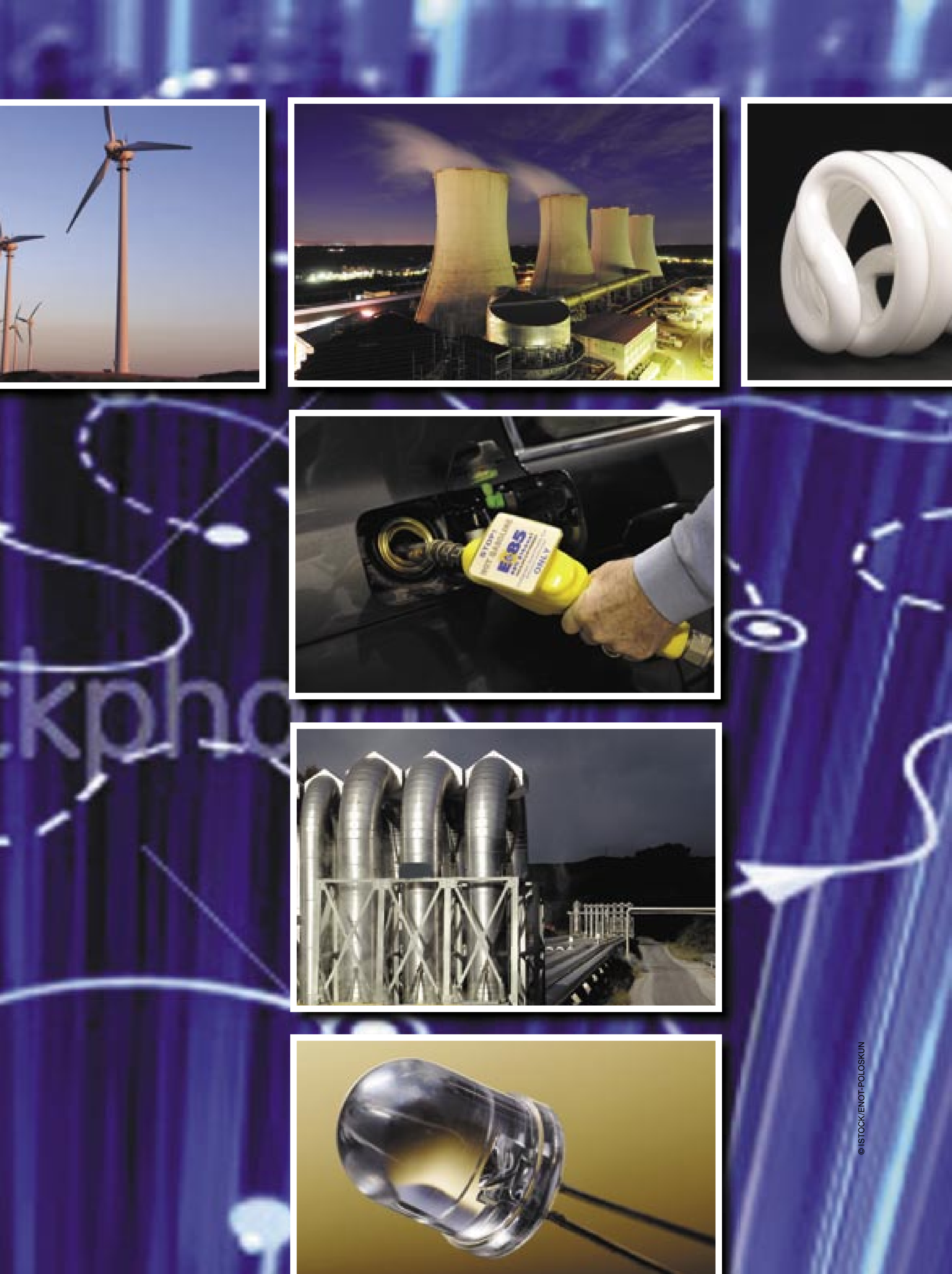
  

Stimulating a Revolution in Sustainable Energy Technology

BY CHARLES WEISS AND WILLIAM B. BONVILLIAN



A consensus is growing that the environmental, economic, and geopolitical costs of the world's addiction to fossil fuels justify a major U.S. federal program to stimulate technological innovation in energy. President Obama and Congress made a down payment on such a program in the February 2009 stimulus bill,[1] advancing some $39 billion toward energy technologies, including $5 billion in research, although the administration's follow-on technology program in the climate bill is now in jeopardy. Given the pervasive role of energy throughout the economy and the international character of the climate crisis, many urge the creation of a program the size of the Manhattan or the Apollo Projects. Beyond the growing consensus for policy action, how should such a program be organized?

An initial rationale for such a program is that market mechanisms alone, such as a carbon charge (a cap-and-trade regime or carbon tax), cannot stimulate the development and deployment of energy technologies fast enough to meet the urgent national need, nor can it overcome the built-in bias in favor of technologies based on fossil fuels. Fossil fuels are convenient and cheap if externalities like war and environment are excluded. The fossil fuel economy is huge, mature, heavily subsidized, pervasive, adept at fending off competition, deeply entrenched in the economy and the political system, and sustained by public expectation of cheap energy. Except in limited circumstances, a new energy technology must compete at scale with existing technology from the moment of its market launch, a daunting prospect. As a result, any innovation in energy technology faces an uneven playing field.

A carbon charge, combined with regulatory standards and other policies to force more efficient energy use, is essential to guide the path of innovation into an environmentally sustainable direction, but it is only part of the answer. The many obstacles on the path from new idea to widespread deployment require that such measures be complemented by direct support, not just at the research and development (R&D) stage, but during the entire process of innovation. Despite the new administration's efforts, policies to increase demand for sustainable energy technologies are likely to be slow in coming and, at the beginning, loaded with loopholes and giveaways.

