Charles Weiss and William B. Bonvillian

Complex, Established "Legacy" Sectors
The Technology Revolutions That Do Not Happen

Americans pride themselves on the scientific and technological prowess that has given rise to a steady stream of innovations in information and communications technology, along with medicine, agriculture, military, aerospace, and many other fields. For a quarter century, innovation policy in the United States has focused on the problems encountered by innovations in these and many other areas—especially on "the valley of death," the gap in implementing innovation that occurs as technologies bring new functions to create new markets and innovators move from research to late-stage development. In contrast, almost no research has focused on a different but critical problem in innovation: fitting new technologies into established economic sectors where innovation is needed and potentially transformational, and where the record of success is much more meager. This is the problem we confront in this article. Put another way, how do we fit discontinuous technologies into established sectoral paradigms?

Complex established "legacy" sectors—like energy, health delivery, the electric grid, building, and transport—present acute needs for systemwide technological innovation. Typically, the United States launches new technologies, and the new functionality they offer, into new territory, creating new economic activities. There was nothing quite like computing, telecommunications, aviation, electricity, or railroads before their advent. It is harder to launch innovations into established sectors occupied by incumbent firms and their aging technologies because they

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In this article, the authors build on discussions of the ideas in their recent book, Structuring an Energy Technology Revolution *(Cambridge, MA: MIT Press, 2009), and in their fall 2009* Innovations *article, "Taking Covered Wagons East: A New Innovation Theory for Energy and Other Established Technology Sectors."*

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resist any change that threatens their business models. Therefore, we tend to incubate the new rather than fix the old, leaving established sectors isolated from innovation, so that they tend to stagnate. That's why Thomas Edison would be comfortable with our electric grid, why we have been working on electronic medical records for 20 years, why energy losses from our buildings are major contributors to global warming, and why a cab ride from Kennedy Airport to Manhattan over potholed highways is something of a Third World experience. The resistance to innovation in our established sectors becomes a drag on their long-term viability and on our economic growth.

The technological systems in these complex established legacy sectors, which we call CELS, are the result of stable and well-defended technological, economic, and political paradigms backed by policies, subsidies, prices, price structures, standards, regulations, incentives, infrastructure, political support, expert communities, technological institutions, innovation systems, career paths, and university curricula that have developed over decades. This multi-faceted CELS paradigm—and the technology lock-in that it ensures—provides the overall structure into which any innovation must be introduced, even though its original purpose, however justified it may have been at the time it evolved, may have long been overtaken by events and become broadly counterproductive. While established sectors will allow advances to existing technologies that fit within the paradigm, they resist breakthroughs that make fundamental structural changes. The prominence and obvious importance of this techno/economic/political paradigm and the critical social problems that often flow from it attract the attention of creative individuals and companies, resulting in a substantial supply of promising ideas at various stages of development and small-scale implementation—just far enough along to give rise to excited stories in the media and to create major frustration on the part of the innovator, but far short of the large-scale deployment that would be needed to make a significant dent in the overall problem.

We tend to incubate the new rather than fix the old, leaving established sectors isolated from innovation. The resistance to innovation becomes a drag on their long-term viability and on our economic growth.

Our inability to introduce innovation into such CELS ties an anchor to our economy. Emerging nations climbing toward developed world status tend to have growth rates two to three times that of the United States because they are starting afresh and bringing the latest innovation into all sectors. The U.S. growth rate is based largely on innovating at the frontiers of technology, so it leads new innova-

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tion waves[1] that generally recur every four or five decades. If we worked not only on innovation at the frontier but on innovation in established sectors, both our growth rate and our quality of life could be significantly enhanced.

In the energy sector, for example, the paradigm supports legacy technologies based on fossil fuels, a structure that is now backed by the power of huge corporations, buttressed by strong and deeply felt public expectations of cheap energy, that mobilize opposition to any proposals for fundamental change.[2] The result is a complex set of interlocking obstacles to the development and market launch of technologies based on alternatives to fossil fuels. Analogous paradigms exist in transport, food, health delivery, the electric grid, building, and many other sectors—based, for example, on the strong public support for personal as opposed to mass transportation, on the political power of industrial agriculture, and on the inability of our fragmented health-care system to promote innovation and efficiency. These paradigms guide not only investments in existing technology, but also the direction of investments in research, development, and demonstration of new technologies.

A NEW, INTEGRATIVE ANALYTIC FRAMEWORK

In a book and in previous papers, we have proposed a new analytic framework to address the problems of fossil fuel-based energy, which we took as a prototype of a CELS. We used the image of "driving covered wagons east" as a metaphor with which to capture the difficulties of introducing innovations in complex established sectors, and suggested that the concepts proposed in our analysis can be applied to innovations in a larger set of legacy sectors.[3] In such sectors, we argued, the chief obstacles to innovation lie in the problems of *market launch*, so that policymakers need to go beyond support to research and development—the traditional focus of American science and technology policy—and examine the entire innovation process.[4] The obstacles to market launch in these systems are well known to specialists in particular areas but have not received the attention they deserve from general innovation theorists.

In this paper, we extend our earlier analysis to address the obstacles to innovation in a broader set of complex established sectors: the health-delivery system, the long-distance electricity grid, the building sector, and air transport. We chose these sectors to illustrate a variety of techno-economic characteristics and impediments to innovation. In all of these sectors, the social benefits of a technological revolution justify public intervention to speed technical change beyond what might be expected from the ordinary activity of free markets, just as they would in energy.[5]

We propose an integrative analytic framework that provides common concepts and vocabulary in order to facilitate the discussion of policies that can stimulate innovation in these critical and apparently disparate economic sectors. Our central focus is on the role of market imperfections as they both encourage and pose obstacles to the development and launch of innovation. Some of the imperfections in the market for technological innovation reward private investments by making

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it possible to obtain monopoly rents. Others impose obstacles to innovation. We therefore introduce the idea of a "quasi-free market" for technology: a market whose imperfections affect the development and launch of any innovation.

We then introduce the idea of a technological/economic/political paradigm that favors existing technology and supports an established complex sector through subsidies and publicly supported infrastructure that benefit existing technology, as well as a variety of other market imperfections.[6] Innovations in such a sector that are consistent with and fit into the prevailing paradigm must overcome the effects of these subsidies; in effect, they must push these innovations up a substantial hill. Beyond this, they face only the same obstacles as any other innovation.

Innovations that threaten an established paradigm, on the other hand, face many additional hurdles on their way uphill. They must contend with the regulations, policies, institutions, and market imperfections that protect the "legacy" technology, as well as non-market opposition from the competitors that benefit from the established paradigm. To return to our covered wagons metaphor, these are the conditions that led our technology pioneers to head westward in the first place.

A dramatic demonstration of the existence of such market imperfections is the fact that some interventions, for example in the building industry, actually have positive aggregate financial net present value, in the sense that the sum of the financial benefits to the various stakeholders that would result from the widespread implementation of the innovation would exceed their aggregate financial costs.[7] In other words, implementing these technologies would not only achieve social benefits but would actually save money overall. More frequently, however, paradigm-threatening innovations in these sectors are driven by non-market considerations: either externalities (costs that users do not pay directly) involving the environment, public health, or security, or other collective benefits that may be critically important to the country or the world but will inevitably cost extra money.

THE "QUASI-FREE" MARKET FOR "STANDARD" INNOVATION

The market in technology is inherently imperfect. Some imperfections work to the strong advantage of the innovator. First and most important, technological innovators seek to gain economic rents through their monopoly on technology, reinforced by the fact that the owner of a technology knows more about it than a prospective buyer does—an advantage known to economists as "asymmetric information." Second, once their new product has been established in the market, innovators benefit from barriers to the entry of competitors. The innovator benefits from various first-mover advantages, for example, the fact that consumers are more likely to identify the new product with the innovator, even after competitors have appeared on the market.[8]

Other market imperfections, on the other hand, work to the innovator's *dis*advantage. These constitute the theoretical justification for specific policy interven-

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tions intended to stimulate research and innovation. Of these imperfections, the most important is the fact that the innovator does not keep all of the social benefits of his or her invention, an imperfection known to economists as non-appropriability. First of all, (s)he must share the value-added of innovation with a variety of stakeholders—most obviously with the user, given the rule of thumb that an innovation must be at least twice as cost-effective as whatever it replaces. Beyond this, technology may "leak" away from its originator by such means as the departure of key personnel or successful patent infringement, or it may even be stolen outright. This non-appropriability, or "knowledge spillover," is the basic policy justification for public support for research and development, since it implies that aggregate private investment in innovation will be less than optimum for society, even ignoring environmental and other externalities.[9]

We have already mentioned the well-known valley of death between applied research and the late-stage development of commercial products; from this point of view, it is an imperfection in the capital markets in the sense that potentially profitable opportunities fail to attract investors.[10] A less obvious market imperfection affecting all innovations is the difficult link between technology and management; for example, a company with excellent technology may suffer from poor management, and vice versa. This is an imperfection because in an ideal free market, technology and management could be "unbundled" from each other, like design and manufacturing in the semiconductor and other IT sectors.[11] The most famous case of this pattern is the failure of the Xerox Corporation to capitalize on the seminal inventions of its own Palo Alto Research Center (Xerox PARC), including the desktop computer, the graphic interface, the mouse, and the Ethernet cable.[12] This is one aspect of the theoretical policy justification for establishing the Defense Advanced Projects Research Projects Agency[13] and its counterparts in intelligence (In-Q-Tel)[14] and energy (ARPA-E),[15] which provide various forms of support extending into the applied development area to firms with technologies deemed critical to defense, intelligence, and energy capability, respectively.

