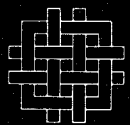




# **TRANSFORMING TECHNOLOGY:**

## **AN AGENDA FOR ENVIRONMENTALLY SUSTAINABLE GROWTH IN THE 21ST CENTURY**

George Heaton  
Robert Repetto  
Rodney Sobin

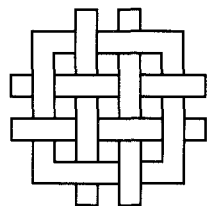


WORLD RESOURCES INSTITUTE

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George Heaton  
Robert Repetto  
Rodney Sobin



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*G.H.*  
*R.R.*  
*R.S.*

## FOREWORD

Countries around the globe have set two potentially conflicting goals for themselves: improving environmental quality, in part by reducing *current* levels of pollution and resource deterioration, and achieving large, sustained increases in economic activity. Indeed, by the middle of the next century, the world economy is projected to be five times larger than it is today. Quite possibly, political leaders will face no greater challenge in the decades ahead than reconciling these two goals. Doing so will demand continuing effort at the highest levels of government, including international cooperation on a scale seldom seen.

What will this reconciliation require in practical terms? If a doubling and redoubling of economic activity is accomplished with the technologies now dominant in energy production, transportation, manufacturing, agriculture, and other sectors, truly catastrophic impacts are likely on global climate, human health, and the productivity of natural systems. Seen this way, reconciling the economic and environmental goals societies have set for themselves will be possible only through a transformation in technology—a shift, perhaps unprecedented in scope and pace, to new technologies that dramatically reduce environmental impact per unit of prosperity.

Of course, it is not only technology that must change; values, lifestyles, and policies must change also. But, economic growth on an unprecedented scale will occur. For much of the world this growth is essential to meeting basic human needs and achieving acceptable levels of personal security and comfort. The bottom-line question remains: with what technologies will this growth occur? Only the population explosion rivals this question in fundamental importance to the planetary environment.

The good news, as this new World Resources Institute report makes clear, is that many emerging technologies offer exciting opportunities to achieve an ecological modernization of industry and agriculture. The bad news is that there is no guarantee that these technologies will be fully explored or exploited. Neither discernible trends in technological change nor current approaches to environmental protection will be sufficient to bring about the needed technological transformation.

Certainly, some of the mega-trends at work should help. As Manfredo Maciotti has noted, “there is less reason to jeopardize our natural inheritance. . . when the future belongs to ‘intelligent’ rather than ‘inert’ technologies, to software rather than to hardware, and to ‘functions’ rather than to ‘products.’” And current environmental laws in the United States and other countries have at least modestly reduced pollution levels in most settings in the face of significant economic expansion over the past two decades. But the persistence of long-recognized environmental problems and the emergence of new challenges, such as global warming, both underscore the need for new policies and new approaches.

Some implications of this view—for example, that pollution prevention is preferable to end-of-pipe approaches—have gained many supporters. Yet, the full implications of asking how “green” technology can be developed and deployed more effectively are just beginning to emerge.

*Transforming Technology* takes a major step forward by analyzing the types of policy change needed to realize modern technology’s potential. As the authors indicate, environmental regulation needs to be overhauled to promote long-term innovation and pollution prevention; more effective economic incentives for investments in clean technologies are long overdue; current measures of industrial productivity need to be reconceptualized so they recognize environmental costs; and altogether more attention needs to be paid to how clean technologies can be transferred successfully from country to country.

Recommending ways to address these issues as well as such concerns as how to educate managers and engineers to think about the environment and how to build environmental objectives into technology development and use, George Heaton, Robert Repetto, and Rodney Sobin both break new ground and consolidate the insights of an increasingly important field. Implicit in their approach to economic and regulatory policy is a new way of thinking about technology and the environment.

The new approaches recommended by Heaton, Repetto, and Sobin are badly needed. Environmental factors should be seen as opportunities, since demands for ecological responsibility are creating

markets for new processes, products, and services. Yet, despite the enormous possibilities, environmental issues are left out of most discussions of national competitiveness, trade, and technology policy.

To bridge these gaps, a new type of cooperation must be forged among the private sector, government, and environmental advocates. Together, they must work “upstream” to change the products, processes, policies, and pressures that give rise to pollution and environmental deterioration.

This report is the first publication of the World Resources Institute’s new Program on Technology and the Environment. In this program, WRI hopes to focus attention on the means needed to achieve large-scale transformation of today’s technologies in order to meet the environmental and economic needs of the 21st century.

The report draws on the results of a symposium convened in Annapolis, Maryland, by WRI in June

1990. Sixty-four experts in science, technology, and management from some eighteen countries provided a fertile source of information and ideas. WRI also commissioned twelve papers covering the connection between technology and the environment in various sectors and policy areas as background material. These papers, listed in an appendix, and a report on the symposium’s suggestions for a publicly supported research agenda are available separately from WRI.

This conference—“Toward 2000: Environment, Technology and the New Century”—was organized in cooperation with the Organisation for Economic Cooperation and Development (OECD) and was supported by the U.S. National Science Foundation and the Hitachi Foundation, all of which have our appreciation.

James Gustave Speth  
*President*  
World Resources Institute

## EXECUTIVE SUMMARY

Two decades of environmental regulation in the industrialized countries have yielded some results, but also demonstrate the limitations of current approaches. In the United States, “pollution control” through end-of-pipe treatment has been countered by the lack of non-point source controls and the steadily expanding scale of economic activity. The ambitious goals adopted twenty years ago have not been met. Meanwhile, developing countries have increasingly joined the pattern of degradation begun in the developed world. The volume of pollutants expands worldwide. New classes of global and regional threats—global warming, ozone layer destruction, acid rain, deforestation, mass extinctions, marine degradation, and others—have emerged. This growing assault on the earth demonstrates that we now risk irrevocably altering the planetary life support system with little grasp of the consequences.

In principle, demands on the earth’s resources could be reduced by diminishing economic growth, limiting population increase, or increasing the resource efficiency of production. However, the third option is the most viable. Demographic momentum points toward a doubling of global population by the mid-21st century. Economic growth is needed to meet the aspirations of most of the world’s people.

These realities leave technological transformation as the primary strategy for avoiding environmental degradation. Technological transformation means widespread, continuing development and adoption of ever less polluting and more resource-efficient products, processes, and services. Technological change has contributed most to the expansion of wealth and productivity. Properly channelled, it could hold the key to environmental sustainability as well.

Technologies to reduce environmental problems while raising economic productivity exist. Studies of major sectors of the economy—energy, agriculture, and manufacturing—demonstrate clearly that far-reaching environmental improvements could be made immediately. For example, many opportunities in industrial pollution prevention and improved energy efficiency are highly profitable today. A variety of new renewable energy technologies, already commercially available, are becoming more widely competitive with conventional fossil fuels.

Emerging revolutions in advanced materials and biotechnology, along with continuing spectacular advances in information technologies and miniaturization, can provide radically new products and processes that harmonize environmental and economic objectives. Investment in environmentally preferable technologies represents an exciting opportunity to enhance competitiveness.

Much more needs to be done to capitalize on this potential. Current best practice must be diffused more rapidly. Environmentally superior products and processes need to be brought to market more quickly. Research and development should be encouraged and channelled in environmentally sound directions.

Technical constraints are not the principal factor limiting technological transformation. The biggest barriers to change are rooted in the social, economic, political, and cultural milieus in which technologies are developed, diffused, and used. Many impediments to technological transformation are imbedded in the structure of public and corporate policy regimes.

**Environmental regulation** should be reformed to encourage technological change. Many environmental laws favor old technologies over new. Relying on “best available technology” standards tends to entrench existing control technologies at the expense of long-term innovation. Regulations have largely been uncoordinated across media (air, water, and land), have focused on “end-of-pipe” pollution controls instead of pollution prevention options, and have provided no incentives for doing better than standards dictate. Cumbersome administrative procedures also impede innovation.

Given this poor record, serious consideration should be given to changes that require regulatory agencies to promote the development and deployment of new technology. This would necessitate a variety of new policy tools. Foremost among them would be greatly expanded use of performance-based standards and economic instruments. Public disclosure requirements, like the Toxic Release Inventory required under the United States Superfund Amendment and Reauthorization Act Title III can also increase public demands and corporate incentives for environmental protection.

**Economic incentives** should be employed in tandem with regulation to encourage technological

transformation. Pollution charges that reflect the full social and economic costs of production, consumption, and waste disposal would provide long-term incentives for investments in clean technologies. Emissions trading also deserves wider use.

**Economic indicators** conventionally underestimate the value of the environment. National income accounts, such as GNP, treat activities that erode the soil, contaminate air and water, and diminish forests and fisheries as contributions to income rather than as consumption of capital. Similarly, measures of industrial productivity and corporate accounts fail to consider the costs of *not* protecting the environment. Without economic indicators that fully reflect the value of the environment, environmentally perverse public policies and private practices are likely to continue.

**Technology policies** have thus far largely ignored environmental objectives. Government support of new technologies through R&D funding, procurement, research consortia, and other mechanisms have led to great strides in aerospace, computers, defense, and medicine. Technology policies could play a critical role in advancing environmentally sustainable technologies while promoting commercial competitiveness. But, large areas of environmentally important “generic” research (widely applicable research too removed from marketable products to be adequately supported by industry but too “applied” for most academic laboratories) remain undersupported. Efforts to translate the fruits of laboratory research into marketable technologies have also been inadequate.

Technology and other policies are particularly critical in the early stages of technological development when an advantage given to one of several competing approaches may “lock in” a technology for many years even if that technology is, in the longer run, an inferior option. To avoid this problem, long-term consequences of technologies must be assessed more thoroughly at an early stage.

**Rapid dissemination of clean technologies** from the industrial countries to the developing and formerly centrally planned countries where over 80 percent of humanity lives and where much of the globe’s economic and population growth will occur is vital for technological transformation. This diffusion of innovation may require new initiatives to overcome barriers in both technology exporting and importing countries to the flow of information,

capital, and trade. A particularly useful role—that of technology broker—could be played by private sector intermediaries: for example, matching partners, arranging financing, and negotiating and managing licensing agreements.

Private companies, the main producers and users of new technologies, are central to any hope for technological transformation. Environmentally affirmative **corporate leadership** is likely to be a stronger force for technological change than public policies. Some companies have realized that environmentally sound investments are often rewarded by cost reductions, improved quality, and product innovation, and they see environmental performance as key to future business success. But many others do not yet treat environmental stewardship as integral to good management practice.

A switch to corporate accounting systems that more accurately reflect both the costs of environmental protection and the cost of forgoing environmental protection could stimulate environmentally sound innovations. Better accounting would show that pollution prevention is often a more cost-effective approach than pollution control. The growing market for “green” products shows that environmental concerns can be profitably integrated into product life-cycle design.

In the long-term, **better educated managers and engineers** are key. Business students must learn to incorporate environmental issues in business planning and decision-making. Engineers must be trained to integrate environmental factors into the design process and not address them as an afterthought. Curricula that bring environmental concerns into the mainstream need to be developed for these future professionals.

For two decades, environmental policy has focused—with only modest success—on abating pollution and cleaning up local problems. Today, newly recognized global hazards pose a profound challenge to society. Rapid technological change stands as the key element in reconciling inevitable economic and population growth with a livable environment. Many resource-efficient technologies are available today and emerging technologies can dramatically transform the economy for environmental benefit. Because technological change is at bottom a social process, it can be accomplished only by redirecting economic, political, and cultural channels in ways that guide the stream of technological transformation.

# I. THE CHALLENGE OF TECHNOLOGICAL TRANSFORMATION

## I.1 Why Technological Change is Key

Despite two decades of intense concern and effort, global environmental deterioration continues on an unprecedented scale (Speth 1990). For the first time, the global systems that control climate and sustain the conditions for life are threatened.

From the beginning of history until 1900 A.D., the world economy grew to \$600 billion; now, it grows this much every two years. By the mid-21st century, the world population will probably double to ten billion and the global economy, now \$16 trillion, could be five times larger. If past practice remains our guide, such growth cannot occur without tremendous environmental destruction.

A thread of hope that this dilemma can be resolved connects technological progress and the environment (Speth 1989). Human impact on the natural environment depends fundamentally on an interaction among population, economic growth, and technology. A simple identity encapsulates the relationship:

$$\text{Pollution} = \frac{\text{Pollution}}{\text{GNP}} \times \frac{\text{GNP}}{\text{Population}} \times \text{Population}.$$

Here, pollution (environmental degradation generally) emerges as the product of population, income levels (the GNP per capita term), and the pollution intensity of production (the pollution/GNP term).

In principle, pollution can be controlled by lowering any (or all) of these three factors. In fact, however, heroic efforts will be required to stabilize global population at double today's level, and raising income and living standards is a near-universal quest. Indeed, economic growth is a basic goal for at least 80 percent of the world's population. These powerful forces give economic expansion enormous forward momentum.

In this field of forces, the pollution intensity of production looks to be the variable easiest to manipulate, which puts the burden of change largely on technology. In fact, broadly defined to include both changes within economic sectors and shifts among them, technological change is essential just to halt backsliding: even today's unacceptable levels of pollution will rise unless the percentage of annual growth in global economic output is matched by an annual *decline* in pollution intensity.

To an environmentalist, technology is a double-edged sword. Consider the automobile, for example. The automobile initially seemed a much less polluting means of transportation than the horse. Now, its severe pollution, energy, and land-use drawbacks are painfully obvious. At the same time, however, technological change offers potential remedies: catalytic converters, new engine types, alternative fuels, advanced materials to substitute for steel, and computer-controlled manufacturing, to mention only a few.

**“  
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Over the last two decades—environmentalism's modern history—technology and the environment have not always been friends. Environmentalists were usually either wary of new technology, viewing it as a potential hazard, or highly optimistic that technological solutions could be forced from reluctant industry by regulation. For their part, members of the technical community were apt either to criticize environmental regulation for constraining their creativity or to view it as only a marginal concern in product and process design.

Unfortunately, policy-makers have regarded these two positions as irreconcilable, too often pitting environmental against economic goals. With environmental problems deepening and technology advancing rapidly in ways that could reduce pollution and waste, a new synthesis needs to be formed so that environmental concerns and economic competitiveness are addressed in tandem. Once this false dichotomy that has bedeviled the development of both policy and industrial technology has been sun-dered, technological innovation can be the key to improved environmental quality.

“

**Technological change is essential just to halt backsliding: even today's unacceptable levels of pollution will rise unless the percentage of annual growth in global economic output is matched by an annual *decline* in pollution intensity.**

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## **I.2 What Is Technological Transformation?**

Technology is fundamentally different from science—the search for knowledge—and, indeed, does not always rely on scientific discovery. Many revolutionary innovations preceded an understanding of the underlying science, and others—for example, mass production techniques—required scant scientific knowledge. Neither is technology the same as invention, which is a new technical idea.

Technological change consists of both innovation—the introduction of a new product, process, or system—and diffusion—the application of innovations in new contexts. Technological change proceeds mostly by modest increments—small improvements made by firms, workers, or consumers to increase efficiency and performance. Radical innovation is a major change from the technological status quo—the advent of the electronic digital computer, for example. Yet, even a revolution of this magnitude rests both on breakthroughs and on the sum of many small improvements over time.

Technological change is a complex, iterative, unpredictable, creative endeavor. It links social and economic needs with technical solutions. Research and development are often, but not always, necessary. Studies show repeatedly that a new technology's ability to fulfill a market need predicts success better than technical sophistication (Freeman 1982). In other words, change is usually demand-driven more than supply-driven.

