William B. Bonvillian and Charles Weiss

Taking Covered Wagons East

A New Innovation Theory for Energy and Other Established Technology Sectors

Frederick Jackson Turner, historian of the American frontier, argued that the always-beckoning frontier was the crucible shaping American society.[1] He retold an old story, arguing that it defined our cultural landscape: when American settlers faced frustration and felt opportunities were limited, they could climb into covered wagons, push on over the next mountain chain, and open a new frontier. Even after the frontier officially closed in 1890, the nation retained more physical and social mobility than other societies. While historians debate the importance of Turner's thesis, they still respect it.

The American bent for technological advance shows a similar pattern. Typically, we find new technologies and turn them into innovations that open up new unoccupied territories—we take "covered wagon" technologies into new technology frontiers. Information technology is an example. Before computing arrived, there was nothing comparable: there were no mainframes, desktops, or Internet before we embarked on this innovation wave. IT landed in a relatively open technological frontier.

This has been an important capability for the U.S. growth economics has made it clear that technological and related innovation is the predominant factor driving of growth.[2] The ability to land in new technological open fields has enabled the U.S. economy to dominate every major Kondratiev wave of worldwide innovation

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In this article the authors draw on the more extensive discussions of their ideas in their new book, Structuring an Energy Technology Revolution *(Cambridge, MA: MIT Press, April 2009).*

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since the mid-19th century.[3] Information technology and biotech are the newest chapters in this continuing story.

REVERSING THE COVERED WAGONS: LANDING IN OCCUPIED TERRITORY

While we appear to have a capacity for standing up technologies in open fields to form new complex technology sectors, we have not been as good at taking our covered wagons back east. We find it hard to go back over the mountains to bring innovation into the already occupied territory of established complex technology sectors. In typical American fashion, we'd rather move on than move back. This helps to explain why a cab ride over the highway system from New York's Kennedy Airport into Manhattan has a distinctly Third World feel, or why Thomas Edison would be very comfortable with our current electrical grid.

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Of course, the story is more complicated than Turner's frontier thesis about American culture. It's hard to reverse the covered wagons and go back to occupied territory. Over time, established technology sectors develop characteristics that resist change. The underlying technologies themselves become cost efficient through standardization, and the phenomenon of "lock-in" sets in. Firms go through Darwinian evolution; the leading technology competitors survive, expand, and become adept at fending off new entrants. They build massive infrastructure that is resistant to competitive models, and they form alliances with government to obtain subsidies, typically through the tax system, to tilt the playing field toward their model.

In other words, established complex sectors, often themselves the result of earlier waves of innovation, combine into a technological/economic/political para-

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digm that is very difficult to unseat;[4] they plant a series of sophisticated minefields to protect their model and resist its disruption. This pattern applies to highly complex sectors of the economy where technologies are a factor; examples include energy, health care delivery, transport, construction, and physical infrastructure, education, and food and agriculture. A complex, established technology sector can be defined as one that involves products and platforms, that groups complex technologies in the way a car holds an internal combustion engine, drive train, battery, computers, fueling systems and tires. Complex sectors also have their own infrastructure, and are supported by established technologies, economic models, public policies, public expectations, patterns of technical expertise and trained workforces. In combination, these sectors become the technological/economic/political paradigm.

The concept of the complex sector is broader than that of complex technology introduced by Robert Rycroft and Donald Kash,[5] and is closer to Christopher Freeman's idea of technology clusters that dominate innovation waves.[6] The idea of such a sector has features in common with the idea of "dominant design," introduced by William Abernathy and James Utterbach[7] and based on Raymond Vernon's product cycle theory:[8] once such a paradigm has set in, the emphasis shifts away from innovation in the overall system towards component innovation in technologies that can be launched on existing platforms.

To be sure, the U.S. is not the only nation to experience the economic and political barriers of complex established sectors. Japan's economy would be stronger if it could bring IT-driven retail efficiencies to a nation of small shops or to pursue large-scale agriculture, not simply small family farms. The frontier thesis aside, innovation in established complex sectors becomes even more complex once technological lock-in has set in.

LESSON FROM CHINA

The remarkable, sustained, double-digit growth of the Chinese economy is due in part to the application of up-to-date technology to established sectors like transport, health care, construction, and energy. Chinese strategy for catching up to the developed economies is based on a unique model that calls for moving to and even extending the technological frontier in these and other sectors, even as it applies well-known technology to huge projects that will modernize its infrastructure. It has organized its economy with large doses of capital, labor, innovation and stern political directives, relying on a rapidly expanding private sector using up-to-date technology to provide the resources to support an inefficient public sector that it will eventually supplant. China's model of pervasive technology advance throughout its economy, of course, has a precedent. in the economy-wide catch-up approach in postwar Japan and in Korea in the 1970s and 1980s.