The status of first mover involves costs as well as benefits. The innovator must achieve sufficient economies of scale to be able to introduce the new product into the market at a cost low enough to be competitive with any existing products. (S)he must absorb the cost of educating consumers, developing distribution channels and repair and maintenance capabilities, driving product costs down the price curve, developing incremental improvements and second-generation products, and identifying and seeing to the production and marketing of complementary products.[16]

We now define a "standard model" innovation as one that is subject to these particular market imperfections. For want of a better term, we shall call the market in which such innovations operate a "quasi-free" market. It is not completely free, not only because it is affected by market imperfections at the stage of market launch, but also because innovation benefits from extensive government funding of early stage research (which greatly exceeds private-sector expenditures at this stage), and major support of science and technical education. [17]

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The term "standard model" does not imply that such innovations face an easy path; on the contrary, they typically face an uphill struggle. The obstacles faced by such standard model innovations—and the policy measures needed to help them overcome these obstacles—have been the near-exclusive focus of the general literature on innovation theory. These obstacles justify the standard recommendations for support to research and development, on the need for policies that bridge the valley of death,[18] recommendations that are valid for virtually all innovations. These standard model innovations include such well-studied phenomena as induced innovation,[19] discontinuous or transformative innovations,[20] enabling or generative innovations,[21] and many kinds of disruptive innovations.[22] Such innovations may be radical (new functionality), secondary (major improvement of established functionality), or incremental.[23] The organization of the innovation process,[24] both at the institutional level and at the face-to-face personal level,[25] likewise presents a profound challenge.

THE COMPLEX ESTABLISHED "LEGACY" SECTOR

We now introduce the concept of the complex established legacy sector, or CELS, and its accompanying technological/economic/political paradigm, which we define as displaying four market imperfections:

1. A tilted (non-level) playing field caused by "perverse" subsidies and price structures that are favorable to existing technologies,[26] and that create a mismatch between the incentives of producers and innovators and the goals of the larger society

2. An established institutional architecture that imposes regulatory hurdles or other policy disadvantages favoring existing technology or discouraging new entrants, accompanied by public support to infrastructure adapted to the requirements of existing technology

3. Well-established and politically powerful vested interests, reinforced by public support, that defend the paradigm and resist the introduction of technologies that threaten their business models

4. A set of market imperfections specific to one or more innovations within the sector, over and above those facing standard model innovations.

These may include the imperfections of network economies, lumpiness, split incentives ("positive pecuniary externalities," a form of non-appropriability), requirements for collective action, and transaction costs.[27] We explore them in the following section.

These paradigms do not inhibit all innovations. On the contrary, innovations that reinforce them constitute the basis of much of the United States' comparative advantage in pharmaceuticals and in fossil fuel, agricultural, military, and aerospace technology. But for innovations that do not fit readily into a given legacy paradigm, for example those in organic agriculture, this four-part structure presents multiple obstacles that inhibit investment at every stage, from research to market introduction. The structures supporting these paradigms have grown up over the

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years precisely because they fulfill their functions well, at least for a substantial proportion of their stakeholders. Indeed, in many cases there would be no issue at all if it were not for some overwhelming non-market collective benefit, such as the environment, public health and safety, or (in the case of energy) geopolitics and national security.

To further complicate matters, policymakers seeking to promote innovation face the problem of defining and obtaining agreement on a clear and measurable standard or metric by which to gauge whether the externalities have been overcome and the social goals have been met, for example, for evidence-based medicine or sustainable agriculture. The same interests that benefit from the existing paradigm are likely to oppose efforts to define and implement such standards.

OVERCOMING OBSTACLES TO MARKET LAUNCH

We now employ the concepts developed above to identify and classify the obstacles to market launch in CELS, in order to lay the groundwork for a brief survey of these obstacles as they apply to innovations in energy, health-care delivery, the long-distance electric grid, buildings, and air transport. Policymakers seeking to encourage such innovations have three objectives: to stimulate a supply of new ways of doing things, to remove obstacles to launching innovations into widespread use, and to eliminate or at least to lessen the mismatch between incentives for established technologies and social goals. Each of these objectives may well take years or even decades to achieve. Ideally, the three should be implemented in parallel; in practice, it may well make sense to start with whichever is more politically practicable at a given moment. Adapting our earlier analysis to this broader canvas, we classify innovations according to the obstacles they are likely to face and discuss the policy interventions best suited to overcoming these obstacles.

Stimulating the supply of new ideas uses the traditional instruments of American science and technology policy: primarily the financing of research and development, but also prizes and professional recognition for major discoveries, and translational research to bridge the valley of death, particularly in the case of inventions important to national security or public health.[28] These measures are needed for almost all innovations in CELS because the subsidies, market imperfections, and institutional impediments typical of such sectors have long discouraged investment in research in these fields or guided it in inappropriate directions.[29]

These "supply-side" measures are appropriate to *early stage ideas*, which are experimental and require a relatively long period of research, development, and perhaps demonstration. Analysis of expected obstacles to their market launch and the interventions needed to overcome them would therefore be premature, since even technical success (let alone economic feasibility) is far from being assured. Examples would include the hydrogen economy and fully autonomous robotic automobiles.

Beyond support to research and development, efforts to stimulate innovation in these CELS need to address both obstacles that result from the structure of the

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"legacy" sector and others that are specific to particular technology. This typically means conceptually simple but politically difficult measures to change prices or price structures, for example, through charging for emissions of carbon dioxide or paying doctors and hospitals more for preventive and less for procedure-based medicine, so as to bring producer incentives more in line with social goals. Below we identify seven categories of barriers to implementing new technology paradigms in CELS. This is not an exhaustive list, but it aims to identify an initial group of significant barriers.

Paradigm-Compatible Innovations

These constitute the most manageable cases of a technology category facing a CELS barrier that may require policy intervention. These innovations can fit into a market niche that falls within the existing paradigm, and can be profitable reasonably soon after market launch, ideally even despite the subsidies to competing legacy technologies. Building up a niche, they can, over time, go through engineering improvements and move down the production cost curve to build momentum for broader entry into the sector. Here, private market mechanisms are more important than interventions through public policy. If these innovations become sufficiently superior to the technologies they replace as to overcome the subsidies to their competitors, their market adoption can follow the "standard model" described earlier. Light-emitting diodes (LEDs) provide a good example of this category. This technology began in specialty niche lighting sectors, and went through cost-cutting and incremental engineering improvements to build up its market base to a point where the technology may emerge as the dominant lighting technology.[30] In other words, over time LEDs, while displacing existing incandescent lighting, are a technology that is compatible within the existing lighting paradigm.

At the beginning, the new technology is likely to be competitive only in special situations, but it may have the potential to improve and expand into existing markets and become a disruptive innovation in the sense defined by Christensen.[31] This "self-expanding" process could be accelerated by public policy intervention, including subsidies, regulatory requirements, guaranteed purchases, or other interventions to encourage scale-up or provide incentives or regulatory requirements for adoption by users if this is justified by some environmental or other social benefit. Examples would include off-grid solar and wind energy, most new drugs and medical devices, and, as noted, energy-saving LEDs.

However, these innovations typically face a series of marketing and design challenges when they attempt to move from early-adopter niche markets to broader-use markets.[32] Impediments include engineering incremental improvements for the technology, selecting the right target markets, developing a concept of the "whole product," positioning the product in the market, formulating a marketing strategy, finding distribution channels, and pricing for emerging markets. These

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must fit a technology adoption lifecycle,[33] with its staged segments of technology innovators, early adopters, early majority users, late majority users, and laggards.

Market Imperfections Facing Counter-Paradigm Innovations

We now turn to six more market imperfections in CELS that pose obstacles to counter-paradigm innovations. These innovations cannot be fit into existing paradigms and require policy interventions before large-scale market launch can occur.[34]

The second of these imperfections concerns innovations that depend on *network economies* derived from industries organized around national or large-scale regional networks. As a way to visualize these networked sectors, just picture the vast system of telephone lines or of wireless cyber connections; examples include the network dominance of Microsoft's operating system in computing or the existing grid system in electricity transmission. Here, a major obstacle is often the absence of agreed standards that facilitate interoperability within the networks. Innovations in the air traffic control system, many elements of the smart grid, and many applications of information and communications technology to the delivery of health services fit into this category. These innovations require the adoption of standards, regulatory incentives, or other policies to facilitate the establishment of such networks and to ensure the interoperability of components and sub-networks. If the innovations are purely technical, they may be introduced by agreement among stakeholders, as long as these are consistent with their competing business strategies. Or they could be imposed by a dominant firm (such as Microsoft in computer operating systems), or directed by a single health payer (such as the U.S. Veterans Administration regarding electronic medical records). The absence of such standards in these networks in effect squanders the advantages conferred by the huge American mass market. If the required standards cannot be set by agreement or by a dominant player or product design, federal government intervention may be necessary, especially if different regulations in different states have the effect of imposing divergent standards.

