Creating Technological Momentum: Lessons from American and Danish Wind Energy Research

by Benjamin K. Sovacool and Janet L. Sawin

Are researchers, public policymakers, and political scientists aware of the factors that lead to the successful diffusion of energy technology? In attempting to address energy and climate challenges, the research process in the United States and other industrialized countries has often been rooted in distinct assumptions concerning science, technology, methodology, scale of implementation, and agents of action.[1] Many researchers, directors, and even scholars have implicitly promoted a linear model of technological development that views government-funded programs as the ideal means of developing new technologies and systems and prioritizes economies of scale and centralization of the research process to achieve ever-larger units. According to this paradigm, the government's role is to eliminate obstacles to energy development and work with large corporations to prepare new technologies for entry into the market.

However, the evolution of wind energy technology in Denmark, represents an exception to this linear approach to energy research and diffusion. Denmark's scientists pursued a bottom-up, decentralized research strategy that was more flexible and involved transparency, information sharing, and experimentation by those in the field. This led to the creation of more advanced and cost-effective wind turbines. Between 1975 and 1988, the US government spent twenty times as much as Denmark on wind power research, funding highly centralized and hierarchical programs. Yet, by 1990, Danish manufacturers were making better turbines than US manufacturers and dominated the world market, supplying 45 percent of the world's turbine capacity.[2] Direct US government expenditures on wind energy research from 1970 to 2007 totaled $1.4 billion, exceeding spending by all other countries. During this same period, US-made turbines, however, accounted for less than 18 percent of global installed capacity.[3] General Electric, the largest turbine manufacturer in the United States, purchased a patent from the German manufacturer Tacke, rather than use domestic turbine designs.[4] Today, Denmark is the uncontested world leader in

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the manufacture of wind turbines and has the highest level of installed wind energy capacity per capita. Although Denmark has spent the least on wind energy research, it has seen more rapid innovation than Germany, Spain, the United States, or the United Kingdom.[5]

Why did so many American turbine designs fail and what made Danish wind turbines superior? What lessons do these experiences offer regarding technological research and the adoption of new technologies? These questions are especially pertinent, as countries throughout the world strive to develop a host of new technologies to address climate change or other energy-related challenges.

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This article explores the different approaches Denmark and the United States have taken regarding wind energy research and diffusion, beginning with a discussion of the linear model of technological development. This model presupposes the research and diffusion process can be broken down into a series of predetermined sequences that begin with basic science and end with commercialization. The author challenges the linear model and offers a different analytical framework to explain why some energy technologies gain momentum and market acceptance while others are unsuccessful. This framework posits that the more technical aspects of research—design, production, standardization, and evaluation—must be coupled with political factors relating to policy and regulation; economic factors that deal with ownership and profitability; and social factors relating to information sharing and participation. The article suggests that to succeed, technologies must not only work, they must also be embraced socially, politically, and economically.

For those wishing to study the relationship between politics and technology more broadly, the article rejects distinctions between the technical and social elements and postulates that technologies must seamlessly commingle these elements to be widely accepted. Anyone wishing to devise new, innovative technologies must overcome a complex mixture of technical, social, political and economic barriers. This article outlines the optimal political and social conditions for a given technology, or set of technologies, to succeed and illustrates how failing to meet these conditions might diminish the effectiveness of other technologies or research approaches or make them altogether unacceptable.

THE LINEAR MODEL OF TECHNOLOGICAL DEVELOPMENT

Since early in the twentieth century, many scientists, researchers and economists, along with universities, national laboratories, and research organizations have subscribed to a classic, linear assembly line model of technological development. While there are differences in how this innovation and research process is described, it accurately reflects the way many researchers structure their efforts. For example, Gallagher and colleagues[6] characterized both hard, sequential and soft, chain-linked variants of the linear model, and Balconi and associates[7] identified strong and weak forms.

Engineers and scientists that adhere to the linear model generally believe that advances in technological development occur in a rational, ordered and predictable manner. They view technological development and diffusion as having at least four phases: (1) basic research, the phase when general discoveries are made, (2) the applied research or invention phase, when engineers create artifacts in laboratories, apply for patents, and model and test prototypes, (3) the market development phase, when technology is passed on to salespeople and managers and (4) the consumption phase, the point when technology is sold to the public and perhaps even modified by users. According to Godin, the linear model has been "the very mechanism used for explaining innovation in the literature on technological change and innovation."[8]

The linear model of innovation gained popularity in the 1910s and 1920s, when scientists began to recognize basic research as the source of new technology. It was during this period that the ideal of pure science was delineated as research performed without commercial or practical ends—a line of inquiry pursued for the benefit of humanity. Basic research or science was held to be distinct from applied science, a field of research occupied with practical discovery, for commercial gain or to achieve a specific purpose. This premise, strongly supported by industrialists and inventors, advanced a causal relationship between basic and applied research, denoting basic research as the foundation of scientific progress.[9] The tenet that basic research must precede applied research and subsequent technical development strongly influenced Vannevar Bush and others, who proposed the creation of the US National Science Foundation. The Foundation was established in 1950 to fund basic research. This principle also motivated investment in American scientific research, in a drive to win the space race of the 1960s and the Cold War of the 1970s and 1980s.