Why a Technology Revolution?

Cannot existing technologies do the job? Isn't the call for research and innovation just an excuse for inaction? Some alternative technologies—chiefly wind-electric and concentrating solar—are nearly competitive with fossil fuels, and a long list of improved practices[2] could, if adopted, avert substantial carbon dioxide emissions. Putting these approaches into practice, however, is far from simple. What, for example, is the likelihood of a 50 percent reduction in car travel for two billion vehicles by 2054, as Princeton professors Stephen Pacala and Robert Socolow suggest as one of 15 actions to stabilize carbon emissions?[3]

In any case, why rely on existing technologies when the potential exists to improve them?[4] This would be like forcing the aviation industry to stick with biplanes after 1920. For example, until basic scientific problems in storage technologies are solved, these inadequacies will limit the long-run contribution of intermittent sources of renewable energy like wind and solar and hold their energy market share at around 10 percent each.

One problem lies in the fact that energy research has been starved for decades, in part due to the wildly fluctuating price of energy that discourages long-term investments in either the public or private sectors. Oil prices may have hit a peak of $140 per barrel the summer of 2008, but they were below $20 per barrel as recently as 1998, and in February, they were below $50 per barrel. According to one leading estimate,[5] private-sector expenditures on R&D in 2007 amounted to less than 1 percent of energy industry revenues, less than half the average of 2.6 percent for U.S. industry as a whole and a small fraction of the 15 percent or more of revenues invested by innovative industries like biopharmaceuticals and semiconductors. Public-sector energy R&D funding in 2007 was half its peak in 1980, and private-sector funding has suffered a similar fate. Even the flood of private venture capital into energy commercialization before the recent economic meltdown—reaching $3 billion in 2007—was often directed to subsidized investments in existing technologies with political clout, most famously corn ethanol. These particular subsidies amounted to a counterproductive policy; one could call it "no lobbyist left behind."

To be sure, even a small percentage of a $1.5 trillion annual energy economy, coupled with limited government R&D, has produced over the past several decades a host of promising energy and energy conservation technologies that are now at all stages of R&D, plus a few, such as light-emitting diodes (LEDs) and off-grid solar, that have been successfully launched in limited niche markets. If these technologies are to be given a chance to emerge, they need support. On the other hand, since we do not really know which of the many competing ideas will turn out to be the most energy efficient and cost-effective, no particular emerging technology has any special claim on support. Thus, any government policies to encourage innovation should be as neutral as possible to create a level playing field that allows alternatives to compete on their techno-economic and, once proper policies are in place, environmental merits.

Energy Technology and the Theory of Innovation

According to the "technology push," "linear," or "pipeline" model of innovation, research intended to push back the frontiers of knowledge—ideally motivated by sheer curiosity about the workings of the natural world—will lead to radical, pathbreaking inventions.[6] These create new functionality and make it possible to do things that have never been done before: watch television, play video clips, scan barcodes, or electrify a region with a single power plant. Once translated into commercial products, these innovations will make profits and give rise to economic growth. While the government and large industry pursued basic research alongside each other in institutions like the Bell Laboratories from the 1950s to the 1980s, the pipeline model has long been dominated by federal support for basic research. The assumption has been that commercialization and widespread deployment will take place without further government intervention.

Basic research in the United States tends to take place in universities and research institutes with federal support, whereas product development takes place in private industry. Compared to the technology transition process in other countries, which is hampered by a variety of regulatory and social constraints, the U.S. system works relatively well. Even so, this institutional separation gives rise to a difficult-to-finance gap between the initial prototype or proof of concept in a university laboratory and a commercializable product that is attractive to the venture capitalist and industry. This gap has become known as the "valley of death," where most new technologies die.[7] In many historic cases, including the Internet, this gap was filled by a timely intervention by the military.[8]

The emphasis on radical innovations embodying new functionality is well suited to the American temperament. Information technology is the most noted example of an innovation that landed in new territory—nothing that had existed before was comparable to the computer. The stereotypical American does not stick around to cope with the underlying problems but prefers to pack the family into a covered wagon, push over the next mountain chain, and open an entirely new frontier. We rarely turn back to deal with the problems connected with the established technology we left behind: we create biotechnology but do not fix the health delivery system; we develop solar photovoltaic cells but allow the electricity grid to languish. We are not good at dealing with the problems created by long-standing, entrenched, pervasive, and efficient "legacy" technologies like those based on fossil fuels.

To deal with such established, complex technology sectors, we need additional conceptual tools. One is the theory of "market pull" or "induced innovation," which in its simplest form states that innovation tends to minimize the use of relatively expensive inputs and maximize the use of inexpensive ones.[9] As a result, a change in the price of a key input like energy, whether through pure market forces or a change in government policy, can affect the direction of innovation, at first through small adjustments like closing the doors of air-conditioned offices or buying smaller cars. If the price changes are expected to last, more expensive energy will lead to the development and introduction of new, energy-efficient products based on existing technologies and, in the longer run, to a change in the direction of applied research. This is the basic theoretical underpinning of the proposal for the carbon charge that has dominated the debate over new energy technology.

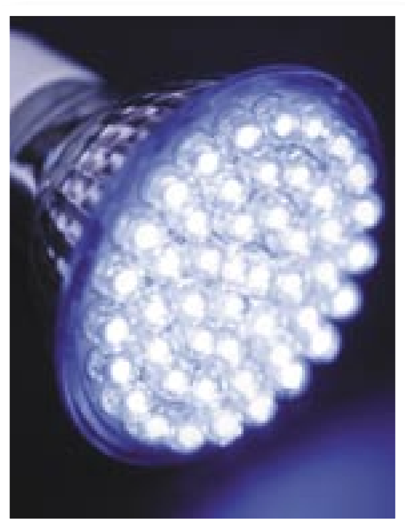
While the "market pull" or "induced" model tends to favor incremental innovation, the "technology push" or "pipeline" model favors radical innovation. In a complex sector like energy, new innovation will require a synthesis of both models: a technology strategy and a pricing program.