A third market imperfection that may impose barriers to innovation is known as "lumpiness." This term is applied here to innovations that require a substantial minimum investment in order to be introduced at full scale against entrenched competition. In many cases, these must first be the subject of full-sized, expensive, and risky demonstrations to prove techno-economic feasibility, safety, and environmental sustainability, as in the case of enhanced ("hot rocks") geothermal technology systems or fourth-generation nuclear power plants. This "lumpiness" problem may be visualized as a boa constrictor swallowing an elephant. These "elephant" technologies typically require large, expensive, engineering-intensive installations that may also give rise to issues of ownership rights and legal liability, as well as of technology. The need for public intervention to promote the introduction of these technologies is especially acute if they are likely to involve extra costs, even when fully developed.

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In the energy field, this set of conditions applies directly to carbon capture and sequestration technology; such major engineering systems, even when fully developed, will add major new facilities and costs to coal-fired generation plants. This technology will require billion-dollar investments in demonstration projects that are likely to be funded privately only if investors are reasonably sure that such technology will eventually be required of them in one way or another. Public-private partnerships and international collaborations are needed here to share demonstration costs, to offer financing support, and also to ensure that performance, safety, and environmental data are collected in a manner consistent with the needs of eventual private investors.

A fourth kind of market imperfection that may impose barriers is the need to effectuate *economies of scale*; therefore, special intervention may be needed to bring down unit costs, improve performance, or organize the market for complementary products and infrastructure. To visualize these economies of scale, one need only imagine the vast array of resources, suppliers, components, and production facilities needed to produce a million cars. The cost and complexity—the required economies of scale—of assembling this vast production system, a "value network" in Christensen's terminology, is what makes entry into such sectors as auto or aircraft production so difficult. This market imperfection is especially important in the manufacture of hardware, such as aircraft or motor vehicles, or for electronic components of information systems; for example, a single semiconductor chip fabrication plant (known as a fab) is a massive production facility requiring a multi-billion-dollar investment.

Here, public intervention—for example, low-cost financing of capital equipment—is justified if there is an urgent social need to expand production beyond that required to meet the needs of assured future markets. The federal government did this to produce aircraft during World War II, and the Japanese government did it during the 1970s in many areas of manufacturing. A well-tested policy measure to encourage expansion of production facilities is guaranteed public purchase. For example, the government can issue a public tender for a quantity of solar water heaters or photovoltaic panels to be installed on military housing, to be awarded to bidders meeting specified conditions.

A fifth kind of market imperfection that may impose barriers to innovation is that of *non-appropriability.* This refers to innovations whose benefits accrue to someone other than the investor.[35] Doctors, for example, may be reluctant to invest in information systems that benefit patients but whose costs cannot be passed on to them. In such cases, it is important to devise ways of overcoming these imperfections, for example, by a mechanism that finances extra initial costs at favorable rates. Even so, the practical difficulties of implementing such systems may require some form of subsidy or regulation, for example, through revisions in building codes or other standards. This is especially true in situations where the non-appropriability was created by government institutions or by regulation. For example, in the case of the electric grid, state-regulated electricity rates prevent utilities from recovering the cost of investments that could result in a more reliable and efficient

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national supply of electricity. Alternatively, these innovations may simply be imposed by fiat by a central paying authority, such as electronic medical records by the U.S. Veterans Administration, or the national health services of the United Kingdom and Scandinavian countries in the case of health services delivery.

A sixth kind of market imperfection is *requirements for collective action.* These typically involve fragmented industries with many units, none of them large enough to invest in innovation. Picture the housing construction industry, for example. It is highly decentralized, with thousands of small firms. Few of them have even a regional, much less a national presence, and only a tiny number have the capital depth to support R&D for the sector. This sector is risk-averse and therefore innovation-averse, and is therefore unwilling to implement new advances until their costs and efficiencies are fully and convincingly proven. Innovations in such industries can come from suppliers, although these suppliers face a significant threshold for proving costs and quality for this highly decentralized sector.

Alternatively, such industries may organize themselves for collaborative, precompetitive research, sometimes with government help. Picture another example, the farming sector, where millions of farms cannot implement or finance innovation without the systematic support of the Agriculture Department's research and development efforts, or without its dissemination efforts through county extension agents bringing these innovations to individual farmers, or without its massive financing programs.[36] Another example is Sematech, a public-private partnership that helped to pull together the semiconductor industry with its diverse equipment suppliers and to bring productivity gains and cost efficiencies to equipment manufacturing processes.[37] In the energy sector, the Electric Power Research Institute supports sector-wide R&D efforts. Such cross-sectoral efforts can suffer from under-investment due to the free rider problem, in which members of the industry benefit from collective research without contributing to it.

Many of the market imperfections in the previous discussion arise from a seventh barrier category: *governmental and other institutional impediments* to innovation. In addition to the long-distance electric grid impediments mentioned earlier, prime examples include the control by state and local jurisdictions over the regulation of energy, and the over-siting of energy facilities and installations, like wind and solar energy farms and their associated long-distance power lines. Another example is local control over building codes, which creates an approval structure that sharply limits the ability to adopt innovations that improve the efficiency of energy use in buildings.

This problem is not restricted to regulatory agencies and may also extend to research agencies and programs. The organizational structure of the National Institutes of Health, for example, is decentralized around some 27 institutes and centers to fulfill the political demands of historical disease groups, a structure that limits needed cross-cutting research initiatives that could accelerate medical innovation. In other cases, government-directed intervention mandates curtail new technology, for example, when interest group politics dictated huge subsidies for

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corn-based ethanol, although it is at best a sub-optimal biofuel technology and a competitor for land used to grow food crops. In another example, the political demand for manned space exploration has curtailed less expensive and more scientifically rewarding robotic exploration.

THE LEGACY SECTORS

We now summarize the obstacles to innovation in five economic sectors, using the analytic framework set forth in the above sections. We provide snapshots of these sectors, briefly noting the technology challenges and the barriers to meeting them. For each sector, we briefly set forth the general structure of its economic/political/technological paradigm, together with its successes and the negative consequences that have led to its being reexamined and the drive to replace it with a technology revolution. We then set forth the desirable characteristics of such a revolution and discuss the difficulties involved in achieving them.

We next briefly characterize some of the most prominent possibilities for technological improvement in the sector and note the obstacles to launching them in the marketplace, using the concepts set forth in the preceding section: the subsidies and price structures creating a tilted playing field, the market imperfections and other obstacles for innovation resulting from this paradigm, and the existing policies, standards, regulations, and economic and political factors that affect the speed and direction of technological change and innovation. We also note some of the policy interventions that could lead to a technological shift in the sector.

Energy

The major problem facing innovations in the energy sector is a deeply entrenched, non-level playing field, backed by powerful companies and strong public support, in which legacy fossil-fuel technologies benefit from a variety of incentives and tax advantages much richer than those for carbon-efficient technologies.[38] These legacy technologies deliver cost-effective, reliable, and convenient energy to users. As a result, the driving force for change comes from the serious environmental and geopolitical externalities of fossil fuels, rather than market demand. The resulting watchwords are energy security and sustainability—objectives that overlap although they do not always coincide.

Although investment in energy research and development has been small, considering the enormous size of the energy economy, it has still given rise to a wide range of promising alternative energy technologies. These face the gamut of categories of impediments to innovation we defined earlier: from impediments to *early stage innovation*, such as those faced by hydrogen fuel cells and fusion, to potentially disruptive technologies, like off-grid wind and solar that are already established in special niches but still face impediments to *paradigm-incompatible innovations*. The energy sector also includes technologies like solar and wind farms, carbon capture and sequestration, enhanced geothermal, and next-genera-

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tion nuclear, which must be launched at large scale and thus suffers from innovation impediments due to *lumpiness.*

Impediments to innovation due to the need for *economies of scale* create inherent costs and risks and require special intervention, such as hardware manufacture for electric vehicles, which requires economies of scale and so risks overexpansion beyond anticipated market needs. Other technologies that face impediments to innovation due to *non-appropriability* offer positive aggregate net value but suffer from market imperfections that make it difficult to translate this into a practical incentive structure, such as many technologies for conservation and efficient energy use. The energy sector is also laced with *governmental and other institutional impediments*, notably the lack of mechanisms to translate research advances into scaled technologies. Each of these impediments to innovation requires a strategic policy response.[39] As we shall see in the later section on air transport, the military, as a major purchaser of fossil fuels, is in a unique position to bridge this gap.

Health-Care Delivery

The existing paradigm of health-care delivery in the United States is a complex system of mixed public and private payers, which has given rise to powerful vested interests—including a rigid system of professions and institutions—that are well positioned to fight rationalization of the system. Together, they support a tariff structure that favors sophisticated medical procedures over non-medical measures to improve public health or promote healthy lifestyles, and a fee-for-service system that rewards doctors and hospitals for expanding services, especially equipment-intensive high-tech procedures, rather than for performance.[40] Of course, medical advances have multiplied in recent decades, so a plethora of vital new procedures and path-breaking medicines are available; therefore the system is also facing a backlog of innovations it must accommodate, complicating the conflict between performance and fee-for-service. Since much of the recovery of fees depends on government entitlements (through Medicare or Medicaid) that guarantee payment, pricing in the system is relatively unconstrained.

