LEMELSON CENTER STUDIES IN INVENTION AND INNOVATION

Arthur Molella and Joyce Bedi, editors, *Inventing for the Environment*

INVENTING FOR THE ENVIRONMENT

EDITED BY ARTHUR MOLELLA AND JOYCE BEDI

THE MIT PRESS
CAMBRIDGE, MASSACHUSETTS
LONDON, ENGLAND

IN ASSOCIATION WITH

THE LEMELSON CENTER
SMITHSONIAN INSTITUTION
WASHINGTON, D.C.

Set in Engravers Gothic and Bembo by Achorn Graphic Services. Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Inventing for the environment / edited by Arthur Molella and Joyce Bedi.
p. cm. — Lemelson Center studies in invention and innovation)
Includes bibliographical references and index.
ISBN 0-262-13427-6 (hc : alk paper)
1. Technological innovations—Environmental aspects. 2. Technology—Environmental aspects. 3. Ecology. I. Molella, Arthur P., 1944–. II. Bedi, Joyce. III. Series.

T173.8 .I6185 2003
363.7—dc21

2002035775

10 9 8 7 6 5 4 3 2 1

CONTENTS

FOREWORD

ERIC LEMELSON

The genesis of *Inventing for the Environment* was a conversation I had in 1997 with Arthur Molella, Director of the Lemelson Center for the Study of Invention and Innovation. Art and I were discussing alternative energy technologies and the effect of new technologies on sustainable development. I suggested that the Lemelson Center consider exploring the complex relationship among invention, innovation, and the environment.

To many people, the word "environment" brings to mind images of untouched, wild nature, of remote landscapes separated from daily life that are (hopefully) protected and enjoyed for their recreational and spiritual values. Other people might think of pollution and related issues such as human health and government regulation. The words "technology" and "innovation," on the other hand, suggest to many people the gadgets that permeate modern life—the personal computer, the cell phone, the fax machine, and thousands of other devices. When I consider the words "technology" and "environment," my background as an environmental lawyer often leads me to think of how technological innovation might help solve many of the myriad threats to the global environment that face us in this new century.

For several decades, we have been taught by the environmental movement and by scientists that we're not separate from our environment. In an increasingly urbanized world, the practical implication of this revelation is that for many people "the environment" means the city and areas surrounding it. Similarly, limiting our thinking to the ubiquitous products of the electronic and information revolutions ignores the importance of other technologies, such as architecture, that shape the built environment of the urban landscape.

The essays in this volume demonstrate the importance of viewing this complex subject from a broad perspective. Human beings have used technology since the dawn of history to shape and craft the environment we live in. We are entering an era in human history when technology has the potential to supply us with plentiful, clean energy from the sun and from other sources, such as hydrogen. The scale of the environmental problems we face challenges us to apply human ingenuity (the basis of technological innovation), to use resources more efficiently and equitably, to reconsider our relationship to the natural world, and to reduce the impact of our species on the biosphere. Readers of this volume will find new and unusual perspectives that will affect the way they think about technology and the environment.

PREFACE

The Jerome and Dorothy Lemelson Center for the Study of Invention and Innovation, based at the Smithsonian's National Museum of American History, was founded on the simple belief that history matters. It is our mission to enhance public understanding of the creative processes involving invention and innovation and to examine these processes in a broad historical context. Guiding all our activities, from symposia and museum exhibits to school programs and book projects like this, is the conviction that historians and innovators have much to learn from each other. We believe that if we bring these two groups together in an informed dialogue on issues of common interest, significant and unexpected findings will emerge.

This strategy seemed particularly appropriate in the case of environment-related inventions, where so much of current practice is based on assessments of past conditions and patterns of change. When we began to explore environmental topics, we were struck by the increasing role, since the nineteenth century at least, of innovative technologies and methods, including the invention of whole new fields such as public health and industrial ecology. In addition, environmental activities are complex and inherently collaborative, involving contributors from many different fields, unified in a common goal of improving the human condition. Coming to grips with such a complex set of activities and approaches requires a broad interdisciplinary perspective. Hence, this volume draws upon the expertise of a wide variety of specialists, including environmental, science, technology, and business historians as well as engineers, scientists, public health experts, architects, and town planners. The subject of invention provides the unifying theme, highlighting contributions from the creative fronts of disparate disciplines.

