Underinvestment: The Energy Technology and R&D Policy Challenge

Robert M. Margolis[1]* and Daniel M. Kammen[2]*

This Viewpoint examines data on international trends in energy research and development (R&D) funding, patterns of U.S. energy technology patents and R&D funding, and U.S. R&D intensities across selected sectors. The data present a disturbing picture: (i) Energy technology funding levels have declined significantly during the past two decades throughout the industrial world; (ii) U.S. R&D spending and patents, both overall and in the energy sector, have been highly correlated during the past two decades; and (iii) the R&D intensity of the U.S. energy sector is extremely low. It is argued that recent cutbacks in energy R&D are likely to reduce the capacity of the energy sector to innovate. The trends are particularly troubling given the need for increased international capacity to respond to emerging risks such as global climate change.

The recent wave of interest in R&D policy in general (*1*) and energy R&D in particular (*2*) comes at an important time, particularly with respect to the development of renewable and low-carbon fossil-fuel energy technologies that are likely to be critical in meeting future energy supply and environmental needs (*3*). In highly industrialized countries, however, government energy technology R&D budgets have been declining significantly in real terms since the early 1980s (*4*). Although the end of the Cold War and low fossil-fuel prices have decreased the level of public attention focused on energy planning, the domestic and global political challenges, and the investments needed to develop clean energy technologies, are now more dramatic and pressing than ever (*5*).

We argue that inputs (R&D funding and research infrastructure) and outputs (innovations in new energy technologies) are closely linked, and that the energy sector dangerously underinvests relative to other technology-intensive sectors of the economy. Declining investments in energy R&D in industrial nations will also adversely impact developing nations that often have limited capacity for energy R&D and rely instead on importing, adapting, or collaborative policies to install new energy systems. This situation is particularly troubling given the need for increased international capacity to respond to emerging risks such as the threats to human and environmental health and global climate change.

[1]Science, Technology and Environmental Policy (STEP) Program, Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544–1013, USA. [2]Energy and Resources Group (ERG), University of California, Berkeley, CA 94720–3050, USA.

*To whom correspondence should be addressed. E-mail: margolis@princeton.edu; dkammen@socrates.berkeley.edu

Trends in International Energy R&D

A recent survey of energy R&D in the 22 member countries of the International Energy Agency (IEA) documents the dramatic declines in the scale and diversity of energy R&D (*4*). In 1995, 98% of all IEA member country energy R&D was carried out by only 10 countries. A comparison of the federal energy R&D budgets for these 10 countries, in 1980 and 1995 (Fig. 1), reveals that the declines were particularly sharp in Germany, the United Kingdom, and the United States, while only Japan and Switzerland showed increases. The changes represent an overall decline of 39% in energy R&D funding. Investments in energy R&D have been falling across the board: Between 1980 and 1995, nuclear funding fell 40%, fossil-fuel funding declined 58%, and funding for renewable energy fell 56%.

In this environment of reduced attention to the broad needs of energy security, diversity, and sustainability, national energy policies have been chaotic. Japan, Spain, and Switzerland increased their budgets for energy conservation R&D by 100% or more between 1980 and 1995, while France, Germany, and the United Kingdom cut back their investments by more than 80%. The variation among countries with respect to nuclear energy R&D was similarly diverse: the United States, Germany, Italy, and the United Kingdom cut back their nuclear R&D budgets by at least 70%, while Japan and France increased their nuclear R&D budgets by 20% and 7%, respectively. Overall, some countries have eliminated broad classes of energy technology R&D from their research portfolios, shifting their priorities toward a favored technology, while other countries have cut back energy technology R&D across the board.

The cutbacks in energy R&D funding among IEA member countries should sound an alarm: The wholesale dismantling of large portions of the industrial world's energy R&D infrastructure could seriously impair our ability to envision and develop new technologies to meet emerging challenges.

