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ENERGY-TECHNOLOGY INNOVATION

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■ **Abstract** Energy-technology innovation (ETI) is the set of processes leading to new or improved energy technologies that can augment energy resources; enhance the quality of energy services; and reduce the economic, environmental, or political costs associated with energy supply and use. Advances achieved through ETI have made large contributions to the improvement of the human condition over the past 100 years. Still more will be required of ETI during the decades ahead if civilization is to succeed in meeting what we believe are the three greatest energy challenges still before it: reducing dependence on oil, drastically upgrading the energy services provided to the world's poor, and providing the energy required to increase and sustain prosperity everywhere without wrecking the global climate with the emissions from fossil-fuel burning. This will require significant enhancements to ETI through deeper analysis of ETI processes, greater investments in ETI, improved innovation policies, and better coordination and partnerships across sectors and countries.

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INTRODUCTION

The term *energy technology* refers to the means of locating, assessing, harvesting, transporting, processing, and transforming the primary energy forms found in nature (e.g., sunlight, biomass, crude petroleum, coal, uranium-bearing rocks) to yield either direct energy services (e.g., heat from fuelwood or coal) or secondary forms more convenient for human use (e.g., charcoal, gasoline, electricity) (1). We also include under the heading of energy technology the means of distributing secondary forms to their end users and the means of converting these forms to energy services (e.g., electricity to light and refrigeration, electricity and gasoline to motive power).

A distinction is often made between *energy-supply technologies*, meaning those used to bring energy forms to a point of final use, and *energy end-use* technologies, meaning those applied at this point of use to convert an energy form to a service such as light or motive power (1). The supply technologies usually receive more attention in discussions of energy-technology innovation (ETI), but the end-use technologies are no less important in principle and in practice often offer greater potential for improvement. It should go almost without saying, finally, that we understand *energy technology* to mean not only hardware but also the software, practices, and knowledge relating to its effective use (2).

Energy technology is important because the most basic of the energy services it delivers—such as heat for cooking and boiling water and making winter in cold climates survivable—are fundamental human needs and because energy for mining, manufacturing, materials processing, construction, transport, communication, computing, comfort, and illumination is essential to economic prosperity. It is also important because the monetary costs of providing energy for these purposes are a significant component of the cost of living, gross domestic product (GDP), and the balance of trade of energy-importing countries.[1] And it is important because

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[1]Expenditures on energy by firms and consumers typically amount to 5% to 10% of the gross domestic product (GDP); for the world as a whole in 2001, the figure was about 7% (1, 3, 4). International energy trade in 2004 was worth about US$900 billion, amounting to 10% of all world trade (calculated from References 4–6). Global investment in energy-supply technologies at the beginning of the twenty-first century was running about US$400 billion per year (1), and the cumulative global investment in such technologies from 2000 to 2050 was predicted in the range of $30–$55 trillion (7) (figures in year-2000 dollars).

the environmental and political impacts of the ways in which energy is supplied are often substantial and in some instances threaten to become intolerable.[2]

Improvements in energy technology, then, are changes that reduce the monetary cost of delivering a given energy service, or increase the quality of the energy service delivered for a given cost, or reduce the environmental or political impacts of providing a given energy service at a cost deemed worthwhile in exchange for the benefit of such reduction. ETI is the set of processes by which improvements in energy technology, which may take the form of refinements of previously existing technologies or their replacement by substantially different ones, are conceived; studied; built, demonstrated, and refined in environments from the laboratory to the commercial marketplace; and propagated into widespread use. Innovation, then, does not consist of research and development (R&D) alone; it is not complete unless it includes the further steps through which the new technologies or improvements attain widespread application.

ETI over the past century and a half has led to large improvements in the quality of energy services, large reductions in the quantities of primary energy forms needed to produce given services, large reductions in the real costs of those services, and, in many (but not all) instances, significant reductions in emissions and other environmental impacts per unit of service delivered. It seems to be a characteristic of contemporary energy debates, moreover, that no matter what one's ideas about which of society's energy challenges is most important or most demanding—for example, limiting costs to consumers, reducing emissions and ecosystem impacts, reducing vulnerability of energy systems to terrorist attack, reducing dependence on imported oil or on oil altogether—substantial further ETI is recognized as a key element of the solution (11–15). It is also increasingly widely understood that ETI holds the key to reconciling some of the multiple goals of energy policy that have hitherto seemed to be in conflict (e.g., making it possible to increase domestic oil production while reducing the impacts of exploration and drilling, making it possible to increase reliance on abundant coal resources while reducing greenhouse-gas (GHG) emissions from coal production).

Policy arguments about ETI arise, then, not about the general need for it but about just how much of what kinds is needed how quickly, about how to

[2]The technologies of energy supply and end use are responsible for most indoor and outdoor air pollution, most of the oil added by human activities to the oceans, most of the accumulated burden of radioactive waste, much of the hydrocarbon and trace metal pollution of soil and groundwater, and the largest part of the annual increment of global-warming potential attributable to emissions of anthropogenic greenhouse gases (GHGs) (1). Dependence on oil for about 35% of global annual use of primary energy, with much of that oil coming from politically unstable regions, supports repressive regimes, foments corruption, funds terrorism, and contributes a potential for armed conflict over access (8, 9). The one sixth of the world electricity supply that comes from nuclear energy is associated with a significant, albeit unquantifiable, risk of nuclear-weapon proliferation through misuse of uranium-enrichment and fuel-reprocessing technologies or theft of reprocessed plutonium by subnational groups (1, 10).

make it more efficient and effective, about how and by whom the needed energy-technology-innovation activities should be conducted and managed, and about how it all should be paid for. Understanding these arguments and participating constructively in the development of viable answers requires delving more deeply into what current energy challenges society expects innovation to address; how ETI works; who does ETI and why; how its costs and outputs are measured; what the recent patterns in conduct, funding, and outcomes of ETI have been; and how gaps between what is needed and what is currently happening can be filled. The remainder of this review takes up these topics in turn.

THE MOST DEMANDING CURRENT CHALLENGES

Although there are, as already suggested, a great many challenges associated with energy supply and end use that can be overcome or diminished with the help of ETI, three great challenges stand out at present as more demanding of innovation than any of the others. In our view, these three challenges are thus the principal drivers of how much and what kinds of performance society needs to extract from its energy-innovation system in the first part of this century, and for that reason, it is appropriate to review their dimensions briefly here as part of the preface to our survey of how that system has been working and how it can be made to work better.

The first of the three challenges, in terms of immediate magnitude of the adverse impacts that need to be reduced, is how to shrink the economic vulnerability arising from oil dependence as well as the balance-of-payments and foreign-policy liabilities associated with oil imports, despite growing demand from the transport sector for liquid fuel and from other parts of the economy for natural gas. This is a problem not only for the United States but also for the great majority of the world's nations, which are heavily dependent on oil and import much of what they use. It is, moreover, a major problem irrespective of the much-debated timing of *peak oil*, the moment when global production of conventional oil reaches its maximum and thereafter commences to decline (16, 17); the dangers of heavy dependence on commodities whose largest and most cheaply extractable remaining resources are concentrated in some of the world's most politically unstable regions are large—even if the time of peak world production is not imminent—albeit even larger if it is.

The magnitude of the oil predicament can be illustrated with some data from the U.S. experience. In 2005, the United States was using about 20.5 million barrels per day of petroleum (18), of which about 60% was imported—the largest oil-import dependence in U.S. history in both absolute and percentage terms. This oil accounted for 39% of U.S. primary energy use. Of the oil total, 12 million barrels per day was motor-vehicle fuel (three quarters of this was gasoline, which went mainly to passenger vehicles, and one quarter of it was diesel fuel, which went mainly to trucks and buses). The "reference" (middle of the range) forecast of the U.S. Energy Information Administration (EIA) in 2005 was that U.S. petroleum use would rise by 2025 to 28 million barrels per day, with all of the increase coming from imports (19).

No possibility was foreseen by the EIA of increasing U.S. domestic oil production above 9 million barrels per day (19). In any case, the implication of the "reference" numbers is plain: Avoiding an increase in the already massive oil imports of the United States over the period 2005–2025 would require this country's preventing, or replacing, 8 million barrels per day of the oil use projected for 2025—almost as much oil as the United States was producing in 2005. This would be an immense achievement, requiring tremendous contributions from ETI on the supply side (above all in nonpetroleum fuels for vehicles) and on the end-use side (above all in increased vehicle efficiency).

The petroleum picture for the world as a whole is even more daunting—80 million barrels per day of petroleum use in 2005, of which nearly 60 million barrels per day was moved in world trade, and total use is expected by the EIA to reach 120 million barrels per day by 2025, nearly 90 million barrels per day of it moving in world trade (20). The largest part of the increased supply is expected to come from the Middle East, which has ~75% of the estimated remaining ultimately recoverable resources of conventional oil (1). China's oil imports in 2025 are projected by the EIA to reach 14.2 million barrels per day, much of this coming from the Persian Gulf (21). The dependencies and vulnerabilities in this projected world of 2025 are staggering to contemplate. And ameliorating them significantly with innovations in avoiding and replacing oil use, above all in transport, will be an even bigger challenge in China, India, and other developing countries than in the United States, given the pace of the expected growth in the number of cars as these countries motorize.

The second of the three dominant, innovation-driving challenges relates to a problem afflicting almost one third of humanity: the lack of modern energy services for two billion poor people worldwide (22–24). The continuing reliance of the members of this group on traditional forms of energy, rather than the relatively safe, clean fuels available to their richer compatriots as well to almost all citizens of industrialized countries, has some major adverse implications.

- Substantial time and effort is needed to procure firewood or other forms of biomass, and as local energy sources become degraded and scarce, this time can increase substantially. This has a disproportionate impact on women and children (which affects the latter's schooling). For example, in rural sub-Saharan Africa, many women have to carry 20 kg of fuelwood an average of 5 km every day (25).
- The inefficient combustion of biomass, the prevalent energy source for the poor, leads to severe and widespread health impacts associated with indoor air pollution (26). The World Health Organization has recently estimated that indoor air pollution from biomass and coal use in poor households is the sixth largest health risk factor in developing countries, accounting for an estimated 1.6 million premature deaths annually (27). Overall, indoor smoke

from these solid fuels is responsible for about 38 million disability-adjusted lost years in developing countries; beyond the human costs, this also has significant economic impacts (27).

- The inefficient use of wood (a main source of energy for the poor) adds to the need for procuring large amounts of it, which often contributes to environmental degradation.

The human health, social, and economic costs of the direct combustion of biomass and coal in the traditional and inefficient manner can be mitigated through the use of cleaner-burning devices or cleaner liquid and gaseous fuels and electricity. New technologies have already begun to play a role in this regard (for example, through the development of improved cookstoves or technologies for decentralized generation of electricity), but much more still needs to be done in meeting this enormous challenge. Technological innovation will continue to play a central role on this front, although making suitable progress will also require new institutional mechanisms and processes (24).

The last of the three challenges,which is almost certain to be even more demanding than the first two challenges as the century wears on, is how to provide energy for humankind without entraining intolerable disruption of global climate by the emissions from fossil-fuel use. It should be noted that this challenge is linked to the previous challenge in that poor people consume little energy at present, and with economic development, their energy consumption will rise even as the rest of the world will continue to need energy to sustain its prosperity.

It is now clear beyond reasonable doubt that the climate of Earth is changing at a pace that is highly unusual against the backdrop of natural variations and that the primary driver of this change is the buildup of anthropogenic GHGs [most importantly carbon dioxide (CO_2), resulting mainly from the combustion of fossil fuels] in the atmosphere since the beginning of the Industrial Revolution (28–30). It is also becoming clear that significant impacts of climate change on ecosystems and on human well-being are already occurring at the modest levels of global-average temperature increase realized to date (30, 31), about 0.8°C above the 1750 value, and it is known that a further 0.6°C increase would ensue after the surface layer of the ocean reached equilibrium with the atmosphere even if atmospheric GHG and particulate-matter concentrations could be stabilized at their current levels (32).