The notions of demonstration, development, and innovation were added to the model as economists and business managers engaged in discussions about technological innovation. Business school researchers studying industrial management of research noted that demonstration and development were often needed to carry a new process or product forward from the laboratory to the point where it was ready for large-scale manufacture. This was seen as translating the findings of applied research into products and processes. Economists extended the model of innovation to encompass the three phases of basic research preceding applied research, which prompts development, followed by production and then diffusion.[10] The classic work of E.M. Rogers is especially relevant here.[11] Rogers conceived of technological development as a four-stage process comprising innovation, diffusion, affects on the social system, and affects over time. This assembly line or linear model of technological development holds immense appeal for stakeholders involved in the research process. It constitutes a powerful resource for groups from various disciplines in their attempts to establish, define, demarcate or maintain their influence on technological development. Scientists often reference this model to justify financial support for projects, engineers to raise the status of their discipline and industrialists to attract workers to their research organizations. The assembly line model helps counter a general fear among scientists about government intrusion into industrial policy because it posits that technological diffusion is more or less automatic and unrestrained and should thus be controlled by scientists rather than politicians. The model also helps mitigate mainstream political fears regarding a loss of technological competitiveness because it suggests that sufficiently funding basic science research will always ultimately yield plentiful technological progress.[12] The linear model can be used to reassure a public fearful of abating technological innovation because it implies that unfettered and well-funded research invariably produces new and innovative technologies for consumption.[13] The model is also attractive in its simplicity. Alternative models of diffusion, with multiple feedback loops and triple helixes of knowledge dissemination, are viewed as overly complicated. They more closely resemble a plate of spaghetti and meatballs than useful descriptive frameworks.[14]

There is evidence that policymakers and scholars worldwide continue to use the linear model to explain technological diffusion in the energy sector. A global survey of energy research activities conducted by Gallagher and associates[15] found that most research institutions—including industry and government firms—envision a four-stage, linear research process that begins with basic research and ends with scaling-up and deployment. Sagar and van der Zwaan[16] identify various steps in the lifecycle of energy technologies, from invention to commercialization to maturation, that they call senescence. The authors argue that research and learning by doing—the two main components of technological innovation—take place during different stages, with research occurring first and learning by doing happening only after initial use of the technology. Others have maintained that similar sequential phases and linear relationships exist in the research process for nuclear power plants, solar photovoltaic (panels), electric vehicles, coal- and oil-gasification systems, offshore and onshore wind turbines and natural gas pipelines.[17]

CHALLENGING THE LINEAR MODEL

Despite the appeal and simplicity of the linear model, it is not the only framework for analyzing technological diffusion. The linear model does not adequately explain why wind energy was readily accepted in Denmark, yet faces challenges in the United States.

In designing the study and presenting a conceptual framework, we decided to use the social science systems approach instead of the linear model. This approach evolved from the field of science and technology studies. In the classic *Networks of Power: Electrification in Western Society*, historian Thomas P. Hughes proposed that energy supply and use takes place within a socio-technical system that extends beyond the domains of science and engineering.[18] Hughes envisioned such a socio-technical system as including a seamless web of technical, social, political and economic factors. Successful socio-technical systems such as electricity grids, telecommunications networks and banks integrate all these factors, with system builders striving to "construct or…force unity from diversity, centralization in the face of pluralism, and coherence from chaos."[19]

In developing the social science systems approach, Hughes explicated the concept of momentum, which he described as an amalgamation of "machines, devices, structures…[and] business concerns, government agencies, professional societies, educational institutions, and other organizations…[that] have a perceptible rate of growth or velocity."[20] Hughes' concept of momentum hypothesizes that the technical performance of a given technology and its compatibility with the existing social and political environment determine whether it is embraced or rejected. It is not enough for successful technologies to be designed and built; they must be designed and built for integration into society. Applying the notion of momentum to develop wind energy technologies tells us that prospective wind turbines must not only work reasonably well (satisfying technical dimensions of momentum), they must also engender political support, demonstrated by favorable regulations and policies, economic support from investors and operators as well as social support from the broader public.