The main questions raised in this volume grew out of a year-long interdisciplinary program series sponsored by the Lemelson Center in 1998 with generous support from the Lemelson Foundation and AT&T, which also collaborated with us in the organization of these events. Throughout that year, we addressed questions about how invention may help—or sometimes unintentionally harm—the environment, recognizing from the outset that inventions are not socially neutral. In addition to issues of benefit and detriment, we considered the implied social arrangements of environmental inventions that promote the status quo or seek to forge a new order. Advocating the use of solar energy or alternative building materials like straw bales, for example, carries with it a call to restructure society as presently conceived. Siting photovoltaics on rooftops and making each home its own power plant eliminates the need for centralized generation and distribution of electricity, thereby providing enormous flexibility in housing patterns. The New Town phenomenon, both today and in the past, predicates a new community paradigm on environmental innovation. Even technologies that improve existing ones, like catalytic converters that make cars more fuel efficient and less polluting, have a broad range of consequences, from the larger economic effects of retooling factories down to the transportation choices made by individual commuters. Inventing for the environment, therefore, includes changing not only technology but also the day-to-day way of life of millions of people. We defined "the environment" in the broadest sense—in terms of the interaction of humans and "nature"—arguing that it is impossible to separate human from natural systems. It is this synthetic approach that guides this volume.

The authors were drawn from the lecture series, the symposium, and the historical tours that were offered by the Lemelson Center. Each part of the book focuses on a question about applying invention to environmental issues. In an attempt to answer these questions, each part features two essays, one by a historian and the other by a practitioner, designed to present a balanced dialogue between history and current practice. The "Portraits of Innovation" highlight individuals whose inventive energies have made significant improvements in the environment.

The essays represent what we believe to be among the most innovative areas of current environmental practice. They explore topics in environmental history, issues of public policy, and examples of technological innovation to question how inventions have affected and can affect the environment. Each aims to take an innovative approach to understanding the interconnections of human and natural systems. Thus, the contents of the book lead from discussions of nature itself, through the built environment, to more specific technologies in such areas as public health and energy. To bring these ideas together, we conclude with an examination of applications of the principles of industrial ecology.

Mixing practitioners and historians is the key, since, as has already been noted, the very concept of the environment is deeply embedded in time and change. Statements about the environment are inevitably teleological and relative, measuring present and future conditions against the past. Advocacy positions, both for and against specific environmental policies and reforms, typically invoke the authority of historical precedent. Defenders of the automobile, for example, point out that the internal-combustion engine, for all its harmful effects on the air we breathe, actually helped to improve urban environments, previously befouled by horses. Champions of alternative energy sources call our attention to neglected stories of roads not taken in such technologies as wind, solar, and tidal energy. Historical examples can provide significant lessons for the present, sometimes even leading to the rediscovery of an old technology, as in the revival of straw-bale construction described in one of our essays. As it explores the history of "inventing for [the benefit of] the environment," it is hoped that this book will indeed put the past to use for the common good.

For some time now, the specialty of environmental history has been a growth industry within the field of history, but the role of invention in that story is still relatively unexplored. When technological invention is introduced, it is often with reference to technogenic problems, such as those associated with nuclear energy or the internal-combustion engine; if offered as a solution, it is usually in the simplistic terms of the technological fix. Rarely has it been examined critically or from multiple perspectives. Perhaps one reason for such one-dimensional interpretations is that invention itself has been viewed too restrictively as a gadget-based approach to technological improvement. When the definition of invention is broadened to include not only mechanical devices but also complex innovative processes of all sorts, social as well as technological, the possibilities expand dramatically.

Despite the interdisciplinary nature of the subject, studies of the environment that cut across disciplinary lines are still relatively rare. The majority of books in both environmental studies and environmental history deal with a single facet of technological or social studies. For example, books on alternative energy sources or the conservation movement abound. In contrast, *Inventing for the Environment* fills a need to cross specialists' boundaries, bring together a range of expertise, and assess the relationships among technologies and philosophies.

