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Energy Innovation From the Bottom Up

PROJECT BACKGROUND PAPER

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Energy Innovation Systems From The Bottom Up: Technology Policies For Confronting Climate Change

Background Paper | by John Alic

Technological innovation is essential for reducing greenhouse gas (GHG) release, especially the carbon dioxide (CO_2) produced in burning fossil fuels, the most important of these gases. Each of the project's three workshops will address a family of technologies with potential for reducing atmospheric CO_2: photovoltaics (PVs); post-combustion capture of CO_2; and air capture. PV systems convert sunlight to electricity directly; leaving aside manufacture and installation, no fuel is burned and no CO_2 released. Post-combustion carbon capture (PCC) would remove CO_2 (for storage) from the flue gas of power plants that burn coal or other hydrocarbons to produce electricity. Air capture would remove CO_2 directly from the atmosphere to reduce its concentration.

Background papers prepared for each workshop survey these technologies, or technological families—three from a larger set. They differ in fundamental ways, which suggests that policies for fostering innovation will need to differ too. The first section in this paper, intended as background for the project as a whole, outlines industry and market characteristics, along with government institutions, likely to matter for policy. The second section discusses innovation itself, more abstractly, as a process of knowledge generation and application. The section following turns to technology and innovation policies, classifying them into three broad and 16 detailed categories. Each workshop will explore the ways in which a portfolio of innovation policies might be tailored to that technology, or family of technologies (PV cells and systems, for example, come in many varieties). The intent is to construct a rough set of roadmaps matching needs and opportunities with policy choices and institutional settings.

1. Three Technologies, Three Settings for Innovation

While public policies influence innovation in many ways, new technologies emerge chiefly from the private sector. There are exceptions. Federal laboratories have innovated in weapons and scientific instruments. In the 1950s, the Atomic Energy Commission (AEC) established the template for nuclear power in the form of reactors designed originally for the Navy's submarines. New medical procedures sometimes emerge from intramural research at the National Institutes of Health (NIH). More commonly, agencies and subagencies foster innovation less directly, paying some of the bills for research, purchasing goods that incorporate new technology (e.g., jet fighters, fly-by-wire avionics), and setting rules for economic competition (antitrust, intellectual property rights). At commercialization—a key event in almost any episode of innovation, marked by the first purchases of goods or services embodying whatever is novel—government is more likely to be a buyer than the seller; PV cells, for example, were commercialized in the late 1950s to supply electrical power aboard the Vanguard I satellite.

Prescription drugs illustrate some of the ways in which government policies and the structure of industries and markets affect paths of technology development, commercialization, and diffusion. Since about 1980, pharmaceutical and biotechnology firms have often collaborated, typically through alliances or partnerships (e.g., joint ventures) that link small companies, sometimes startups, with expertise in biotechnology and much larger pharmaceutical manufacturers. The latter have access to capital for investment, extensive marketing networks, and experience in managing clinical trials and securing approvals from the Food and Drug Administration (FDA)—all lacking in most biotechnology firms. Government is involved not only through the FDA but NIH, which now distributes about $30 billion annually for research, mostly to universities (and medical schools).

Since the 1950s, NIH research has expanded at rates unmatched elsewhere in government. Congress appropriated $317 million to NIH for research (basic plus applied) in 1960 and $861 million to the Department of Defense (DoD). In the early 1970s, NIH moved ahead of DoD, and today it has five times more money for research. This is not an artifact of the end of the Cold War—DoD's total budget is at an all-time high—but the result of the political appeal of research into the causes and cures of dread diseases. The government's health care spending has at the same time fueled demand for drugs (and other medical treatments). The federal and state governments pay nearly two-thirds (including tax expenditures) of a national health care bill now nearly $2.5 trillion. Without NIH research, biotechnology and pharmaceutical firms would begin the search for new drugs with a much-diminished knowledge base. Without government spending on health care, the market for high-priced new drugs would be much diminished and pharmaceutical and biotechnology firms would have less incentive to spend their own money on drug development.

Both the "high politics" of health care reform and the "low politics" of FDA approvals (plus much in between, such as the activities of disease lobbies) will influence continuing innovation in pharmaceuticals. Innovations in PVs, PCC, and air capture will likewise respond to the energy policy of the Obama administration, post-Kyoto international negotiations, and bureaucratic politics in the Department of Energy (DOE) and its laboratories, and likely DoD as well. The influences will be felt differently in the several industries from which innovations emerge. PV manufacturers compete in a relatively transparent global market. Homeowners and firms in the power generation industry alike can compare prices and assume that products will live up to claims, or come close, because PV manufacturers otherwise risk future business. At the same time, the major national markets in which PV systems are sold, including those of Germany, Spain, Japan, and the United States, the four largest (ordered by 2007 sales), are heavily conditioned by government policies. Like so many energy markets, they are best viewed as artificial constructs. Tax credits, feed-in tariffs (guaranteed high prices for PV-generated electricity), and other subsides offset costs that remain relatively high, despite several decades of technological advance, turning unattractive investments into profitable opportunities (e.g., for German farmers who cover barnyard roofs with PV panels). In somewhat similar fashion, an array of U.S. government subsidies created an artificial market for nuclear power, one that peaked in 1966 and 1967, when utilities ordered more than 60 nuclear plants (few of which in the end operated profitably, subsidies notwithstanding).[1]

For PV technology, politics and policy have influenced the pace of market growth more than directions of technical advance, much as for microelectronics. By contrast, politics and policy seem likely to have a determining influence over the technological evolution of PCC and air capture. Few if any firms will invest large sums, in the way that thin-film PV manufacturers or semiconductor firms have, betting that their choices of technology will earn them future profits. Indeed, there will never be a "market" for PCC or air capture similar to those for PV systems or integrated circuits.