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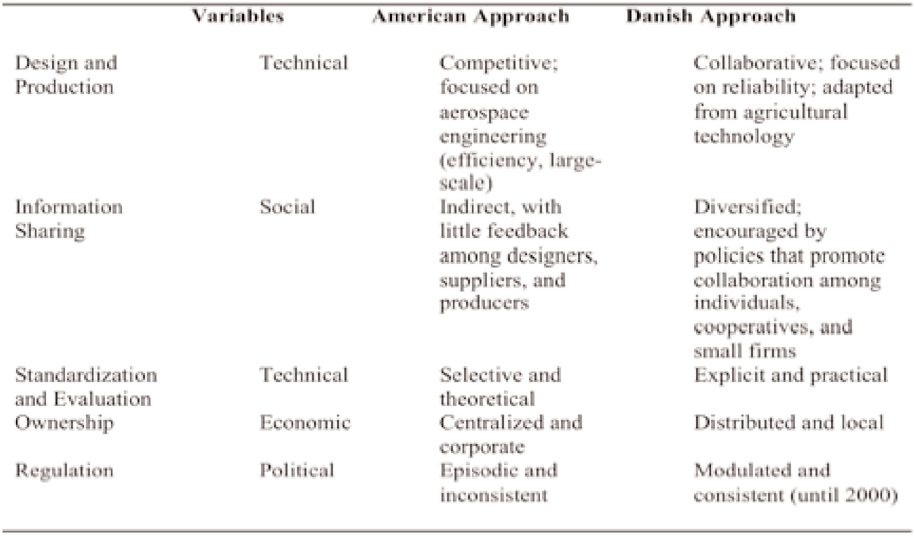
Synthesizing from the excellent work of Buen, Breukers, Garud, Heymann, Jorgensen, Karnoe, Sawin, Toke, and Wolsink, we propose that these can be reduced to a set of common variables related to the process of research and diffusion.[21] Design and production efforts, which tend to emphasize the scientific and technical aspects of technology development, along with standardization and evaluation, which are essential to providing feedback, are important and have been incorporated in many variants of the linear model. Such efforts, however, must be augmented with variables that relate to patterns of policy, which delve into politics and forms of legislation; forms of ownership, which touch on economic issues, including investor confidence and market penetration; and information sharing, which involves a social dimension consisting of participation, understanding, and consumer acceptance.

In contrast to the linear model, our framework presupposes that innovation and research cannot be reduced to a specific set of steps or processes. Research involves dynamic feedback flowing in multiple directions between stages and among designers, investors, regulators, and users. Moreover, our research implies that government-funded programs may not always be the best way to develop new technologies. In addition, decentralization and participatory modes of research may offer advantages over centralized and proprietary modes.

Table 1: American and Danish Wind Research Approaches



	Variables	American Approach	Danish Approach
Design and Production	Technical	Competitive; focused on aerospace engineering (efficiency, large-scale)	Collaborative; focused on reliability; adapted from agricultural technology
Information Sharing	Social	Indirect, with little feedback among designers, suppliers, and producers	Diversified; encouraged by policies that promote collaboration among individuals, cooperatives, and small firms
Standardization and Evaluation	Technical	Selective and theoretical	Explicit and practical
Ownership	Economic	Centralized and corporate	Distributed and local
Regulation	Political	Episodic and inconsistent	Modulated and consistent (until 2000)

This more complex assessment of the research process helps explain why a reductionist US assembly-line and top-down approach to wind turbine research and innovation failed to create momentum whereas a more interactive and dynamic Danish bottom-up approach generated significant momentum. These examples are at opposite extremes, and many wind research and diffusion efforts likely fall somewhere between the two. Table 1 summarizes the differences between the American and Danish approaches, broken down according to variables corresponding to different aspects of momentum: design and production (technical), information sharing (social), standardization and evaluation (technical), ownership (economic), and regulation (political).

WIND ENERGY RESEARCH IN THE UNITED STATES

The US strategy for wind energy research began with efforts to determine the ideal size for wind turbines, followed by a rush to create a marketable product. This approach resulted in turbines that were not widely accepted. US research programs built wind turbines based on the flawed premise that they should incorporate principles of aerospace design. Researchers focused primarily on efficiency and scale, placing minimal emphasis on reliability. This led to several problems with the finished product, ranging from blade-throw and lightning damage, to problems with bugs ice affecting operation of the turbine parts. All these things affect airplane turbines differently than wind turbines.[22] Consequently, US-made turbines began failing in large numbers in the mid-1980s. Inflated performance projections generated false expectations. The media, which portrayed wind farms as tax scams, served to enhance the negative perception of wind power among the public. This, and other factors, triggered a backlash against wind power and the industry suffered serious long-term damage. There was also little pressure to develop independent mechanisms for disclosing and evaluating information. As one research director lamented, the only feedback his company received came in the form of lawsuits.[23]

THE MEDIA, WHICH PORTRAYED WIND FARMS AS TAX SCAMS, SERVED TO ENHANCE THE NEGATIVE PERCEPTION OF WIND POWER AMONG THE PUBLIC.

In terms of design and production, US scientists and engineers applied science based on aerospace framing, and focused mostly on aerodynamic efficiency. Early US efforts largely took a big science approach via the Mod Program, administered jointly by the National Aeronautics and Space Administration and the US Department of Energy (DOE). The Mod Program was a concerted attempt to apply high technology research in building a reliable and cost-competitive wind turbine and nearly half of all federal spending on wind research in the 1970s was funneled into this program. The program focused on designing large-scale turbines, with the goal of producing a series of 3 MW to 5 MW machines—significantly larger than commercially available 100 kW wind turbines.[24] The program made several assumptions in deciding to focus on large-scale turbines. It was believed that big companies in heavy industries—already familiar with high-volume mass production of large equipment—would be the country's primary suppliers of wind energy. Users were expected to be utility managers and planners accustomed to building power plants in the 100 to 1,000 MW range. Moreover, large turbines were expected to serve as an archetype leading to smaller designs.

