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The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The
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Editorial

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Energy, Geopolitics, Sustainability, and Engineering

New realities affecting energy are constantly emerging—not only because of recent events in Iraq and the Middle East, but also because of CO_2 emissions and concerns about global sustainability. Energy is a complicated nexus among four major components: energy, geopolitics, sustainability, and engineering.

The Energy Proposition. The availability of energy, whether human, animal, biomass, fossil, nuclear, or other, has always been essential to the development of human societies.

The Geopolitical Proposition. Control of energy sources is essential to independence and national security. As a corollary, a nation, or, more generally, a social group, must either have sources of energy in its own domain or must project power, economically, politically, or militarily, to control them elsewhere.

The Sustainability Proposition. Reliability of energy supplies and control of the environmental consequences of energy use are essential to the long-term survival of our species. Conflicts arise when nations or social groups differ in their positions on sustainability.

The Engineering Proposition. The task of engineering is to make energy available by exploiting existing sources, finding new ones, reducing the impacts on the environment, and improving the effectiveness of energy use. Consider, for example, that we use a little more than 34 quads of energy but lose almost 58 quads in transportation, conduction losses, etc.

Making energy available and using it while preserving sustainability is, of course, only one aspect of the quintessential mission of engineering (with science) to extend the human reach. That mission is influenced as much by geopolitical realities as by scientific and engineering considerations. While operating in the framework of these realities, however, engineering can also shape them. In the twentieth century, internal combustion engines and turbines revolutionized transportation, and since the middle of that century, nuclear energy has reshaped the geopolitical balance of power.

But engineering cannot go it alone. A close connection with science is a given and has been immensely fruitful. Less of a given, and less familiar territory, is explicit involvement in geopolitical issues and in the global dialogue about sustainability. Usually, engineers have little influence on political decisions and merely respond after the fact.

Because Earth not only contains within itself immense quantities of energy but also receives immense quantities from outside, the long-term possibilities and their implications for human development are enormous. The question being debated hotly in our time is how we can secure a long-term energy future without destroying ourselves and our environment. The challenge is to gain time while we continue to work on a broad front to ensure our future.

To do so, we must remain wary of shortsighted decisions that make it difficult to reduce our energy consumption and its geopolitical and environmental impacts. The United States uses 26 percent of global energy. Even though we have substantially decreased our energy consumption per dollar of GDP, we still consume roughly twice as much energy *per capita* as other countries with the same GDP. The problem involves more than SUVs and blazing lights. For instance, a small but symptomatic fact is that, with 80 percent of the U.S. population living in urban areas, urban planners have thus far largely overlooked energy consequences.

The sober reality about our future perspectives is that, if the number of Americans interested in pursuing education in engineering continues to decline, and if industry finds it increasingly necessary to rely on lobbying and legalistic solutions to technological problems, we will lose our ability to innovate in energy and other fields of technology. At the same time, we will be less and less able to exert leadership in the productive and equitable uses of Earth's resources and to defend the values we hold dear. U.S. leadership is essential if the Earth is to become more sustainable and less prone to violent conflicts and if a long-term future of global energy abundance is to become an uplifting reality.

The papers in this issue are based on presentations from the Symposium on Energy Futures: Opening New Pathways for Innovation in Energy Technology, which was held in December 2002. The symposium was hosted by NAE and the Energy Future Coalition and was cochaired by Timothy E. Wirth, president of the United Nations Foundation, and **Wm. A. Wulf**, NAE president; Robert W. Fri of Resources for the Future was the moderator. The topics addressed will be familiar to readers of *The Bridge*, but they are approached here in a sociopolitical context. The discussion in this issue is focused on what is possible and what is probable at the technology horizon and in market terms.

Environmental policy has been a principal determinant of technological innovation.

How Environmental Forces Shape Energy Futures

Robert W. Fri is visiting scholar at Resources for the Future.

Robert W. Fri

Environmental policy is in large measure energy policy. In the past 30 years, chiefly in the developed world, the demand for environmental quality has had a strong influence on how energy is produced and used. In fact, environmental policy has been a principal determinant of technological innovation in energy. Environmental forces will continue to shape the direction of energy technology but in new ways that place unfamiliar demands on the process of innovation.

The profound influence of environmental requirements on energy technology is apparent everywhere. Automobiles are equipped with catalytic converters and computer-controlled combustion to reduce smog-producing emissions. Electric power plants have become complex factories with electrostatic precipitators, flue-gas desulfurizers, and selective catalytic-reduction units (to control nitrogen oxides). New technologies, like combustion-turbine combined-cycle plants to produce electricity and automobiles with hybrid power plants, are entering the energy system, at least partly because of their attractive environmental characteristics. Finding gas and oil has become less expensive than ever thanks to three-dimensional seismic technology. And a variety of technologies that make energy use more efficient have gradually reduced the amount of energy, and so the amount of pollution, required to produce a unit of GDP.

Up to now, however, most of these innovations have occurred in developed countries, where the demand for environmental quality has been matched by the ability to pay for it. In this setting, the environmental drivers behind innovation have had two common characteristics. First, they have targeted problems, such as visible smog, increased asthma in children, and turbid rivers, that can be understood easily and do not require much explanation to stimulate people to take action. And second, the costs and benefits of solving these problems have fallen mainly on the same groups of people. As a result, existing political institutions have been able to make the trade-offs necessary to impose the public good of environmental quality on private energy markets. I do not mean to suggest that the intersection of environmental and energy policy has been without controversy. But experience has shown that well developed political systems can solve well understood environmental problems within their jurisdictional boundaries, even when there is considerable controversy.

Looking ahead, however, it appears that the most challenging environmental problems will not exhibit these happy properties. The environmental drivers of the energy system will be unfamiliar and will impose new demands on the process of technological innovation. In this article, I will describe three drivers and assess their significance for innovation in energy technology.

Global environmental problems are difficult to manage within traditional institutions.

Global Environmental Problems

Climate change and the loss of biodiversity are the most important problems in the new class of global environmental problems that will take center stage in the next several decades. Unlike the problems of the past, these challenges are neither easy to understand nor easy to manage within traditional institutions. The new problems have two main attributes that differentiate them from past problems.

First, the natural systems involved are large and complex—in fact, global in their reach. As a result, their behavior is very difficult to describe and almost impossible to predict in any detail. Nevertheless, even though the details of how global systems work are not fully understood, enough is known about them to raise serious concerns about anthropogenic threats to them. This creates a dilemma—the need to act, the need to do something, is often clear long before science can say specifically what needs to be done.

Climate change is both a good example of this tension and the problem most likely to bedevil the energy system. The basic physics of the greenhouse phenomenon dictates that increased concentrations of gases like carbon dioxide will result in more solar energy being retained in the atmosphere rather than radiated back into space. Reliable measurements show that concentrations of atmospheric carbon dioxide have been increasing steadily, mostly as a result of human activity. Despite some lingering debate, most scientists now agree that average surface temperatures of the planet have also risen over the past several decades. So, on the fundamentals, the conclusion that humanity is emitting greenhouse gases that are warming the planet seems fairly compelling.

But much is not known. The mitigating effects of clouds and terrestrial carbon sinks, for example, are two important phenomena that are not completely understood. As a result of these uncertainties, models of climate behavior are still approximations subject to change. Moreover, the spatial resolution of the models is sufficiently coarse to make difficult all but the most general conclusions about the location and severity of changes in temperature and precipitation that may accompany climate change. These and a variety of other concerns have created large residual uncertainties about the behavior of the climate system that are properly the subject of extensive research programs.

The policy dilemma is clear. On the one hand, a good scientific case can be made for doing something about climate change, and a rich menu of technologies that would moderate the changes and mitigate their effects is not hard to imagine. Indeed, a number of thoughtful reports have already laid out research programs for the development of technologies to contain greenhouse gas emissions and mitigate their effects. On the other hand, because of the unknowns about the behavior of the climate system, scientists cannot yet identify a level of concentration of atmospheric greenhouse gases that would not be dangerous in some sense (beyond the rather vague goal enunciated in the Framework Convention on

Climate Change). Not enough is known to set a precise goal to inform policies for reducing these emissions. Given these circumstances, it is not surprising that public opinion about climate change ranges from strong support for immediate, forceful action to a reluctance to do anything until the science is more conclusive.

The other departure from the past is that the benefits and costs of managing global environmental systems will fall on populations widely separated in both time and space. This makes it very hard to make trade-offs among the parties that cause and the parties that are affected by the deterioration of these systems.

The separation in space is clear. The cost of reducing greenhouse gas emissions will fall mostly on the nations that burn fossil fuels. In the near term, they will be in the developed world; in the longer term, developing countries will dominate the demand for fossil fuels. But there is no reason to suppose that the distribution of positive and negative impacts of climate change will parallel the intensity of fossil-fuel use. In fact, not releasing carbon into the air is likely to be of most benefit to nations that don't burn much fossil fuel at all, such as low-lying and island countries, sparsely populated areas in higher latitudes, and African nations on the ragged edge of desertification.

The temporal separation of the incidence of benefits and costs is less apparent, but equally important. Because climate change is a function of the stock of long-lived gases in the atmosphere, simple logic dictates that to stabilize (much less reduce) concentrations of these gases, emissions must be reduced to near zero. In other words, putting enough stuff into the air to do damage takes decades, and getting it out will take just as long.

This means that our generation cannot eliminate the possible dangers to the climate system no matter what we do. We will necessarily pass along some of the problem to future generations—indeed, probably quite a lot of it. We are unaccustomed to such a situation. Heretofore, developed countries have approached virtually all environmental problems with the conviction that we *should not* leave anything undone for our successors. We do not have much experience in resolving only part of a problem in a way that shares the burden equitably with future generations.

The challenge of global environmental problems as drivers of the energy system is thus as much a challenge of governance as of technology. These problems have imprecise goals and spatial and temporal dimensions that extend beyond the reach of existing political institutions; in addition, their characteristics are far removed from the experience of most people. Nevertheless, the protection of global environmental systems will persist as one of the most important determinants of innovation in energy technologies for decades to come.

Public opinion on climate change ranges from strong support for action to extreme reluctance.

Energy Needs of Developing Countries

It is both necessary and desirable that for the next century the increase in the demand for energy will be overwhelmingly in the developing world. It is necessary because some forms of energy, especially electricity, are prerequisite to economic development; development simply does not occur without them. It is desirable because other energy demands result from development; increasing wealth leads to the consumption of services like personal mobility, which in turn requires energy. For the poor of the world to be more comfortable and secure, as they ought to be, they will need more of the services that energy provides.

But simply meeting the demand for a major increase in energy consumption is not the central challenge. After all, the developed world met the challenge, and emerging economies in Asia are meeting it today. Indeed, some have argued that increased energy use could be quite modest over the long haul if efficiency gains accompany the rising demand for energy services.

The needs of the developing world will drive the development of the energy system in two more indirect ways. For one thing, coal will be the fuel of choice for the large increase in electricity production that must accompany economic development, because coal is the cheapest and most secure resource for this purpose. Of course, the unconstrained burning of coal results in substantial emissions of both conventional air pollutants and carbon dioxide. Controlling conventional pollutants is not a major technical challenge, but the cost of meeting it could divert scarce resources from investments in economic growth. Controlling carbon dioxide emissions in the growing economies of the developing world will be more difficult, mainly because the costs of control could be very high and the benefits remote from the immediate needs of the poor.

A second issue related to the environmental importance of energy growth in the developing world is that the demand for energy services will arise mainly in cities, where much of the growth in world population will take place. Between 1975 and 2015, for example, the number of cities with more than 10 million persons is projected to rise from four to 22. During the same period, the developed world will add one city in this class—three, up from two. Considerable population growth will also take place in smaller cities. Moreover, energy use is disproportionately concentrated in cities. Cities require energy per person three or four times the world average simply to provide mobility, comfort, and municipal services.

Cities require three or four times as much energy per person as other places.

Rapid urbanization will thus result in the concentration of conventional pollution in cities in the developing world. Because of this concentration, technologies that have worked reasonably well in the developed world may not work as well for the environmental problems of megacities. For example, using personal automobiles to provide mobility in future cities may be to invite gridlock, no matter how cleanly or efficiently they run.

The challenge will be to provide energy services in the great population concentrations of the developing world in new, environmentally friendly ways. The challenge involves the design of urban infrastructure as much as innovation in technologies for producing and using energy. A good example of how infrastructure decisions affect the way cities run is the use of cell phones in China. By relying on wireless technology, development there has simply leapfrogged the hardwire infrastructure of the developed world's communications systems.

Reengineering of the Developed World

Since the early 1970s, environmental constraints on the energy system in the developed world have become steadily more stringent. During this period, new technologies have met these progressively tighter environmental requirements in two ways. In the case of existing capital stock, the policy generally has been to continue to run existing technologies and to add equipment to clean up pollution after it is produced. New plants and equipment, on the other hand, are often designed to produce less pollution in the first place. So far, however, environmental requirements have done little to encourage the replacement of existing capital stock with new technology.

Future environmental requirements are likely to become even more restrictive. With the emergence of global environmental problems, new strictures will come into play, of course, but controls of conventional pollutants will also be tightened. Active litigation in the developed world over nitrogen oxide emissions from electric power plants and new standards for photochemical oxidants, toxic materials, and small particulate emissions are examples of how the screw is turning on pollutants that have been regulated for more than three decades.

The issue thus raised is whether cleanup technologies can remain solutions to environmental problems for existing capital stock. As additional cleanup devices for power plants and automobiles become increasingly costly, the economic case for continuing to run existing plants is deteriorating. In addition, legal and regulatory pressure to accelerate the turnover of capital stock are increasing. For example, current litigation is focused on whether old power plants should have to meet new source performance standards. If these trends persist, as seems likely, future environmental requirements could result in the acceleration of the development and deployment of new energy technologies in the developed world.

Implications for Technological Innovation

The direction in which environmental drivers will push the energy system seems reasonably clear, even though it is risky to predict the specific technologies that will ultimately prevail. In general, the energy system can be expected to move in the direction of decarbonization, either through a shift to less carbonaceous fuels or through the sequestration of carbon dioxide produced by conventional fossil sources. Economic success in the developing world will stimulate large demands for electricity production and pollution control equipment, mostly with conventional technologies. At the same time, rapid urbanization will redefine the way energy services are provided to megacities, in the design of both urban infrastructure and of energy technologies themselves. Pollution control in the developed world is likely to shift from cleanup technologies to inherently less polluting technologies.

In many ways, a more interesting question is how these same environmental drivers will influence the innovation process itself. Arguably, it will become more difficult.

One difficulty is rooted in the nature of global environmental issues, which tend to require that mitigating actions be taken well before the physical systems at risk are fully understood. In addition, as I noted earlier, these problems cannot be resolved in one generation; thus, in some form, the problems will be passed along to succeeding generations. Moreover, because of the complexities of the natural systems involved, public support is harder to muster than for local pollution problems. All of these circumstances have made it difficult to set goals for innovative technologies. In fact, because of the uncertainties of global environmental problems, goals will have to be set and reset over time.

A second difficulty is the mismatch between the need for technological innovation and the "lumpy" permanence of infrastructure investments that will be made in the developing world. Developing economies need a rapid buildup of electric power systems and the metropolitan infrastructures that accompany rapid urbanization. Thus, large investments in long-lived energy production and consumption technologies are bound to be made; indeed, many investments are already being made. As a result, incorporating technological improvements in the capital stock of the developing world presents serious difficulties. The embedded investment in coal-fired power plants in the United States is the result of a similar difficulty and may be an instructive parallel of what could easily happen in the developing world.

Finally, there is likely to be a great deal of political conflict about how to reshape the energy system in response to these drivers. New technologies are likely to benefit people who pay few of the costs, and those who pay the costs may receive few of the benefits. Conflicts of fundamental values are increasing. The poor may be willing to endure considerable short-term environmental costs to achieve economic well-being and may think it entirely fair that the rich bear some of the costs. Moreover, the people who are well-off do not agree about what constitutes quality of life among the rich. One need only observe the controversy surrounding the Kyoto Protocol to see all of these problems at work.

Environmental policy, then, will remain a dominating force in energy policy, and the need for environmental protection will continue to shape the energy system in the coming decades. But there are also substantial institutional obstacles to the creation of conditions conducive to technological innovations to meet these needs. On the one hand, it is probably unrealistic to expect that science will be able to support a case for the urgent diversion of substantial resources to mitigate the risks of energy production and use to global environmental systems or to local pollution in the developing world. On the other hand, failing to set goals that create meaningful incentives for innovation might be even more risky, and incomplete science should not be used as an excuse for inaction. The development of policies and institutions that reconcile these extremes may be the most important challenge to innovation in the energy system.

Acknowledgment

I have borrowed liberally from the work of two colleagues. The material on rapid urbanization is based on a presentation at the symposium by George Bugliarello, chancellor, Polytechnic University. Milton Russell, senior fellow at the Joint Institute for Energy and Environment, University of Tennessee, has written thoughtfully on intergenerational stewardship. While I am deeply indebted to both of these scholars, and to others who have shaped my thinking, I am of course responsible for errors and omissions in interpreting their work.

The next industrial revolution will transform energy production and consumption.

New Energy Technologies
Necessities and Opportunities

Timothy E. Wirth, a former United States senator from Colorado, is president of the United Nations Foundation.

Timothy E. Wirth

Modern energy services are essential to economic development everywhere in the world. Sustained economic progress depends on secure, reliable, and affordable energy supplies. But the current pattern of global energy development—especially its reliance on fossil fuels—brings substantial harm along with its benefits. Three great challenges have emerged that government energy policies to date, particularly in the United States, have largely failed to address:

- the danger to political and economic security from the world's dependence on oil
- the risk to the global environment from climate change
- the lack of access by the world's poor to the modern energy services they need for economic advancement

None of these problems can be solved overnight, but aggressive goals and practical near-term initiatives can accelerate movement toward sounder and more secure energy practices. These steps can also be politically attractive, if they are advanced collaboratively by the constituencies involved, acting in their own self-interest, because the transition to new patterns of energy production and use will create an array of economic opportunities.

The world stands at a crossroads between old, familiar energy practices that create economic, environmental, and security risks and new practices that will open up strategic opportunities for those agile and innovative enough to embrace them. The next industrial revolution, already under way but still in low gear, will transform energy production and consumption. Technological breakthroughs will reduce the dependence on oil and launch an era of cleaner, more efficient, and more secure kinds of power for the global economy. The market rewards for those breakthroughs will be immense. Over the next two decades, up to $15 trillion will be invested in new long-term energy projects (Toepfer, 2001; WEC, 2000a).

If investment is directed toward the right technologies, society will also reap great benefits. Technologies that result in low net carbon emissions will reduce the risk of global warming. Decreasing dependence on oil, especially in the transportation sector, will lessen the danger of economic disruptions from political unrest in oil-producing regions. Technologies that rely on locally available resources will provide the world's poor with greater access to the electricity and fuels they need for development. Technologies that accomplish all three will make the world a safer, more equitable, more prosperous place.