The motivation for reform comes, first, from the fact that the resulting system provides the United States with relatively poor public health for much of its population: around 15 percent of citizens have limited access to care, and high costs are straining the capacities of employers and insurance companies to pay. The huge medical cost of the baby boom demographic bulge also may eventually threaten the federal government's fiscal stability. Market and political motivations to reform the system are lacking because most people are satisfied with the care they now receive and are shielded from its cost by the third-party payment system and by cost-shifting to government. The expense and inefficiencies built into the health-care delivery system have also become significant motivations for reform. A further motivation is the fact that much medical technology has never been subjected to objective tests of effectiveness.[41]

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A wide range of innovative applications of information technology (IT) to health-care delivery are at or near techno-economic readiness. These include technologies for digitizing health care, standardizing medical reporting, improving communication among different actors in the system, and building databases to evaluate performance and efficiency. Also in the works are instant transmission of complete medical histories and of precision digital test data, such as advanced imaging, and ways to obtain immediate real-time results of many tests, along with better ways to compare real-time actual performance against standards of care and best practices, and to perform precision remote robotic surgery through online connections.

Although the IT innovation wave transformed productivity in a number of economic sectors, to date, its entry into health-care delivery in the United States has been limited. In contrast, IT innovations have been implemented successfully through the Veterans' Administration and in single-payer systems in Scandinavia and the United Kingdom, so we do have information on their potential. In the United States, several systems have been implemented at pilot scale or in limited markets, but full-scale deployment has been hindered by lack of standardization of reporting formats and harmonization of payment procedures and state regulations that would make it possible to achieve *network economies*.

More important, because performance and efficiency are not adequately rewarded in the existing U.S. fee-for-service model of health-care delivery, institutional and professional resistance to IT-based performance and efficiency reforms has been significant and ongoing. The incentives for doctor and hospital actors in the system are tilted toward performing more and more services, systemically driving up costs and therefore compensation.[42] Aside from the lack of performance incentives, the existing system resists transparent benchmarks for medical outcomes and efficiency so that medical consumers and employer providers too often fly blind through the system. An IT-based technology incursion that would enable a transparent measurement and benchmarking system has not been adopted because the fee-for-service delivery model does not offer the level of economic rewards needed to implement it. The situation exemplifies the mismatch between producer incentives and social goals that is typical of a CELS.

Innovation in the health-care delivery system is impeded by *governmental and other institutional impediments*. The federal government funds some 40 percent of the health-care system through coverage for the elderly (Medicare) and poor (Medicaid), the two most expensive medical populations. Thus far, it has attempted partial rationing of innovation by limiting access to some procedures under Medicare and Medicaid, rather than through cost and performance competition. Despite occasional forays into reform, the political system has not proved able to restructure the fee-for-service model that is sustained with political support from the elderly, hospitals, and medical professions.

IT innovations face another problem: they require investment and therefore place unsustainable costs on health-care providers, whereas the benefits of these investments are likely to rebound to their patients and to insurance companies,

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neither of which will accept the costs. This is an impediment to innovation due to the market imperfection of *non-appropriability*. Also impeding innovation in the health sector is the need for *network economies* that can be achieved only in the presence of large-scale networks, and that therefore require the adoption of standards or other requirements to ensure the inter-operability of the sub-networks through which information is to be communicated.

Unlike the situation for health-care delivery systems, it is tempting to assume, because the biotech sector appears so successful, that improved pharmaceuticals and devices for use in hospitals and by physicians can readily overcome impediments to *paradigm-compatible* innovations that slot nicely into the existing system and face only the normal problems of the standard innovation model: the need for research support and venture capital to bridge the valley of death. The same is true of technology for digitizing the back-office operations of hospitals and private physicians. However, the picture is more complex when examined closely.

Even paradigm-compatible medical innovation faces a series of hurdles. First, bringing a new drug through development, clinical trials, and Food and Drug Administration (FDA) approval costs approximately $1 billion.[43] This means that biotech and pharma companies must develop drugs and devices that satisfy a substantial market; non-"blockbuster" drugs are problematic, preventing them from being paradigm compatible. Although technological advances promise progress on "personalized" medicine—individualized drugs and devices that will fit individual needs—to date, the existing economic model has hindered rather than incentivized this approach. Innovation impediments due to *lumpiness* also affect drugs for diseases of the developing world, and those that affect small populations, along with vaccines, new contraceptives, and new antibiotics, as well as other remedies that immediately cure a disease or condition or that involve large potential liabilities. These categories of drugs do not offer prospects for blockbuster status and therefore do not fit into the existing paradigm.[44]

Second, although the National Institutes of Health (NIH) is the nation's largest research and development organization, it is organized around a biological model for drug development, and generally does not support work on innovation for devices, practices, or systems. A growing research model that promises a new generation of medical advance, the "convergence" model of integrated, cross-disciplinary research combining life, engineering, and physical science research design,[45] is limited by organizational problems at NIH and FDA. Neither is well organized to support non-biological research directions, despite their promise; if these opportunities are to be realized, new approaches to peer review, education, and cross-institute and agency collaboration and research processes will need to be tested and adapted by NIH, and the FDA will have to examine and revise its evaluation capabilities and procedures.

Thus *governmental and other institutional impediments* in the area of drug, device, and systems innovation exist in the health sector, even apart from the problems in the health-care delivery system discussed above. Other impediments to innovation arise due to *economies of scale*: innovations of important but limited

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reach face limits in their ability to scale up within the current market structure. Other major issues are connected with developing a system of evidence-based medicine and undertaking the research for cost-effectiveness criteria to implement such a system in order to measure and document the successes and failures in meeting public health goals and to start to shift away from a fee-for-service system to performance-based medicine.

In summary, although the biotech sector has been a model of successful innovation, and medical research has received far more federal research investment than other sectors, there are structural organizational challenges to innovation in both health-care delivery and the next generation of pharmaceuticals and medical devices.

The Electric Power Grid

The high-voltage, long-distance electric power grid in the United States has been the subject of criticism because of limits on its reliability, its inability to accommodate renewable power sources, and its inability to adapt to IT advances.[46] The recent emphasis on environmental issues has created pressures for increased efficiency, as well as measures to facilitate the incorporation of intermittent, renewable sources of energy, and has stimulated discussion of possible means to overcome the many obstacles created by a fragmented regulatory system.

Electricity charges in the United States, to summarize briefly, are largely regulated by 50 state commissions. These generally restrict utility revenues to a fixed percentage of investment and are therefore reluctant to permit new investments, since they are likely to result in rate increases that consumers will resist. Different parts of the long-distance electric power grid in the United States are owned by different electric utilities, depending on geography, with the result that no single entity feels responsibility for the reliable and cost-effective operation of the whole grid, and no state commission is eager to approve utility investments with that purpose. In any case, the benefits from such an investment would come back to the consumer in the form of increased reliability and lower rates, and to the environment in the form of reduced carbon dioxide emissions and other forms of pollution, rather than to the utilities in the form of increased profits—a classic example of environmental externalities and *non-appropriability* due to split incentives.

The result is a grid that has relatively poor reliability, unnecessarily high cost, below-standard efficiency, and consequently a high environmental footprint, specifically high carbon dioxide emissions and contributions to global warming. Underlying these problems is a longstanding under-investment in the long-distance grid and in research and development on ways to improve it. The highly complex process of generating and distributing electricity has three stages—generation, transmission, and distribution—as we describe in more detail in the ensuing paragraphs.

Thus, any effort to restructure the electric grid system runs headlong into a highly balkanized structure, with different jurisdictions controlled by different

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institutions at different levels of government. The number of utility actors involved is startling. "America's electric power industry is highly fragmented, divided among more than 3,100 separate entities, under a variety of forms of investor and public ownership."[47] Apart from the pricing of generation, transmission, and distribution noted above, "Diverse state regulatory policies predominate regarding electric industry structure, generation adequacy, energy resource mix, transmission siting and cost recovery and retail electricity prices."[48]

The pricing and regulation of these stages is not integrated, so that electricity market transactions are divided, as discussed below, based on location and on distribution systems. The Federal Energy Regulatory Commission (FERC) has sole jurisdiction over pricing rates in wholesale high-voltage transmission, but cannot set prices for the local systems that distribute lower-voltage power to end users. FERC has very limited authority over the construction of utility lines; pricing of generation and transmission over local distribution systems is set by state regulators under varying state laws. To add to the complexity, the 1990s saw partial and piecemeal deregulation. Some states deregulated, some did so partially, and others didn't deregulate at all. The generation market therefore contains both deregulated and regulated elements operating under a regulated wholesale high-voltage system under FERC. The result is a classic example of *governmental and other institutional impediments* that affect a broad range of promising innovations.

Reliability oversight of the grid as a whole is the responsibility of the FERC, which delegates some responsibilities to the North America Electric Reliability Corporation or NERC. The latter divides North America into eight regulatory regions, which do not match up with the three major grid "interconnection" regions. Since relatively few high-voltage transmission lines connect any one region to the others, consumers in one region are largely limited to energy generated in that region.