US researchers participating in the program did not collaborate with other designers, producers and suppliers. They made little effort to scale up research and undertook little product development between steps. In other words, US researchers started with a high-tech systems design and attempted to build all its components at once. They also sought the lightest construction materials and ignored the structural dynamics of the blades, which suffered an excessive rate of fatigue fractures. An adherence to gigantism (large, multi-megawatt machines) further limited the interaction points that would have enabled producers to learn from one another and weakened the linkages between government agencies such as the US National Renewable Energy Laboratory (NREL) and private industry. Finally, government regulators often dictated goals that they theorized were desirable for wind turbines and insisted that researchers build designs to satisfy these ideals, rather than allowing them to investigate alternatives that might have proved superior.

Information sharing was insufficient throughout nearly all steps of the chain, from research to commercialization. Knowledge was distributed indirectly among the researchers, with efforts further hampered by the small number of users and the few existing mechanisms for providing feedback. This, in turn, restricted the flow of information between suppliers and producers. Furthermore, the extent of interaction between producers and suppliers was poor, with most relationships consisting of one-time, short-term contracts motivated by profit at the expense of knowledge sharing and interactive learning. Thus, engineers ended up insulated from the problems encountered in construction, operation and maintenance. Designers' belief in the supremacy of their high-tech designs rendered them blind to other technological possibilities. American engineers mistook early failures as normal start-up difficulties, a trend exacerbated by the fact that several US companies had a two-year backlog of turbine orders in the early 1980s. Problems with these earlier turbines were expediently solved by repairing the turbines, rather than improving overall design.

Standardization and evaluation techniques were selective, with little emphasis on comparative testing. Standards were based on somewhat general engineering concepts that failed to evolve with hands-on knowledge and feedback from users. Researchers at such laboratories focused on developing high-tech designs based on fundamental scientific principles, but their research focused more on creating theoretical models and less on improving physical materials and hardware. NREL, for example, took three years to develop advanced wind turbine blades; during the same period, Danish researchers completed an entire turbine development cycle, introducing new models every two to three years.

Development and ownership of turbines in the United States was—and remains—highly concentrated among a few large firms, rather than being spread broadly among the public, as is the case in Denmark. The DOE reports that private corporations and independent power producers dominated the U.S. wind industry in 2007, owning 84 percent of all capacity (14,280 MW); utilities owned another 14 percent (1,790 MW for investor-owned utilities and 526 MW for publicly owned utilities). Communities owned approximately 2 percent (or 308 MW).[25] It is not farmers, landowners and participants in local cooperatives who own, work, and live with the machines, but distant shareholders unfamiliar with the technology. In other words, there remains a fundamental gap among development, ownership and usage.

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Government funding and policy choices have strongly influenced consolidation and corporate ownership. For example, while the DOE funded wind projects at more than thirty institutions, laboratories, and universities in the fiscal year 1979, nearly 90 percent of the funds went to eight large aerospace companies and to defense contractors such as Boeing, General Electric, and Raytheon.[26] Similarly, federal investment and production tax credits have been designed to benefit corporate and centralized ownership that is typically distant from the location of the turbines themselves. To take advantage of the federal production tax credit for wind energy, project owners must have a significant and steady ten-year income from other projects available to offset tax losses associated with operating wind farms.[27] Such credits functionally exclude individuals, cooperatives, communities, and small corporations from developing renewable energy projects, because it is more difficult for these groups to acquire enough capital to reap the benefits of the credits.

In many ways, US policies have been inconsistent and poorly designed. Over the years, many programs have been created and then left unfunded or they have been abruptly cancelled. In addition, policy interventions have been episodic, and policies have done little, if anything, to increase stakeholder involvement or information sharing. Because government policy strongly incentivized investment but not performance, more than 95 percent of the world's new wind turbines were installed in California during the "California Wind Rush" of 1981 to 1985. A federal tax incentive covered 25 percent of wind capital costs, and a California state tax write-off covered an additional 25 percent. With half the cost of each project covered, developers focused on building wind farms to take advantage of tax credits rather than on building them to produce electricity.[28] The policy changed in 1985, when the federal tax incentive was unexpectedly discontinued and the California tax credit was reduced to 10 percent. Manufacturers found themselves unable to improve designs and decrease costs fast enough to justify investment and a majority abandoned the market.