The induced innovation model assumes that a technology can enter the marketplace more or less automatically once the appropriate market incentives are well established. This is not always the case, especially when it faces competition from established technologies, such as those dependent on fossil fuels. Obstacles to innovations based on the results of long-term research may appear at the classic valley of death between proof of concept and first product. Others may appear at a later stage, when the product is ready for market launch at scale. The latter stage is particularly critical for innovation in complex established sectors like energy.

Overcoming Obstacles to Market Launch

Policies intended to overcome these obstacles require a further elaboration quite different from those derived from the technology push approach traditional to U.S. science policy. A new analytic method to identify institutional gaps in existing policies for the promotion of innovation can help policymakers design them.[10] This method arises from a careful assessment of a dozen or so promising energy technologies, classified into groups according to the obstacles they are likely to encounter once they near the point of market competitiveness. From

Market mechanisms alone cannot stimulate the development and deployment of energy technologies fast enough to meet the urgent national need.



these groupings, three policy packages and three new institutions emerge that will help overcome the obstacles.

Promising Energy Technologies

Potentially sustainable energy technologies include well-known innovations like wind-electric and solar photovoltaics, as well as some that may have received less focus from the general public. The latter include

• LEDs, which are replacing incandescent and fluorescent bulbs in a variety of lighting application (see the box on the upper right of this page);

• enhanced "hot rocks" geothermal technology, which, if perfected, could open up much of the United States and other countries to this renewable, non-carbon-emitting technology (see the box on the right of this page);

• carbon capture and sequestration (CCS), which, if perfected, could capture the carbon dioxide emitted by large fixed installations like power plants and cement kilns and permanently store it in saline aquifers or under the seabed (see the box at the top of page 15); and

• improved battery technology, which would overcome a critical energy storage bottleneck in the development of solar and wind electricity and plug-in hybrid cars (see the box on the bottom of page 15).

LIGHT EMITTING DIODES (LEDS)

LEDs are smaller, more flexible, longer lasting, and potentially much more efficient than either fluorescent or incandescent light bulbs. They consist of a sandwich of semiconductors so constituted that it converts electric voltage directly into light—the reverse of photovoltaic panels, which convert light into electricity. If they follow the cost-cutting curve of other semiconductors, they might be half the price of fluorescents in 10 years. Widespread use of LEDs could save as much as 10 percent of all electricity use worldwide. The market for LEDs as specialty lighting already exceeds that for incandescent lighting. Presently available inorganic LEDs emit light at a set of precise wavelengths that differs from natural white light. Further research is needed to cut production costs and achieve more natural light qualities.

ENHANCED ("HOT ROCKS") GEOTHERMAL ENERGY

Today's geothermal technology extracts the heat caused by the decay of radioactive elements in the Earth's crust from water in natural underground reservoirs near the hot rocks along tectonic plates. In contrast, enhanced geothermal—a promising new renewable technology that could become a major source of baseload electricity over much of the world—artificially inserts water via an injection well into dry, hot subterranean rocks.

Modern technology enables deeper drilling to access hot rock areas across much of the globe, not just along tectonic plates. Enhanced geothermal systems now being developed and tested in a handful of developed nations involve production wells, drilled near hot rocks to extract the heated water or steam and feed it into heat exchangers, turbines, or other devices to produce useful energy. The systems use explosives or hydraulic pressure to fracture the rocks between the two wells and form an artificial underground reservoir of hot water flowing between the two wells. The hot, extracted water is recycled so that pollution and water use are minimized. Further research and demonstrations at scale are needed to lower the costs of drilling and reservoir formation.

These emerging technologies fall into one or more of six broad categories, each of which requires a different set of policies:

• *Experimental technologies requiring support for long-range research.* For many of these technologies, such as fusion or hydrogen fuel cells for transport, consideration of market launch can be reserved for such time as their properties and environmental consequences are more clearly delineated. Others, such as batteries assembled from benign viruses, may require translational research that links breakthrough results in science with their potential practical applications and, in promising cases, follows through with support to the launch of the technology through the prototype stage.

• *Potentially "disruptive" technologies—those that might displace well-established incumbents*[11]*—that can be launched in niche markets*. In addition to needing support for research and development, promising technologies that are approaching commercialization and can be launched and scaled up in niche markets may also require support for prototyping and development and some public incentives to speed adoption beyond what market forces alone would accomplish. These technologies include LEDs, off-grid wind power, solar photovoltaic, and solar thermal power.

• *Innovations that face immediate market competition from legacy technologies but will be uncontested*. A number of technologies are unlikely to provoke political or non-market economic opposition to their market launch, nor will they have an unavoidable cost or environmental disadvantage. These are typically components in existing platforms or technological systems like cars or electric power grids and, in favorable cases, can stimulate major overall changes in these systems. Examples include improved batteries in plug-in hybrid cars, on-grid solar photovoltaic, and enhanced geothermal (once demonstrations are successful), all of which are components in larger systems.

