fossil-fuel equivalent. 1 exajoule (EJ) = 10^{18} joules = 0.95 quadrillion Btu.

greater than fivefold increase in world population and a somewhat less than fourfold increase in average energy use per person (41). Fossil-fuel use increased more than 150-fold, rising from 12% of the modest energy use of 1850 to 79% of 2000's much larger total. By 2005, fossil fuels were contributing 81% of the world primary energy supply, 82% in China, and 88% in the United States (42); even in the electricity sector (where nuclear, hydropower, wind, solar, and geothermal energies make their largest contributions), fossil fuels accounted for two-thirds of global generation (Table 4).

The huge increase in fossil-fuel use over the past century and a half played a large role in expanding the impact of humankind as a global biogeochemical force (43), not only through the associated emissions of CO₂, oxides of sulfur and nitrogen, trace metals, and more, but also through the mobilization of other materials, production of fertilizer, transport of water, and transformations of land that the availability of this energy made possible (44). At the end of the 20th century and the beginning of the 21st, the fossil-fuel-dominated energy supply system continued to impose immense environmental burdens at local, regional, and global scales, despite large investments and some success in reducing emissions to air and water per unit of energy supplied (29).

Fine particles appear to be the most toxic of the usual air pollutants resulting from the combustion of fossil and biomass fuels, and whether emitted directly or formed in the atmosphere from gaseous precursors, they have proven difficult to control (45). The concentrations of fine particulates in urban air in the United States, Western Europe, and Japan have mostly been falling in recent years, but in cities across the developing world the concentrations have risen to shockingly high levels—often several times the WHO guidelines (29). As noted above in connection with Table 1, population exposures to particulate matter from the combustion of fossil and biomass fuels indoors are even greater, with commensurate impacts on health.

A major regional impact of fossil-fuel combustion is wet and dry deposition of sulfur and nitrogen, much of it in acidic forms. Of the sulfur oxide and nitrogen oxide emissions that are the precursors of this fallout, the former are somewhat easier to control

technologically. Global emissions of both are now increasing, however, as rapid expansion of poorly controlled sources in Asia, and to a lesser extent in Africa and Latin America, is now more than offsetting reductions in the industrialized countries (29).

Mid-range projections for energy growth over the next few decades show world use of energy reaching 1.5 and 2 to 2.5 times the 2005 level by 2030 and 2050, respectively; electricity generation in these “business-as-usual” cases nearly doubles by 2030 and triples by 2050 (46). Although these are daunting numbers from the standpoint of sustainability, the problem is not that the world is running out of energy. It isn't (37, 47). But it is running out of cheap and easy oil and gas, and it is running out of environmental capacity to absorb, without intolerable consequences, the impacts of mobilizing these quantities of energy in the ways we have been accustomed to doing it (48).

Much discussion of the oil issue has been framed around the contentious question of “peak oil” (49): When will global production of conventional petroleum reach a peak and begin to decline, as U.S. domestic production did

around 1970? The question derives its importance from the proposition that reaching this peak globally will presage large and long-lasting increases in the price of oil, plus a costly and demanding scramble for alternatives to fill the widening gap between the demand for liquid fuel and the supply of conventional petroleum.

Oil-supply pessimists argue that the peak of conventional oil production could occur any time now; oil-supply optimists say it probably won't happen until after 2030, perhaps not until after 2050. Similar arguments go on about conventional supplies of natural gas, the total recoverable resources of which are thought to be not greatly different, in terms of energy content, from those of crude petroleum.

In my judgment, it's difficult to tell at this juncture whether the optimists or the pessimists are closer to right about when the world will experience peak oil, but the answer is not very important as a determinant of what we need to be doing. After all, it's clear that heavy oil dependence carries substantial economic and political risks in a world where high proportions of the reserves and remaining recoverable resources lie in regions that are unstable and/or controlled by authoritarian governments that have sometimes been inclined to wield oil supply as a weapon. It's also clear that world oil use (which is dominated by the transport sector and, within it, by motor vehicles) is a huge producer of conventional air pollutants, as well as being about equal to coal burning as a contributor to the global buildup of the heat-trapping gas CO₂ (29, 42). Given these liabilities, it makes sense to be looking urgently for ways to reduce oil dependence (while working to clean up continuing uses of oil), no matter when we think peak oil might occur under business as usual.

Indeed, the problem of how to reduce the dangers from urban and regional air pollution and from overdependence on oil in the face of rising worldwide demand for personal transportation is one of the two greatest challenges at the energy-economy-environment intersection. The other one is how to provide the affordable energy needed to create and sustain prosperity everywhere without wrecking the global climate with the CO₂ emitted by fossil-fuel burning.

Climate is the envelope within which nearly all other environmental conditions and processes important to human well-being must function (50). Climate strongly influences (so climate change directly affects) the availability of water; the productivity of farms, forests, and fisheries; the prevalence of oppressive heat and humidity; the geography of disease; the damages to be expected from storms, floods,