The 1935 Public Utility Holding Company Act, the 1980 Wind Energy Systems Act, the 1984 Renewable Energy Industry Development Act, provisions of the Energy Policy Act of 1992 and several other legislative policies have never been fully implemented or they have been allowed to expire despite continuing to be necessary. The failure to phase out these policies gradually and predictably created cycles of boom and bust in the American wind energy industry. For example, the Energy Policy Act of 1992, which provided a Production Tax Credit for wind energy provided beginning with 1994, has been allowed to expire three times since 1999 and then retroactively extended for a few years each time, creating great uncertainty in the market place. The Senate renewed the tax credit in October 2008, but for only one year. In addition, US government policy has often been internally inconsistent, with federal research focused on centralized, large-scale, utility-owned projects, while legislation such as the Public Utilities Regulatory Policy Act of 1978 has aimed to advance decentralized, small-scale, independently owned projects.

WIND ENERGY RESEARCH IN DENMARK

Danish researchers started with low-tech windmill designs. They scaled up technologies in small steps and continually engaged in product development. They used a collaborative network to undertake design of hubs, high-quality shafts, mechanical brakes, electronic control systems, components of the yaw-system and quality gears. As technology advanced, costs slowly declined and Denmark's market share rose. By 1985, Danish wind turbine manufacturers had captured 50 percent of the world market and were responsible for making the turbines that produced about 700 MW of the 1,500 MW of wind power in California. Before consolidation in 2001, four of the world's six largest wind turbine manufacturers were Danish.

Design and production of wind turbines were markedly different in Denmark. Designs were derived from experience with agricultural equipment, and engineers prioritized reliability over aerodynamic efficiency. Unlike their early US counterparts, who came primarily from the aviation industry, Danish researchers recognized that aviation aerodynamics were not directly applicable to wind turbine technology, where the speed of the blades must adapt to constantly changing wind pressure. While the propellers and blades of an aircraft work under forced airflows, wind turbine blades have reverse tensions. Designers created a collaborative network to share information and experiences with other designers, as well as producers and suppliers. They also emphasized the importance of gradual scale-up steps, implementing numerous product development stages to facilitate trial-and-error learning. As a result, they were able to consider accumulated, practical experience, making many small modifications and continually comparing their results with theoretical models. Government regulators encouraged designers to experiment with a variety of specifications and configurations to gain empirical experience with the technology from the ground up.

Information sharing was diversified and encouraged, so much so that the process of learning by doing could also be termed learning by interacting. The Association of Danish Wind Power Owners and the Association of Danish Wind Mill Manufacturers emerged in 1978. They promoted information sharing, resulting in the establishment of multiple direct learning points among thousands of users who were incentivized to provide critical input and contributions. The Danish model supported many small competitors that worked to address potential problems with blade design, structural dynamics, and introduction of light materials, creating variations in a relatively small market.

Danish regulators established formal standardization and evaluation mechanisms early on and had a government-funded test station, the Test Station for Smaller Turbines, by 1978. Unlike SERI and its successor NREL in the United States, which focused mostly on theoretical research, the Danish Test Station published comparative tests of wind turbines so that testing standards coevolved with the technology. Denmark also intertwined financial incentives with data collection, offering tax credits and subsidies in exchange for annual reports on wind power performance from operators.

The ownership of Danish wind projects has historically been at a decentralized local level rather than concentrated in the hands of large corporations. This grew out of the long tradition of cooperatives in Denmark, as well as a grassroots interest in wind power that evolved during the 1970s. In 1973, the construction of Sweden's Barseback nuclear plant, only 20 kilometers from Copenhagen, precipitated the rise of strong public opposition to atomic power and put wind energy on the national agenda. The Organization for Information about Atomic Power (OOA), formally created in 1974, established contacts with researchers, gained access to discussions in Parliament and influenced the energy policymaking process. Throughout Denmark, it promoted the vision of a self-sufficient, local community within an idyllic village as the typical motif. As a result, between 1974 and 1978, communities began to embrace wind power. Most owners of wind turbines were grassroots entrepreneurs and do-it-yourself builders. By 2005, only 12 percent of wind farms were utility owned and individuals and cooperatives owned the remaining 88 percent.[29]

Danish wind energy policies remained relatively consistent and balanced until 2000. Policies in Denmark steadily progressed in accordance with changing circumstances and lessons learned. The Danish Ministry of Energy, established in 1979, supported wind technology by first promoting an investment subsidy, which gradually declined as costs fell. The Ministry then implemented feed-in tariffs, financing, streamlined permitting and a carbon tax.[30] Danish policy also promoted broad involvement at virtually all levels of the wind industry, such as including stakeholders in discussions about the siting and permitting of wind turbines, the ownership of wind farms and the design of wind technologies. Particular emphasis was placed on including Danish electricity companies, researchers at the Risø National Laboratory, the Danish University of Technology and local cooperatives.[31] Regulators also cultivated the growth of the industry by implementing policies that were flexible enough to rectify temporary challenges. As turbine technologies advanced and costs declined, the government gradually reduced subsidies for direct investment from 30 percent in 1979 to 10 percent 1988 and repealed them entirely in 1989.