• *Innovations that face immediate market competition from legacy technologies and will be contested.* These are component innovations that have inherent cost disadvantages and can be expected to face

CARBON CAPTURE AND SEQUESTRATION (CCS)

The United States, China, and India have huge coal reserves that supply the bulk of their cheap baseload electric power and, unfortunately, their planet-warming carbon dioxide emissions. CCS technology would capture the carbon dioxide at large fixed installations like electric-generating plants or cement kilns, put it into a supercritical (near liquid) state, transport it by pipeline, and inject it into permanent storage in saline aquifer formations, which are pervasive in the United States and China (but not India), or beneath the ocean floor. This will add at least 25–30 percent to the consumer cost of coal-fired electricity, an added expense that utilities and consumers will not accept in the absence of a cap-and-trade regime, carbon tax, or regulatory requirement. Different aspects of this technology have been tested or are in practical use at megaton scale, but total annual carbon dioxide emissions from coal-fired plants are thousands of times larger. At least several large, expensive demonstration projects under different geological conditions are needed to prove the safety and effectiveness of this technology, the permanence of the carbon dioxide storage, and the precise costs. These must be carefully designed and operated, and closely monitored to illuminate the best operating practices. Applying new capture technologies to retrofit existing powerplants, not just new ones, also requires research. International collaborative research on CCS, specifically including Indian and Chinese scientists and engineers, is a critical global priority.

IMPROVED BATTERIES

The size, weight, power, recharge time, and expense of existing batteries limit the advance of hybrid and all-electric cars. Their cost also hinders the widespread deployment of intermittent sources of renewable energy, such as wind and solar, in the electric grid. New lithium ion batteries with nanotechnology features promise to be cheaper, lighter, and more powerful. What is more, they promise faster charging speeds, so that they can, for example, capture and store the regenerative energy of a rapidly braking car for reuse.[1] All-electric cars using these advanced batteries will save energy and improve automobile performance, although the balance between these two objectives depends on government policy and consumer choice. Fifty-mile range, fuel efficiency of 150 miles per gallon, and 0–60 miles-per-hour acceleration in four seconds are all within sight for a plug-in hybrid car that can be charged overnight—or more rapidly if recharging advances continue—from a household electric outlet. Electric cars are intrinsically more energy-efficient than those run by internal combustion engines, but more carbon dioxide emissions can be averted if the extra electricity they need is generated from renewable sources.

In addition to nanotechnology-based battery features, a series of major storage advances that could prove transformative is emerging: carbon nanotube-based ultracapacitors; benign viruses that self-assemble into battery components; and artificial photosynthesis, with the development of an inexpensive catalyst to cleave water into hydrogen and oxygen for storage.[2]

1. B. Kang and G. Ceder, "Battery Materials for Ultrafast Charging and Discharging," *Nature* 458, no. 7235 (12 March 2009): 190–93.

2. For more on nanotube-based ultracapacitators, see D. Halber, "Researchers Fired Up over New Battery," *MIT Tech Talk* 50, no. 16: 1, 5. For more on batteries using viruses, see Y. J. Lee et al., "Fabricating Genetically Engineered High-Power Lithium-Ion Batteries Using Multiple Virus Genes," *Science* 324, no. 5930 (22 May 2009): 1051–55. For more on artificial photosynthesis, see M. W. Kanan and D. G. Nocera, "In Situ Formation of an Oxygen-Evolving Catalyst in Neutral Water Containing Phosphate and Co^{2+}," *Science* 321, no. 5892 (22 August 2008): 1072–75.

economic, political, or other nonmarket opposition from recipient industries that must be overcome, or policy objections from advocacy groups that must be met, over and above the obstacles faced by the preceding categories. Examples include CCS, cellulosic biofuels, and also fourth-generation nuclear power.

• *Incremental innovations in conservation and end-use efficiency.* Efficiency in established and new technologies offers an ongoing source of energy savings. The deployment of innovations such as improved internal combustion engines, building technologies, efficient appliances, improved lighting, and new technologies for electric power distribution is limited by the short time horizons of potential buyers and users, who typically refuse to accept extra initial costs unless the payback period is very short.

• *Improvements in manufacturing technologies and processes.* Entry of new technologies is limited by cost barriers that can be cut by manufacturing advances. The improvements needed to scale up manufacturing so as to drive down costs, improve efficiency, and move efficient new energy products into the market more quickly are likely to be inhibited by the reluctance of cautious investors to accept the risk of increasing production capacity in the absence of an assured market.

Policies to Support Innovation

Policies classified into technology-neutral packages can be matched to these six technology groupings, making it possible to fit a policy package to each launch pathway by which a new technology can arrive in a market at scale. This approach is the opposite of the present pattern of energy legislation. Congress now writes its energy bills by giving each technology a separate title with a unique form and level of financial support depending on the technology's political muscle. To stimulate the technologies needed to reduce carbon dioxide emissions while promoting technology neutrality, it is critical that Congress shift this process, focusing not on specific technologies but on the technology support mechanisms. Innovators would then apply for this support depending on the prospective cost-efficiency and sustainability of their new technologies. The support policy elements include the following:

• *Front-end technology nurturing.* Technologies in all the above six categories need support before they are close to commercialization. This includes direct government funding for long- and short-term R&D and for technology prototyping and demonstrations.

• *Back-end incentives.* Closing the price gap between emerging and incumbent technologies may require incentives ("carrots") in the form of tax credits, loan guarantees, low-cost financing, price guarantees, government procurement programs (including military procurement for quasi-civilian applications such as housing), new-product buy-down programs, and general and technology-specific intellectual property policies. While experimental technologies are in too early a stage to need incentives, and many disruptive technologies may be able to emerge out of market niches into a competitive position without further incentives beyond R&D support, other categories are likely to require these carrots. These include secondary component technologies facing uncontested or contested launches, incremental innovations in technology for conservation and end use, and technologies for manufacturing processes and scale-up. Carrots may also be relevant to some disruptive technologies as they make the transition from niche areas to more general applicability.

• *Back-end regulatory and related mandates.* Regulatory and related mandates ("sticks") may be needed to encourage component technologies facing contested launches and also may be needed for some conservation and end-use technologies. In addition to emissions taxes, these include standards for particular energy technologies in building and construction and comparable sectors; regulatory mandates, such as renewable portfolio standards; and fuel-economy standards. A system of carbon charges, such as an effective cap-and-trade program, may make many of the back-end proposals listed above less necessary insofar as it would induce similar effects through pricing mechanisms.