The diverse perspectives represented in this book suggest a sense of integration and unification that forms an ecological mindset once popularly known as holism. Not only must the relationship between technology and the natural world be looked at holistically; as Richard White and Steven Pyne argue, this must be done with a recognition that there may be no distinction between the natural and the artificial, between nature and human culture, in the first place. Simply put, technology is not separate from nature. History shows that the distinctions that humans and societies draw between the two are themselves cultural artifacts that have often been politically and ideologically based. But, as a number of papers in this volume argue, once the porosity of the boundary is admitted, all kinds of inventive possibilities open up. Rejecting bipolar concepts of nature and culture can allow for more interesting, seemingly paradoxical strategies, such as those offered by the new field of industrial ecology. Most of all, the integration of nature and technology widens the field of play for the creative imagination, encouraging inventive solutions that view technological society in the broadest ecological terms—and that is what *Inventing for the Environment* is about.

The Lemelson Center gratefully acknowledges the generous support of the Lemelson Foundation and AT&T in the production of *Inventing for the Environment.*

PORTRAIT OF INNOVATION: ROBERT H. SOCOLOW

MARTHA DAVIDSON

My object in living is to unite
My avocation and my vocation
As my two eyes make one in sight

—Robert Frost, "Two Tramps in Mud Time"

Robert Socolow recites these lines from a favorite poem. The verses, which he first encountered in high school, reverberate in his life. Socolow, a physicist, is a former director of Princeton University's Center for Energy and Environmental Studies, the present editor of the *Annual Review of Energy and the Environment,* and a pioneer of energy efficiency research. Though drawn to science from an early age, he has also had a lifelong love of the humanities, especially the arts and languages, and a keen interest in other cultures. These diverse perspectives have led him to pose challenging questions about the environment and to foster multi-disciplinary efforts to answer them.

Born in New York in 1937, Socolow, the eldest of three children, acquired strong ethical values from both home and school. His mother, a remedial reading specialist, cultivated in him an appreciation of music and museums. His father, an attorney who wrote an early text on radio broadcasting law, provided a role model for community service through his work with Jewish organizations. The family's involvement with Reconstructionism, an emerging modernizing movement in Judaism, was an important influence. Socolow attended Fieldston, a high school of the Society for Ethical Culture. "Between Reconstructionism and Ethical Culture," he says, "I got a double dose of liberal values: public service, internationalism, anti-prejudice, pro-science, anti-sectarian, pro-rationality."

It was school, too, that nourished his interest in science. Although there were no scientists in his family, Socolow had inspiring science teachers at

Fieldston and felt the aura of the renowned physicist J. Robert Oppenheimer, who had attended the same school about 30 years earlier. Socolow, like Oppenheimer, chose Harvard for college.

Entering Harvard in 1955, Socolow intended to major in chemistry. Parental encouragement and his own inclinations ("I had a strong belief that I should learn everything. . . . I thought I could try to learn all the ideas taught at Harvard!") led him to select a broad range of courses along with science classes. Among the most memorable were a survey of the fine arts and a poetry class taught by Archibald MacLeish. Socolow also took a remarkable course in the Russian language taught outside the university. Already conversant in French, which he had studied in high school and during a summer spent with a French family, Socolow became comfortable with Russian as well.

In 1957, Socolow was invited to work as a summer student at the Brookhaven National Laboratory, where groundbreaking work in physics was being done. "I lived on site, breathed the excitement of physics. I changed my major from chemistry to physics upon returning to Harvard [and] I decided I wanted to participate in the discovery of the laws of fundamental particles. . . . It was a fascination."

Graduating summa cum laude in 1959 with a B.A. in physics, Socolow was awarded Harvard's Sheldon Travel Fellowship. It enabled him to travel for a full year through Russia, Asia, and Africa, returning via the Middle East. "My agenda was to be a sponge," he says. The journey left him with thousands of lasting impressions, particularly regarding the effects of colonialism and the strength of nationalism at that time. While traveling, Socolow read a book in which Albert Schweitzer described his decision to spend his twenties pursuing music and philosophy and to delay answering the call he felt to devote himself to social and medical problems. "I needed permission from myself to stay in physics, and here it was," Socolow recalls. He returned to Harvard in 1960 for graduate studies, and he completed a Ph.D. thesis in theoretical high-energy physics under a young professor, Sidney Coleman.