R&D Investments and Energy Innovation

An environment of reduced or volatile budgets for energy R&D and implementation demands careful evaluation and allocation of financial, material, and human resources. Although the aggregate returns on investments in R&D across sectors have been studied (*6*), little work

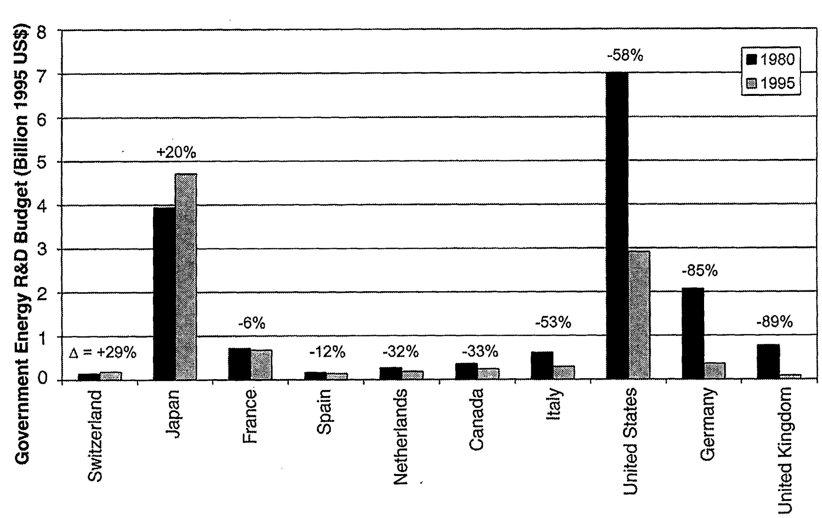

Fig. 1. Government energy R&D budgets for selected IEA countries showing the difference in spending (Δ) between 1980 and 1995 (*4*). Data for France before 1990 are unavailable, and while we display 1990 and 1995 data for France, this comparison likely understates the decline in R&D funding in France.

has been done on the energy sector. Investments in particular technologies are inherently risky, and past efforts to "pick winners" among energy options have produced a number of high-profile failures (*7*). It is therefore critical to develop a variety of useful metrics that can be used to guide energy policy. We consider two measures: patents and the pattern of private-sector investment.

Between 1976 and 1996, the total U.S. investment in R&D increased from roughly $100 to $200 billion [values in constant 1996 dollars (*8*)], and the number of U.S. patents issued increased from roughly 70,000 to 110,000 (Fig. 2A). Thus, between 1976 and 1996, both R&D investments and the number of patents issued in the United States roughly doubled (*9*). The proportional increase of patents with R&D investments during this period provides empirical support for the hypothesis that there is a significant link between R&D investments and innovation.

The total number of U.S. energy-related patents and the total of both public and private U.S. investments in energy R&D between 1976 and 1996 are shown in Fig. 2B. Again we find that R&D investments and patents are highly correlated (*10*), but here the trend reveals a dramatic boom-bust cycle between 1976 and 1996: U.S. energy R&D investment rose from $7.6 billion in 1976 to a high of $11.9 billion in 1979, and then decreased through the 1980s and early 1990s to a low of $4.3 billion in 1996. Similarly, the number of patents related to energy technology rose from 102 patents in 1976 to a high of 228 in 1981, and then declined to a low of 54 in 1994. The cutbacks in energy-related R&D had a significant impact on innovation in the energy sector.

The divergence between the overall trends (Fig. 2A) and energy sector trend (Fig. 2B) between 1976 and 1996 is striking. Yet despite the diverging trends both figures convey a similar message: For the U.S. economy as a whole and for the energy sector specifically, R&D investments and patents were highly correlated between 1976 and 1996. This supports the hypothesis that investments and innovation are closely linked, and the view that patents may be a useful barometer of R&D activity (*11*).

A second measure of commitment to developing new energy technologies is R&D intensity (defined as R&D as a percentage of net sales). Examining R&D intensity across sectors reinforces our concern about the level of investment in energy technology R&D. As illustrated in Fig. 3, the energy sector's R&D intensity is extremely low in comparison to many other sectors. In fact, the "high-technology" drugs and medicine, professional and scientific equipment, and communications equipment sectors exhibit R&D intensities that are more than an order of magnitude above the 0.5% of sales devoted to R&D in the energy sector. The energy sector also compares unfavorably to other established high-volume activities such as the industrial chemicals sector.