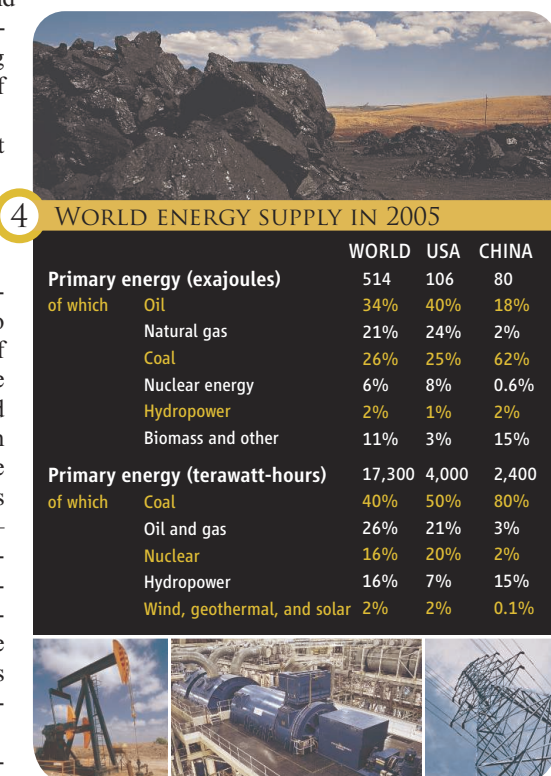


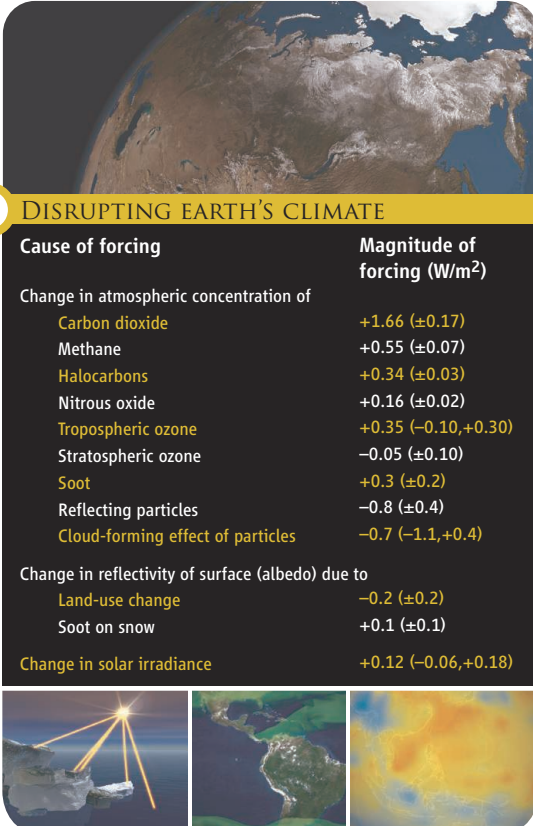
Table 4. World energy supply in 2005. About a third of the primary energy is devoted to electricity generation. Net electricity = gross generation less the electricity used within the generating facility. In the “primary energy” column, hydropower is counted as energy content, not fossil-fuel equivalent. “Other” includes wind, geothermal, and solar energy (42).

droughts, and wildfires; the property losses to be expected from sea-level rise; the investments of capital, technology, and energy devoted to ameliorating aspects of climate we don't like; and the distribution and abundance of species of all kinds (those we love and those we hate). A sufficient distortion in the climatic envelope, as recent human activities are well on the way to achieving, can be expected to have substantial impacts in most of these dimensions.

Indeed, after a rise in global average surface temperature of about $0.75^\circ \pm 0.20^\circ\text{C}$ since 1880–1900 (51), changes in most of these categories, and significant damages in many, have already become apparent (5, 10, 16, 52, 53). Large impacts from seemingly modest changes in global average surface temperature underline the reality that this temperature is a sensitive proxy for the state of the world's climate, which consists of the patterns in space and time not only of temperature and humidity but of sun and clouds, rainfall and snowfall, winds and storm tracks, and more. (The sensitivity of the temperature proxy for the state of the climate is often illustrated by the observation that the difference in global average surface temperature between an ice age and a warm interglacial—drastically different climates—is only about 5°C .)

There is no longer any serious doubt that most of the climatic change that has been observed over the past few decades has been due to human rather than natural influences (54). As shown in Table 5, the largest of the positive human “forcings” (warming influences) has been the buildup of CO_2 in the atmosphere over the past two and a half centuries. (About two-thirds of this buildup has come from fossil-fuel burning and the other one-third from land-use change.) Other important contributors have been methane from energy supply, land-use change, and waste disposal; halocarbons from a variety of commercial and industrial applications; nitrous oxide from fertilizer and combustion; and soot from inefficient engines and biomass burning. Partially offsetting cooling effects have been caused by the reflecting and cloud-forming effects of human-produced particulate matter and by increased surface reflectivity due to deforestation and desertification.

Facing the menace of growing, human-caused disruption of global climate, civilization has only three options: mitigation (taking steps to reduce the pace and the magnitude of the climatic changes we are causing); adaptation (taking steps to reduce the adverse impacts of the changes that occur); and suffering from



| 5 DISRUPTING EARTH'S CLIMATE | |
|---|---|
| Cause of forcing | Magnitude of forcing (W/m^2) |
| Change in atmospheric concentration of | |
| Carbon dioxide | +1.66 (± 0.17) |
| Methane | +0.55 (± 0.07) |
| Halocarbons | +0.34 (± 0.03) |
| Nitrous oxide | +0.16 (± 0.02) |
| Tropospheric ozone | +0.35 ($-0.10, +0.30$) |
| Stratospheric ozone | -0.05 (± 0.10) |
| Soot | +0.3 (± 0.2) |
| Reflecting particles | -0.8 (± 0.4) |
| Cloud-forming effect of particles | -0.7 ($-1.1, +0.4$) |
| Change in reflectivity of surface (albedo) due to | |
| Land-use change | -0.2 (± 0.2) |
| Soot on snow | +0.1 (± 0.1) |
| Change in solar irradiance | +0.12 ($-0.06, +0.18$) |

Table 5. IPCC estimates of principal human-produced and natural forcings since 1750. Forcings are essentially changes in Earth's energy balance, measured in watts per square meter of the planetary surface, with positive values denoting warming influences and negative values denoting cooling. The uncertainty range is given in parentheses. Large volcanic eruptions produce negative forcings of a few years' duration due to the particles they inject into the atmosphere, but they are not included in the table because no trend is evident in the size of this effect over time. Effects of the 11-year sunspot cycle are likewise not shown because they average out over time periods longer than that. Note that the IPCC's best estimate of the contribution of the net change in input from the Sun since 1750 is some 14 times smaller than that of the CO_2 (30).

impacts not averted by either mitigation or adaptation. We are already doing some of each and will do more of all, but what the mix will be depends on choices that society will make going forward. Avoiding increases in suffering that could become catastrophic will require large increases in the efforts devoted to both mitigation and adaptation.