But market forces alone will not accomplish this transformation at the pace or on the scale necessary to shift our reliance away from a single transportation fuel, stabilize the carbon load in the atmosphere, and provide opportunity to the billions of people now consigned to energy poverty. Meeting the energy challenge of this century will require both far-sighted leadership in individual countries and extensive cooperation across the spectrum of international activity—among states and between public investment and private enterprise. Ultimately, success will depend largely on market response, but the choices officials make today will determine when the future of energy will become a reality and how fast, how far, and how copiously the associated benefits will flow.

The potential gains are diverse and substantial. Indeed, speeding up the development and adoption of new energy technologies would be attractive even if the world did not face the risk of oil crises and climate change. The shift will spin off dynamic enterprises and new jobs in the industrialized world and tap latent potential for growth in developing nations. Leadership in the new industries will not depend solely on the availability of natural resources, but also on technological know-how, a skilled labor force, openness to innovation, efficient financial structures, and the strategic foresight to prepare and adapt to the new era. Although the transition will create dislocations, the benefits for the world at large and for the United States in particular will be more than enough to compensate for the costs.

Some of the new technologies are poised for broad commercial application. Power from wind, solar, geothermal, and biomass is already the lowest cost option in some settings. Constant incremental invention has been improving the energy efficiency of buildings, appliances, lighting, computers, and power-generating equipment. Fuel cells, superconducting wires, high-speed electronic controls for the management of power grids, and other possibilities now only barely imagined are just beyond the horizon. The capture and permanent sequestration of carbon dioxide from fossil-fuel combustion is the subject of increasing attention. These technologies hold the promise of significant reductions in both energy consumption and environmental pollution.

The pace of progress, however, will depend on political will, technological advance, skilled labor, sustained incentives for innovation . . . and time. Change will not happen overnight. To sustain the momentum of ongoing discoveries of cost-effective alternatives, it is urgent that we make a beginning.

The next industrial revolution will transform energy production and consumption.

The Energy Future Coalition was established in response to that imperative as an agent of change, dedicated to mobilizing business, civil society, and government to reform the ways energy is created, used, priced, and managed. The coalition's objectives are global, but its immediate focus is the United States, the largest and often most wasteful consumer of energy. America holds many of the keys to the new era—extraordinary wealth, exceptional power, and a singular, proven capacity for innovation. By showing the way to the efficient use and revolutionized production of energy at home, the United States can become a leader of the new energy economy and turn the world away from a dead-end dependence on the fuels of the past.

Security

The global economy will be at risk as long as it depends exclusively on oil for transportation. The price of oil rises and falls suddenly and unpredictably over time, and most of the world's oil is located in political earthquake zones. At the same time, the oil trade causes a staggering transfer of wealth, often from countries that can ill afford the cost. Growing demand for oil, particularly in China, India, and Brazil, will mean a transfer of more than $1 trillion over the next 20 years to the Persian Gulf, where the great bulk of the world's oil reserves are located (Lugar and Woolsey, 1999).

The need for both oil and the money it earns threatens the world's security. Oil provides the riches that trickle down to those who would harm the United States and other nations. The flow of funds to certain oil-producing states has financed widespread corruption, perpetuated repressive regimes, and spawned hatreds that derive from rigid rule and stark contrasts between rich and poor. Terrorism and aggression are by-products of these realities. Iraq may have used its oil wealth to buy the ingredients of mass destruction. In the future, some oil-producing states may try to trade access to oil directly for weapons.

The global economy will be at risk as long as transportation depends on oil.

Although the problem is clear, change will not be easy. For the past three decades—since October 1973, when Arab nations imposed a six-month embargo on oil exports to the United States—America has vowed to reduce its dependence on foreign oil. Each of the last seven presidents has pledged to steer the nation toward greater energy security, but the problem has only worsened. The United States now imports more than half of its oil, a quarter of it from the Persian Gulf. Other countries are even more import-dependent—Japan, for example, buys 75 percent of its oil from the Gulf (EIA, 2002). Of the one trillion barrels of world reserves, fully two-thirds are in the Persian Gulf, only 4 percent in the United States (EIA, 2003). As a result, a substantial portion of the world economy is vulnerable to disruptions in a highly volatile region.

The only effective long-term approach to reducing dependence on oil is to increase efficiency in transportation and to develop alternative fuels. Relying more heavily on domestic oil supplies would have little effect; by any measure, these are inadequate in the United States and in all but a few countries of the world. Even with increased production, substantial vulnerability would remain, because marginal changes in world oil prices reverberate quickly through national economies.

The transition away from oil will take decades, but it is inevitable—global production of oil is expected to peak in the first half of this century. The challenge (and the opportunity) for the United States and other oil-dependent countries is to speed up the transition through smart policies and new technologies. In the transportation sector, vehicle efficiency can be significantly increased by shifting more rapidly away from the standard internal-combustion engine—first to hybrid electrics and then to fuel cells. The production of ethanol from sustainably grown biomass would diversify the world's transportation-fuel supply, stimulate economic growth in rural areas, and contribute no net carbon to the atmosphere. Coal, the world's most abundant conventional energy resource, could become a low-cost feedstock for hydrogen if its carbon content can be captured and permanently stored.

Electric power systems can be made more reliable and less vulnerable to attack through diversified energy supplies and distributed generation. A decentralized power system is inherently safer than a hub-and-spoke system with large power plants dependent on distant fuel sources. A decentralized system would also be less susceptible to fluctuating voltages, blackouts, and other interruptions that are damaging and disruptive to an increasingly digital global economy. Even in the United States, there could be a place on the grid for power generated by home- and factory-based fuel cells, wind farms, solar panels, and other forms of renewable energy, which would also reduce emissions of greenhouse gases and lessen the risk of global climate change.

Environmental Protection

What environmentalists say about energy, as John Holdren (Teresa and John Heinz Professor of Environmental Policy at Harvard University) recently observed, is "not that we are running out of energy but that we are running out of environment—that is, running out of the capacity of air, water, soil and biota to absorb, without intolerable consequences for human well-being, the effects of energy extraction, transport, transformation and use" (Holdren, 2002). Some of the harm has been done on the ground and under the sea, where the extraction and transport of fossil fuels have torn apart landscapes (strip mining) and assaulted coastal ecosystems (oil spills). The burden must also be borne by people who have no choice—who breathe air polluted by lignite, lead additives in gasoline, and cooking fuels used in poorly ventilated shacks. The highest cost—the harm that global warming threatens to inflict on a global scale—will be borne by all of us.

It is now reasonably evident that we must either hold the level of accumulated carbon in the Earth's atmosphere below 550 parts per million (i.e., double pre-industrial levels) or run a high risk of catastrophic shifts in global climate patterns. Without such constraints, the legacy of a century of burning fossil fuels is projected to increase average temperatures by 2.5°F to 10.4°F and raise sea levels by as much as three feet, even with substantial technological advances in the global energy system (IPPC, 2001).

Most experts expect atmospheric temperatures to continue rising at least until midcentury, no matter how rapidly the output of greenhouse gases can be checked. If no substantial changes are made in the world's energy systems, levels of carbon dioxide, methane, and other gases will rise steadily and may bring not just gradual warming but extreme temperature and climatic instability. As the National Research Council stated in a recent report (NRC, 2002):

> *Recent scientific evidence shows that major and widespread climate changes have occurred with startling speed. For example, roughly half the north Atlantic warming since the last ice age was achieved in only a decade, and it was accompanied by significant climatic changes across most of the globe . . . . Abrupt climate changes were especially common when the climate system was being forced to change most rapidly. Thus, greenhouse warming and other human alterations of the earth system may increase the possibility of large, abrupt, and unwelcome regional or global climatic events.*

Half of all jobs worldwide depend directly on natural resources—fisheries, forests, and agriculture—that are potentially affected by climate change (United Nations Development Programme et al., 2000). For example, 70 million people in Bangladesh live in crowded lowlands near the sea, and very large populations in Indonesia and Malaysia are similarly threatened by sea-level rise. In Africa, we can already see drought-diminished agricultural productivity and increasingly scarce potable water, and intensifying hunger, malnutrition, and human misery. Mass flight from such conditions could destabilize fragile governments and erode investments in poverty reduction.

Half of all jobs in the world depend on natural resources that are affected by climate change.

Energy for Development

It makes no sense to leave developing countries behind in terms of climate, the modern energy system, or the global economy. We live in an interdependent age in which no nation is a protected refuge. What happens anywhere to the economy, the environment, and security has impacts on everyone everywhere. Our national security compels us to take an enlightened approach to international progress in service of the kind of worldwide stability necessary for peace, trade, and cooperation.

If the poor countries of the world use coal and oil as wastefully in their development as the industrialized West did, we will all be dealing with the consequences of a warmer world for hundreds of years. But if we invest in clean energy development at home and help emerging economies adopt it, we will not only protect our climate but also create new markets for our products. For many developing countries, the adoption of a dispersed system of energy production based on indigenous, sustainable resources would enable them to leapfrog most of the conventional, centralized, environmentally harmful systems of the industrialized world.

Of the world's six billion people, roughly one-third enjoy the kind of energy services we take for granted—such as electricity at the flick of a switch. Another third have these services intermittently. The final third—two billion people—have no access to modern energy services (WEC, 2000b). Not coincidentally, the two billion energy-deprived people are the world's most impoverished people—living on less than $2 per day. And their ranks will grow; the 50 poorest nations will triple in size over the next 50 years (United Nations Population Fund, 2002).

For the poor of the world, especially in rural areas, energy use involves high cost, exposure to pollution, and the time-consuming drudgery of collecting and transporting traditional fuels—often gathered by hand and used at great harm to the local environment. Equally important, the poor lack the benefits of modern energy services—lights to read by, refrigeration to store medicines, transportation to get products to market, let alone telecommunications and information technology—prerequisites all for economic growth and the alleviation of poverty.

Mobilizing the economic and political will to change is a formidable challenge.

Rich nations cannot ask the poor to refrain from using the energy essential for growth, even as the rich consume 10 times as much energy per capita (World Summit on Sustainable Development, 2003). They can, however, widen the options available to countries that require large new inputs of energy to modernize their societies and economies, to lift their people out of poverty, and to put themselves on a faster, steadier track to prosperity. As a matter of self-interest alone, the developed nations of the world have every reason to help their needier neighbors generate power efficiently and as much as possible from non-fossil fuels.

The G8 Task Force on Renewable Energy concluded in 2001 that "renewable energy resources can now sharply reduce local, regional, and global environmental impacts as well as energy security risks, and they can, in some circumstances, lower costs for consumers" (G8 Renewable Energy Task Force, 2001). An investment of $250 billion over 10 years would provide renewable energy to 1 billion people—200 million in the OECD countries and 800 million in the developing world. Although in the first decade costs would be marginally higher than the costs of continued reliance on conventional energy production—because of higher initial capital costs—in the long term, at realistic real discount rates, the costs would be lower.

Effecting Change

Any forecast of the energy future must be hazy at best. Clearly, oil and coal will remain important sources of energy for some time, and natural gas and renewable energy sources are likely to capture an increasingly large market share. Beyond this, however, very little can be predicted with assurance. The decisions that will define the way ahead have not yet been made. Nevertheless, the long lifetime and high cost of energy infrastructure require that we take decisive early steps to encourage the development and deployment of alternative technologies. Innovation will not flourish on its own merits alone but will reflect the support it receives and the setting in which it is exploited.

In terms of policy, no matter which sectors or countries are involved, leaders must determine a responsible course of short- and medium-term measures that will advance the long-term transition to new energy sources and uses. These steps should begin with putting limits on greenhouse gas emissions. They should also include more rapid adoption of new vehicle technology and alternative fuels; truly clean use of coal by capturing emissions; a digital-age electric power system that facilitates small-scale, networked power generation; and new financial tools to encourage private-sector investment in energy development outside the industrialized West.

The Energy Future Coalition and the National Academy of Engineering convened this Symposium on Energy Futures to focus on new pathways for innovation in energy technology and policy. Our discussions confirmed that a broad range of technologies can be brought to bear—from clean energy options that are gaining a growing share of the market today to, possibly, carbon-converting microbes in the future.

Mobilizing the economic and political will to make this transition is a formidable challenge. No single nation or banker, no automaker or inventor, can effect such complex, profound, long-standing change. And only America can take the lead—not only because the United States consumes one-fourth of the world's energy or because of its technological primacy, its deep pockets, and its vulnerability to oil shocks and to terrorism. The reality is that where America goes, others will follow. America's example, for good or for ill, will set the tempo and direction of action, far beyond our borders and far into the future.

The most important thing is to begin. President Kennedy, whose bold commitment led America to the triumph of the first manned moon landing, often told the story of the aged Marshal Lyautey of France debating with his gardener about the wisdom of planting a certain tree:

"It will not bloom," the gardener argued, "for decades."

"Then," said the marshal, "plant it this afternoon."

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Two scenarios of our energy future challenge current corporate strategies and energy policies.

Meeting Future Energy Needs
Choices and Possibilities

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Ged Davis

Recent discussions of energy policy have almost inevitably been focused on the short term. The effects of the conflict in the Middle East on oil prices and availability, as well as potential threats to oil supplies from terrorism, require urgent consideration. However, we must not allow our immediate concerns to cloud our vision of the future. Policies to deal with future energy needs and ensure their sustainability must be set in train now.

Future challenges fall into three time frames, each of which presents particular but interrelated policy questions. In the short term, the key issues are the dynamics of oil pricing and our ability to deal with shocks to the energy system. In the medium term (to 2020), we will have to bring new sources of supply to maturity and deal with emergent risks. In the long term (to 2050), the focus will be on the availability of resources beyond the era of hydrocarbons, climate change, and the capacity to meet the energy needs of eight to nine billion people. Analyses of the needs of each time frame should inform what we do *now*. Providing energy requires long lead times, and we cannot delay making investment decisions without incurring future costs.

This article is focused on possible longer term developments in the energy industry and alternative futures for 2050 based on Shell's current long-term scenarios (Shell International, 2001). These are not projections, predictions, or preferences; they are stories about the future relevant to Shell's business—developed to challenge the underlying assumptions of current corporate strategies and energy policies.

Exploring the future of energy is particularly challenging because we appear to be entering a period of innovation in energy development, and there are several different paths the energy system might take. Between now and 2050, those paths will be determined by a wide range of needs, possibilities, and choices by consumers, business, and governments. Let us start by looking at possible energy requirements.

Links between Energy and Income

Recent UN midrange population forecasts indicate a global population of some eight to nine billion people in 2050, 80 percent of whom are likely to be living in cities. At the same time as the population increases, incomes will rise, and with them the demand for energy. The pattern of economic development throughout the world suggests that, as annual per capita GDP reaches about $3,000 and as industrialization and urbanization take hold, the demand for energy will increase dramatically. By the time income reaches $10,000 per capita, industrialization will be complete; at $15,000 per capita, energy demand will slow; by the time it reaches the current income level of OECD countries, less energy-intensive services will dominate economic growth and energy demand will reach a plateau and could even decline.

At the moment, about one billion people worldwide rely mainly on biomass or animal waste for fuel; these people are not even on the bottom rung of the energy ladder. Another four billion have yet to enter industrial development fully, but by 2050 many of them will have incomes well above $3,000 per capita, meaning that we must be prepared for the global demand for energy to double or triple. Much will depend on whether the future demand in countries such as China and India reaches a plateau at closer to 100 or 200 GJ per capita. In Europe today average annual per capita consumption is close to 150 GJ.

We believe that the fundamental drivers of the patterns of longer term energy use will be the balance between personal and social priorities, resource constraints, and technology options.

Personal and Social Priorities

Energy choices may reflect predominantly personal decisions made through the market or collective decisions made by governments. The attitudes of governments and public opinion on questions such as energy and the environment and energy security will significantly influence the way future energy systems develop. Personal choices that reflect values, environment, and lifestyles will also be influential and will be reflected in patterns of consumption. At higher income levels, these factors tend to override concerns about affordability.

We believe oil supplies will not peak before 2025.

Resource Constraints

The second driver is the availability of energy resources. Some commentators believe that there will be imminent constraints on the ability of fossil fuel resources to meet increases in energy demand. However, we think oil supplies, including unconventional sources and natural gas liquids (NGLs), will not peak before 2025, and could be even later. This view is based on recent estimates by the U.S. Geological Survey that there are some three trillion barrels of ultimately recoverable resources of conventional oil; Shell's own estimate is even higher. In addition, another trillion barrels could come from heavy oils and NGLs.

The outlook for natural gas is more complex. As much as two trillion barrels of oil equivalent conventional natural gas are potentially available. However, there is more uncertainty about the precise amount we will be able to recover, because half of the estimated gas has yet to be discovered. In addition, there may be very large reserves of unconventional gas, as well as the emergence of new technologies to convert both coal and oil into gas. This means the range of resource availability is extremely wide; it could peak as early as 2025 or not until well after 2050.

A further challenge will be to provide the infrastructure to bring those resources to market. Much of the world's gas supply is situated in remote areas far from end-users. The investment required to construct pipelines and to transport gas to European and Asian markets will be substantial and will have a very long payback time. To ensure that investments are timely, commercial and political drivers will have to be aligned and decisions made soon.

Renewable energy sources (called "renewables") offer a variety of alternative energy sources with the potential to meet all of our energy needs. Geothermal and solar energy alone could each supply 250 GJ per year to 10 billion people, assuming economically viable technology is available. With the exception of Asia and Europe, most regions of the world could be self-sufficient. However, widespread use of these intermittent sources of energy will depend on the development of new forms of energy storage and competitive economics.

Technology Options

Technology has always been a key determinant of energy requirements. For example, over a period of 250 years, advances in steam engine technology increased the thermal efficiency of the transformation of coal 25 fold; over any 50-year period, it increased by 2 to 7 fold.

We now appear to be entering a very innovative period in energy development when more resources than ever before will be devoted to scientific research and technological development. Information and communications technology offer new ways of analyzing information and sharing knowledge. We could see advances in biotechnology and materials technology, such as carbon nanofibers and computing, that would support the development of biofuels, fuel cells, and new energy carriers (such as hydrogen), micropower networks, and new solar technologies. Each of these developments has the potential to have a major impact on the energy system. However, it is difficult to predict which technologies will make the biggest contribution.

Advances in technology are likely to be discontinuous rather than evolutionary.

Traditional fuels could also benefit from technological innovation. With technological advances, coal, which currently has significant environmental disadvantages, could reemerge as a fuel for power generation. New approaches to carbon sequestration could provide solutions to increased concentrations of atmospheric carbon dioxide from emissions. And what if we had a publicly acceptable, safe nuclear option?