In the early stages of technology development, several models may compete. One may become dominant if early gains in market share are reinforced by economies of scale and “learning curve” effects (Arthur 1990). Early market advantages created by superior corporate strategy or public

policies can then lock society onto a particular technological trajectory—sometimes a technologically inferior trajectory. For example, the standard English-language typewriter keyboard (QWERTY), designed to suit the needs of early mechanical typewriters built a hundred years ago is now demonstrably inefficient but is so deeply imbedded in minds and machines as to be immutable (Hammond 1990). For this reason, the “right” design factors must be embedded in the early development of new technologies, and technological systems need to be evaluated for their environmental characteristics.

The needed fusion of economic and environmental objectives requires technologies that meet two criteria. First, they must be able to transform industry and transportation from materials-intensive, high-throughput processes to systems that use fuel and raw materials highly efficiently, rely on inputs with low environmental costs, generate little or no waste, recycle residuals, and release only benign effluents. The need, in short, is for technological systems that are environmentally “closed”—that is, detached as much as possible from natural systems.

Second, because the first criterion can't be fully met while human annual consumption of nature's land-based output approaches 40 percent and such non-renewable resources as fossil fuels are being rapidly depleted, new technology must help societies live strictly off nature's income rather than consuming nature's capital. An honest accounting of the costs of such “capital depletion” would show that few societies are doing anything of the sort today.

For any economic system—firm, industry, nation, or community of nations—environmental damage over time is in one sense a function of the consumption of inputs from environmentally unsustainable processes, the generation of pollution and post-consumption waste, and other factors. This damage won't stabilize and decline until pollution per unit of output and materials consumption per unit of output—factors that are at their core technological—decline rapidly enough to outweigh growth in economic output. “Technological transformation for environmental sustainability” is thus a process that reduces environmental damage per unit of output (or value added) fast enough to outpace production increases (Speth 1990).

Bringing about this transformation will be neither certain, quick, nor easy. Many adverse trends in global environmental quality are evident. Nevertheless, the current moment offers unique potential, in part because of new technological developments in such fields as biotechnology, information

systems, and advanced materials. These advances could create a new technical base for long-term environmentally sustainable development. Even now, emerging and on-the-shelf technologies offer tremendous gains. To name but a few, steelmaking processes halve energy use, photovoltaic and wind systems substitute for fossil fuels, bioengineered plants dramatically cut the need for pesticides, and computerized control of manufacturing systems reduce waste.

Other hopeful signs can be found in industry, government, and the universities. Many businesses' new environmental standards far exceed regulatory requirements while achieving sound economic results. Environmental investments attract capital quickly. Academic research is turning toward environmental issues, and government agencies are experimenting with new policies to encourage technological change.

## II. THE ENVIRONMENT AND TECHNOLOGY: A NEW CONTEXT

### II.1 New Environmental Imperatives

Throughout the 20th century but especially in the post World War II period, environmental pollution increased dramatically. Globally, pollution is still increasing, and global environmental problems pose new challenges. Four long-term trends, described below, characterize this situation (Speth 1988a).

#### *From Modest to Huge Quantities*

Environmental problems are as old as humanity, but the 20th century has produced enormous quantities of pollution because of economic and population growth. Within the century, population has increased more than threefold and the world economy has expanded twentyfold.

Figure 1 traces global emissions of two major pollutants: sulfur oxides and nitrogen oxides. Figure 2 shows atmospheric concentrations of contributors to global warming and ozone depletion. All show enormous increases: sulfur oxides by about 446 percent and nitrogen oxides by about 900 percent over the years 1900 to 1980, to cite only two examples (Dignon and Hameed 1989 in WRI 1990, p. 4). Other environmental problems have multiplied correspondingly. The quantity of municipal solid waste in the United States has doubled in three decades. Trends like these cannot persist. The earth's assimilative capacity is finite. Continued pollution, even at today's levels, is unsustainable. Continuing the increase in emissions of recent history would be ecologically disastrous.

#### *From Gross Insults to Microtoxicity*

Before World War II, smoke, sewage, and soot were the main environmental concerns. These basic threats to public health are still acute in developing countries and in Eastern Europe. Since 1950, however, synthetic organic compounds and radioactive materials have posed a different kind of problem. Many such substances are highly toxic in minute quantities and highly persistent in biological systems or the atmosphere.

Such substances, though imbedded in modern life, pose extraordinary risks. Of 70,000 chemicals in

commercial use, about half are classified by the U.S. Environmental Protection Agency (EPA) and the Organisation for Economic Cooperation and Development (OECD) as definitely or potentially harmful to human health (IIED and WRI 1987, p. 205). For perspective here, approximately 1,500 new chemicals are introduced into commerce in the United States each year (Conservation Foundation 1987, p. 136).

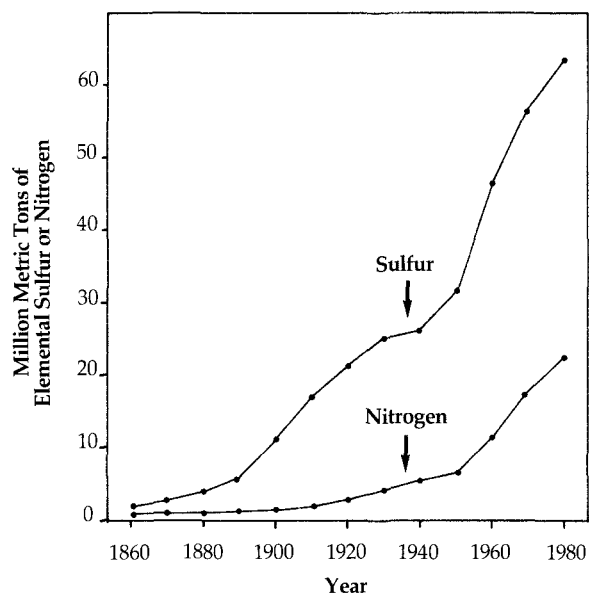
Improper design, use, and disposal of these substances has had large costs. In the United States, for example, 2,000 to 10,000 hazardous waste sites require clean-up, at a cost that could range from \$20 billion to \$100 billion (IIED and WRI 1987, p. 207). Every year perhaps a million cases of acute pesticide poisoning occur worldwide, plus some unknown larger number of lesser incidents (UNEP 1987, p. 96). High-level radioactive wastes, like the 21.4 billion curies of spent U.S. nuclear fuel, still have no permanent disposal sites (US CEQ 1990, p. 448). These experiences illustrate the challenges ahead in managing new technologies with environmental prudence.

“  
**The notion that pollution is mainly a problem in highly developed economies is a myth.**  
”

#### *From Developed to Developing World*

The notion that pollution is mainly a problem in highly developed economies is a myth. Many of the most dramatic and alarming examples of environmental degradation can be found in Eastern Europe and developing countries in Africa, Asia, and Latin America. Cities in these regions are usually more polluted with sulfur dioxide and particulates than most of the cities in OECD countries. Even more alarming, the situation seems to be getting worse. Available data for Asian countries suggest that sulfur dioxide pollution went up about 10 percent a year between 1973 and 1984. Pesticide use is also accelerating rapidly. Developing countries now consume 45

**Figure 1.** Global Emissions of Nitrogen and Sulfur Oxides from Fossil Fuel Combustion



Source: J. Dignon and S. Hameed, "Global Emissions of Nitrogen and Sulfur Oxides from 1860 to 1980," *The Journal of Air Pollution Control Assoc.*, (1989), Vol. 39, No. 2, p. 183

percent of all insecticides and 10 percent of fungicides and herbicides produced annually (UNEP 1987, p. 96).

Rapid economic development explains part of this proliferation of environmental hazards. Population growth is fastest in developing countries, and their economic output increased sixfold between 1965 and 1985. The consequences of pollution, however, may be disproportionately severe. Among large segments of those populations, exposure is high. In a ten-country sample of population blood-lead levels in industrial and developing countries, Mexico, India and Peru ranked as three of the top four. DDT in human milk was highest in China, India, and Mexico (UNEP and WHO 1987, pp. 18–22). And the worst industrial accident in history, the methyl isocyanate release of December, 1984, occurred in Bhopal, India (Ayres and Rohatgi 1987).

Many of the problems of environmental degradation in developing countries are well-understood and technically preventable. Again, the history is one of technologies and manufacturing systems applied with short-term goals foremost, to the detriment of long-term environmental realities. Widespread adoption of more appropriate technologies

will be necessary to correct this imbalance, but the necessary resources are not yet in sight.

### ***From Local to Long-Term Global Effects***

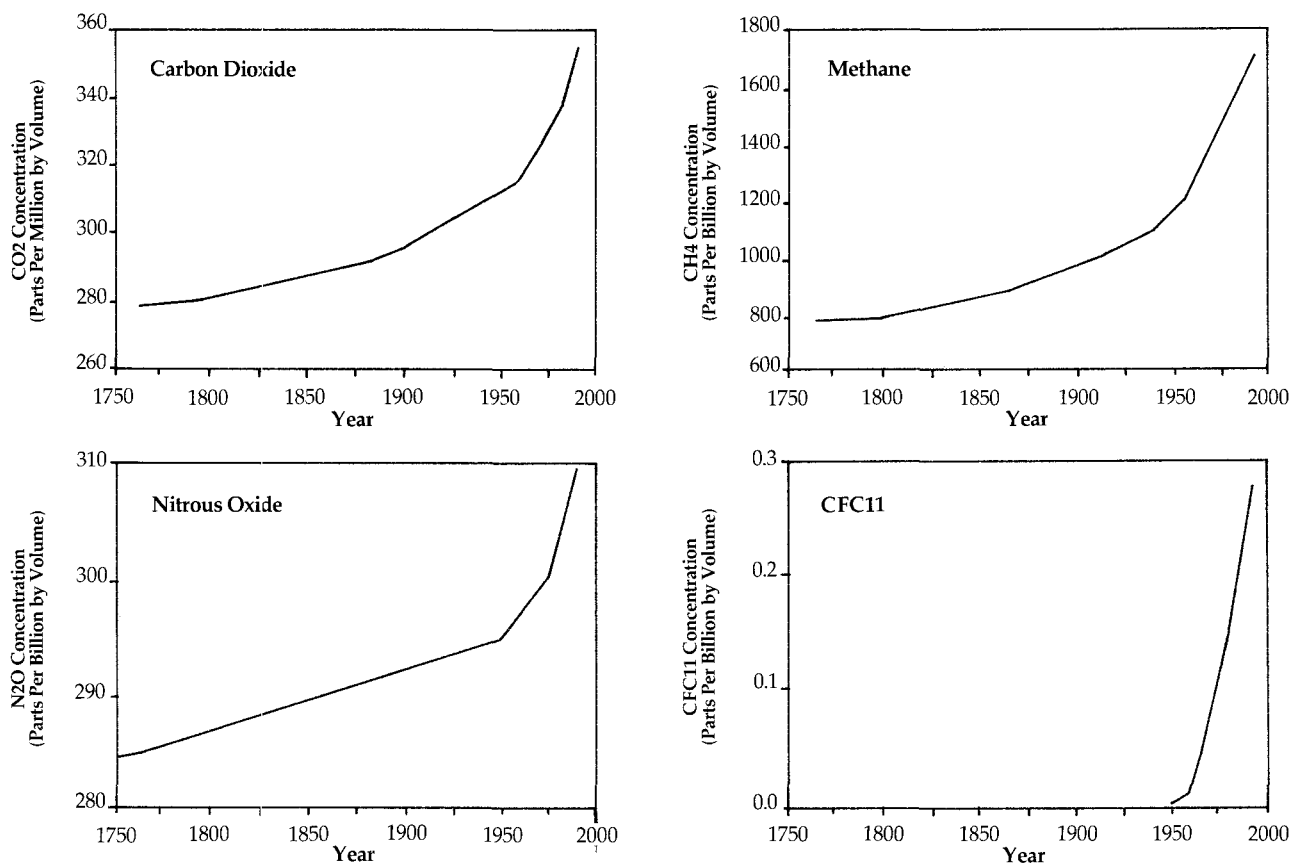
When the first generation of environmental laws was passed during the early 1970s, pollution was usually viewed as a local and acute problem. Today, this view is no longer tenable. Since the worldwide scale and intensity of pollution abated little, and scientific knowledge has grown, pollution has come to be recognized as a global and chronic phenomenon. This means not only that pollution can be found everywhere but also that its impacts are now large enough to alter the fundamental natural processes that support life.

Long-range transport of air pollutants is now recognized as the source of acid deposition that has emerged as a major problem in Europe and North America, as well as in parts of Asia and Latin America. While acidification of surface waters has long been a concern, pollution's threat to vegetation looms larger. Recently, air pollution has been implicated as a primary factor in forest decline. In Europe, *Waldenschaeden* ("forest damage") has struck over half of German trees (MacKenzie and El-Ashry 1989). Over a half million square miles of China are under assault by acid rain (Southerland 1990). In the United States, ozone damage to U.S. crops costs \$1 billion to \$5 billion yearly (MacKenzie and El-Ashry 1989).

The discovery of an ozone "hole" over Antarctica reinforced many scientists' fears and offered a major motivation for adopting the precedent-setting international accord in Montreal in 1987 to limit chlorofluorocarbon (CFC) use. Global warming from the accumulation of carbon dioxide, methane, CFCs, and other greenhouse gases presents another profound global challenge. Resulting changes in weather patterns and predicted sea level rise could wreak widespread environmental and social havoc, and cost all nations enormous sums. Although the industrial nations have been the greatest source of greenhouse gas emissions, developing nations are growing contributors to the problem, so global solutions are required.

To respond to these new dimensions of the age-old environmental challenge, the world economy's "industrial metabolism" must be tamed (Ayres 1989). Like an organism that eats its food, metabolizes it at some rate and excretes, an industrial system does environmental damage as it consumes inputs of natural resources and generates harmful residuals. Just as an organism dies if its rate of consumption exhausts its available resource base or if its wastes destroy its habitat, industrial

Figure 2. Global Greenhouse Gas Concentrations



Source: "Climate Change, the IPCC Scientific Assessment," World Meteorological Organisation and United Nations Environment Programme, Executive Summary, (1990), p. xvi

systems cannot indefinitely devour natural resources or exceed life-sustaining natural systems' regenerative capacity.

## II.2 Extraordinary Technological Potential

Today, the climate for innovation seems uniquely rich, poised between technological revolutions in progress and others just emerging. If environmental goals are integrated into these innovations, the transition to a sustainable future will happen faster, cost less, and have longer-lasting results.

The current moment offers an unmatched technical potential for environmental improvement, a fluid climate for technological advance, which badly needs to be exploited. The reservoir of available but unused technology is large. Developments on the horizon could yield major benefits if they are deployed and managed with an environmentally sustainable future in mind.

If this vital transformation has a watchword, it is prevention. Until now, most environmental technologies have been designed as 'end-of-pipe' controls. Stack gas scrubbers and automotive catalytic converters are prototypical of this approach. However, products, processes and systems can also be designed to prevent pollution. Pollution prevention, where feasible, is usually more effective and less expensive than are fix-it-later strategies.

### *More Efficient Technologies*

Enormous improvements in the quality of the global environment could be made with existing technologies, often at no, or small, additional cost. In agriculture, for example, alternative practices that exploit natural cycles and interrelations while decreasing reliance on such off-farm inputs as synthetic fertilizers can drastically reduce environmental damage. Increasingly, these practices are also being recognized as economically competitive with

conventional input-intensive farming systems (Benbrook 1990; Faeth et al. 1990).

The examples of currently available energy-saving technology are even more dramatic. For example, Dow Chemical's Louisiana Division's returns on investments in energy efficiency averaged 198 percent for 167 audited projects carried out over seven years (Ayres 1990). Much more fuel-efficient automobiles—doubling today's average gas mileage—are also at hand (Bleviss 1988). New low-emissivity windows can rival walls in their insulating capability (Bevington and Rosenfeld 1990).