Far from stabilizing, however, under midrange projections of fossil-fuel use in the twenty-first century, the atmospheric concentration of CO_2 would soar from the 2005 value of 380 ppm by volume (ppmv) to 550 ppmv (twice the preindustrial value) by 2060 and ~700 ppmv by 2100.[3] On such a trajectory, the world could

[3]These figures correspond to the Intergovernmental Panel on Climate Change scenario IS92a, developed for the Intergovernmental Panel on Climate Change's Second Assessment Report, which falls in the middle of the range of CO_2 emissions projected in the wider range of scenarios developed for the Third Assessment Report (28).

well find itself, even before the middle of the century, in a climatic state characterized by sharply increased incidence of floods, droughts, heat waves, wildfires, and severe tropical storms; disappearance of coral reefs; accelerated sea-level rise driven by the irreversible disintegration of the Greenland and West Antarctic ice sheets; expanded ranges of tropical diseases; and decreased agricultural productivity (28–35). Today's decision makers would then be cursed by their descendants for failing to take heed of the maxim (popularized by former Presidential Science and Technology Advisor John H. Gibbons) that "If you don't change course you'll end up where you're heading" (J.H. Gibbons, unpublished speech).

But changing course will not be easy. In 2004, nearly 80% of world primary energy use was still being supplied by fossil fuels,[4] essentially all of the CO_2 from the combustion of which was poured into the atmosphere. The problem is compounded by the technical difficulty and high cost of modifying fossil-fuel technologies to capture the carbon, by the uncertainties concerning cost and performance of various approaches to sequestering the captured CO_2 away from the atmosphere (which would need to be done on a scale of the order of hundreds of billions tons in the twenty-first century to have a large effect on the problem), and by the slow turnover time of fossil-fuel-burning technologies in the energy system (10–15 years for motor vehicles, 50 years for power plants) (which makes new low-emission and no-emission alternatives slow to fully replace the old technologies once the new ones have become economically competitive or required by regulation).

A measure of the magnitude of the climate-change challenge for ETI can be derived from a simple calculation of the combinations of energy-efficiency improvements (measured as declining ratio of energy to real GDP) and deployment of new carbon-free energy supplies[5] that would be needed in the twenty-first century to stabilize atmospheric CO_2 below 550 ppmv—a level that was once thought by many to represent a reasonable target for climate-change mitigation efforts but now seems increasingly likely to be too high to avoid damages that could be intolerable. Such a calculation shows that achieving this modest, probably inadequate goal would require a sixfold increase in carbon-free energy supply by 2050, compared to the year-2000 level of 100 exajoules per year, and a 15-fold increase by 2100 if world GDP growth averaged 2.4% per year over the century and the energy intensity of GDP fell at 1% per year (the long-term historical rate). If the energy intensity of GDP declined at 2% per year over the whole world and the whole

[4]This percentage takes account of both commercial and noncommercial energy forms, with figures for the former (mainly petroleum, coal, natural gas, nuclear energy, hydropower, wind, and commercialized biofuels) taken from the 2005 edition of the BP annual statistical compendium (5) and figures for the latter (noncommercialized fuelwood, charcoal, crop wastes, and dung) extrapolated from 2003 values given in an International Energy Agency (IEA) statistical summary issued in 2005 (4).

[5]Carbon-free energy supplies are those derived from renewable energy resources (such as sunlight, wind, and sustainably grown biomass), from nuclear fission and fusion, and from advanced fossil-fuel technologies that are able to capture their CO_2 and sequester it away from the atmosphere.

century—a huge achievement for innovation on the end-use side—carbon-free energy supply would still need to triple over the course of the century (36).

More sophisticated analyses sustain the point that an immense amount of ETI on both the supply-side and the demand-side will be needed to stabilize atmospheric CO_2 at the 550 ppmv level and much more, much faster if it is to be stabilized in what now appears to be the considerably more prudent range of 400–450 ppmv (37, 38). The magnitude of this challenge should provide more than ample motivation for the excursion into the workings of ETI that follows.

THE ENERGY-TECHNOLOGY INNOVATION PROCESS

In this section, we discuss the ETI process first in terms of overlapping stages of activity, then in terms of management of the process, and finally in terms of international dimensions of the process.

Stages of Energy-Technology Innovation

A number of stylized models of the innovation process (not restricted to energy technology) have been proposed and refined during the last century. Initially, these models conceived of innovation as a linear, sequential process beginning with research, proceeding to development, then to demonstration, and finally to diffusion in the marketplace. Later, this theoretical model was refined to capture two-way or iterative "chain-linked" interactions whereby learning in one phase was linked to the other phases (39). Margolis (40) developed this model further in the context of ETI with emphases on the variety of actors involved and the role of public policy in stimulating supply and demand for energy technologies (see Figure 1). Another model proposed by Ken-ichi Imai described the Japanese practice of merging the research, development, demonstration, and deployment (RD^3) phases, so that there is substantial overlap between each stage; in this last formulation, none of the stages occurs in isolation, and the more the stages overlap and thus interact with each other, the more efficient the integrated innovation process (41).

As currently understood, then, technological innovation is characterized by multiple dynamic feedbacks between different stages of the process (42); as Fri (43) states, "the process of innovation is typically incremental, cumulative, and assimilative." It is nonetheless often useful for analytical and prescriptive purposes to treat the stages separately, and we frequently do so in this article. The stages of ETI to be considered comprise fundamental research, applied research, development, demonstration, precommercial and niche deployment, and widespread deployment (often also called diffusion). Technology transfer between countries is often envisioned as a part of diffusion, but it can also occur at earlier stages.

R&D Energy research and development (ER&D) includes basic or fundamental research in areas deemed likely to yield discoveries with potential application to

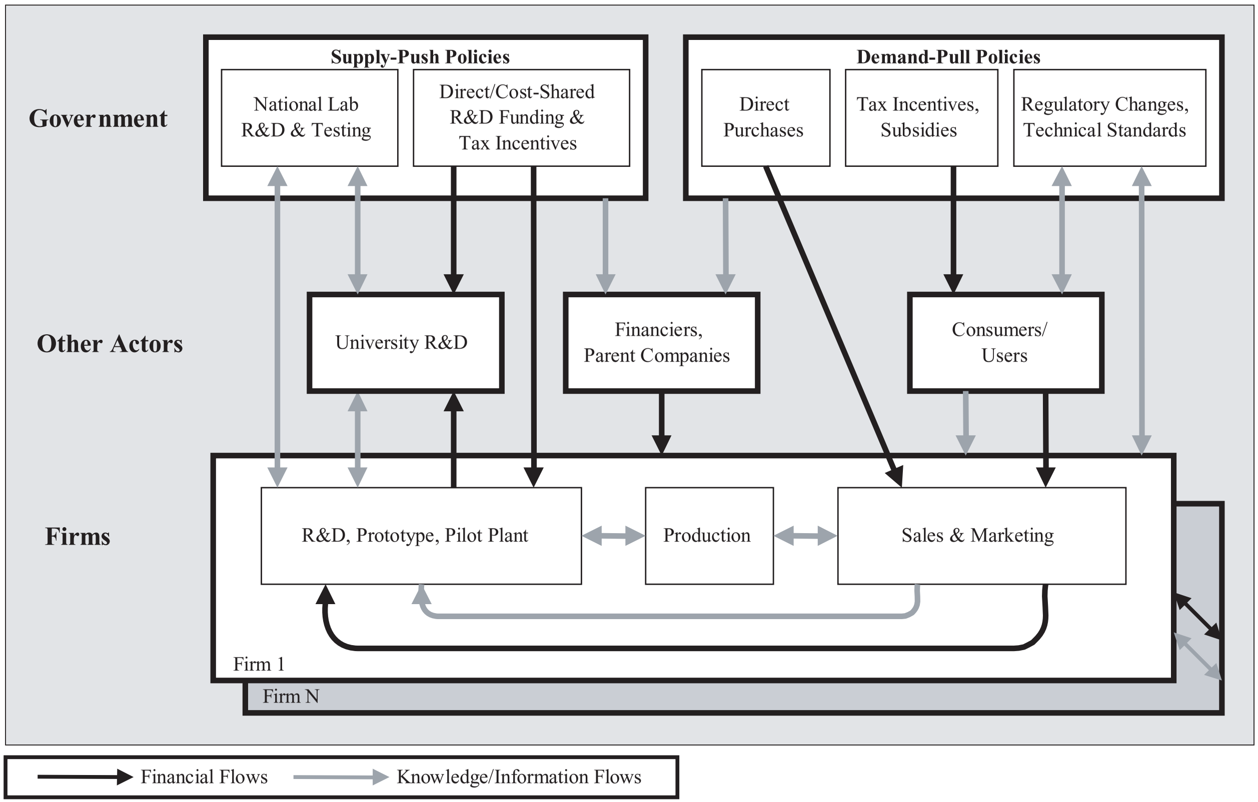

Figure 1 An illustration of actors and their interactions in energy-technology innovation (40).

the improvement of energy technologies, applied research directed at the invention or improvement of specific energy technologies, and development aimed at converting the fruits of fundamental and applied research into working prototypes of new or improved technologies.

The U.S. Department of Energy (DOE) defines *basic energy sciences* as comprising materials science, fusion/plasma sciences, combustion research, chemistry, geosciences, energy biosciences, advanced computation and simulation, and engineering sciences. Obviously, work in these fields can yield discoveries that are ultimately found useful not only in multiple energy technologies but also in nonenergy applications: Advances in materials that led to better thermal barrier coatings for jet engines were further refined through additional R&D for use in gas turbines in power plants, resulting in substantial energy-efficiency and emissions benefits (44); the development of photonic band-gap crystals for the control of light propagation improved solar cells as well as sensors, lasers, and other telecommunications equipment (45).

Of course, a definition of ER&D that includes fundamental research of these kinds also implies that some research done by organizations with nonenergy missions is, by definition and in effect, energy R&D, and this complicates the counting of how much ER&D is being done and by whom. It is an easy matter to count the basic energy sciences work supported by DOE because it is so labeled, but how much work done in materials science or chemistry with support from entities with wider missions should be counted is not obvious.

In the United States and most other industrialized countries, it is generally the case that the relative role of government in the funding and conduct of ER&D shrinks and that of the private sector grows as one moves from basic energy research to applied research on specific energy technologies, and the trend toward a smaller public and greater private role continues as one moves from applied research to development (2, 11). This is so in part because the fruits of private investment in innovation are more likely to be appropriable by the firm doing the investing further along the innovation chain toward commercial deployment, and it is so, in part, because firms are interested in investing in activities that will bring returns sooner rather than later. In addition, governments have come to recognize that private firms generally do a better job than public agencies in the later stages of shaping technologies to meet the requirements of the marketplace (which firms are in the business of understanding as a matter of their survival).

Where governments do get involved in applied-energy-technology research and even in development, it is, or ought to be, with specific aims and appropriate rationales in mind (11). Closing the gaps between the public's interest in ETI and the private interest in it arising from the existence of important public-good or externality characteristics of the technologies involved is one example of an appropriate rationale. Another example is the desire to compensate for an industry's unwillingness or inability to support as much investment in innovation as society's interests warrant because of the structure of the industry, i.e., the need for very large investments to make headway on R&D (lumpiness of the needed investments) or the long time horizon for the prospective benefits (11). Such considerations account for the heavy government presence, in the United States and many other industrial countries, in applied R&D in nuclear fission (externality, lumpiness), nuclear fusion (externality, lumpiness, long time horizon), and renewable energy (externality, public good, structure of the industry). Another reason for government involvement may be specialized relevant capabilities, such as some of those of the U.S. national laboratories that could not readily or practically be mounted in the private sector.

Over the past decade or so, it has been increasingly widely recognized in industrialized and developing countries alike that R&D partnerships, government-industry, industry-university, government-industry-university, can often combine to good effect the motivations and virtues for R&D that characterize these different sectors (46, 47). As a result, such partnerships have blossomed across a variety of fields of R&D endeavor, including energy, along with international partnerships in the government-government, industry-industry, and university-university varieties (which are discussed in more detail below).

DEMONSTRATION Demonstration projects play an important part in a number of ways that help bring technologies closer to the market. Such projects

- Test new technologies in conditions approximating real-world applications, thereby gathering technical and economic performance data that can help refine and improve technologies so as to enhance their potential for commercialization;
- Help in scaling up technologies—this is especially critical in cases where the laboratory version of the technology is useful for testing the concept but where the eventual application of technology must happen at a much larger scale (such as in power plants, for example); and
- Demonstrate the real-world feasibility of new technologies to manufacturers and potential buyers, thereby increasing the chances of adoption (48).