Institutions to Support Innovation

Comparing existing energy innovation institutions with the innovation system requirements revealed by the analytic review described above highlights three major institutional gaps:

• the lack of an agency capable of doing translational research connecting potential scientific and technological breakthroughs to practical technology demonstration and implementation;

• the lack of a financial organization capable of financing large-scale demonstrations of new engineering-intensive technology, manufacturing scale-up, and conservation-oriented investments; and

• the lack of an organization capable of formulating strategy and roadmaps for the systematic development and introduction of new energy technology, as well as the policies needed to take advantage of the opportunities and overcome the obstacles that it identifies. (See the box on page 17 for an example of how the policy elements and institutions would help advance improved battery technology.)

In February, the U.S. government filled the first of these gaps, at least in principle, by establishing and funding the Applied Research Projects Agency for Energy, commonly known as ARPA-E,[12] which received $400 million as part of the stimulus bill.[13] ARPA-E is modeled on the federal government's most successful translational research agency, the Defense Advanced Projects Research Agency (DARPA) of the Department of Defense. The details of the institutional design of ARPA-E are critical to its effectiveness[14] and are now under intensive study and implementation inside the Department of Energy. In essence, ARPA-E would aim to identify potential scientific breakthroughs and translate them through the proof of concept or prototype stages into energy technologies.

To bridge the second gap, the administration could establish a government corporation that would recruit engineering, financial, and management expertise of the kind found in the private sector and operate outside the limits of government procurement systems in an environment comparable to that of a commercial firm. These capabilities would enable the corporation to finance demonstrations of engineering-intensive technology, as well as investments in conservation technology and accelerated manufacturing scale-up of promising equipment. Congress is now considering such an entity.[15]

Global warming, energy security, and economic competitiveness are inextricably linked and raise tricky questions of international relations.

A public-private partnership that undertakes strategic analysis of different aspects of energy technology; carries out roadmapping exercises for preferred trajectories of critically important technologies, including timetables and milestones; and identifies the policies and levels of support needed to make this timetable a reality would bridge the third gap. This entity should also assure a full environmental analysis of proposed new technologies so we do not travel down counterproductive dead ends. The best example of such a partnership in recent U.S. history is Sematech, a consortium of U.S. semiconductor chipmakers and their suppliers, initially funded by DARPA. It accelerated technology advances and manufacturing efficiencies that helped restore the competitiveness of the American semiconductor industry in the 1990s.

POLICIES TO STIMULATE IMPROVED BATTERY TECHNOLOGY

Batteries are critical for solving the storage problem inherent in intermittent renewable energy systems, especially solar and wind, as well as for increasing the viability of plug-in hybrid and, potentially, electric cars. As noted in the box on lithium ion batteries on page 15, the next generation of advanced batteries needs to be much cheaper than those in current use in hybrid cars. They also need to be smaller, lighter, and faster charging.

How could we accelerate battery advances? Batteries seem simple to the user but involve complicated electrochemical and physical processes on time scales ranging from seconds to a few quadrillionths (10^{-15}) of a second, or the time it takes light to pass through the thickness of a human hair. Unsurprisingly, important outstanding questions remain about the basic scientific processes involved, requiring a substantial increase in support to basic research in universities and research institutes. First, then, battery technology is a promising experimental territory that justifies a major *R&D focus*.

Next in the process is an opportunity for *translational research*. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) received $400 million in February's stimulus legislation and is now being supported by Energy Secretary Steven Chu. The agency's primary task will be to identify potential scientific advances that can be translated over a three- to five-year period into technological breakthroughs at the proof-of-concept or prototype stages. Promising opportunities that could be accelerated by an ARPA-E process include recent advances in self-assembled batteries using benign viruses[1] or nanotechnology designs for rapid recharge.[2]

Translating research advances should not occur in a void. The importance of battery technology for sustainable transportation and electricity generation justifies larger-scale public involvement in speeding their development and deployment. To this end, a *collaborative roadmapping* exercise could be important. A formal energy technology strategy and follow-on roadmap involving public, private, and academic sectors is not yet in place. In the interim, the Department of Energy and ARPA-E could collaborate with manufacturers of batteries and automobiles in developing a strategy and roadmap to speed the introduction of improved battery technologies into the marketplace faster than would occur through market processes alone.

By considering the implications of the new storage technology for the expansion of solar and wind energy into the national electric grid, this collaboration would smooth the path for this technology's entry. It will also be important to develop a strategy for identifying further research opportunities and speeding the large-scale introduction of improved batteries into ordinary hybrid, plug-in, and, potentially, electric cars as soon as their performance, safety, and reliability is satisfactorily proven. Once improved batteries are developed and proven, small models could be introduced into niche industries, like cordless hand tools, while U.S. car manufacturers test and then market them in high-end cars.

As new entrant technologies near market launch, expansion of support from ARPA-E and other sources will likely be needed for research on improved manufacturing processes, followed by low-cost financing by the proposed *government corporation* to speed technology demonstrations, scaled-up manufacturing, and deployment, thereby reducing cost barriers. Energy committees on the House and Senate sides of Congress are now considering legislation for such a financing entity. The market for plug-in hybrids or electrics themselves can be stimulated by further *back-end policy measures,* such as strengthened fuel-efficiency standards, a carbon tax on vehicle emissions, military procurement of new vehicles, or even a direct subsidy or tax credit to private purchasers. Policies will also be needed to ensure that renewable sources of energy are used to charge the plug-in vehicles.

