

# **CREATING INCENTIVES FOR ENVIRONMENTALLY ENHANCING TECHNOLOGICAL CHANGE: LESSONS FROM 30 YEARS OF U.S. ENERGY TECHNOLOGY POLICY**

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## **Introduction**

The production and consumption of energy satisfies private needs and wants, but in doing so creates negative externalities, including environmental degradation and security risks. It also contributes positively to economic and social development. These externalities, both negative and positive, provide the rationale for public involvement in the energy sector. As managing climate change is added to the environmental, economic and security issues that have led to government intervention in the energy sector in the past, designing effective policy to promote innovation and diffusion of the next generation of energy technologies becomes ever more pressing. This is because effective management of climate change requires a radical departure from our current ways of producing and consuming energy.

While the rationale for government intervention is strong, the ability of governments to effectively promote technology innovation for commercial goods, such as power-generation technology, remains a daunting challenge. By examining the role of the U.S. government in the development of four electricity generating technologies, this paper draws lessons on how to effectively design policies to stimulate energy technology innovation, with a focus on the role of policy in the commercialization phase. Two of the technologies examined in this paper, gas turbines and coal-fired atmospheric fluidized bed boilers, are fossil fuel based. These technologies are currently commercially competitive for grid-connected power applications. The other two technologies, solar photovoltaics and wind turbines are based on renewables. Grid applications of these two renewable technologies are currently subsidized, although they are the most cost-effective technology for some off-grid applications.

This paper is organized as follows. It begins with a brief discussion of the role of government in technology commercialization. The second section describes the issues driving energy policy over the last three decades and the specific policies implemented in the United States to address these concerns. The third section examines the role of these policies in the development of each of the four technologies. This section concludes with a comparison of the similarities and differences that government policy played in the development of each of the four technologies. This sets the stage for the concluding section, which draws policy lessons from these histories that can be applied as we move forward in designing strategies for the development of the next generation of energy technologies, technologies that would be viable in a greenhouse-gas constrained world.

## **The Role of Government in Technology Commercialization**

In the United States, there is a consensus that the government should play a role in basic science. More contentious is the proper role for government in technological development. Although no consensus exists, over the past several years there has been a growth in government sponsored R&D in basic technology, meaning investments in technological development that is high-risk and either generic or satisfies a public mission [1]. It is much trickier to consider what the government role should be as a technology approaches commercialization. Scholars have identified the "valley of death" and the "mountain of death" in the technology innovation process<sup>1</sup>. These concepts illustrate the difficulty in

successful commercialization (i.e. the fact that most new technologies “die” before they are successfully commercialized). The mountain of death is a concept used to explain the difficulty in commercially providing the first-of-a-kind capital good. For technologies such as power plants, which may be standardized but not mass-produced, the initial plant is much more expensive than the 5th or 10th plant. The valley of death is applicable for mass-produced goods. In this case, most businesses based on a technological innovation fail due to an extended period of negative net cumulative cash flow. Clearly, some technological innovations survive this climbing expedition to become commercial successes. For private goods, after basic R&D, we rely on the private sector to bring technologies through commercialization. In the case of privately provided public goods, government must intervene.

Energy, while traded in the market as a private good, has huge environmental externalities. To put this another way, some public goods, such as clean air, are dependent on how we produce and consume energy. Such public goods are privately produced. As a private commodity good, energy technologies must compete largely based on price. There are some characteristics that are desired in addition to a low-price. These include: security of fuel supply, fuel flexibility, modularity, speed of start-up and shut-down, and environmental performance. These characteristics can be helpful in capturing market niches. For example, as will be discussed in the next section, gas turbines were able to capture the niche for peaking power long before they were cost competitive with base-load coal plants. But as long as environmental requirements are met, the bottom-line - cost of electricity – most often rules, making it difficult for new generating technologies to capture a market niche based on other qualities. This closes off one important path to commercialization, quality improvements that allow a good to charge higher prices to the lead adopters. Under these circumstances, if we want to capture the public goods associated with energy use, government action will have to go beyond investing in technological inventions (basic R&D) and play a role in commercialization, i.e. government action will be needed to escape the mountains and valleys of death.