The demonstration phase of ETI in market economies was long considered to be primarily the province of industry for both funding and performance, with a few conspicuous exceptions, such as nuclear power, where the combination of public-good motivations, links to national-security programs, and magnitude of financial risk dictated heavy government involvement at this step on the path to commercialization. Over the past 15 years, however, a combination of factors has led to a trend of increasing government involvement in the demonstration phase of a wider variety of technologies. A primary driver of this trend was recognition of the magnitude of the obstacles blocking the path between R&D and commercialization—often referred to as "the valley of death" (11)—accompanied by analysis of the success, in the 1970s and 1980s, of the Japanese model of the role of government in working with industry to traverse this path. Another driver was the recognition that if public goods and externality considerations (e.g., reduced oil-import dependence, reduced GHG emissions) were sufficient to justify substantial government investments in applied energy-technology R&D then it should also be justifiable for the government to make further investments in the demonstration, so that the fruits of its earlier investment do not languish in "the valley of death" (11).

DEPLOYMENT Even if the technical feasibility of a new technology has been demonstrated, it still may not compete in the market with already established technologies for a variety of reasons. The main categories of barriers include cost, information, market organization, infrastructure, regulations, and slow capital stock turnover (49–51).

There is a relatively poor understanding about the processes of energy-technology deployment. It is important to distinguish between early deployment and widespread deployment because of the potential need for intervention early in the process of deployment to help exploit niche markets, promote the buy down of products to reduce costs, and otherwise help a technology reach its "tipping point" into widespread commercial deployment. *Diffusion* "is the process by which an innovation is communicated through certain channels over time among the members of a social system" (52).

Two general descriptive models are used to describe different aspects of technology deployment: the S-curve or life-cycle model and the learning- or experience-curve model. The S-curve describes the technology growth (e.g., increase in production volume or market penetration) trajectory over time, whereas the learning curve describes the cost trajectory as a function of increasing cumulative production. Grübler & Gritsevskii (53) extended the notion of the learning curve to include not only cumulative production, but also cumulative investments in research, development, and demonstration (RD&D) based on the detailed case of solar photovoltaic (PV) cells in Japan (54).

The life-cycle or S-curve model indicates that diffusion and growth of a technology takes place in three phases: slow growth at the beginning when cost or other advantages over the entrenched competition are small or restricted to niche markets or not generally understood, followed by accelerating growth as the advantages grow and/or become more widely appreciated, followed by a period of tapering off of the growth rate as the market becomes saturated and/or more advanced technologies materialize and become increasingly competitive. S-curve models provide some general insights into the diffusion process because they have been documented for many cases of technological deployment, not only for energy technologies (see Reference 42). At the beginning, when growth is nascent, it is useful to support early adopters who demonstrate the technology and help exploit niche markets. When the growth in the technology begins to take off, it often occurs through networks and geographical clusters. As economies of scale are achieved, the growth is rapid and nonlinear. At the top of the S curve, the growth rate declines precipitously as another technology begins to substitute for the initial one, or as the market reaches saturation.

The learning-curve model describes how unit costs of production often decrease with increasing production experience (usually expressed as the percentage by which the unit cost decreases with every doubling of cumulative production) (55). As noted by Arrow (56), "Learning is the product of experience. Learning can only take place through the attempt to solve a problem and therefore only takes place through activity." Learning occurs in every phase of the innovation process (and also as the phases interact with one another), but learning by doing occurs later in the innovation process as experience is gained in producing and using the technology. Learning by doing can lead to cost reductions, improvements in the manufacturing process, greater proficiency in the operation of a technology, and new ideas for design and marketing. Learning by doing can also lead to institutional transformation to enable the introduction and diffusion of new technologies (57).

Learning curves are attractive to economists and modelers because data tend to be more readily available on unit costs (or prices) and production than data on other indicators of technological change. But the rate of learning can vary enormously among different sectors and technologies, and in some cases, different learning rates have been assessed for the same energy technologies (42, 58). *Learning rates* (i.e., the percentage improvement in cost or performance with each doubling of production) for energy technologies have been estimated at between 10% and 30% (59). Of course, the learning rate itself may undergo changes at different stages of the production process.

Reductions in unit costs may occur without necessarily being a result of learning by doing (e.g., as relative energy prices rise and fall, input costs vary, or policy changes take effect). Conversely, greater deployment does not always lead to lowering of costs. For example, imposition of policies that guaranteed prices for wind power in Denmark, Germany, and the United Kingdom led to large expansions in wind power nearly irrespective of declines in unit costs (60).

Although it has become popular to estimate learning curves for different energy technologies, their utility is limited for several reasons. Learning curves are merely descriptive of declines in unit costs as production accumulates, but they do not explain how or why the reductions in cost or expansion in output were achieved. Investments in and management of R&D (as well as in demonstration projects) are only implicit in learning curves. Thus, although it is tempting to use learning curves to estimate the future performance of energy technologies, they cannot be used with any accuracy to predict how new energy technologies may perform in the marketplace. Other methodologies, such as case study, barrier, and incentives-type analyses, are necessary to complement learning-curve analyses.

Key assumptions often behind learning curves, depending how they are construed, are (*a*) free knowledge flows across firms in the same industry and (*b*) steady product input prices, both of which are usually not true in the real world. Learning curves also fail to explicitly account for lags between investment in innovation and declines in unit costs or expansion of production. Indeed, it has been shown that the ability to raise capital and to take on the risk of large investments, in combination with lower purified silicon prices (a spillover from the semiconductor industry), mainly led to the ability of solar PV firms to lower unit costs and increase production of solar PV electricity (61).

A number of barriers to economically efficient technology diffusion have been identified including (*a*) the existence of transaction costs (62), (*b*) market failures such as imperfect information and failure to account for environmental externalities (63, 64), (*c*) the proprietary nature of technology (65), and (*d*) the problem that technology is tacit (not outright or explicit). A firm is a bundle of proprietary assets, and these assets include technological capabilities and skills (66). Other barriers include the recipient or buyer's capacity to absorb technology, the importance of being able to learn by doing, the appropriateness of the technology to its new setting, the costs of the advanced technologies for both acquisition and deployment, indigenous technological capabilities, and uncertainty. Finally, access to technology cannot be automatically equated with improved technological capabilities that can contribute to economic growth (67). All of these market failures imply a need for government intervention, insofar as policies and regulations can create incentives for and eliminate barriers to the effective acquisition, absorption, and deployment of technology.

Organization of Energy-Technology Innovation

The organization of ETI activities takes many forms. In most countries, innovation activities are conducted by private firms, universities, research institutes, nonprofit institutes, and the government, although different actors play stronger roles in some countries when compared with others. In Japan, the government has traditionally taken a strong role in coordinating ETI activities through its Ministry of Economy, Trade, and Industry [formerly the Ministry of International Trade and Industry (MITI)], as documented in the case of solar PV by Watanabe (68). The Europeans have stressed and exemplified cross-country collaboration and coordination. In the United States, the private sector exercises greater autonomy, although there has been an emphasis on public-private partnerships since the 1990s. In developing countries, the government typically takes a very strong role in funding and coordinating ETI. These various entities can collaborate in a range of combinations, within countries and internationally. As discussed below in Recent Patterns of Energy-Technology-Innovation Activities, the private sector accounts for the majority of expenditures for energy R&D in International Energy Agency (IEA) member countries, although governments account for a large fraction as well. Still, because of the lack of data, it is hard to assess with any accuracy the relative efforts in particular areas of ETI of various actors in various countries.

In many countries, public-private partnerships have been used as a way to share costs or leverage investments, to share risks, to create networks to facilitate the innovation process, and to spur research in areas that might not be pursued by the private sector if the probable benefits are for the public (e.g., energy security, global climate change) (69). These public-private partnerships take many forms. The U.S. government has created a number of high-profile public-private partnerships in the energy area, including FreedomCar and FutureGen. Although the promise of public-private partnerships is substantial, they are not always effective. In the case of the U.S. Partnership for a New Generation of Vehicles (PNGV), for example, the Big Three automakers joined forces in a research program aimed at developing a vehicle that achieved three times the average fuel economy of 1993 cars by 2004. But, the Japanese firms Toyota and Honda eclipsed the program and brought advanced hybrid vehicles into commercialization before the concept prototype was even produced in PNGV (70). Still, it appears that the establishment of PNGV in the United States spurred MITI to create the Advanced Clean Energy program in Japan in 1997, although Toyota released its first Prius that same year (71). In China, the Ministry of Science and Technology has catalyzed and partially funds a set of public-private partnerships, involving universities, enterprises (both state and privately owned), and other research institutes, to spur the development and deployment of hybrid-electric and fuel-cell vehicles.

International Aspects

International aspects of the ETI process take on particular importance because of the global character of the challenges that, as we argued above, are the most demanding drivers of such innovation: oil dependence, poverty reduction, and climate change.

TECHNOLOGY TRANSFER Technology is understood to encompass both tangible goods and products, such as machinery, and tacit information, such as skills and knowledge (42). International technology transfer is thus the transfer of hardware, e.g., tooling for factories, and also the transfer of intangible assets, e.g., product design and the capability to manufacture a product. Brooks (41) argues that *technology transfer* is "a way of linking knowledge to need" and that it is a process of cumulative learning. This succinct definition of technology transfer illuminates several important characteristics of technology transfer. It affirms that technology should be conceived as knowledge (72) and that technology transfer is a process of communication and education on the part of all parties involved. Martinot et al. agree that "technology transfer is fundamentally a process of learning" (73). As many countries have liberalized their markets, much technology transfer has occurred through the market.

Some argue that there is little that is unique about the process of technology transfer to distinguish it from technology deployment in general (41). If this is true, one can explore the theories about technological diffusion as they might apply to technology transfer. In terms of incentives for technology deployment, particularly in early deployment, policy and competition factors seem to provide the strongest incentives to firms. For example, new regulations and laws, along with increased market competition in the recipient country, can affect the technology transfer and diffusion process (74). Much technology transfer occurs through international trade, licensing arrangements, and foreign direct investment, but it is not necessarily an automatic process. There can also be ethical, political, environmental, and diplomatic motivations for technology transfer and diffusion.

Barriers and incentives for technology transfer tend to be fairly specific to a particular circumstance (75). It has proven difficult to determine which ones are generally most significant and especially which ones matter the most for sustainable or clean technology transfer (76). There is general agreement that special barriers and incentives for energy or environmental technology transfer do exist, but paradoxically, one of the most recent and comprehensive studies of the transfer of sustainable technology concludes that, "there are no corresponding overarching theories" about environmentally sound technology transfer, only a "number of pathways" (76). This Intergovernmental Panel on Climate Change study concludes that the pathway is determined by the role of the key stakeholder: government, private sector, or community.

Thus, the incentives and barriers to sustainable technology transfer depend to some extent on who is participating in the process (77). So although there may be no theory of sustainable-technology transfer, generalizations have again been formed about how such technology is usually transferred, what barriers exist, and how those barriers could be overcome. Empirical studies are beginning to show on a case-by-case basis which barriers and incentives are the most important in environmentally related technology transfer (78).

Many different actors and organizations engage in the process of technology transfer. Because so much technology transfer occurs in the market, the vast majority is conducted by private companies through licensing arrangements, foreign direct investment, and trade. Governments and nongovernmental organizations (NGOs) also engage in technology transfer, usually to enhance social welfare. One prominent example is aid organizations that help bring small-scale energy technologies, such as microhydropower, improved cookstoves, and biogas plants, to rural areas in developing countries.

Many other barriers are commonly cited in the literature to explain why it is generally difficult to transfer technologies from advanced-industrial countries to developing countries, such as concerns about intellectual property rights, competition, poor communication, lack of supporting infrastructure, unrealistic expectations, cultural differences, and the appropriateness of technologies for the recipient country (75, 79). But, it should be noted that the barriers and incentives for technology transfer are highly dependent on the particular context in which it occurs.