There is a lesson here for the U.S. If innovation is key to growth, and if a nation is bringing innovation into many sectors—both established sectors and those at the technological frontier—then it may be able to boost its growth rate significant-

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ly. U.S. growth might look different if we could find ways to cut the Gordian knots that tie up our ability to innovate in established complex technology sectors and bring innovation into those occupied territories, not just into the cutting economic edge of advances in new breakthrough technologies.

This might mean bringing innovation into our inefficient and expensive healthcare delivery system, along with new biotech-derived drugs. It could mean bringing IT simulations and game-based learning into K-12 education, or new materials and information technology into our transportation or construction infrastructure, or e-government into the widespread delivery of government services. The list of possibilities is long. Perhaps we could even take our innovation covered wagon back east and bring innovation into our complex, deeply entrenched, heavily subsidized energy sector.

UNIFYING THE THREE MODELS OF INNOVATION

In order to contemplate stretching our scientific and technological capabilities to established sectors of the economy, like energy, we need a working theory of innovation for these sectors. Its design depends on a clear concept of how technological innovation takes place in the sectors in response to market forces, and how this process can be influenced by public policy. We see three models of this process, each of them the product of a particular period of technological history.

The first of these models is the so-called pipeline or linear model, associated with Vannevar Bush,[9] in which basic research intended to push back the frontiers of knowledge leads to applied research, which in turn leads to invention, to prototyping, to development, and finally to innovation, by which we mean widespread commercialization or deployment. While subsequent literature showed that this process wasn't really linear—technology influenced science as well as the other way around[10]—"pipeline" is still the term generally associated with this technology supply approach.

This model was inspired by the World War II–era success of atomic energy, radar, and other technologies derived from advances in fundamental scientific knowledge;[11] it regained prominence in the 1990s from the example of the information revolution[12] and from the promise of similar revolutions in bio- and nanotechnology. In these examples, the government, and often the military establishment, played a prominent role in shepherding these technologies through the innovation process. This is a "technology push" model, with the government supporting R&D and to an extent helping push the resulting advances toward the marketplace.

The second of these models is the so-called induced innovation concept explored in detail by the late Vernon Ruttan,[13] in which technology and technological innovation respond to the economic environment. This concept holds that the technology in use in any economic sector—and, given enough time, the direction of development and research—responds to changes in the market, for example, to

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price signals by minimizing the use of expensive inputs and maximizing the use of inexpensive ones.

By extension, this model would predict that technology and technological innovation would also respond to the policy environment, for example by improving worker and product safety and decreasing pollution as policies in these areas are tightened. The induced innovation model was one of several models that responded to the realization that nations that were superior in basic research, such as the Great Britain of the 1950s and 1960s, were not necessarily leading innovators, and that a majority of new products used existing technologies to meet new market needs rather than emerging from basic research. This model involves "market pull": the market inspires and pulls technological innovations from firms toward implementation in the market.

The third concept can be only sporadically glimpsed in the innovation literature.[14] However, we argue that innovation requires not only technology supply and a corresponding market demand for that technology, but also organizational elements that are properly aligned to link the two. There must be concrete institutions for innovation, and organizational mechanisms connecting these institutions, to facilitate the evolution of new technologies in response to the forces of technology push and market pull. We need this third element in our innovation model framework: the idea that innovation requires organizations anchored in both the public and private sectors, to form the new technology and to launch it, if innovation theory is to be practical, creating ideas we can actually implement.

These three theories fit into a historical context. The induced technology model was partly a product of the historical perspective of the 1960s through the 1980s, with advances derived largely from incremental gains in existing technology. Throughout that era, of course, the kind of innovation described by the pipeline model was humming along, bringing out an IT revolution in the 1990s after decades of government R&D inputs. While the induced model best fits incremental innovation, the pipeline model best fits breakthrough or radical innovation. Underlying both of these developments were organizational issues, vital for our innovation system, yet largely unexplored.