The scholarship on public goods in which government is both the producer and consumer, such as military equipment and space exploration, concludes that effective commercialization depended on government activity to support both supply-push and demand-pull [3, 4, 5, 6]. Similar results were found in this comparative study of four power sector technologies. In each case, government action influenced the pace and direction of technological change through a combination of supply-push and demand-pull policies. Furthermore, this analysis identifies five industry sector characteristics that influence the level of government effort necessary to support commercialization: the size, strength and risk of the private market niche; industry structure; firm financial capability; firm technological capability; and sources of innovation.

### **Drivers of Power Sector Development in the U.S.: 1970 to 2000**

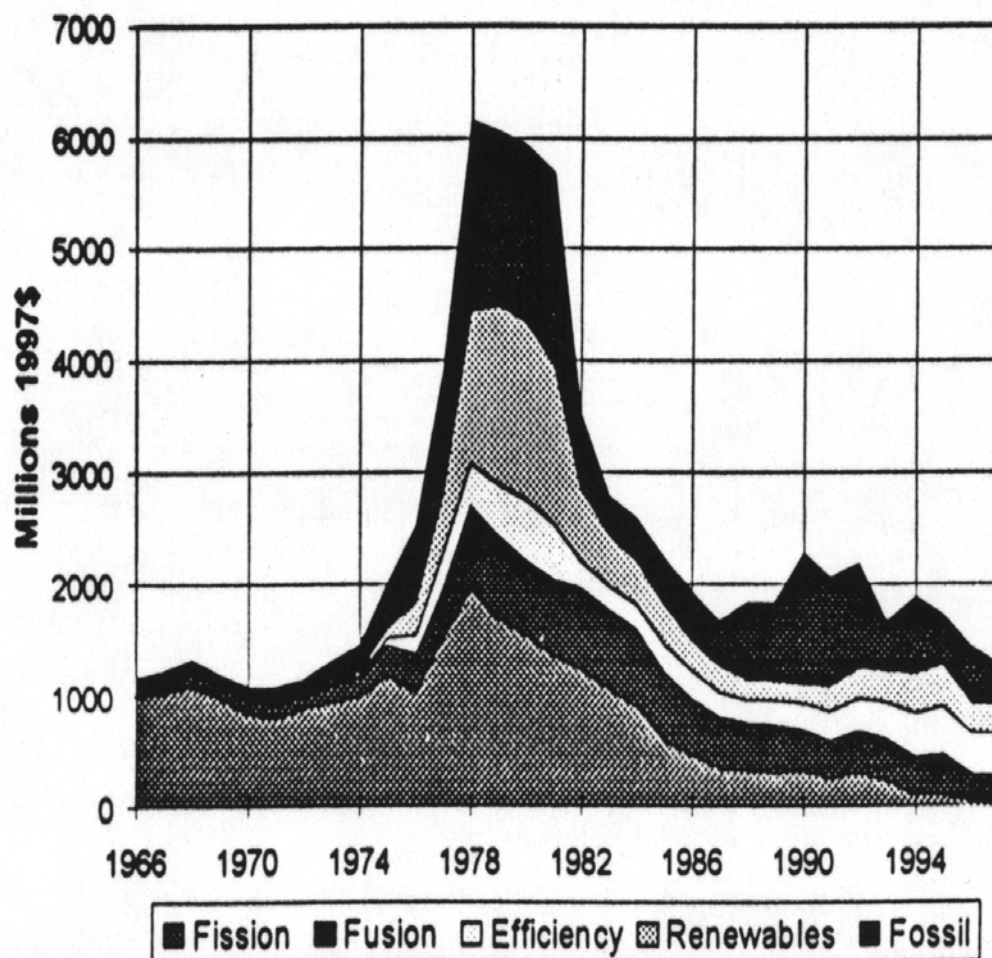
Over the past 30 years, three factors have driven technological change in the U.S. power sector. The first is a concern that was prevalent during the oil crises of the 1970s and that continues to raise its head as exemplified by the Persian Gulf War of 1992. The second driver is a set of environmental concerns that started in the 1970's with the local and regional problems of urban smog and acid rain, and now includes concern about climate change. The final driver is the end of the era of decreasing electricity prices, brought on in part by the first two driver<sup>ii</sup>. Together these drivers created windows for new power technologies. It is important to note that they also created new approaches for providing energy services (i.e. demand-side management). Demand-side management involves both organizational and technological innovation, and is worth examining in the context of policy as a driver of technological innovation, but is outside the scope of this paper.