INTERNATIONAL COOPERATION International cooperation on ETI encompasses joint activities that may be of a government-to-government, firm-to-firm, university-to-university, or NGO-to-NGO nature, but they can also include cross-sector partnerships in all combinations. Governments are not—and need not be—directly involved in all of these activities, but the availability of resources for many of them (and, to at least some extent, the incentives and disincentives for all of them) are matters of government policy (80). Intergovernmental organizations also engage in and promote collaboration; the IEA, for example, has more than 40 Implementing Agreements for energy-technology collaboration (81). The vast majority of international energy-technology collaboration is conducted within and between private firms, especially multinationals and joint-venture firms.

Rationales for international energy-technology collaborations include sharing costs, risks, and resources for basic scientific research or long-term propositions (e.g., fusion); increasing the utilization of facilities; reducing the costs of emerging technologies through accelerated learning; and sharing costs for RD&D on technologies that are expected to provide public benefits (e.g., carbon capture and storage technologies). One might also want to gain access to technologies (usually from a developing country's point of view) or to promote the development of innovative capabilities at home and abroad to promote long-term competitiveness. Sometimes, international cooperation can promote interaction and discussion within partner countries, and it is often useful for developing mutually acceptable solutions to common problems (e.g., reducing the transport of airborne particulates). Governments and industry may also wish to collaborate to demonstrate technologies and to promote precommercial deployment of advanced energy technologies through the exploitation of niche markets and cost buy-down mechanisms to overcome financing barriers to deployment (12). Often international organizations may promote the demonstration and deployment of cleaner and more energy-efficient technologies in developing countries—the Global Environment Facility is a prominent example.

Firms often collaborate to gain access to location-specific data (e.g., geologic storage potential for CO_2 in a particular region), to explore how a technology might work in a different country (e.g., using local raw materials such as high-sulfur coal), or to gain understanding about market conditions in places where they might want to sell their product. Nongovernmental entities may collaborate to create a Track-II mechanism for communication about sensitive topics (e.g., climate change policy or the Pugwash Conferences on Science and World Affairs) or to promote greater understanding and expand insights and perspectives among scientists, policy makers, and academics about the challenges and opportunities in other countries (e.g., through workshops and conferences).

There are a number of potential drawbacks to international collaboration on innovation in energy technologies, including high transaction costs, difficulties in protecting intellectual property rights (81), and using international technology collaboration as an excuse to slow progress or take no action domestically.

Government funding for international energy-technology collaboration varies widely among countries. Private-sector funding can be assumed to be relatively large, but there is a lack of reliable data for both private and public spending because the data are often not collected and because firms consider such investments to be proprietary in nature (12).

Some prominent examples of international collaboration on ETI include the International Thermonuclear Experimental Reactor (ITER) and the Carbon Sequestration Leadership Forum (CSLF). Initiated in 1986, ITER is an international research collaboration to develop fusion nuclear power and now includes scientists and engineers from China, Europe, Japan, Korea, Russia, and the United States (82, 83). CSLF is an ongoing international climate change initiative designed to improve carbon capture and storage technologies through coordinated R&D with international partners and private industry (84–86).

MEASURING ETI INPUTS, OUTPUTS, AND OUTCOMES

There are numerous ways to measure ETI, but unfortunately no metric adequately encompasses the processes of innovation, spanning basic research to broad commercial deployment. Some metrics capture efforts on basic energy R&D, for example, whereas others serve as better indicators of technological deployment. Still, it is worthwhile to consider the different ways that innovation can be assessed through indicators, so long as one is explicit about what each indicator actually measures without taking liberties and assuming that a given indicator is indicative of innovation more generally.

One can assess technological innovation in general by using quantitative metrics and qualitative assessment techniques, and this is true of ETI as well. Quantitative metrics include spending or investments for innovation; the number of programs and partnerships; the number of technical publications; the number of patents filed, granted, and cited; and the use of life-cycle or S-curves; and the calculation of learning rates. The diversity of the innovation system, coordination and management of technological innovation, and the successes and failures of programs and projects can be assessed with qualitative methods, including the use of surveys or case studies. In most cases, all of these tools—both quantitative and qualitative—are complementary, and when used in combination with one another will help present a more complete and accurate picture of ETI. Another way to group these metrics is to classify them in three categories: input, output, and outcomes. There are pros and cons for using each of these metrics, and each will now be discussed in turn in the energy context using the input, output, and outcomes categories.

Input Metrics

Input metrics try to measure both tangible and intangible contributions to the innovation process. For the earlier stages of innovation, these inputs include, but are by no means limited to, financial investments into energy RD&D, existing scientific and knowledge ("old stock"), and the practical problems and ideas from which new inventions arise. In later stages of innovation, inputs include funding for demonstration and deployment programs, materials and fuels to run demonstration projects, and the developed inventions that are moving into the phases of demonstration and deployment. Human resources are essential to the inputs because many of the tacit contributions to innovation are embedded in people's minds owing to education, training, and learning from past innovative efforts (87) [also, see table 1.1 in Freeman & Soete (88, pp. 7–8) for a useful breakdown of inputs and outputs in the innovation process].

Perhaps the most commonly used input metric of trends in innovation, and for ETI in particular, are investments (or spending) by government and/or the private sector (for example, References 47, 89, 90). One can also measure ETI intensities (e.g., U.S. energy R&D spending/GDP). The obvious benefit of this metric is that government spending data tend to be readily available and can be tracked year to year, so that trends can be discerned (see, for example, Reference 91). Using investments as a metric is problematic because these are relatively comprehensive for R&D but not necessarily so for demonstration, and even less so for deployment. When investment data are inclusive of the later stages of innovation, it is frequently impossible to ascertain how they are allocated among the different stages. It is also exceedingly difficult to obtain detailed data about private-sector spending because such information is usually considered proprietary. Much industrial R&D is conducted by diversified corporations, and evaluating the portion of their R&D spending that is relevant to energy is difficult as a practical and theoretical matter (92). Data on ER&D expenditures are collected by a number of government agencies within countries, but the task of collecting comparable international data is daunting because of variations across countries in categories and definitions for R&D funding (12). The IEA collects data for member countries on energy RD&D expenditures, but these data do not encompass deployment activities. No comparable statistics are collected and synthesized for developing countries, so far as the authors are aware.

Measuring human resources is the other frequently used input metric for innovation in general. Human resources are often measured in terms of the number of scientists and engineers in aggregate, by sector, or on a per capita basis. Data are often collected in terms of the highest degree attained (e.g., bachelor's, master's, doctorate). This measure of R&D personnel is useful in a number of ways. The main drawback to using data on the number of people engaged in R&D activities is that this metric does not account for the quality or efficiency of the work. Although there may be a large number of people engaged in R&D, their output may be poor. Also, when comparing the number of people engaged internationally in ETI, one must be especially careful because there can be many more people employed in a developing-country setting where the cost of labor may be cheap, but the research infrastructure may be much poorer. This input metric is difficult in an energy context because it is hard to ascertain when scientists and engineers are working purely in the energy domain.

Output Metrics

Metrics for innovation output try to measure the product of the innovation process resulting from the later stages of ETI. Common output metrics are the number of papers published in peer-reviewed journals; the number of patents filed, granted, or cited; blueprints; specifications; the number of new technologies generated (e.g., new plants, new production lines); and the number of process innovations.

The number of technical papers published is often used as an indicator of research productivity, and more generally innovation, although it is rarely used to measure ETI specifically. It is probably not used so much in the energy realm because of the fuzziness of the boundaries about what exactly one would consider an energy technology. It is hard to imagine where to begin in measuring technical papers on energy innovation. Consider all of the articles that led to the gains in materials science that led to improved coatings for gas turbines or advances in electrical controls that permit hybrid-electric engines or thermostats to be adjusted almost continuously. Finding and analyzing all such articles would be an almost infinite task. Counting the number of technical papers might be useful, however, for programmatic or partnership evaluation. Using this metric in cross-country comparisons can also introduce some bias because the emphasis on publications may be greater in some countries than others, and many scientific journals are published in English, which might make English-speaking nations overrepresented (93).

Patents filed, granted, or cited are another metric of innovation in general and also for ETI more specifically. As with R&D investments, the main advantage of measuring patents is that data tend to be readily available, at least in industrialized countries. It is important to note that patents filed and granted are usually considered to be an output indicator of R&D (or invention) activity, not of wider innovative success because the invention might not be widely deployed (94). As noted by Archibugi & Coco (93), international comparisons in patents are problematic because the quality of patents varies substantially across countries, as does the propensity to patent in foreign countries. The same problem one encounters with respect to defining an energy technology when considering which patents are energy related and which are not (and when patents filed in a nonenergy sector might have implications for the energy sector) occurs in the patent realm. In addition, certain industries tend to patent more frequently than others and thus will vary in the energy context, depending on which industry is doing the innovation (88).

Technology produced is the most seemingly tangible output metric because surely one can assess technologies that have emerged from the innovation process. Private firms are likely to strongly emphasize this metric because technologies that emerge through the innovation process and end up being commercialized provide tangible, direct benefits to the company. Toyota's Hybrid Synergy Drive, for example, a set of technologies that are being commercially deployed, was the result of concerted innovative efforts by the company. This metric is unfortunately fraught with problems as well. To begin with, technologies are often not well defined and discrete. Technologies can also be tacit knowledge that is not codified into blueprints or patents. For energy technologies, this can be a special challenge because many so-called energy technologies relate to more energy-efficient system integration, which relies heavily on the accumulated knowledge of those doing the integration. Consider the developer of a "green" building who must treat the building as an integrated system, so that when he/she chooses to install super energy-efficient windows, knows that he/she must downsize the heating, ventilating, and air-conditioning system accordingly, continuously making such adjustments as each individual technology is introduced to the building system to reduce the total energy consumption of the building. Innovations in how to better integrate the system are likely to be easily missed by those counting energy-savings technologies, such as low-emissivity windows, but may prove to be far more important than each individual technology in terms of total energy saved. Counting and measuring such process innovations is not only difficult but sometimes infeasible.

Outcome Metrics

Beyond outputs, there is a broader category of metrics for the results of innovation, and these can be called outcome metrics. *Outcome metrics* tend to reflect the success of the deployment or diffusion of technologies generated in the innovation process, and in the energy domain, they can include measures of market penetration, the economic benefit of technologies, technological learning, energy efficiency or energy intensity, emissions intensity, and changes in the energy mix. There can also be program or project-based outcomes.

Quantification of the costs and benefits of ETI programs is often attempted for the purpose of calculating the relative economic success of innovative activities, but as noted by a major National Research Council study (95) on the benefits of U.S. government efficiency and fossil-energy R&D programs, there are many kinds of energy-related benefits, and many cannot be as easily quantified as to their costs. Benefits of ETI programs cannot only be realized as economic benefits of products that enter the marketplace, but also as environmental, national security, options (those technologies that have been invented that are on the shelf and available for commercialization), or knowledge (defined as knowledge resulting from R&D programs that may spill over into other sectors or be of use later) benefits.

For energy-efficiency technologies, one can measure the extent of their deployment by looking at trends in energy efficiency or energy intensity (energy use/GDP). Of course, such metrics measure the cumulative impact of all energy-efficiency technologies, not individual technologies. Similarly, one can look at emissions intensity (emissions/GDP) to assess the deployment of environmental technologies. Depending on the specific nature of the emissions, the metric could either be as broad-brush as an energy-intensity metric (e.g., carbon intensity), or it could assess the degree of deployment of specific technologies used in more limited settings (e.g., sulfur emissions from power plant plumes).

The number of programs and partnerships in an area of innovation is another metric of interest. Of course, one could have a large number of very small programs or a small number of very large programs and have a similar impact. Nonetheless, one can measure the size of such programs and partnerships by the number of employees and investments. The quality of programs and partnerships is probably of most interest and can be assessed better through qualitative techniques. Still, if a country or corporation has no (or many) innovation programs or partnerships in a certain area of importance or interest, this is worth noting. Both the United States and European Union, for example, have created numerous international partnerships related to addressing global climate change. But if one largely failed to commit significant money to these programs, and the other invested billions of dollars, then the success of the programs would probably be more limited in the former case.

Qualitative Assessment

Some innovative efforts cannot be easily quantified but are worth assessing because they are so important. Two examples in the energy realm are the diversity of the ETI system and the management of innovation process. In assessing unquantifiable aspects of ETI, such as the adequacy of ETI capabilities and the efficiency of technology transfer and diffusion, one must use qualitative techniques, including interdisciplinary assessment. Two techniques that have been employed to assess ETI are surveys of participants of innovation processes and case studies of programs and partnerships (see, for example, References 47 and 95).