R&D intensities are expected to vary across sectors, and the low investment levels in energy are in part related to the uncertainty caused by deregulation. However, the differences between sectors, as illustrated in Fig. 3, are so striking that they force us to confront a critical question: In terms of encouraging technological change, is the energy sector being viewed more as a low-technology sector or as a high-technology economic driver? Technology and technology policy play a pivotal role in finding, transforming, and utilizing energy resources, particularly in an environmentally sound manner. The challenges and expense of energy R&D, and the

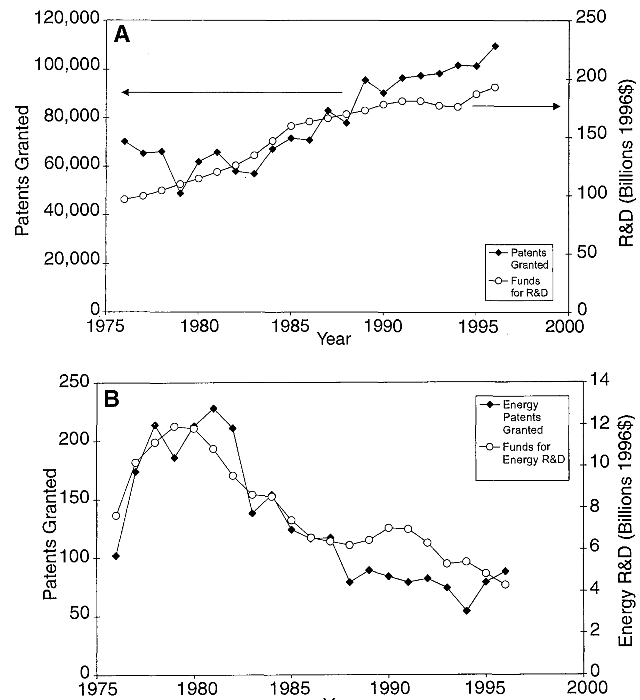

Fig. 2. Total and energy-specific patents and R&D investments between 1976 and 1996 in the United States. (**A**) Total U.S. patents include all patents granted in a given year (*14*). Total U.S. investments in R&D include both public and private R&D (*15*). (**B**) Data on energy technology patents were generated from keyword searches on patent titles in (*14*). The keywords (in italics) included in the searches were as follows (asterisk denotes any string of characters): (*oil* or *natural gas* or *coal* or *photovoltaic* or *hydroelectric* or *hydropower* or *nuclear* or *geothermal* or *solar* or *wind*) and (*electric** or *energy* or *power* or *generat** or *turbine*). Total U.S. energy R&D includes both public and private R&D investments related to energy. It was defined as the sum of the following: DOE energy technology R&D (*16*), nonfederal industrial energy R&D (*17*), and R&D funded through the Electric Power Research Institute (*18*), which is not captured in (*17*).

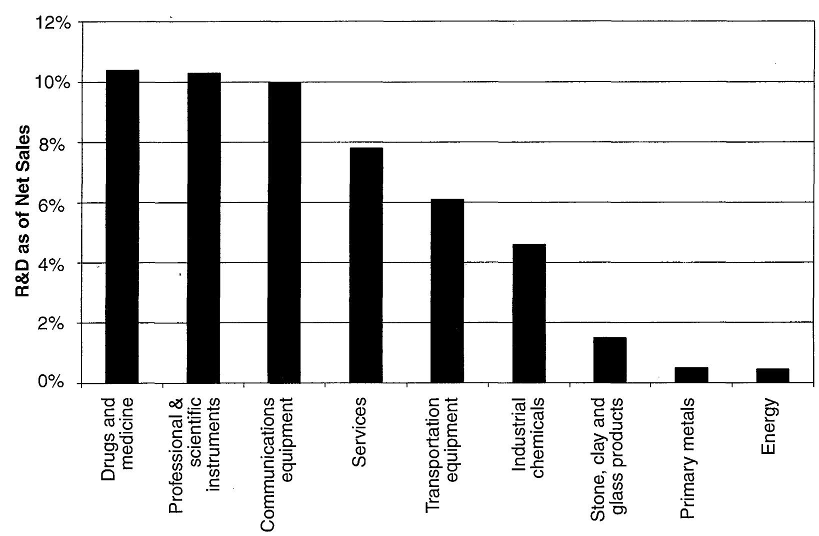

Fig. 3. R&D as a percentage of net sales for selected sectors in the United States in 1995 (*12*). Data for each industrial category, except energy, were drawn directly from (*17*). The data shown include both public and private funding for R&D. Energy R&D as a percentage of net sales was calculated from total (public and private) industrial energy R&D (*17*) and total energy expenditures in the United States (*19*). The energy R&D data in (*17*) are gathered across industrial sectors, that is, they are for industry as a whole. Services include business, health, engineering, and other services. The most recent year that data are available for Communications Equipment is 1990, and for Industrial Chemicals, 1992.