In August of 1961, after a summer spent working on arms control issues at RAND in California, Socolow was an aide at a Pugwash Conference held in Stowe, Vermont. Pugwash Conferences, inspired by a 1955 manifesto of Bertrand Russell and Albert Einstein and named for the site in Nova Scotia where they were first held, bring together scientists to discuss controversial issues of global importance, such as nuclear disarmament.

Although serving officially as a driver, Socolow acted also as an unofficial interpreter for some of the Russian scientists at that meeting, including Nikolai Bogoliubov and Igor Tamm.

Back at Harvard, Socolow decided that he had to reject a career in arms control. "One had to become as knowledgeable about weapons as those who loved them," he concluded. "I so disliked weapons that I couldn't force myself to learn about them. Arms control couldn't be my field."

While in graduate school, Socolow met Elizabeth Sussman, a Vassar undergraduate. They were married in 1962. Elizabeth became a graduate student in English at Harvard, where she received a Ph.D. in 1967. In 1964, Socolow received his Ph.D. and accepted a postdoctoral fellowship from the National Science Foundation for study at Berkeley and at the European Center for Nuclear Research (CERN) in Geneva. At a meeting in Budapest during his time at CERN he developed a strong bond with a North Vietnamese physicist. The two of them hoped to contribute to a resolution of the growing conflict in Vietnam, but their efforts were unsuccessful.

Socolow returned to the United States in 1966 as an assistant professor at Yale University. There he fulfilled an aspiration to teach quantum mechanics, and he also continued his antiwar efforts, though with a sense of futility. He openly supported draft resistance and organized, along with three other faculty members, Yale's 1969 "Day of Reflection," a symposium on scientists and war work. To represent the views of researchers who worked with the Department of Defense, Socolow invited Marvin Goldberger of Princeton University. That contact changed the course of Socolow's career.

Socolow had planned to spend the summer of 1969 in California, working at the Stanford Linear Accelerator. Goldberger told Socolow and a Yale colleague, John Harte, about a special summer study run by the National Academy of Sciences at Stanford that was to examine institutions for the management of the environment, using a proposed jetport in the Everglades as a case study. Socolow decided to stay away from the Accelerator for four weeks to participate in the Everglades study as a volunteer.

The National Academy study argued against the construction of the jetport. It cautioned developers about the importance of water conservation in the Florida interior to the development of the state's west coast. Not long after the study was completed, plans for the jetport were abandoned, and the federal and state governments created the Big Cypress National

Preserve, a huge interior water conservation area, to help both the Everglades and the development of Florida's west coast. "It was a heady beginning to a career," Socolow says. "I had found a way to combine my social concern and my science, and I didn't look back." Along with that discovery, there was another major development in his life that year: the birth of his first child, David. His second child, Seth, was born 2 years later.

Socolow's personal awakening to the environment that summer of 1969 coincided with a larger burst of national awareness of the Earth's fragility. We had seen the first photos of our planet taken from space. Environmental issues commanded the public's attention. President Nixon created the Council on Environmental Quality and the Environmental Protection Agency.

At Yale, Socolow's perspective had shifted. "Look at this environmental science—why didn't I learn it when I was learning physics? Why aren't there examples that convey environmental reality in the physics textbooks?" he wondered. "And, so, why not provide a supplementary text and try to bring environmental problem solving into introductory science courses?" With John Harte, he proposed the volume that was published 2 years later as *Patient Earth*.

The double meaning of the title was intentional: the Earth is patient with us, who mistreat it; and it is a patient, deserving of our care. The book was a compilation of case studies representative of environmental conflicts or collisions of values that its authors thought were likely to recur for many years. Topics included urban blight, population control, resource management, conservation, the ecological impact of the military, and alternative uses of land. The book explored philosophical and moral aspects of environmental issues as well as scientific ones, and it promoted social activism by individuals and citizen groups as well as action by legislatures and courts to remedy the problems described.