A 2007 report for the UN Commission on

Sustainable Development, focused on what to do, emphasizing mitigation and adaptation equally, concluded that the chances of a “tipping point” into unmanageable degrees of climatic change increase steeply once the global average surface temperature exceeds 2° to 2.5°C above the pre-industrial level, and that mitigation strategies should therefore be designed to avoid increases larger than that (52). Having a better-than-even chance of doing this means stabilizing atmospheric concentrations of greenhouse gases and particles at the equivalent of no more than 450 to 500 parts per million by volume (ppmv) of CO_2 (55, 56).

A mitigation strategy sufficient to achieve such stabilization will need to address methane, halocarbons, nitrous oxide, and soot as well as CO_2 , but the largest and most difficult reductions from business-as-usual trajectories of future emissions are those needed for CO_2 itself. The difficulty in the case of CO_2 emissions from the energy system resides in the current 80% dependence of world energy supply on fossil fuels, the technical difficulty of avoiding release to the atmosphere of the immense quantities of CO_2 involved, and the long turnover time of the energy-system capital stock (meaning that the shares of the different energy sources are hard to change quickly) (57). In the case of the 15 to 25% of global CO_2 emissions still coming from deforestation (essentially all of it now in the tropics), the difficulty is that the causes of this deforestation are deeply embedded in the economics of food, timber, biofuel, trade, and development, and in the lack of valuation and marketization of the services of intact forests (58).

Stabilizing atmospheric CO_2 at 500 ppmv would be possible if global emissions from fossil-fuel combustion in 2050 could be cut in half from the mid-range business-as-usual figure of 14 billion metric tons of carbon in CO_2 per year. Numerous studies of how reductions of this general magnitude might be achieved have been undertaken (59), and, notwithstanding differences in emphasis, virtually all have shown that: (i) such reductions are possible but very demanding to achieve; (ii) there is no single silver-bullet approach that can do all or even most of the job; (iii) it is essential, in terms of both feasibility of the ultimate aim and cost of achieving it, to begin reductions sooner rather than later; (iv) the quickest and cheapest available reductions will be through improving the efficiency of energy end-use in residential and commercial buildings, manufacturing, and transport, but costlier measures to reduce emissions from the energy supply system will also need to be embraced; and (v) without major

improvements in technology on both the demand side and the supply side—and a major expansion of international cooperation in the development and deployment of these technologies—the world is unlikely to achieve reductions as large as required.

The improved technologies we should be pursuing, for help not only with the energy-climate challenge but also with other aspects of the energy-economy-environment dilemma, are of many kinds: improved batteries for plug-in hybrid vehicles; cheaper photovoltaic cells; improved coal-gasification technologies to make electricity and hydrogen while capturing CO₂; new processes for producing hydrogen from water using solar energy; better means of hydrogen storage; cheaper, more durable, more efficient fuel cells; biofuel options that do not compete with food production or drive deforestation; advanced fission reactors with proliferation-resistant fuel cycles and increased robustness against malfunction and malfeasance; fusion; more attractive and efficient public transportation options; and a range of potential advances in materials science, biotechnology, nanotechnology, information technology, and process engineering that could drastically reduce the energy and resource requirements of manufacturing and food production (60).

Also urgently needed from S&T in the energy-climate domain are improved understanding of potential tipping points related to ice-sheet disintegration and carbon release from the heating of northern soils; a greatly expanded research, development, and demonstration effort to determine the best approaches for both geologic and enhanced biologic sequestration of CO₂; a serious program of research to determine whether there are “geoengineering” options (to create global cooling effects that counter the ongoing warming) that make practical sense; and wide-ranging integrated assessments of the options for adaptation (61).

Adequately addressing these and other needs in the science and engineering of the energy-environment interaction would probably require a 2- to 10-fold increase in the sum of public and private spending for energy research, development, and demonstration (ERD&D) (62). This sounds daunting, but the amounts involved are astonishingly small compared to what society spends for energy itself (63). There are signs that the private sector is ramping up its efforts in ERD&D in response to the challenge, but for reasons that have been abundantly documented (64), the public sector must also play a large role in the needed expansion. Sadly, until now there has

been precious little sign of that happening, notwithstanding abundant rhetoric from political leaders about new technologies being the key to the solution (65).

Moving Toward Elimination of Nuclear Weapons

Throughout the Cold War, the world's nuclear arsenals (which reached tens of thousands of nuclear weapons on each side in the USA-USSR confrontation and hundreds each in the possession of the United Kingdom, France, China, and probably Israel) were recognized by nearly everyone as a threat to the existence of a sizable part of the human population and to the well-being of most of it, if any significant fraction of them were ever used. Following the peaceful end of the Cold War at the beginning of the 1990s, however, the salience of the threat from these nuclear weapons rapidly receded in the minds of most people. The most plausible political source of a nuclear conflagration had disappeared, and the only related set of worries that retained any widespread salience was a concern—initially much less compelling and immediate than the Cold War's nuclear threat had been—about the possible acquisition of nuclear weapons by rogue states and terrorists.

The tendency toward complacency about dangers from nuclear weapons in the possession of the major powers was reinforced by considerable shrinkage in the U.S. and Russian arsenals—as weapons now deemed surplus were retired from active service and a process of dismantling was begun—and subsequently by conclusion of the Moscow Treaty of 2002, which appeared to promise further significant cuts. Meanwhile, the refocusing of residual concerns about nuclear weapons on issues of proliferation and terrorism proceeded apace, driven by the initial discovery of a nuclear weapon program in Iraq, the Indian and Pakistani nuclear tests of 1998, the revelation of A. Q. Khan's proliferation network, the unmasking of North Korea's nuclear weapon program, and the exercise of frighteningly organized and destructive (even if non-nuclear) terrorist capabilities on September 11, 2001.

To be concerned about nuclear proliferation and the possibility of nuclear terrorism certainly wasn't and isn't wrong (66). But to believe that the nuclear weapons still in the possession of the United States, Russia, and the other *de jure* nuclear weapon states (67) are not themselves still a major threat to the world is to underrate both the direct threat of their use that remains and the ways in which their existence influences the proliferation and terrorism threats.