The diversity of the ETI system is desirable for many reasons. In terms of activities, it helps hedge risks, given that there will be a few "big hits" and even more failures that cannot be foreseen *ex ante* in the innovation process. As a matter of government policy for individual countries, policy makers may be concerned about the adequacy, diversity, and focus of government-funded innovation programs and thus may commission studies on these questions [see, for example, the U.S. President's Council of Advisors on Science and Technology (PCAST) report on *Federal Energy Research and Development for the Challenges of the 21st Century* (11)]. Another aspect of diversity relates to the kinds of actors and stakeholders involved in innovation processes.

The coordination and management of ETI is also of great interest because the efficiency and productivity of innovation processes are strongly affected by its management. Management can be judged to some extent by the quantitative metrics above, but the effectiveness of a manager's vision, coordination, strategic choices, leadership, and ability to wisely halt poorly performing projects is better assessed through surveys, interviews, and case studies.

RECENT PATTERNS OF ENERGY-TECHNOLOGY-INNOVATION ACTIVITIES

The great majority of energy innovation worldwide takes place in industrialized countries, although many developing countries also have active efforts to develop and deploy new energy technologies. Better understanding of the magnitude and nature of these activities is essential to assessing the state of energy innovation. Developing a detailed understanding of this kind, however, is a complex and difficult task given the range of activities and sectors that encompass energy innovation and the numerous actors involved (92). Furthermore, within these groups of countries, both the public and private sectors are involved in funding and performing energy innovation. This section will discuss both the inputs for and outputs of ETI, paying attention to public- and private-sector efforts as well as the outcomes of such activities.

Public-Sector Energy Research, Development, and Demonstration

Figure 2 shows trends in public energy research, development, and demonstration (ERD&D) expenditures of major industrialized countries that account for almost 95% of the estimated total such expenditures by all IEA member countries. Figure 3 shows the distribution by category over the same period.[6] A few points are particularly notable and important.

- Public ERD&D for all of these countries showed a significant upward spike in the wake of the oil crises of the 1970s. But for most countries, these budgets peaked in the early 1980s and then declined significantly. As a result, the current ERD&D spending of countries such as Germany, Italy, and the United Kingdom are a small fraction of their historical peaks. Japan is the only major industrialized country whose recent ERD&D spending in real terms is well above its spending in the early 1980s—having had annual ERD&D budgets that were less than half that of the United States in the mid-1970s, it now invests more in ERD&D than the United States (and on a per-unit-GDP basis, far outstrips all other countries). Japan and the United States together account for about 75% of the estimated total ERD&D spending by IEA countries.
- Nuclear fission remains the single largest component of the total ERD&D spending by these countries, despite a steep decline over the past two decades. In 2002, it accounted for about a third of the overall public expenditures on ER&D. Japan's fission ERD&D spending accounted for almost 80% of the IEA total and about 60% of the country's total ERD&D budget. Much of the fission RD&D at present is targeted toward nuclear supporting technologies, which include general nuclear safety and environmental protection as well as decommissioning of power plants and fissile materials control.
- Conservation RD&D has been the major gainer in the past three decades, with expenditures quadrupling in real terms between 1975 and 2002. Japan and the United States currently account for over 80% of the total IEA expenditures in this category.
- Coal and renewables ERD&D budgets have declined significantly compared to their peak levels in the 1980s. At present, coal accounts for only about 40% of the fossil RD&D budgets. Within renewables, the two largest subcategories are solar PVs and biomass (about a third and a quarter of the total, respectively).

[6]There may be some additional activities in government agencies that do not get picked up as ERD&D investments. For example, in the United States, work at the Department of Defense and the National Aeronautics and Space Administration was instrumental in the development of fuel cells (11).

- Spending on other technologies and research—which includes RD&D, among other things, on energy systems analysis and hydrogen—now is the second-largest category, recovering from a steep decline in the early 1980s. But it should be noted that this is also a catchall category, so comparisons across time may not be very meaningful.

Although there are few systematic separate data on funding for demonstration activities, these investments can often be substantial and in many cases involve contributions from public and private sources. For example, the U.S. government's Clean-Coal Technology program, initiated in 1986, involving 35 projects that covered advanced power generation, environmental control technologies, coal processing, and industrial applications, received \$1.8 billion from the federal government and about \$3.4 billion from industry. Other prominent examples of major demonstration and commercialization efforts include the unsuccessful Clinch River Breeder Reactor Project and the Synthetic Fuels Corporation (11).

The European Union, through its Framework Programmes for Research and Technological Development, also funds a range of energy innovation activities. The sixth Framework Program (2002–2006) has allocated €890 million for sustainable energy systems and €670 million for sustainable surface transport. The fifth Framework Program (1998–2002) budgeted about €1 billion for cleaner energy and economic and efficient energy programs.

Although there are no systematic and detailed data on public ER&D spending in developing countries, data from China and India indicate that these governments also invest fairly heavily in this area. China spent the equivalent of about 3.1 billion 2000 PPP\$ (year-2000 U.S. dollars converted from local currency using purchasing power parities) in the year 2000 (96) and India, about 0.9 billion 2000 PPP\$ in 1996–1997 (latest years for which data are available) (97).

Private-Sector R&D

Industry is a major funder and performer of ER&D. For example, a recent study by the National Research Council (95) estimated that between 1978 and 1999 industry accounted for almost two thirds of the total energy R&D expenditures within the United States. Firms engage in energy-related R&D for two main reasons: Such activities aid the development of new products or improvement of existing products and improve the firms' own energy usage (and allow them to meet regulations); the ultimate intention, of course, is to stay in business and maintain or increase their competitive position in the marketplace.

As mentioned above, accurately tallying energy-technology-related R&D investments in the private sector is an almost impossible task. There are a number of reasons for this (51, 92).

- An enormous range of technologies can have an impact on the energy-consumption characteristics within various sectors. For example, finite element analysis software help in the improving structural design in automobiles, leading to lighter and more fuel-efficient cars; advanced control technologies help reduce the energy consumption in buildings; and new catalysts help make more efficient processes in the chemical industry.

- Many firms that play a major role in the energy sector are diversified industrials (such as General Electric, Hitachi, Siemens, and Toshiba), which have a wide variety of energy-related products/services as part of an even larger portfolio of offerings. Hitachi, for example, has products and services that span business and consumer electronic devices and electrical appliances, computers and networks, power, industrial and building technologies, medical and life sciences equipment, and semiconductors. Because firms generally do not release disaggregated R&D expenditure data (even if they could), it is impossible to assess what fraction of their overall R&D effort is relevant to energy-technology R&D. A few firms, however, do release R&D expenditures by business segment. For example, Siemens had a total R&D expenditure of about €5.2 billion in 2005, out of which transportation, lighting, and power accounted for about a third. Automation and control, which includes building technologies and industrial solutions and services, accounted for another fifth.
- Many firms that generally would not be considered energy-technology developers have R&D activities that have an impact on the energy sector. Examples include firms such as Engelhard that develop catalysts and additives, which can enhance the efficiency and efficacy of chemical and refining processes, or firms such as DuPont and Dow that develop advanced polymers that replace materials that are heavier (such as steel) or are more energy intensive to produce (such as aluminum).

In recent years, there has been much concern about cutbacks in private-sector ER&D and about the changing nature of industrial R&D (to a model that emphasizes short-term, business-unit driven model) and its implications for the future of energy innovation (see, for example, References 11, 89, and 98). These concerns are catalyzed mainly by reductions in global public ER&D budgets compared to the peak values in the late 1970s and early 1980s, reductions in ER&D investments, a move toward a shorter-term focus in parts of the private sector, and the increasing urgency of tacking climate change and other pressing problems.

Some data certainly support this position: The National Science Foundation's annual survey of industrial R&D indicates that (public and private) funds for industrial energy R&D showed an almost continuous decline in the 1980s and 1990s, with the 1999 levels about a fifth of the peak value in 1980 (in real terms) (See http://www.nsf.gov/statistics/iris/search_hist.cfm?indx=21). Similarly, data on ER&D expenditures by major U.S. energy producers (99) show a marked decline over the past decade and a half; the 2003 expenditures of US$858 million were less than half of the 1989 level in real terms. Conversely, firms in many other categories

TABLE 1 Some major energy-technology firms and their 2004–2005 R&D spending (in U.S. millions) (100a)

Transportation	**R&D spending**	**Electric utilities**	**R&D spending**
Vehicle manufacturers		Tokyo Electric Power, Japan	361
DaimlerChrysler, Germany	7691	Korea Electric Power, South Korea	349
Ford Motor, United States	7400	Kansai Electric Power, Japan	227
Toyota Motor, Japan	7370	Vattenfall, Sweden	80
General Motors, United States	6500	Taiwan Power, Taiwan	69
Volkswagen, Germany	5650		
		Heavy machinery	
Automotive systems suppliers		Volvo, Sweden	1346
Robert Bosch, Germany	3939	Caterpillar, United States	928
Delphi Automotive Systems, United States	2100	Komatsu, Japan	453
		Cummins, United States	241
Aircraft engines			
Snecma, France	1025	**Power generation/diversified industrials**	
Rolls-Royce, United Kingdom	541	Siemens, Germany	6882
		General Electric, United States	3091
Oil and gas		United Technologies, United States	1256
Integrated firms		Mitsubishi Heavy Industries, Japan	971
TotalFinaElf, France	863	Asea Brown Boveri, Switzerland	690
Exxon Mobil, United States	649	Alstom, France	457
Shell, United Kingdom	553		
BP Amoco (now BP), United Kingdom	439	**Home appliances**	
ENI, Italy	349	Whirlpool, United States	315
Petro China, China	315	Electrolux, Sweden	309
Oilfield services			
Schlumberger, United States	467		
Halliburton, United States	250		

(such as diversified industrials and automobile manufacturers) do not show a clear downward trend, especially in countries other than the United States (100). Table 1 lists the 2004–2005 R&D expenditures of some major energy-technology firms, as an illustration of these sizes of these expenditures and the range of relevant firms. It is difficult to carry out interannual comparisons of R&D spending of many firms because of mergers and acquisitions, sales of units, and restructuring, which can significantly impact R&D numbers.

Deployment

Promoting deployment of energy technologies involves a range of policies (often not financial in nature), as described below, but in many cases, there are explicit subsidy provisions that help deploy emerging technologies. One prominent example is the Japanese program for dissemination of PV systems, whereby the government provided the equivalent of US$200 million in subsidies between 1993 and 1998, and these investments stimulated market actors to invest the equivalent of $300 million. Another example is the German "100/250" wind power program, whereby the government gave subsidies of DM330 million (1995DM), and market actors provided another DM650 million (1995DM) (55).

Assessing Outputs and Outcomes

Although it obviously would be desirable to be able to correlate energy-innovation activities with downstream technological change (or effects of such change), the very nature of innovation and technological change makes it almost impossible to carry out a one-to-one mapping between a particular project and eventual changes in technologies and products because these changes are often the result of a number of R&D advances that are interconnected and build upon other work.

As noted in the previous section, the most commonly used metrics for ER&D output are publications and patents as proxies for advances in knowledge and innovation, respectively. But even this is difficult in the energy area because of the wide scope of the area and the kinds of technological advances that can have an impact in it. Still, there have been some efforts to make such assessments [see, for example, Margolis & Kammen (90), who use this analysis as a way of making a case for underinvestment in ER&D], but these kinds of attempts remain beset with difficulties (101).

Another way to gain a better understanding of the effect of energy-innovation activities is through an assessment of impacts at a programmatic level rather than specific activities. An excellent example of such an analysis comes from a recent National Research Council study (95), which estimated that the U.S. DOE's energy-efficiency and fossil-energy program, with an initial $7 billion investment between 1978 and 2000 in its energy-efficiency program and $10.5 billion investment over the same period in its fossil-energy program, yielded benefits of $30 billion, and $11 billion, respectively (with additional environmental benefits of $64–$90 billion).