It seems clear that advances in technology play a central role in energy transitions. But these changes are more discontinuous than evolutionary. The steam engine, electric dynamo, internal combustion engine, nuclear fission, and combined-cycle gas turbines all succeeded by offering superior or new qualities—often transforming lifestyles as well as energy supplies.

Scenarios for 2050

In our scenarios, *Dynamics as Usual* and *Spirit of the Coming Age*, we set out two alternative future energy stories for 2050 that explore the impacts of some of these technologies. Both scenarios recognize the potential for discontinuities and the emergence of new manufacturing technologies.

The *Dynamics as Usual* scenario focuses on choices by citizens for clean, secure, increasingly sustainable energy. As resources become increasingly scarce, these choices lead to reliance on renewables. The alternative scenario, *Spirit of the Coming Age*, focuses on energy choices by consumers in response to revolutionary new technologies that transform the energy system. In this scenario, there is a surprising increase in the use of fossil fuels and the development of worldwide carbon sequestration.

These two scenarios, which are discussed in more detail below, reflect differences in energy resources, the timing and nature of developments in technology, and social and personal priorities. Although they outline distinctly different paths, they have important common features, including the vital role of natural gas as a bridge fuel for at least the next two decades; pressures on the oil market as new vehicle technologies are adopted; a shift towards distributed heat and power supply for economic and social reasons; and the potential for renewables (if robust energy storage solutions are found).

Dynamics as Usual

In *Dynamics as Usual* the policy emphasis for the coming decade is on energy security and environment, with government as the clear leader in setting priorities. The urgent demand for secure, clean, sustainable energy stimulates a drive for energy efficiency. The bias is towards reinforcing existing technologies, particularly the internal-combustion engine. Advanced internal-combustion and hybrid engines are developed that can deliver the same performance as standard vehicles using as little as one-third the fuel.

Over time the costs of these vehicles decreases until they are lower than those of conventional cars. The large-scale market penetration of these superefficient vehicles disrupts oil markets, leading to weaker oil prices. As demand for transport and heating fuels grows in developing countries, oil prices recover. These price pressures also spur advances in oil recovery techniques thus expanding recoverable reserves. Oil demand then grows steadily, though weakly, for another 25 years.

Also in the coming decade, with strong government support in OECD countries, renewable energy grows rapidly for two decades through established electricity grids. As turbines increase in scale, exceeding 3 MW, the costs of wind energy continue to fall. The commissioning of a 200 MW photovoltaic manufacturing plant before 2010 dramatically reduces manufacturing costs. By 2020, a wide variety of renewable sources supplies 20 percent of the electricity in many OECD markets and nearly 10 percent of global primary energy.

By 2020, growth stalls because rural communities that were happy to accept a few windmills refuse to accept hundreds of them. A shortage of land and environmental concerns prevent the large-scale development of electricity from biomass. With little progress on energy storage, concerns about the reliability of the power grid block further growth of wind and solar power. Although the public supports renewables, limited electricity growth constrains expansion in OECD countries. In developing countries, renewables are still not fully competitive with low-cost conventional resources.

In the 2020s, as renewables stagnate and security concerns about gas increase, it is not clear what the main source of future energy supplies will be. Nuclear energy makes a partial comeback, particularly in Asia. Investments in energy efficiency buy some time, but it is becoming increasingly difficult to meet rising environmental standards with established technologies. In the 2020s, deep energy policy dilemmas must be confronted.

The use of natural gas expands rapidly in the early part of the century—reflecting economic and environmental advantages in liberalized markets. Where gas is available, it fuels most new power generation and accounts for three-quarters of incremental increases in OECD capacity until 2015. Older coal plants that cannot meet tightening emissions standards are increasingly replaced by gas.

The rising costs and logistical complexity of expanding coal deliveries from northern mines prompt China to embark on major gas import projects. Pan-Asian and Latin American gas grids emerge, and the large-scale liquefied natural gas trade is increasingly competitive. By 2020, gas is challenging oil as the dominant source of primary energy. However, because many users import gas, unease about supply security is growing. Uncertainties about the availability of long-term resources and fears of political disruption in supplying countries begin to slow the growth of gas use.

At the same time, new nuclear plants are also having trouble competing in deregulated markets. Most existing nuclear capacity is maintained, but nuclear power steadily loses market share in OECD countries. There is limited expansion in some developing countries, but there is little public or political support for new investments in technologies that might reposition nuclear energy as a premium clean fuel.

The Dynamics as Usual *scenario shows a steady decline in the use of oil and coal.*

So how are energy policy dilemmas resolved? A new generation of renewable technologies emerges in the 2030s. The most important are organic and thin-film, embedded solar materials. New ways of storing and using distributed solar energy are developed. By 2050, renewables supply one-third of world primary energy, as well as incremental energy needs. As hydrocarbon-based liquids become scarce in the 2040s, advances in biotechnology, together with vastly improved vehicle efficiency, enable a relatively smooth transition to liquid biofuels.

In summary, this scenario shows a steady decline in the use of oil and coal, an increase in the use of gas in the early part of the century, then a decline after 2025, and a sharp increase in the use of new renewables and biofuels. This takes place in a very competitive environment characterized by the rise of new energy industries.

Spirit of the Coming Age

The second scenario, *Spirit of the Coming Age*, outlines a world in which new and superior ways of meeting energy needs are developed to meet consumer preferences. The scenario is characterized by experimentation and many failures. Solutions trigger technology revolutions, and discontinuities arise from seemingly mundane parts of the energy system.

In the early twentieth century, a new engine technology, coupled with a portable, dense fuel, transformed transportation. This revolution began with fuel in a box, sold in local hardware stores, that was adequate for limited travel along the few paved roads. Efficiency considerations drove the development of today's fueling infrastructure—now a valuable economic asset, as well as a barrier to change.

Developments in the early twentieth century were based on remarkable discoveries and inventions in the 40 years prior to 1910—from tires and gasoline engines to gas turbines and airplanes. Each of these developments became possible through the entrepreneurial drive to bring new products to market. A century after the technology that made personal transport possible, mobility is considered essential to the freedom, flexibility, convenience, and independence people want, and increasingly expect. Today time is precious.

In the Spirit of the Coming Age *scenario, governments are reluctant to intervene in energy markets.*

In the *Spirit of the Coming Age* scenario, governments are reluctant to intervene. They do not subsidize renewables, and they allow energy choices to be made through markets. New energy options made possible by new technologies are critical. In the first decade, the demand for stationary fuel cells—with businesses willing to pay a premium to ensure highly reliable power—helps drive fuel cell system costs below $500 per kW.

Low-cost fuel cells provide a platform for transport uses, stimulating further cost reductions—until they are well below the cost of conventional power and heat technologies. At this point, suppliers of home appliances turn to fuel cells. Commercial and residential buildings install low-cost systems—fuelled from the established natural gas grid—and trade spare peak-time electricity through markets. Hot water is provided by surplus fuel-cell heat.

As fuel cell costs drop, interest in transport applications increases. Initially, liquid fuel—from oil, gas, or biomass—is reformed into hydrogen in vehicles. Fuel cells help sustain the demand for personal mobility and offer environmental benefits for urban transport. The new economics of fuel cells and breakthroughs in cheap hydrogen storage in the second decade provide a basis for rapid commercial development. By 2025, one-quarter of the OECD vehicle fleet uses fuel cells, which also account for one-half of new vehicles in OECD countries and one-quarter of new vehicles worldwide. The global automobile industry rapidly consolidates around the new platform.

In the second quarter of the century, China uses advanced hydrocarbon technologies as a bridge to a hydrogen economy. By 2025, China's huge and growing use of vehicles is creating an unacceptable dependence on imported oil. Concerns about the sustainability of regional gas resources and the reliability of external suppliers encourage the use of indigenous coal, but this creates logistical and environmental problems. The scarcity of land limits opportunities to develop biofuel. India faces similar problems, and growing global demand for gas and hydrogen spurs advances in in-situ extraction of methane and hydrogen from coal and oil shales.

These advanced hydrocarbon developments build on established infrastructure and technologies, as well as on the cash flow and resources of existing fuel suppliers. China is able to make use of these technologies—as well as indigenous advances—to extract energy from its coal resources and deliver it by pipeline rather than by many thousands of trains. A new industry based on mine-mouth hydrogen production and carbon sequestration is developed, which enables the development of transport and power systems based on fuel cells.

Hydrogen is widely produced from oil, gas, and coal with an increasing trend toward the extraction and sequestration of carbon dioxide at the source. The demand for gas continues to grow and finally outstrips the demand for oil. However, renewables become increasingly important in the second quarter of the century, and sequestration peaks at 2.3 billion tonnes per annum by 2050, one-fifth of total emissions.

In summary, in the *Spirit of the Coming Age* scenario, energy supplies continue to evolve from solids through liquids to gas (first methane then hydrogen), supplemented by electricity directly from renewables and nuclear power. Large-scale renewable and nuclear energy schemes to produce hydrogen by electrolysis become attractive after 2030. Renewable energy becomes a bulk supply business and expands rapidly.

Hydrogen is transported in gas grids until demand justifies investment in dedicated hydrogen pipelines. A century-long process of hydrogen infrastructure development begins.

Conclusion

Although these two scenarios explore different energy paths, emissions of carbon dioxide turn down by 2040 in both. Emissions slow earlier in *Dynamics as Usual* in response to social pressures but then accelerate again after 2025. In *Spirit of the Coming Age*, they rise faster initially but peak earlier—and sharply decline with the expansion of carbon sequestration. Atmospheric concentrations remain below 550 ppmv for the remainder of the century and appear to remain on track to stabilize below this level.

The way both scenarios develop depends on decisions we make now and on technological breakthroughs. As important as it is to focus on short-term and medium-term challenges, we must also pay attention to preparing the energy industry for the long term to ensure sustainability and security. This will require not only well crafted policies, but also astute political leadership.

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The U.S. electricity-supply system is in urgent need of modernization.

Powering the Digital Age

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Kurt E. Yeager

Three years ago, the National Academy of Engineering voted "widespread networks of electrification" the number one engineering achievement of the twentieth century (NAE, 2000). A key issue today is whether these networks will be the critical infrastructure that powers the twenty-first century or will be left behind as industrial relics. The modern technological world enabled by access to electricity—from electronics and computers to information technology—is rapidly moving away from its supporting infrastructure. As a result, the U.S. electricity-supply system is in urgent need of modernization (EPRI, 1999).

The supporting electricity infrastructure must keep pace with the digital transformation of the economy. Global competition, which impacts virtually every business in the United States, is a major driver in the move to digitally controlled electricity use. It is hard to imagine a major industrial process, manufacturing facility, or commercial business in 2020 that will not use digital control and interactive links to its consumers. These links will be most effective if they are managed by an "energy web" that integrates power generation and power flow with information and communication. The energy web will become a national system in which "every node in the power network is awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, and interconnected with everything else" (Silberman, 2001).

We use the term "smart grid" to describe the backbone of this energy web—an intelligent, electronically controlled power system that will supercede today's electromechanically controlled system. And the sooner the better. The greatest benefit of the smart grid will be the opportunities it opens for society as a whole. A transformed electricity system would, for example, enable a substantial increase in productivity, improve energy efficiency and resource utilization, and generate substantial additional wealth to meet the growing societal and environmental needs of the twenty-first century. By 2020, a transformed electricity/information infrastructure could conceivably enable as much as $2 trillion a year in additional GDP for the U.S. economy. The aging U.S. population will be increasingly dependent on a smaller but more productive workforce, and a smart infrastructure will ensure that today's high levels of productivity can be sustained and expanded (EPRI, 1999).

Engine of Growth

The primary engine of U.S. productivity growth is the constantly shrinking digital computer, which has evolved from mainframes to PCs to microprocessors in just a few decades. The pattern of computing power has been one of distributing intelligence, first to institutions and industrial processes, then to individuals, and now to appliances, machines, and tools of all types. An estimated 15 billion microprocessors are operating in the United States today embedded in devices of all sorts—from automobiles to thermostats. A principal force for productivity enhancement in the next 20 years will be the proliferation of cheaper, more powerful microprocessors, coupled with the networking of these devices via the Internet or its successor.

Once microprocessors are connected, they can be optimized for productivity gain and, through the advantages of "networked intelligence," they can link and govern multiple processes at the same time. As networks become larger, the components—the constantly shrinking microprocessor—become smaller. Today there are tens of billions of microprocessors; tomorrow there are likely to be trillions. Simple microprocessors have become so cheap and so plentiful they are referred to in the trade as "jelly beans." They are expected to continue shrinking to the level of "dust," which will enable the distribution of sensors and intelligence in ways that are almost unimaginable today. Microprocessors and their derivative "nanoprocessors" might, for example, be used to coat the surface of a machine to create the equivalent of a nervous system fully attuned to its environment. With the digital technology "platform," in time the electricity and information networks—both running on electrons—will converge into a new "mega-infrastructure" (Figure 1). Some say this is already happening.

Infrastructure Implications

Despite its promise, digital technology remains a "thoroughbred technology" because of its speed and fragility. Digital technology is highly sensitive to even slight disruptions in power (an outage of less than a fraction of a single cycle can cause a crash), as well as to variations in power quality caused by transients, harmonics, and voltage sags (EPRI, 2001). The demand for "digital-quality power," reliable, high-quality power to serve digital applications, now represents less than 10 percent of total electrical load in the United States. It could reach 30 percent by 2020 under business-as-usual conditions and as much as 50 percent under optimum conditions (i.e., a power system revitalized with new all-electronic switches and controls).

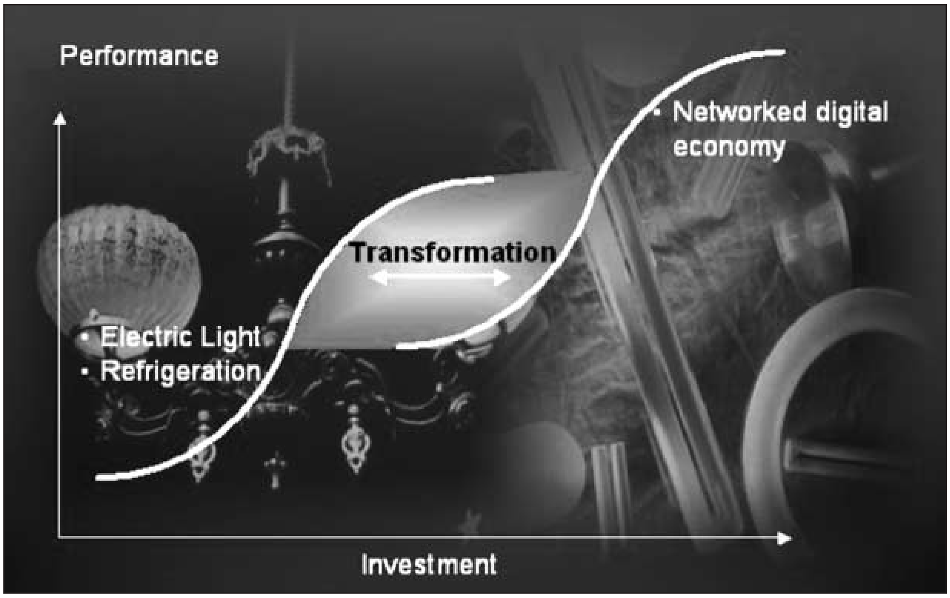

FIGURE 1 Breaking the limits on electricity value.

In contrast to the rapidly growing need for high-quality power, the electricity-supply infrastructure has actually changed very little, and the rate of investment in infrastructure upgrades is at an all-time low. Capital expenditures for electricity infrastructure were only about 12 percent of electricity revenues during the 1990s, less than one-half of historic minimum levels and below the level reached only briefly during the Depression. In short, the electricity-delivery system is not keeping up with the demands of the digital economy. The transmission and distribution systems were designed for the industrial era of the 1950s and 1960s, when mechanical switching and radial-network design were adequate. Annual investment in the transmission system alone has been cut in half since 1975. Despite increased demands on the system, plans for capital expenditures and the current lack of investment confidence and incentives suggest that underfunding will continue.

Thus the gap is widening between the economy and the critical infrastructure that supports it (Figure 2). Without substantial investment, the electricity-supply system will almost certainly become an increasing drag on future U.S. economic growth.

Signs of Trouble

There are already signs of trouble. Because of the obsolete mechanical control of the electricity-supply system today, it is unnecessarily vulnerable in its capacity, reliability, and security, as well as its capability to meet consumer expectations in the twenty-first century. These limitations could lead to an economic decline that cascades through the system, leading to large losses of revenue to consumers and power suppliers.

A survey of economic losses in key industries sponsored by the Electric Power Research Institute (EPRI) showed that the aggregate economic loss from power disturbances of all types represents more than 1 percent of U.S. GDP (EPRI, 2001). These costs are parasitic in nature and are largely unnoticed, but roughly $400 per person in economic loss from power disturbances is being passed along to consumers every year in the form of higher prices for goods and services. Moreover, for businesses that are highly dependent on the digital economy, power-conditioning equipment and backup power systems account for as much as 60 percent of the cost of construction of new facilities. This figure is dramatically higher than estimates of just a decade ago, and economic losses are almost certain to increase in the years ahead unless steps are taken now to improve power reliability.

The survey sampled a cross-section of 985 firms in three sectors of the economy that are particularly sensitive to power reliability: "digital economy" (e.g., data storage, financial services, online services, etc.); fabrication and essential services; and continuous-process manufacturing. These three sectors account for 40 percent of GDP. The study revealed that the greatest losses from power outages were in the continuous-process industries, which suffered the loss of raw materials, as well as down time and equipment damage (Figure 3). The greatest loss from problems with power quality (e.g., sags in voltage, etc.) was in the fabrication industries, often as a result of equipment damage. The total for all three sectors was more than $50 billion. If we extrapolate these losses to the full economy, a conservative estimate of total losses would be at least $120 billion per year, which means an additional cost of about 50 cents for every dollar of electricity purchased.

There are other troubling signs of problems with the current power infrastructure. Serious incidents reflecting constrained capacity, often accompanied by price spiking and questionable financial dealings, have occurred in six of the last seven years. These problems have affected the Northeast, the Midwest, and California. Most

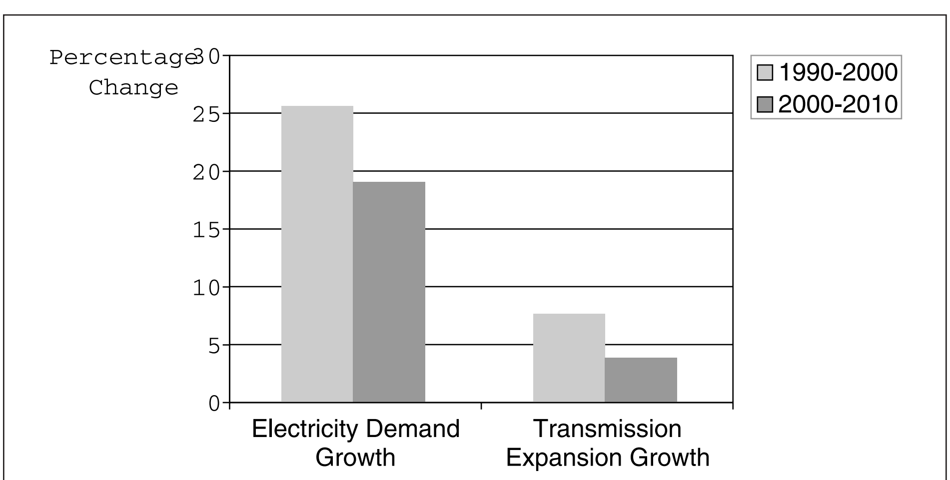

FIGURE 2 Increasing constraints on the transmission grid. Source: Adapted from NERC, 2001, 2002.