The induced and pipeline models have been viewed as separate and distinct paths, one led by industry, the other largely by government. We must combine and integrate these induced and pipeline innovation models if we are to adequately describe the innovation framework we will require for innovation in energy or other complex technology. The induced technology literature has rested primarily on market pull and the role of firms in filling technology needs based on changing market signals. It does not deal directly with the role of government. The pipeline literature, in contrast, discusses the government role. A focus on the organization for innovation offers us the opportunity to bring these separate strands together. Although the literature is limited, the organization of innovation at the institutional level reflects on connections between firms, the academy, and government entities like the Defense Advanced Research Projects Agency (DARPA).

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Firms, universities, and government organizations will be major players in new energy technology. What is more, the dominant literature on technological innovation in recent years has remained focused on the strengths and weaknesses of the pipeline model, because of the importance of the IT and the biotech innovation waves for which this model provides a good description. This pipeline literature pays too little attention to how the overall economic and policy environment affects technological innovation in complex networks of both related and unrelated technologies, and the induced model often pays too little attention to the governmental role.[15] To date neither has focused much on the third direction, innovation organization.

In sum, the literature on innovation policy, whether pipeline, induced, or organizational, has not fully confronted the problems involved in complex technology sectors. These sectors require a very different analysis from the three separated strands that have been the focus of the American literature on technological innovation. Each of these models does helpfully describe aspects of the innovation process relevant to energy technology. But only by integrating all three in a unified approach can we move toward a better grasp of the task before us: innovation in a complex established sector. Indeed, in taking on this task we will be able to draw a new series of policy prescriptions quite different from the approaches that have been articulated to date in other sectors.

INNOVATION IN ENERGY: THE FOUR-STEP ANALYTIC FRAMEWORK

The most difficult step in developing and deploying new technology in energy and other complex, established sectors will be launching these technologies into extremely complex and competitive markets for technology. This "point of market launch" perspective is the basis for our argument that any program of government support for innovations in these technologies should be organized around the most likely bottleneck to their introduction to the market.[16] This goes beyond the long-standing focus of pipeline theorists on the valley-of-death stage between research and late-stage development.[17]

We start with the principle that public policies to encourage technological innovation should enable alternative technologies to compete on their merits; that is, they should be as technology-neutral as possible. This leads us to argue for an integrated consideration of the entire innovation process, including research, development, and deployment or implementation, in the design of any program to stimulate innovation in energy or any other complex, established technology. This requires drawing on both pipeline and induced innovation models. In addition, we see deep systems issues of organization for innovation that must be considered, because new organizational routines will be needed across both the public and private sectors to facilitate integrated policies to support innovation.

These considerations lead to a new framework for innovation policy, which we have worked out in some detail for energy technology. It requires a four-step analy-

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sis, which we propose as the basis for innovation policy in this area. We believe that a similar approach is likely to be applicable to technological innovation in sectors of comparable complexity.

The **first step** of this analysis requires assessing many promising technologies, based on the likely bottlenecks in their launch path, and classifying them into groups that share the same likely bottlenecks. For the energy sector, we found the following technology pathways:

Experimental Technologies. This category includes experimental technologies that require extensive long-range research. The deployment of these technologies is sufficiently far off that the details of their launch pathways can be left to the future. Examples include hydrogen fuel cells for transport, genetically engineered bio-systems for CO_2 consumption, and, in the very long term, fusion power.

Disruptive Technologies. These are potentially disruptive technological innovations[18] that can be launched in niche markets and that may expand from this base as they become more price-competitive. Examples include LEDs and wind and solar electric, which are building niches in off-grid power.

Secondary Technologies—Uncontested Launch. This group includes secondary (component) innovations that will face market competition the moment they are launched, but will likely be acceptable to recipient industries if their price range is reasonable. These technologies must face the rigors of the tilted playing field, such as a competing subsidy or the obstacle of a major cost differential, without the advantage of an initial niche market. Examples include advanced batteries for plug-in hybrids, and enhanced geothermal and on-grid wind and solar technologies.

Secondary Technologies—Contested Launch. These are secondary (component) innovations that have inherent cost disadvantages, and/or that can be expected to face economic, political, or other non-market opposition from recipient industries or environmental groups. They must overcome these obstacles in addition to those facing the technologies in the two preceding categories. Examples include carbon capture and sequestration, biofuels, and fourth-generation nuclear power.

All four of above categories segment evolving technologies into different launch pathways, so that relevant policies for each can be designed to support their launch. A significant majority of energy technologies now contemplated are component or secondary technologies that fall into the third and fourth categories above. This complicates the technology launch picture because component technologies will not land in open frontiers, but will land in existing systems or platforms—that is, in occupied territory. While the potential for disruptive technologies that can open new energy frontiers will increase, that opportunity will take time to evolve.