CONCLUSIONS

The comparison between Danish and American approaches to wind research and diffusion—how each country relied on different methods of design and production, information sharing, standardization and evaluation, ownership and regulation—underscores the importance of shaping momentum to favor a desired technology. In the United States, a "bigger is better" ideology, strong belief in technical efficiency and sequential phases of research, hierarchical management, centralization and rapid search for economies of scale in gigantism resulted in overconfidence in the potency of American wind energy research and the production of inferior wind turbines that were rejected by investors and communities. The combination of inconsistent policies and the lack of standards and a certification process culminated in long-term damage to the domestic wind industry. The Danish bottom-up strategy, based on the dynamic principles of learning by doing, the accumulation of knowledge from multiple actors and adoption of consistent policies produced significant momentum in favor of wind energy. This led to the creation of a strong domestic industry and made Denmark the long-term leader of wind energy technology in the global marketplace.

The Danish and US experiences with wind energy technologies reveal a few important lessons for energy development and diffusion and possibly for the research process as a whole. First, they show that a government's approach to technology development is at least as important as the amount of funding appropriated to research. Efforts that create momentum—transparency, information sharing, learning from mistakes, consistency and quality of research—can be more meaningful than vast research expenditures.

The process of innovation can be non-linear, dynamic and unpredictable. A clearly demarcated relationship between research spending and innovation does not exist. High levels of funding can breed greed and waste and they offer no guarantees. In the wind energy industry, early US government research efforts focusing on the development of large-scale wind turbines were extremely expensive and relatively unsuccessful. Most modern wind turbines deployed around the world did not arise from the large-scale wind turbines that emerged from these programs, but instead from smaller-scale Danish turbines scaled up on an incremental basis, incorporating knowledge gained from experience in the field. This conclusion becomes particularly relevant in light of recent calls for increased funding for energy research similar on scale to the Apollo Project or for a quintupling to decupling of research funding to address challenges related to climate change.[32]

A bottom-up approach to technology development and diffusion into the marketplace can be at least as effective as a top-down approach. Governments should resist the temptation to take overly bureaucratic approaches to research and instead promote diversification, flexibility, openness, and inclusion. In terms of encouraging diversification, research funds should be distributed among multiple actors, rather than consolidated in the hands of a few corporations. For example, mandating that a significant share of government contracts go to small companies can engender decentralization and greater experimentation that leads to different designs early on in the research process. Cost sharing, instead of merely subsidizing investments, also ensures that the companies receiving government funds have a stake in the outcome. Governments should promote flexibility stipulating desired end-goals but not dictating specific designs, such as the axis of a wind turbine, the number of blades or the size of the machine. This practice reduces the ability of researchers to experiment with all types of designs and might lead to the failure to consider more efficient, reliable or cost-effective options. Information sharing generates confidence in a technology and reduces perceived risks. It also increases the opportunity to reduce opposition to unexpected problems that arise early on in the development process, rather than after technologies have entered the market. Including multiple stakeholders is equally important. Augmenting research strategies so that they involve more local actors can encourage community participation. Participation by cooperatives and individuals plays a significant part in overcoming barriers to the public's acceptance of energy technologies. Local communities benefit by experiencing a shared sense of pride and involvement and are more likely to keep machines in better condition. To increase utility experience and confidence with the technology and reduce opposition to perceived risks, electric utilities and energy companies must be involved in the research and testing processes from inception. Including electric utilities in the research process assures that their concerns are considered, making it easier to transfer technologies and knowledge gained in the field.

Formal standards and certification procedures must be established in the development and diffusion of a technology. Standards and certification prevent substandard technologies from entering the marketplace, generate confidence in a technology and reduce perceived risk. Standards also render other policies–such as investment tax credits—more effective, help build a strong domestic manufacturing capacity and reduce the need for costly follow-up efforts that lengthen the time needed for construction or maintenance.

Government research must be carried out in parallel with policies designed to create a sustained and growing market for the relevant technologies. Technological breakthroughs in design or performance do not automatically translate into social acceptance. Diffusion of technology is often successful when promoted and properly assisted by government policy. The common elements in success stories from Denmark and elsewhere are their governments' long-term commitments to advancing a technology, effective and consistent policies, use of gradually declining subsidies and incentives and a strong emphasis on government research and market penetration. Not only do well-designed and successfully implemented market-creation policies attract the private sector to invest in research, but new and evolving technologies will be far more likely to secure a significant share of the market if governments are clearly and truly committed to their development and diffusion over the short and long term.

Above all, the success of wind energy technologies— measured by the rate and level of their development and diffusion—has been as much a matter of policy choice and consistency as financial largesse and technical skill. The lesson here for establishing future alternative technologies and the research processes in the energy sector and beyond is twofold. First, government policy is an essential component of any strategy intended to develop and diffuse technology into society. Second, technological development does not always occur through a highly centralized, bureaucratic, linear, hierarchical research system. For governments around the world invested in rapidly transitioning to a low- or zero-carbon energy future, these lessons constitute important reminders that the marketplace alone will rarely, if ever, sufficiently advance new technologies. Ultimately, effective research policy and government incentives must be consistent, long-term, and phased out gradually over time, with the goal of advancing a technology, reducing its costs, and creating a sustained and predictable market.