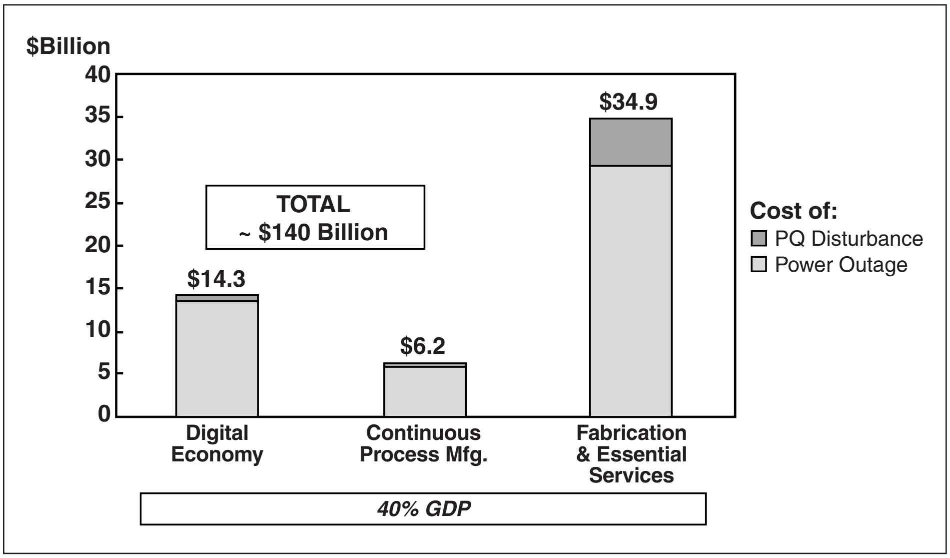

FIGURE 3 Annual cost of power outages and disturbances, by business sector.

observers have concluded that these problems would have been even worse if it had not been for the economic downturn and the resulting temporary impact on electricity demand.

Development of the Twenty-First Century Power System

Advanced technology now under development, and in many cases ready for deployment, holds open the promise of fully meeting the electricity needs of a robust digital economy. In broad strokes, the envisioned system-architectural framework encompasses an integrated, self-healing, electronically controlled electricity-supply system of extreme resiliency and responsiveness that is fully capable of responding in real time to the billions of decisions made by consumers and their increasingly sophisticated microprocessor agents. In short, the potential exists to create an electricity system that is as efficient, precise, and interconnected as the billions—ultimately trillions—of microprocessors it will power (Figure 4).

This smart power system is conceived as an electricity/information infrastructure that will enable the next wave of technological advances in the economy to flourish. The electricity grid will be always on and "alive," interconnected, interactive, and merged with communications in a complex network of real-time information and power exchange. It will be self-healing in the sense that it will constantly monitor and correct itself to keep high-quality, reliable power flowing. The system will sense disturbances and counteract them, or instantaneously reconfigure the flow of power to cordon off damage before it can propagate. It will be able to integrate traditional central power generation seamlessly with an array of locally installed, distributed power sources (e.g., fuel cells and renewables) into a more robust regional network. This transformed power system would become a superhighway network for electronic commerce, the electrical equivalent of transforming the unpaved roads of the nineteenth century into the highway system of the twentieth century.

To complete the picture, new digital technology will also open the consumer gateway, which is now constrained by the meter, allowing price signals, decisions, communications, and network intelligence to flow back and forth through the two-way "energy/information portal." This will be the linchpin technology that leads to a fully functioning marketplace with consumers responding in real time (through their microprocessor agents) to price signals. This tool would enable consumers and providers to move beyond the commodity paradigm of twentieth-century electricity service, quite possibly ushering in a new array of energy/information services as diverse as today's telecommunications services.

The energy/information portal would have the following specific capabilities:

- advanced pricing and billing processes that would support real-time pricing
- consumer services, such as billing inquiries, service calls, outage and emergency services, power quality, and diagnostics
- information for developing improved building and appliance standards
- consumer-load management through sophisticated, on-site, energy-management systems
- easy "plug-and-play" interconnection of distributed-generation sources

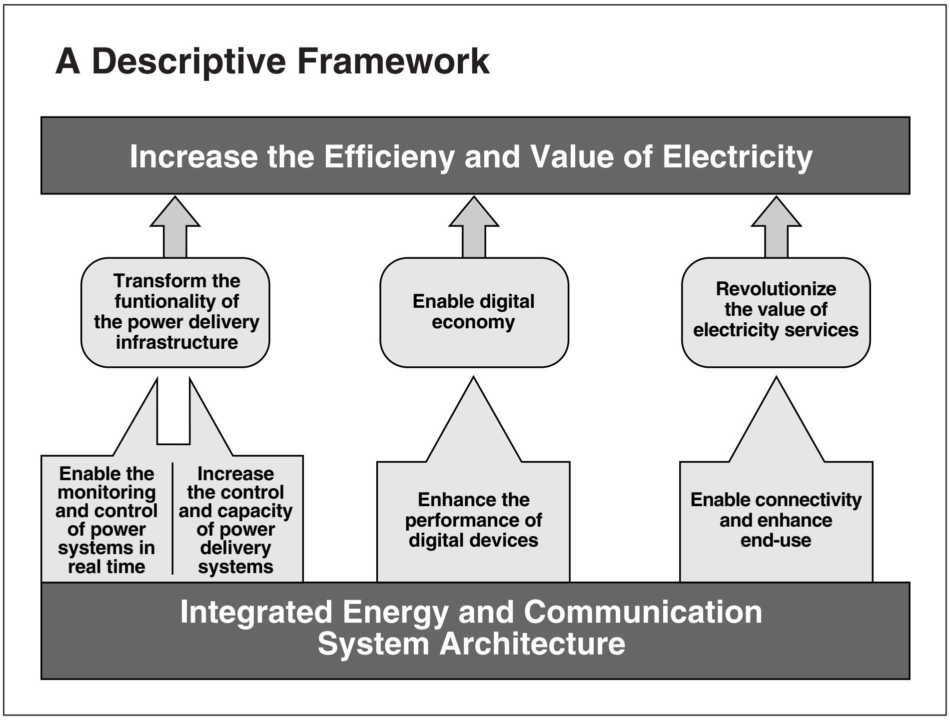

FIGURE 4 Integrated energy and communication system architecture.

- system operations, including dispatch, demand response, and loss identification
- load forecasting
- long-term planning
- green-power marketing and sales

These capabilities have the potential to improve dramatically the reliability and productivity of the electricity-supply and delivery functions. In addition, they will lead to cost savings and increased productivity for end-use consumers.

Building Blocks

The basic building blocks of the power system of the future include advanced sensors, data-processing and pattern-recognition software, and solid-state power-flow controllers, such as the flexible AC transmission system (FACTS) to reduce congestion, react in real time to disturbances, and redirect the flow of power as needed. There are three primary objectives: to optimize the overall performance and robustness of the system; to react quickly to disturbances to minimize their impact; and to restore the system after a disturbance.

An array of real-time sensors will monitor the electrical characteristics of the system (e.g., voltage, current, frequency, harmonics, etc.), as well as the condition of critical components (e.g., transformers, feeders, circuit breakers, etc.). The system will constantly "fine tune" itself to achieve an optimal state, constantly monitoring itself for small problems that could lead to larger disturbances. When a potential problem is detected and identified, its severity and consequences will be assessed. Various corrective actions can then be identified, and computer simulations used to determine the effectiveness of each action. When the most effective response has been identified, a situational analysis will be presented to the operator, who can then implement the corrective action very efficiently by taking advantage of the grid's automated control features, such as dispatch control of distributed resources and parameter tuning of solid-state power-flow controllers.

When there is an unanticipated disturbance, it can be quickly detected and identified. An intelligent islanding or sectionalizing scheme, for example, can be activated instantaneously to separate the system into self-sustaining parts to maintain electricity supply for consumers according to specified priorities and to prevent blackouts from propagating.

Following system reaction to a major disturbance, steps will be taken to return the system to a stable, operating regime. To do so, the state and topology of the system must be monitored and assessed in real time so alternative corrective actions can be identified and the effectiveness of each determined by look-ahead computer simulations. The most effective actions would then be implemented automatically. Once a stable operating state has been reestablished, the system will again start to self-optimize.

Meeting these objectives will be an iterative process, with system optimization as the primary goal during normal operation. When a disturbance occurs, the operating objectives will shift from reaction to restoration, and finally, back to optimization. In this sense, the smart power-delivery system can be called self-healing.

Technology Requirements

One of the key technologies for a smart power-delivery system is a real-time, wide-area monitoring system. Elements of such a system are already in operation on both the transmission and distribution system. For example, the wide-area measurement system (WAMS), originally developed by Bonneville Power Administration, is a system based on high-speed monitoring of a set of measurement points by means of phasor measurement units, "concentration" of these measurements by means of phasor data concentrators, and generation of displays based on these measurements. WAMS provides a strong foundation on which to build a real-time, wide-area monitoring system for a self-healing grid. The system architecture will define the data, communications, and control requirements.

Substantial work has been done by EPRI and others to determine the root causes of failures in critical components, such as transformers, cables, surge arresters, and other devices, to develop monitoring and diagnostic systems for these components. The next step is to develop fault-anticipation technology that will provide early warnings and forecast failures. Work on fault anticipation for overhead distribution systems is currently under way.

Following a terrorist attack or a major disruption of the grid from natural causes, the initial reaction will focus on creating self-sufficient islands in the power grid; those islands will make the best use of the network resources still available. Adaptive islanding will require new methods of intelligent screening and pattern extraction that can rapidly identify the consequences of various island reconnections. Adaptive load forecasting will also be used to dispatch distributed resources and other resources in anticipation of section reconnection and to help stabilize the overall transmission-distribution system.

Once predictions have been made about the effectiveness of potential control actions, the identified actions must be carried out quickly and effectively, which will require automating many operations to make human intervention in both transmission and distribution systems more efficient. The challenge is to develop new equipment with the required intelligence and to develop strategies for retrofitting existing equipment.

By acting quickly enough to provide real-time control, solid-state power-flow controllers, such as FACTS and custom-power devices, can increase or decrease power flow on particular lines, thus alleviating system congestion. These controllers can also improve system reliability by counteracting transient disturbances instantaneously, which will make it possible to operate the system closer to its thermal limits. After nearly 25 years of research, FACTS and custom-power controllers based on silicon power electronics are now entering utility service. The major developmental challenge now is to reduce the cost of these systems so they can be widely used.

Conclusion

Electricity has had a long history of stimulating and sustaining economic growth and improving the efficiencies of all aspects of production, especially the productivity of labor and energy. The combination of a smart power-delivery system, the energy/information portal, and the use of microprocessors could enable a new wave of economic growth. At the same time, this new, integrated energy/information infrastructure will introduce greater efficiencies into the uses of energy, labor, and capital.

Improving worker productivity is particularly important as we look toward the demographic challenges of the new century. The growing social needs of an aging population will ultimately affect all countries, both in the developed and the developing worlds, and worker productivity will have to increase substantially to meet the social costs of the retired population. The technology of electricity production, delivery, and end use, combined with advances in information technology, will be critical to boosting productivity (Jorgensen et al., 2002; McGuckin and van Ark, 2001). Our estimates suggest that productivity may grow by as much as 25 percent over business as usual; this will translate into trillions of dollars of additional revenue. Infrastructure transformation will be essential to achieving society's needs and aspirations in the twenty-first century.

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Microgeneration technologies could lead to paradigm shifts in energy delivery.

Microgeneration Technology
Shaping Energy Markets

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Robert W. Shaw, Jr.

Over the last few decades, developments in technology have incrementally refined the way energy is produced and delivered to customers. But in fundamental ways the energy system remains much as it was in the 1950s. Nuclear reactor technology has the potential to create a paradigm shift in the electric-generation sector, but because of public concerns about reactor safety and waste disposal, its promise has not been fully realized.

Today technology development supported by government and the private sector that has been under way for decades has begun to yield results—microgeneration systems are now available commercially and are beginning to penetrate energy markets. The emergence of microgeneration technologies could lead to paradigm shifts in two key elements of the energy delivery system: distributed generation and hydrogen systems.

Distributed Generation. Based on a number of newly commercial technologies for power generation, such as fuel cells, as well as substantial refinements in traditional, engine-based systems, we can now envisage an electric system in which power is generated very close to the load being served; the generators will be several orders of magnitude smaller (i.e., 10 to 1,000 kW) than traditional utility generation stations of 100 to 1,000 MW. Distributed generation systems will have several advantages over the existing central station/electric grid system:

- high levels of reliability
- modularity that permits incremental additions in capacity
- potentially very low capital cost (on a $/kW installed basis) as a result of mass production economies (not possible with the central station paradigm)
- the capture of waste heat that can then be used at the site through combined heat and power (CHP) systems
- minimal environmental footprints, particularly in CHP systems
- customer control (not practical in the large, impersonal, and often remote existing system)

Hydrogen Systems. Hydrogen has long been a widely produced, widely consumed commodity in our industrial society. However, its use as a fuel replacing natural gas and oil, although recognized as a possibility, has not been pursued because of the perceived difficulty of establishing a distribution infrastructure. But with advances in technology, distributed generation of hydrogen for use in direct-combustion applications, as well as in fuel cells, will not only be feasible, but will also be increasingly attractive economically.

This article describes some of the developments in technology that are making these two paradigm shifts possible and the most significant barriers to their large-scale market penetration.

Distributed Generation Systems

Emerging technologies for the distributed generation of electric power and related control and system-integration technologies are categorized in Figure 1. In the last decade, substantial technical progress has been made in many of the areas shown in this figure.

The technical developments described briefly below are all leading toward the commercial introduction of small-scale, distributed generation systems that offer customers economical, reliable power generated locally. These systems, which are penetrating markets at levels that were almost unthinkable only a few years ago, are in the vanguard of profound, fundamental changes in the world's electric system.

Fossil-Fuel Microgeneration Technologies

Some of the most interesting developments in this area are in traditional internal-combustion engines, microturbines, Stirling engine systems, and solid-oxide fuel cells.

Widely used in backup power and peaking applications for decades, *internal-combustion engines* have been refined substantially in the last few years to achieve expected lifetimes of up to 50,000 hours in continuous operation, higher efficiencies (now better than 30 percent), and lower emissions of criteria pollutants (low enough so they can be operated in most metropolitan air sheds). European companies have introduced engine systems in the range of 10 to 100 kW with CHP integration that can achieve customer paybacks in one to three years. Prime-power internal-combustion engine systems with CHP have become commonplace in commercial applications (e.g., in multistory city-center office buildings, food processing plants, and retail outlets) in both the United States and Europe. Systems for handling residential loads (5 to 10 kW) are now being introduced in Europe.

In the last three years, *microturbine-based gensets* in the 30 to 200 kW range have been introduced commercially by a number of companies on both sides of the Atlantic and in Japan, often with CHP capability, using the high-grade heat available in the turbine exhaust stream. With technology lineage in aircraft auxiliary turbines and truck turbochargers, microturbines have

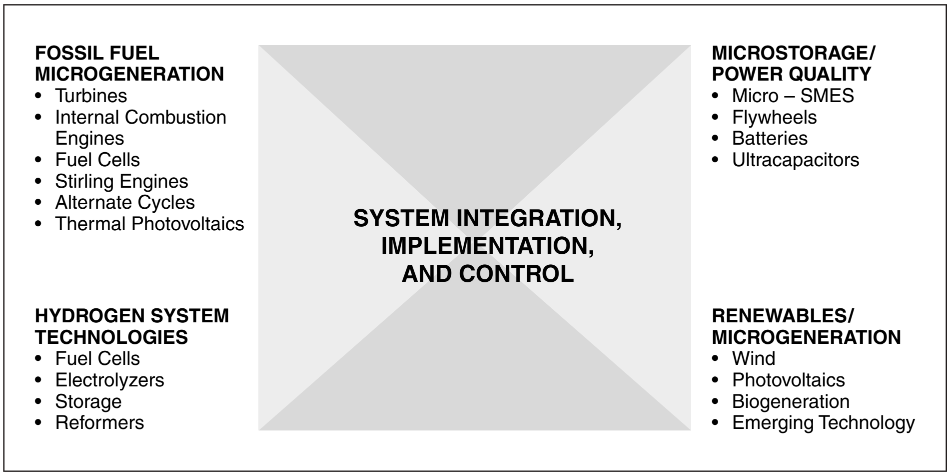

FIGURE 1 Categorization scheme for microgeneration technologies.

single-component cores, air bearings, and custom-designed recuperators, as well as very sophisticated power electronics to convert high-frequency (50,000 to 100,000 Hertz) AC power to DC power and then back to line-frequency AC. Efficiencies are improving but are typically less than 30 percent, particularly if compression of the natural gas fuel stream is required. Costs are below $1,000/kW but still much higher than for internal-combustion engine gensets. Microturbine manufacturers expect that product costs will decline significantly as production volumes increase, simply because of learning curve effects.

The Stirling cycle has been investigated for many years but has been plagued by difficult engineering problems. In the last five years, several entrepreneurial companies have addressed and solved these persistent problems and have introduced 5 to 50 kW *Stirling engine gensets* commercially. Because the working fluid in Stirling systems is heated via external combustion of fuel, they are very versatile and can run on low-grade synthesis gas, landfill gas, biogas, and even waste heat, as well as concentrated solar radiation. With inherently high efficiency (the first commercial units are in the 30 to 35 percent range, and laboratory demonstrations have shown better than 40 percent) and components producible by traditional automotive engine suppliers, Stirling microgenerators have the potential to be exceptionally attractive economically.

Although *solid-oxide fuel cells* (SOFCs) are not yet available commercially, substantial progress has been made in the last five years on fuel cell couples in which the electrolyte is a ceramic (typically yttrium-stabilized zirconium). Even though difficult technical problems of thermal stability and sealing remain to be solved, precommercial systems are now being demonstrated by a number of companies worldwide. SOFCs operate at high temperature (600 to 1,000°C), thus offering excellent potential for CHP applications, and have the advantage that they can operate on lightly pre-reformed fossil fuels, instead of the pure hydrogen stream required by polymer-membrane systems. SOFCs have inherently high efficiency (40 percent or better).