---

1. Y. J. Lee et al., "Fabricating Genetically Engineered High-Power Lithium-Ion Batteries Using Multiple Virus Genes," *Science* 324, no. 5930 (22 May 2009): 1051–55.

2. B. Kang and G. Ceder, "Battery Materials for Ultrafast Charging and Discharging," *Nature* 458, no. 7235 (12 March 2009): 190–93.

A Global Approach to a Global Problem

National solutions can at best only partially solve the problem of stimulating energy innovation: global warming, energy security, and economic competitiveness are inextricably linked and raise tricky questions of international relations.

China has recently surpassed the United States to become the world's leading emitter of carbon dioxide. It has been building 500-megawatt coal-burning plants—the typical size of a large plant—at a rate of more than one a week.[16] India is likewise building coal plants. On the other hand, given their late start in industrializing (combined with the long residence time of CO_2 in the atmosphere), the emerging economies of China, India, and the rest of the developing world will need decades to catch up with the aggregate CO_2 contribution of the developed industrialized economies. As the first beneficiaries of the Industrial Revolution, the advanced economies have an ethical and highly practical obligation to get their own energy houses in order and assist the developing countries in doing so.

Issues of innovation and research collaboration raise these ethical and practical issues in acute form. American, European, and Japanese companies rightfully see innovation as a source of future market competitiveness and expect to develop export markets and create green jobs as a result of their investments in this area. Spurring economic competition will be vital to encouraging technology innovation. This is yet another aspect of the important role of market forces in speeding a shift to a low-carbon environment.

On the other hand, it is important to the future of the planet that emerging economies like China and India limit their contribution to global warming by adopting sustainable energy technologies as fast as possible. To facilitate this, the developed countries may well need to ensure that these technologies are available on favorable terms to both their domestic and internationals markets. It will therefore be critical to get the balance right between business competition and incentives, on the one hand, and international technological collaboration, on the other.

Not all improved energy technology will come from the presently advanced economies. Indeed, the United States has scarcely been a leader in energy innovation in recent years, while India and China are making major investments in research, development, and manufacturing capacity and expect to develop competitive new products and industries as a result. It is in the interest of the United States and other developed nations that they and others do so, because technology efficiency will be improved and technology spillovers are more robust if there are an increasing number of entrants in this field. This will benefit their own economic development and environment[17] as well as the world environment. On balance, the more investments other countries make in their own improved energy technology, the better customers they will be for the United States. America needs to strive for a new model of competition *and* collaboration, taking advantage of the dynamic tension and interaction between each.

An important approach to these issues is through international collaboration on pre-competitive research—that is, applied research on general problems that does not directly result in proprietary products. The Pew Center on Global Climate Change and the Asia Society have just issued a constructive report setting forth a list of technical subjects on which such collaboration might well begin.[18] If we can work out new synergies between nations on pre-competitive research, the international aspects of development and commercialization may resolve themselves since, following a successful market launch, multinational firms increasingly operate at a global scale to speed new technologies into world markets.

Even pre-competitive research may raise difficult diplomatic problems, however. China and India may be reluctant to make significant investments in technologies like CCS that would help mitigate global warming but that would also raise the cost of the coal-derived electric power that is critical to their plans for economic development. If the United States does adopt a carbon charge on domestic energy resources, there will be considerable political pressure from U.S. industry to impose a border adjustment tax on energy-intensive imports from countries that do not impose such a charge, lest the U.S. firms risk market capture from non-complying offshore competitors with significantly lower energy costs.

The potential for such technology border charges would no doubt increase the attractiveness of technical cooperation on carbon-saving technology like CCS. These charges also would pose a major challenge to the world trading system, not least because of the difficulty of calculating the energy content of any given import. Indeed, subsidies for energy production and use are so ubiquitous that the technical problems in imposing such charges may be extremely difficult to solve, even if they can be designed in such a way as to satisfy the formal requirements of the World Trade Organization.

The potential difficulties inherent in this situation suggest the need for a broad, frank, constructive international expert dialogue concerning the many perverse national subsidies and other policies, however politically entrenched, that contribute to environmentally and economically unsustainable energy production and use in virtually every country. Discussing existing national carbon energy subsidies could well be a first step to tackling this underlying and often unacknowledged problem. Such informal but semi-official discussions might be based in universities or private think tanks. They could raise awareness in the participating countries of the contribution of these policies to the global problem of climate change and prepare the way for serious progress in developing an international trading regime consistent with the requirements of energy sustainability.[19] Technical discussions along these lines can complement the more politically charged international negotiations over emissions targets that now constitute a major feature of international environmental diplomacy.

A Daunting Challenge

The management of ARPA-E and of the proposed government corporation for technology financing faces difficult challenges. First, the success of both will require staff who have industrial experience and technical know-how but also a feel for policy and the public interest. Second, all the agencies—from Department of Energy's Office of Science to its applied agencies like Energy Efficiency and Renewable Energy and Fossil Energy—involved in selecting competitive applications for stimulating energy technology will face the challenge of making technological judgments that are as consistent as possible with the principle of technology neutrality while recognizing that it is impossible to eliminate the element of judgment from their work. Suppose, for example, a company requests public financing for pipelines for the transportation of biofuels or of carbon dioxide for sequestration. Such an investment will specifically favor a particular technology. Agencies will also have to make careful judgments regarding the likely environmental impact of the technologies they are asked to support. At the policy level, government will have to decide the proper combination of sustainable energy and energy security. Technology neutrality is thus an aspiration rather than an invariable requirement. Even so, it is a principle worth striving for—the present dominance of technology-specific legislation risks locking in particular technologies driven not by the merits of optimal efficiency but rather the relative power of congressional lobbies.