slow turnover time for current power generation infrastructure, mean that the energy sector's extremely low R&D intensity is a cause for concern not only today, but also for decades to come (*12*).

Responding to Energy and Environmental Needs

The energy technology and policy options of industrial and developing nations are closely linked together in a global energy economy. During the past 50 years the progression to cleaner fuels and more efficient use of fossil fuels has resulted in an annual decrease in the emission of carbon to the atmosphere of about 0.08 g of carbon per megajoule of energy produced (*13*). This rate of "decarbonization" is not sufficient even to meet the modest Kyoto Protocol target of a 5% decrease in greenhouse gas (GHG) emissions from industrial nations by 2010. Many scientists have instead argued that emissions reductions of 70% or more are necessary to stabilize the atmospheric GHG concentrations at 550 or 450 parts per million (*5*). Achieving these levels would require a doubling or tripling, respectively, of the current rate of decarbonization. Without a sustained and diverse program of energy R&D and implementation, we are crippling our ability to make the necessary improvements in the global energy economy.

Declining investments in an area at the heart of the environment-economy nexus is detrimental for both long-term U.S. energy security and for global environmental sustainability. First, it is necessary to understand and evaluate the impacts of current energy R&D efforts. Second, meeting the emerging global challenges will require increasing both U.S. and international energy R&D. Finally, a broader collaborative environment is needed to support diverse energy research and implementation options and policies that work within and between highly industrialized and developing nations.