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**Enormous improvements in the quality of the global environment could be made with existing technologies, often at no, or small, additional cost.**

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Enormous waste reduction is within reach. The Office of Technology Assessment (OTA) estimates that about half of all environmentally harmful industrial wastes in the United States could be cut with available technology; with some R&D, another 25 percent could probably be eliminated (Hirschhorn 1990). Even with current technology great gains are possible. Industry can make use of more recycled paper, metal, glass, waste oil, and plastics than it now does, and higher recycling rates would reduce the need to process virgin materials and the burden on waste-disposal facilities.

Why is this rich, near-term potential not being realized? Many explanatory factors—lack of information, lack of capital, management failures, and short-sighted or obsolete public policies that impede environmental improvements—are detailed later in this report. But technology is not the limiting factor: technical solutions available right now could make dramatic environmental improvements at small or negative cost.

### ***Revolutionary New Technologies***

Revolutionary technological developments on the horizon could yield enormous environmental benefit, if developed appropriately. Biotechnology,

still in its commercial infancy, could fuel a new and environmentally sounder “green revolution,” freeing farming from heavy dependence on agricultural chemicals. Although widely recognized for their pharmaceutical potential, biological tools are also likely to profoundly affect a wide variety of industrial activities. Enzymes used as industrial catalysts, microbial recovery of metals (biohydrometallurgy,) waste degradation, and biomass fuels and feedstocks are but a few examples. These applications could lower the energy- and pollution-intensity of production while decreasing dependence on fossil fuels. Like other new technologies, biotechnology may not represent an unequivocal environmental gain. Fears that poorly designed or poorly understood genetically engineered organisms might become pests—a self-replicating environmental hazard—once released into the environment are reinforced by limits to our understanding of ecology.

Materials technology, equally dynamic, shows even more immediate application. Products based on specially engineered materials probably now comprise more than a third of U.S. GNP—over \$1 trillion yearly (US OTA 1990). Because composite materials typically perform better than conventional materials per unit of weight, they require less raw material and produce less waste. Perhaps most important, materials design has become so highly sophisticated that engineers can now incorporate environmental criteria rather than deal with them as an afterthought. Here too, though, potential environmental drawbacks need consideration. Composites and other specially engineered materials are usually very difficult to recycle and may use more toxic substances.

The term “information technology”—encompassing developments as diverse as real-time monitoring of effluent streams, computer-controlled manufacturing, software development, and chemical and biological sensors—undoubtedly covers the broadest range of potentially important new technologies. All these technologies could have an enormous impact on pollution prevention and control. The application of computers to manufacturing systems not only greatly increases their efficiency and flexibility but also makes possible real-time monitoring of reaction conditions and effluent streams. When coupled with sensors that recognize changes in such conditions, automated processes can both prevent pollution and use input materials and energy more efficiently.

The challenge is not only to encourage these revolutionary developments for their potential but also to ensure that environmental factors are designed at the earliest possible stage.

## ***The Promise of Dematerialization***

Dematerialization describes a technological shift away from economies based on enormous and increasing consumption of raw materials (Herman et al. 1989). Some modern societies seem to be dematerializing, and dematerialization is certainly a consequence of many of today's most creative technological changes. Nevertheless, these trends are by no means universal, nor are they moving fast or consistently enough toward environmental improvement.

One measure of dematerialization is the consumption of energy, steel, cement, and other materials in relation to changes in GNP. For instance, U.S. steel consumption per unit of GNP has dropped 30 percent since 1974 (Williams et al. 1987); and while GNP has risen by about 50 percent in western industrial countries over the same period, energy consumption grew by only 14 percent (Colombo and Lanzavecchia 1990). Nationally, the data reveal significant divergences. Countries such as Sweden have reduced energy and materials consumption in comparison to growth rates enough to make environmental gains at little or no cost. Japan and Norway seem to have improved the environmental efficiencies of their economic structures, though fast growth has limited the net environmental benefit. Still other countries, notably in Eastern Europe, have experienced no or environmentally negative structural change (Jänicke et al. 1989).

Technological change and new information make dematerialization possible. The obvious trend in industrial countries is away from resource-intensive (high-volume) production toward knowledge-intensive (high-value) production. In the United States, for example, the pattern of investment has shifted dramatically: information-related technology now comprises around 40 percent of all new capital investment (US OTA 1988). Indeed, because information can often substitute for material inputs, information is the fundamental agent of dematerialization.

Miniaturization and hyperminiaturization (nanotechnology) also promise the performance of countless industrial functions with vastly less energy and material expenditures. Many developments that were recently inconceivable are already on-line: turbo-chargers for automobile engines, fiber optic cables one-fortieth the weight of copper cables, or a 25,000 rpm micropump implanted in a patient's heart (Colombo and Lanzavecchia 1990).

## ***Globalization***

*Globalization* means the removal of national barriers to information, investment, and trade. Despite debate about the extent of globalization and

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**Miniaturization and hyperminiaturization promise the performance of countless industrial functions with vastly less energy and material.**  
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its desirability, science and technology have unquestionably become highly internationalized. In the 1960s, for example, two-thirds of the non-communist world's R&D was done in the United States; now, the United States share is probably less than half. Foreign holders of U.S. patents have doubled, from about 20 percent in 1970 to more than 40 percent today (US NSF 1989). International trade has grown enormously, from about 7 percent of GNP in the United States in 1960 to around 15 percent today (US NAE 1988, p. 17). The penetration of industrial markets by developing countries was one of the major economic phenomena of the 1970s. The growing speed with which technology can diffuse internationally means that environmental problems of global scope can call forth technological responses of equal scope.

## **II.3 Competitiveness and Environmental Technology**

Technology holds the key to commercial competitiveness in the developed economies. High-technology exports have long been the most favorable aspect of American trade balances; global markets for high-technology products are growing faster than markets for other products; and high-technology companies export, on average, three times more of their production than other manufacturers do (US NSF 1989).

Whether environmental investment undermines competitiveness is more controversial. Some studies suggest that pollution control expenditures lower productivity growth (Jorgenson and Wilcoxon 1989; Barbera and McConnell 1990). Recent work argues that such investments contribute to productivity growth if productivity is measured appropriately to include reductions in environmental damage costs (Repetto 1990). In economic policy, what is measured often assumes paramount importance; what is unmeasured is ignored. Measurements of GNP and productivity, the foundation on which national and international economic policies are

built, are grossly inadequate from an environmental standpoint. GNP statistics ignore resource depletion, valuing activities like polluting aquifers or depleting topsoil as generating income rather than as depleting assets. Conventional productivity measures encompass only marketed outputs and inputs, ignoring the costs of harmful outputs like pollution.

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**In the electric power industry, the cost of emissions as unpriced outputs in the 1980s was about as large as the cost of labor to the industry.**

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Economists need to develop measures that put the benefits and the costs of environmental protection on an equal footing. Initial analysis conducted at WRI suggests that this is a difficult, but feasible, task (Repetto 1990). A study of the electric power industry, develops the concept of environmental productivity and demonstrates that the cost of emissions as unpriced outputs in the 1980s was about as large as the cost of labor to the industry. Technologies that reduced environmental damages over the decade thus contributed substantially to economic productivity, and conventional productivity measurements significantly understate the productivity improvements that occurred.

Approaching the question from the narrower point-of-view of stockholders, however, many investments in environmental technology make good business sense. Better process control, for example, often yields both substantial cost savings and environmental benefits. Some companies, of course, have long realized this: environmental programs in Dow Chemical, 3M, and DuPont are frequently cited as examples (Ehrenfeld 1990). Nevertheless, many analyses of manufacturing practice confirm

that widespread ignorance of the economic benefits of improved process control greatly inhibits waste reduction (Hirschhorn 1990).

A new motivation for investments in environmental technology appears to be arising in the development of “green consumer” markets. European companies have mounted particularly aggressive product development and marketing strategies, playing to a large consumer market receptive to environmentally preferable products (Cairncross 1990).

The strength of consumer environmental consciousness and the expected implementation of stronger regulations during the 1990s has made Europe a particularly promising market for U.S. environmental technology and services. Some environmental services firms reported 60 percent revenue growth in 1989 (Sternberg 1990). Automobile and industrial catalyst technology illustrates a similar trend. While the U.S. market grows slowly, new European legislation holds the promise of 30-percent yearly growth, to a \$500-million market in 1993 (Chynoweth et al. 1990).

Growth in hazardous waste management and treatment markets has been widely noted, and recent projections indicate a \$30-billion yearly total by the mid-1990s (Heller 1990a; Heller 1990b). The obvious opportunity has prompted many new corporate ventures, such as DuPont’s recently announced new environmental services business unit, projected to grow to \$1 billion yearly within 10 years. The size of investments in pollution prevention and control is unprecedented: Bayer, from West Germany, reports a level equal to 20 percent of its manufacturing costs, and Chevron predicts increases of 10 percent a year, which will make anti-pollution activities its principal area of corporate growth (Cairncross 1990).

Some companies recognize environmental investments as a profitable opportunity, but this perception is not yet nearly widespread enough. The Conference Board of Canada has put the problem well, characterizing “the task of building an environment industry [as] the great enterprise in the 1990s and beyond.” (Conference Board of Canada 1990).

### III. SCENARIOS OF TRANSFORMATION: SECTOR STUDIES

In the coming decade a thorough transformation of technology can begin. This technological transformation—fueled by key developments in energy, agriculture, and industrial production—can move society away from the material-intensive, high-throughput economy of the past toward a growing economy of great material and energy efficiency. Emerging and existing technologies enable us to envision an economy that moves toward the goal of living off nature's income instead of its capital.

#### III.1 Energy

Energy moves the entire economy but poses some of the gravest environmental issues. Exciting technologies—available now or in the next decade or two—may revolutionize the way we produce electricity and fuels, transport ourselves and our goods, and control the indoor environment. Even with today's technology, the United States could meet 30 percent of its energy demand with renewable resources at competitive prices (US DOE 1990), but instead meets only 9 percent from these sources. Existing and emerging technologies offer great environmental potential and highly profitable possibilities to firms with vision and foresight.

##### *Electric Power Production and Energy Storage*

The seeds of post-fossil fuel power generation are germinating in the laboratories of scientists and engineers and in the plans of entrepreneurs. A variety of renewable energy technologies and technologies applicable to both renewable and fossil fuels are just becoming competitive. Others are here today.

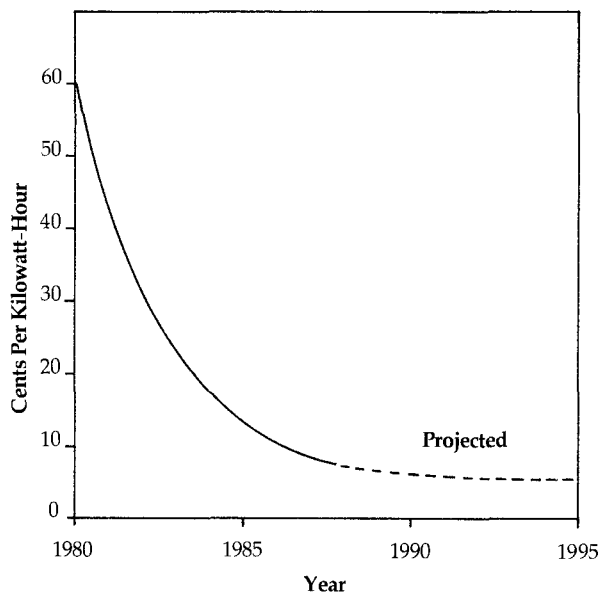
Several technologies, including cogeneration of electricity and heat by combined-cycle gas turbines and fuel cells, are applicable to the exploitation of both fossil and renewable fuels. A combined-cycle power plant, which links a gas turbine with a steam generator and turbine, can raise thermodynamic efficiencies in electricity generation from about 35 percent in new central steam plants to nearly 50 percent (Burnett and Ban 1989). These efficiencies can be increased up to 80 percent when waste heat is recovered for industrial, space,

and water heating. Furthermore, these turbines can be installed quickly and at lower cost than central steam power stations, making the technology attractive for utility planning in both developed and developing countries.

Astounding progress has been made in the past two decades in commercializing renewable energy technologies. Since 1973 the price of photovoltaic (PV) electricity production has decreased from \$15 per kilowatt-hour (kWh) to \$0.30. New manufacturing plants taking advantage of economies of scale are expected to bring this cost down to \$0.15 per kWh by the mid-1990s (Hubbard 1989). The newest solar thermal power stations operated by Luz International in California generate electricity at \$0.08 per kWh down from \$0.24 in 1984. They anticipate being able to generate power at \$0.05 per kWh by 1994 (WRI 1990, p. 158). Wind power has grown from near zero in the early 1970s to 1660 megawatts (MW) of electric power capacity worldwide (85 percent in California and much of the remainder in Denmark). Over this period, generation costs at favorable wind sites have decreased to between \$0.05 and \$0.09 per kWh (AWEA 1990). Figures 3 and 4 illustrate the cost trends for solar thermal and wind-derived electricity. As shown in Figure 5, costs for a number of renewable electricity generation systems compare well with the \$0.05 to \$0.09 per kWh costs for new coal- and oil-fired central power plants and the \$0.10 per kWh cost of nuclear fission, especially since sunlight and wind neither release pollutants nor accumulate fissile products, and they can't be embargoed.

Continued cost reductions in renewable energy will require not only more research but also increased production so that economies of scale and manufacturing efficiencies can be achieved. Wind power's improved performance has largely come about from experience gained in siting, maintenance, manufacturing, and organization though the development of lighter composite turbine blades and microprocessor controls has also contributed (Weinberg and Williams 1990). If conversion efficiencies achieved in the laboratory for photovoltaic cells through the use of layered cells that absorb different wavelengths of light, new materials, and better assembly techniques can be matched in

**Figure 3. Cost Trends: Solar Thermal Electricity**



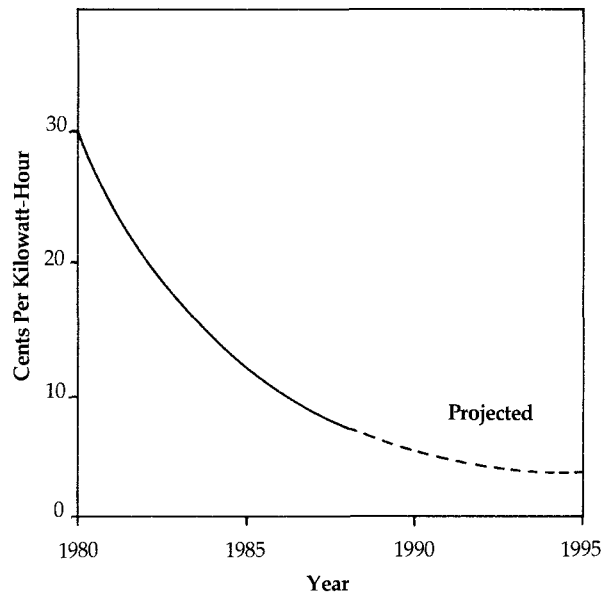
Source: United States Department of Energy, (1990)

mass production, we may also see large-scale use by utilities of the technology in the latter part of the 1990s (Carlson 1989; Hubbard 1989). In the United States, provisions of the Public Utilities Regulatory Policies Act of 1978 that denied power producers certain regulatory benefits once their facilities exceed 80 megawatts have been a major impediment to expansion of Luz International's solar thermal system, inhibiting achievement of economies of scale (Sklar 1990). Such economies that come with actual production and deployment of the technology are at least as important as laboratory research and development in making new technologies competitive.