Notes

[1] Benjamin K. Sovacool, "Replacing Replacing Tedium with Transformation: Why the U.S. Department of Energy Needs to Change the Way it Conducts Long-term Research" *Energy Policy* 36 no.3 (March 2008): 923-928; Jorgensen, Ulrik and Peter Karnoe, "The Danish Wind-Turbine Story: Technical Solutions to Political Visions?" In Arie Rip, Thomas J. Misa, and Johan Schot (Eds.) *Managing Technology in Society: The Approach of Constructive Technology Assessment* (London: Pinter Publishers, 1995): 57-82.
[2] Matthias Heymann, "Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990," *Technology & Culture* 39 no. 4 (October 1998): 641-670.
[3] U.S. Department of Energy, Energy Efficiency and Renewable Energy Program, *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007* (Washington, DC: U.S. DOE, May 2008).
[4] David Appleyard, "A Look at Wind's Key Players: What Next in Wind," *Renewable Energy World* 12 no. 1 (January/February 2007).
[5] Paolo Agnolucci, "Wind Electricity in Denmark: A Survey of Policies, Their Effectiveness, and Factors Motivating Their Introduction," *Renewable and Sustainable Energy Reviews* 11 (2007): 951-963;
Staffan Jacobsson and Volkmar Lauber, "The Politics and Policy of Energy System Transformation—Explaining the German Diffusion of Renewable Energy Technology," *Energy Policy* 34 (2006): 256-276; Ger Klaassen, Asami Miketa, Katarina Larsen, and Thomas Sundquist, "The Impact of Research on Innovation for Wind Energy in Denmark, Germany, and the United Kingdom," *Ecological Economics* 54 (2005): 227-240.
[6] Kelly Sims Gallagher, John P. Holdren, and Ambuj Sagar, "Energy-Technology Innovation." *Annual Review of Environment and Resources* 31 (2006): 193-237.
[7] Margherita Balconi, Stefano Brusoni, and Luigi Orsenigo. *In Defense of the Linear Model: An Essay* (Milan: CESPRI, Working Paper No. 216, April 2008).
[8] Benoit Godin, "The Linear Model of Innovation: The Historical Construction of an Analytical Framework," *Science, Technology, & Human Values* 31 no. 6 (November 2006): 639-667.
[9] Ibid.
[10] Daniel J. Kevles, "The National Science Foundation and the Debate over Postwar Research Policy, 1942-1945," *ISIS* 68 no. 241 (1977): 5-26; Bruce Smith, *American Science Policy Since World War II* (Washington, DC: Brookings Institution, 1990); Daniel Lee Kleinman, *Politics on the Endless Frontier: Postwar Research Policy in the United States* (London: Duke University Press, 1995); David M. Hart, *Forged Consensus: Science, Technology, and Economic Policy in the United States, 1921-1953* (Princeton, NJ: Princeton University Press, 2000); A. Hunter Dupree, *Science in the Federal Government: A History of Policies and Activities* (Baltimore: Johns Hopkins University Press, 1986).
[11] E.M. Rogers, *Diffusion of Innovations* (New York: Free Press, 1962); M. Rivera, and E. M. Rogers, "Innovation diffusion, network features, and cultural communication variables." *Problems & Perspectives in Management* 2 (2006): 126-135.
[12] David H. Guston "Stabilizing the Boundary between US Politics and Science: The Role of the Office of Technology Transfer as a Boundary Organization," *Social Studies of Science* 29 no. 1 (February 1999): 87-111.
[13] David Hounshell, "Commentary: Industrial Research," In Karl Grandin, Nina Wormbs, Anders Lundgren, and Sven Widmalm (Eds.) *The Science-Industry Nexus: History, Policy, Implications* (New York: Watson Publishers, 2004): 59-65.
[14] Benoit Godin, "The Linear Model of Innovation: The Historical Construction of an Analytical Framework," *Science, Technology, & Human Values* 31 no. 6 (November 2006): 639-667.
[15] Kelly Sims Gallagher, John P. Holdren, and Ambuj Sagar, "Energy-Technology Innovation," *Annual Review of Environment and Resources* 31 (2006): 193-237.
[16] Ambuj D. Sagar and Bob van der Zwaan, "Technological Innovation in the Energy Sector: Research, Deployment, and Learning-by-Doing," *Energy Policy* 34 (2006): 2601-2608.
[17] Sondes Kahouli-Brahmi, "Technological Learning in Energy-Environment-Economy Modeling: A Survey," *Energy Policy* 36 (2008): 138-162; T. Jamasb, *Technological change theory and learning curves: progress and patterns in energy technologies* (Cambridge: EPRG Winter Research Seminar, University of Cambridge, 2006).
[18] Thomas P. Hughes, 1983. Networks of Power: Electrification in Western Society, 1880-1930 (Baltimore: Johns Hopkins University Press, 1983).
[19] Thomas P. Hughes, "The Evolution of Large Technological Systems," In Wiebe E. Bijker, Hughes and Trevor J. Pinch (Eds.) The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology (Cambridge, MA: MIT Press, 1987): 52.