The policy responses to this interlocking set of drivers were multifaceted. Policies included both supply-push (stimulating technological innovations), and demand-pull (creating a market for emerging energy technologies). For supply-push, the federal government funded a variety of R&D programs. Demand-pull

policies included environmental regulations, regulation and deregulation of fuels and electric utilities, and subsidies for specific technologies.

The energy R&D budget grew slowly during the mid-1970s. In 1977, the Department of Energy was formed to consolidate all energy R&D activities. This also marked the heyday of energy R&D in the United States, with budget levels in the late 1970s about six times those of 1970, as shown in Figure 1. The growth occurred in alternatives to fossil fuels such as nuclear fission and fusion, renewables, and demand-side efficiency as well as advanced fossil fuel technologies. In the early 1980's, government R&D budgets were cut dramatically. This change in policy reflected both the return to low oil prices and the small-government, free-market philosophy of the incoming Reagan administration. Renewables and nuclear fission suffered the most dramatic drops. Fossil fuel research also dropped dramatically although it regained some of its budget in the late 1980s and early 1990s. Current budget levels are approximately the same as those preceding the huge increase around 1980, although the energy R&D portfolio has greater diversification. These similar levels can be deceiving; as a fraction of GDP, federal energy R&D is at its lowest point in 30 years (0.036 in 1966, 0.016 in 1997) [2]<sup>iii</sup>. In FY1999, energy R&D budgets increased by 15%; this may signal the beginning of a growth trend in energy R&D budgets<sup>iv</sup>.

**Figure 1: Energy Technology R&D Budget Authority of DOE and Predecessor Agencies, 1966 to 1997<sup>v</sup>.**



The demand-pull policy that had the greatest impact on energy technology developments during this period is the Public Utilities Regulatory Act (PURPA) of 1978. This was a first step in the deregulation of the vertically integrated utility industry in the United States. It mandated utilities to purchase electricity from particular types of small-scale power producers, called qualifying facilities (QFs), which included industrial co-generators and renewable sources such as wind, solar, and mini-hydro. PURPA required utilities to pay for this electricity at avoided cost, with the determination of avoided cost left to the individual states [9]. The price paid to the QFs varied widely from state to state, due to differences in methodologies for calculating avoided cost as well as differences in the need for new generating capacity [10]. Legal challenges to PURPA delayed its implementation until 1983 [11]. Once implemented, PURPA had a large impact on the non-utility generation of electricity for resale, which grew from 3.5% of total US electricity generation in 1978 to 11% in 1996 [12]<sup>vi</sup>.

The next step in the deregulation of the electric power industry occurred in 1992 with the passage of the Energy Policy Act. This act created a new generating entity, the wholesale generator (also known as independent power producer, or IPP), which could sell electricity without being regulated as a utility. This act is leading to the breakup of the vertical integration in the U.S. utility industry. It is again being implemented on a state-by-state basis, with some states creating regulations or incentives for the adoption of renewables as part of their restructuring legislation<sup>vii</sup>. This next step in the deregulation of the electric power sector is also expected to have considerable impact on energy technology trajectories.

Natural gas was also subjected to regulation and deregulation during the 1970s and 1980s [13, 14]. During the 1970s, price controls on natural gas created shortages. In response, in 1978, the U.S. Congress enacted two laws that had significant short-term impacts on technology diffusion in the electric power sector: the Natural Gas Policy Act and the Power Plant and Industrial Fuel Use Act. The Natural Gas Policy Act deregulated the natural gas industry over a seven-year period, with the deregulation of new gas not occurring until 1985. This approach to deregulation meant that substantial increases in supply and decreases in price did not occur until 1985. While the Natural Gas Policy Act dealt with the long-term issue of creating more supply, the Power Plant and Industrial Fuel Use Act was aimed at managing the shortage in the near-term by prohibiting utility and industrial users from building new gas fired capacity. The fuel use act ended in 1987. As will be discussed later, the regulation of natural gas was instrumental in the pattern of gas turbine development and diffusion [14].