Even if one cannot correlate specific kinds of technological change with a particular energy-innovation activity or program, advances in particular technologies and sectors over time are amenable to useful quantification, for example, through the analysis of learning rates. McDonald & Schrattenholzer (58) have examined learning rates for a range of energy technologies and found a median value of learning rates of about 16% to 17% (with a wide distribution). Although some improvements in performance of these technologies can be attributed to greater experience with project and plant planning and operation, many improvements are also a result of technological change that results from R&D activities.

At an even broader level, one can assess macrolevel changes in the energy sector through measures such as *energy intensity* (i.e., energy use per unit of gross domestic product) and *carbon factor* (i.e., carbon emissions per unit of energy use). Economy-wide improvements in energy intensity can come from changes in the sectoral composition of the economy (for example, a move from manufacturing to services reduces energy intensity), and technological change also contributes significantly to the process. Similarly, even though reductions in carbon factor mostly result from a shift in the fuel-supply mix, such shifts are still underpinned by new technologies that allow for suitable utilization of new fuel sources. Overall, the rates of return to society from ETI investments have been seen to be high (to the extent they can be assessed) (11).

Figures 4 and 5 shows the changes in the energy intensity and carbon factor over time at the global and Organisation for Economic Co-operation and Development (OECD)-wide level as well as for a few major energy users. Global energy intensity declined at about 1.4% per year between 1975 and 2000; the energy intensity for OECD countries declined at about the same rate, as it did for India. Although the United States has shown a 1.9% annual decline over the same period, more than twice as fast as the rate of decline in Japan, its energy intensity remains at least 50% higher than Japan. China has shown a remarkable decline of over 5% per year during that period [some analysts believe its real rate of decline may be a bit lower (J.E. Sinton, personal communication)], although its energy intensity in 1975 was almost three times the world average. Generally, structural shifts in the economy (i.e., an increasing contribution of the service sector to the GDP) as well as more efficient conversion and end use of energy contribute to improvements in energy intensity. Not all countries, however, have seen reduction in their energy intensity over the past few decades. For example, as the South Korean economy has become more manufacturing intensive, its energy intensity has gone up. As Figure 5 shows, the carbon factor has been showing a decline in industrialized countries (albeit at a much slower rate than for energy intensity), except in India and China, where this has increased over time as the contribution of fossil fuels to the energy economy has grown.

Similarly, the oil intensity of most industrialized countries worldwide has declined over the past few decades. For example, the oil intensity of OECD countries was 0.136 kilotons of oil equivalent (ktoe) per million 2000 PPP$ of GDP in 1980 and dropped to 0.083 by 2003 (102). Oil accounts for most of the consumption of hydrocarbons, although the use of natural gas has risen in the past decade or so. China, as in the case of the overall energy intensity, showed a remarkable decline, with its oil intensity dropping from 0.126 in 1980 to 0.046 in 2003. In the case of India, however, this metric held steady over this period, rising slightly from 0.042 in 1980 to 0.043 in 2003 (103).

There has also been some progress in moving away from the reliance on biomass energy in developing countries. Although complete data on the use of biomass (combustible renewables and waste) are not available, IEA estimates indicate a decline in the fraction of the primary energy supply contributed by biomass in non-OECD countries, even as the absolute use has gone up somewhat. In 1980, biomass use was equivalent to about 617 million tons of oil equivalent (mtoe) in this group of countries, which was almost 22% of their total primary energy supply (TPES); by 2003, the total use had risen to 964 mtoe, which was an estimated 18.6% of the TPES. For China and India, the two largest consumers of biomass in the world, estimated biomass use as a fraction of TPES dropped from 0.30 and 0.61, respectively, in 1980 to 0.15 and 0.38 in 2003 (104).

Although one might expect a correlation between ERD&D expenditures of a country and the trajectory of its energy intensity or carbon factor, an examination of major OECD countries does not show any clear correlation between these (57). Thus, ERD&D is not a sufficient condition for changes in the energy sector; deployment policies and programs, as well as broader energy policies, play a major role in moving the results of R&D into the marketplace. We elaborate further on this in the next section.

There are no estimates or detailed analyses of energy-innovation activities targeting the energy needs in developing countries of the estimated two billion poor who do not have access to sufficient and modern energy services. It would be fair to say that these activities receive only a minuscule portion of the global expenditures on energy innovation. Furthermore, traditional developers of commercial energy technologies rarely focus their attention on this group, although their work may have spin-off benefits for particular applications. For example, improvements in PV modules and balance-of-system components have underpinned advances in PV-based energy systems for rural applications. Conversely, some targeted development programs, mostly in government laboratories, independent research institutes, academia, and NGOs, have led to technologies aimed at improving energy services for the poor (prominent examples are improved cookstoves, solar PV lighting systems, and village-level biogas and microhydropower systems). Funding for such technology development may come from international and local development funds, as was the case for the *jiko* stove in Kenya, or from national governments, as in the case of the Indian and Chinese cookstove programs (24).

PROMOTING ENERGY-TECHNOLOGY INNOVATION

Given that improved and new energy technologies will play a key part in meeting the enormous challenges facing the energy system, the promotion and enhancement of ETI takes on great significance. We now discuss the various barriers that may impede ETI and ways to overcome them, as well as other approaches to enhance the pace and effectiveness of ETI.

Enhancing Energy Research and Development

Probably the most significant barrier to ETI is inadequacy of funds, especially for R&D, in relation to the challenges that are faced by energy system. There has been significant discussion of, and attention focused on, this issue. Although some of the concerns about the public ER&D budgets are well founded, it should be noted that a major portion of the rapid decline in the early 1980s was in nuclear R&D. In fact, the total nonnuclear ER&D within the major IEA member countries has remained relatively flat (in real terms) since 1982. Still, given that this period has seen the emergence of the recognition of the climate problem—the most daunting challenge that the world's energy system has faced—it is clear that the response in terms of enhancing public ER&D budgets has been practically nonexistent. In comparison, the previous oil crises led to a much sharper and vigorous (although short-lived) response. It should also be noted that government investments in R&D in turn stimulate private-sector investments in innovation.

Looking beyond total budgets, there are three other aspects of energy innovation that merit further examination (92).

- ER&D portfolio (i.e., allocation of the input)
- Effectiveness of ER&D expenditures (i.e., input-output relationships)
- Effectiveness of implementation and diffusion of new technologies (i.e., utilization of output)

Certainly in terms of the allocation of the ER&D budgets, there have been some major changes over the past two decades (as Figure 2 shows), although the focus on coal and renewables is limited in relation to their status as a continuing major source of existing (for coal) and potential (for renewables) energy supply globally. A suitable allocation of the budgets requires a portfolio analysis, which examines the range of activities being undertaken in terms of their relevance to various fuel-supply and end-use segments, cost and scale, time horizon, and risk profile, with the intention of balance across these attributes in relation to the nature of the challenges, opportunities, and constraints. There have been some attempts at doing portfolio analyses (11) within industrialized countries, but it is not clear whether there have been similar efforts in developing countries.

Improving management of R&D processes, a topic that has occupied many an analyst, is increasingly germane as ER&D expenditures come under greater scrutiny. Problems identified in the past with the U.S. DOE's management of energy innovation (and likely to be true for other organizations) include the narrowness of programs, inability to stop nonperforming programs, poor coordination of activities across program boundaries, weak coordination of fundamental and applied RD&D, congressional "earmarking," lack of clear leadership and authority, and limited technical skills among management employees. Progress has been made in recent years on many of these problems, particularly in the development of criteria for starting, continuing, and stopping projects; developing performance metrics for midstream review; soliciting external peer review; and establishing partnerships with the private sector and academia (105). In addition, reviews of the U.S. DOE's programs have consistently suggested that there are significant gains to be had through improved management of DOE programs (13, 47). Possible steps could include improved communication, coordination, and peer review in DOE's ERD3 program and pursuing increased coherence and self-restraint in the congressional earmarking process for ERD3 appropriations (13).

Promoting Deployment of New Technologies

Another important set of issues concerning the promotion and enhancement of ETI relates to implementation and diffusion of new technologies. There are a number of barriers that can impede or constrain the uptake of new technologies (with the last two barriers listed here being particularly important in developing countries) (48, 51).

- Cost
- Infrastructure
- Slow capital stock turnover
- Market organization
- Information
- Financing options

Successfully overcoming these barriers requires careful design of policies and programs. The rest of this section discusses policies and programs that promote deployment of new and improved technologies (49, 51).

COST The uptake of new technologies generally depends on the users/customers being offered some beneficial attributes in comparison with established, incumbent technologies. Cost is often the most important of these attribute and becomes the primary barrier to the diffusion of new technologies. In the case of energy technologies, this is particularly important for new technologies and products that offer environmental benefits because the costs of environmental externalities are rarely, if ever, fully captured; environmentally cleaner technologies offer benefits that are not monetized (and therefore the higher costs of these technologies cannot be offset, which places them at a disadvantage). This imbalance can be remedied through the use of regulations (that set standards for environmental performance and therefore impose a levy on more polluting technologies), through the use of market-based instruments (such as pollution taxes or emission caps), through direct subsidies to new technologies, or through the removal of subsidies from more polluting technologies.

Furthermore, the costs of incumbent technologies generally reduce over time via scales of economy and (technological and market) learning, making it more difficult for newer entrants to compete. As mentioned above, as a new technology is deployed, learning effects help reduce its costs, allowing it to become cost competitive with the established technologies; this requires a “learning investment,” as shown in Figure 6. Although manufacturers generally absorb most of these learning investments (and also invest in R&D, which can help make the learning curve steeper), public policies targeted at early deployment of alternative technologies can also play a major role in assisting learning.

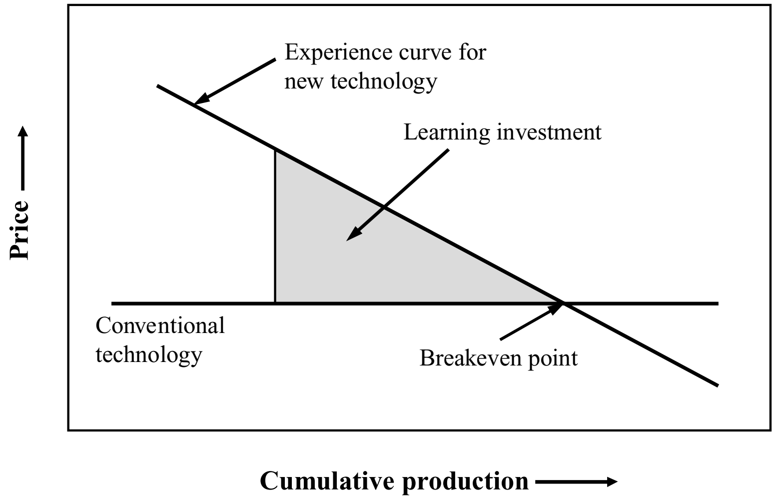

Figure 6 Learning investments needed for introduction of new technologies.

In the case of renewables, for example, there have been a number of major policies enacted by governments of several countries to facilitate and promote the early deployment of emerging technologies. Examples of renewables policies include the Public Utilities Regulatory Policies Act of 1978 in the United States, the Non-Fossil Fuel Obligation under the 1989 Electricity Act in the United Kingdom, and a renewable energy feed-in tariff under the German Electricity Feed Law. In some cases, programs may also aim to promote specific technologies, for example, Japan's Sunshine and New Sunshine projects have targeted PV (with support for R&D, demonstration, and deployment), with the result that Japan accounts for about 40% of the global PV production. Germany, the world leader in wind energy, has had an aggressive program supporting R&D in wind energy as well as deployment policies and incentives at both the federal as well as the state levels. Although these various programs have been quite successful at lowering the prices for renewables technologies, the cost of natural gas-based generation has declined even faster, thus impeding large-scale deployment of these technologies for mainstream power generation. But the recent rise in the cost of natural gas if perceived as being long-term in nature may yet provide an opening for renewables.

Direct procurement itself can be leveraged as an important component of deployment policy. The U.S. Energy Policy Act of 1992 requires "guidelines to encourage the acquisition and use of [energy-efficient] products by all Federal agencies"; this can have a substantial impact because the U.S. federal government is the world's largest purchaser of energy-related products. Similarly, the European Union is using E.U.-wide procurement and coordinated procurement among member states to promote the development and deployment of new energy-efficient technologies (104).