### ***Fuels and Energy Storage***

Storing solar and wind power is an interesting challenge. Advanced batteries, compressed air, and stored hydroelectric potential (that is, pumping water uphill into a reservoir) may all come into play, but an especially appealing option is production of hydrogen, a fuel that releases only water vapor and minute amounts of nitrogen oxides when burned. Hydrogen derived from the electrolysis of water offers a clean and efficient means of storing solar energy for later use as a fuel for vehicles, industrial processes, residential use, or electricity production. Technology trends suggest that,

**Figure 4. Cost Trends: Wind-Derived Electricity (at Sites with Greater than Thirteen Mile Per Hour Wind)**



Source: United States Department of Energy, (1990)

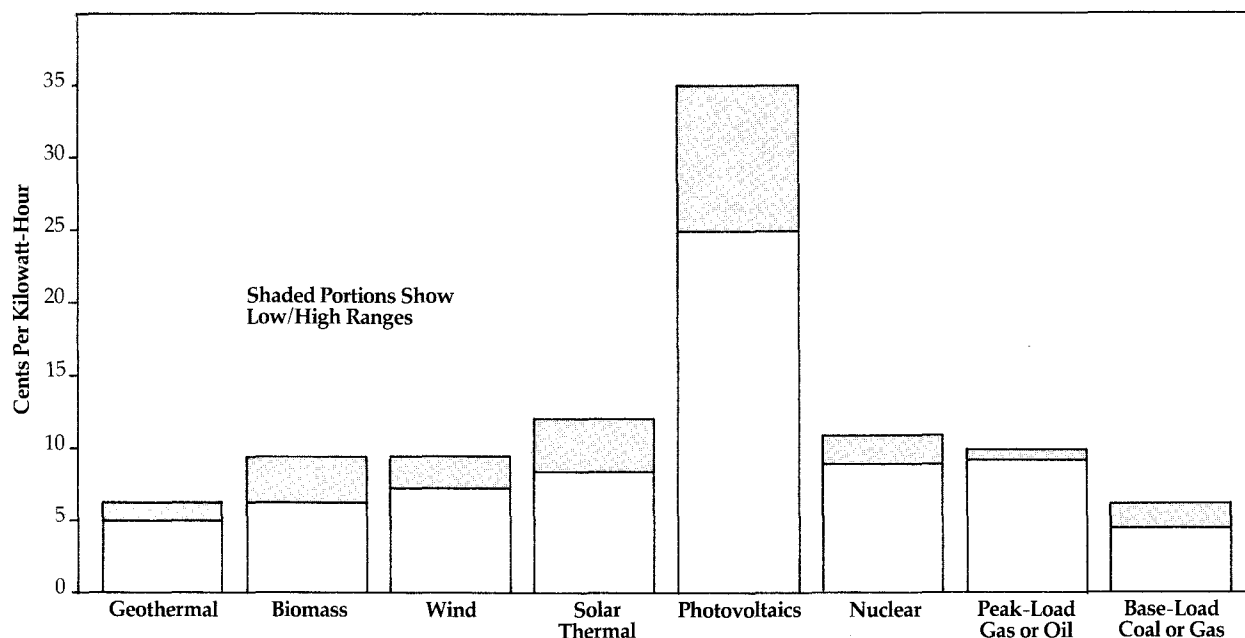
with appropriate public policies, solar and hydrogen technologies could soon begin fueling a transition to a post-hydrocarbon economy (Ogden and Williams 1989).

As for biomass, another storehouse of solar energy, technological advances promise improved production of fuels from this source. Genetic engineering techniques and a growing understanding of enzyme structures may greatly improve the efficiency of conversion. Of particular promise is the industrial-scale use of enzymes to degrade cellulose fibers and woody tissues. This process allows wastes from agriculture, forestry, and food processing, as well as urban wastes and biomass energy crops, to be converted into convenient (and renewable) liquid and gaseous fuels and into feedstocks for the chemical industry.

### ***Transportation***

Traffic jams under smoggy skies and the repeated crises in the Middle East reflect our dependence on uncertain oil supplies and the large environmental costs associated with the automobile. Transportation, which accounts for 27 percent of U.S. energy demand and 63 percent of U.S. oil use, need not entail such a high cost to the environment,

Figure 5. Electricity Costs for New Generating Capacity



Source: United States Department of Energy, (1990)

health, and economic security (US DOE 1989; MacKenzie 1989). Prototype cars from Volvo, Toyota, Renault, General Motors, and other firms achieve fuel economies of 66 to nearly 100 miles per gallon (mpg) of gasoline or diesel fuel. Yet, the U.S. passenger car fleet averages 19 mpg and new cars average 28 mpg (Bleviss 1988; US DOE 1989). Some of these prototypes are roomy, safe, and speedy as well as economical in fuel use. Multi-valve engines, electronic fuel injection, lightweight materials, improved tires, and aerodynamic styling are already common on the road. Current prototypes are proving the viability of continuously variable transmissions, energy-storage flywheels, improved electronic controls, advanced materials, and a new generation of the two-stroke engine. These new motor vehicle technologies greatly improve the energy economy of gasoline and diesel engines and can be transferred to the next generation of renewably fueled vehicles.

New nonfossil vehicle fuels are inevitable. The Daimler-Benz prototype hydrogen car and hydrogen buses built by Billings Energy Corporation for Provo, Utah, offer a glimpse into transportation's future. They are clean, emitting only water vapor and traces of nitrogen oxides when they run. Prototype electric cars are also tantalizing; they can

run for 120 miles at 55 miles per hour on a single charge and can be recharged at night when electricity demands are low. General Motors has plans to manufacture an electric passenger car soon (Judge 1990). Both hydrogen and electric vehicles need better means of storing energy. Batteries take hours to recharge, and stored hydrogen is either bulky (cylinders or metal hydrides) or energy-intensive (liquid hydrogen). As with progress in solar and wind power, advances will come from innovations on the factory floor as well as from discoveries at the laboratory bench.

### ***The Indoor Environment***

Nearly two-fifths of U.S. energy use occurs at home or in the commercial sector and about two-thirds of electricity demand is from buildings (US DOE 1989; Kelly 1990). Heating, cooling, ventilation, lighting, cooking, and the various electrical equipment found in the modern home and office provide many opportunities for energy efficiency gains. Much of the technology exists today. Already, superinsulated homes in frigid Scandinavia and Minnesota use only a tenth to a third of the energy required by a typical American home (Gibbons et al. 1989). One home builder in chilly

Chicago, the Bigelow Group, guarantees that its town houses and single-family homes will not cost more than \$100 and \$200, respectively, to heat annually (Bevington and Rosenfeld 1990). New buildings can be built cost-effectively to use 40 to 50 percent less energy than is typical for new American buildings (Kelly 1990).

Similar energy savings (50 percent to several-fold) are achieved by the best commercial and prototype refrigerators, furnaces, air conditioners, and lighting fixtures. The compact fluorescent light bulb—a new, efficient, cost-effective yet still underutilized technology—uses 25 percent of the power required by an equivalent incandescent light bulb and generally pays for itself in a year or two. Over its lifetime, a single 18-watt compact fluorescent bulb replacing 75-watt incandescent lighting can prevent a ton of carbon dioxide emissions from a coal-fired generating station (Lovins 1989).

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Technologies emerging in the marketplace, such as advanced high-efficiency windows, will further improve building energy efficiency. Each year, windows cost the United States as much energy as it gains from a year’s Alaskan North Slope oil production (Bevington and Rosenfeld 1990). Heat-reflecting transparent coatings and layers of insulating vacuum or special gases enable these new windows to rival well-insulated walls in their heat-blocking ability (Bevington and Rosenfeld 1990; Granqvist 1989). These coatings also keep rooms from overheating on sunny days, saving on air-conditioning expense. The next generation of windows will incorporate “active” or “smart” electrochromic coatings that will

automatically control light reflectance in response to the intensity of outside sunlight.

Smart windows may be one component of the evolving technology of “smart buildings.” Like a body maintaining homeostasis, smart buildings automatically adjust heating, cooling, ventilation, and even lighting to maintain a comfortable interior environment. Far more sophisticated and efficient than standard thermostatic controls, these systems respond to changing temperature by optimally controlling ventilation by computer. For example, excess heat from office equipment can be redistributed to cooler parts of the building where it is needed, thus maintaining comfort and saving energy. Smart building systems can also incorporate “occupancy sensors” that turn off lights in empty rooms.

Many other technologies can improve energy efficiency in the residential and commercial sectors, ranging from simple low-flow shower heads, to ground-source heat pumps, to large commercial water chillers that run at night and save the cooling power for the peak hours of the day. Numerous opportunities such as these remain to be grasped.

### **III.2 Agriculture**

The challenges for agriculture in the coming decades will be to increase production to feed a population doubling to 10 billion by the mid-21st century while protecting the resource base—soil, water, and genetic diversity—upon which that production depends. To meet these challenges, agriculture must combine “cutting edge” high technology with the tried-and-true methods of the past. Both spliced genes and recycled manure have a place in tomorrow’s highly productive and environmentally friendly farming systems. Both biotechnology and “alternative” agriculture have the potential to transform agriculture in the new century.

#### ***Biotechnology***

In the last 20 years, scientists have made extraordinary progress in deciphering the molecular mechanisms of life, developing a powerful set of technologies in the process that can manipulate living organisms with unprecedented scope and precision. Biotechnology is only in its infancy, but its potential applications in agriculture, medicine, and industry are revolutionary.

Biotechnology permits much more rapid and precise transfer of genetic traits into agriculturally useful organisms than do conventional breeding

methods. Also, in contrast to traditional breeders, biotechnologists can transfer genes from virtually any living species and can even custom modify genes in the laboratory. Numerous livestock and crop species, including two major grain crops, corn and rice, have already had “foreign” genes inserted into their chromosomes (Moffat 1990; Schneiderman and Carpenter 1990).

Biotechnology’s environmental implications are vast. Proponents predict that biotechnology will liberate farmers from pesticides and synthetic fertilizers while increasing the quality and quantity of their production. Critics fear that genetic engineers will inadvertently create pests and pathogens from otherwise benign organisms and unleash ecological havoc by releasing them into the environment. Critics further contend that corporations will exploit biotechnology to reinforce their sales of pesticides and other agrichemicals and will further narrow agriculture’s genetic base. Clearly, however, biotechnology will grow in importance; and, if used wisely, can make agriculture more sustainable.

For example, the bacterium *Bacillus thuringiensis* (B.t.) produces a protein that is toxic to some insect orders but has no ill effect on other animals. B.t. toxin has been used as a safe biological pesticide for many years but suffers from a short field life. Undergoing field trials are crop plants that have been “engineered” to make the B.t. toxin in their tissues. Implanted in corn, B.t. toxin could, without any insecticides, control the European corn borer, which now causes \$500 million of damage annually in the United States (Twombly 1990). Also, because B.t. toxin would affect only insects that ate from the protected plant, beneficial nontarget insect species would not be harmed. Biotechnology has also made inroads against plant fungal and viral diseases and may provide protection while lessening the need for fungicides (many of them suspected carcinogens) or for insecticides to control insects that spread certain crop viruses (Schneiderman and Carpenter 1990).

Greatly improved understanding of the mechanisms of plant physiology and the interactions among plants, microbes, and the soil are opening up other frontiers. Scientists now understand better how plants respond to such stresses as heat, drought, freezing, poor soil, and disease. Armed with this understanding and the tool-box of biotechnology, they can make crop and forestry species more resistant to these stresses than conventional plant breeders can.

Further in the future, biotechnologists may be able to manipulate very complex genetic characteristics,

such as nitrogen fixation and photosynthesis. Synthetic fertilizers, which are polluting and energy-intensive agricultural inputs, might become unnecessary if nitrogen fixation can be transferred from leguminous crops (for instance, soybeans, peas, beans, and alfalfa) to grains like wheat and corn. The genetic engineering of nitrogen fixation would involve the coordinated manipulation of numerous genes from both the crop plant and certain bacteria (*Rhizobia*) that are essential to the process.

Genetic modifications to improve the photosynthetic efficiency of crops would allow more solar energy to be captured in the form of biomass. This would increase the production of food per area of land and increase the availability of biomass as an energy resource and chemical feedstock—helping to create renewable bases for energy production and industry.

Biotechnology is not without environmental risks. Efforts by numerous firms and public laboratories to make crop plants resistant to synthetic herbicides have been criticized because this could lead to increased use of herbicides that damage water resources and ecological cycles. The fear that releasing genetically modified organisms might result in unintended disaster is fed by the realization that little is known of the interactions between farms and natural ecosystems. Advances in the ecological sciences are needed to keep up with progress in biotechnology.

### **Alternative Agriculture**

“Alternative” agriculture is another way of releasing food and fiber production from its heavy reliance on synthetic pesticides, fertilizers, and feed additives. Alternative techniques are demonstrating that high yields can be maintained without damage to soil, water, and ecological processes.

Unlike biotechnology’s laboratory-derived reductionist approach, alternative agriculture is based on the understanding of natural nutrient cycles and ecological relationships. Alternative agriculture views the farm as a holistic system in which production processes interact synergistically. For example, this season’s corn benefits from the soil nitrogen left by last season’s soybeans while breaking up the pest and disease complexes that would otherwise plague next season’s soybeans. Today’s alfalfa improves the soil while providing feed for livestock, which in turn enriches the soil with its manure. The variety of production provides an ecological and economic resilience that insures farmers against supply and market collapses, major risks for intensive monocultures.

Alternative agriculture reduces the need for off-farm inputs, such as chemical fertilizers, pesticides, and feed additives that pose health and environmental risks. The methods decrease soil erosion and can improve soil quality. The best alternative practices can reduce production costs and sometimes improve yields over conventional techniques. Many farmers who have embraced these methods have profitable and productive operations that are less financially dependent on government subsidy programs (US NRC 1989).

Is alternative agriculture an approach of the past or of the future? The answer is both. While embracing some age-old practices like crop rotations, the methods of alternative agriculture are neither passive nor unsophisticated—nor are they incompatible with biotechnological advances. Alternative agriculture is knowledge- and information-intensive. For example, integrated pest management (IPM)—one important part of alternative agriculture—employs a wide ensemble of pest-control methods, including: growing pest-resistant cultivars; introducing or augmenting populations of natural enemies; using pest diseases, insect hormones, and pheromones (sex attractants); practicing crop rotations; and using various tillage techniques, in addition to judicious application of conventional pesticides. IPM requires frequent monitoring or “scouting” of pest levels, a good understanding of pest species behavior under various conditions, and well-timed performance of farm operations (planting, tilling, harvesting, and specific pest control measures). Alternative agricultural approaches to disease control, soil management, and livestock operations likewise emphasize precisely measured resource management. In contrast, in conventional farming, chemical inputs are typically applied at levels beyond what is economically profitable or ecologically desirable (Benbrook 1990).

#### ***Other Agricultural Technologies***

Sustainable agriculture can include other technologies for metering out inputs highly efficiently. For example, drip irrigation is far more water efficient than conventional irrigation methods. If linked to soil moisture sensors, a drip-irrigation system can provide water exactly where and when needed. Fertilizers, if not obviated by alternative or biotechnological techniques, could also be applied efficiently through a drip irrigation apparatus. Technologies for timely and precise information on soil fertility, pest levels, and disease occurrences could allow farmers to apply inputs optimally with low environmental costs. Imagine

the environmental benefits that could result if farmers could program their farm machinery to apply fertilizer or pest control agents only where and when required instead of dousing fields regularly on generalized advice from chemical vendors or extension agents.