Utilities will be the sole customers for PCC, and then only if compelled by government (or made financial offers they cannot refuse). While some experience exists with small-scale installations in other industries (e.g., for capturing CO_2 to carbonate beverages), technological choices remain clouded and likely first costs and operating costs for both new plants and retrofits to existing plants are unknown (policymakers could decide the costs of technically feasible retrofits are unacceptable, as utilities will probably claim). Demonstration projects can reduce but not eliminate uncertainties; even after PCC systems are up and running, cost figures will depend on accounting assumptions and are likely to be disputed. There will be no published prices and probably no fully standardized designs. Utilities will negotiate contracts with suppliers, including suppliers of technical services, to design, develop, and install PCC equipment for individual power plants, as they did when installing scrubbers beginning in the late 1970s to remove sulfur dioxide from flue gases, as required under the Clean Air Act. Both utilities and their suppliers will probably have incentives to exaggerate costs, utilities to justify rate increases and suppliers to increase their own profitability. Meanwhile, technical asymmetries will make it difficult for utilities to know if they are making poor choices, as for nuclear power in the 1960s.

Utilities negotiate contracts with suppliers from positions of technical weakness compared to firms in other industries. Aerospace companies, for example, can assign capable and experienced scientists and engineers to evaluate available PV technologies when designing satellites for telecommunications firms or intelligence agencies. Chemical manufacturers seek competitive advantage through proprietary processes; they too employ large staffs of technical specialists. The engineering departments of utilities, by contrast, rarely engage in R&D. Instead, t hey are occupied mostly in operations and maintenance (O&M) work on existing power plants. Electricity is a commodity and utilities typically follow business strategies that seek profits through approvals for higher rates and reductions in O&M costs.

Air capture awaits proof-of-principle as a practical technology. A few startups have spent a few million dollars. Far

[1] In 1967, the capacity of reactors on order exceeded the capacity of those that had been completed by 25-30 times. In the absence of construction and operating experience, costs were grossly underestimated. See, e.g., Irvin C. Bupp and Jean-Claude Derian, *Light Water: How the Nuclear Dream Dissolved* (New York: Basic, 1978), pp. 70ff, who write "what was missing … was independent analysis of actual cost experience" (p. 76). Once large numbers of new plants came online, the best performed well while the worst were truly abysmal. Capital costs (per kilowatt) differed by three times or more, and construction times by almost as much. Capacity factor (or availability)—the ratio of power actually produced to that theoretically available in continuous full-load operation—a common measure of reliability, ranged from less than 35 percent to nearly 80 percent (comparable to the best fossil-fueled plants of the time). See *Nuclear Power in an Age of Uncertainty* (Washington, DC: Office of Technology Assessment, February 1984), which emphasizes the wide range in outcomes.

too many uncertainties remain for future prospects to be judged with any confidence. Should air capture seem viable, contractors will probably conduct much of the development, demonstration, and deployment for DOE or another agency. Decades of experience in defense with technologically complex equipment and systems, along with past DOE programs, point to some of the pitfalls. DoD employs tens of thousands of engineers and scientists, both military officers and civilians, some at world-class facilities such as the Naval Research Laboratory. Pentagon managers can also seek technical advice from federally-funded research and development centers including Mitre and RAND, and advisory bodies such as the Defense Science Board. Even so, technology-related cost overruns and performance shortfalls are common, and some programs are cancelled after billions of dollars in expenditures (as could yet happen with the Joint Air-to-Surface Standoff Missile, not an especially complicated system).

In contrast with the relative transparency of PV markets, closed-door negotiations and sealed bids for PCC and air capture would make it easier to hide opportunism and self-dealing. Here DoD contracting is not necessarily the extreme case, accusations of misconduct in Iraq notwithstanding. With large expenditures of taxpayer dollars at stake, watchdogs of all kinds—congressional committees and the Government Accountability Office, investigative journalists and nongovernmental organizations—scrutinize DoD programs for "waste, fraud, and abuse." This certainly exists: in 2004, a former Principal Deputy Assistant Secretary of the Air Force admitted to steering contracts to Boeing, which then hired her. Yet the surprise here lay not so much in the existence of bid-rigging but in the conspirators' belief that they could escape detection: their eventual exposure reinforced deterrence, which, given so many people on the alert for corruption, is probably stronger when a federal agency is one party to a contract than for business-to-business transactions. As Siemens' recent admissions of bribery show, malfeasance has not disappeared from the electrical equipment industry.[2]

None of this will surprise. The point is simply that in the absence of market competition, firms may be tempted to seek profits through collusion rather than technological innovation. And when innovations do result, the costs may be high. Because not only technologies but also markets and market participants differ, innovation pathways for PV systems, PCC, and air capture will differ.