Renewable Microgenerators

Intensive efforts devoted to the development of renewable energy systems by governments and the private sector for more than 30 years have begun to yield serious commercial offerings in two areas: wind energy technology and photovoltaics.

Wind energy technology has evolved rapidly in the last two decades, and wind turbines in the range of 500 kW to 3 MW are now deployed commercially around the world in large-scale wind farms. Commercially available wind energy systems produce electric energy at costs that are competitive with electricity generated by conventional power plants and available on the grid. Although in principle wind turbines can be sited individually (and often are at remote locations, such as telecom repeater stations, off-grid cabins, and research stations in Antarctica), they are not suitable for distributed generation in urban areas. Therefore, they will only contribute in a minor way to the paradigm shift.

Photovoltaic modules are available on the world market at less than $3.00/W.

The most significant technical advances in distributed renewable-energy systems have occurred in *photovoltaics*, the direct generation of electricity via sunlight absorbed by, and exciting electrons in, a semiconductor. Progress on thin-film photovoltaic devices (e.g., using films of semiconductors, such as amorphous silicon, CdTe, and copper-indium-diselenide) has been somewhat disappointing. However, the performance of crystalline silicon, particularly thin-ribbon polycrystalline silicon, continues to improve (12 to 20 percent efficiency). Costs have come down progressively on an 80 percent experience, or "learning," curve. Photovoltaic modules are now available on the world market at less than $3.00/W, and building-integrated photovoltaic systems (e.g., roof tiles, decorative panels, sun shades, and skylights) are being widely installed in grid-connected applications in Europe, Japan, and the United States. Meanwhile, the off-grid market in developing nations and some commercial applications (e.g., obstruction and construction lighting, call boxes, signal lights, and sign lighting), as well as numerous telecom applications, continues to grow.

Annual worldwide production of photovoltaic modules is now in the 500 MW range, and the overall market continues to grow at 20 to 35 percent per year (Maycock, 2003; Schmela, 2002). Large producers and small entrepreneurial companies are expanding production capacity rapidly using highly automated manufacturing technology that continues to drive down the cost per watt. Even at today's installed costs of $5 to $6/W, photovoltaics can compete with conventional peaking power in parts of the United States, Western Europe, and Japan. Incentives offered by many governments make the economics even more attractive (Eckhart et al., 2003).

The challenge is to reduce the scale of hydrogen production systems while maintaining product cost.

Power Quality and Storage

Technical developments in power quality and storage are too numerous to be discussed adequately here. By way of illustration, superconducting magnet technology developed by the Fermilab for accelerator applications has been adapted to create a small-scale superconducting magnetic energy storage (micro-SMES) device for voltage stabilization and momentary carryover during sags in line voltage. The micro-SMES has been available commercially for several years. Another unique technology now entering the commercial market for telecom backup power is the zinc-air fuel cell, in which tiny pellets of zinc are oxidized on the anode side of a fuel cell with an advanced air cathode to generate electricity when the grid is down. When the line voltage is again available, fresh zinc pellets are regenerated from the oxide in the system.

Hydrogen Systems Technology

The basic technologies for producing hydrogen via the reforming of fossil fuels or via the electrolysis of water have long been known. Industrial-scale steam-methane reformers (SMRs) are ubiquitous in the chemical and petrochemical processing industries. Indeed, hydrogen is one of the most widely produced commodities in the world economy (Heydorn and Zuanich, 1998). The challenge, addressed by numerous companies in the last few years, is to reduce the scale of hydrogen production systems while maintaining reasonable product cost.

Distributed Electrolysis

Technology developments in both proton-exchange membrane (PEM) electrolysis and alkaline electrolyte (KOH)-based electrolyzers have led to the commercial introduction of systems capable of producing 50 to 5,000 standard cubic foot (scf)/hour of pure (99.99+) hydrogen gas via water electrolysis. At bulk power costs (< 3 cents/kWh), these electrolyzers can produce hydrogen at prices competitive with hydrogen transported as a compressed gas in tube trailers, or cryogenically as liquid H_2. Applications include generator cooling, semiconductor processing, and hydrogenation of food products. When hydrogen vehicles are introduced commercially, these electrolyzers could also be used to refuel them, even at individual residences.

Small-Scale Reforming

Downsizing industrial-scale reformers has never been proven economical, but several entrepreneurial companies have achieved excellent results in the last few years with novel reactor designs and unique catalysts that enable distributed production of H_2 at costs competitive with much larger systems. Commercial introduction of these small-scale (2,000 scf/hour) SMRs is just beginning in industrial applications. These systems are also ideally suited for siting at "gas stations" for hydrogen-vehicle refueling.

Proton Exchange Membrane Fuel Cells

Enormous effort in the last decade has gone into the development of proton exchange membrane (PEM) fuel cell stacks and systems. Not only has membrane technology advanced, but significant advances have also been made in lifetime, efficiency, and cost reduction of PEM fuel cell systems. Despite this progress, PEM technology has proven to be much more difficult to perfect and is still more expensive than many had expected. To date, there has been no large-scale commercial introduction of PEM fuel cells for stationary or automotive applications.

Hydrogen Storage

The major advance in hydrogen storage has been the improvement in compressed-gas storage tanks. Using carbon-fiber technology to strengthen aluminum tanks, pressures of 5,000 psi are now routinely achieved, and 10,000 psi tanks are under development. Work also continues on various metallic and nonmetallic hydrides, as well as on carbon nanotubes, as storage materials; some early versions of small-scale hydride storage systems are available commercially. Although acceptable volumetric energy density for hydrogen storage is still a challenge, thanks to technical progress on several fronts it is of much less concern than it was even a few years ago.

Hydrogen-Fueled Vehicles

The idea of a hydrogen-fueled vehicle fleet has captured the public imagination because it has the potential to reduce criteria pollutants dramatically and could ultimately lead to a fully sustainable transportation energy system based on the renewable generation of hydrogen. Because of the technical and economic challenges of introducing PEM fuel cell-powered vehicles, automakers have deferred the large-scale introduction of PEM-based fleets (although two Japanese automakers recently introduced fuel-cell vehicles in limited numbers in California). However, several automakers are looking into hybrid vehicles in which an internal-combustion engine would be operated with hydrogen as a fuel. Now that the distributed generation of hydrogen is technically available at reasonable prices, the hydrogen-hybrid vehicle may be a way to introduce hydrogen as an automotive fuel. Eventually, this might lead to the development of a hydrogen fuel infrastructure even before the cost of PEM fuel cell technology is brought down to an economical level.

Market Entry

Essentially all of the new energy technologies discussed in this article are "disruptive technologies" (Bower and Christensen, 1995; Christensen, 2000). As

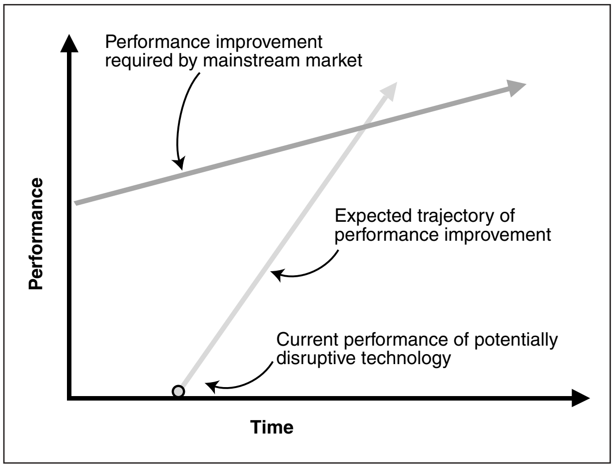

FIGURE 2 Performance trajectories for mainstream and disruptive technologies. Source: Bower and Christensen, 1995.

Figure 2 shows, disruptive technologies often enter the market with significant performance disadvantages (e.g., cost, efficiency, lifetime), but by serving niche markets in which they are competitive, they gain experience, improve performance, and eventually surpass the performance of established technologies, even though mainstream technologies may also improve in performance over time.

For example, microturbine generators entered the market with cost and performance disadvantages when compared to the electric grid. Initially, they have been most successful in markets where they have a unique advantage, such as on-site power generation in oil fields where flare gas is used as a fuel. As production quantities increase, microturbines can be expected to work their way down the experience curve on cost, and performance will improve as a result of technical improvements based on field experience. Thus over time, they will be able to compete in the mainstream market.

Photovoltaic devices provide another illustration. Introduced early in the space program, they were, and remain, extremely expensive devices when used in space applications. As refinements in device and production technology have been made over time and as unit volumes have increased, costs have come down and efficiency has improved. Photovoltaic systems can now address a broader market, and photovoltaic-generated electricity is now competitive with conventionally generated peak power in many markets. Further reductions in module cost (to the range of $2.00/W), which are clearly achievable, will open up even larger markets and, in turn, will make the technology even more competitive with central station generation.

It is important to recognize that distributed generation technologies must compete against the cost of delivered power at the load, not just against the cost of central generation at the bus bar. Transmission and distribution costs (including capital, as well as operating costs, such as tree trimming, transformer replacement, and resistance loss) can be two to three times the cost of bulk power. Unfortunately, in the United States maintenance and upgrades to the power grid have sometimes been less than adequate. As a result, the power grid has a reliability risk that may be unacceptable to end-users with critical electrical loads, which, because they require advanced electronics controls, are often vulnerable to even minor voltage sags, as well as to outages of any duration.

Furthermore, as a result of social and regulatory decisions made over time, the actual cost of providing electric service to certain customers (e.g., remote/rural homes or villages) may be far higher than a utility can charge. In these situations, distributed generation may be economically attractive to the utilities serving customers in those locations.

The kinds of entry markets in which distributed generation systems may build "beachhead" positions (to use Geoffrey Moore's terminology [1999]) are indicated in Figure 3. Distributed systems have already made a substantial penetration into the worldwide power market. A recent survey by the World Alliance for Decentralized Energy indicates that penetration is 7 percent of generation worldwide and as high as 30 to 50 percent in some countries (Brown, 2002). Over time, these percentages are likely to increase significantly, and distributed-generation systems will become more attractive economically and demonstrate exceptional reliability; the central station/transmission and distribution grid model of electricity supply will gradually be displaced.

The established paradigm of a petroleum-based transportation system will also come under attack by hydrogen over time. The issue of how to establish a hydrogen infrastructure has been hotly debated, and no simple solution has emerged. One model considered likely is that fleets will convert to hydrogen-fueled vehicles, perhaps the hydrogen-hybrid vehicle discussed earlier. In an alternative model, the dual-fuel hybrid, existing hybrid vehicles would be outfitted with a small compressed-gas hydrogen tank with a 100-mile range; longer range requirements would be met by the existing gasoline tank (Shaw, 2002a,b). With this model, hydrogen fueling stations could be installed in city centers only (perhaps initially in only two or three cities), thus avoiding the need to equip all of the (approximately) 100,000 U.S. gas stations with hydrogen fueling capability at one time. As the fleet size increased, hydrogen fueling would expand outward from the city center, and to more cities over time. This model is similar to conventional market-entry strategies for consumer products. Incentives, such as convenient "green" parking spaces and access to HOV lanes, could be provided for early adopters of dual-fuel hybrids.

- Remote, non-grid-connected markets
  - ➤ Telecom
  - ➤ Village power
  - ➤ Mobile power (boats, RVs)
  - ➤ Portable power
  - ➤ Standby power
- High-cost, grid-connected market niches
  - ➤ Rural villages
  - ➤ Undeveloped areas
  - ➤ Peak power
  - ➤ Voltage stabilization
- Intermediate-cost, grid-connected mainstream markets
  - ➤ Engine sets/CHP at commercial loads
  - ➤ Grid-connected standby units
  - ➤ Grid disconnection situations

FIGURE 3 Entry market niches for distributed-generation technologies.

No matter which approach to the creation of a widespread hydrogen infrastructure is adopted, there is little doubt that distributed generation of hydrogen will be a key component, with small-scale SMRs being the choice where natural gas is available and electrolyzers where it is not. These technologies are available today and, therefore, can facilitate earlier-than-expected development of the hydrogen infrastructure.

Removing Barriers

A major shift in an industrial paradigm will always encounter resistance from established interests. Despite the attractive economics of distributed generation in many applications, electric utilities often regard it as a threat. They argue that using the grid as a backup to distributed systems would "strand" (make uneconomical) existing utility assets that were approved through the regulatory process. In some cases, utilities advocate economic penalties for customers who disconnect from the grid or use it as a backup. Some jurisdictions have taken a proactive position in support of distributed generation, including adopting "net metering" provisions that allow small-scale generators to sell excess power back into the grid. But even in supportive jurisdictions, utilities have often adopted a go-slow approach that makes implementation of distributed generation difficult.

A reasonable concern voiced by utilities is so-called "islanding"—when the grid is down, if grid-connected distributed-generation systems send current into the grid, they can create a safety hazard for line workers. The recent adoption of the IEEE standard covering interconnection for distributed systems should help ease this concern (COSPP, 2003), but some utilities continue to apply their own standards or simply stonewall interconnection entirely. With more experience, many concerns about distributed generation will be addressed by rigorous engineering methods and will fade from view. The fundamental question of the right to interconnect will have to be addressed through restructuring legislation at the state or federal level.

As for the hydrogen infrastructure, the paradigm shift will occur when all of the interested players sense that the economics are acceptable and that the market demand is there. Virtually all of the major oil and automobile companies are actively involved in developing and testing hydrogen-generation systems and vehicle power plants using hydrogen (both fuel cells and internal-combustion engines). Governments throughout the world have shown their support for the transition to hydrogen by funding technology development and by resolutely supporting air quality standards that make cleaner vehicles essential. At some point, there will be a shift equivalent to a phase change in physical systems, and the pieces will line up to bring the hydrogen infrastructure into being. As Seth Dunn has pointed out, "Structural change can occur with surprising speed when people stop taking the dominant paradigm for granted" (Dunn, 2000, 2001).

Conclusion

Efforts to develop distributed generation and hydrogen-production systems in the last decade and more have begun to pay off commercially with the entry into energy markets of products that provide economical, reliable power generation at small scale and distributed systems for the production of hydrogen at customer locations. As these new technology-driven products continue to penetrate their respective markets, major shifts in the way these markets operate will inevitably follow.

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Biological systems might be engineered to satisfy a greater part of our energy needs.

Biological Solutions to Renewable Energy

Hamilton O. Smith, Robert Friedman, and J. Craig Venter

Hamilton O. Smith

Robert Friedman

J. Craig Venter

Although biological systems contribute very little to current U.S. energy requirements, they are capable of very large-scale effects. Our modern oxygen atmosphere was created 3 billion years ago by photosynthetic cyanobacteria. Our fossil fuels are derived from chemical energy accumulated over many millions of years by photosynthetic and biochemical processes that converted light energy into carbohydrates, proteins, and fats, the biological storage forms for light energy.

Today, terrestrial plants produce about 120 billion metric tons of biomass (dry weight)[1] globally each year (IPCC, 2001). The energy in this biomass totals about 2,400 quads[2] (1 quad = 10^{15} Btu). Modern economies, however, rely extensively on fossil fuels rather than biomass for their energy. In 2001, the world consumption of fossil fuels totaled about 315 quads, about one-quarter of which was consumed in the United States (BP, 2002).

Coal, natural gas, and petroleum met about 85 percent of the energy needs of the U.S. economy in 2001 (EIA, 2001).[3] Unfortunately, the combustion

[1] Carbon estimates based on 1g C ~ 2g dry weight biomass.
[2] Assuming 5 kcal/g dry weight.
[3] All U.S. energy statistics are from this source.

Hamilton O. Smith is science director, Robert Friedman is VP, environmental and energy policy, and J. Craig Venter is president at the Institute for Biological Energy Alternatives in Rockville, Maryland.

of these fossil fuels also emitted large quantities of carbon dioxide into the atmosphere—close to 1.6 billion tons of carbon. Moreover, close to 25 quads of petroleum had to be imported. The remaining 15 percent of U.S. energy needs was met by carbon-free sources (nuclear electric power and conventional hydroelectric power) and carbon-neutral sources (biomass). Biomass energy is carbon neutral, that is, although carbon dioxide may be emitted to the atmosphere, the amount emitted is the same as the amount removed to create that biomass in the first place. Carbon-neutral biomass provides about 3 percent (3 quads) of U.S. needs, mostly from burning wood and waste; about 0.15 quads of primarily corn-derived ethanol is blended into gasoline. But the potential for biomass energy is much larger.

The question then is by how much and in what way biological systems might satisfy a greater part of our energy needs? Should we simply burn more biomass, or should we convert it to fuels, such as ethanol, methanol, hydrogen, or methane? Or is it possible to develop continuous biological processes that produce, for example, large amounts of hydrogen?

In 2002, J. Craig Venter founded the Institute for Biological Energy Alternatives (IBEA), a not-for-profit research institute located in Rockville, Maryland, to seek ways to exploit genomic knowledge and genetic engineering methods to optimize biological organisms for efficient production of alternative fuels and for carbon sequestration. IBEA is also undertaking large-scale genomic sequencing of environmental microbial populations to discover new organisms that might be of value for carbon sequestration or fuel synthesis.

Sargasso Sea Project

Only a minute fraction of the microbial organisms on earth have been examined. Many, perhaps most, of them cannot be readily grown in the laboratory. And yet, there may be some extraordinarily interesting metabolic processes in undiscovered organisms that would be extremely useful for carbon sequestration or fuel production. To explore the possibilities, IBEA is undertaking a mission to explore oceanic microorganisms. Recently, IBEA sampled and analyzed the microbial content of surface waters (down to 5 meters) at certain locations in the Sargasso Sea, a relatively defined area of the Atlantic Ocean off the coast of Bermuda. Preliminary analysis of the RNA in microbes in the size range of 0.1 to 0.8 microns reveals a few dominant organisms, plus a considerable diversity of less common species. Genomic libraries of the microbial mixtures are being sequenced to an extent sufficient to assemble the complete genomes of the most prevalent species and to sample the biochemical diversity of less common species. Once the genomic sequences are known, it may be possible to recover the genes that carry out potentially interesting metabolic processes and insert them into laboratory organisms for more detailed studies of their potential usefulness. In addition to this discovery process, IBEA plans to examine and evaluate currently known microbial organisms for applications to energy needs.

Energy-Relevant Metabolic Processes

Autotrophic organisms extract energy either from sunlight or from chemical reactions involving inorganic electron donors, such as hydrogen sulfide or iron. All other living systems either directly or indirectly use energy captured by autotrophs. Sunlight is the ultimate renewable energy source; inorganic electron donors are generally consumables. Biological processes that produce renewable energy must therefore generally use solar energy either directly or indirectly. Photosynthetic organisms use solar energy and carbon dioxide to produce carbohydrates, and the carbohydrates are used as stored chemical energy or to build biomass (proteins, fats, cellulose, etc.), which can be used directly as burnable fuel.