There are two other categories that must be accounted for. These are crossovers because they include the above new technology categories as well as existing energy-related technologies:

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Incremental Innovations in Conservation and End-Use Efficiency. For the energy sector, a focus on conservation and end-use efficiency can yield early and widespread gains. The implementation of these innovations is limited by the short time horizons of potential buyers and users, who typically refuse to accept extra initial costs unless the payback period is very short. Examples include improved internal combustion engines, building technologies, efficient appliances, improved lighting, and new technologies for electric power distribution.

Improvements in Manufacturing Technologies and Processes. These are improvements for which investment may be inhibited because cautious investors are reluctant to accept the risk of increasing production capacity and driving down manufacturing costs until they see an assured market. To drive down costs and improve efficiency will require advances in both manufacturing processes and technologies appropriate to the new energy technologies summarized above; support will also be required to scale up manufacturing so that efficient new products can move into the market more quickly.

The **second step** of our analysis is to classify support policies for encouraging energy innovation into technology-neutral packages, and then to match them to the technology groupings developed in the first step of the analysis. Here we see three policy elements.

"*Front-End*" *Technology Nurturing.* For technologies in all six of the categories above, technology support is needed on the front end of innovation, before a technology is close to being commercialized. This includes direct government support for R&D in both the long term and short term, and for technology prototyping and demonstrations.

"*Back-End*" *Incentives.* Incentives (carrots) to encourage technology transition on the "back end" may also be needed as a technology closes in on commercialization. Such carrots can encourage secondary/component technologies facing both uncontested and contested launch, along with incremental innovations in technology for conservation and end use, and technologies for manufacturing processes and scale-up. They may also be relevant to some disruptive technologies as they transition from niche areas to more general applicability. These incentives include tax credits of various kinds for new energy technology products, loan guarantees, low-cost financing, price guarantees, government procurement programs, buydown programs for new products, and general and technology-specific intellectual property policies. As one example, procurement by the U.S. Defense Department, the nation's largest owner of buildings and facilities, could offer potential energy cost savings to the department over time by using its facilities as an efficiency testbed, and could help ascertain the optimal approaches to building technology. However, there are challenges: How can abuses be avoided that may arise in deviating from lowest-cost procurement criteria? How could such procurement be reconciled with the technology-neutral strategy advocated here? Despite potential complications, this may be one of the better levers for lifting energy infrastructure out of the current technology "steady-state."

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"*Back-End*" *Regulatory and Related Mandates.* Regulatory and related mandates (sticks), also on the back end, may be needed in order to encourage component technologies facing contested launch and also some conservation and end-use technologies. These include standards for particular energy technologies in the building and construction and comparable sectors, regulatory mandates such as renewable portfolio standards and fuel economy standards, and emission taxes.

Just as there is no "one-size-fits-all" R&D program, which requires R&D efforts to be tailored to particular technology categories, so particular "carrots" and "sticks" may fit one group of technologies but not another. Loan guarantees may work for major utilities building next generation nuclear power plants, but likely will not be useful to small firms and startups with limited capital access deploying new solar technologies. Analytical work is needed to evaluate the relative economic efficiency of particular back-end incentives or regulations. It should be noted, too, that in the energy sector, a system of carbon charges, such as a cap-and-trade program, can substitute for many (although certainly not all) of the back-end proposals listed above, both carrots and sticks, because it would induce similar effects.

As suggested in the previous section, the optimal approach to bringing innovation into complex, established sectors would bring to bear three models of the innovation process: the induced, the pipeline and the organizational models. A technology supply approach is unlikely to be effective unless it is accompanied by the demand-side price signals called for by the induced innovation model. Even when they are technically ready, new entrants cannot compete on price with existing mature, efficient, and cheap energy technologies because the fossil fuel-based industry does not have to pay for the environmental and security externalities that it can now avoid. On the other hand, induced innovation depends on a robust technology supply program, supported by a strong pipeline innovation system, to enable the technologies that are needed to create alternatives and drive down costs. This is particularly true when the technology transformation being sought is as dramatic as the one we seek in energy. Innovation in a complex sector like energy is not either/or—both the induced and pipeline models are required.