2. Innovation as a Process: Not Just R&D

Innovation is sometimes pictured, mistakenly, as governed by logic: as if firms began with R&D and proceeded in more-or-less orderly fashion to commercialization, guided by managers who keep one eye on technological advance and the other on market opportunities. Such images are misleading. Innovation is a process of learning, highly uncertain, mixing trial-and-error with trial-and-success. As venture capitalists understand, the majority of attempted innovations fail: investors expect the occasional successes to more than compensate for losses elsewhere in their portfolios. As managers in the pharmaceutical industry know, most potentially attractive drug molecules drop out of consideration long before clinical trials. Indeed, pharmaceutical firms generate new molecular structures in huge numbers for quick, mass-production screening tests even when making use of "rational" drug design methods. And quite fundamental research too, while often portrayed in hindsight—i.e., in the archival literature of science—as guided by logic, is not so seemingly rational in practice. It might be better described as insightful improvisation. Much the same is true of design and development, the core activity of technical practice in industry and hence the source of much technological innovation.[3]

Design and development differs from research in being a matter of synthesis—envisioning and creating something new—rather than analysis in search of understanding. A fluid, open-ended activity often conducted in the absence of well-accepted evaluative criteria (unlike science where the test is simple: conformance with observed natural phenomena), design and development is fundamentally a matter of technological choice. The final configuration of the product or system results from iterative decisions among large numbers of alternatives, with hundreds, thousands, perhaps millions of choices made over years or perhaps decades in accordance with debatable criteria, only in part technical. Some decisions have far reaching implications: a power plant's baseline operating conditions (temperatures, pressures) and energy source (nuclear, solar concentrator, pulverized or gasified coal). Others concern details: welding processes for joining piping and procedures for inspecting those welds.

Technical analysis, with testing the most costly and time-consuming activity in the overall process, relies on mathematical models and methods for predicting performance. The methods themselves come from R&D, viewed as a knowledge-

[2] At the end of 2008, the German-based firm "pleaded guilty to charges of bribery and corruption and agreed to pay fines of $800m in America and €395m ($540m) in Germany, on top of an earlier €201m." "Bavarian Baksheesh," *Economist*, December 20, 2008, p. 112. Much earlier, in the 1960s, General Electric, Westinghouse, and more than two dozen other suppliers were convicted in U.S. courts of fixing prices for equipment sold to over 60 electrical utilities.

[3] Alfred Marshall recognized as much many years ago, writing "when a business man … is trying experiments, at his own risk, to see whether some new method, or combination of old methods, will be more efficient …. [h]e works generally by trained instinct rather than formal calculation …." *Principles of Economics*, Eighth edition (London: Macmillan, 1930), p. 406.

Table 1. Innovation System Components and Examples. [a]

ORGANIZATIONS (FORMAL)	INFRASTRUCTURE AND KNOWLEDGE BASE (NONPROPRIETARY)	INSTITUTIONS (FORMAL AND INFORMAL)
private, profit-seeking firms (and alliances among them)	computer, telecommunications networks	law and policy
nonprofits (government agencies and laboratories; universities and other not-for-profit laboratories; professional associations)	open digital software, computational models, and databases	disciplinary communities, scientific and technical; informal interorganizational networks
	openly available data, information, knowledge, and methods (books, scientific and technical journals, reference literature, databases) [b]	rules and norms for validating, accepting, and circulating technical knowledge and information

[a] In a study restricted to, say, computing, organizational forms beyond those listed might be relevant, such as user groups. Some observers, moreover, might for some purposes define an innovation system strictly in terms of institutions, omitting the other two categories entirely. This table has been constructed to fit the particular problem of policymaking for climate and energy, for which careful assessment of technologies themselves will sometimes be critical, and also to fit the United States, where much or most innovation comes from private firms, with government and universities in essential, but supporting, roles.

[b] Knowledge has more extensive built-in explanatory structure than information, and information more structure than data. Given enough *data* on the physical-chemical characteristics of CO_2 over a range of temperatures and pressures, for example, *information* can be organized and presented in tabular form. A phase diagram could then be constructed—a standard form of *knowledge* in physics and chemistry—depicting the conditions of temperature and pressure for which CO_2 exists in equilibrium as solid, liquid, or gas; the table structures the "raw" data and the phase diagram structures the tabular information to link the original observations with accepted chemical-physical theory.

generating activity. Design and development, by contrast, is a matter of knowledge application. In conventional usage, "R&D" includes both knowledge generation and knowledge utilization.[4] These are perhaps better considered as separate activities, on the basis that knowledge generation supports innovation but does not constitute innovation.

Design and development practitioners do not begin to use new tools, such as predictive methods based on mathematical models, until their accuracy has come to be accepted, which often depends on both testing and field service experience. Methodologies for predicting costs and performance of PCC equipment, for example, will probably be developed in parallel with testing of prototypes scaled up in stages, with test results used to validate and calibrate computational models. Systems perspectives help capture the multiplicity of technical activities that go into these processes, which is particularly important for climate change because this is an issue of global scale with time horizons of decades to centuries. Thousands of technological advances and millions of technological choices will be needed. Many policies and many government agencies will be involved, in many countries. Innovations will come from many tens of thousands of firms, employing hundreds of thousands of people. No single invention or discovery, no matter how dramatic, is likely to provide more than one small piece of the puzzle. For many reasons, then, not least of which is the uncertainty endemic to innovation, the proper way to think about GHGs and climate change is in terms of technological systems, energy systems, the climate system itself, policy systems, social systems, and the world system of inter-related economies and nation-states. These are all analytical constructs, of little use until made more concrete.