Fuel can also be produced by fermentation reactions that convert carbohydrates to ethanol, methane, and hydrogen (Figure 1). Some of the adsorbed solar energy might also be diverted directly into hydrogen production.

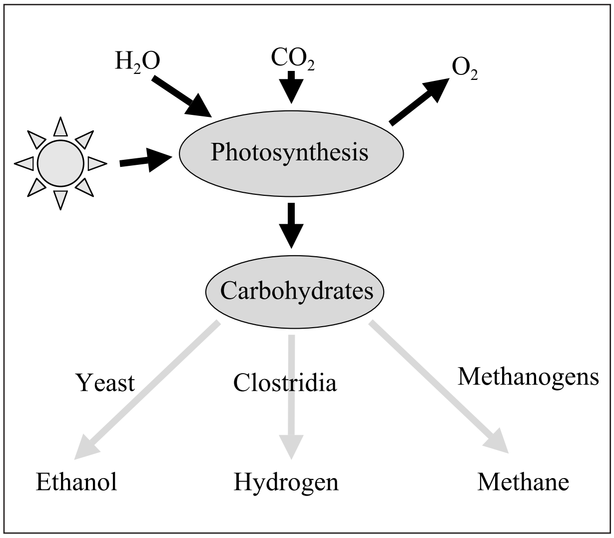

FIGURE 1 Sugar fermentations by microbes can yield a variety of fuels.

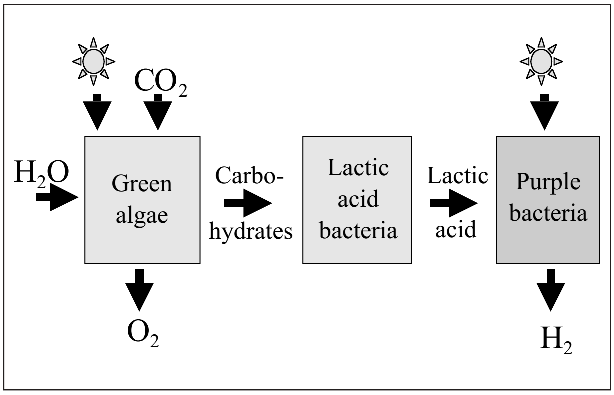

FIGURE 2 A three-stage, continuous, hydrogen-production system. Source: Rechenberg, 1996.

Fermentation Reactions

Approximately 1.7 billion gallons of ethanol are produced every year in the United States. The two-stage production process involves photosynthetic production of carbohydrate from corn and then fermentation (using yeast) of the carbohydrate into ethanol. A bushel of corn yields 2.5 gallons of ethanol, and an acre of corn yields, on average, 125 bushels; the United States plants about 70 million acres of corn. Thus the potential yield of ethanol from our entire corn crop would be 22 billion gallons, or a bit less than 20 percent of our automotive fuel needs if engines were adapted to run on pure ethanol (we use about 110 billion gallons of gasoline per year).

The overall efficiency of ethanol production from photosynthesis is low; 10 percent is often cited as a practical upper limit for the conversion of solar energy into carbohydrate by a plant. But even under the best conditions, a corn plant has about a 1 percent conversion rate of sunlight into carbohydrate. The conversion of the chemical energy in cornstarch into ethanol energy is approximately 50 percent. Thus the overall efficiency of the conversion of sunlight energy into ethanol energy is about 0.5 percent. Moreover, ethanol production is currently about break-even in terms of the energy consumed in production and the energy obtained from the ethanol.

Other fuels can be produced by fermentation of carbohydrates. For example, the anaerobic bacterium *Clostridium butyricum* can produce hydrogen with a theoretical yield of about 0.5 m^3 of hydrogen per kg of glucose (Kataoka et al., 1997). Hydrogen could be produced in factories similar to those that now produce ethanol, and *Clostridium* could replace yeast. However, because not all of the hydrogen in glucose is converted to hydrogen gas, less of the chemical energy of glucose is captured in hydrogen than in ethanol.

Scientists in Germany have adopted a different, more efficient approach to producing hydrogen gas from the hydrogen in carbohydrates. They have devised a three-step bioreactor for continuous hydrogen production (Figure 2). In the first step, green algae produce carbohydrate by photosynthesis. In the second step, the carbohydrate is piped to a reactor of lactic acid bacteria that convert the sugar to lactic acid. Theoretically, each mole of glucose molecule is converted to two moles of lactic acid, although actual yields are somewhat lower. In the third stage, the lactic acid is routed to a fermenter containing purple bacteria where it is used as a substrate for hydrogen production. An advantage of this system is that all of the hydrogen atoms in the lactic acid can be converted to hydrogen gas by the purple bacteria (Table 1).

Some archaeal species produce methane. For example, the acetoclastic methanogens (e.g., *Methanosarcina* and *Methanosaeta*) produce methane from acetic acid. If this reaction were coupled to the one above that yields acetic acid, the overall yield from glucose would be glucose plus water yields methane plus hydrogen and carbon dioxide, a greater yield of useful fuel. Genetic engineering might be used to transplant the methanogen pathway into *Clostridium* for more efficient conversion of glucose to fuel.

TABLE 1 Biological Reactions That Yield Potential Fuels

Net Reaction	Representative Organism
sugar → **ethanol** + carbon dioxide	yeast
hydrogen + carbon dioxide → **methane** + water	*Methanococcus jannaschii*
sugar + water → **hydrogen** + acetic acid + carbon dioxide	*Clostridium burtyricum*
acetic acid → **methane** + carbon dioxide	*Methanosarcina*
carbon monoxide + water → **hydrogen** + carbon dioxide	*Carboxydothermus hydrogenoforma*
lactic acid + water → **hydrogen** + carbon dioxide	Purple bacteria
H^+ + ferredoxin^{-1} → **hydrogen** + ferredoxin^0	Cyanobacteria, green algae

Direct Production of Hydrogen by Photosynthesis

Even though some of the reactions in Table 1 produce hydrogen indirectly from photosynthesis, producing and transporting the carbohydrate products of photosynthesis to the fermentation facilities where the hydrogen is produced is costly and energy consuming. It may be feasible to genetically engineer photosynthetic organisms to produce hydrogen directly.

For several decades, we have known that green algae can produce hydrogen directly from water. The enzyme hydrogenase catalyzes the reaction: hydrogen ion plus ferredoxin^{-1} yields gaseous hydrogen plus ferredoxin^{0}. Hydrogen ions and electrons are intermediates of the photosynthetic process, derived from the splitting of water, and are normally used to drive the synthesis of ATP and reduce carbon for production of carbohydrates, proteins, and fats. Normally, photosynthetic systems produce oxygen and carbohydrates but do not evolve hydrogen. However, under anaerobic conditions, hydrogenase, which is an oxygen-sensitive enzyme and is normally not expressed, becomes induced and active and catalyzes conversion of the protons and electrons to hydrogen.

Scientists at the University of California, Berkeley, have found that sulfur deprivation of *Chlamydomonas reinhardtii*, a green algae, turns off the normal photosynthesis pathways, causing cells to stop emitting oxygen and stop producing carbohydrate, protein, and fat energy reserves (Figure 3). Hydrogenase is induced and activated by the low oxygen tension, and the stored energy reserves are then used to produce hydrogen. Once the stores are depleted, sulfur must again be added to return the system to normal photosynthesis. By cycling between sulfur and nonsulfur metabolism, hydrogen can be cyclically produced in a two-stage process.

Although these studies have demonstrated the feasibility of producing hydrogen by photosynthesis, they involve either multiple stages and routing of media and substrates or the intermittent evolution of hydrogen. A continuous process involving a single photosynthetic organism in which solar energy is used to split water and produce hydrogen and oxygen would be much more desirable. The cyanobacterium, *Synechocystis sp. PCC6803*, would be a good choice for the photosynthetic organism because genomic information is available about the biochemical potential of this organism, and it could probably be genetically engineered more easily than eukaryotic algae or plants.

Photosynthesis is carried out by a complex but coordinated set of membrane systems (Figure 4). The first step, the splitting of water and resultant charge separation of a proton and an electron, is accomplished by photosystem II (PSII) using photon energy captured by chlorophyll. The electrons are used to generate a proton gradient for synthesis of ATP and then are given an additional energy boost by photons gathered in photosynthesis system I (PSI).

The net reaction of photosynthesis is: carbon dioxide plus water plus light energy yields carbohydrate plus oxygen. Normally, no hydrogenase is made, but it may be possible to manipulate the photosynthetic apparatus genetically to accentuate the hydrogenase reaction and produce hydrogen directly.

For example, under anaerobic conditions, hydrogenase could be induced and activated, and it would catalyze, in a side reaction, the formation of hydrogen from protons and ferredoxin^{-1}. One possibility would be to alter the regulation of the chromosomal copy of the hydrogenase gene to decrease its oxygen sensitivity, thus making it active under aerobic conditions. Another possibility would be to introduce an over-expressing

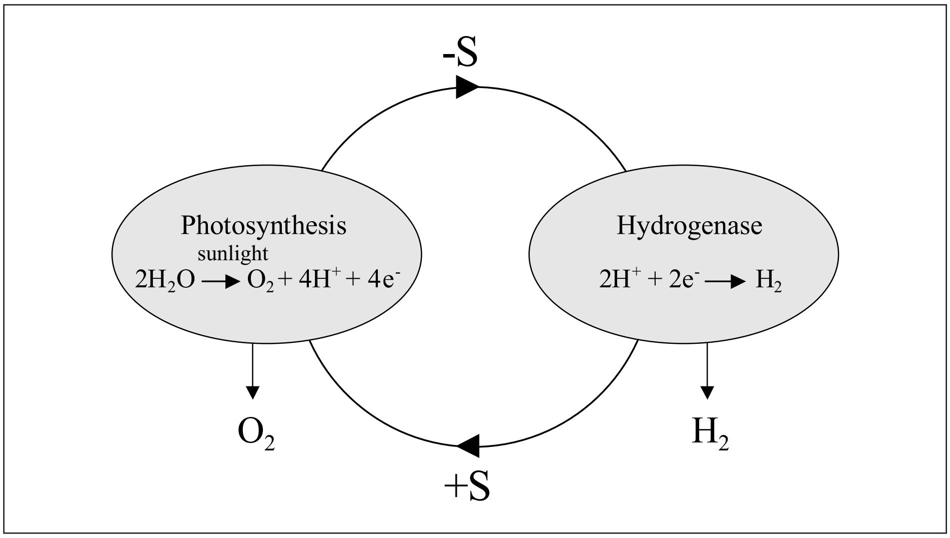

FIGURE 3 Photobiological production of hydrogen gas in the green algae *Chlamydomonas reinhardtii*, achieved by cycling between +S and –S. Source: Ghirardi et al., 2000; Melis et al., 2000.

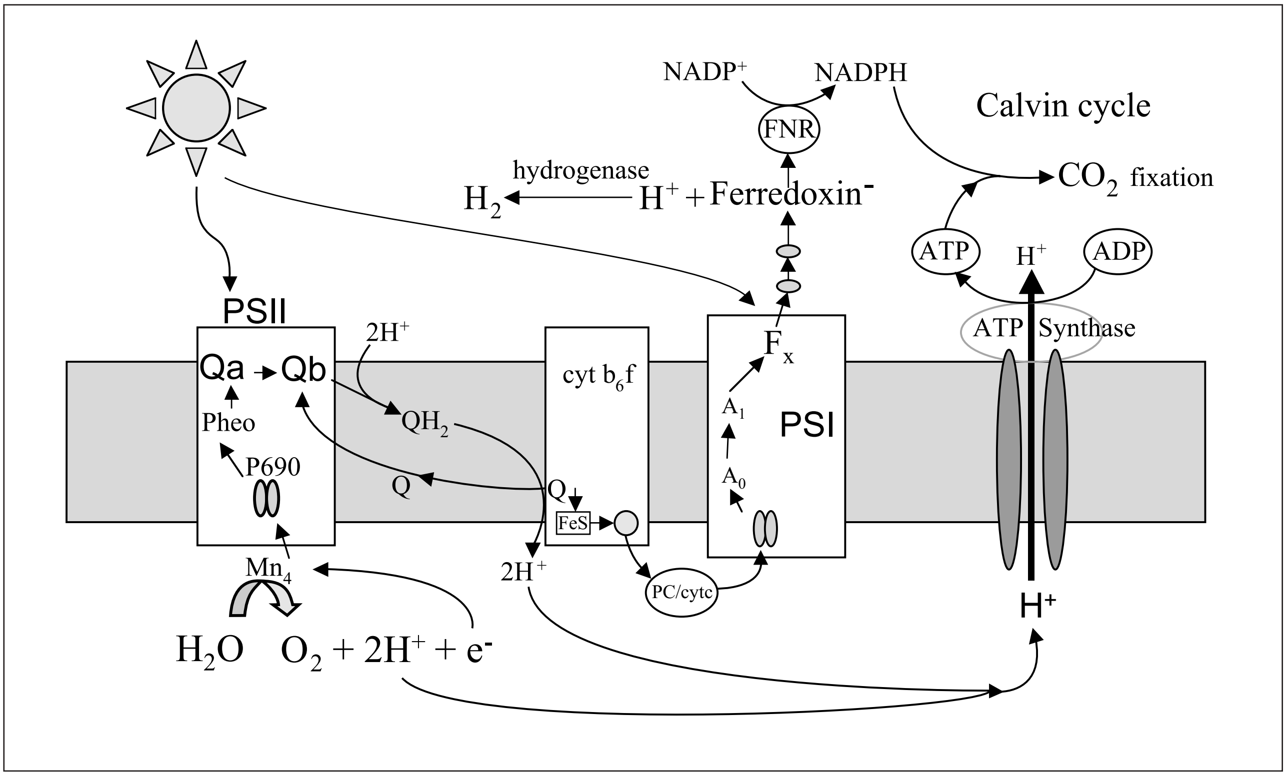

FIGURE 4 Photosynthesis pathways for cyanobacteria and plants.

hydrogenase gene using an appropriate plasmid vector. The cloned gene could be from another organism that produces a hydrogenase with lower sensitivity to oxygen. The extensive library of microbial genomes could be used to search for such an enzyme. Projects such as the Sargasso Sea genome analysis may yield enzymes with desirable properties.

IBEA will also explore the feasibility of changing or broadening the light adsorption spectrum of the light-adsorbing pigments (primarily chlorophyll and phycocyanin) used by the cyanobacteria. One could possibly "graft-on" pigments from another species by cloning or directly modify the pigments by genetically engineering the pathways by which the pigments are synthesized. In general, IBEA plans to undertake detailed studies of the components of the photosynthesis apparatus and attempt to genetically engineer changes that will lead to the efficient conversion of light energy into hydrogen.

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NAE News and Notes

NAE Newsmakers

Arthur E. Bergles, Clark and Crossan Professor of Engineering, emeritus, Rensselaer Polytechnic Institute, was elected a **foreign member of the Italian National Academy of Sciences** for his contributions to heat transfer and his support of international scientific cooperation.

David P. Billington, Gordon Y.S. Wu Professor of Engineering at Princeton University, received a **2003 Director's Award for Distinguished Teaching Scholars** from the National Science Foundation (NSF). The award was established in 2001 to promote scholarship by academicians to interest undergraduate students from all areas of study in mathematics, science, technology, and engineering. Dr. Billington plans to develop teaching materials that introduce students to major engineering innovations of the twentieth century and the thinking of outstanding engineers. The materials will highlight the efficiency, economy, ethical, and aesthetic choices intrinsic to engineering design.

On April 29, 2003, the National Academy of Sciences (NAS) announced the election of 72 new members and 18 foreign associates from 11 countries in recognition of their distinguished and continuing achievements in original research. Six of the electees are members of the National Academy of Engineering: **Praveen Chaudhari**, director, Brookhaven National Laboratory, Upton, New York; **David G. Forney, Jr.**, Bernard M. Gordon Adjunct Professor, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology; **Solomon W. Golomb**, Andrew and Erna Viterbi Professor of Communications and University Professor, University of Southern California, Los Angeles; **Karl Hess**, Swanlund Endowed Chair and professor, Department of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign; **William D. Nix**, Lee Otterson Professor of Engineering emeritus, Department of Materials Science and Engineering, Stanford University; and **Eli Yablonovitch**, professor of electrical engineering, University of California, Los Angeles. NAE foreign associate **Herbert Kroemer**, professor of electrical engineering and of materials, University of California, Santa Barbara, was elected as a foreign associate of the NAS.

Four NAE members were recently inducted as **fellows of the Computer History Museum** in Mountain View, California. The fellows designation is bestowed annually on individuals of outstanding merit and accomplishment who have made fundamental contributions to the field of computing. The four new fellows are: the late **John Cocke**, a retired fellow of the I.B.M. T.J. Watson Research Center, for the "development and implementation of reduced instruction set computer architecture and program optimization technology"; **Charles Geschke**, chairman of the board, Adobe Systems, Inc., for "accomplishments in the commercialization of desktop publishing with John Warnock and for innovations in scalable type, computer graphics, and printing"; **Carver A. Mead**, Gordon and Betty Moore Professor of Engineering and Applied Science, emeritus, California Institute of Technology, for "pioneering the automation, methodology, and teaching of integrated circuit design"; and **John Warnock**, chairman, Adobe Systems, Inc., for "accomplishments in the commercialization of desktop publishing with Charles Geschke and for innovations in scalable type, computer graphics, and printing."

Charles Elachi, director of the Jet Propulsion Laboratory, received the **2002 Takeda Award** given by the Takeda Foundation of Japan. The award honors outstanding achievements in the creation and application of new engineering knowledge to benefit human needs. Dr. Elachi was recognized for his work on space-borne radar instruments to monitor the global environment.

William L. Johnson, Ruben and Donna Mettler Professor of Materials Science, Engineering, and Applied Science, California Institute of Technology, has been elected a **fellow of ASM International** (the Materials Information Society) "in recognition of his distinguished contributions to the field of materials science and engineering," particularly the invention of bulk metallic-glass-forming alloys and the development of bulk metallic glasses as structural materials. Dr. Johnson has also been selected to receive the **2004 Robert Franklin Mehl Award**

and the **2003 Fellow Award**, both from the Minerals, Metals and Materials Society for contributions to materials science. In addition, Dr. Johnson received a **Highly Cited Researchers Certificate** for "his accomplishments as one of the most highly cited and influential researchers in his field."

Wolfgang G. Knauss, Theodore von Karman Professor of Aeronautics and Applied Mechanics, and **Dr. Anatol Roshko**, Theodore von Karman Professor of Aeronautics, emeritus, both of California Institute of Technology, were **honored with special symposia** at the 14th U.S. National Congress of Theoretical and Applied Mechanics. Dr. Knauss was recognized for his "leadership and many contributions to the mechanics of structures and materials." Dr. Roshko was recognized for his "seminal contributions to our knowledge of separated flows and shear-layer turbulence."