Large-scale renewable energy sources—wind and solar farms and geothermal fields—will often be built in areas separated from existing transmission facilities, requiring major new build-out. However, the regulatory structure is so divided and generally reluctant to embrace major and costly infrastructure investments that developers face almost insuperable obstacles in obtaining the multiple regulatory approvals needed both for the build-out itself and for absorbing the extra costs that they entail into the rate structure. In addition, the business model for most utilities is based on the sale of power, a system that does not reward conservation, efficiency, or reduced fossil fuel use. In other words, the system does not align producer incentives with social goals. Most state regulators do not require that a portion of their energy be generated from renewables ("renewable portfolio standards"). Since renewables are still more costly than coal or gas, accommodating renewables within the existing balkanized structure of the grid is problematic.

The next level of grid innovation is even more complex. The "smart grid"—which can integrate IT into the electricity grid—promises information flows that could yield both increased reliability of supply and major efficiency savings.[49] The cost of electricity varies widely in the course of a day or an hour, so a technology

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that allows users to see these varying costs and adjust their consumption to reduce their costs could help level out usage and therefore costs, avoiding peaks in consumption and spikes in prices. These technologies could also automatically program in these efficiencies based on preset user demand choices and preferences. At present, however, electricity users are blind to these cost-saving opportunities.

A smart grid also offers individual households the ability to move from being simple users to become storage and generation sites, and to sell power into the grid. Such a two-way system would offer dramatic new flexibility, making electricity markets and therefore consumption significantly more efficient. However, achieving this advance involves overcoming the highly fragmented and decentralized system described above, with its many participants with differing interests and many constraints.

The two-way features of the smart grid can also play a critical role in enabling the small-scale installation of renewable resources (wind, solar, geothermal, tidal, hydropower) and the widespread use of electric or hybrid vehicles. The current grid system, which long predates interest in renewables, is limited in its ability to incorporate them, despite the need to reduce the amount of electricity derived from burning coal, currently the source of half the electricity the country uses. Many renewable technologies could be introduced at the household or local scale, but these sources are outside the grid and can only serve the particular household or local, not broader needs; a smart grid could be a significant inducement to introducing smaller-scale renewables.

A smart grid system would also support the broader introduction of electric and hybrid vehicles. Recharging could take advantage of optimal pricing with corresponding efficiencies. Once recharged, the storage systems for these vehicles could sell power back into the grid, offsetting charging costs. The grid is also fragile, facing threats of blackouts; to avoid these, utilities must always have significant excess capacity. Smart grid technology includes automated information systems that "could mean a self-healing, self-optimizing power-delivery system that anticipates and quickly responds to disturbances."[50]

Implementation of a new grid will require overcoming obstacles posed by several market imperfections that are characteristic of CELS. First, innovation in the grid is hindered by the need for *network economies* that can be achieved only through national or large-scale regional networks. These will require the adoption of standards, and of regulatory and incentive policies to assure the interoperability of components and sub-networks, and to facilitate the establishment of new innovative networks within the established grid network.

Second, innovation within the grid is impeded by the problem, as noted, of *non-appropriability,* in which the benefits of innovation accrue to someone other than the investor. While utility investors would have to accommodate and implement smart grid features that could benefit consumers, for example, the power sale business model that underlies price regulation in most states treats such investments as non-recoverable costs. These and other obstacles derive from *governmental and other institutional impediments* that are largely regulatory, the product of

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historical developments in an earlier technological era, and embedded in entities unwilling to surrender jurisdiction or power. The highly balkanized regulatory structure, divided between state and federal agencies and imposing varying business models, sharply limits the ability to introduce innovation progress, and creates *collective action impediments* to innovation.

The IT technologies and software that would form the foundation of the smart grid are largely available, although cyber security and other particular R&D challenges still remain to be resolved. Technology implementation is the central problem, requiring, initially, setting of common standards, and establishment of testbeds and demonstrations. The Commerce Department's National Institute for Standards and Technology (NIST) has begun work on smart grid standards with industry, and the 2009 stimulus legislation[51] has provided $4.5 billion for initial efforts at technology implementation. However, the scale of work required to extend the reach of transmission and to incorporate smart features will require a financing effort at a much larger scale in this sector, which already has $800 billion in established capital plant and infrastructure. In sum, establishing a grid that is both smart and more efficient will require federal leadership, public and private financing, common standard setting, and a major effort at regulatory harmonization between state and federal agencies to overcome these structural barriers.

Buildings

Some 40 percent of U.S. carbon dioxide emissions come from buildings,[52] making building technology one of the most important areas for stimulating technological innovation. Saving carbon dioxide emissions and mitigating global warming is a non-market incentive; but energy is a cost to the occupants of a building and saving it should be a market incentive. A 2009 study by McKinsey & Company found that investing in energy-efficient buildings (combined with certain other non-transportation efficiency steps) could reduce energy consumption in the United States by 23 percent by 2020.[53] This would amount to annual savings totaling $130 billion to $1.2 trillion, with reductions in greenhouse gas emissions of 1.1 gigatons, or a complete "stabilization wedge" in the Pacala-Socolow construct.[54] These gains could be achieved largely by using existing efficiency approaches and technologies for an investment of about $50 billion per year over a period of 10 years. The McKinsey research found that a comprehensive strategy, executed at scale, could reduce the annual consumption of non-transportation end-use energy from 36.9 quadrillion BTUs in 2008 to 30.8 quadrillion BTUs in 2020—saving 9.1 quadrillion BTUs relative to a business-as-usual baseline.[55]

There are significant barriers to achieving these gains. Energy efficiency typically requires a significant up-front investment in exchange for savings over the lifetime of the deployed technologies and measures. But the benefits are strewn across some one hundred million locations and billions of devices used at residential, commercial, and industrial sites; this dispersal of benefits, plus the transaction costs involved in choosing and implementing the necessary technology, means that

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efficiency is rarely a leading priority for anyone.[56] *Non-appropriability* is also a significant problem in this sector: in many cases the financial benefits go to someone other than the investor. Why should a builder undertake efficiencies that benefit the purchaser, or a landlord undertake those that benefit tenants, when they cannot pass along the extra costs? These environmental benefits go largely to the public at large, making them a valuable but non-market incentive.

Other structural barriers abound. The manufacture of hardware and the technical services involved in many innovations are subject to *economies of scale* and therefore may require special intervention to bring down unit costs and improve performance. In addition, the construction sector is highly decentralized, consisting of huge numbers of small, geographically dispersed and under-capitalized firms that are not well set up for *collective action* and hence undertake very little research and development, or indeed experimentation of any kind. As a result, the cost, reliability, and efficiency savings from building efficiency technologies must be proven at major scale before these firms will take the risk of implementing them.

In addition, the sector is rife with *governmental and other institutional impediments* to innovation. While building codes could in principle provide a regulatory mechanism for efficiency improvements, these codes are a regional responsibility, with thousands of jurisdictions involved. Few jurisdictions have an incentive to take on a national energy goal, since they would have to impose significant new requirements and costs on construction firm constituents. Besides, the social goal of energy efficiency is very hard to measure; only the federal government could likely assemble the expertise and investment required to develop the accurate standard efficiency metrics needed.

Air Transport

The technological/economic/political paradigm of air transport presents a somewhat different picture. In this case, the end of the era of new aircraft designs being spun off from military to civilian use has been accompanied by a legacy of under-capitalized, low-margin airlines, which as a group are not organized for *collective action*. This limits the ability of manufacturers to undertake major research and development efforts for new advances on their behalf.

American aviation evolved as a close collaboration between the military and civilian aircraft firms. For example, in the 1920s and 1930s, the Navy's aviation leadership carefully planned and organized its procurement spending to nurture and build a strong network of aircraft and engine makers to assure the military of a strong industrial base of aircraft suppliers.[57] In the post-Cold War period, however, military and civilian aircraft markets increasingly diverged. The military required highly maneuverable supersonic aircraft with advanced avionics and fire control systems; civilian markets required stable, long-range reliable aircraft of limited maneuverability. Military jet engines were designed for maximum thrust, and civilian engines for low fuel consumption. The focus of military aircraft on

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stealth technology found no counterpart in civilian markets. The development of cruise missiles and precision-strike technologies, first exhibited during the Gulf War, allowed the military to significantly reduce the number of strike aircraft it required, further limiting the ability of aircraft makers to shift costs between the civilian and military sectors.

Even in military transport, the military's need for short-distance landing capability (C-17) created a divergence from civilian airliner prototypes that could use longer runways. Only aircraft types that could be used both for military tankers and civilian transport seemed readily transferable between the two sectors, but contracts for military tankers have been bogged down in a long-term procurement battle.[58] To be sure, some underlying technologies are transferable between sectors; composites, "fly by wire" (electronic as opposed to hydraulic controls), GPS navigation, and various engine advances have been shared. Overall, however, the close convergence and mutual support between the military and civilian sectors, which historically was highly productive, has declined significantly.

The aircraft manufacturing industry has consolidated as well. Boeing is the only remaining U.S. maker of civil aircraft, and there are only two U.S. jet engine makers. Globally, Europe has one civil aircraft maker and one engine maker, and those in Russia face financial challenges. There are makers of smaller civil transport aircraft in Canada and Brazil, component makers in Asia, and a potentially emerging aircraft sector in China. With the U.S. military's cancellation of the F-22 procurement for another generation of interceptors to replace the F-15, only one aircraft is now under development for the military: the F-35 Joint Strike Fighter. This aircraft has been long delayed, requiring a two-decade design and development process, and rapidly rising per-unit costs have sharply curtailed the volume of military purchases.[59] Aside from unmanned aerial vehicles (UAVs), which have limited civilian transferability, no new fixed-wing aircraft are under design in the United States for either civilian or military needs, probably for the first time in a century. Boeing is struggling to complete development and enter production for the 787 civilian airliners, and the military F-35; the drawing boards are largely empty.