Third, the proposed corporation for financing demonstration projects, conservation investments, and manufacturing scale-up faces the problem of keeping congressional pork within bounds. The pork barrel, after all, is as American as apple pie and cannot be excluded from—indeed, will be essential to the passage of—a program that will cost many billions of dollars. But pork cannot drive this critical program without risking its integrity. The early Iowa presidential primary and the power of the farm lobby have led to unjustified subsidies for corn ethanol, a biofuel of, at best, marginal environmental benefit. In the 1970s, the Synfuels program, which was intended to help the United States achieve long-term energy independence by developing technologies for converting coal into liquid fuels, failed in part because it succumbed to congressional pressure to scale up experimental technologies to job-creating demonstration projects before they were ready to go beyond laboratory or pilot scale.[20] This history is one reason it is important to create an independent corporation for technology financing protected as much as possible from congressional pressure.

Another danger of the pork barrel is that it tends to reward the sponsors of existing technology rather than the longer-range prospects of promising ideas that lack lobbying power. Here again, recent history offers discouraging precedent. As legislators worked to gather support for the Senate's Climate Security Act of 2007,[21] the first cap-and-trade bill to emerge from a major congressional committee, much of the prospective revenue stream from the proposed cap-and-trade regime was promised to industrial constituencies, to the near exclusion of support to research, development, and innovation.

After the Obama administration passed its 2009 stimulus package,[22] which contained no earmarks and billions to support R&D and various energy technologies, it proposed in its FY2010 budget documents a follow-on $150 billion energy R&D and technology development program to advance those jump-started initiatives. The president frequently cited the program, called the "Clean Energy Technology Fund," during the campaign. However, the climate change legislation emerging from the House Energy and Commerce Committee in May 2009 was subjected to the same bidding war from affected energy-intensive industries—coal, utilities, autos, oil refineries, and biofuels—as the 2007 Senate climate bill. By the time the mark-up dust settled, the president's proposed fund was not funded, and energy R&D was set at less than a billion a year, while industry subsidies garnered many billions. Without a successor source in place, the new stimulus investments in energy and the technology momentum they are now building are in danger of falling off a funding cliff.

If we can work out new synergies between nations on pre-competitive research, the international aspects of development and commercialization may resolve themselves .

It is critical that funding for R&D survive these pressures if the massive needs for energy R&D and technology deployment are to be met. The International Energy Agency, for example, estimates that some $45 trillion in research and technology implementation will be required worldwide over the next four decades if we are to halve current carbon dioxide levels by 2050, the target set by G8 nations last summer.[23]

Industry must be involved in strategy development and share in the funding and management of demonstration projects if they are to be effective. This will require federal energy technology leaders, through new institutions such as ARPA-E, to bridge some broad cultural divides between sectors. The mature energy industry underfunds research. Many in the industry have only recently acknowledged the legitimacy of the climate problem. Their style is worlds apart from the entrepreneurial and sometimes highly focused culture of the champions of various emerging energy sources.

Ideally, involvement in the strategy and roadmapping process will convince legacy energy companies that it is in their interest to get ahead of the inevitable transition to an energy economy in which carbon dioxide emissions are no longer free. This is particularly important for the coal and utility industries, whose support and involvement would be required if CCS technology is to be developed and demonstrated at the necessary scale. At the same time, it is important to ensure that industry does not capture the exercise in its own short-term interests.

In its guidance to the strategy and roadmapping efforts, ARPA-E and the Department of Energy can encourage the involvement of the most far-sighted elements of the established energy industry, and gradually bring along the rest of that industry, while at the same time broadening the horizons of the proponents of the promising new technologies. In this way, a new generation of energy officials will help to form a broader view of national and global energy problems and how best to address them. This approach differs from the pattern of Sematech, the best existing model of collaborative roadmapping in an advanced industry. Here, the idea originated with the private sector, and the CEOs of the five major semiconductor companies sat on the board.[24]

The development and deployment of CCS and other sustainable energy technologies would be much easier if a carbon charge were enacted or seen to be imminent. The same is true of serious international technological collaboration by India and China on technologies like CCS. Direct promotion of technological innovation is an essential part of the structure of a sustainable energy technology revolution but cannot be a substitute for a carbon charge. A workable solution will require complementary policies of new technology supply and price-induced demand.

Technology Supply That Complements Demand

Structuring an energy technology revolution is perhaps the most challenging technological research, development, and deployment effort the United States has ever faced. Such a program must be of great size, address the entire innovation process, and provide support to a wide variety of alternative technologies while remaining as neutral and pork free as possible.

There is every reason to begin this program of direct support to innovation immediately, since it will be necessary and probably can be enacted faster than a sound carbon charge. The $39 billion in funding for new energy R&D and technology implementation included in the stimulus bill earlier this year and the president's call for a $150 billion, 10-year "Clean Energy Technology Fund" in his FY2010 budget—if he can get his proposal back on legislative track—have already begun to show the way.

New designs, a true technology strategy, and new institutions will build out this foundation. Together, a program that pushes the technological frontiers will encourage innovation, and a permanent and substantial carbon pricing system will bring the resulting new technologies into a competitive price range. However, the two do not have to come into place simultaneously. We can start now to speed advances in technology.

Charles Weiss is a distinguished professor of science, technology, and international affairs at Georgetown's Walsh School of Foreign Service and was the first science and technology advisor to the World Bank. He may be contacted at weissc@georgetown.edu.

William B. Bonvillian is the director of Massachusetts Institute of Technology's Washington office and an adjunct faculty member at Georgetown. He served for 17 years as a senior advisor in the U.S. Senate.

Weiss and Bonvillian authored *Structuring an Energy Technology Revolution* (MIT Press, April 2009), which provides a more detailed exploration of points made in this article.

NOTES

1. *The American Recovery and Reinvestment Act*, Public Law 111-5, 17 February 2009, 111th Congress, 1st Session.