Concerning the possibility that these major-power weapons might in fact be used, highly relevant facts (which polls show are largely unknown to the U.S. public) are as follows: (i) These arsenals still contain altogether about 20,000 nuclear weapons, of which the United States possesses about half; (ii) most of the U.S. and Russian nuclear weapons are not covered by the Moscow Treaty, which governs only a subcategory called “operationally deployed strategic nuclear weapons” (and which also lacks any provision or mechanism for verification); (iii) the United States and Russia each continue to maintain about 2000 strategic nuclear weapons on short-reaction-time alert, increasing the chance of use by mistake or malfunction; and (iv) the United States and Russia both reserve the “right” of first use of nuclear weapons, including in response to non-nuclear threats. While the chance of large-scale use of U.S. and Soviet/Russian nuclear weapons certainly diminished with the end of the Cold War, then, the danger has by no means completely disappeared (68, 69).

The existing nuclear arsenals and the postures of their owners toward their potential uses and improvement are hardly unconnected, moreover, from the dangers of nuclear proliferation and nuclear terrorism. The evident intentions of the current nuclear weapon states to retain large arsenals indefinitely, to maintain high states of alert, to continue to threaten first use of nuclear weapons even against states that do not possess them, and to pursue development of new types of nuclear weapons for increased effectiveness or new purposes are manifestly incompatible with the bargain embodied in the Non-Proliferation Treaty and corrosive of the nonproliferation regime (70).

More specifically, with these stances the nuclear weapon states forfeit any moral authority to which they might aspire on questions of nuclear weapon possession, and they reduce the chances of gaining the cooperation of the world community on technology-transfer restrictions and sanctions directed against proliferators. They also directly encourage proliferation by reinforcing the view that nuclear weapons have great political and military value and by undermining confidence that nonpossession of nuclear weapons means a country need not fear being attacked with them.

Nuclear proliferation itself, when it occurs, tends to increase both the incentives and the opportunities for further proliferation, as well as expanding the opportunities for terrorist acquisition of nuclear weapons. The expansion of opportunities accompanying proliferation

comes not merely because nuclear weapons, nuclear weapons expertise, and nuclear explosive materials have been put in additional hands in additional locations, from which they may spread further (as the Khan network so appallingly demonstrated), but especially because they have been placed into contexts where there has been no experience in controlling them. Constraints on the numbers, dispersion, and contemplated uses of nuclear weapons are important, therefore, both to reduce the probability of accidental, erroneous, unauthorized, or authorized use and to reduce the chances of nuclear weapons coming into the possession of additional proliferant states or terrorists.

Ultimately, however, the only alternative to continued proliferation is achievement of a universal prohibition on nuclear weapons, coupled with means to ensure confidence in compliance. If possession of nuclear weapons does not tend toward zero, it will tend instead toward universality; and though no one can predict the pace of this, it will mean, in the long run, that the probability of use of these weapons will tend toward unity (71). There are, moreover, powerful arguments that a prohibition of nuclear weapons is not only a practical and moral but a legal necessity, under international law (72). It is also telling that, over the years, more and more of the people who have had command over the U.S. nuclear arsenal and the policies governing its use have reached the conclusion that pursuing prohibition is the only sensible option (73).

While the contrary is often claimed, prohibition does not require “un-inventing” nuclear weapons (an impossibility). Societies separately and together have productively prohibited murder, slavery, and chemical and biological weapons without imagining that these have been un-invented. Nor is verification an insurmountable obstacle. Verification, with further innovations both technical and social, can be more effective than most suppose (74); and in any case, the dangers to the world from cheating are likely to be smaller than the dangers to be expected in a world from which nuclear weapons have not been banned (75).

As for timing, the buildup of the global nuclear weapon stockpile from a dozen in 1946 (all in the possession of the United States) to the peak of about 65,000 in 1986 took just four decades; another two decades later, the number had fallen by more than two-thirds (76). I see no reason the world shouldn't aim for getting to zero in another two decades; that is, by about 2025. Crucial early steps in that direction include declarations by the nuclear weapon

states that they will never, in any circumstances, use nuclear weapons first or against countries that do not possess such weapons; de-alerting of all nuclear forces; a series of progressively deeper cuts in total numbers of nuclear weapons (strategic and nonstrategic, deployed and nondeployed), with physical destruction of all of the weapons made surplus by these cuts and disposition of their nuclear explosive materials in ways that effectively preclude their reuse for weapons, and with internationally agreed means of verification; ratification and entry into force of the Comprehensive Nuclear Test Ban Treaty; and negotiation of a cutoff of production of nuclear explosive materials for weapons (77).

S&T can contribute to achieving such progress in several ways: through technical advances that make verifying weapon-reduction agreements easier (and thus make agreeing to them easier); through other technical advances that make nuclear energy technology less likely to be used for nuclear weaponry and/or more likely to be detected if this happens; through applications of science and engineering to the task of reducing the dangers of accidental, erroneous, or unauthorized use of nuclear weapons, as well to the task of obviating any need for nuclear explosive testing of weapons, for as long as these still exist; and through S&T-based integrated assessments clarifying dangers and pitfalls on the path to zero and how to avoid them.

Almost certainly, getting to a world of zero nuclear weapons will be as much a matter of political wisdom, political courage, and diminution in the motivations for armed conflict of any sort as a matter of S&T per se. But in the domain of diminishing motivations for conflict, the alleviation of the other shortfalls in sustainable well-being discussed here—to which, as I have tried to show, S&T have large contributions to make—will be indispensable (78).

What Else Is Needed?

Beyond the points made already here about the contributions needed from S&T with respect to the five specific challenges on which I have focused, I want to mention some cross-cutting desiderata. We need:

- A stronger, clearer focus by scientists and technologists on the largest threats to human well-being;
- Greater emphasis on analysis of threats and remedies by teams that are interdisciplinary, intersectoral, international, and intergenerational (as the problems are);
- Undergraduate education and graduate

training better matched to these tasks;

- More attention to interactions among threats and to remedies that address multiple threats at once;
- Larger and more coordinated investments in advances in S&T that meet key needs at lower cost with smaller adverse side effects;
- Clearer and more compelling arguments to policy-makers about the threats and the remedies; and
- Increased public S&T literacy.