In 1969–70, in addition to editing *Patient Earth*, Socolow learned about the environmental research conducted by faculty in other Yale departments—biologists, geologists, economists, and professors in the School of Forestry. For the academic year 1970–71, Socolow had a Yale University Fellowship, a kind of sabbatical. He pondered his next career move and considered offers of research positions at science policy centers newly created at Harvard and Cornell. Ultimately, Marvin Goldberger, the Princeton professor who first awakened Socolow's interest in the environment through the Everglades study, persuaded him to join Princeton's faculty, as

an associate professor in the Department of Mechanical and Aerospace Engineering (MAE). Socolow's principal responsibility would be to articulate and lead the research program of a new Center for Energy and Environmental Studies (CEES), which the University was forming in the School of Engineering and Applied Science. In addition to Goldberger, four senior Princeton professors would guide the effort: the physicist George Reynolds, the electric propulsion expert Robert Jahn, the combustion expert Irvin Glassman, and the economist William Bowen.

At Yale, senior professors had raised the funds to sponsor Socolow's research. At Princeton, proposal writing was Socolow's responsibility, and he began reading successful proposals from various departments. One from the School of Architecture described a sociological study of a New Jersey planned-unit housing development called Twin Rivers. "In an 'aha!' moment," Socolow remembers, "I thought, 'What if I study the same community, with energy flow questions in mind, to understand what determines the energy used in the most common kinds of housing?'" Richard Grot, another member of MAE, quickly responded to the idea, pointing out that the replicated units of the development provided a research opportunity.

Over the next 7 years, Socolow, Grot, David Harrje (a rocket engineer), some colleagues in statistics and psychology, and several graduate students made extensive studies of the units at Twin Rivers. They monitored energy use and experimented with ways to reduce it by modifying the building shell. They showed that savings in annual heating of up to 75 percent were possible. The team published its findings in a book titled *Saving Energy in the Home: Princeton's Experiments at Twin Rivers.* Their discoveries about common construction practices and the importance of small details for energy efficiency stimulated the practice of retrofitting, which became widespread by the 1980s.

Socolow's decision to study middle-class housing was deliberate, he says: "I'm interested in the environmental impact of the way we live. That's dominated by middle class consumption. . . . Decisions that determine middle-income housing are replicated millions of times."

At Princeton, in the wake of the 1973 oil crisis, Socolow ran the American Physical Society 1974 summer study on energy use. The meeting helped legitimate the study of energy efficiency by physicists. Socolow, along with Marc Ross at Michigan, Arthur Rosenfeld at Berkeley, Robert Williams then at Michigan and later a colleague at CEES, and quite a few other physicists, questioned two widely held assumptions among scientists: that society can achieve well-being only through ever-greater expenditures of energy, and that physicists should work only on problems of energy supply, not of energy use. The Twin Rivers project, carried out by physicists and engineers, was a model of a new application of physics research.

In his first years at CEES, parallel with his work on energy efficiency, Socolow launched a second multi-disciplinary study, this one focusing on the proposed construction of Tocks Island Dam on the Delaware River, just above the Delaware Water Gap, between New Jersey and Pennsylvania. Tocks Island Dam was slated to be the largest dam in the Northeast. The study explored the analytical methods of ecologists, hydrologists, energy analysts, and economists, calling into question the applicability of the assumptions used in each field. Early work on the resulting book, *Boundaries of Analysis: An Inquiry into the Tocks Island Dam Controversy*, co-edited with colleagues Harold Feiveson and Frank Sinden, may have influenced the decision of Governor William Cahill of New Jersey to question the dam in his role as a member of the Delaware River Basin Commission. Cahill's concerns changed the political balance, and the project was scuttled a few years later. Today, a stretch of the Delaware is a part of the National Wild and Scenic River System. Socolow observes: "It is not much of an oversimplification to say that in the United States, until the Tocks Island dam controversy, all dams of that type that had been proposed were built; after Tocks Island, all similar dam proposals were rejected before construction."