From 1970 forward, environmental concerns had a significant impact on the utility industry, although environmental regulation had limited direct impact on the development of new generation technologies. Starting in 1971, the Clean Air Act regulated SO<sub>2</sub> and NO<sub>x</sub> emissions [15, 16]. The SO<sub>2</sub> emission caps created challenges for the users of high sulfur coal, which at the time was the dominant fuel for power plants in the Midwest and Eastern part of the country. Compliance by existing plants was achieved largely through scrubbers and fuel-switching, rather than new clean-coal generating technologies. For new plants, atmospheric fluidized bed combustion (AFBC) was able to meet the requirements for sulfur control without additional equipment, and was considered one of the "best technologies" by the EPA. However, it proved a cost-effective option only for the niche market of low-grade fuels. The control of SO<sub>2</sub> created an advantage for gas turbines, as they could meet sulfur regulations with no additional equipment. Neither SO<sub>2</sub> nor NO<sub>x</sub> regulation created openings for non-fossil technologies because the additional cost of control technology to meet regulatory requirements did not bridge the gap between the cost of fossil-fuel and renewable technologies. While environmental regulation was not a particularly strong demand-pull mechanism, except perhaps for gas turbines, environmental concern was one stimulus for the R&D investment growth of the late 1970s.

## **The History of Technology Development and Diffusion: Wind Turbines, Solar Photovoltaics, Fluidized Bed Coal Boilers, and Gas Turbines**

The abbreviated histories below draw on detailed investigations into the technological and policy histories of four power sector technologies. The full studies are available as working papers or theses. The studies of wind turbines, solar photovoltaics, and fluidized bed coal boilers were undertaken as part of the Environmental Technology and Public Policy Program at MIT [17, 18, 19, 20, 21]. The gas turbine discussion is based on research by Darian Unger and Howard Herzog at the Energy Lab at MIT and a doctoral thesis by W. James and Watson at the Science Policy Research Unit at University of Sussex [14, 22].

These four technologies were chosen for several reasons. First, they are all power sector technologies that must compete against each other to gain market share. This allows control for the economic and policy environment of the end users (utilities, co-generators and independent power producers), while allowing for variation in the structure of manufacturing. Second, all of these technologies have entered the power sector during the last four decades, a period when environmental concerns were on the rise. Third, each of these technologies were in or through the commercialization phase; gas turbines and fluidized bed coal boilers are now cost competitive in private markets while the two renewable technologies still require subsidies to be cost-competitive for grid-generated electric power. Because we wanted to draw lessons about the government role in the commercialization process, this was an important criteria. This criteria led us to study atmospheric fluidized bed combustion (AFBC) rather than integrated gasification combined cycle (IGCC) technology, even though IGCC is believed to be a better technology for the future use of coal as it will allow more readily for separation and sequestration of carbon [2]. It is also worth noting that we did not include nuclear power in our study because of its unique characteristics that include security concerns and lack of public acceptance in the United States.

One limitation of this study is its focus almost exclusively on the United States. Because the U.S. policies have been directed largely toward U.S. firms, the lessons drawn from this work are valuable. Nonetheless, given the increasingly global structure of the power sector supply industry combined with the fact that governments around the world invest in energy R&D and provide incentives for the adoption of energy technologies, an even better understanding could be gained by a global study.

### *Wind Turbines<sup>viii</sup>*

Wind turbines are one of the oldest technologies for harnessing energy. The first windmills for generating electricity were developed in 1888, with reliable wind generated electricity available by the early 1920s [23]. Stand-alone wind turbines were used extensively in the midwestern United States prior to the Rural Electrification Act which brought centrally generated power to these areas by the late 1940s [24]. Between the 1940s and 1970s, no effort was put into wind turbine innovation. The changing forces in the electric power sector, including the oil crises and environmental concerns, spurred renewed interest in this technology in the 1970s [24, 25].

Over the past two decades, technological innovation in wind turbines has been impressive. The cost of wind generated electricity has dropped from 25 cents per kilowatt-hour in 1980 to its current price of about 5 to 7 cents per kilowatt-hour. Nonetheless, wind turbines are not currently cost competitive for grid application. Wind power accounts for less than 1/2 percent of the grid connected electricity in the United States [26]. Over 90 percent of this capacity are located in California<sup>ix</sup>. Most of these turbines were installed during a relatively short boom period in the mid-1980s, as shown in Figure 2.

The technological challenges to building a reliable, efficient, and inexpensive wind turbine are mechanical and structural reliability, power constraints, and efficiency. Innovations addressing mechanical and structural reliability included new blade materials such as fiberglass and wood epoxy, teetered hubs, and models for simulating turbulence in aerodynamics. The issue of power constraints relates to the suitability of the turbine to turn on and off at appropriate wind speeds. This issue has been addressed by

innovations in electronics, gearing, and variable pitch blades. The issue of efficiency has been addressed through blade designs including filament and tape wound fiberglass, tapered and twisted blades, and special airfoils, as well as through the development of better analytical techniques for turbine design.