While incremental advances are being obtained in composite materials and improved avionics, overall larger-scale innovation is on the decline in air transport. The cause is largely the market imperfection of *lumpiness:* the requirement of large-scale, engineering-intensive investments to develop advanced new aircraft prototypes. While supersonic airliners could cut travel time on long-distance routes, for example, these time efficiencies cannot be priced high enough to offset the major development costs and higher operating costs.

Breakthrough innovation is being sought in one area of aviation: developing a non-petroleum fuel source, essentially an innovation in the energy sector. As the military faces both strategic and tactical problems because of its petroleum dependence, it is working to develop biofuels for operational energy. It is reviewing applications for its tactical weapon systems, particularly aircraft, but also combat ships and vehicles, and supporting equipment. The Navy has been a leader;

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Navy secretary Ray Mabus has announced plans to operate a carrier task force, including its aircraft and support ships, on biofuels by 2016, and half of the rest of the fleet by 2020.[60]

Fuel constitutes some 40 percent of the civilian airline industry's costs; volatile oil prices have brought the industry to the brink of collapse several times in recent decades. Like the military, it is hungry for an alternative fuel. However, the civilian airline sector is undercapitalized and not equipped for *collective action* to undertake a research and development effort. Because of the vast number of existing aircraft and the low rate of fleet turnover, any alternative fuel that is developed must operate in existing engines. Engine makers are interested and prepared to cooperate, but are awaiting military research, development, and procurement.

While the civilian sector is ready to cooperate and very interested in the results, Defense Department (DOD) leadership will be mandatory if progress is to be made. The department could apply its traditional systems approach to this effort as it has in many other sectors. It could undertake the research, the development, the prototyping, the demonstrations, and the test bed analysis, and then create an initial market for a new technology. This system-wide innovation approach enabled the department to lead American technology advance in the second half of the 20th century in such areas as space, nuclear power, computing, and the Internet. What are the issues facing DOD if it were to undertake such an approach in biofuels?

The established Fischer-Tropsch methods of processing coal, biomass, or a combination for biofuels have limited advantages for reducing greenhouse gas emissions.[61] Therefore, interest has shifted to research and development in hydrotreated renewable jet fuels.[62] Among these, algae may be the most promising biofuel candidate, because it has a high oil content and does not require the diversion of croplands for production. However, the research and development in this area will require considerable time and additional investment; it will need to drive down production costs to be competitive with oil. A recent RAND study[63] has found that the prospects are uncertain for commercial production of alternative fuels at a level adequate to meet military goals by 2020. Efforts by the military to test and certify alternative fuels are ahead of actual commercial development and new infrastructure for such fuels. The RAND authors also argue, although some in the military argue otherwise, that DOD goals for alternative fuel use in tactical weapons systems should be based on potential national benefits because the department itself can likely continue to access petroleum fuels despite any supply threat; it can obtain priority access even if it has to pay a premium price.

Air transport faces impediments to innovation due to the requirement for *economies of scale*, and therefore may require special intervention to bring down unit costs, improve performance, or organize the market for complementary products and infrastructure. This, combined with the impediment of *lumpiness* in the form of the requirement for massive engineering-intensive investments, makes innovation increasingly difficult. Traditionally, such innovation has evolved through military support of the sector. But the introduction of new military air-

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craft has dramatically slowed and new civilian air transport aircraft introductions have slowed in parallel. The most significant area of pending innovation for aircraft is a shift to biofuels from petroleum fuels. As suggested above, these benefits are significant: reducing the highly deleterious economic effects on civilian (and military) air transport of petroleum-only fuel dependence, with the corresponding societal benefits of a stronger air transport system, as well as aiding in the externalities problem of reduced CO emissions. However, only the military is equipped to introduce the large-scale and systemic investment required. The civil transport sector is ready to cooperate, but it remains to be seen whether the military will muster the scale of effort required. This constitutes an innovation impediment due to *non-appropriability;* neither the private nor the governmental aviation sectors may be able to fully realize the societal or economic benefits.

OVERCOMING LEGACY BARRIERS

Innovations in CELS thus call for a somewhat different approach from the "standard model" innovations that have been the major preoccupation of innovation theory. In these sectors, policy interventions are essential on both the supply and the demand sides: on the one side to promote improvements in scientific knowledge and technological performance, and on the other to overcome the advantages enjoyed by entrenched legacy technologies. Ideally, the two sets of measures should be put into practice together at more or less the same time, since both are likely to take some years to have practical effect. In practice, however, the vagaries of politics may dictate that only one or the other of the two—i.e., either research support or policy change—may turn out to be practicable at any given time. In that case it would be worthwhile to support the one that shows signs of political support in the anticipation that the other will gain momentum from the advance of the first.

In previous work, we have set forth categories of policy interventions and related them to the obstacles faced by different alternative technologies as they neared market launch. Here we expand and refine this approach by relating each category to our analysis of the structure of the market for technology. In brief, "standard model" innovations face the imperfections associated with the "quasi-free market" for technology, some of which favor innovation while others pose obstacles to it. "Paradigm-consistent" innovations face additional obstacles due to perverse incentives that help to entrench the prevailing structure. "Counter-paradigm" innovations face still further obstacles and may require further analysis to identify the particular market imperfection or government failure responsible for these obstacles.

We see five broad categories of policy interventions to encourage innovation.[64] The first of these consists of "*front-end, supply-side*" policy measures that can be applied to virtually all innovations, whether standard model, paradigm consistent, or counter-paradigm. These include direct government support for research and development, technology prototyping, and demonstrations.

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Innovations that seek to penetrate CELS, on the other hand, require demand-oriented measures to overcome the extra barriers we have discussed in earlier sections of this paper. This is the case for both paradigm-consistent and counter-paradigm innovations. This second category consists of policy changes to *level the playing field*, through such measures as halting fossil fuel subsidies and imposing a carbon charge (for alternative energy) or performance-based medical fees (to encourage "high-touch" medicine).

Such measures are important long-run elements of any strategy to encourage innovations that seek to penetrate CELS, including innovations that fit into the relevant paradigms and that therefore have the potential to expand into disruptive innovations from initial niche markets.[65] All of these technologies face well-defended perverse subsidies or price structures that favor existing technology. Policy measures to level the playing field therefore threaten a variety of interests and face considerable political opposition. For this reason, it may be politically more tractable—although economically less efficient—to provide incentives or regulatory requirements in order to counter the advantages enjoyed by legacy technologies.

The third and fourth categories—discussed below—consist of "*back-end*" or "*demand-side*" *policy measures.* The third category consists of *incentives* that encourage the adoption of a technology as it moves to commercialization—on the "back end" of the innovation system. Such "carrots" can encourage a range of activities, from secondary or component technologies, to incremental engineering advances, to fostering manufacturing processes and scale-up. The incentives could include tax credits of various kinds for new technology products, loan guarantees, low-cost financing, price guarantees, government procurement programs, buy-down programs for new products, and shared benefits for encouraging collective action.[66]

Of these measures, one of the most powerful is the use of government purchasing power to create a market for a specified technology, or for any technology that can meet a specified performance standard.[67] The Department of Defense is the nation's largest owner of buildings and facilities and could specify that a percentage of military housing or other buildings must be powered by renewable energy to meet emissions reduction targets, or that a proportion of military vehicles and ships must be powered by biofuels. This would assure industry of a market of sufficient scale to justify investment in the necessary research, development, and manufacturing capacity. In tight fiscal periods like the present, this may be the most effective way to mobilize funds to support innovation. The Defense Department could also use its facilities as an efficiency test bed, and in effect generate guidelines available for the entire building sector on efficiency and cost savings for particular technologies.[68]

The fourth category of policy measures consists of "back-end" *regulatory and related mandates* that create pressure to adopt technologies that are likely to be opposed by legacy firms in the established sector. These could include, for example, standards for particular energy efficiencies for automobiles and appliances, or

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in the building and construction and comparable sectors. Alternatively, it could involve a straightforward requirement that alternative technologies be used—as in requirements in many states that a certain percentage of electricity be generated from renewable energy ("renewable portfolio standards"), or that the use of an established technology be banned outright, as in the federal legislative ban on incandescent light bulbs. Demand-side pricing strategies, such as the use of a carbon charge, represent another approach, which can be economy-wide rather than sector-specific.

The fifth category consists of policy measures suitable to overcome the market imperfections we identified earlier in this paper as specific to counter-paradigm innovations in CELS. We have already discussed these in connection with the individual sectors we reviewed, and we summarize some of them briefly here. Achievement of *network economies* can be facilitated by imposition of or agreement on standards for performance and interoperability. Large demonstrations in *lumpy* sectors, like those for carbon sequestration, can be funded by public-private partnerships. Problems of *non-appropriability* (i.e., split incentives) can be overcome by schemes to finance the extra installation costs of conservation measures at favorable rates—a form of subsidy—or information technology for health information. Transaction costs that impede *collective action*, such as measures of energy conservation on buildings, can be mitigated by providing information via publicly funded websites or technical assistance.