An "innovation system," for purposes of this project, is a particular type of social system, one in which technological innovations—new applications of technical knowledge—take shape and diffuse.[5] (Except for their role in the adoption of technological innovations, social innovations will be left out of account.) Table 1 summarizes the chief ingredients: organizations; infrastructure and knowledge base; and institutions.

The fundamental divide among organizations is that between profit-seeking firms and other formal organizations (i.e., also having well-defined boundaries, paid employees, internal management hierarchies). On one side of the divide, employee incentives, especially for managers, trace ultimately to profitability; on the other side, they do not. This divide has special importance for innovation because motives for creating, sharing, and exploiting scientific and technical knowledge—the chief ingredients of innovation—differ on the two sides.

[4] Energy analysts sometimes add another "D" to R&D, with RD&D standing for research, development, and demonstration, or, alternatively, research, development, and deployment (or diffusion); some go so far as to write RDD&D. These abbreviations collapse essential distinctions among: (1) research, intended to generate new knowledge; (2) preliminary design, through which new technological concepts are generated and explored; (3) development, which includes activities such as quantitative analysis to predict performance and prototype construction and testing; and (4) detailed design, which entails a series of fine-grained decisions, based in part on the findings of developmental analysis and testing, to pin down and specify final attributes. Demonstration is an identifiable stage for some innovations—e.g., when technologies must be scaled up as a prelude to final design. For others, demonstration is effectively subsumed within normal developmental tests and trials, as for a new PV cell. Diffusion, the spread of applications following initial commercialization (i.e., market introduction) typically involves iterative technical improvement and adaptation based in part on information exchange between users and innovating organizations. Cost reduction (or perhaps simply increasing performance/price ratios) often accompanies these improvements. Terms such as deployment and technology transfer are also best avoided; they too easily suggest smooth and predictable processes, as if new products could be force-marched into the economy or a "package" of technology somehow passed from one party to another, rather than the more usual learning, accompanied by stops and starts, twists and turns, trial and error.

Put differently, R&D is an accounting category, defined in somewhat artificial but nonetheless relatively consistent fashion across the economy and reported in corporate financial statements and in surveys such as that conducted by the Census Bureau as a basis for the National Science Foundation's annual estimates of business R&D spending. Most "demonstration" fits the standard definitions of R&D and is included in reported spending totals; "deployment" and "diffusion" do not (indeed they are very different activities) and coupling them with "R&D" is misleading.

[5] See, e.g., Richard R. Nelson, ed., *National Innovation Systems: A Comparative Analysis* (New York: Oxford University Press, 1993); Charles Edquist, ed., *Systems of Innovation: Technologies, Institutions and Organizations* (London: Pinter, 1997); and, for a recent review of the United States, David C. Mowery, "*Plus ca change*: Industrial R&D in the 'Third Industrial Revolution,'" *Industrial and Corporate Change*, Vol. 18, No. 1, 2009, pp. 1-50.

Infrastructure and the (nonproprietary) knowledge base, the raw material of innovation, provide common resources and mechanisms for knowledge sharing among individuals and within and among organizations (e.g., in networks linking biotechnology and pharmaceutical firms). Most of the formally codified knowledge of technology and science is nonproprietary and freely available. This part of the knowledge base includes facts and theories, empirical regularities, and mathematical models for predicting the behavior of natural, technical, or social systems (e.g., for calculating the efficiency of a steam power plant). Specialized technical knowledge may be difficult and demanding to apply, calling for extensive education, training, and experience; yet anyone who can locate, understand, and exploit such knowledge is in principle free to do so.

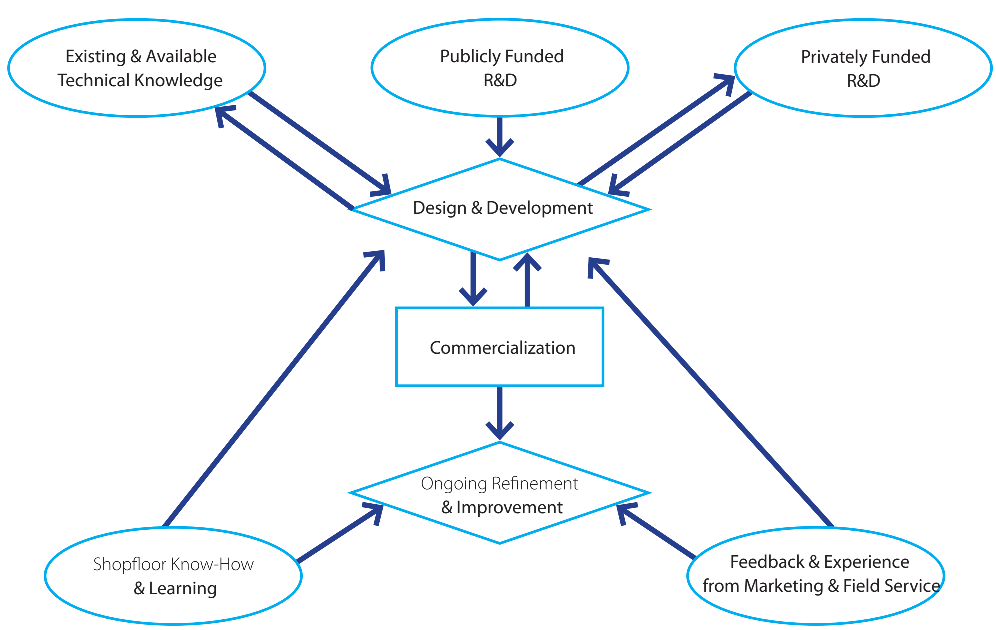
Codified knowledge is not enough. Effective application requires complementary skills, including tacit know-how and unwritten but widely accepted rules-of-thumb, most of this gained through experiential learning rather than formal education. Firms, moreover, complement the publicly available knowledge base with proprietary know-how, developed and held within the organization (perhaps leaking out, but slowly). This knowledge might include the recipe for Popeye's chicken or for growing crystals of PV-grade silicon. When seeking new business, companies that supply power generation equipment (and technical services) count on, and advertise, their reservoirs of experience-based know-how; since the knowledge is intangible, utilities cannot know exactly what they are buying.