John Preskill, MacArthur Professor of Theoretical Physics, California Institute of Technology, is a recipient of the **2002 ASCIT (Associated Students of Caltech) Teaching Award**.

Theodore Y. Wu, professor of engineering science, California Institute of Technology, has been elected a **foreign member of the Chinese Academy of Sciences**. Dr. Wu was recognized for his "distinguished contributions to fluid mechanics."

Preview of the 2003 Annual Meeting

The 2003 NAE Annual Meeting is scheduled for Sunday and Monday October 12 and 13, 2003. As in the past, orientation and a black tie dinner for our new members will be held on October 11, the Saturday before the meeting. Meetings of peer committees will be held concurrently to initiate the selection of candidates for the 2004 election. A guest program is being planned for Monday, October 13, and a symposium on Engineering Ethics will be held following the meeting on October 14–15.

Pre-Meeting Activities

Saturday, October 11

NAE Council meeting

Peer committee meetings

Special events for Class of 2003:

- Lunch with Council
- Introduction to the National Academies and to NAE
- Council reception and dinner honoring Class of 2003 (black tie)

Annual Meeting

Sunday, October 12

Brunch

Estate planning seminar

Induction ceremony

Awards ceremony—Founders and Bueche Awards

Gilbreth Lectures

Reception

Monday, October 13

Continental breakfast

Home Secretary and Foreign Secretary breakfasts

NAE Business Meeting

Member briefings

Lunch

Section meetings

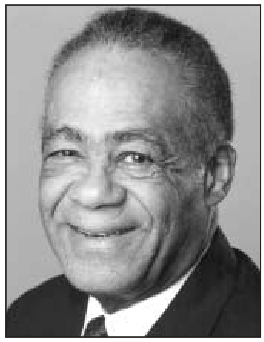
Dinner and dance at the J.W. Marriott with entertainment by the Capitol Steps

Post-Meeting Activities

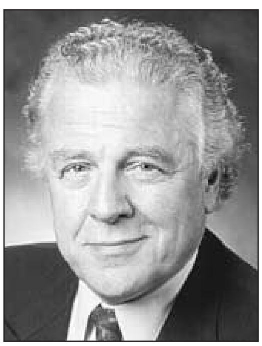
The NAE Program Office will hold a symposium on Engineering Ethics all day Tuesday, October 14, and Wednesday morning, October 15. The symposium is free and open to all NAE members. Hotel room rates (at the State Plaza and J.W. Marriott) will be extended for attendees of the Annual Meeting.

NAE Council Membership Update: Spring Election Results; Two Members Complete Service

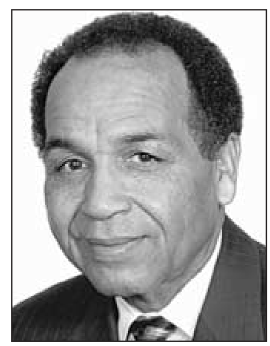

George Bugliarello


John B. Slaughter


Ruth M. Davis


Michael P. Ramage


Paul E. Torgersen


Delon Hampton

A new foreign secretary and councillor were elected, and three councillors were reelected to the governing Council of the National Academy of Engineering (NAE) in the spring 2003 election. All terms begin July 1, 2003.

George Bugliarello, chancellor, Polytechnic University, Brooklyn, New York, will become the new NAE foreign secretary. During his four-year term, he will oversee the international activities of NAE and coordinate contacts with engineering academies in other countries. As a consultant abroad for UNESCO and OECD, Dr. Bugliarello has reviewed science and engineering-related policies of Greece, Italy, Portugal, and Turkey. He was also a member of the NATO Science for Peace Steering Group and the Science for Stability Steering Group and a specialist for the U.S. Department of State in Venezuela and Central Africa. He succeeds **Harold K. Forsen**, retired senior vice president, Bechtel Corporation, Kirkland, Washington, who has served as NAE foreign secretary since 1995.

Newly elected councillor **John B. Slaughter** is president and CEO, National Action Council for Minorities in Engineering, New York. **Ruth M. Davis**, president and CEO, Pymatuning Group, Inc., Alexandria, Virginia; **Michael P. Ramage**, retired executive vice president, ExxonMobil Research and Engineering Company, Moorestown, New Jersey; and **Paul E. Torgersen**, John W. Hancock, Jr., Chair and president emeritus, Virginia Polytechnic Institute and State University, Blacksburg, were reelected to second terms. Each councillor serves a term of three years.

On June 30, 2003, **Delon Hampton**, chairman of the board, Delon Hampton & Associates, completed six years of service as councillor, the maximum allowed under NAE bylaws. Dr. Hampton was recognized for his distinguished service during a luncheon held in his honor in conjunction with the May meeting of the NAE Council in Hollywood, California. NAE Foreign Secretary Harold Forsen, who will step down on June 30 following 11 years of service—eight years as an officer and three years as a councillor—was recognized in February 2003.

Draper and Russ Prize Recipients Honored

L to R: Bob Evans, 2003 Charles Stark Draper Prize Committee chair; Bradford W. Parkinson, 2003 co-recipient of the Draper Prize; Ivan A. Getting, 2003 co-recipient of the Draper Prize; Wm. A. Wulf, NAE president; and Vince Vitto, president and CEO of the Charles Stark Draper Laboratory.

NAE President **Wm. A. Wulf** hosted the NAE Awards Dinner and Presentation Ceremony on February 18 to honor the 2003 recipients of the Charles Stark Draper Prize and the Fritz J. and Dolores H. Russ Prize. The formal dinner was held at the historic Union Station in Washington, D.C.

Ivan A. Getting and **Bradford W. Parkinson** received the **Charles Stark Draper Prize** for pioneering the concept and development of the Global Positioning System (GPS). Organized around a "constellation" of 24 satellites evenly spaced in orbit around the Earth, GPS makes it possible for anyone with a receiver to pinpoint geographical location to within 10 meters, for most equipment. GPS is used in a wide array of systems, from air traffic control to mechanized farming, from mineral surveys to search and rescue operations, from national defense systems to environmental monitoring. Few engineering innovations have had as revolutionary an impact as GPS.

Dr. Ivan A. Getting, an NAE member since 1968, has had an illustrious career, highlighted by many milestones. He developed the first high-speed, flip-flop circuit, a fundamental component of original digital computers developed in the 1940s. In 1940 at Massachusetts Institute of Technology, he headed a group responsible for the development of virtually all ground radars used during World War II; and in the 1950s, during his tenure at Raytheon, the company became the first to produce transistors commercially and was responsible for the development of the Sparrow III and Hawk missile systems. In 1960, Getting became the founding president of The Aerospace Corporation, which made major contributions to ballistic missile defense and NASA's Mercury and Gemini space programs. The Aerospace Corporation's research laboratories also contributed to developments in radio astronomy, laser isotope separation, and high-power chemical lasers. Dr. Getting's work on the design of GPS and its operational value, as well as on planning, negotiation, and reaching agreements

L to R: Wm. A. Wulf, NAE president; Willem J. Kolff, 2003 recipient of the Fritz J. and Dolores H. Russ Prize; and Robert Glidden, president of Ohio University.

Dr. Ivan A. Getting delivers his acceptance speech.

with all of the system's stakeholders was critical to its success.

Dr. Getting has received numerous prestigious honors and awards, including the President's Medal of Merit, the Air Force Exceptional Service Award, the Kitty Hawk Award, and the John Fritz Medal. He is a fellow of the American Physical Society, the Institute of Electrical and Electronics Engineers (IEEE), and an Honorary Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He earned a B.S. from Massachusetts Institute of Technology as an Edison Scholar in 1933. He was a Rhodes Scholar at Oxford University, and was awarded a Ph.D. in astrophysics in 1935. He resides in Coronado, California, with his wife, Helen.

Dr. Bradford W. Parkinson, an NAE member since 1990, was the "chief architect" and first program manager of GPS. He worked on GPS from the concept phase through the engineering development and implementation phases of the system.

Dr. Parkinson served in the U.S. Air Force from 1957 to 1978, when he retired as a colonel. Early in his career, he headed the Department of Astronautics and Computer Science at the U.S. Air Force Academy. Dr. Parkinson created and ran the NAVSTAR GPS Joint Program Office from 1972 to 1978, during which time he received the Defense Department Superior Performance Award for the best program director in the Air Force. Since 1984, Dr. Parkinson has taught at Stanford University and conducted research on innovative ways to take advantage of GPS technology's extraordinary centimeter-level accuracy. Recently, under FAA sponsorship, Dr. Parkinson and his students developed a fully blind landing system for aircraft; in testing, a Boeing 737 made more than 100 successful landings without human assistance.

Dr. Bradford W. Parkinson delivers his acceptance speech.

The same principles were used in the development of a robotically guided and driven farm tractor, capable of tracking within two inches of a predetermined line on an unmarked field. In the months and years to come, these and other of Dr. Parkinson's pioneering efforts will bring real benefits to people everywhere.

Today, Dr. Parkinson is the chairman of The Aerospace Corporation and cochair of the Jet Propulsion Laboratory Advisory Council. He is a member of several associations and committees, including the American Astronautical Society, IEEE, the Presidential Commission on Air Safety and Security, and the Royal Institute of Navigation. Dr. Parkinson has also received many distinguished awards, such as the Discover Innovation Award, the NASA Public Service Medal, and the AIAA Von Karman Lectureship and Aerospace Contribution to Society Medal. He earned a B.S. in general engineering at the U.S. Naval Academy in 1957 and an M.S. in aeronautics and astronautics from Massachusetts Institute of Technology in 1961. In 1966, he received a Ph.D. in aeronautics and astronautics from Stanford University. He resides in Mountainview, California, with his wife, Virginia.

Dr. Willem J. Kolff, an NAE member since 1989, received the **Fritz J. and Dolores H. Russ Prize** for his pioneering work on artificial organs, beginning with the artificial kidney, thus launching hemodialysis, a new field of medicine. More than 1.2 million patients worldwide are being kept alive through the life-sustaining therapy of hemodialysis, which is offered in nearly every country in the world.

Dr. Kolff, who graduated from Leyden Medical School in 1938, developed the first practical artificial kidney with materials scrounged from a local factory and concealed from the Nazis in occupied Holland during World War II. Although the device was cumbersome by modern

Dr. Willem J. Kolff celebrates receiving the 2003 Russ Prize.

standards, the "hemodialyzer" was as effective as it was resourceful. In September 1945, the first patient was saved by the device.

Dr. Kolff and his family immigrated to the United States and settled in Cleveland, Ohio, in 1950, where he became head of the Department of Artificial Organs and professor of clinical investigation at the Cleveland Clinic Foundation. He began work on an artificial heart, and in 1957, a totally artificial heart was implanted in the chest of an animal for the first time. In 1967 at the University of Utah, he became director of the Institute for Biomedical Engineering and the Artificial Organs Division. Under Dr. Kolff's leadership, the University of Utah developed one of the leading centers for research on artificial organs. In 1982, under his supervision, the first "permanent" artificial heart was implanted in a human patient, Dr. Barney Clark.

Dr. Kolff has published more than 300 articles in scientific journals. In addition, he has received many prestigious awards, including the Armory Prize, the American Medical Association Scientific Achievement Award, and the Lasker Clinical Award. He was awarded the rank of commander in the Order of Oranje-Nassau by Queen Juliana of the Netherlands, the first time this award has been presented to an individual living in the United States and the highest tribute for accomplishments in science conferred by the government of the Netherlands upon a native of that country. Dr. Kolff received his M.D. from the University of Leyden Medical School, Holland, in 1938, and his Ph.D. from the University of Gröningen, Holland. He resides in Newtown Square, Pennsylvania.

In Memoriam

WILLIAM E. COOPER, 78, retired staff consultant, Teledyne Brown Engineering, died on May 18, 2002. Dr. Cooper was elected to NAE in 1985 for converting theoretical stress analysis for use in national and international codes and standards, primarily nuclear codes and standards.

STANLEY BACKER, 82, professor emeritus of mechanical engineering and senior lecturer, Massachusetts Institute of Technology, died on January 18, 2003. Dr. Backer was elected to NAE in 1992 for furthering the understanding and engineering of fibrous materials to improve their performance in ocean and other engineering applications.

EDGAR F. CODD, 78, retired fellow, IBM Research Laboratory, and database management consultant, died on April 18, 2003. Dr. Codd was elected to NAE in 1981 for originating the relational approach to the organization of large databases.

Message from the Foreign Secretary

Harold K. Forsen

As you all know, this will be my last report as NAE foreign secretary. Professor **George Bugliarello**, chancellor of Polytechnic University, was elected my successor, effective July 1, 2003, and we are indeed fortunate to have someone of his background and skill to promote our international activities. I have really enjoyed the position during the two terms I served. The support and advice I received from many of you have been greatly appreciated and truly useful. Thank you all very much.

Much has happened since my last column appeared. Thanks to continuous efforts by me and the NAE Council, the Membership Policy Committee agreed to recommend (and the Council approved) an increase in the number of foreign associates elected each year to 12 percent (from 10 percent) of the number of members elected. In real numbers, this means an increase of roughly 2 per year. Remember, foreign associates can only be nominated by members. Therefore, I encourage you all to work on ways to nominate deserving international researchers and leaders for foreign associate membership. To put this into perspective, NAS is increasing the number of its foreign associates elected each year to 18; they currently have more than twice as many foreign associates as NAE.

Before September 11, 2001, the National Academies had been working with the Russian Academy of Science (RAS) on high-impact terrorism and had been planning a follow-up meeting and workshop on the subject. In fact, I was scheduled to fly to Russia on September 11. After a couple of delays, the follow-up meeting finally took place March 17–21 of this year. On the U.S. side, the committee is made up mostly of NAE members, including new foreign secretary George Bugliarello and President **Bill Wulf**.

On March 18, after the meeting, we invited our Russian foreign associates and guests to a dinner. All but one attended, and it turned out to be a wonderful opportunity to discuss how we might work with RAS to ensure Russia's representation in the International Council of Academies of Engineering and Technological Sciences (CAETS). The problem cannot be solved easily, but both sides are working on it.

RAS, especially our foreign associates there, would like to work much more closely with NAE. One of the suggestions was that we try to develop a Frontiers of Engineering (FOE) program with them, but it might be difficult to find funding. We currently have bilateral FOE meetings with Germany (GAFOE) and Japan (JAFOE), and we work very hard to raise money to support our share of them. It is not immediately obvious what additional sources could be tapped to support a third bilateral meeting. We might expand GAFOE to include Russia and other European countries, assuming funding and organizational issues on the European side could be resolved.

GAFOE's most recent meeting in Ludwigsburg, Germany, April 30 to May 3, 2003, was a great success (see Janet Hunziker's report in this issue of *The Bridge*). For the first time, Denmark sent a young member of their academy to participate in GAFOE. Like previous guests from European CAETS academies, he found the meeting most impressive, and he strongly urged us to expand GAFOE to include all interested European CAETS academies. In the past, we have invited CAETS academies in the area to send one or two researchers to GAFOE meetings held in Europe. Only a few have accepted, however, even though our host in Europe, the Alexander von Humboldt Foundation, has agreed to accept as many as six guests from CAETS academies. This is a work in progress that CAETS should continue to develop.

Speaking of CAETS, the twenty-fifth anniversary of its founding takes place this year, and the biennial Convocation of the CAETS Academies has rotated to the United States. NAE President Bill Wulf will be the president of CAETS for 2003. The convocation will take place in Hollywood, California, May 18–22, preceded by the NAE Council meeting there May 16–17. The subject for this fifteenth Convocation of CAETS was "Engineering Bytes," the intersection of information technology and entertainment. The meeting included presentations and tours of local film studios, university programs, and other resources.

During the last annual meeting in Washington at the Foreign Secretary's breakfast for new and returning foreign associates, Dr. Eric Forssberg of the Royal Swedish Academy of Engineering (IVA) invited us to hold a foreign associates meeting in Sweden. With the help of IVA secretary, Dr. Per Storm, we scheduled a meeting for April 28–29, just before the GAFOE meeting in Germany. Fourteen foreign associates were able to attend. All of the associates from Sweden, two from Russia, and two from the United Kingdom met the first night for dinner and the next day for a program describing NAE and IVA activities—including a tour of Ericsson's research facility. Judging by the very positive feedback we have received, including requests to expand the program, we are convinced that these meetings should be continued and expanded as appropriate.

Finally, thank you all again for a wonderful opportunity to serve. It has been a most rewarding experience.

Harold K. Forsen
Foreign Secretary

New Center for Engineering Education Addresses Critical Issue

How do we close the gap between engineering practice and education? What can we do to increase the retention rate for engineering students at the undergraduate and graduate levels so that the most promising students stay in the field? What can engineering faculty do to improve their instructional skills? These are a few of the timely questions the new NAE Center for the Advancement of Scholarship on Engineering Education (CASEE) is working to address as part of NAE's commitment to improving engineering education. Ultimately, CASEE's work will benefit employers, engineering schools, and engineering graduates.

"Developing and maintaining a vibrant, well educated workforce is an important issue for our nation," noted **Alice Gast**, vice president for research at MIT and chair of the CASEE Advisory Committee. "I believe CASEE fills an important role in coordinating and leading scholarly inquiry into engineering education, and I am pleased with the excellent beginning the center has made."

CASEE's broad-based initial efforts will involve working collaboratively with representatives of all sectors of the engineering community. A Senior and Postdoctoral Fellows Program will provide opportunities for distinguished opinion leaders to catalyze advancements nationally as well as in their own organizations. The Research Community Affiliates Program will serve as a vehicle for coordination and dissemination for campus-based education centers pursuing initiatives to improve engineering education. The Implementation Network Affiliates Program will link academic and industrial entities willing to run experiments and pilot projects in innovative approaches to engineering education. The National and Regional Workshops Program will disseminate research findings to all of the nation's nearly 350 colleges of engineering.

In addition, an electronic portal will provide links to journals focused on education research in various engineering and science disciplines. A Web-based clearinghouse that summarizes available evidence on best teaching practices and strategies will be a useful tool for improving learning in a variety of venues.

The CASEE initiative has received strong and growing support from professional engineers, educators, federal officials, and corporate leaders. As NAE President **Wm. A. Wulf** observed, "We are seeing real momentum, both in the program and in the financial support being offered for the center. This spring, the National Science Foundation approved a $200,000 grant; the Applied Materials Corporation made a generous gift; and individual NAE members are stepping up too, in reply to our recent appeal for their philanthropic support for CASEE." For more information, visit the CASEE website at *www.nae.edu/casee*.

FIRST Robotics Competition National Championship

"The excitement of the championship event is incredible, but what's most powerful is that FIRST is inspiring the next generation of science and technology heroes. The diversity of talent, the quality of thinking and the level of energy you see, hear, and feel from these students will impact their lives and their world well beyond this weekend's 'Super Bowl of Smarts.'"