In our previous work, we set forth a series of four analytical steps that can be applied to identify barriers to innovation and the policy measures and institutional changes needed to help overcome them. We applied these to the energy sector.[69] In the *first step* of this analysis, we assessed promising technologies that could foster significant innovation in each sector and classified them into groups that face the same obstacles to market launch. In the *second step,* we matched support policies for encouraging innovation to the technology groupings developed in the first step of the analysis. In this paper, we propose applying these steps to other CELS.

In the *third step* of our energy analysis, we surveyed existing institutional and organizational mechanisms to support innovation, to determine what kinds of innovations (as classified by the likely impediments in their launch paths) do not receive federal support at critical stages in the overall innovation system. This could be described as an institutional "gap analysis." This third step requires analysis in each of the sectors we have reviewed. In the building sector, for example, we lack institutions that can implement test beds to develop the price and efficiency data that would enable this highly dispersed sector to implement new efficiency technologies.

In the *fourth step* of our energy analysis, we recommended new institutions and organizational mechanisms to fill the technology gaps identified in the third step, on both the front and back ends of the innovation system. In the sectors reviewed in this paper, the gaps might include mechanisms to provide translational research, technology financing, or technology roadmapping. Many sectors lack an overall collaborative strategy, for example, between the public and private sec-

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tors to develop a strategy and eventually a roadmap of the details involved in developing and deploying new technologies at scale, in order to overcome the barriers we have discussed. This step, too, requires further analysis, sector by sector.

In all the sectors we have discussed, we see major potential advantages to international collaboration, not only with developed countries or regions like Europe, Japan, and Australia, but also with "innovative developing countries" like India and China. First, all of these countries are undertaking major investments in research, development, and innovation, so that we in the United States have much to learn from them. Indeed, these countries may well out-compete the United States in these areas in both the short and long run if we do not mount a serious research, development, and innovation effort. Second, the technologies we have been discussing are not only sources of national competitiveness and employment, but are also global public goods. We have an interest in the implementation of environmentally sustainable technology all over the world—especially technologies that mitigate the emission of carbon dioxide into the shared atmosphere. This means that we must seek a balance between innovation that results in jobs and economic growth at home—a major incentive for technological progress and implementation—and the world-wide implementation of carbon-saving technology.

STRUCTURING TECHNOLOGY REVOLUTIONS IN LEGACY SECTORS

The information revolution is the prototype for the American conception of a technological revolution. Telecommunications, retail, brokerage, publishing, government, even social interactions all have been transformed by this seemingly unstoppable juggernaut. Yet the fossil-fuel based energy economy, the health-care delivery system, the long-distance electric grid, the building industry, and air transport—sectors that are critical to U.S. economic growth and quality of life—have not undergone comparable transformations, and indeed have successfully resisted or avoided such major technological change.

The framework we have developed makes it clear that innovations in these apparently unrelated sectors share common obstacles to market launch, and that this resemblance exists because such innovations are all attempting to enter one or another CELS. These obstacles exist in addition to those facing "standard" innovations that do not seek to penetrate this kind of well-defended technological/economic/political paradigm.

The obstacles faced by innovations in these sectors are well known to specialists in individual fields but have not been studied by more general innovation theorists in the United States.[70] As a result, policy-makers seeking to promote overall innovation in the U.S. economy tend to stress the better-studied problems facing what we have called "standard" innovations. This has its advantages as a political strategy. It is easier for legislators to vote money for research, development, demonstration, and (in special cases) even for venture capital, than to tackle the underlying structure of subsidies, regulations, infrastructure, and other market

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imperfections that favor, for example, fossil fuels, procedure-intensive medicine, or a fragmented long-distance electric grid.

Still, the policies that reinforce the prevailing paradigm—and the political forces that underlie them—must eventually be addressed. From the strategic point of view, moreover, these measures are consistent with the likely lead time between support to research and development and the achievement of practical results—a lead time that may well turn out to be comparable with the time it takes to develop popular and political support for the policy changes needed to allow a technology revolution in these sectors.

The common barriers we have identified should make it easier to identify policy measures suited to the special features of each legacy sector, and to transfer the lessons of experience from one such sector to another. The four-step strategic analysis we have set forth may help guide processes to resolve the barriers to the innovations needed in legacy sectors. To tackle these sectors we must expand our innovation theory toolset to include not only the technology policy framework of the past three decades, and the *valley of death* between research and late stage development, but also the problem of *market launch* into established sectors. Technology revolution in CELS is so essential to future American economic growth that the special hurdles facing innovation in these fields must be consciously recognized and addressed by innovators and policymakers. Otherwise, we cannot fully realize the economic and social well-being that we have built in the past half-century around broad applications of technological innovation.

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2. Charles Weiss and William B. Bonvillian, *Structuring an Energy Technology Revolution* (Cambridge, MA: MIT Press, 2009), 6, 29–30, 38.
3. William B. Bonvillian and Charles Weiss, "Taking Covered Wagons East: A New Innovation Theory for Energy and Other Established Technology Sectors," *Innovations* no. 4 (Fall 2009), 289–300. The reference is to hypothetical technology pioneers who, having driven their metaphorical covered wagons westward to the new frontier, go back over the mountains to the eastern United States whence they came, to insert their technologies into the legacy sectors they earlier left behind.
4. Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 34, 37–55.
5. By public intervention, we mean intervention by any entity not motivated by private profit: i.e., government, inter-governmental or non-governmental organizations, private foundations, or even individual philanthropists.
6. This argument builds on the paradigm concept used by Perez, *Technological Revolutions*, 15ff.
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11. Suzanne Berger, *How We Compete: What Companies around the World Are Doing to Make it in Today's Global Economy* (New York: Doubleday Currency, 2005), 59–92, 251–277.
12. Douglas K. Smith and Robert C. Alexander, *Fumbling the Future* (Lincoln, NE: iUniverse 1999); Warren Bennis and Patricia Ward Biederman, *Organizing Genius: The Secrets of Creative Collaboration* (New York: Basic Books, 1997), 63–86. The only exception was the laser printer, which Xerox did market.
13. William B. Bonvillian, "The Connected Science Model for Innovation: The DARPA Model," in *21st Century Innovation Systems for the U.S. and Japan*, ed. Sadao Nagaoka, Masayuki Kondo, Kenneth Flamm, and Charles Wessner (Washington, DC: National Academies Press, 2009), 206–237. Available at http://books.nap.edu/openbook.php?record_id=12194&page=206.
14. Rick E. Yanuzzi, "In-Q-Tel: A New Partnership Between the CIA and the Private Sector," *Defense Intelligence Journal* 9, no. 1 (2000); Glenn Fong, The "CIA in Silicon Valley: In-Q-Tel & the Search for a New Government-Industry Partnership," paper presented at the annual meeting of the International Studies Association, Honolulu, March 5, 2005. Available at http://www.allacademic.com/meta/p71327_index.html.
15. William B. Bonvillian, "Will the Search for New Energy Technologies Require a New R&D Mission Agency?" *Bridges* 14 (July 2007). Available at http://www.ostina.org/content/view/2297/721/.
16. Melissa Schilling, *Strategic Management of Technological Innovation*, 86–97.
17. The military establishes a variation of the quasi-free market when it is the initial customer for technologies or equipment, including via "fly-offs" between competing designs and "second sourcing" from competing manufacturers.
18. The pipeline and induced innovation models that govern "standard model" innovations are discussed at length in Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 13–36.
19. Vernon Ruttan, *Technology, Growth and Development: An Induced Innovation Perspective* (New York: Oxford University Press, 2001).
20. Geoffrey A. Moore, *Crossing the Chasm: Marketing and Selling Technology Products to Mainstream Customers*, rev. ed. (New York: Harper Business, 1999).
21. Vernon Ruttan, *Is War Necessary for Economic Growth?* (New York: Oxford University Press, 2006); Jonathan Zittrain, *The Future of the Internet and How to Stop It* (New Haven, CT: Yale University Press, 2008).
22. Clayton Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Boston, MA.: Harvard Business School Press, 1997). See also footnotes 40, 42, and 65.
23. Frederick Betz, *Strategic Technology Management* (New York: McGraw-Hill, 1993), 20–22.
24. Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 26–28; William B. Bonvillian, "Power Play: The DARPA Model and U.S. Energy Policy," *The American Interest* (Nov.–Dec., 2006), 40–47.
25. Bennis and Biederman, *Organizing Genius*, 196–218.
26. A perverse subsidy as originally defined is a subsidy that encourages behavior contrary to public policy, for example, for overgrazing or deforestation. See Norman Myers and Jennifer Kent, *Perverse Subsidies: How Tax Dollars Can Undercut the Environment and the Economy* (Washington, DC: Island Press, 2001). These subsidies are technically market imperfections, since they shift prices, and hence supply and demand, away from what they would be in the absence of the subsidy.
27. These imperfections may also hinder innovations that do not face the full panoply of a CELS. Mobile telephony, for example, spread more rapidly in Europe and the Far East than in the United States in part because the early adoption of agreed technical standards facilitated the achievement of network economies. For the same reason, radio frequency identification tags

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(RFIDs) required industry-wide standards for their acceptance. See, generally, Rob Atkinson, "RFID: There's Nothing to Fear Except Fear Itself," speech at the 16th Annual Computers, Freedom and Privacy Conference, May 4, 2006, 3. Available at http://www.itif.org/files/rfid.pdf. Examples of the need for collective action to support innovation are found in such disparate industries as organic agriculture, home building design, and municipal garbage collection.