Most, if not all, of these aims would be advanced by wider acceptance, within the academic scientific and engineering communities and elsewhere, of the proposition that applied, interdisciplinary, and integrative work by individual scientists and technologists and by teams is not necessarily less rigorous, less demanding, or less worthy of recognition—and certainly not less valuable to society—than work that is narrower or “purer” (79).

The role of the AAAS in advancing these ideas has been and remains immensely important. It is the largest, most diverse, and most interdisciplinary of U.S. scientific societies, and it is also the most influential. Our flagship publication, *Science*, has the largest paid circulation among all the peer-reviewed science journals in the world and enjoys a well-earned reputation for discerning coverage of the intersection of S&T with public policy (as well as for cutting-edge reports on disciplinary research in multiple fields). The extraordinary intellectual smorgasbord of our annual meeting makes it the year's most important gathering for the growing segment of the S&T community interested in the interactions among S&T disciplines and in the influence of S&T on the human condition. It also draws, appropriately, by far the most and best media coverage of any scientific meeting (80).

As a visit to the AAAS Web site at www.aaas.org will reveal, there is much more. A remarkable array of interdisciplinary, intersectoral, practice- and policy-oriented centers, programs, and initiatives operate out of AAAS headquarters and engage the energies of members and the attention of publics and policy-makers all around the world. The AAAS R&D Budget and Policy Program provides the most comprehensive and continuously up-to-date coverage available anywhere on patterns, priorities, and policy underpinnings of U.S. government investments in S&T. Since 1973, the AAAS Science and Technology Policy Fellowship programs have been installing postdoctoral to mid-career scientists and engineers in key venues of the federal government where their insights can inform real-world policy-making

while they learn how the policy process works and how it can be made to work better; there have been something in the range of 2000 of these AAAS S&T fellows, and this tremendous body of talent and experience now constitutes a major part of the national community of teaching and practice in science, technology, and public policy. And the extraordinary AAAS Project 2061 has become a major force in strengthening S&T education in our schools and communities.

What More Can Individuals Do?

Individual scientists and technologists concerned with the roles of S&T in the pursuit of sustainable well-being have available to them an array of avenues and opportunities for effective thought and action. Perhaps the most obvious of these, given what I have just said about the AAAS, is to increase one's support for, participation in, and use of the relevant activities and resources of this organization. The similar activities of other science- and engineering-oriented professional societies, academies, and nongovernmental organizations (NGOs) likewise need and deserve increased participation and support.

More specifically, I would urge every scientist and engineer with an interest in the intersection of S&T with sustainable well-being (in all the senses I have explored here and more) to read more and think more about relevant fields outside your normal area of specialization, as well as about the interconnections of your specialty to these other domains and to the practical problems of improving the human condition; to improve the aspects of your communication skills that are germane to conveying your understandings about these interconnections to members of the public and to policymakers; to actively seek out additional and more effective avenues for doing so (including but not limited to increased participation in the relevant activities of the AAAS and other NGOs); and indeed to "tithe" 10% of your professional time and effort to working in these and other ways to increase the benefits of S&T for the human condition and to decrease the liabilities (81).

If so much as a substantial fraction of the world's scientists and engineers resolved to do this much, the acceleration of progress toward sustainable well-being for all of Earth's inhabitants would surprise us all.

References and Notes

1. See especially the classic treatise on sustainable development by the World Commission on Environment and Development, G. H. Brundtland, chair, *Our Common Future* (Oxford Univ. Press, 1987), and the more comprehensive and analytical update by the National

Research Council Board on Sustainable Development, *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, DC, 1999).

2. A number of the formulations in this section are adapted from J. P. Holdren, G. C. Daily, P. R. Ehrlich, in *Defining and Measuring Sustainability* The Biogeophysical Foundations, M. Munasinghe, W. Shearer, Eds. (World Bank, Washington, DC, 1995), pp. 3–17.

3. The quoted formulation is from Robert Kates.

4. This was the key insight in Paul Ehrlich's *The Population Bomb* (Ballantine, New York, 1968), as well as one of those in Harrison Brown's prescient earlier book, *The Challenge of Man's Future* (Viking, New York, 1954). The elementary but discomfiting truth of it may account for the vast amount of ink, paper, and angry energy that has been expended trying in vain to refute it.

5. WHO, *The World Health Report 2002* (WHO, Geneva, 2002); see also K. R. Smith, M. Ezatti, *Annu. Rev. Environ. Resour.* **30**, 291 (2005).

6. UN Development Programme (UNDP), *The Human Development Report 2005: International Cooperation at a Crossroads* (UNDP, New York, 2005).

7. An unsurprising conclusion from Table 1 is that poverty is a bigger cause of loss of life in today's world than high consumption is. More surprising to some, although known to specialists since the early 1980s, is that indoor air pollution from the use of solid fuels in primitive stoves for cooking, boiling water, and space heating in developing countries is a far bigger killer than the outdoor air pollution in all of the world's cities. See K. R. Smith, A. L. Aggarwal, R. M. Dave, *Atmos. Environ.* **17**, 2343 (1983). Also surprising to many is WHO's finding that, already in 2000, climate change was approaching urban air pollution as a contributor to global mortality, principally through the effects of increases in heat waves, floods, droughts, and the incidence of certain tropical diseases. For a discussion of the WHO estimate, arguing that it is conservative, see J. A. Patz et al., *Nature* **438**, 310 (2005).

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10. UN, *The Millennium Development Goals Report* (UN, New York, 2006).

11. World Bank, *Global Monitoring Report: Millennium Development Goals* (World Bank, Washington, DC, 2007).

12. See U.S. Dept. of Commerce, *2007 Statistical Abstract of the United States* (U.S. Government Printing Office, Washington DC, 2007). The United States compounds its distinction as the meanest of wealthy countries in aid-giving by claiming the record for the fraction of its aid that is "tied": that is, the money must be used to purchase goods and services from the donor (6).

13. Millennium Ecosystem Assessment (MEA), *Ecosystems and Human Well-being: Biodiversity Synthesis* (World Resources Institute, Washington, DC, 2005).

14. G. C. Daily, Ed., *Nature's Services: Societal Dependence on Natural Ecosystems* (Island Press, Washington, DC, 1997).