#### ***A Synergistic Package***

If agriculture is to meet ever-growing demands at diminished environmental costs, it will need technological innovation from many sources. Biotechnology and alternative agriculture are not separate and incompatible options. But many who advocate one are relatively ill-informed and skeptical of the other, sometimes even antagonistic. Clearly, future agricultural technologies must include a rich diversity of approaches. Farmers of the next decade may grow genetically engineered disease-resistant soybeans on one conservation-tilled field while monitoring real-time soil moisture data from a nearby insect-resistant cornfield and analyzing feed requirements for their cattle by computer.

### **III.3 Industrial Production**

The ideal industrial system would transform energy and materials into goods at very high efficiencies—efficiencies approaching the limits imposed by the laws of thermodynamics. As much material and energy as possible would be recovered from process wastes and from post-consumer refuse. Such a system would also avoid such hazardous substances as chlorinated hydrocarbons and toxic heavy metals. Although this is an ideal, proven technical and managerial approaches can already deliver big gains in the efficiency of industrial production.

#### ***Pollution Prevention***

As a manufacturing goal, “zero discharge” can be thought of as an environmental analog to the quality goal of “zero defects”—a goal that implies continuous improvement. Already, some firms have embarked on ambitious pollution prevention programs to approach these targets for at least some categories of pollutants.

One chemical manufacturer, Monsanto, established in 1988 a goal to reduce toxic air emissions by 90 percent by 1993 and has stated that its goal for itself, its contractors, suppliers, and shippers should be “zero spills. Zero releases. Zero incidents. And zero excuses.” (Hirschhorn 1990). General Dynamics reduced hazardous waste

production by 72 percent in 1984-88 and has a 1991 goal of zero hazardous waste generation. 3M cut waste by 50 percent over the past 15 years and plans to cut out another 50 percent by the year 2000 (Hirschhorn 1990). Since 1960, Dow Chemical has reduced its production of hazardous wastes from 1 kg per kg of saleable product to 1 kg per 1,000 kg of saleable product (Ehrenfeld 1990). Over 80 years, the Bayer AG Leverkusen sulfuric acid plant reduced sulfur dioxide emissions by 98 percent per ton of sulfuric acid produced (Hirschhorn 1990). Chevron and Polaroid are among the other firms that have adopted ambitious pollution prevention programs.

Preventing pollution often raises a firm's profits, not costs. Hirschhorn (1990) and Huisingh (1989) report many industrial pollution prevention projects with pay-back periods ranging from a month to three years. Table 1 provides some examples. These returns, in the form of diminished disposal fees and saved energy and materials, do not even include the benefits of decreased exposure to liability from hazardous waste disposal or improved reputation among increasingly "green" consumers.

The range of pollution prevention options are myriad and the feasibility of applying them depends on the particulars of each industry and each facility. Sometimes it is as simple as placing a lid

on a vat of solvent. In other cases, significant changes in product or process—for instance, eliminating the use of heavy metals or replacing organic solvents with aqueous or mechanical processes—are required.

In any event, the limiting reagent of pollution prevention is generally not as much the "hardware" of technology as the "software" of corporate management. Experts in pollution prevention are more likely to identify corporate leaders' attitudes, organizational structures, and perceived internal incentives as the primary determinants of pollution prevention success than any set of machines, devices, or technical capabilities (Ehrenfeld 1990; Hirschhorn 1990).

### ***Computer Monitoring and Control***

As computer-aided design, computer-aided manufacturing, robotics, and other manifestations of the microelectronic revolution continue to enter the factory, we can expect simultaneous improvements in industrial productivity, product quality, and environmental performance. Sophisticated computers can make the production process highly efficient. When linked with advanced sensors that monitor in real-time the conditions inside a reactor vessel, a column, or a waste stream, and with actuators (pumps, motors, valves, power supplies, and

**Table 1.** Examples of Successful Pollution Prevention

<b>Industry</b>	<b>Method</b>	<b>% Reduction of wastes</b>	<b>Payback</b>
Pharmaceutical production	Water-based solvent replaced organic solvent	100%	< 1 year
Equipment manufacture	Ultrafiltration	100% of solvent and oil, 98% of paint	2 years
Farm equipment manufacture	Proprietary process	80% of sludge	2.5 yrs.
Automotive manufacture	Pneumatic cleaning process replaced caustic process	100% of sludge	2 years
Microelectronics	Vibratory cleaning replaced caustic process	100% of sludge	3 years
Organic chemical production	Adsorption, scrap condenser, conservation vent, floating roof	95% of cumene	1 month
Photographic film processing	Electrolytic recovery ion exchange	85% of developer, 95% of fixer, Ag and solvent	< 1 year

*Source:* Huisingh, 1988.

other equipment), they can precisely control the flow of material or energy inputs.

For example, distillation columns governed by “feed-forward” software that incorporates mass- and heat-transfer equations can save up to 15 percent of the steam required in a manual facility while increasing rates of production. A plant of this kind can also be built at lower cost per unit of production capacity than a plant with less sophisticated controls. One paper mill that employs automation to control chemical and energy inputs optimally has reduced its energy requirements by almost a fifth while improving product uniformity by almost a third (Ross and Steinmeyer 1990). In these and other cases, computer-directed optimization saves energy and materials by applying only the required amount of an input and only when needed. The quality and uniformity of the product is also improved, so discards and rejects are fewer.

Continuing computerization of industrial production and increased employment of robots will improve productivity and, in the process, decrease waste and pollution. Computer hardware and software are becoming ever more sophisticated and accessible. Monitoring and sensing technologies are also growing in capability. For example, in the pharmaceutical industry certain fermentation and organic synthesis reactions can be analyzed precisely in seconds or minutes using computerized Fourier transform infrared spectrographic (FT-IR) methods in lieu of labor-intensive, hour-long chromatographic analysis (Schneider 1990). Computerized gas chromatography-mass spectrometry (GC-MS) equipment allows the chemical industry and other industries to monitor their processes and effluents precisely and rapidly. In each case productivity and product-quality improvements can go hand-in-hand with environmental performance improvements.

### ***Incremental and Radical Process Changes***

Many environmental efficiency improvements in industry are the result of continual incremental advances. For example, computer controls, like those just discussed, and a series of mechanical innovations have led to a greater than 30-percent improvement in energy efficiency for electric-arc steelmaking furnaces (Ross and Steinmeyer 1990). Annual energy efficiency gains in ethylene production have averaged 3 percent over the last three decades resulting in a net 60 percent decline in energy requirements for production (Ross and Steinmeyer 1990). While these incremental innovations can offer significant gains over time, occasionally more radical process changes can offer

very large environmental and commercial advantages.

Again using steel as an example, “direct steel-making,” being pursued by at least seven nations, could turn steelmaking from a three-step operation to a one-step process. The elimination of coking ovens (which can cost \$250 million each) would streamline production costs while eliminating an important source of hazardous air emissions (*Scientific American* 1990).

The copper mining industry, which has used the same basic methods of ore smelting for six millennia, is also ripe for technological change. During the 1980s, unknown to most people, the action of the bacterium *Thiobacillus ferrodoxins* has grown to account for 30 percent of U.S. copper production and is credited with saving the U.S. domestic copper industry (Debus 1990). “Biohydrometallurgy” applicable to gold and other minerals, too, could eliminate some of the air pollutants—such as sulfur dioxide and heavy metals—associated with conventional smelting. Despite the promise of biological mining techniques, including possible *in situ* mineral recovery, the industry has invested very little in R&D (2 percent of sales in the United States) and almost nothing in biological techniques. Mining engineers are rarely trained in biological sciences, and biotechnological efforts in this area have been minute. Research in this field could pay big dividends.

Progress in chemical catalysis may greatly improve the efficiency and environmental performance of industrial chemistry. New biological and inorganic catalysts might improve product yields, cut down on by-products, enable less energy-intensive reaction conditions (lowered temperatures and pressures,) encourage use of alternative feedstocks, and lead to large-scale production of previously non-industrial compounds. Genetic engineering and scientists’ growing understanding of the biophysical mechanisms of enzyme activity are leading to “protein engineering”—the custom design of protein molecules (Hahn et al. 1990)—which, in turn, could lead to the development of new classes of industrial catalysts. Such progress, in the laboratory and in industrial application, may go a long way toward decreasing the energy intensity, waste production, and fossil fuel reliance of the chemical industry.

### ***New Processes for New Products***

New processes also lead to new products. Chemical vapor deposition (CVD), a technique to layer thin coatings of materials on surfaces, is an emerging manufacturing technology with potentially

large environmental and commercial benefits. CVD is used to make thin-layer photovoltaic cells and to apply special coatings to windows—two environmentally significant technologies discussed above. The technique has also recently been used to place thin diamond coatings onto surfaces, which can greatly increase the durability of industrial cutting and grinding tools, can increase the heat tolerance and speed of integrated circuits, and may beget a new class of semiconductor devices (Amato 1990). CVD, if applied at the industrial scale, might greatly decrease the cost of solar power, improve the energy efficiency of homes and offices, and increase the speed of computation.

No doubt, many other new and emerging technologies for manipulating matter with great precision—for example, scanning tunneling electron microscopy or x-ray lithography—will reinforce the “dematerialization” trend and may enable the economy to do much more with much less.

### **Recycling**

Another environmental challenge for industrial society is waste management. Sustainable natural systems reuse essentially all materials, but human economies release materials into the environment at profligate rates—rates that far outstrip nature’s assimilative powers. In most industrial nations, low rates of recycling increase the environmental impacts of both the disposal and production of goods. Furthermore, processing virgin materials is generally far more energy-intensive and polluting than recycling. The most energy-intensive step in processing is typically the conversion of raw materials (for example, ores, logs, crude oil) into basic commodities (aluminum, paper, gasoline, for instance). In the United States, recovery rates for discarded glass, steel, and paper are estimated to be 15 percent, 21 percent, and 30 percent, respectively (US OTA 1989). Aluminum is recycled at relatively higher

rates (about 45 percent) but only 2 percent of plastics are recycled despite similar energy savings for recycling each of these materials.

Currently, most products are designed with little consideration of their ultimate disposability or recyclability. Changes in product design to permit easy sorting and disassembly would improve recycling’s economic and technical feasibility. For example, BMW will label and design plastic automobile components for ease of disassembly and recycling, but other automobile manufacturers have not yet considered recyclability in their design of polymeric components. BMW’s approach would increase recovery of plastics and steel from automobile hulks. But, mixing materials inextricably, as in current automotive designs, may put auto shredders out of business and exacerbate the waste of materials (Clark and Field 1990). To encourage better product design, the European Community and several member states are considering moving toward legislation that will increase manufacturers’ responsibility for environmentally safe disposal of their products.

The technology for recycling is already available. For steel, electric-arc furnace operations, which can use 100-percent scrap inputs in contrast to the 30-percent maximum for basic oxygen furnaces, have improved the demand for scrap steel. For the recovery of many metals (for instance, aluminum, lead, steel, platinum-group), glass, many grades of paper, and some plastics, the technology of recycling is not the limiting factor. Collection and sorting, manual operations, except for magnetic separation of iron and steel, pose the main technological problems.

As this review shows, achieving the environmental and economic benefits of high recycling rates will take the combined efforts of policymakers and engineers. They must design and deploy both technologies and social incentives to induce producers and consumers alike to participate.

## IV. IMPEDIMENTS TO TRANSFORMATION

The foregoing discussion of technological possibilities in energy, agriculture, and industrial production presents an unequivocal picture of extraordinary untapped potential. Many factors account for this: public policies; management practices; economic, legal, and institutional structures; inadequate information; insufficient R&D; and others. All must be changed if we are to move toward environmentally sustainable economic growth.

In each sector, many environmentally preferable technologies already “out there” are not widely used—even though “rational” economic analyses might suggest that they should be. For example, a number of industrial firms have established energy-efficiency and pollution-prevention projects that quickly yielded annual financial rates of return in excess of 100 percent, implying that such technological opportunities were previously available but unrealized. Energy efficiency in the home, another example, is also underexploited according to present-value analyses of appliance, lighting, and heating options. Thus, great improvements in environmental efficiency—in energy use, in materials use, in air and water pollutant releases—are within easy reach today without apparent sacrifices in economic well-being.

Emerging technologies—advanced materials, biotechnology, and electronics, among others—are poised to deliver radically improved environmental performance in each sector. Rapid decreases in the cost of photovoltaic arrays offer one hopeful sign of what tomorrow’s technological reality may be. Crops that do not need pesticides provide another.

In each sector, diverse promising approaches to technological transformation deserve support. For example, biotechnology and alternative agriculture are not mutually exclusive. They can be applied together synergistically. No single energy technology should be chosen as *the* answer to our problems lest a failure of that technology become a disaster. Diversity of approaches brings resilience and improves the chances of finding better technologies and strategies.

The limiting factors for technological transformation are not primarily technological but are instead part of the social, economic, political, and cultural milieu in which technologies are developed, diffused, and used. Market incentives, the

structure of regulations, the content and quality of research and education, and social values and preferences all determine technological trajectories.

Perhaps the most fundamental impediment to environment-saving technological advance is the ubiquitous public goods/externalities problem. Prices of goods and services rarely reflect the social costs of environmental services. This pervasive market failure overshadows all other obstacles in energy, agriculture, and manufacturing. For example, the price of a gallon of gasoline does not fully reflect the costs to public health, agriculture and forestry, and ecological integrity that are associated with the production, distribution, and use of the fuel. Because users cannot capture the economic benefits of environmentally preferable technologies, their use is inhibited. Neither firm nor individual has much incentive to spend money and effort to benefit others unless compelled by social forces such as government policies, legal action, or public pressure. The incorporation or “internalization” of external costs would change the relative returns of various technological options, generally in favor of environmentally preferable technologies.

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**”**

Perverse incentives created by governments are another major impediment to technological transformation. They can make environmental improvements less attractive to the makers and users

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**Prices of goods and services rarely reflect the social costs of environmental services. This pervasive market failure overshadows all other obstacles in energy, agriculture, and manufacturing.**

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of technology. Some of these technological disincentives are regulatory while others are fiscal—taxes and subsidies. For example, billions of dollars of agricultural subsidies in many industrial countries promote the overapplication of pesticides, synthetic fertilizers, and other agrichemicals while inhibiting crop rotations and other sound environmental practices. Electric utilities in most U.S. states are regulated with a bias that favors generating electricity over more economically and environmentally sound investments in improved energy efficiency. Industries face product-approval mechanisms and permitting requirements that can reinforce the technological status quo and inhibit the entry of environmentally superior products and processes into the market. Likewise, technology-based environmental standards that prescribe design constraints rather than performance requirements can inhibit innovation.

Although many firms have moved vigorously to improve energy-efficiency and pollution-prevention efforts, most industrial managers overlook profitable opportunities to better their environmental performance. In agriculture, many farmers over-apply fertilizers and pesticides on advice from vendors, extension agents, and neighbors rather than using these inputs only when justified by on-farm soil conditions and observed pest levels. Understanding of alternative agriculture techniques, though increasing, remains low. Consumers in many nations seem willing to reflect their environmental concerns in their choices and uses of consumer products, but they, too, generally remain poorly informed about environmental risks and

trade-offs. Environmental improvements in technology will come slowly without better information.

The high cost of capital in the United States has demonstrably inhibited the development and application of new technologies (Landau and Hatosopolous 1986). Although improved process control and other waste-reducing measures may look better when investible capital is scarce, environmental technology imbedded in new products and processes is a long-term investment. High capital costs inhibit investing in R&D and replacing old inefficient capital stock. Heavily indebted farmers may also try to maximize their current receipts at the expense of soil, water, and air quality.