Publicly supported R&D for the development of wind turbines took two different approaches, a "big science" effort and practice-driven component innovation. The big science effort, administered jointly by the National Aeronautics and Space Administration and the Department of Energy, and known as the Mod Program, was a concerted attempt to apply U.S. expertise in high-technology R&D to the challenge of building a reliable, cost-competitive wind turbine for grid connected electricity generation. Nearly half of federal wind spending during the 1970s, (\$200 to \$300 million), was spent on this program [24, 30, 31, 32]. It involved construction of several large turbines, with the goal of producing a 3 to 5 MW machine. Although the private firms acted as contractors for building these turbines, they did not contribute financially. The size was considerably larger than commercial wind turbines of that era, which were around 100 kW. The decision to focus on such a large machine was based on the following assumptions: (1) large companies in existing heavy industries would be the primary suppliers of wind turbines and were accustomed to high-volume production of large equipment, (2) utilities would only be interested in large wind turbines, as they were accustomed to power plants in the 100 to 1000 MW range, and (3) the large turbines were viewed as a technological umbrella; if they were successful smaller turbines could be based on the same design [31]. With NASA at the helm, an aerospace philosophy dominated, emphasizing lightweight designs. In hindsight, the rationales proved incorrect and the design focus proved ineffective. No commercial turbines of the 3 to 5 MW size have been built. There were some useful, albeit expensive, achievements through the Mod Program. It was instrumental in demonstrating that medium-scale wind turbines (100 kW) could successfully deliver high-quality electricity to the utility power grid. It also demonstrated the ability to operate at variable speed while connected to a utility grid and gathered much experimental data.

In contrast to the NASA-led Mod Program, DOE sponsored innovation in smaller turbines and small turbine components. The Solar Energy Research Institute, later renamed the National Renewable Energy Laboratory, administered this program. Of the 12 key innovations in wind turbine components that we identified in our research, seven relied on partial or total public funding, and three were developed in the private sector for other industries and transferred for use in wind turbines. We were unable to identify the funding source for the remaining two [17].

As these statistics indicate, the federally funded supply-push efforts were supplemented by innovation in the private sector. During the early and mid-1980s, when incentives to invest in wind energy were highest, a large amount of innovative activity occurred and a great many companies began producing wind turbines [33]. By 1985, 28 manufactures had installed turbines in California, half of them foreign firms [35]. Without the incentives of the market there would have been only laboratory invention and no technological change in commercially available wind turbines [34, 36].

Because we were unable to find detailed data on the level of diffusion of each of these component innovations, we relied on two proxies as indicators of whether wind turbines were adopting component innovations: (1) specific yield which measures the power generated by a turbine per swept rotor area, and (2) decreases in the cost of wind generated electricity. Both measures indicate that turbine performance improved throughout the California "wind rush" of the 1980s, suggesting the diffusion of component innovation, as there were no major breakthroughs in overall turbine design. This conclusion is augmented by interviews with companies that were producing turbines during the 1980s. Those with longevity improved their turbine design over time by improving specific components.