15. Growing concern about global climate change, which is driven largely by the buildup of CO₂ and other greenhouse gases in the atmosphere, has helped drive increased demand for biofuels because of the impression that they are CO₂-neutral. This is indeed the case if the biomass being used for energy is replaced by new growth as rapidly as it is burned, and if no fossil fuels are used for growing the energy crop, harvesting it, transporting it, and converting it into the desired fuel form. Most often the latter condition is not met in the real world, as it most emphatically is not in the case of corn ethanol, which is by far the most rapidly expanding biofuel enterprise in the United States. But a biofuel operation that is short of CO₂-neutral may still offer some greenhouse gas-abatement benefit compared to direct burning of fossil fuel. See, e.g., A. E. Farrell et al., *Science* **311**, 506 (2006), and J. Hill, E. Nelson, D. Tilman, S. Polasky, D. Tiffany, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 11206 (2006).

16. Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: Impacts, Adaptation, and Vulnerability* (Contribution of Working Group II to the Fourth Assessment Report of the IPCC, Cambridge Univ. Press, Cambridge, 2007).

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Science **313**, 1068 (2006); and UN Environment Programme (UNEP), *Vital Water Graphics* (UNEP, Washington, DC, 2002).

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19. For further detail about human transformations of land and related impacts, see especially the classic by B. L. Turner et al., Eds., *The Earth As Transformed by Human Action* (Cambridge Univ. Press, Cambridge, 1991), as well as R. DeFries, G. Asner, R. Houghton, Eds., *Ecosystems and Land Use Change* (Geophysical Monograph Series, vol. 153, American Geophysical Union, Washington, DC, 2004) and (21).

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21. P. M. Vitousek, P. R. Ehrlich, A. H. Ehrlich, P. A. Matson, *Bioscience* **36**, 368 (1986). NPP is the part of the energy captured by primary producers (mostly plants) that is not used by the plants for their own metabolic processes; hence, it is available for consumption by other organisms or addition to stocks.

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23. F. S. Chapin III et al., *Nature* **405**, 234 (2000). See also R. Dirzo, P. H. Raven, *Annu. Rev. Environ. Resour.* **28**, 137 (2003) and (13).

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25. Good catalogs of the research needs in these domains have been provided by the MEA (13, 20) and by the indicators project of the H. John Heinz III Center for Science, Economics, and the Environment: Heinz Center, *The State of the Nation's Ecosystems* (Cambridge Univ. Press, Cambridge, 2002); Heinz Center, *Filling the Gaps: Priority Data Needs and Key Management Challenges for National Reporting on Ecosystem Condition* (Heinz Center, Washington, DC, 2006).

26. See, e.g., B. Soares-Filho et al., *Nature* **440**, 520 (2006).

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28. The approach being promoted by Tilman and colleagues on the use of mixed prairie grasses as feedstock for cellulosic ethanol production is a good example [D. Tilman, J. Hill, C. Lehman, *Science* **314**, 1598 (2006)].

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33. T. P. Hughes et al., *Science* **301**, 929 (2003).

34. L. Mee, *Sci. Am.* **295**, 79 (November 2006) and (29).

35. For more extensive discussions of what is required to sustain the integrity and services of the oceans—including not only scientific and technological but the all-important management and governance dimensions—see, e.g., Pew Oceans Commission, L. E. Panetta, chair, *America's Living Oceans: Charting a Course for Sea Change* (Pew Oceans Commission, Arlington, VA, 2003) and (13).

36. M. K. Hubbert, in National Research Council, *Resources and Man* (W. H. Freeman, San Francisco, 1969), chap. 8.

37. J. Holdren, P. Herrera, *Energy* (Sierra Club Books, NY, 1971).

38. J. Goldemberg, Ed., *The World Energy Assessment* (UNDP, UN Department of Economic and Social Affairs, and World Energy Council, New York, 2000).

39. Much of this was already clear from the pioneering report of the 1970 summer workshop organized at the Massachusetts Institute of Technology (MIT) by Carroll Wilson, *Study of Critical Environment Problems* (MIT Press, Cambridge, MA, 1970). A more recent synoptic account is the chapter on "Energy, Environment, and Health," J. P. Holdren, K. R. Smith, convening lead authors, in (38). See also (16, 19, 20, 29).

40. Data for Fig. 1 were compiled and reconciled from J. Darmstadter, *Energy in the World Economy* (Johns Hopkins Univ. Press, Baltimore, MD, 1968); D. O. Hall, G. W. Barnard, P. A. Moss, *Biomass for Energy in Developing Countries* (Pergamon, Oxford, 1982); BP