[20] Thomas P. Hughes, 1983. Networks of Power: Electrification in Western Society, 1880-1930 (Baltimore: Johns Hopkins University Press, 1983).

[21] Ulrik Jorgensen and Peter Karnoe, "The Danish Wind-Turbine Story: Technical Solutions to Political Visions?" In Arie Rip, Thomas J. Misa, and Johan Schot (Eds.) *Managing Technology in Society: The Approach of Constructive Technology Assessment* (London: Pinter Publishers, 1995): 57-82; Matthias Heymann, "Signs of Hubris: The Shaping of Wind Technology Styles in Germany, Denmark, and the United States, 1940-1990," *Technology & Culture* 39 no. 4 (October 1998): 641-670; Janet Sawin, "*The Role of Government in the Development and Diffusion of Renewable Energy Technologies: Wind Power in the United States, California, Denmark, and Germany, 1970-2000"* (PhD Diss., Boston, MA: Tufts University, 2001); Raghu Garud and Peter Karnoe, "Bricolage versus Breakthrough: Distributed and Embedded Agency in Technology Entrepreneurship," *Research Policy* 32 (2003): 277-300; Janet Sawin, *Mainstreaming Renewable Energy in the 21st Century* (Washington, DC: Worldwatch Institute); J. Buen, "Danish and Norwegian Wind Industry: The Relation between Policy Instruments, Innovation, and Diffusion," Energy Policy 34 (2006): 3887-3897; David Toke, Sylvia Breukers, and Maarten Wolsink, "Wind Power Deployment Outcomes: How Can We Account for the Differences?" *Renewable and Sustainable Energy Reviews* 12 (2008): 1129-1147.

[22] Janet Sawin, "*The Role of Government in the Development and Diffusion of Renewable Energy Technologies: Wind Power in the United States, California, Denmark, and Germany, 1970-2000"* (Boston, MA: Tufts University, 2001, Ph.D dissertation).

[23] Raghu Garud and Peter Karnoe, "Bricolage versus Breakthrough: Distributed and Embedded Agency in Technology Entrepreneurship," *Research Policy* 32 (2003): 277-300.

[24] Vicki Norberg-Bohm, "Creating Incentives for Environmentally Enhancing Technological Change: Lessons From 30 Years of U.S. Technology Policy," *Technological Forecasting and Social Change* 65 (2000): 125-148.

[25] U.S. Department of Energy, Energy Efficiency and Renewable Energy Program. *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007* (Washington, DC: U.S. DOE, May 2008).

[26] Janet Sawin, *The Role of Government in the Development and Diffusion of Renewable Energy Technologies: Wind Power in the United States, California, Denmark, and Germany, 1970-2000* (Boston, MA: Tufts University, 2001, Ph.D dissertation).

[27] Brandon Owens, "Beyond the Production Tax Credit (PTC): Renewable Energy Support in the U.S.," *ReFocus* (November/December 2004): 32-34.

[28] Karlynn S. Cory, Stephen Bernow, William Dougherty, Silvan Kartha, and Eric Williams, "Analysis of Wind Turbine Cost Reductions: The Role of Research and Development and Cumulative Production," *Presentation to the American Wind Energy Association WINDPOWER Conference, June 22, 1999.*

[29] David Toke, "Are Green Electricity Certificates the Way Forward for Renewable Energy? An Evaluation of the United Kingdom's Renewables Obligation in the Context of International Comparisons," *Environment and Planning C* 23 (2005): 361-374.

[30] Paolo Agnolucci, "Wind Electricity in Denmark: A Survey of Policies, Their Effectiveness, and Factors Motivating Their Introduction," *Renewable and Sustainable Energy Reviews* 11 (2007): 951-963; Benjamin K. Sovacool, Hans Henrik Lindboe and Ole Odgaard,"Is the Danish Wind Energy Model Replicable for Other Countries?" *Electricity Journal* 21 no. 2 (March 2008): 27-38.

[31] Ger Klaassen, Asami Miketa, Katarina Larsen, and Thomas Sundqvist, "The Impact of Research on Innovation for Wind Energy in Denmark, Germany, and the United Kingdom," *Ecological Economics* 54 (2005): 227-240.

[32] Gregory F. Nemet and Daniel M. Kammen, "U.S. Energy Research and Development: Declining Investment, Increasing Need, and the Feasibility of Expansion," *Energy Policy* 35 (2007): 746-755; S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science* 305 (2004): 968-972; M. Hoffert, et al, "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet," *Science* 298 (2002): 981-987.