Institutions, finally, refer to the norms, rules (including laws), and conventional practices that guide and structure behavior by and among individuals and organizations. Institutions have both formal and informal dimensions; they permeate firms and other organizations, the economy (markets are particular types of institutions), and society. More than two centuries ago, provisions for patenting inventions were written into the U.S. constitution. Today the legislated law of patent protection coexists with case law and the internal policies and routines of the Patent and Trademark Office. Patent law and enforcement aim to balance the social benefits stemming from inventions induced by the prospect of a time-limited grant of monopoly against the harm caused by those monopolies through restriction of competition. As part of that balance, the law requires inventors to disclose technical details. The intent is to encourage others to invent around or supersede the patent. To take a different example, when engineers and scientists exchange information that their employers might consider proprietary, they behave (or misbehave) in ways governed by unwritten norms of trust and reciprocity as well as formal rules such as confidentiality agreements and trade secrecy laws.

Since innovation systems are analytical constructs assembled out of elements such as those in Table 1, they have no necessarily fixed identity. The system of interest might be bounded nationally, supranationally (the European Union), or subnationally (Silicon Valley). It might alternatively be defined on an industry basis: innovation proceeds very differently in the (U.S.) pharmaceutical industry and the (U.S.) automobile industry, and somewhat differently in the U.S. and Japanese automobile industries.

Figure 1 shows major sources and flows of knowledge in innovation. The representation is quite general, to accommodate

Figure 1. Knowledge Flows in Innovation.



variation across technological families while remaining sufficiently concrete to frame the discussion of policies in the next section.

The figure depicts three sources of knowledge flowing into design and development. (Proprietary technical knowledge, such as company-specific technical practices, has been omitted for simplicity.) Of these, the openly-available technical knowledge base discussed in connection with Table 1 is always essential and in some cases may be all that is needed even for radical innovation. Intel, for example, commercialized the microprocessor in 1971 by reducing to practice a well-known but previously unrealized idea: the incorporation of all elements of a computer's central processing unit, or CPU, on a single integrated circuit (IC) chip.[6] For this, Intel engineers and scientists had no need of new research findings. What they did need was the right opportunity, which appeared in the form of a customer willing to purchase such a chip instead of a set of custom ICs, in this case for a desktop calculator.[7]

Radical innovations, then, sometimes emerge through design and development alone (or, put differently, through "R&D" without a research component). In other cases—the laser is one example—new knowledge is essential. As indicated at the top in Figure 1, this may come from publicly-financed R&D or from work internally financed by the innovating organization. Because innovations draw on knowledge from many sources, and because what is known, or thought to be known, may have to be reconsidered, revised, or extended as design and development proceeds, the entire process is heavily infused with learning; because the work often reveals previously unanticipated needs for new knowledge, several sets of arrows in Figure 1 point in both directions.

Radical innovations also emerge through the coalescence of many individually incremental advances, which come together to create something new and different—e.g., the Internet. Starting in the 1960s, the slowly evolving technology of wide-area computer networks drew on the independently evolving technological families of ICs and software, later joined by fiber-optic communications. DoD sponsored the Internet's early ancestors. For more than two decades, the number of computers linked in DoD's network inched upward, passing 10,000 only in 1988. The immediate triggers for the Internet we know came a few years later, with the conceptualization of the World Wide Web by scientists at the European physics laboratory, CERN, and the development of the pioneering browser, Mosaic, by graduate students at the University of Illinois. Much innovation takes place in more-or-less similar fashion: gradual advances eventually come together to yield something that seems, to outsiders and in retrospect, dramatically new and different. Often, a closer look reveals a rather different story.

3. Classifying Technology and Innovation Policies

Every innovation is different, as is every technology and every industry. The fundamental uncertainty of innovation means that government officials cannot be certain in advance which policy tools will be most effective; like decisionmakers in the private sector, they can only support a diversified portfolio. And because industries and technologies differ, and technological innovation emerges chief from private firms that do business in markets with considerable variation in critical features, innovation-enhancing policies may need to differ too.