- Amoco, *Stat. Rev. World Energy* (BP, London, annual); and (36). Graphic courtesy of S. Fetter.
41. J. P. Holdren, *Popul. Environ.* **12**, 231 (1991).
 42. International Energy Agency, *Key World Energy Statistics 2007* (OECD, Paris, 2007).
 43. P. J. Crutzen, W. Steffen, *Clim. Change* **61**, 251 (2003).
 44. For earlier discussions of this issue, see, e.g., J. Holdren, P. Ehrlich, *Am. Sci.* **62**, 282 (1974) and the references cited in (20, 21, 37).
 45. C. A. Pope *et al.*, *JAMA* **287**, 1132 (2002); J. Kaiser, *Science* **307**, 1858 (2005).
 46. U.S. Energy Information Administration, *International Energy Outlook 2007* (U.S. Department of Energy, Washington, DC, 2007).
 47. See, e.g., IPCC, *Climate Change 2007: Mitigation* (Working Group III Contribution to the IPCC Fourth Assessment Report, IPCC, Geneva, 2007).
 48. J. P. Holdren, *Innovations* **1**, 3 (2006).
 49. Credit for the idea of approximating the production trajectory of a depletable resource as a Gaussian curve and for insights about the significance of the peak year and how to predict it belongs to the late geophysicist M. King Hubbert, who in the 1950s used this approach to correctly predict that U.S. domestic production of conventional oil would peak around 1970 (36) and references therein. He also predicted that world production of crude petroleum would peak between 2000 and 2010. Reviews, extensions, and critiques of Hubbert's approach now constitute a considerable literature; see, e.g., K. Defeyes, *Hubbert's Peak: The Impending World Oil Shortage* (Farrar, Straus & Giroux, New York, 2002), and C. J. van der Veen, *Eos* **87**, 199 (2006).
 50. Some of the formulations about climate in what follows have been adapted from (48).
 51. The beginning of the buildup of atmospheric greenhouse gases attributable to human activities dates back to even before 1750, the nominal start of the Industrial Revolution and the zero point used by the IPCC for its estimates of subsequent human influences. Earlier human contributions to atmospheric greenhouse gas concentrations came principally from deforestation and other land-use change (43). The human influences on global average surface temperature did not become large enough to be clearly discernible against the backdrop of natural variability until the 20th century, however. See especially J. Hansen *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 14288 (2006), as well as (16).
 52. P. Raven *et al.*, *Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable* (UN Foundation, Washington, DC, 2007).
 53. UNDP, *Human Development Report 2007-2008: Fighting Climate Change* (UNDP, Washington, DC, 2007).
 54. Even the IPCC, which by its structure and process is designed to be ultraconservative in its pronouncements, rates the probability that most of the observed change has been due to human influences as between 90 and 95% in its 2007 report (30).
 55. For convenience, the IPCC and other analysts often represent the net effect of all of the human influences on Earth's energy balance as the increased concentration of CO₂ alone that would be needed to achieve the same effect, starting from a reference point of 278 ppmv of CO₂ in 1750. In 2005, when the actual CO₂ concentration was 379 ppmv, the additional warming influences of the non-CO₂ greenhouse gases and soot were the equivalent of another 100 ppmv of CO₂, and the cooling effects of human-produced reflecting and cloud-forming particles and surface reflectivity changes were (coincidentally) equivalent to subtracting about the same amount of CO₂. Thus, the net effect was about what would have been produced by the actual CO₂ increase alone (see Table 5).
 56. The relationship between climate forcing (represented as the CO₂ concentration increase that would give the same effect as all of the human influences combined) and the corresponding change in global average surface temperature must be expressed in probabilistic terms because of uncertainty about the value of climate "sensitivity," which is commonly defined as the temperature change that would result from forcing corresponding to a doubling of the 1750 CO₂ concentration. See especially S. Schneider, M. Mastrandrea, *Proc. Natl. Acad. Sci. U.S.A.* **102**, 15728 (2005) as well as (30).
 57. About 27.5 billion tons of CO₂, containing 7.5 billion tons of carbon, were emitted by fossil-fuel combustion in 2005. The replacement cost of the current world energy system is in the range of \$15 trillion, and the associated capital stock has an average turnover time of at least 30 to 40 years. See, e.g., International Energy Agency, *World Energy Outlook 2006* (OECD, Paris, 2006) and (52).
 58. P. Moutinho, S. Schwartzman, Eds., *Tropical Deforestation and Climate Change* (Instituto de Pesquisa Ambiental da Amazônia, Belem, and Environmental Defense, Washington, DC, 2005).
 59. M. Hoffert *et al.*, *Science* **298**, 981 (2002); S. Pacala, R. Socolow, *Science* **305**, 968 (2004); P. Enkvist, T. Naucler, J. Rosander, *McKinsey Quart.* **1**, 35 (2007); J. Edmonds *et al.*, *Global Energy Technology Strategy* (Battelle Memorial Institute, Washington, DC, 2007) and (47).
 60. See, e.g., N. Lane, K. Matthews, A. Jaffe, R. Bierbaum, Eds., *Bridging the Gap Between Science and Society* (James A. Baker III Institute for Public Policy, Rice Univ., Houston, TX, 2006).
 61. D. W. Keith, *Annu. Rev. Energy Environ.* **25**, 245 (2000); P. J. Crutzen, *Clim. Change* **77**, 211 (2006); and (52).
 62. See, e.g., President's Committee of Advisors on Science and Technology, *Federal Energy Research and Development for the Challenges of the 21st Century* (Executive Office of the President of the United States, Washington, DC, 2007); World Energy Council (WEC), *Energy Technologies for the 21st Century* (WEC, London, 2001); National Commission on Energy Policy (NCEP), *Breaking the Energy Stalemate* (NCEP, Washington, DC, 2004); and G. F. Nemet, D. M. Kammen, *Energy Policy* **35**, 746 (2007).
 63. Expenditures of firms and individuals for energy are generally in the range of 5 to 10% of gross domestic product—in round numbers, perhaps a trillion dollars per year currently in the United States and five times that globally. Estimates of expenditures by governments on ER&D depend on assumptions about exactly what should be included, but by any reasonable definition are currently not more than \$12 billion to \$15 billion per year worldwide. Private-sector investments in ER&D are much more difficult to estimate; but, if following the general pattern in the United States they are assumed to be twice government investments, then the public/private total for the world is in the range of \$35 billion to \$50 billion per year, which is equal to at most 1% of what is spent on energy itself. By contrast, many other high-technology sectors spend 8 to 15% percent of revenues on R&D [see (62)].
 64. See, e.g., K. S. Gallagher, J. P. Holdren, A. D. Sagar, *Annu. Rev. Environ. Resources* **31**, 193 (2006); President's Committee of Advisors on Science and Technology, *Powerful Partnerships: The Federal Role in International Cooperation on Energy-Technology Innovation* (Executive Office of the President of the United States, Washington, DC, 1999); and (62).