That is how NAE member **Dean Kamen** describes the atmosphere at the FIRST Robotics Competition National Championship, which was held April 10 to 12 at Reliant Stadium in Houston. For more than a decade, FIRST—For Inspiration and Recognition of Science and Technology—has been teaming engineers with high school students and their teachers in a unique collaboration designed to let students experience the most exciting aspects of engineering, science, and technological application and to develop an awareness of the importance of collaboration and teamwork in technology-oriented endeavors.

These goals are accomplished through a deceptively simple process: teams of engineers, teacher, and students—jointly sponsored by their schools and by individual corporations—spend six weeks developing robots that meet the specific criteria and demands of that year's "game." (The 2003 robots had to move and stack plastic storage containers to rack up points, while opponent robots attempted to disrupt their efforts.) The teams compete in a series of regional competitions, and the winners compete in the national championship event.

Founded by Kamen, with NAE member and MIT professor **Woodie Flowers**, the FIRST Robotics Competition—and its more recent middle school sibling, the FIRST LEGO League—draws on the sports competition model to convey the message that being smart is "cool," that scientific and technological achievement are as worthy of celebration as achievements in sports, and that careers in science and engineering can be accessible to students of all backgrounds. The FIRST model, which builds on the concepts of "coopetition"—cooperative competition—and "gracious professionalism"—a multifaceted notion that includes community service—has been extraordinarily successful. Since the initial event in 1992, when 28 teams competed in a New Hampshire high school gym, the annual FIRST Robotics Competition has grown to 800 teams involving more than 20,000 students, mentors, sponsors, and other volunteers. The program is supported by a growing network of national corporations; and some of the nation's leading colleges and universities offer scholarships to FIRST participants.

"NAE is very supportive of programs like FIRST because we share so many of the same goals: raising the public's appreciation for and involvement in science and engineering; building students' thirst for science, math, and technology-oriented knowledge; increasing the number of young people who are excited about pursuing engineering careers; and increasing the size and diversity of the engineering workforce," observes NAE President **Wm. A. Wulf**. "My wife [NAE member **Anita Jones**] and I have both participated in FIRST competitions. They were extraordinary experiences, and I encourage all NAE members—and their employers—to consider participating in FIRST or another well run program that gives students a hands-on sense of the excitement of engineering." More information on FIRST is available at *www.usfirst.org*.

Sixth German-American Frontiers of Engineering

On April 30 to May 3, the sixth German-American Frontiers of Engineering Symposium was held at the Schlosshotel Monrepos in Ludwigsburg, Germany. Situated in parkland near Monrepos Lake and a baroque-style castle built between 1760 and 1803, the setting was conducive to the exchange of ideas and information that is such an important part of the meeting.

Modeled on the U.S. Frontiers of Engineering Symposium, this bilateral Frontiers meeting brought together 60 engineers ages 30 to 45 from German and U.S. companies, universities, and government. Like the U.S. Frontiers symposium, the goal of the meeting is to bring together emerging engineering leaders in a forum where they can learn about leading-edge developments in a range of engineering fields, thereby facilitating an interdisciplinary transfer of knowledge and methodology. In the case of the bilateral Frontiers, there is the added dimension of helping build cooperative networks of younger engineers that cross national boundaries. NAE works with the Alexander von Humboldt Foundation to organize this activity.

NAE member **Sangtae Kim**, vice president and information officer, Lilly Research Laboratories, and Albert Weckenmann, professor, University of Erlangen-Nürnberg, cochaired the organizing committee and the symposium. The four topics covered at the meeting were optical technologies, micromanufactured systems, biomedical sensors, and information technology. Presentations by two Germans and two Americans in each of the four areas covered optical pattern recognition and security systems; production of silicon microphones for hearing instruments and mobile phones; functional, diffuse, optical spectroscopy (a noninvasive diagnostic technique for breast cancer); and reconfigurable computing architectures. The discussions among the participants, both during the formal sessions and during breaks, receptions, and dinners, were spirited and interesting. The group took a break from the plenary sessions on Friday afternoon for a tour of the Residential Palace in Ludwigsburg and a walk through the palace gardens followed by dinner in the wine country near Hessigheim.

Funding for the meeting was provided by the Alexander von Humboldt Foundation, the NAE Fund, and the National Science Foundation. Plans are under way for a seventh GAFOE meeting to be held in Washington, D.C., in 2004.

For more information, contact Janet Hunziker in the NAE Program Office at 202/334-1571 or by e-mail at *jhunziker@nae.edu*.

Some of the participants at this year's GAFOE Symposium.

The Keck Futures Initiative and Keck Center of the National Academies

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On April 15, 2003, the W.M. Keck Foundation of Los Angeles, California, announced a 15-year, $40-million grant to the National Academies to underwrite the Futures Initiative, a program designed to stimulate new modes of inquiry, break down conceptual and institutional barriers, and realize the untapped potential of interdisciplinary research. Specifically, the program will engage scientists, engineers, and health professionals to identify subjects to guide cutting-edge interdisciplinary research and will encourage and reward outstanding communication between disciplines, as well as between the scientific, engineering, and health communities and the public.

The Futures Initiative has four distinct elements: conferences of outstanding researchers from diverse disciplines and professions; grants to selected conference participants to pursue follow-on research; National Academies Communication Awards for talented communicators who synthesize technical issues and communicate them effectively; and a consensus study exploring how funding organizations and academic institutions can facilitate productive interdisciplinary research. The staff of the Futures Initiative will be located in Irvine, California, in offices near the Beckman Center.

In recognition of the Keck Foundation's strong support, the academies building at 500 Fifth Street in Washington, D.C., has been named the Keck Center of the National Academies. A formal dedication was held on May 13, 2003.

NAP Offers PDF Files

The National Academies Press (NAP) is in the process of posting PDF (Adobe's Portable Document Format) files of all NAP reports on the National Academies Press website <*http://www.nap.edu*>. NAE members can access the PDF files for free by clicking on the NAP publications link on the NAE membership home page.

Free digital PDFs will also be available to everyone in developing countries, NAS and IOM members, congressional members and staff, journalists, National Academies staff, sponsors, and current volunteers. For those not in one of the groups listed above, the digital files will be available for 40 percent off the list price of the printed book. Files of individual chapters can also be purchased.

Calendar of Meetings and Events

June 10	Center for the Advancement of Scholarship on Engineering Education Advisory Committee Meeting
June 11	NAE Audit Committee Meeting
June 12	NRC Governing Board Executive Committee Meeting
June 12–13	Committee on Diversity in the Engineering Workforce Meeting *Woods Hole, Massachusetts*
June 16–17	NAE/IOM Committee on Engineering and the Health Care System Meeting
June 23	Membership Policy Committee Meeting
July 8	Charles Stark Draper Prize Committee Meeting
July 15	NRC Governing Board Executive Committee Meeting
August 5	New Council Member Lunch and Orientation *Woods Hole, Massachusetts*
August 6–7	NAE Council Meeting *Woods Hole, Massachusetts*
August 8–9	NRC Governing Board Meeting *Woods Hole, Massachusetts*
August 22	Bernard M. Gordon Prize Committee Meeting
September 9	NRC Governing Board Executive Committee Meeting
September 18–20	U.S. Frontiers of Engineering Symposium *Irvine, California*
September 23	Charles Stark Draper Prize Committee Meeting
October 8	NRC Governing Board Executive Committee Meeting
October 9	Bernard M. Gordon Prize Committee Meeting
October 10	NAE Finance and Budget Committee Meeting
	NAE Council Meeting and Dinner
October 11	NAE Council Meeting
	NAE Peer Committee Meetings
October 12–14	NAE Annual Meeting
October 20	Center for the Advancement of Scholarship on Engineering Education Advisory Committee Meeting
November 12	NRC Governing Board Executive Committee Meeting
November 12–13	NRC Governing Board Meeting
November 20–22	Japan-American Frontiers of Engineering Symposium *Irvine, California*
December 4	NAE/ASEE Assembly Meeting
December 5–6	Committee on Membership Meeting *Irvine, California*
December 11	NRC Governing Board Executive Committee Meeting

All meetings are held in the Keck Center or the National Academies Building, Washington, D.C., unless otherwise noted. For information about regional meetings, please contact Sonja Atkinson at *satkinso@nae.edu* or (202) 334-3677.

The National Academies Update

Presidents' Statement on Affirmative Action

On April 1, 2003, NAE President Wm. A. Wulf, National Academy of Sciences President Bruce Alberts, and Institute of Medicine President Harvey Fineberg issued the following statement:

This week the U.S. Supreme Court is hearing arguments in two cases that challenge the right of colleges and universities to account explicitly for race in student admissions. At stake is the legality of what has become the broad consensus among the leaders of America's colleges and universities, as well as many leaders of business, the military, and other sectors. For at least 25 years, since the Supreme Court's ruling in the landmark Bakke case, U.S. colleges and universities have initiated and experimented with a wide variety of admissions systems that rest on three basic premises:

- racial diversity is a compelling educational interest that is fundamentally compatible with the social and economic mission of institutions of higher learning;
- racial diversity cannot be achieved effectively through programs that substitute geographical location or socio-economic status for race; and
- conscious attention to race as a factor in admissions does not compromise the principle of merit in the selection of students or the high standards for academic excellence to which our colleges and universities aspire.

This argument is no less applicable to the specific goals and responsibilities of the nation's scientific, engineering, and health care enterprise. We hope that the Supreme Court will permit colleges and universities to apply appropriate programs and policies to achieve the diversity that is necessary to the future of this enterprise, to the mission of higher education, and to fulfilling America's great promise of opportunity for all.

Scientific and technological progress has been largely responsible for the enormous advantages now enjoyed by more Americans than at any time in history. National security, the health of our nation, and the strength of our economy depend heavily on the advancement of science, technology, and medicine. Although there have been those throughout history who have tried to pit high standards for scientific achievement against increased opportunity, the reality is that enlarging the franchise has enriched everyone.

Diversity in science, engineering, and the health professions is both a means and an end. It is a means toward even greater technological and economic progress, because creativity, productivity, and success in these fields depend greatly on openness to diverse ideas and experiences. And it is an end, because science, technology, and medicine—just like the humanities, law, art, theater, sports, or the military—should not be accessible to only the privileged few. Medicine offers an especially compelling case. Diversity of the physician work force will improve access to health care for underserved populations. And diversity among managers of health care organizations makes good business sense.

There is overwhelming evidence that diversity enhances educational experience and benefits scientific, technological, and medical advancement. Is it attainable through programs that do not consciously and explicitly account for those attributes that combine to create the sought-after diversity? The answer appears to be no. Thus far, attempts to achieve racial diversity by including factors that may appear to correlate with race—rather than race itself—have proved to be ineffective.

There is a fundamental difference between denial of due process or of equal treatment and the conferring of preference based on race. It is critical to understand that increasing the probability of admission for some students does not automatically deny admission to other students who may erroneously believe that they are otherwise assured a place. A multitude of factors go into the admissions decisions of selective colleges and universities, and the assumption that any single factor is sufficient to deny admission to an applicant without that factor is wrong.

The idea that the inclusion of race as a factor in admissions policies compromises the principle of merit is a mistaken one that rests on misperceptions about the precision with which existing technologies measure current and future academic performance. It is still a widely held but erroneous perception that standardized test scores, in this case often the SAT, provide an objective and accurate gauge of future student success. A solid body of research leads to a more subtle conclusion that is directly relevant to the case before the Supreme Court.

Standardized test scores do exactly what they were designed to do: When used with other measures, such as high school grades, they predict freshman grade point averages reasonably well. Nevertheless, the strength of that correlation is such that there is substantial room for error. Some low-scoring students will excel in college, and some high-scoring students will fail. A university's complex goals and mission cannot be achieved by relying solely on test scores.

The common misconception that test scores are reliable but imperfect predictors of future performance has far-reaching implications, as noted in a 1999 study from the National Research Council of the National Academies, *Myths and Tradeoffs: The Role of Tests in Undergraduate Admissions*. Indeed, the claim that a student with a higher test score should be guaranteed admission over another student with a lower score is not scientifically defensible. Standardized tests are not designed to make fine distinctions at any point on their scale, or to provide information about all the factors that influence success in college and beyond. Tests are useful primarily when administrators need to sort applicants into broad categories—those who are quite likely to succeed academically at a particular institution and those who are unlikely to succeed. Still, flaws remain. Because of the gap between majority and minority scores, a statistical outcome is that a greater proportion of minority candidates are misclassified as unlikely to succeed.

On the whole, scientific, medical, and technical progress goes hand in hand with the goal of diversity. Taking that goal seriously strengthens the nation's economic, academic, and social well-being.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at <*http://www.nap.edu*> or by phone at (800) 624-6242. (*Note: Prices quoted by NAP are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.*)

Beyond the Molecular Frontier: Challenges for Chemistry and Chemical Engineering. The chemical sciences are at the forefront of efforts to find new energy sources, improve the environment, design chemicals that can imitate biological processes, detect and respond to terrorist attacks, create new drugs and artificial human organs, and further our understanding of the chemical behavior of human cells. To maintain its leadership position in the chemical sciences, the United States must attract the very best minds, which means recruiting more women and minorities and revising undergraduate and high school curricula to make chemistry more appealing to students. The study concluded that strong financial support from the federal government will be necessary to facilitate discoveries in the chemical sciences and to ensure that a technically proficient workforce is available in the future. Industry can assist by offering fellowships for doctoral students in the chemical sciences and chemical engineering, and chemists and chemical engineers can help by more effectively communicating with the public and the news media. The report outlines 13 "grand challenges" for the 21st century to inspire young people to study chemical sciences, to apprise policy makers of the potential achievements of chemistry, to challenge the creativity of practicing scientists and engineers, and to stimulate advances that would benefit society. Paper, $34.95.

Completing the "Big Dig": Managing the Final Stages of Boston's Central Artery/Tunnel Project. Boston's Central Artery/Tunnel Project, a 7.8-mile system of bridges and underground highways and ramps, is the most expensive public works project ever undertaken in the United States. The original cost estimate of $2.6 billion has already been exceeded by $12 billion, and the project will not be completed until 2005, seven years late. The Massachusetts Turnpike Authority (MTA), the public steward of the project, requested that the National Research Council carry out an independent assessment of the project's management and contract administration practices, with a focus on the present situation and measures that should be taken to bring the project to a successful conclusion. This report presents the committee's findings and recommendations pertaining to cost, scheduling, and transitioning from the current organization dominated by consultants to an operations organization composed largely of full-time MTA staff. The report recommends that MTA establish an external, independent, peer-review program to address technical and management issues until the transition to operations and maintenance is complete; begin a media campaign now to teach drivers how to use the new system safely; and develop, immediately implement, and maintain a comprehensive security program. Paper, $18.00.

Critical Information Infrastructure Protection and the Law: An Overview of Key Issues. This report presents the results of a symposium held in October 2001 to identify issues related to critical information infrastructure protection (CIIP). Although the symposium was scheduled long before September 11, the events of that day heightened the nation's awareness of interdependencies between critical infrastructures. The symposium participants agreed that despite the urgency of protecting infrastructures, well established constitutional and statutory principles of privacy and civil liberties must also be protected. The report examines a range of legal issues associated with CIIP, particularly issues that affect the willingness of private-sector companies and organizations to cooperate with the government to prevent, detect, and mitigate cyberattacks. As dependence on common technology and interconnected systems increases, technical vulnerabilities can be overcome only through collective, concerted action. Trust among the groups and individuals that must share information is a prerequisite for the successful protection of the nation's critical information infrastructures in an atmosphere of openness and cooperation. However, the report concludes that government has failed to establish trust between the public sector and the private sector for several reasons. The reasons for this failure are examined, and suggestions are put forward for addressing the difficulties. Paper, $25.00.

Environmental Information for Naval Warfare. An understanding of the distribution of friendly, enemy, and neutral forces and facilities and the nature and significance of the environment they occupy is key to "battle-space awareness." A shared awareness of the battle space among allied military forces is highly desirable but difficult to achieve. A complex meteorological and oceanographic effort, referred to by U.S. Naval Forces as METOC, has focused on the collection, assimilation, analysis, and dissemination of information about and predictions of the nature and significance of the environmental character of the naval battle space. The Office of the Oceanographer of the Navy and the Office of Naval Research requested that the National Academies undertake a study to develop an investment strategy to enhance the value of METOC contributions to battlespace awareness. The major findings and recommendations in this report are based on a business model approach to two METOC mission areas—investment allocations and management of risk—to ensure that environmental information is presented in a way that conveys to warfighters an appropriate level of confidence in its content, to ensure that efforts to enhance environmental information are carried out in a way that maximizes resources, and to create a system for information exchange that allows a high degree of informed involvement by warfighters. Paper, $44.75.

Exposure of the American Population to Radioactive Fallout from Nuclear Weapons Tests: A Review of the CDC-NCI Draft Report on a Feasibility Study of the Health Consequences to the American Population from Nuclear Weapons Tests Conducted by the United States and Other Nations. This National Research Council (NRC) report recommends that the draft report issued by the Centers for Disease Control and Prevention (CDC) and the National Cancer Institute (NCI) be published promptly, despite its limitations. Publication should be followed by a reanalysis of data on the fallout of iodine-131 and the related risk of thyroid cancer in light of information learned from the Chernobyl accident. The report recommends that CDC urge Congress to prohibit the destruction of all remaining records relevant to fallout and that researchers with firsthand knowledge of nuclear-weapons tests and fallout patterns be interviewed and the information they provide archived. A comprehensive, understandable public summary should be made part of the final report, widely disseminated, and posted on the CDC and NCI websites. Paper, $18.00.

Funding Smithsonian Scientific Research. Federal support for U.S. science and technology is widely agreed to be a great public good. Nevertheless, government managers are responsible for ensuring that public investments in science and technology are allocated wisely and produce high-quality results. This report was conducted to address concerns about some scientific research conducted by the Smithsonian Institution that is partly funded by direct appropriations from the federal government without peer-reviewed competition. The Smithsonian requested that the National Academies, in partnership with the National Academy of Public Administration (NAPA), evaluate whether the federal research funding now given by direct appropriation should be transferred to the National Science Foundation to support its competitively awarded research grants. The committee was asked to provide specific recommendations and a rationale (with criteria) for some Smithsonian research to continue to be exempt from competitive, peer-reviewed grant programs because of its uniqueness or special contributions. The committee was also asked to review the scientific research centers that report to the Smithsonian's under secretary for science; to consider the effects on the Smithsonian, the research centers, and the relevant scientific fields of reallocating the current federal support to a competitive process; and to recommend ways to evaluate the programs that would continue to receive direct federal appropriations and compare them with other research in the field. This report presents the findings and recommendations of the National Academies' committee; NAPA will issue a separate report. Paper, $27.25.

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