2. Princeton professors Robert Socolow and Stephen Pacala's 15 "wedges"—established practices or technologies that can be scaled up by 2050 to stabilize carbon in the atmosphere—are among the best documented. R. Socolow and S. W. Pacala, "A Plan to Keep Carbon in Check," *Scientific American*, no. 3 (September 2006): 50–57.

3. Ibid.

4. See, for example, N. Stern, *Stern Review on the Economics of Climate Change* (London: H. M. Treasury, 2006), http://www.hm-treasury.gov.uk/stern_review_report.htm (accessed 29 May 2009).

5. The source for the data in this paragraph is G. Nement and D. Kammen, "U.S. Energy R&D: Declining Investment, Increasing Need, and the Feasibility of Expansion," *Energy Policy* 35, no. 1 (2007): 746–55.

6. In his report to President Franklin D. Roosevelt, science advisor Vannevar Bush extolled the merits of federal support to basic research to drive new technologies and suggested establishing what would later become the National Science Foundation. V. Bush, *Science: The Endless Frontier* (Washington, DC: Government Printing Office, 1945), 1–11, http://www.nsf.gov/od/lpa/nsf50/vbush1945.htm (accessed 28 May 2009); discussed in D. E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington, DC: Brookings University Press, 1997).

7. L. Branscomb and P. Auerswald, *Between Invention and Innovation: An Analysis of Funding for Early-State Technology Development*, NIST GCR 02-841 (Gaithersburg, MD: Economic Assessment Office, Advanced Technology Program, National Institute of Standards and Technology, 2002), http://www.atp.nist.gov/eao/gcr02-841/contents.htm (accessed 28 May 2009).

8. V. W. Ruttan, *Is War Necessary for Economic Growth? Military Procurement and Technology Development* (New York: Oxford University Press, 2006).

9. V. W. Ruttan, *Technology Growth and Development: An Induced Innovation Perspective* (New York: Oxford University Press, 2001).

10. The analysis summarized here and the technology assessments on which it is based is found at greater length in C. Weiss and W. B. Bonvillian, *Structuring an Energy Technology Revolution* (Cambridge, MA: MIT Press, 2009).

11. A disruptive technology begins in lower-profit market segments ignored by larger firms (which typically concentrate on adding extra functions to high-profit products) and improves, expands, and displaces well-established incumbent technologies. Examples include the personal computer, which displaced mainframes, and low-cost airlines, which displaced legacy carriers. See C. M. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Cambridge, MA: Harvard Business Press, 1997).

12. *The America Competes Act*, Public Law 110-69, 9 August 2007, 110th Congress, 1st session, S. 5012.

13. *The American Recovery and Reinvestment Act*, note 1.

14. W. B. Bonvillian, "Power Play, the DARPA Model and U.S. Energy," *The American Interest* 2, no. 2 (2006): 39–48.

15. Legislation to create such an entity has now been proposed by energy committee leaders in Congress. See, *21st Century Energy Technology Deployment Act*, 110th Cong., 2nd sess., S. 3233, *Congressional Record* 154, no. 114, daily ed. (11 July 2008); and *Clean Energy Investment Bank Act*, 110th Cong., 2nd sess., S. 2730, *Congressional Record* 154, no. 38, daily ed. (6 March 2008). Pending energy legislation in both the Senate Committee on Energy and Natural Resources and the House Energy and Commerce Committee is considering such a financing entity within the Department of Energy.

16. Running a single 100-watt incandescent light bulb for 24 hours a day for a year requires 714 pounds of coal; a 500-megawatt plant would light 4 million of these bulbs for a year. For a further comparison, the Energy Information Administration of the U.S. Department of Energy projects that the United States will have added about 77 gigawatts of generating capacity from all fuel types between 2008 and 2015, http://www.ea.doe.gov/oiaf/aeo/electricity.html (accessed 29 May 2009).

17. Climate mitigation is in China and India's direct interest because the melting of the Himalayan and other mountain glaciers is beginning to affect the flow of the great rivers of Asia—the Yangtze, the Indus, and the Ganges, to cite only three—that provide the bulk of these countries' irrigation and urban water supply. For a general overview of the problem of melting glaciers worldwide, see B. Orlove, "Glacier Retreat: Reviewing the Limits of Human Adaptation to Climate Change," *Environment* 51, no. 3 (2009): 22–34.

18. Initiative for U.S.-China Cooperation on Energy and Climate Task Force, *Common Challenge, Collaborative Response: A Roadmap for U.S.-China Cooperation on Energy and Climate Change* (Washington, DC, and Arlington, VA: Asia Society and Pew Center on Global Warming, 2009).

19. These discussions might be modeled on the bilateral U.S.-Japanese discussions of economic policy, motivated by trade tensions that took place during the first Bush administration. A second model is the multilateral discussions among European finance ministries that preceded the submission of unified proposals for Marshall Plan assistance derived from agreed calculations of the requirements for foreign exchange needed to finance European reconstruction after World War II.

20. L. Cohen and R. Noll, *The Technology Pork Barrel* (Washington, DC: Brookings Institution Press, 1991).

21. *The Climate Security Act*, 110th Cong., 2nd sess., S. 3036, *Congressional Record* 154, no. 85, daily ed. (22 May 2008); original legislation introduced as *America's Climate Security Act of 2007*, 110th Cong., 1st sess., S. 2191, *Congressional Record* 153, no. 158, daily ed. (18 October 2007).

22. *The American Recovery and Reinvestment Act*, note 1.

23. International Energy Agency (IEA), *Energy Technology Perspectives 2008: Scenarios and Strategies to 2050* (Paris: IEA, 2008).

24. L. Browning and J. Shetler, *Sematech: Saving the U.S. Semiconductor Industry* (College Station, TX: Texas A&M Press, 2000).