Institutional and legal impediments to environmental improvement typically are rooted in problems of incomplete incentives. For example, landlords have little incentive to make buildings and appliances energy efficient if tenants pay utility bills, and tenants may have little incentive to make long-term investments in the building. In manufacturing, because firms are not responsible for disposing of their products after purchasers discard them, they have almost no incentive to design goods for ease of recyclability or for benign disposal. In most communities, rubbish and waste disposal is financed out of general tax revenues, so consumers are not faced directly with disposal costs either.

Finally, change is psychologically and politically difficult. Current technological systems include more than just the physical capital of machines, buildings, and infrastructure. Large amounts of human capital are also invested. Engineers, managers, farmers, employees, regulators, and the general public are accustomed to familiar systems that do not fully integrate environmental factors into decision-making or routine operations. New technologies and institutions threaten and annoy the constituencies forced to change behavior. Workers may lose jobs. Consumers may be inconvenienced. Yet, companies that fail to adapt fail to survive, and professionals may lose stature to colleagues who adapt to the new.

The impediments to technological change are given greater urgency by today's global ecological threats and economic imperatives. Across sectors we find strikingly similar impediments, but also the possibility of common solutions.

## V. INADEQUATE POLICIES

Government actions and corporate management decisions—public and private policy—profoundly influence the direction of technological change. In most circumstances, policy decisions have ignored environmental consequences. In many others, environmental protection measures have not adequately encouraged the development or deployment of new technology. Often, resistance to policy change has entrenched existing technologies against environmentally and economically superior alternatives. Against this backdrop, six critical policy areas that influence technology development—regulation, economic incentives, technology policy, management, international policy, and education—deserve particular attention.

### V.1 Environmental Regulation

Since the United States inaugurated modern environmental regulation some two decades ago, its primary focus has been to protect the public against rampant environmental hazards. Environmental laws on air, water, waste disposal, and other areas instructed regulatory agencies to abate pollution quickly and forcefully. Regulatory controls based on technical standards enabled the government, relatively rapidly, to demand needed modifications in products and processes that spawned environmental hazards.

Today, however, “second generation” environmental problems require more complicated solutions. If promoting rapid continuous technological transformation is today’s mission, then requiring all pollution sources to install abatement equipment is not enough. The development and deployment of technologies economically and environmentally superior to those in current use must be stimulated through a wide range of mechanisms. It is in this respect that current regulatory policy appears least adequate. Lessons from U.S. and other industrial nations’ regulatory experience should also be valuable to the developing and Eastern European nations, where environmental regulation is less mature.

Regulatory policy design often exhibits systematic biases against new technology and in favor of the status quo (Heaton 1990). In product regulation regimes—pharmaceuticals, pesticides, toxic

chemicals—risks from new products are scrutinized severely, but products long on the market, often more risky and less efficient, are “grandfathered” into a tolerated status. Post-market surveillance of old technology is weak. This bias puts a burden on innovation.

Many environmental laws also distinguish between new and old pollution sources. Typically, stronger controls are required of new sources, based on the sound premise that new plants can control pollution more effectively and cheaply than old ones. Unfortunately, this approach also creates a disincentive to modernize plants and equipment and prolongs the life of old sources. If technological innovation is to be encouraged, the distinction between new and old sources must be modified. The ideal incentive structure would equalize the marginal costs of abating pollution among new and old sources. Economic instruments such as tradeable emissions permits lead in this direction and should be applied much more widely than they are now.

Basing regulations squarely on firms’ performance is also important. In air pollution, water pollution, and other areas, legislative mandates encourage regulators to base standards on best available technology (BAT). Although this approach diffuses known, effective pollution control techniques rapidly—thus creating a broader market for them—it also narrows the range of technological options. Sticking with conventional technologies on which standards are based is less risky for regulators, regulated sources, and engineering consultants than adopting less familiar technologies. This creates a high hurdle for entrepreneurs trying to develop and market new technologies. Theoretically, standards based on BAT can legally be met by other techniques with equivalent performance characteristics, and BAT requirements are continually updated as improved technology creates a market for technological innovation. In practice, however, the risks involved in substituting another technology weigh heavily in favor of the technology on which the standard is based. Moreover, the difficulty encountered and time consumed in promulgating new standards almost guarantee that today’s best available technology will remain standard far into the future, thus creating a disincentive to fundamental, longer-term change.

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**Technological advances in effluent monitoring and information processing open new possibilities for basing regulations on the environmental performance of each pollution source.**

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Technological advances in effluent monitoring and information processing open new possibilities for basing regulations on the environmental performance of each pollution source. More reliable and less costly ways of monitoring source performance already permit much broader use of emissions trading, effluent charges, and other performance-based policies. For example, the new Clean Air Act Amendments in the United States will allow electric utilities to trade sulfur-abatement credits among themselves, with compliance monitored by in-stack, on-line emissions monitors. The greater efficiency this flexibility will allow will justify the added monitoring costs many times over as utilities choose among the use of low-sulfur coal, scrubbers, clean-coal technologies, and emissions trading to meet their performance requirements at minimum cost. The same flexibility could now be achieved in other regulatory settings as well.

Administrative procedures in regulatory agencies often inhibit the introduction of innovative new technology. The U.S. EPA advisory committee on Technology Innovation and Economics, charged with advising the agency on administrative ways to ease the introduction of new technologies, found that permitting procedures pose significant barriers to untried technology (TIE 1990). Drawn out, expensive, inconsistent, and inflexible permit procedures are great burdens on innovators, particularly small, creative, entrepreneurial firms whose capital is very limited. These procedures may impose inappropriate requirements on technologies that do not conform to pre-existing administrative categories. Permits that prescribe design constraints leave little room for innovation and generally provide no incentives for firms to exceed legal requirements. Although most U.S. statutes include variance or waiver provisions for innovative technologies, such provisions remain far underutilized. EPA is currently exploring ways to make them more effective.

Several characteristics of the standard-setting process favor technologically conservative results. The overwhelming workload leaves no room for experimentation. If point-source standard-setting remains the norm while the number of pollutants and point sources proliferate and government resources stagnate, then policy-makers will have little choice but to focus on the best available technology as the only way to get anything done. The information demands on regulators, who must tailor control requirements to disparate industrial conditions and defend them as reasonable and fair under administrative law, necessitate simple, standardized prescriptions.

The burden of information also forces regulators to rely heavily on the regulated industry for information about technical options. In fact, firms outside the regulated industry perceiving regulation as a chance to invade and gain market share might often prove a much more fertile source of innovation, were regulatory approaches structured to widen market opportunities for them. Especially in technologically rigid or mature industries, the most innovative or disruptive responses to regulation are not likely to be developed by the firms on which the onus of compliance falls but by small firms, potential new entrants, suppliers, and firms from abroad.

Regulatory agencies are generally not organized to promote wide-ranging technological change. The EPA, for example, is organized to administer uncoordinated environmental statutes dealing with particular problem areas. Its attention thus focuses on air pollution, water pollution, and hazardous wastes—not on major industries or economic sectors. Without major efforts at coordination, regulatory activities shift residuals from one medium to another. If, however, the focus of technological transformation is on major economic activities such as transportation, energy production, manufacturing, and agriculture, new organizational approaches may be necessary.

If environmental regulation is to promote technological transformation consistently and systematically, then its focus, not its purpose, must change. Technological change must be moved to center stage and seen as a potential solution to environmental problems, rather than their source (Speth 1988b).

The first step is to reorient the regulatory process with an affirmative mandate to promote technological innovation. This will take new tools, and the agencies must be firmly encouraged to use them. These tools include increased support for cooperative R&D, demonstration and testing projects, strengthened waiver procedures for new

technologies, and, especially, a greatly expanded use of performance-based standards and economic instruments.

Policy analysis in regulatory agencies also needs to be refocused. At present, scenarios of possible technological change play only a marginal role in the economic impact and risk analyses required in standard-setting. Ideally, what is needed is industry-specific microanalysis of potential for technological change over different time frames, encompassing both economic and environmental performance and looking particularly to generators of new technology outside the mainstream.

Regulatory scrutiny, too, should be refocused away from its current preoccupation with controlling new technologies and toward increased scrutiny of existing products and processes with the goal of effective risk reduction. This could be accomplished through many means, including periodic review of existing products, increased use of emissions trading and economic incentives, similar standards for new and old sources of pollution, and increased use of disclosure and liability rules for existing sources of environmental risk. The essential goal, however, should be to create, through regulation, an incentive to replace the inferior technologies of the past with today's environmentally superior products and processes.

## V.2 Economic Incentives

Economic incentives and regulation are different instruments for achieving policy goals. Regulations command specific results; economic incentives work through markets or prices to signal appropriate behavior. Each has advantages in certain circumstances. Economic incentives are more efficient when noncoercive signals to a large population of firms and households let them choose in their own self-interest, based on their own superior information about the social costs and benefits of their available options.

A vast variety of public policies affect producers' and consumers' economic incentives. Few have been devised and implemented expressly to improve environmental quality. In fact, in industrial and developing countries alike, most government policies affecting economic incentives ignore environmental consequences, and many inadvertently exacerbate environmental damage. Changing economic incentives in several sectors would benefit the economy and the environment: in agriculture, in energy production and use, and, as supplements to environmental regulations, in industry.

In the agricultural sectors of virtually all highly developed countries, governments have subsidized

farming to such an extent that potential supply far exceeds domestic and export demands. Agricultural price supports and accompanying supply regulations have encouraged high-input agricultural techniques that generate serious nonpoint source pollution problems and have discouraged ecologically balanced systems of sustainable agriculture. The U.S. subsidy program, for example, encourages farmers to maintain intensively farmed monocultures, despite economic inefficiencies, environmental damage, and the availability of economically and ecologically superior alternatives (Faeth et al. 1990).

Americans' profligate use of energy, compared to any other country's consumption patterns, is largely the result of public policy: the decision to keep the price of petroleum products much lower than in other industrial countries. Many other public policies and institutional arrangements also work against energy efficiency and the development of environmentally superior alternative energy sources. On the positive side, recent changes in the structure of electric utility rate regulation in several U.S. states have made it equally advantageous for utilities to generate electricity, buy it from cogenerators and other independent suppliers, or conserve it by supporting demand-side management programs. Such reforms provide tremendous new opportunities for entrepreneurs and innovators in the energy industry.

Using economic incentives to supplement environmental regulations is not a new idea, but it has rarely been done effectively. Charges on pollution or resource use, marketable permit systems, deposit-refund systems, and removal of barriers to market activity (such as exchanges of water or emissions rights) are all ways of making environmental controls more efficient. A large literature assesses the virtues and drawbacks of these approaches as compared with conventional regulation (Stavins 1990). It shows that neither approach is a panacea or universally applicable. For example, some substances are so toxic that they must be banned or strictly controlled. Moreover, the laws, institutions, and systems for environmental protection have already been put in place in most countries, constraining choices among future policy options. Nonetheless, marketable permits and other incentive policies can be fit into many parts of the existing framework to provide greater flexibility and efficiency.

Today, in addition, environmental policy must attack a new generation of diffuse problems for which regulatory solutions would be difficult, while recognizing that some environmental problems have eluded conventional regulatory controls.

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In particular, diffuse nonpoint pollutants (for example, agricultural runoff), pollution created by numerous small generators (household refuse, for instance), and environmental problems caused by congestion cannot be well managed with permits, effluent/emission standards, or compliance monitoring and enforcement. Incentive-based policies that confront individual generators with the costs of their actions would be more effective and efficient.

Newly emerging technologies support a shift toward incentive-based policies such as industrial effluent charges, highway congestion charges, and municipal refuse disposal fees linked to the volume and composition of wastes. In particular, the development of real-time effluent and emission monitoring technologies enable accurate assessment and precise imposition of pollution charges and enforcement of emission trading. These monitoring technologies can also improve drastically the accuracy and reliability of environmental disclosure schemes, such as the U.S. Toxic Release Inventory (SARA Title III). “Electronic license plates,” already in use in several cities to monitor traffic, make highway congestion charges technically feasible. Simple laptop computers in trash-collection trucks allow collection personnel to record each household’s weekly disposal of mixed and separated trash, facilitating computerized monthly billing. Technological capabilities have already far out-run environmental management systems.

The implications are far-reaching. For one, we can begin to shift the tax base away from socially desirable activities—saving, risk-taking, and work—toward socially harmful activities—pollution and congestion. As we do so, the economic burden of the tax system will fall dramatically. For example, shifting a dollar from the income tax to an environmental tax will boost labor force participation

and savings, an economic gain, while reducing pollution damage, another economic gain.

Economic incentives are also an attractive policy mechanism for encouraging technological transformation. The logic is simple: under a pollution tax or marketable permit system, reducing pollution has a real dollar value to a firm. Because trade-offs for investments in pollution prevention, recycling, and pollution control are easily assessed across the board, firms are more likely to make such investments. If all environmental control options are on an equal footing, the demand for improved technology should increase and prompt more R&D and investment.

Developing nations and the formerly centrally planned economies, where environmental institutions have been relatively immature and regulations have been weak, are promising places for implementing “green” taxes and other economic incentives. They might make more cost-effective environmental and economic progress than they otherwise would if they heed the regulatory lessons learned in industrial countries.

### V.3 Technology Policy

An enormous range of public programs and policies affect technological innovation. Technology policy—a subset—can be defined more manageably as government actions *intended* to promote the development and diffusion of new technology. Even here, the range of mechanisms is vast: R&D tax credits to encourage industrial research, technology transfer programs that move inventions out of federal labs into private hands, government-supported research consortia that bring firms and universities together, and strengthened intellectual property rights to encourage investments in new technology.

In fact if not in principle, the U.S. government is deeply committed to technology policy and has been since World War II. Federal technology policy can point to some outstanding successes. The first generation of computers arose from far-sighted military support for a revolutionary technology (Flamm 1988). Today, federal support for biological sciences is paying off in the biotechnology industry.

Federal technology policies transfer massive resources from public to private sectors: public monies underwrite close to half but public institutions perform only around 11 percent of total R&D (US NSF 1989). This support is by no means distributed evenly. Defense, health, space, general science, and energy received 93 percent of the total in 1990, a distribution consistent with historical

patterns. Within this enormous federal commitment to technology, environmental needs are almost invisible.

Another measure of federal technology policy toward the environment is shown in research outlays for the environmental sciences. The following points stand out: federal support fell in real terms during the 1980s, despite increases in support to other fields and has shifted significantly away from applied research toward basic research. (See Table 2.)

competitiveness. Technology is the key to both vital challenges. Both policies cut across many technical areas and both would support generic technology not adequately developed in private firms. Ironically, the movement away from applied research in environmental areas that could be relevant to industry comes at a time when applied research relevant to industrial competitiveness is enjoying increased support. Federal funding of Sematech (a public-private semiconductor research

**Table 2.** Federal Environmental Sciences Research Obligations

	1980	1983	1986	1989
	—Million \$—			
Current \$ Total	1291	1251	1482	1691
1982 \$ Total	1488	1201	1293	1337
Basic (1982 \$)	616	557	654	748
Applied (1982 \$)	872	644	639	589
% All Federal R&D	11.7	8.8	9.0	8.6

*Note:* Derived from US NSF, *Science and Engineering Indicators 1989*, Tables 4-11, 4-12.

Support for research in the environmental sciences, including work on ecological and health effects of pollution, is distinctly different from support for environmental technology. Although figures on direct federal support in this area are unavailable, the amount is undoubtedly minuscule. Indeed, the movement away from applied research support indicates that what little funding there had been for fields related to technology development was eroded during the 1980s. Not surprisingly, EPA research budgets have suffered similarly, contracting 25 percent in real terms during the 1980s.