Let's examine a concrete and current policy example for this balance. To induce an energy transformation, Congress has focused on a cap-and-trade approach intended to send pricing signals that increase demand for new energy technologies and efficiencies. It has preferred this approach to a carbon tax or to higher gas or other sector-specific taxes, which it considers to be more politically onerous. On June 26, 2009, the House of Representatives passed by a narrow margin a cap-and-trade bill, HR. 2454. As a result of political compromises with affected industries and interests, the economic pressures to reduce greenhouse gasses in the early years of the bill will be limited, because the "cap" tightens only gradually and the auctions scale up only over time. The House bill is also limited in its application of the pipeline model—i.e., on the technology-supply side—in that it provides only a marginal increase in energy R&D and includes provisions for technology implementation that back only a limited range of technologies—namely, those sought

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by politically powerful industries: coal, oil refinery, and automobile. The approach in the House bill, then, is tilted toward a gradually phased-in induced model; it is not balanced with a strong technology supply model.

The third element in the trio of models of the innovation process must now be introduced: the organizational model. The **third step** of our analysis, then, is to survey existing institutional and organizational mechanisms for the support of innovation, to determine what kinds of innovations (as classified by the likely bottlenecks in their launch paths) do not receive federal support at critical stages of the innovation process, and what kind of support mechanisms are needed to fill these gaps. This could be described as an institutional gap analysis. In energy, for example, we do not have the capacity to translate our research into innovation, to finance the scale-up of promising technologies, and to form an overall collaborative strategy between the public and private sectors to roadmap the details involved in developing and deploying the new technologies at scale.

> Where complex technology sectors like energy are involved, we need to have Congress legislate standard packages of incentives and support across common technology launch areas, so that some technology neutrality is preserved and the optimal emerging technology has a chance to prevail.

The **fourth step** in our analysis is to recommend new institutions and organizational mechanisms to fill these technology gaps identified in the third step, by providing translational research, technology financing and roadmapping.

To summarize, the first of these four steps draws on pipeline theory, suggesting that support from the government pipeline will be important to creating, launching, and enhancing a range of technology options. But since the technology streams will need to land in the private sector at a huge scale, the second step relies on induced innovation theory. It concentrates on the policy or demand signals that will induce the private sector to take up, modify, and implement the technology advances that originate from the innovation pipeline. Whether these come from a demand pricing system like the cap-and-trade scheme proposed for carbon-based energy, from technology incentives, or from regulatory requirements, they will need to be coordinated and, to the extent possible, will need to be technology neutral. The third and fourth steps draw on the innovation organization theory we advanced here: that the gaps in the innovation system will need to be filled for the

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handoff to occur between pipeline and induced models, especially at the points where technology supply push meets market demand pull.

This proposed new integrated framework has implications beyond policy theory; it also leads to a different logic for the practical design of technology legislation. In effect, our discussion of steps one and two implies that the current legislative process for technology innovation in energy is exactly backwards. The incentive structure should be legislated first in a way that will preserve the fundamental technology neutrality needed in this complex technology area, rather than the present practice of legislating separately for each technology first, with a different incentive structure for each one. This unfortunate process has become a standard model for innovation legislation, for example, in the major energy acts of 2005 and 2007.[19]

In contrast, where complex technology sectors like energy are involved, we need to have Congress legislate standard packages of incentives and support across common technology launch areas, so that some technology neutrality is preserved and the optimal emerging technology has a chance to prevail. Particular technologies can then qualify for these packages based on their launch requirements. It is important to get away from the current legislative approach of unique policy designs for each technology, often based on the legislative clout behind that particular technology.

APPLYING INTEGRATED INNOVATION ANALYSIS TO COMPLEX SECTORS

The American economy would be well served if it developed a capacity to move technological innovation more efficiently into established, complex economic sectors like energy. Our traditional model for innovation relies on launching innovation into open fields; we could improve our innovation-based growth rate if we learned how to drive our technology-laden covered wagons into old frontiers as well as new. This requires a new innovation framework, which integrates the three separate models for innovation we have articulated: the pipeline and induced models, and the model for institutional organization of innovations that backs them up. This framework requires a new focus on the moment of technology launch, as well as on the traditional focus of innovation policy on the "valley of death."

But even if we equip ourselves with a new model for innovation policy in complex established sectors like energy or health care delivery—for taking our technology covered wagons east—we should not underestimate the difficulty of the process for introducing new technology at the massive scale demanded. In energy, this process has eluded us for the last four decades. These complexities underscore the need for a comprehensive new theoretical approach.

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