Most such policies can viewed through their effects on learning—individual, organizational, and social or institutional. Individuals command personal storehouses of knowledge, built from experiential and classroom learning and added to, subtracted from, or otherwise modified over a lifetime (e.g., as information found to be false is discarded). Organizations rely on employees who understand consumer or investor behavior, financing and how to put together a business plan, cost estimating procedures, methods for predicting the service life of steam generating units. They combine and integrate the knowledge of employees, each of whom brings a somewhat distinctive store to the workplace, turning it to ends determined by managers or, in the public sector, government officials. Learning paces diffusion (when household consumers choose an Energy Star refrigerator, when corporate headquarters asks the divisions to conduct or update energy audits, when utilities order new equipment or the U.S. Army re-engines its tanks to reduce consumption of fuel that costs $200 per gallon delivered in the field). The common feature, for innovation, is active utilization of knowledge: technical knowledge does not just sit in databases or libraries; it serves individual, organizational, and societal objectives.

Since technologies and technical knowledge take many forms, any classification of policies must seek a balance between over-simplification and over-complication. For simplicity, Table 2 omits regulatory inducements to innovation. It also omits "nontechnology policies" such as antitrust, which have often had large impacts, as illustrated by the stimulus for entrepreneurial software firms that followed IBM's decision to unbundle software from hardware while under investigation by the Justice Department for monopolizing computer markets.[8]

[6] Federico Faggin, one of the Intel codevelopers, recalled that "The idea of a 'CPU on a chip' had been around since the mid-1960s." Federico Faggin, *BYTE*, March 1992, pp. 145-150; quotation on p. 146.

[7] William Aspray, "The Intel 4004 Microprocessor: What Constituted Invention?" *IEEE Annals of the History of Computing*, Vol. 19, No. 3, 1997, pp. 4-15. Texas Instruments designed a microprocessor about the same time as Intel but did not try to commercialize it.

[8] For this and other examples of policy influences on innovation, see John A. Alic, David C. Mowery, and Edward S. Rubin, *U.S. Technology and Innovation Policies: Lessons for Climate Change* (Arlington, VA: Pew Center on Global Climate Change, November 2003).

Table 2. Technology Policies. [a]

	POLICY	COMMENTS
I. DIRECT GOVERNMENT FUNDING OF KNOWLEDGE GENERATION	1. R&D contracts with private firms (fully funded or cost shared).	Normally support government missions, such as defense.
	2. R&D contracts and grants with nonprofits.	Mostly universities, mostly basic research.
	3. Intramural R&D in government laboratories.	Wide range of activities, depending on agency. Some laboratories much more capable than others.
	4. R&D contracts with consortia or collaborations.	Proprietary interests of participating organizations may limit R&D to generic, pre-competitive work.
II. DIRECT OR INDIRECT SUPPORT FOR COMMERCIALIZATION AND PRODUCTION	5. R&D tax credits.	Unlikely to alter firms' risk/reward assessments. Difficult or impossible to target.
	6. Patents.	The stronger the protection, the weaker the incentives for diffusion through imitation or circumvention.
	7. Tax credits or production subsidies for firms bringing new technologies to market.	Tend to push technologies into the marketplace from supply side.
	8. Tax credits or other subsidies for purchasers/users of new technologies.	Create demand pull, in contrast to technology push (above).
	9. Procurement.	Powerful stimulus when government is a major customer.
	10. Demonstration projects.	Intended to validate technologies viewed by market participants as too risky for investments of own funds.
	11. Monetary prizes.	Administratively simple, once rules have been set.
III. DIFFUSION AND LEARNING	12. Education and training.	Many established channels act slowly (e.g., university degree programs).
	13. Codification and diffusion of technical knowledge (e.g., screening, interpretation, and validation of R&D results, support for databases).	Usually must await acceptance as valid, useful (e.g., information and knowledge generated through demonstration projects).
	14. Technical standards.	Depends on consensus; negotiated compromises among competing interests may lock in inferior technologies.
	15. Technology/industry extension.	Time consuming, costly to reach large numbers of firms, individuals.
	16. Publicity, persuasion, consumer information.	Competing interests may attenuate, perhaps distort, the message.

[a] The classification in this table is restricted to measures with some level of political legitimacy in the United States. It excludes nontechnology policies and regulatory measures, which sometimes act as powerful inducements to innovation.

The policies in Table 2 have been grouped in three broad categories:

I. Direct financing of knowledge creation through R&D;
II. Measures that induce private spending on innovation or foster commercialization and production; and
III. Diffusion-related policies intended to speed applications through information and learning.

The second category, in particular, is somewhat miscellaneous, including policies as different as patent protection and government financing of demonstration projects. Nonetheless, the threefold division highlights the extent to which governments can, if they choose, call on non-R&D policies, in particular the generally undervalued measures that foster individual, organizational, and social learning.