References and Notes

1. See, for example, "Unlocking Our Future: Toward a New National Science Policy" (House Committee on Science, U.S. House of Representatives, 1998); D. E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Brookings Institution, Washington, DC, 1997); "Allocating Funds for Science and Technology" (Committee on Criteria for Federal Support of Research and Development, National Research Council, Washington, DC, 1995); R. M. May, *Science* **275**, 793 (1997); *ibid.* **281**, 49 (1998).
2. See for example, J. J. Dooley, *Energy Policy* **26**, 547 (1998); "Federal Research: Changes in Electricity-Related R&D Funding," *GAO/RCED-96-203* (U.S. General Accounting Office, Washington, DC, 1996); "Federal Energy Research and Development for the Challenges of the Twenty-First Century" (Energy Research and Development Panel, President's Committee of Advisors on Science and Technology, 1997); M. G. Morgan and S. F. Tierney, *Issues Sci. Technol.* **15**, 81 (1998).
3. See, for example, A. K. N. Reddy, R. H. Williams, T. B. Johansson, Eds., *Energy After Rio: Prospects and Challenges* (United Nations Development Program, New York, 1997); E. A. Parson and D. W. Keith, *Science* **282**, 1053 (1998); R. T. Watson, M. C. Zinyowera, R. Moss, D. J. Dokken, Eds., *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses* (Cambridge Univ. Press, Cambridge, UK, 1996).
4. "IEA Energy Technology R&D Statistics, 1974–1995" (International Energy Agency, Organisation for Economic Cooperation and Development, Paris, 1997).
5. This point is illustrated in discussions of the central role played by energy technology in responding to climate change; see M. I. Hoffert *et al.*, *Nature* **395**, 881 (1998); A. P. Kinzig and D. M. Kammen, *Global Environ. Change* **8**, 183 (1998).
6. See Z. Griliches, *Science* **237**, 31 (1987); R. E. Evenson, P. E. Waggoner, V. W. Ruttan, *ibid.* **205**, 1101 (1979); E. Mansfield, *ibid.* **175**, 477 (1972). For reviews of the economic literature see N. L. Stokey, *Rev. Econ. Stud.* **62**, 469 (1995); M. I. Nadiri, "Innovations and Technological Spillovers," *NBER Working Paper 4423* (National Bureau of Economic Research, Cambridge, MA, 1993).
7. L. R. Cohen and R. G. Noll, *The Technology Pork Barrel* (Brookings Institution, Washington, DC, 1991).
8. Dollar values (unless otherwise noted) have been converted from current to constant 1996 dollars by using the gross domestic product chain-type price index (available at www.bea.doc.gov/bea/dn/0898nip3/table3.htm).
9. A linear regression with R&D as the independent variable and patents as the dependent variable yields an R^2 of 0.72 and a t statistic of 7.0 (significant at the 1% level).
10. A linear regression with energy R&D as the independent variable and energy-related patents as the dependent variable yields an R^2 of 0.84 and a t statistic of 10.0 (significant at the 1% level).
11. The investment-patent record for fossil-fuel, renewable, and nuclear energy has been studied separately (R. M. Margolis and D. M. Kammen, *Energy Policy*, in press).
12. Energy products are generally sold at very small margins (fractions of a cent per kilowatt-hour) so that alternate measures, such as the price/earnings ratio for energy companies, also warrant study.
13. N. Nakicenovic *et al.*, *Energy* **18**, 401 (1993).
14. The U.S. Patent and Trademark Office's "Patent Bibliographic Database" is available at www.uspto.gov/web/offices/ac/ido/oeip/patbib/index.html.
15. "National Patterns of Research and Development Resources" (National Science Foundation, Washington, DC, published annually). The most recent volume of this NSF publication (and many others) is available at www.nsf.gov/sbe/srs/pubdata.htm.
16. See "Federal R&D Funding by Budget Function" (National Science Foundation, Washington, DC, published annually), Table 12. We define U.S. Department of Energy (DOE) Energy Technology R&D as the sum of expenditures for fossil-fuel energy, nuclear energy, magnetic fusion, solar and renewable energy, and energy conservation.
17. Data on R&D are included in "Research and Development in Industry" (National Science Foundation, Washington, DC, published annually).
18. "Annual Report" (Electric Power Research Institute, Palo Alto, CA, published annually).
19. "State Energy Price and Expenditure Report 1995" (Energy Information Administration, U.S. Department of Energy, Washington, DC, 1997).

20. We thank S. DeCanio, S. Devotta, J. Holdren, H. Dowlatabadi, R. May, A. Rosenfeld, and V. Ruttan for comments and advice. Supported by the Summit Foundation and the Class of 1934 Preceptorship at Princeton University, both awarded to D.M.K.

REVIEW

Photovoltaic Technology: The Case for Thin-Film Solar Cells

A. Shah,[1] P. Torres,[1*] R. Tscharner,[1] N. Wyrsch,[1] H. Keppner[2]

The advantages and limitations of photovoltaic solar modules for energy generation are reviewed with their operation principles and physical efficiency limits. Although the main materials currently used or investigated and the associated fabrication technologies are individually described, emphasis is on silicon-based solar cells. Wafer-based crystalline silicon solar modules dominate in terms of production, but amorphous silicon solar cells have the potential to undercut costs owing, for example, to the roll-to-roll production possibilities for modules. Recent developments suggest that thin-film crystalline silicon (especially microcrystalline silicon) is becoming a prime candidate for future photovoltaics.

The photovoltaic (PV) effect was discovered in 1839 by Edmond Becquerel. For a long time it remained a scientific phenomenon with few device applications. After the introduction of silicon as the prime semiconductor material in the late 1950s, silicon PV diodes became available. They were soon indispensable for supplying electrical power to telecommunications equipment in remote locations and to satellites. Then, in the 1970s, a major reorientation took place in the general perception of the energy supply problem: The oil crisis of 1973 led to a general public awareness of the limitation of fossil fuels; many governments (including those of the United States, Japan, and several European

[1]Institute of Microtechnology (IMT), University of Neuchâtel, Rue A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland. [2]University of Applied Science, Avenue de l'Hôtel-de-Ville 7, CH-2400 Le Locle, Switzerland.

*To whom correspondence should be addressed. E-mail: peter.torres@imt.unine.ch