Socolow, succeeding Reynolds and Glassman, served as director of CEES from 1979 to 1997. Among his colleagues were Robert Williams, an influential analyst of energy technology and policy, and Frank von Hippel, a specialist in nuclear energy and arms control and a leader of Russian-US arms control collaborations. Socolow saw his job as twofold: to connect CEES with the rest of the university through formal teaching and supervision of work by undergraduates and graduate students, and to "infect the disciplines" at Princeton, to nudge the academic enterprise to take the environmental challenge seriously.

Socolow believes CEES has had an impact on a lot of individual careers of people with straight science backgrounds, typically physics backgrounds: "I describe our place as a roundhouse. They come in, oriented in one direction . . . and we help them turn about thirty degrees, and they leave in a different direction, . . . still using physics, but in a different way." Socolow advises students to get a firm grounding in physics or another discipline

before getting involved in multi-disciplinary policy work. He feels strongly that traditional scientific training is an irreplaceable foundation for innovative work on environmental issues.

In 1983, Socolow participated in a Pugwash Conference in Venice. His motive was to meet the physicist Evgenie Velikhov, a senior officer of the Soviet Academy of Sciences, who was seeking collaborations with American scientists. Socolow was concerned about the demonization of the USSR during the early Reagan era and saw science as an arena to build communication and to address common aims. In Moscow in 1984 at Velikhov's invitation, Socolow worked with Russian counterparts to launch a collaboration between Soviet and US scientists in the general area of energy efficiency, ultimately involving the National Academy of Sciences in the United States as well. The collaboration continued for a full decade.

In 1984, at the 25th-year reunion of his Harvard class, Socolow met someone else of importance in his life. His first marriage had ended 2 years earlier, and at the reunion he was introduced to Jane Ries Pitt, widow of a former classmate and herself a Harvard alumna. They married in 1986, and Socolow became stepfather to her two children, Jennifer and Eric. Jane Pitt Socolow, a physician and a professor at Columbia University, directs a research program in perinatal and pediatric HIV infection. She shares her husband's commitment to use science to solve society's problems.

One of the societal issues that concerns Socolow is the relationship between technologies used in countries of the Earth's northern hemisphere and those used in less industrialized countries of the southern hemisphere. Thanks especially to the regular visits of Amulya Reddy (from Bangalore, India) and Jose Goldemberg (from Sao Paulo, Brazil), CEES conducts much original research on technologies that support the industrialization of developing countries in environmentally responsive ways. In *Perspectives in Energy* (January 1991), Socolow wrote: "To solve the problems of the South, there is no reason to confine attention to those technologies and policies that have worked in the North. Indeed, one of the great stimuli to innovation over the next decade will be to confront the problems of the South as new problems, and to devise original solutions for them."

Socolow, Williams, and their colleagues and students have been exploring a number of technologies for transportation and electricity tailored to the needs of developing countries. Working against a widely held assumption that technologies should be deployed in such countries only after they have been fully tested in industrialized societies, Socolow and his colleagues are advocating the deployment of certain technologies first in developing areas of the world.

Socolow has been the editor of the *Annual Review of Energy and the Environment* since 1993. With the help of an editorial committee, he selects themes and solicits articles that bring research in the natural and social sciences and in technology to the attention of a wide community of scientists, engineers, and policy analysts in the academy, government, in industry, and in non-governmental organizations. Socolow stepped down as director of CEES in 1997, when he took a sabbatical that included travel in China and India. He teaches innovative courses in environmental science, technology, and policy based at the MAE Department and at Princeton's Woodrow Wilson School of Public and International Affairs.

Socolow's most recent interest is industrial ecology. Industrial ecology encompasses two lines of analysis. The first, introduced by Robert Frosch and Nicholas Gallopoulos and developed by Braden Allenby, Thomas Graedel, and Robert Laudise at AT&T, is concerned with material flows within industry. It takes natural ecology as a model, particularly in looking at waste products. In nature, one organism's wastes become another organism's food. These researchers seek opportunities for the waste products of one industry to become the raw materials of another. The second line of thinking, led by Robert Ayers at Carnegie Mellon University, traces the flow of materials—arsenic, for example, or lead—through both the natural and industrial environments, on a regional or a global scale.