Table 3 summarizes the advantages and disadvantages of each policy in the institutional setting of the United States. Perhaps the most important observation embedded in the comments in Tables 2 and 3 has to do with variations in operating style and effectiveness among the agencies and subagencies of the famously fragmented U.S. government. Agencies with well-defined, well-accepted missions, such as DoD (and the National Science Foundation, which has the mission of supporting relatively fundamental research), have learned, sometimes painfully, how to further those missions while maintaining public and political support. Others, including DOE, have been hobbled by ill-defined or disputed missions. DOE's national security mandate, which traces to legislation establishing the AEC in 1946 that gave civilians the responsibility for building, maintaining, and overseeing nuclear weapons, has never been seriously questioned (except by the armed forces, which for years tried to take full operational control of warheads and managed, step by step, to do so). Other AEC/DOE activities have been controversial, again from the beginning. In the 1950s, for example, opponents of public utilities (which continue to generate about one-quarter of U.S. electricity), fearing or perhaps pretending to fear that the "secret" of the atom bomb might become a pretext for expansion of public power, tried to shape AEC initiatives to their liking. To most of the commissioners and the AEC staff, on the other hand, nuclear electricity was a minor issue or a distraction. They were more concerned to keep elite scientists attached to the AEC weapons laboratories by providing opportunities for non-military research, whether in reactor design or high-energy physics. That is the reason some facilities were designated, after interminable debate, as "national" laboratories. The idea was to confer status so as to be able to compete with research universities for scarce talent.[9] When the successors to the AEC expanded into non-nuclear energy technologies in the 1970s, there was no solid basis for consensus on just what the new mission was to be and how it might be justified. Political conflict combined with unresolved disputes between laboratory managers and Washington to rob DOE of workable ways to set priorities and keep to them.[10]

[9] Richard G. Hewlett and Jack M. Holl, *Atoms for Peace and War, 1953-1961: Eisenhower and the Atomic Energy Commission* (Berkeley: University of California Press, 1989), especially pp. 198-208, 410-429, and 493-514.

[10] Even so, evaluations of DOE R&D yield more positive results than might be expected, as recounted in *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978-2000* (Washington, DC: National Academy Press, 2001). While the National Research Council study committee found much to criticize, the answer to the question posed in their title could be summarized as "sometimes, and probably more often than not." On the other hand, not much money was spent: the DOE energy R&D budget was cut sharply in the early 1980s and remained low during for much of the period.

Table 3. Technology Policies Compared.

	POLICY	STRENGTHS	WEAKNESSES	OTHER COMMENTS
I. DIRECT GOVERNMENT FUNDING OF KNOWLEDGE GENERATION	1. R&D contracts with private firms.	Proven effectiveness in mission agencies, especially defense.	In the absence of a well defined and widely accepted mission, can be hard to defend politically and to manage; may attract pork-barrel spending.	Established mechanisms, ample experience base in mission agencies for selection of technical objectives and evaluation of competing proposals.
	2. R&D contracts and grants with nonprofits.	Many centers of research excellence; strong competition (for funds, faculty, graduate students, etc.).	Applicable experience base smaller for applied R&D than for more basic work.	Well-established agency procedures. often based on external peer review or internal merit review.
	3. Intramural R&D in government laboratories.	High levels of expertise and excellent facilities in some laboratories.	Poorer track records in laboratories that lack strong, stable sense of mission. Quality may suffer in absence of strong competition for project-level funding.	Internal merit reviews for allocating funds internally often questioned, criticized. Not all laboratories deeply integrated into national innovation system.
	4. R&D contracts with consortia or collaborations.	Can reduce duplication of effort and clarify technical objectives through discussion, negotiation.	Precompetitive consortia tend toward lowest-common-denominator R&D. Competing firms may be reluctant to contribute their best people and ideas.	Some duplication in R&D often desirable.
II. DIRECT OR INDIRECT SUPPORT FOR COMMERCIALIZATION AND PRODUCTION	5. R&D tax credits.	Popular, relatively uncontroversial.	Difficult to target toward particular technologies; efforts to do so susceptible to pork barreling. Legislative authorization has been extended more than ten times but never made permanent, adding uncertainty to business planning.	In effect in various forms since 1981, credits are based on increases in R&D spending over previous years. Because firms normally pursue R&D and commercialization for business reasons which tax credits affect little if at all, credits often subsidize work that would be conducted anyway.
	6. Patents.	Powerful incentive for innovation in some industries and technologies.	Adds only modestly to incentives in industries where patents add little to competitive advantage. Recent criticism has argued that "junk" awards have harmed innovation by raising risks of possible infringement.	Most effective in pharmaceutical (including biotechnology), chemical, and basic materials industries, in which product composition or processing can be protected.
	7. Tax credits or production subsidies for firms bringing new technologies to market.	Well-suited, in principle, to targeting of particular technologies.	Subject to attack as corporate welfare and susceptible to political manipulation; the larger the credits or subsidies, the more likely they will go to the best lobbyists rather than the best ideas.	Over the past several decades, at least two dozen programs have subsidized biofuels alone, one reason why U.S. energy policy has so often been derided as incoherent.
	8. Tax credits, other subsidies for purchasers/ users of new technologies.	As above.	As above, though less likely to attract lobbying because benefits are harder to channel to particular firms.	Feed-in tariffs, for example, subsidize electricity generated from renewable sources rather than initial investment.
	9. Government procurement.	A major stimulus, historically, in aerospace and electronics.	In absence of mission-imposed discipline within the responsible agency, political considerations may dominate.	Government often purchases existing items in relatively small quantities relative to market size (e.g., PV installations), limiting impacts.
	10. Demonstration projects.	Can explore applications, resolve uncertainties, where market has yet to develop.	Tainted by past undertakings widely viewed as wasteful and ineffective, such as energy projects in the 1970s and 1980s.	Technical objectives may be compromised by desire to show positive results so as to maintain political support, funding.
	11. Monetary prizes.	May attract entrants who would not otherwise participate in government programs. Publicity may accelerate diffusion, adoption, and adaptation.	Contestants must usually have own access to funding. Over longer term, "losers" may emerge as superior alternative (and the prize may in hindsight be seen to have distorted market incentives).	Limited to innovations that can be envisioned.; rules may be difficult to define for other than simple technical achievement such as direct flight into space (e.g., when manufacturing cost also a criterion). Little experience within U.S. government.
III. DIFFUSION AND LEARNING	12. Education and training.	Powerful, pervasive mechanisms for diffusion of knowledge.	Workforce training policies fragmented and underdeveloped compared with education. Quality, particularly of shorter education/ training courses, highly variable.	Several agencies support graduate study in science and engineering through fellowships and research assistantships. Technicians in fields such as aviation maintenance and electronics sometimes receive initial training in the military.
	13. Codification and diffusion of technical knowledge.	Expert consensus on best practices reduces technical risks and uncertainties.	Institutional (and sectoral) settings tend to be poorly understood.	Many well-established mechanisms (reference documents, consensus best practices, computer-aided engineering methods and databases, technical review articles, etc.) fall outside traditional government purview.
	14. Technical standards.	Potential for deep and lasting impact.	Usually slow. Negotiations among competing private interests may lead to consensus without public-interest representation.	Special interests have powerful incentives to seek control of the process.
	15. Technology/industry extension.	Can directly address knowledge gaps, misunderstandings.	Labor intensity drives up costs.	Long-term acceptance, viability yet to be established in the United States, except in agriculture.
	16. Publicity, persuasion, consumer information.	Possible to reach large numbers of people and organizations at relatively low cost.	Unlikely to alter vested interests or have much effect on cost-based household spending decisions.	Many Americans skeptical, cynical about information from government.