INFORMATION Provision of information to consumers—especially individuals and small enterprises—when they are making energy-relevant decisions can help them make appropriate choices among various technologies/products. This is particularly pertinent in the energy area where the energy-use metrics of goods can vary widely. Labeling programs, mandatory and voluntary, are the most common way of providing such information to consumers. The former category requires information about performance on particular energy-use characteristics such as the EnergyGuide labels required of home appliances or the fuel economy estimates required of new automobiles in the United States; many other industrialized countries have similar programs. The latter category often reflects endorsement signifying the achievement of a certain minimum performance (as in the case of Energy Star appliances in the United States). A European study has found that labels played a role in the decision making of a third of the consumers (104). And the U.S. Enivironmental Protection Agency estimates that the Energy Star program resulted in savings of about 30 million metric tons of carbon in 2004 and provided savings of $9.3 billion to consumers (106).

Performance standards are another way to promote the deployment of improved energy technologies. These can be applied for particular categories of products (such as electric appliances) or a market-wide or a manufacturer-based average (107).

SLOW CAPITAL STOCK TURNOVER Energy technologies often have lengthy operating lives. For example, power plants may operate for 40–50 years, and automobiles may be on the road for more than 10 years. This presents a hurdle to the introduction of new technologies. Tighter performance standards (or those that ratchet down over time) provide an incentive to phase out older (generally more polluting) technologies. Thus, the Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in 1987, helped accelerate the phaseout of chlorofluorocarbon-based energy technologies and allowed the introduction of alternatives such as hydrocarbon refrigerators. Similarly, the U.S. Clean Air Act has provided the impetus to phase out old and dirty coal-based power plants. Another interesting example comes from Japan where an onerous inspection regime (*Shaken*) provides a disincentive to keep cars on the road for a long time.

INFRASTRUCTURE In many cases, energy technologies are associated with specific infrastructure: Power plants require an extensive transmission and distribution grid, railroads require a track network, and automobiles require road as well as maintenance infrastructure. The introduction of new technologies and infrastructure are often impeded by existing infrastructure; furthermore, the time and significant investment (see Reference 42) needed for new infrastructure provides an additional barrier. The case of hydrogen offers a particularly salient and contemporary example. The potential benefits of a move toward hydrogen likely will not be realized without a storage and distribution infrastructure, but the development of such an infrastructure is seen as an insurmountable technical and economic barrier (108).

Public policies are critical in this regard; governments play a major role in the development of new infrastructure, either through direct support or through policies that provide suitable incentives.

MARKET DEVELOPMENT AND ORGANIZATION The development and organization of markets are essential elements of the widespread deployment of new technologies. Such markets help underpin the emergence of a manufacturing base through the provision of a steady supply of customers. Although eliminating/reducing market barriers (such as cost) obviously helps develop markets, explicit and strategic efforts such as targeting niche markets or *market transformation* efforts, which address stakeholder needs and concerns in adopting new technologies and help overcome market inertia, can also play helpful roles (50). Public-private partnerships can play a particularly critical role in this area by ensuring the appropriate development of markets.

FINANCING OPTIONS The availability of finances can often be an impediment in the deployment of energy technologies. This is particularly important in developing countries where the financial markets are not fully developed and a number of organizations (especially micro-, small-, and medium-scale enterprises and small-scale power developers and other energy providers) and individual consumers (especially the poor) have limited access to traditional routes of financing. In many cases, development banks and agencies have started targeting these areas (realizing that high economic and social returns are possible through the provision of energy services that have an income-generation potential) either directly or through intermediate organizations. A prominent example of the latter is the Indian Renewable Energy Development Agency, which promotes, develops, and extends financial assistance for renewable energy and energy-efficiency/conservation projects. It is supported by a several major international development agencies (including the World Bank, Asian Development Bank, KFW Germany, the Dutch and Danish aid agencies) and, as of March 2005, had disbursed the equivalent of more than $820 million in loans. Innovative approaches such as microcredit have played a big role in transforming the availability of finance for poor individuals with no formal credit guarantee/history; Grameen Bank in Bangladesh, the pioneer in microcredit, now operates Grameen Shakti, which aims to help deliver renewable energy to rural households in Bangladesh.

All in all, successful energy innovation requires careful planning and coordination on the various fronts discussed above (and among the various relevant actors). A particularly successful example of this comes from Japan where a government-initiated program of PV development encouraged broad involvement of cross-sectoral industry and induced significant industry investment in PV R&D. This led to rapid decreases in solar cell prices, which coupled with a deployment program led to increased production of these cells. This, in turn, stimulated further PV R&D investments, leading to a "virtuous cycle" between R&D, market growth, and price reduction (68).

Furthermore, given that most of the challenges facing the energy system are global in scope, addressing them will require appropriate actions across industrialized and developing countries. In many cases, international cooperation is useful (and even necessary) on ER&D projects (as in the case of the ITER program). But it is increasingly recognized that international cooperation on all aspects of energy innovation (and relevant capacity building in developing countries) is necessary to meet these global challenges, and indeed, such cooperative efforts have the potential to yield significant benefits (12). Yet, it must be noted, this issue mostly continues to be overlooked, although recent initiatives (such as the Asia Pacific Partnership on Clean Development and Climate) may make some contribution on this front.

SUMMING UP AND LOOKING AHEAD

Greater appreciation for and understanding of ETI activities and processes are important for two main reasons. First, they can help improve and strengthen the ETI itself. Second, an enhanced understanding can help in the analysis and design of energy and environmental policies by better assessments of the potential contribution of such innovations over time and also by the design of more effective policies to stimulate and guide innovation efforts that address the kinds of challenges outlined in this review. This section summarizes what is relatively well known about ETI, what primary gaps in our knowledge still remain, and what can be done to ameliorate those gaps and improve policies that spur and harness innovation to address the energy-related challenges facing us today.

What Is Clear

Several important conclusions about ETI have emerged from the many studies of the topic during recent decades, notwithstanding the lack of knowledge about many aspects of how the energy-technology-innovation system works. These robust conclusions include the following:

- Past investments in ETI, public and private, led to large improvements over the course of the twentieth century in the performance of specific energy technologies, energy sectors, and the whole energy systems of nations and the world, as measured in increased technical efficiency, increased reliability, and decreased cost and environmental impact per unit of energy output and per unit of economic product.
- Where and when it has been possible to make at least rough comparisons between the investments in and the returns from ETI, the rates of return to society from these investments have been seen to be high.
- Governments in most advanced industrialized countries (with the notable exception of Japan) have sharply cut back their investments in ETI during the last two decades. Although there is some evidence for cutbacks in

private-sector ETI as well, data limitations make it difficult to evaluate with accuracy how much the private sector has cut back its funding, when this trend emerged, and whether it will be sustained. Clearly, global public investments rose dramatically in response to the 1970s' oil crises, declined precipitously during the 1980s, and have held steady since then (and it is likely that private investments followed a somewhat similar trend). In the face of the enormous challenges of global climate change and ever-increasing oil dependence, there has been no analogous rise in investments as occurred in the late 1970s by either the public or private sector. And the needs of the energy poor continue to be largely ignored.

- Factors that may hinder investments by private firms include the long timescales for turnover in energy-supply and energy end-use technologies and for development and demonstration of new energy technologies (especially supply technologies) to the point of commercial competitiveness; the inconstancy of incentives to develop alternatives to conventional oil and natural gas as a result of the substantially unpredictable ups and downs in the market prices for these energy commodities; and the absence of both agreed valuations and market signals reflecting those valuations for the societal benefits from reduced oil dependence and reduced GHG emissions.
- Rates of improvement in energy-technology performance with respect to reducing oil and gas dependence, providing adequate and modern energy services to the global poor, and reducing GHG emissions will need to be much greater than the recent historical rates of improvement in these terms if the national and global challenges set forth here are to be met. It is not clear what exact level of investment in ETI would be optimal to address these critical challenges, but it is surely much higher than current levels.
- Improvements in the productivity of investments in ETI are attainable through improved understanding and management of the innovation process short of overall increases in the level of resources being made available. It is unlikely, however, that such increases in the productivity of investments in innovation at a given level of resources would be sufficient to close the large gaps between recent rates of innovation and what will be required to meet oil-dependence and climate-change challenges.
- It is in the nature of research that the productivity of different lines of investigation cannot generally be predicted in advance. Attempting to increase productivity by confining investments to sure things tends to cut off the high-risk/high-reward lines of investigation that often turn out to be the sources of the greatest gains. Energy-innovation programs need to be shaped and need to be evaluated as portfolios that distribute their investments across degrees of risk and time frames for anticipated returns as well as across end-use sectors and primary energy sources.
- Intersectoral partnerships (among various combinations of industry, academia, national laboratories, other governmental and semigovernmental

entities, and NGOs) offer major potential for combining different forms of comparative advantage for ETI, perhaps most importantly in the historically problematic transitions from applied research through development, demonstration, and widespread deployment.

- The three most demanding drivers of ETI—reducing oil and gas dependence, reducing GHG emissions, and meeting basic human energy needs—share the characteristic that both the benefits of progress and the costs of failure transcend national boundaries. This characteristic should be understood as motivating an increased degree of international cooperation on ETI toward these ends.

Knowledge Deficits

The picture of ETI that can be painted at the current state of knowledge is imperfect and incomplete, for a number of reasons elaborated above.

- The innovation "chain" or "pipeline" (typically characterized as basic research, applied research, development, demonstration, and diffusion) is in reality not a linear progression but a web of overlapping processes and feedbacks that are as yet far from fully understood. The web includes partnerships and interactions within and among sectors (government, industry, academia, NGOs) and across national boundaries that have barely begun to be mapped, not to say analyzed and understood.
- The most frequently presented and studied measures of the energy-technology-innovation system are only input measures, e.g., magnitudes of monetary commitments and outlays for the conduct of R&D and for R&D facilities. But even these measures are limited in accuracy by the overlapping boundaries just mentioned, by lack of clarity and agreement about what counts as energy work, and by gaps and ambiguities in the available data about what the private sector is doing.
- Measures of outputs and outcomes (publications, patents, sales and market penetration for new technologies, measures of performance of technologies, sectors, or the whole energy system) are plagued by the same definitional and boundary problems as the input measures, and they are difficult to correlate with inputs because of variable time lags between input and outputs and because of the difficult to separate roles of factors inside and outside the energy-technology-innovation system in determining outputs and outcomes.
- Although the importance of the demonstration and diffusion phases of innovation is obvious, the state of understanding of how they work remains weak. The role of learning in cost reduction and other improvements in performance in the course of demonstration and diffusion has been a major focus of study, but how learning actually works and how its course can be influenced and predicted remain inadequately understood in the energy field and in others.

The resulting lack of understanding of how incentives for and investments in ETI translate into actual progress in the improvement of energy technologies and the deployment of the improved versions in the real world is a handicap to formulating effective ETI strategies in the private and public sectors alike. At the most obvious level, these shortcomings in understanding make it difficult to answer the perennial question about investment in innovation, "How much is enough?"

The knowledge deficit about how ETI actually works has inevitably led to inadequate representation of the technological-innovation process in the energy-economic computer models increasingly relied upon to forecast the results of different policy choices and therefore to make appropriate policy decisions (see Reference 109 for a useful review of these models). Although these models vary in their level of detail about the energy sector, their ability to forecast over the long term, their connection to the global economy, and their treatment of technological change, they all make assumptions about the role of technological change and the ETI process, and these assumptions can profoundly affect their results.

Many energy-economic models incorporate technological change by including an exogenous function, such as a decline in energy use per unit of output over time; only a few attempt to incorporate endogenous technological change (such as learning by doing) over time (and generally treatment of this issue remains imperfect). This is for the following reasons: Our understanding of ETI is still far from complete, often data are not available, and it is difficult to model the dynamic innovation process. Improvements in energy intensity have been shown to exist nearly everywhere in the world and are useful additions to the models, but the rate of decline varies substantially among countries, so the choice of the decline rate is fraught with assumptions.

The models that disregard policy-induced technological change thus tend to underestimate the pace of ETI and overestimate the costs to the economy of various energy and environmental policies (110, 111). Technologies that are available at the time a given model is run, for example, are sometimes entered as baselines and then assumed to be constant in the future with no improvement in their performance or unit costs. Yet all that is known about ETI indicates that over time new technologies always substitute for older technologies, and unit costs of energy technologies almost always decline as cumulative production increases. As our understanding of ETI process improves, and models are adapted to reflect the improved understanding, they can be used to more effectively assess appropriate policy interventions.