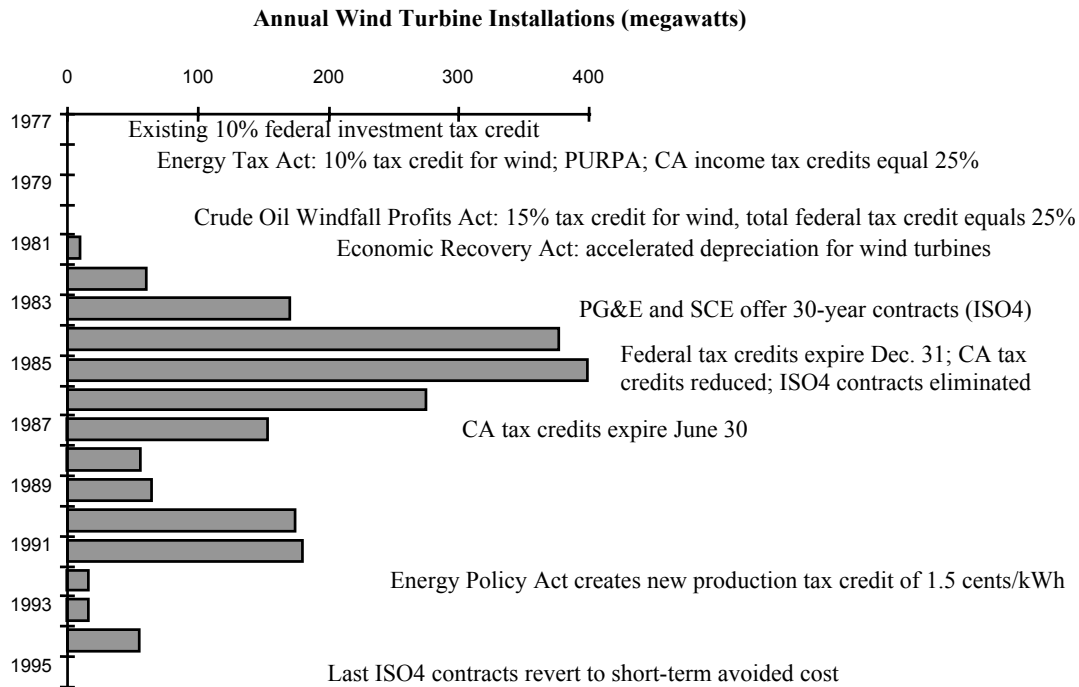
NREL is continuing its work, both by sponsoring advanced wind turbine designs and innovation for specific components [37]. These programs both require cost sharing by the private sector. NREL is now also providing funds for demonstrations to utilities that install small test plants using the latest technology. In recent years, with the falling off of the utility market for wind turbines, as will be described below, this has been the only way to get the new technologies tested under actual operating conditions. Electricity

restructuring is changing this picture. Some states are creating renewable portfolio standards and systems benefits changes to support the adoption of wind turbines and other renewable energy technologies<sup>x</sup>.

Throughout the 1980s, wind generated electricity remained considerably more expensive than fossil generated electricity (average short-term buyback rates in California were about three cents per kWh, while the cost of energy for the best turbines installed on good sites was estimated at five cents per kWh). Three public policy interventions on the demand-side together created the market for this technology: PURPA, tax subsidies, and the characterization of the wind resource. The wind turbine market grew in California not because it was the only state with a viable wind resource, but because of the state's approach to implementation of PURPA and tax incentives. California's avoided cost calculations were generous, although they were not the highest in the country. It was not until California instituted long-term contracts in 1983 that installations soared. These long-term contracts made it easier for developers to borrow capital for an emerging technology. The gap between California's avoided cost and the price of electricity generated from wind was filled by federal and state tax credits totaling 25 percent. The years 1984 and 1985 were the peak of wind turbine installation in California. In 1985 the federal tax credits expired, the California tax credits were reduced, and the long-term contracts were eliminated. In 1987 the California tax credits expired. The wind market diminished considerably at this point as shown in Figure 2.

In sum, the big science efforts were not effective, but the efforts in small turbine components were. Because the component research was driven by the needs of the market, the government created market was important for both public and private sector innovation. The demand-pull policies were too inconsistent to create a lasting industry. They only acted in concert and strongly over a short period of time. The pattern of new turbine installations in California clearly shows a correlation to the presence of the tax credits and long-term contracts. Most manufactures did not survive the removal of these incentives, and many were not able to complete a second or third round of product design and refinement. The cost of electricity from wind turbines has come down quickly, but not far enough to make them economically competitive. A drop in energy prices further curtailed the market for wind energy by lowering utilities' avoided cost, and thus the price turbine operators received for generation. The drop in energy prices also weakened the perceived need to pursue development of renewable energy sources through federal R&D expenditures.

**Figure 2: Economic Policies and Wind Turbine Annual Installations in California<sup>xi</sup>**



*Solar Photovoltaics<sup>xii</sup>*

The first application of solar photovoltaics was in the space program, starting in the late 1950s [38]. Manufacturing of PV cells for terrestrial power generation began in the early 1970s. Because of their high costs, PV cells were initially limited to applications that were distant from the electric power grid and for which cost was not a barrier (e.g. remote telecommunications) or non-essential consumer products with low power demand (e.g. pocket calculators).

The efficiency of PV cells has increased dramatically since the early 1970s. It is difficult to give single numbers on efficiency as this depends on the PV material and design approach. In 1976, efficiencies ranged between 5 to 15 percent. By 1996, they had increased to a range of 15 to almost 25 percent. Note that this is data for PV cells and not complete modules [39, 40, 41].