4. Conclusion

A dominant perception currently is that confronting climate change will bring near-term economic penalties, while benefits will follow only after many decades, and then in the form of dangers averted.[11] An alternative view, more optimistic, holds that entrepreneurial innovation in many parts of the world could generate new wealth, feed economic growth, and invert the calculations of at least some of those who now oppose GHG-reducing measures. While such a prospect cannot be guaranteed, policymakers can take steps now to ensure it will not be foreclosed.

Key ingredients of such an innovation system, more like that which led to the computer revolution and the Internet, would include:

- Intense domestic competition, within government and in the U.S. industries from which innovations will emerge.
- Targeted education and training programs, for both young people and those in mid-career, to ensure adequate pools of workers with needed skills.
- National commitment, less martial but otherwise not unlike that underlying Cold War national security policy.
- Internationally, an environment balancing competition, a powerful force during the Cold War, and cooperation, as is common in Big Science (where commercial competition does not interfere, as it sometimes has in biomedical research).
- Also internationally, a distributed innovation system with opportunities for contributions by developing countries.

It is sometimes said that developing economies will be recipients of technology transfers from the advanced economies, presumed to be primary sources of innovation. No doubt that will be the case in some circumstances. But climate change, a global problem, will be best addressed if developing countries make direct and independent contributions of their own to GHG-reducing innovations, and can profit by doing so.

Within the United States, competition bred the Internet, the guiding hand of DoD notwithstanding. Individuals and firms chased profits through innovations in hardware and software, later in Internet-enabled services. Federal agencies and subagencies competed for appropriations to finance R&D and procurement. Inside DoD, the Army, Navy, and Air Force, each of which operates its own laboratories and extramural research arm, fought for money and approvals for the technologies they preferred. Non-service organizations, such as the Defense Advanced Research Projects Agency, early sponsor of wide-area computer networks, also contributed, along with the National Security Agency, a major purchaser of supercomputers. Universities competed to attract not only funds but new faculty stars and the best graduate students for their science and engineering programs.

As yet, nothing like the multiplicity of organizations that contributed to the Internet while competing for missions, money, and prestige can be discerned for energy and environmental technologies. "Green" entrepreneurial activity has surged, but does not approach the scale or the record of technological achievement visible as long ago as the 1960s in microelectronics and computing. Within government, DOE monopolizes energy-related R&D as no agency, not excluding DoD, dominated digital electronics. Military innovation during the Cold War was slow and costly. Competition has its wasteful side. Yet dramatic leaps did result—nuclear submarines in the 1950s, intelligence satellites in the 1960s, precision-guided missiles in the 1970s, stealthy aircraft in the 1980s. While it would be wrong to conclude that U.S. technological prowess won the Cold War, military technological innovation did make major contributions. A farsighted response to climate change should begin with the construction of a similar innovation system, this one with peaceful ends.

[11] Hence the disagreements excited by the Stern review of climate change, based on contrasting views of the proper methods for weighing investment decisions with very long time horizons. See, e.g., Nicholas Stern, "The Economics of Climate Change," *American Economic Review: Papers and Proceedings*, Vol. 98, No. 2, 2008, pp. 1-37.