What to Do

We believe that there are a number of clear actions that could be taken to enhance the likelihood that ETI efforts will help address the many important economic, environmental, and security challenges associated with energy production and consumption. These recommendations can be encapsulated as follows:

- Continuing and expanded study of the energy-technology-innovation system is warranted, with the aim of filling in many of the deficiencies in understanding outlined in this review, in order to improve the capacity to manage the system better and thereby to improve the results derived from any given level of resources devoted to such innovation. As part of this process, the private sector should be encouraged to make available more complete and detailed data relating to its energy-technology-innovation investments.

- Combined public and private investment in ETI is not remotely commensurate, at present, with the magnitude of the energy challenges faced by individual nations and the world as a whole in the twenty-first century, even allowing for the improvements in innovation management and thus productivity that are likely to be possible with increased understanding and attention. Considerably higher levels of investment are warranted.
- Certain public policies also have the potential to stimulate technological change in the energy sector (technological change that results from policy is often called induced technological change) [see, for example, Goulder (110)]. In our view, two kinds of policies are needed at this time. First, there is a need for policies that will stimulate market demand for deploying existing or precommercial technologies to start addressing the obvious challenges immediately [see Pacala & Socolow (38) for details]. Incorporating the social costs of oil dependence and GHG emissions into the prices of the relevant energy sources (e.g., through carbon taxes, gas taxes, or cap-and-trade systems) would be one way to create additional incentives for innovation. Second, given the long planning horizons and capital-intensive investments associated with the energy sector, appropriate long-term policy signals (e.g., GHG concentration targets or stable tax incentives for private innovation) are needed to more cost-effectively induce technological change in firms.
- Improving the environment for and encouragement of multisectoral partnerships and international cooperation in ETI should become a part of the energy strategies of all countries and of all the relevant multilateral institutions.

As our understanding improves about the dynamics and processes of ETI and about the interplay between such innovation and government policies, we should be able to improve these innovation processes and their contributions to enhancing and reshaping the energy system. This, in turn, should help us realize the potential of ETI to meet the grand challenges of providing energy to the two billion people who lack access to modern energy services, reducing oil and gas dependence, and providing affordable energy services to sustain the global economy without wrecking the global climate.

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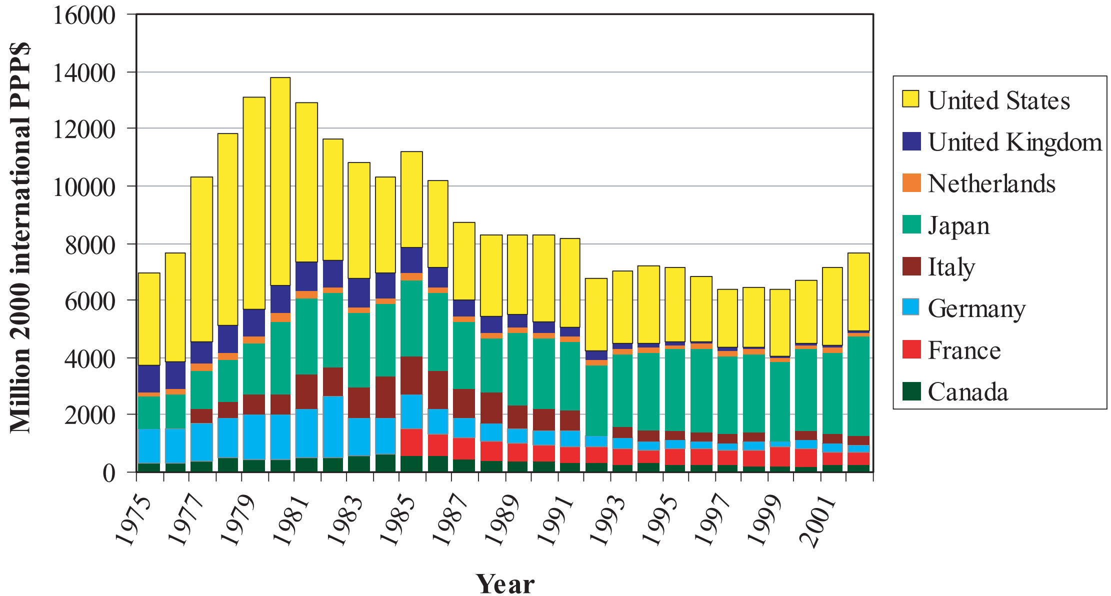

Figure 2 Trends in energy research, development, and demonstration expenditures by major International Energy Agency (IEA) member governments. Data are not available before 1985 for France and also not available for Italy for 1975–1976 and 1993. Abbreviation: PPP$, year-2000 international purchasing-power-parity dollars converted from local currency using data from the World Development Indicators database. Source: IEA Energy Technology R&D online database at http://www.iea.org/Textbase/stats/rd.asp

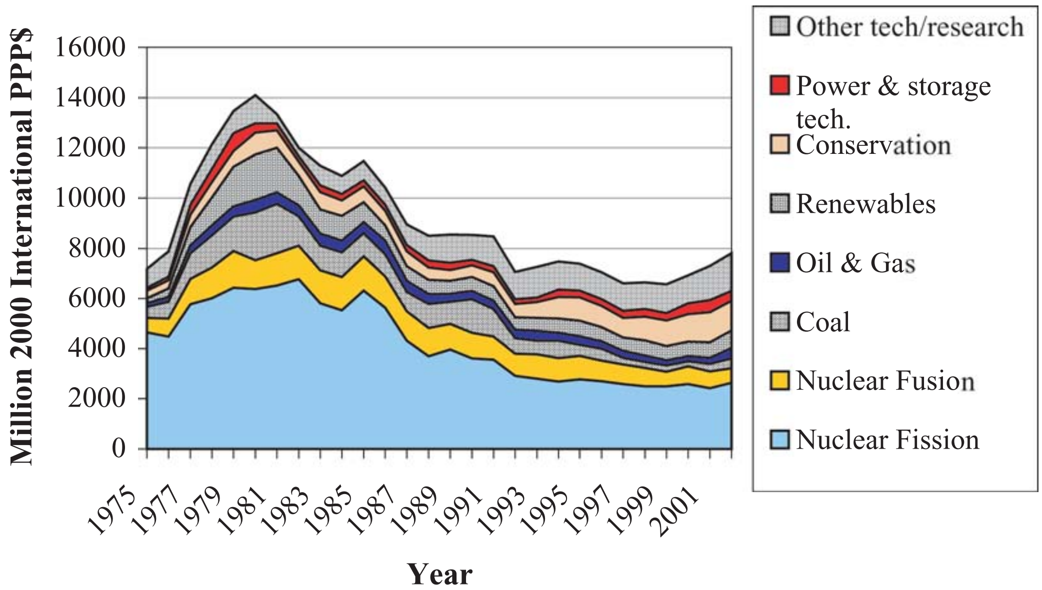

Figure 3 Trends in energy research, development, and demonstration expenditures by major International Energy Agency (IEA) member governments, by category. Abbreviation: PPP$, year-2000 international purchasing-power-parity dollars converted from local currency using data from the World Development Indicators database. Source: IEA Energy Technology R&D online database at http://www.iea.org/Textbase/stats/rd.asp

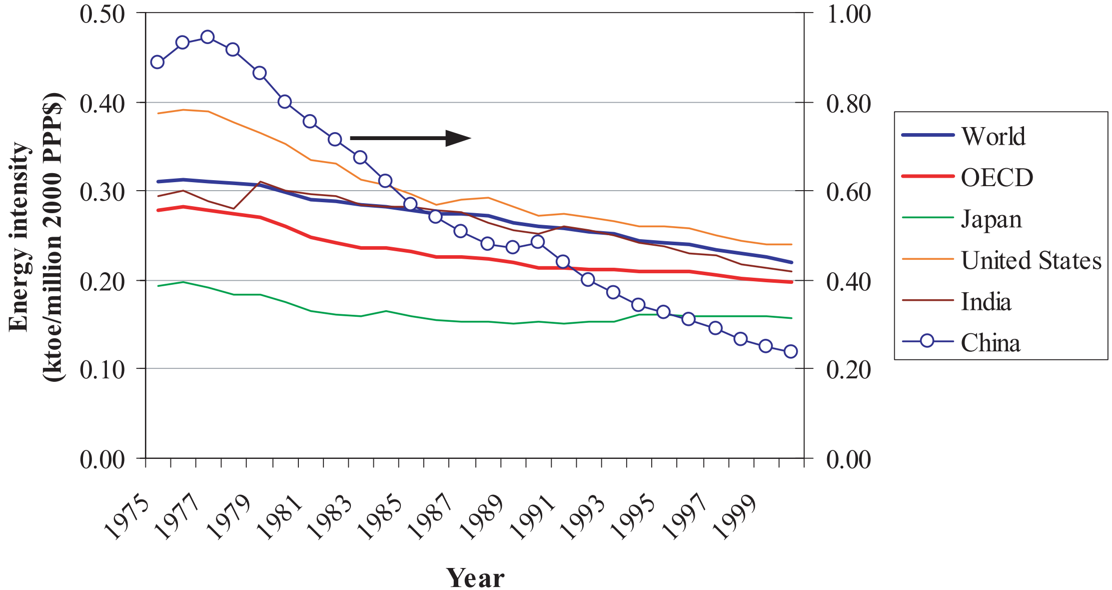

Figure 4 Trends in energy intensity for major countries. Energy values for China are presented on the right ordinate. Abbreviations: ktoe, kilotons of oil equivalent; PPP$, year-2000 international purchasing-power-parity dollars converted from local currency using data from the World Development Indicators database. Source: World Development Indicators online database. http://devdata.worldbank.org/data-query/

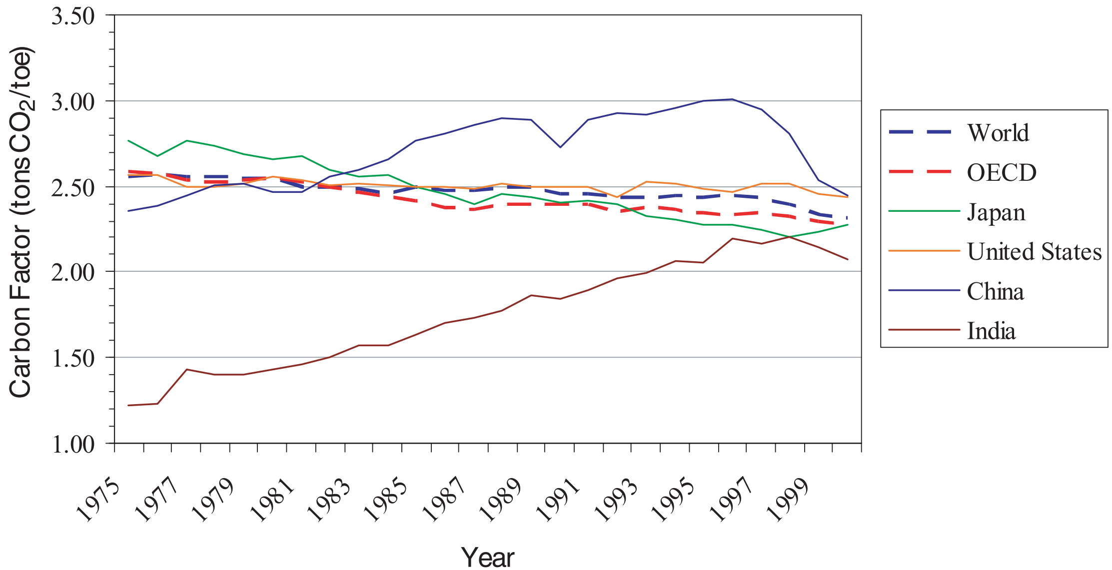

Figure 5 Trends in carbon factor for major countries. Abbreviation: ktoe, kilotons of oil equivalent. Source: World Development Indicators online database. http://devdata.worldbank.org/data-query/

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Contents

Errata

An online log of corrections to *Annual Review of Environment and Resources* chapters (if any, 1997 to the present) may be found at http://environ.annualreviews.org