As seen in Table 3, EPA's share of total federal R&D is only half what it was in 1980. Consistent with the general trend, EPA has shifted toward basic research and has dramatically decreased its support for applied research and development, the areas closest to commercial technology.

A federal technology policy toward the environment could play a vital role in promoting technological transformation. This policy avenue should be developed not only in technical mission agencies like the NSF or the National Institute of Standards and Technology (NIST) but also in regulatory agencies like the EPA.

In many respects, the realization that we need a federal technology policy toward the environment is analogous to the reawakening of interest in an industrial technology policy to enhance U.S.

consortium), the NSF network of engineering research centers, and the Commerce Department's Advanced Technology Program (Heaton 1989) all bespeak a new government commitment to a civilian technology policy—but one that has not included the environmental performance of new technologies. In such key industries as transportation, energy, construction, and chemicals, the environmental and economic dimensions of innovation must be pursued together.

A federal technology policy for technological transformation should not concentrate on technologies of immediate commercial significance. Making money from new technologies should be left to private firms. What government can do effectively, however, is to support the generic technical areas on which commercial technology will subsequently be based. Private firms are unlikely to support work here because only rarely can they profit from the results.

Generic or base technologies have a wide range of potential applications but do not themselves involve marketable products. In virtually every area of civilian technology, these base technical capabilities could be vastly improved. The result would be major benefits in pollution prevention and control. A few examples in the energy sector illustrate the point. Photovoltaic energy conversion is potentially a key technology. Further

**Table 3. EPA R&D Obligations**

	1980	1983	1986	1989
	—Million \$—			
Total Current \$	345	241	317	374
% Federal R&D	1.3	1.0	0.7	0.6
Total 1982 \$	407	231	277	296
Basic, 1982 \$	16	21	34	24
Applied, 1982 \$	273	146	156	206
Development, 1982 \$	118	63	87	66

*Note:* Derived from US NSF *Science and Engineering Indicators 1989*, Tables 4–6.

advances in materials engineering applied toward increasing photovoltaic conversion efficiencies could profoundly improve future energy prospects, with important environmental and commercial consequences. As discussed earlier, advances in energy-storage technologies are also critical. Many fundamental physical and chemical properties of combustion itself remain poorly understood. Further knowledge could lead to increases in energy efficiency and decreases in the release of hazardous emissions. On a larger scale, experiments on the technical and social characteristics of alternative infrastructures—for example, solar hydrogen-fueled towns or cities without cars—have not been attempted.

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**The realization that we need a federal technology policy toward the environment is analogous to the reawakening of interest in an industrial technology policy to enhance U.S. competitiveness. Technology is the key to both vital challenges.**  
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In manufacturing, similar opportunities abound. Improving our ability to apply extremely thin coatings on surfaces through, for instance, chemical vapor deposition, is likely to have widespread significance. Industrial competitiveness in electronics, optics, tools, motors, and engines as

well as solar energy, may be profoundly influenced by today's national and corporate research. More work on materials-separations technologies that can be used to improve the efficiency and cost-effectiveness of recycling low-valued wastes into high-valued goods is badly needed while further research on microbial metabolism of minerals can influence the environmental and economic performance in mining and minerals.

Agriculture is rife with generic technologies that are rarely supported by private R&D and only modestly funded by public institutions. Cases in point are biological control of insect pests and low-input soil-management techniques. More generally, applied ecological research remains underdeveloped compared to other farm- and forest-management technologies.

Through many policy mechanisms besides direct research funding, generic technologies can be advanced (Ross and Socolow 1990). Most of them have been used elsewhere. For example, targeted centers of excellence could bring technical expertise to bear on commercially significant problems, as several successful state technology-development programs do today (Osborne 1990). Technology-transfer programs from federal laboratories, cooperating with and giving private firms ownership of technology, have begun in a wide variety of areas but are still embryonic in environmental technology. Demonstration and testing programs, the basis of the agricultural extension service and many other initiatives in the United States and abroad, could also be used effectively for environmental technology. One of the most powerful mechanisms is government procurement, provided that it is fully utilized. Procurement, particularly through the Defense Department, has been one of the main means of creating markets for new technology (Nelson 1984). Except for limited purchases

of recycled goods and energy-efficient lighting, and some specialized solar power applications, government procurement remains almost untried in environmental fields.

### ***More Information and Analysis***

Measurement, technology assessment, and analysis also constitute an important, but neglected, aspect of an environmental technology policy. New indicators of environmental performance need to be developed both for the economy as a whole and for industrial and consumer products and processes. The statistical base on which much of economic policy rests—GNP and productivity accounting—is seriously flawed from an environmental standpoint and needs to be reformulated. Inside firms, widespread acceptance of environmental accounting would bring environmental costs higher on the agenda when corporate decisions are made.

Consumers remain poorly informed about the environmental characteristics of products in common use. New environmental performance criteria and application data, along with appropriate means of disseminating this information, are urgently needed.

Because environmental policy has concentrated on managing existing hazards, little attention has been devoted to envisioning or evaluating the technological future. Far too little analysis has been done of the positive and negative potential of emerging technologies: biotechnology, advanced materials, information technology, and others.

The ability of environmental policy to move toward technological transformation is also limited by a paucity of innovative, well articulated policy proposals. The basic design of regulatory standards and analysis (such as the environmental impact statement) have remained intact for some twenty years, but environmental problems have changed. Policy experimentation is needed, particularly proposals addressed to the new global contexts. Policy analysis of this nature should be supported in universities, research institutes, private companies, and government.

Existing public institutions could spearhead a government technology policy directed toward the environment. In the United States, the National Science Foundation (NSF), Environmental Protection Agency (EPA), the National Institute of Standards and Technology (NIST), the Departments of Energy, Transportation and Defense, and many of the national laboratories could be given the new mandate—and new means—to support the development of environmental technology.

An institutional alternative would be to designate a lead agency—or create a new lead institution for environmental technology. Japan among other countries, has chosen the latter course. The Ministry of International Trade and Industry (MITI) has recently established a Research Institute for Innovative Technology for the Earth (RITE) focused on research leading to commercially viable future technology. A similar concept for the United States is contained in a 1990 proposal by Senator Albert Gore, Jr., for a Strategic Environmental Research Program (Gore 1990). Arrangements of this type deserve serious consideration.

## **V.4 International Policy**

Globalization, long recognized in finance, manufacturing, and science, has only recently developed in environmental policy. Global warming, species extinction, and ozone depletion—problems that cut across national boundaries and force the world community to recognize its common future and to search for transnational solutions—contribute to this new awareness (WCED 1987).

**“**

**Environmental pollution has expanded from a localized domestic policy concern into a matter for international diplomacy, challenging the fundamental premise of national sovereignty.**

**”**

Environmental pollution has expanded from a localized domestic policy concern into a matter for international diplomacy, challenging the fundamental premise of national sovereignty (Mathews 1989). But, as environmental problems have become global, so too has the potential for technical solutions. The developed countries in North America, Europe, and East Asia share an essential technical parity across most fields. Science and technology have become profoundly international. Research is often conducted cooperatively across borders, and knowledge is rapidly transmitted worldwide. All national sources of technology can participate in new cooperative arrangements, and advances can be diffused more rapidly.

Nations are beginning to cooperate to resolve international environmental problems. The 1987

Montreal Protocol on Substances that Deplete the Ozone Layer provides a useful precedent because many nations have agreed to act together to address a global environmental hazard and because it establishes a procedure whereby a limited number of signatories can convene expert groups to respond to new scientific knowledge. Signatories are also creating an institutional mechanism in the World Bank, United Nations Environment Programme, and the United Nations Development Programme to transfer financial and technical resources from advanced countries to help less developed countries implement the accord.

Unfortunately, such initiatives fall far short of the need. The most difficult problems lie in the developing world and in the formerly centrally planned economies. They range from vast increases in carbon dioxide emissions in China to deforestation in the Amazon and to toxic effluents in Eastern Europe. Developing countries show some of the world's highest economic and population growth rates, and their environmental problems expand at an even more alarming pace.

Theoretically, technology now on the shelf could solve these problems. The resources devoted to the efforts, however, are minuscule in comparison to the need. A massive effort to transfer technology from developed to developing countries could contribute more than any other action to environmental sustainability.

Judged by available resources, technical expertise, and experience, multinational companies are best able to develop and transfer technologies to combat global environmental degradation. Governments and international institutions are essential as well: disseminating nonproprietary technologies, especially the "software" of environmental management; dispensing aid; measuring effectiveness and monitoring compliance with agreements.

The principal elements of a successful technology-transfer program must therefore include at least five components (Smart 1990). First, industrial countries must reduce the impact of their own activities on the environment. Second, substantial financial resources must be raised in developed countries and transferred to developing countries by international institutions. Third, barriers to the flow of technology, capital, and trade must be reduced or eliminated. Fourth, industrial nations and developing countries must formally agree on financial support and the conditions of technology transfer. Last, developing countries must invest in technology acquisition, cultivating necessary local skills and promoting appropriate local policies and institutions.

New forms of intermediation may be useful in promoting transfers of environmentally beneficial

technologies to developing countries and Eastern Europe. Matching technologies and potential applications, brokering partnerships, facilitating negotiations, supervising licenses and other agreements, and assembling financial packages and other deal-making functions require considerable investments in management. The return from most developing country markets are, however, too small to justify such investments for major corporations, and smaller companies cannot afford them. Public-private cooperation may be able to fill this gap by creating new intermediary mechanisms.

## V.5 Management Policy

Since the technology to solve environmental problems will be developed almost exclusively by industry, management policies constitute probably the single most important force for—or against—technological transformation. Many, but by no means all, major companies have realized that environmental improvement is vital to their future.

A fundamental challenge of environmental management is to convince those who design and control technology in private firms that their competitive agenda complements the societal goal of sustainable economic growth. An important first step is to ensure that corporate accounting systems charge the full costs of waste generation to the responsible processes and plants, including not only processing losses and the costs of waste disposal but also regulatory costs, liability risks, and losses in community goodwill. Accountability is the cornerstone of management responsibility.

Changing management's focus away from "end-of-pipe" pollution-control devices toward pollution prevention is another important step. The constraints on widening the use of pollution prevention techniques are not predominantly financial or technical. More often, pollution prevention is ignored because of informational, attitudinal, or institutional problems. Plant managers and workers often do not look for pollution-prevention opportunities because they may not perceive acting on them to be in their interest. In too many companies, neither career incentives nor accounting practices make pollution reduction appear worthwhile. Eliminating these barriers is a critical management responsibility. As discussed earlier, an external regulatory framework emphasizing economic incentives that put pollution prevention on an equal footing with pollution control and other methods of cost reduction can reinforce management efforts.

A third critical element of environmental management is to engender a new perception of the

stakeholders in corporate decision-making. As Richard Mahoney, the chief executive officer of Monsanto puts it, "Companies must earn the right to do business" (Ehrenfeld 1990). He suggests that management must involve local communities, workers, government, and other interested groups in decisions previously made in relative isolation inside the firm. Public policies that give these stakeholders access to information about companies' environmental performance—for instance, Title III of the U.S. Superfund Amendments and Reauthorization Act—have had a remarkable effect on corporate policies (Baram et al. 1990).

Since market preferences are the most important shaper of business decisions, managers also need to reevaluate long-term market trends. Many companies have already grasped the competitive advantages in "green" products and processes (Cairncross 1990). Although markets are autonomously moving in this direction, management—and public—policy should be directed toward capitalizing and reinforcing the trend.

## V.6 Education

In the long term, the best hope for an environmentally sustainable future rests in the education of the general population. If people demand environmental quality as citizens and consumers, technology will ultimately respond. However, the likelihood of technological transformation depends largely on the designers and manipulators of technology, the managers and engineers. Changes in how managers and engineers are educated are thus especially important.

Recently, American management education has been accused of myopic emphasis on short-term financial returns at the expense of fundamental, longer-term development of technology and manufacturing competence (Dertouzos et al. 1989; Hayes and Abernathy 1980). A similar critique can be leveled at management education's neglect of

the environment. Few business schools offer courses in environmental management. The traditional curriculum typically emphasizes the mastery of skills field by field, as if such crosscutting concerns as environmental management did not exist. Continuing this educational pattern almost ensures that tomorrow's managers will neither appreciate environmental problems nor have the skills to attack them.

The horizons of managers in industry may have changed more quickly than those of their educators. Spurred by government regulation, legal liability, citizen demands, and consumer preferences, top managers and many corporations vocally emphasize the importance of environmental concerns in the business world and their proper management. Business schools are just beginning to respond with new courses and integrative approaches to curriculum development (Post 1990).

Engineering education looms even more critical: engineers design the technologies that create—and solve—environmental problems. Here, engineering education seems a few steps ahead of the business schools, since courses in environmental sciences, regulation, and design have long had a place in the engineering curriculum. However, such courses are usually offered in the context of separate environmental engineering curricula and are not integrated into the training of students in traditional engineering disciplines.

A few environmental courses, taught on the periphery, will not be sufficient. Instead, an environmental consciousness must pervade engineering, especially in design courses. Industrial design is an exercise in integrating many competing criteria. If the education of designers emphasizes environmental concerns, environmental factors will complement other design considerations in new product and process technology. If environmental concerns intrude as an afterthought, forced by regulation or external pressure, the technical solutions are likely to fall short.

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## REFERENCES

- Amato, Ivan. 1990. "Diamond Fever." *Science News*, vol. 138, pp. 72-74.
- Arthur, W. Brian. 1990. "Positive Feedbacks in the Economy." *Scientific American*, vol. 262, no. 2 (Feb.), pp. 92-99.
- AWEA (American Wind Energy Association). 1990. *Wind Energy in the 80s—A Decade of Development*. American Wind Energy Association release, 30 March.
- Ayres, Robert U. 1989. "Industrial Metabolism." In Ausubel, J. H., and H. E. Sladovich, eds., *Technology and Environment*. Washington, D.C.: National Academy Press, pp. 23-49.
- \_\_\_\_\_. 1990. Presentation at the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13-15 June.
- Ayres, Robert U., and Pradeep K. Rohatgi. 1987. "Bhopal: Lessons for Technological Decision-Makers." *Technology in Society*, vol. 9, pp. 19-45.
- Baram, Michael S., Patricia S. Dillon and Betsy Ruffle. 1990. *Managing Chemical Risks: Corporate Response to SARA Title III*. Center for Environmental Management, Tufts University, Medford, Mass., May.
- Barbera, Anthony J., and Virginia D. McConnell. 1990. "The Impact of Environmental Regulations on Industry Productivity: Direct and Indirect Effects." *Journal of Environmental Economics and Management*. vol. 18, pp. 50-65.
- Benbrook, Charles M. 1990. *Agriculture's Next Technological Fix: A Sectoral View*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13-15 June.
- Bevington, Rick, and Arthur H. Rosenfeld. 1990. "Energy for Buildings and Homes." *Scientific American*. vol. 263, no. 3 (Sept.), pp. 76-86.
- Bleviss, Deborah L. 1988. *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s*. New York: Quantum Books.
- Burnett, W. M., and S. D. Ban. 1989. "Changing Prospects for Natural Gas in the United States." *Science*, vol. 244, pp. 305-10.
- Cairncross, Frances. 1990. "Cleaning Up." *Economist*, Special Section, 8 Sept.
- Carlson, David E. 1989. "Low-Cost Power from Thin-Film Photovoltaics." In Johansson, T. B., et al., eds., *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning*. Lund, Sweden: Lund Univ. Press, pp. 595-626.
- Chynoweth, E., et al. 1990. "Catalysts." *Chemical-week*, 27 June.
- Clark, Joel P., and Frank R. Field III. 1990. *Recycling: Boon or Bane of Advanced Materials Technologies?: Automotive Materials Substitution*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13-15 June.
- Colombo, Umberto, and Guiseppe Lanzavecchia. 1990. "Dematerialization and the Knowledge Industry." Draft prepared for *The Frontiers of Technology*. Forthcoming, Florence, Italy: Le Monnier.
- Conference Board of Canada. 1990. *The Globe 90 Conference: Report of the Rapporteurs General*. Vancouver, British Columbia, 23 March.
- Conservation Foundation. 1987. *State of the Environment: A View Towards the Nineties*. Washington: Conservation Foundation.
- Debus, Keith H. 1990. "Mining with Microbes." *Technology Review*, vol. 93, no. 6 (Aug./Sept.), pp. 50-57.
- Dertouzos, M. L., et al. 1989. *Made in America: Regaining the Productive Edge*. Cambridge, Mass.: MIT Press.
- Dignon, J., and S. Hameed. 1989. "Global Emissions of Nitrogen and Sulfur Oxides from 1860 to 1980." *Journal of the Air Pollution Control Association*. vol. 39, no. 2, p. 183.
- Ehrenfeld, John R. 1990. *Technology and the Environment: A Map or Mobius Strip*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13-15 June.
- Faeth, Paul E., et al. 1991. *Paying the Farm Bill: U.S. Agricultural Policy and the Transition to Sustainable Agriculture*. World Resources Institute, Washington, D.C..
- Flamm, Kenneth. 1988. *Targeting the Computer*. Washington, D.C.: Brookings Institution.
- Freeman, Christopher. 1982. *Economics of Industrial Innovation*. Cambridge, Mass.: MIT Press.