 65. K. S. Gallagher, A. D. Sagar, D. Segal, P. de Sa, J. P. Holdren, *DOE Budget Authority for Energy Research, Development, and Demonstration Database* (Energy Technology Innovation Project, Cambridge, MA, 2006).
 66. National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (National Academy Press, Washington, DC, 1994); G. Allison, *Nuclear Terrorism: The Ultimate Preventable Catastrophe* (Henry Holt, New York, 2004); M. Bunn, *Securing the Bomb 2007* (Project on Managing the Atom, Cambridge, MA, and Nuclear Threat Initiative, Washington, DC, 2007).
 67. The term "de jure nuclear weapon states" refers to those certified as legitimate albeit temporary possessors of such weapons by the Non-Proliferation Treaty (signed in 1968 and entering into force in 1970), in exchange for their agreement to make progress toward nuclear disarmament (Article VI) and to assist non-nuclear weapon states in acquiring the benefits of peaceful useful energy (Article IV). They are the United States, the Soviet Union (now Russia), the United Kingdom, France, and China.
 68. National Academy of Sciences, Committee on International Security and Arms Control, *The Future of U.S. Nuclear Weapons Policy* (National Academy Press, Washington, DC, 1997).
 69. John P. Holdren, "Beyond the Moscow Treaty," testimony before the Foreign Relations Committee, U.S. Senate, 12 September 2002 (www.belfercenter.org/files/holdren_testimony_9_12_02.pdf).
 70. See, e.g., Canberra Commission on the Elimination of Nuclear Weapons, *Report of the Canberra Commission* (Department of Foreign Affairs, Commonwealth of Australia, Canberra, 1996) and (68).
 71. This was recognized already in the prescient book that Harrison Brown, then a young chemist working in the Manhattan Project, started writing even before the Hiroshima and Nagasaki bombs were exploded: *Must Destruction Be Our Destiny?* (Simon & Schuster, New York, 1946). The Polish/British Manhattan Project scientist Joseph Rotblat also reached this conclusion before World War II ended, left the project as a result, and spent the rest of his 97 years working for the elimination of nuclear weapons (including through the Pugwash Conferences on Science and World Affairs, which he helped organize and lead and with which he shared the 1995 Nobel Peace Prize). See J. Rotblat, *Scientists in the Quest for Peace: A History of the Pugwash Conferences* (MIT Press, Cambridge, MA, 1972); J. Rotblat, in *Les Prix Nobel 1995* (Nobel Foundation, Stockholm, 1996); and J. P. Holdren, *Science* **310**, 633 (2005).
 72. International Court of Justice, *Int. Legal Materials* **35**, 830 (1996).
 73. G. L. Butler, "Abolition of Nuclear Weapons," speech at the National Press Club, 4 December 1996 (www.wagingpeace.org/articles/1996/12/04_butler_abolition-speech.htm); A. Goodpaster, chair, *An American Legacy: Building a Nuclear-Weapon-Free World* (Stimson Center, Washington, DC, 1997); G. Schultz, H. Kissinger, W. Perry, S. Nunn, *Wall Street Journal*, 6 January 2007, Op-Ed page. General Butler was the commander of all U.S. strategic nuclear forces; General Goodpaster was Supreme Allied Commander in Europe; Schultz, Kissinger, and Perry all served as U.S. secretary of defense.
 74. Committee on International Security and Arms Control, National Academy of Sciences, *Monitoring Nuclear Weapons and Nuclear-Explosive Materials* (National Academy Press, Washington, DC, 2005).
 75. J. P. Holdren, in M. Bruce, T. Milne, Eds., *Ending War: The Force of Reason: Essays in Honour of Joseph Rotblat* (St. Martin's Press, New York, 1999), chap. 4.
 76. Natural Resources Defense Council, *Table of Global Nuclear Stockpiles, 1945–2002*, November 2002 (www.nrdc.org/nuclear/nudb/datab19.asp).
 77. See, e.g., (68–70, 73) and National Academy of Sciences, Committee on Technical Issues Related to Ratification of the Comprehensive Nuclear Test Ban Treaty, *Technical Issues Related to Ratification of the Comprehensive Nuclear Test Ban Treaty* (National Academy Press, Washington, DC, 2002).
 78. See also J. P. Holdren, "Arms Limitation and Peace Building in the Post-Cold-War World" (Nobel Peace Prize acceptance lecture on behalf of the Pugwash Conferences on Science and World Affairs), *Les Prix Nobel 1995* (Nobel Foundation, Stockholm, Sweden, 1996).
 79. A multidecade trend in the right direction is evident in the establishment and success of increasing numbers of interdisciplinary graduate degree programs focused on various dimensions of the science-technology-society intersection in universities of the first rank in the United States and around the world, as well as in the increasing number of prestigious prizes focused on such work and the increasing recognition of its importance by academies of science and engineering through the election of members whose careers have been largely in this domain.
 80. This and the subsequent paragraph have been adapted from my candidate statement in the 2004 election for president-elect of the AAAS.
 81. Although I have been advocating this title for decades, the idea is certainly not original with me. I note here that a similar idea was a major theme in J. Lubchenco's AAAS presidential address in 1997 [*Science* **279**, 491 (1998)].
 82. I owe thanks for insight and inspiration to several late mentors (among them Harrison Brown, Roger Revelle, Gilbert White, Jerome Wiesner, Harvey Brooks, and Joseph Rotblat); to other mentors still very much alive (among them Paul Ehrlich, George Woodwell, Richard Garwin, Murray Gell-Mann, and Lewis Branscomb); to previous presidents of the AAAS who have shared my preoccupation with the links between S&T and sustainable well-being (among them Peter Raven, Jane Lubchenco, Shirley Ann Jackson, and Gil Omenn); to my wife (the biologist Cheryl E. Holdren); and to colleagues, students, and friends—too numerous to list here—at all of the institutions where I've worked or visited. I thank the editors of *Science* for their patience and assistance with this essay, and the AAAS staff—above all Alan Leshner and Gretchen Seiler—for their exceptional support throughout my term in the Association's leadership. My work on the topics discussed here has been supported by the John D. and Catherine T. MacArthur Foundation, the William and Flora Hewlett Foundation, the David and Lucile Packard Foundation, the Heinz Family Philanthropies, the Energy Foundation, the Winslow Foundation, the Henry Lucie Foundation, and many individual donors to the Woods Hole Research Center. I am most grateful to all of them.

ERRATUM

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Association Affairs: "Science and technology for sustainable well-being" by John P. Holdren (25 January, p. 424). In Table 4, the heading reading "Primary energy (terawatt-hours)" should have read "Net electricity (terawatt-hours)." In ref. 73, the positions held by G. Schultz, H. Kissinger, W. Perry, and S. Nunn were incorrectly described. The text should have read "Schultz and Kissinger served as U.S. secretary of state, Perry was secretary of defense, and Nunn was chair of the Senate Armed Services Committee."