Socolow became involved with industrial ecology when he was asked to head a 1992 workshop on industrial ecology and global change at Snowmass, Colorado. "Industrial ecology gave my career a second wind," he says. "With industrial ecology, I'm able to return to the resource and environmental issues and themes that first brought me into environmental work and that motivated *Patient Earth*." Socolow has been using the industrial ecology approach to address the fate of three elements: carbon, lead, and nitrogen.

The carbon problem that interests Socolow is called carbon sequestration. It is a way to slow down global warming, by reducing the rate of increase of the atmospheric concentration of carbon dioxide. Socolow explains that the version of carbon sequestration that interests him "involves continuing to use fossil fuels, but preventing most of the carbon in these fuels from reaching the atmosphere." He continues: "For example, after capturing the carbon at a power plant as carbon dioxide, one might send the

carbon dioxide back below ground into deep saline aquifers capable of retaining the carbon dioxide for thousands of years with very little leakage back into the environment. Carbon sequestration is essentially a challenge to the conventional thinking, which holds that the fossil fuel industries cannot be part of the solution to the greenhouse problem." Socolow helped promote this field of research by running a workshop on carbon sequestration in Washington in 1997. Early indications from research at CEES on technical approaches to the sequestration of the carbon in fossil fuels suggest that these technologies offer one of the least costly approaches to mitigating the greenhouse problem. From this perspective, hydrogen is the transportation fuel of the future: hydrogen is most of what is left chemically when carbon is extracted from a fossil fuel, and hydrogen fuel becomes harmless water when its energy is used.

Socolow's work on lead has focused on the lead battery. He and his CEES collaborator Valerie Thomas concluded that the lead battery could become one of the first examples of a hazardous product managed in an environmentally acceptable fashion. Industrial ecology makes the distinction between dispersive and recyclable uses of materials: because lead used as a gasoline additive cannot be recovered, it is a dispersive use, while the use of lead in a battery is a recyclable use. Accordingly, Socolow found himself confronting a new question: What should be the criteria for deciding when recycling is environmentally acceptable? These criteria include, Thomas and Socolow decided, nearly 100 percent collection of used batteries; environmentally clean battery dismantlement, secondary lead refining, and battery reassembly; low worker exposures at each step; and exports of used batteries only to places where equivalent stringent environmental standards are in effect.

Socolow has also published a number of papers on nitrogen. Fertilizer production and other human activities have more than doubled the Earth's natural rate of nitrogen fixation, contributing to ecosystem imbalances, air pollution, ozone depletion, and greenhouse effects. Socolow's paper "Nitrogen Management and the Future of Food: Lessons from the Management of Energy and Carbon," published in the *Proceedings of the National Academy of Sciences*, suggests how productive approaches to carbon management, such as focusing on end-use efficiency, encouraging markets in pollution rights, and conducting targeted research and development, can be applied to the emerging challenge of nitrogen management, at scales ranging from the cornfield to the entire globe.

Socolow's work increasingly focuses on ethical aspects of environmentalism. In a 1996 talk at the Yale Institute for Social and Policy Studies, he argued for a moral and reverent response to the Earth's vulnerability:

> Wherein is the moral imperative to enhance those portions of the scientific enterprise likely to illuminate critical environmental issues? It arises from our obligation to preserve the capacity of future generations to enjoy experiences that they value as much as we enjoy what we value.... Each generation must provide the next generation with new capabilities in order to compensate for bequeathing to the next generation a natural environment more degraded than the one it inherited. Where geology threatens to impoverish, the intergenerational accounts must be balanced by scientific understanding, new instruments and devices, and more subtle and effective policies.

Socolow remains optimistic about the Earth's future. "The problem," he says, "is that the Earth is small, compared to the exuberance of the human species. We will have a very challenging time adjusting to the fact that the cumulative effect of the many wonderful things so many of us want to do on this planet is a changed planet. But I believe people will negotiate their way through the environmental challenge. I believe in democracy more than I believe in technocracy. My optimism originates in a conviction that people have a lot of common sense."