28. For recent efforts at NIH on translational medical research, see Gardiner Harris, "Federal Center Will Help Develop Medicines," *New York Times*, January 22, 2011. Available at http://www.nytimes.com/2011/01/23/health/policy/23drug.html?_r=1; Carla Garnett, "Collins Gives Update on NCATS at Town Hall Meeting," *NIH Record* 63 no. 7, April 1, 2011. Available at http://nihrecord.od.nih.gov/newsletters/2011/04_01_2011/story1.htm.
29. While innovative sectors like semiconductors, biotechnology, and pharmaceuticals spend 15 percent or more of annual revenues on R&D, and the U.S. industry average as a whole is 2.6 percent, the energy sector average is less than 1 percent. Gregory Nemet and Daniel Kammen, "U.S. Energy R&D: Declining Investment, Increasing Need and the Feasibility of Expansion," *Energy Policy* 35 (2007): 747.
30. Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 73–79.
31. Christensen, *The Innovator's Dilemma*, xviii–xxiv.
32. Moore, *Crossing the Chasm*.
33. Everett M. Rogers, *Diffusion of Innovations* (Glencoe, NY: Free Press, 1962).
34. The applicability of this framework need not be limited to complex established sectors. Cell phones, for example, are an example of a network-enabled innovation, and indeed, their rapid deployment in Europe can be ascribed to the rapid adoption of a uniform standard.
35. This variant of the market imperfection of non-appropriability is known technically as a "split incentive" or a "positive pecuniary externality," an externality where the benefits of an economic decision accrue to others who are separated from the transaction or investment. Typically these benefits operate through pricing mechanisms rather than through actual resource or technical advantages. See, for example, Christiano Antonelli, "Pecuniary Externalities: The Convergence of Directed Technological Change and the Emergence of Innovation Systems," Bureau of Research on Innovation, Complexity and Knowledge (BRICK) Working Paper #3, (February 2008), 1–4. Available at http://www.carloalberto.org/files/brick_03_08.pdf.
36. This well-established paradigm favors input-intensive, industrial agriculture over organic agriculture, but this is another story, one worthy of further analysis along the lines of this paper.
37. Larry Browning and Judy Shetler, *Sematech: Saving the U.S. Semiconductor Industry* (College Station, TX: Texas A & M Press, 2000).
38. This theme is explored in depth in Weiss and Bonvillian, *Structuring an Energy Technology Revolution*; Bonvillian and Weiss, "Taking Covered Wagons East."
39. Policy prescriptions in energy are discussed in detail in Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 37-56, 151-190.
40. The problems facing innovations in the American system of health-care delivery are discussed in detail in Clayton M. Christensen, Jerome H. Grossman, and Jason Hwang, *The Innovator's Prescription: A Disruptive Solution for Health Care* (New York: McGraw Hill, 2009).
41. In 2009, Congress attempted to reform the system through the Patient Protection and Affordable Care Act of 2010, P.L. 111–148, which was signed into law March 23, 2010. This legislation passed on party-line votes that threaten the long-term political viability of the reforms. It expanded the scope of the entitlements in an attempt to resolve a fundamental structural problem in the system: the forty million people outside the existing system, who face inadequate care because they lack affordable coverage. This expanded coverage was also included to build political support for the legislation. Overall, the legislation focused more on rearranging the system's financial plumbing than on confronting the contradictions between fee-for-service and performance and efficiency. Although it included provisions on the effectiveness of health care and on IT-based records, it did not focus strongly on ways to innovate, either in new medical technology or delivery systems.
42. Christensen and his colleagues propose a major restructuring and rationalization of the U.S.

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health-care delivery system to bring stakeholder incentives in line with the needs of overall system efficiency. Christensen et al., *Innovator's Prescription*; see especially chapters 6 and 7, and "Epilogue."

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45. MIT, *The Third Revolution: The Convergence of the Life Sciences, Physical Sciences, and Engineering.* White Paper, January 4, 2011. Available at http://web.mit.edu/dc/Policy/MIT%20White%20Paper%20on%20Convergence.pdf.
46. This summary relies on data and insights from Peter Fox-Penner, *Smart Power: Climate Change, the Smart Grid, and the Future of Electric Utilities* (Washington, DC: Island Press, 2010); Yinuo Geng, "Toward Implementation of the Smart Grid in the United States," unpublished paper, SAIS, Johns Hopkins University, October 13, 2010.
47. Mason Willrich, "Electricity Transmission Policy for America: Enabling a Smart Grid, End-to-End," MIT-IPC-Energy Innovation Working Paper 09-003, Cambridge MA: MIT Industrial Performance Center, July 2009, 7. Available at http://web.mit.edu/ipc/research/energy/pdf/EIP_09-003.pdf.
48. Willrich, "Electricity Transmission."
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50. Clark W. Gellings and Kurt E. Yeager, "Transforming the Electric Infrastructure," *Physics Today* 57, no. 12 (December, 2004): 45–51.
51. American Recovery and Reinvestment Act (ARRA) of 2009, P.L. 111–5.
52. Energy Information Agency, "Emissions of Greenhouse Gasses in the United States 2001," Report No. DOE/EIA-0573(2001) Washington, DC: EIA, December, 2002. Available at http://www.eia.doe.gov/oiaf/1605/archive/gg02rpt/index.html.
53. McKinsey & Company, *Unlocking Energy Efficiency in the U.S. Economy*, iii–xiv.
54. S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science* 305 (13 August 2004), 968–972.
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56. McKinsey & Company, *Unlocking Energy Efficiency*, viii.
57. William F. Trimble, *Admiral William A. Moffett: Architect of Naval Aviation* (Annapolis, MD: Naval Institute Press, 2011), 111–199.
58. Peter Cohan, "Boeing's Big Tanker Contract Has National—and State—Winners and Losers", *AOL Daily Finance*, February 25, 2011. Available at http://www.dailyfinance.com/2011/02/25/boeing-airbus-tanker-contract-winners-losers/; Caroline Brother, "Boeing and Airbus Prepare (Again) for Tanker Battle," *New York Times*, June 16, 2009. Available at http://www.nytimes.com/2009/06/17/business/global/17boeing.html.
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required to purchase one F-35 aircraft. *The Economist* cites "Augustine's Law" in "Defense Spending in a Time of Austerity," August 26, 2010. Available at http://www.economist.com/node/16886851?story_id=16886851.

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62. Hydrotreated renewable jet (HRJ) fuel is a term used to describe any feedstock or process that leads to fuel that is chemically identical to crude oil-based kerosene, the standard jet fuel. The U.S. Air Force is testing such fuels derived from plant and seed oils, animal fat, and waste oils. A 50 percent biofuel blend of such oils and petroleum is expected to be approved for all Air Force jets by 2013.
63. James T. Bartis and Lawrence Van Bibber, *Alternative Fuels for Military Applications* (Santa Monica, CA: Rand, 2011), ix–xix. Available at http://www.rand.org/pubs/monographs/MG969.html.
64. This section expands on our discussions in Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 37–50, 151–191, and Bonvillian and Weiss, "Taking Covered Wagons East," 294–299.
65. Christensen and his colleagues, in their study of the U.S. health care delivery system, recommend that niche markets protected from regulatory obstacles be used as launching points for disruptive innovation. Such niches are valuable when they do exist, but they are likely to be unavailable to innovations seeking to penetrate at scale a full-fledged CELS paradigm as we have defined it. Christensen et al., *The Innovator's Prescription*, 385ff.
66. Particular "carrots" and "sticks" may fit one kind of firm but not another. For example, loan guarantees may work for major utilities building next-generation grid systems, but may not be as useful to small firms and startups with limited capital access that are deploying smart-grid IT systems for consumers. Analytical work is needed to evaluate the relative economic efficiency of particular back-end incentives or regulations.
67. John Alic, Daniel Sarewitz, Charles Weiss, and William Bonvillian, "A New Strategy for Energy Innovation," *Nature* 466 (July 15, 2010): 316–317.
68. The DOD has requested $30m in its FY12 Budget for Installation Energy Testbeds. See Statement of Dr. Dorothy Robyn, Deputy Under Secretary of Defense (Installations and Environment) before the Senate Armed Services Committee Subcommittee on Readiness and Management Support, March 17, 2011, 8–11. Available at http://armed-services.senate.gov/statemnt/2011/03%20March/Robyn%2003-17-11.pdf.
69. Weiss and Bonvillian, *Structuring an Energy Technology Revolution*, 37–50, 151–191; and Bonvillian and Weiss, "Taking Covered Wagons East," 294–299.
70. There is a rich scholarly literature on "socio-technical systems," typically emphasizing the historical and social dimensions of technological paradigms. See, for example, *Research Policy* 39, no. 4 (May 2010), 435-510 (special section); Knut H. Sorenson and Robin Williams, *Shaping Technology, Guiding Policy: Concepts, Spaces, Tools* (Cheltenham, UK: Edward Elgar, 2002).

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