- Gibbons, John H.; Peter D. Blair and Holly L. Gwin. 1989. "Strategies for Energy Use." *Scientific American*, vol. 261, no. 3 (Sept.), pp. 136–43.
- Gore, Albert J., Jr. 1990. Release from the office of Sen. Albert J. Gore on the Strategic Environmental Research Program, 28 June.
- Granqvist, Claes G. 1989. "Energy-Efficient Windows: Options with Present and Forthcoming Technology." In Johansson, T.B., et al., eds., *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning*, Lund, Sweden: Lund Univ. Press, pp. 89–123.
- Hahn, Karl W., Wieslaw A. Klis, and John M. Stewart. 1990. "Design and Synthesis of a Peptide Having Chymotrypsin-Like Esterase Activity," *Science*, vol. 248, pp. 1544–47.
- Hammond, Allen L. 1990. *Putting the Right Gene in the System: How Technology Changes*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- Hayes, R.H., and W.J. Abernathy. 1980. "Managing Our Way to Economic Decline." *Harvard Business Review*, vol. 58, pp. 67–77.
- Heaton, George R., Jr. 1990. *Regulation and Technological Change: Charting a New Emphasis*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- \_\_\_\_\_. 1989. "Commercializing Technology Development: A New Paradigm of Public-Private Cooperation." *Business in the Contemporary World*. (Autumn), pp. 87–98.
- Heller, K. 1990a. "Knowhow Cleans Up." *Chemicalweek*, 2 March.
- \_\_\_\_\_. 1990b. "Commercial Firms: Will the Boom Continue?" *Chemicalweek*, 22 Aug.
- Herman, Robert; Siamak A. Ardekani, and Jesse H. Ausubel. 1989. "Dematerialization." In Ausubel, J.H., and H.E. Sladovich, eds., *Technology and Environment*, Washington: National Academy Press, pp. 50–69.
- Hirschhorn, Joel S. 1990. *The Technological Potential: Pollution Prevention*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- Hubbard, H.M. 1989. "Photovoltaics Today and Tomorrow." *Science*, vol. 244, pp. 297–304.
- Huisingh, Donald. 1988. *Good Environmental Practices—Good Business Practices*, Wissenschaftszentrum Berlin für Sozialforschung [Science Center Berlin] (FS II 88–409).
- IIED (International Institute for Environment and Development) and WRI (World Resources Institute). 1987. *World Resources 1987*. New York: Basic Books.
- IPCC (Intergovernmental Panel on Climate Change). 1991. *Climate Change: The IPCC Scientific Assessment*. World Meteorological Organisation and United Nations Environment Programme.
- Jaffe, Adam B., and Robert N. Stavins. 1990. *Evaluating the Relative Effectiveness of Economic Incentives and Direct Regulation for Environmental Protection: Impacts on the Diffusion of Technology*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- Jänicke, Martin, Harold Mönch, Thomas Ranneber, and Udo E. Simonis. 1989. Economic Structure and Environmental Impacts: East-West Comparisons, *Environmentalist*, vol. 9, no. 3, pp. 171–83.
- Jorgenson, D.W., and P.J. Wilcoxon. 1989. *Environmental Regulation and U.S. Economic Growth*. Harvard Institute of Economic Research, Discussion Paper No. 1458, Cambridge, Mass.
- Judge, Paul C. 1990. "Race on for an Electric Car Battery." *New York Times*, 18 July, pp. D1, D7.
- Kelly, Henry C. 1990. *Energy and Economic Growth Revisited*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- Landau, Ralph, and George N. Hatsopolous. 1986. "Capital Formation in the United States and Japan." In Landau, R., and N. Rosenberg, eds., *The Positive Sum Strategy: Harnessing Technology for Economic Growth*. Washington, D.C.: National Academy Press, pp. 583–606.
- Lovins, Amory B. 1989. *Energy, People and Industrialization*. Paper commissioned for the Hoover Institution conference "Human Demography and Natural Resources," Stanford, Calif., 1–3 Feb.
- MacKenzie, James J. 1989. *Breathing Easier: Taking Action on Climate Change, Air Pollution, and Energy Insecurity*. Washington: World Resources Institute.
- MacKenzie, James J. and Mohamed T. El-Ashry. 1989. "Tree and Crop Injury: A Summary of the Evidence." in MacKenzie, James J., and M.T. El-Ashry, eds., *Air Pollution's Toll on Forests and Crops*. New Haven, Conn.: Yale University Press.
- Mathews, Jessica T. 1989. "Redefining Security." *Foreign Affairs* vol. 68, no. 2 (Spring), pp. 162–77.
- Moffat, Anne Simon. 1990. "Corn Transformed." *Science*, vol. 249, p. 630.

- Nelson, Richard R. 1984. *High-Technology Policies: A Five Nation Comparison*, Washington: American Enterprise Institute.
- Ogden, Joan M., and Robert H. Williams. 1989. *Solar Hydrogen: Moving Beyond Fossil Fuels*. Washington: World Resources Institute.
- Osborne, David. 1990. "Refining State Technology Programs." *Issues in Science and Technology*, vol. 6, no. 4 (Summer), pp. 55–61.
- Post, J.E. 1990. "The Greening of Management." *Issues in Science and Technology*, vol. 6, no. 4 (Summer), pp. 68–72.
- Repetto, Robert. *The Concept and Measurement of Environmental Productivity: An Exploratory Study of the Electric Power Industry*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- Ross, Marc H., and Robert H. Socolow. 1990. *Technology Policy and the Environment*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- Ross, Marc H., and Daniel Steinmeyer. 1990. "Energy for Industry." *Scientific American*, vol. 263, no. 3 (Sept.), pp. 88–98.
- Schneider, Ilene. 1990. "MonitIR 400 Challenges Liquid Chromatographic Techniques." *Genetic Engineering News*, vol. 10, no. 8 (Sept.), pp. 6, 30.
- Schneiderman, Howard A., and Will D. Carpenter. 1990. "Planetary Patriotism: Sustainable Agriculture for the Future." *Environmental Science & Technology*, vol. 24, pp. 466–73.
- Scientific American*. 1990. "Science and Business," *Scientific American*, vol. 262, no. 3 (Mar.), pp. 79–80.
- Sklar, Scott. 1990. Testimony before the U.S. Senate Committee on Energy and Natural Resources, Solar Energy Industries Association release, 15 May.
- Smart, Bruce. *International Technology Transfer*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- Southerland, D. 1990. "China's Industrial Pollution Posing Severe Health Hazards." *Washington Post*, 12 Aug., p. A18.
- Speth, James Gustave. 1990. *Needed: An Environmental Revolution in Technology*. Paper prepared for the World Resources Institute symposium "Toward 2000: Environment, Technology and the New Century," Annapolis, Maryland, 13–15 June.
- \_\_\_\_\_. 1989. "Can the World Be Saved?" *Ecological Economics*, vol. 1, pp. 289–302.
- \_\_\_\_\_. 1988a. "Environmental Pollution: A Long-Term Perspective." *Earth '88 Changing Geographic Perspectives*. Proceedings of the Centennial Symposium. National Geographic Society. pp. 262–82.
- \_\_\_\_\_. 1988b. "The Greening of Technology." *Washington Post*, 20 Nov., p. D3.
- Stavins, Robert N. 1990. "Toward a New Era of Environmental Policy: Economic Incentives for Environmental Protection and Resource Management." Prepared for C.T. Foreman, ed., *Regulating the Future*, Washington, D.C.: Center for National Policy.
- Sternberg, K. 1990. "Environmental Services." *Chemicalweek*, 2 March.
- TIE (Technology Innovation and Economics Committee). 1990. *Permitting and Compliance Policy: Barriers to U.S. Environmental Technology Innovation*. Report and Recommendations of the Technology Innovation and Economics Committee. Washington, D.C.
- Twombly, R. 1990. "Firms Foresee High Stakes in Emerging Biopesticide Market." *The Scientist*, vol. 4, no. 14 (9 Jul.), pp. 1, 8–9, 28.
- UNEP (United Nations Environment Programme). 1987. *The State of the Environment*. New York: Butterworth.
- UNEP (United Nations Environment Programme) and WHO (World Health Organisation). 1987. *Global Pollution and Health*.
- US CEQ (United States Council on Environmental Quality). 1990. *Environmental Quality: 20th Annual Report*. Washington, D.C. p. 448, T. 20.
- US DOE (United States Department of Energy). 1989. *Energy Conservation Trends: Understanding the Factors That Affect Conservation Gains in The U.S. Economy*. (DOE/PE-0092), Sept.
- \_\_\_\_\_. 1990. *Energy For Today: Renewable Energy*. Prepared for U.S. Department of Energy by the Solar Energy Research Institute. (SERI/SP-220-3554), March.
- US NAE (United States National Academy of Engineering). 1988. *The Technological Dimensions of International Competitiveness*. Washington, D.C.: National Academy of Engineering.
- US NRC (United States National Research Council). 1989. *Alternative Agriculture*. Washington, D.C.: National Academy Press.
- US NSF (United States National Science Foundation). 1989. *Science and Engineering Indicators 1989*. Washington, D.C.: National Science Board of the National Science Foundation.
- US OTA (United States Congressional Office of Technology Assessment). 1990. *Materials Tech-*

- nology: Integrating Environmental Goals with Product Design*. 1990. Project Proposal from the Congressional Office of Technology Assessment, Washington, D.C., June.
- \_\_\_\_\_. 1989. *Facing America's Trash: What Next for Municipal Solid Waste?*. Washington, D.C.
- \_\_\_\_\_. 1988. *Technology and the American Economic Transition*. Washington, D.C.
- \_\_\_\_\_. 1986. *Serious Reduction of Hazardous Waste For Pollution Prevention and Industrial Efficiency*. Washington, D.C.
- WCED (World Commission on Environment and Development). 1987. *Our Common Future*. New York: Oxford University Press.
- Weinberg, Carl J. and Robert H. Williams. 1990. "Energy from the Sun," *Scientific American*, vol. 263, no. 3 (Sept.), pp. 146-55.
- Williams, Robert H., Eric D. Larson and Marc H. Ross. 1987. "Materials, Affluence and Industrial Energy Use." *Annual Review of Energy*, vol. 12, pp. 99-144.
- WRI (World Resources Institute). 1990. *World Resources 1990-91*. New York: Oxford University Press.

## APPENDIX

### Background Papers Commissioned for “Toward 2000: Environment, Technology and the New Century”

- Benbrook, Charles M. “Agriculture’s Next Technological Fix: A Sectoral Review.”
- Clark, Joel P. and Frank R. Field, III. “Recycling: Boon or Bane of Advanced Materials Technologies? Automotive Materials Substitution.”
- Ehrenfeld, John R. “Technology and the Environment: A Map or Mobius Strip?”
- Hammond, Allen L. “Putting the Right Gene in the System: How Technology Changes.”
- Heaton, George R., Jr. “Regulation and Technological Change: Charting a New Emphasis.”
- Hirschhorn, Joel S. “The Technological Potential: Pollution Prevention.”
- Jaffe, Adam B. and Robert N. Stavins. “Evaluating the Relative Effectiveness of Economic Incentives and Direct Regulation for Environmental Protection: Impacts on the Diffusion of Technology.”
- Kelly, Henry C. “Energy and Economic Growth Revisited.”
- Repetto, Robert. “The Concept and Measurement of Environmental Productivity: An Exploratory Study of the Electric Power Industry.”
- Ross, Marc H. and Robert H. Socolow. “Technology Policy and the Environment.”
- Smart, Bruce. “International Technology Transfer.”
- Speth, James Gustave. “Needed: An Environmental Revolution in Technology.”

### Symposium Reports

- Heaton, George R., Jr., Marc H. Ross and Robert H. Socolow. “Technological Transformation for Sustainable Development: A Public Research Agenda.” A report produced with financial support provided by the National Science Foundation.

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Two dominant concerns influence WRI's choice of projects and other activities:

The destructive effects of poor resource management on economic development and the alleviation of poverty in developing countries; and

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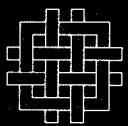
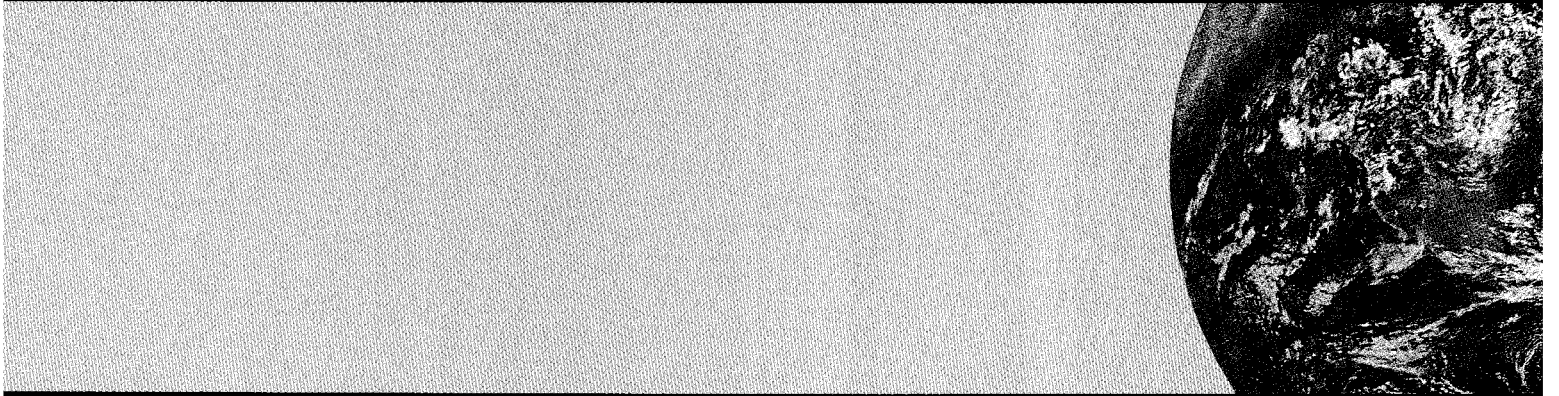
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