Decreases in cost have also been dramatic. Between 1976 and 1996, the cost for a PV module dropped by almost a factor of 10, from over \$50 per peak watt in 1976 to about \$5 per peak watt (in constant 1992 dollars) in 1996 [42]. R&D successes account for the largest part of this decrease. The rise in the microelectronics industry also contributed by providing reduced cost material for the fabrication of one type of photovoltaic cell (crystalline-silicon). However, demand-pull has been a limited factor, at least until the last couple of years, in these decreases in costs. Output grew by almost an order of magnitude during the last decade, from total shipments of 6,850 peak kilowatts in 1987 to 46,345 peak kilowatts in 1997 [43]. Nonetheless, the industry remains characterized by labor-intensive production lines, old processing equipment, and small plant capacities<sup>xiii</sup>.

Despite the significant decreases in cost and increases in efficiency, PV is not yet cost competitive with other grid connected power generating technologies, and is amongst the more costly of the renewable options. Thus, photovoltaics are gaining a commercial market through off-grid applications. Much of the

growth in sales over the last decade has been in international markets. This is for two reasons: (1) the decrease in the cost of photovoltaics has made them the least-cost technology for some rural applications, and (2) growing concern about climate change has led to a growth in the bilateral and multilateral programs that promote and fund the adoption of PV for rural electrification in developing countries [44].

The goals of the U.S. PV program have been to reduce costs and increase reliability. Costs have been addressed by increasing efficiency or decreasing the material and/or manufacturing cost. Reliability of cells has been a key concern as early models degraded and thus lost considerable efficiency over time. There have been three main approaches to PV innovation: flat-plate cells using single crystalline and polycrystalline silicon, flat-plate cells using thin films, and arrays using concentrators. Within each of these approaches, R&D has addressed materials (wafer production), cell fabrication, and module construction. In the last couple of years, U.S. R&D has also focused on the development of manufacturing technology for the photovoltaics industry. Each of these research thrusts had the potential to address the concerns of cost-competitive PV electricity by bringing down the cost of PV units and/or increasing their efficiency.

In our research we identified 20 key innovations in PV over the past 3 decades. We were able to identify the source of R&D funding for 14 of these. Only one of the 14 innovations was completely financed in the private sector. Of the remaining 13, nine were developed totally with public funding, and the remaining four were public-private partnerships. (We suspect the innovations for which we could not identify funding sources were developed in the private sector). In any event, despite this incomplete picture, the large impact of publicly funded research and development on this industry is clear.

The first federal R&D program, the Flat-Plate Solar Array Project, ran from 1975 to 1985 [43]. It focused on developing crystalline-silicon PV systems. Over the course of this project, progress was made on the three main technological challenges facing the PV industry: (1) costs decreased from a \$75 per Wp to \$5 per Wp; (2) efficiency increased from five to 15 percent; and (3) long-term warranties were introduced by manufacturers of PV modules, indicating that the problem of long-term degradation had been addressed [45].

Concern about Japan's dominance in the amorphous silicon (a-Si) research led the United States to launch its own initiative, which lasted from 1982 to 1992 [46]. During this project, a-Si cell efficiencies increased from the 5 to 11 percent. This program was followed in 1994 by the Thin Film PV Partnership. Currently most thin-film is amorphous silicon, however the partnership is also pursuing other materials including copper indium diselenide and cadmium telluride. A key goal of the current program is to bring the thin-film technology into pilot production.

There are several other recent PV initiatives. The Photovoltaics Manufacturing Technology Project (PVMaT) began in 1990 and focuses on manufacturing issues related to materials, modules, and balance of systems components [39, 41, 47, 48]. This project aims to bring down the cost of PV through manufacturing improvements; it is debated whether manufacturing programs alone will be able to make PV a cost competitive technology.

In 1997, NREL formed the Concentrator Alliance to further pursue this avenue of PV R&D. NREL and Sandia national labs have also participated in moving PV technology to the marketplace through cooperative research and development agreements (CRADAs) [48, 49].

In sum, the strengths of the U.S. Solar R&D program have been: (1) a parallel path strategy, (2) collaborations between industry, universities, and national labs including public-private partnerships with cost sharing, (3) attention to the full range of RD&D needed, from basic scientific work through to manufacturing, including attention to all components, materials, cells, and modules. Critiques of the solar PV R&D program include: (1) a lack of consistency in funding that created fits and starts in technological progress, and (2) concern that manufacturing R&D was not begun soon enough. Overall the trend has

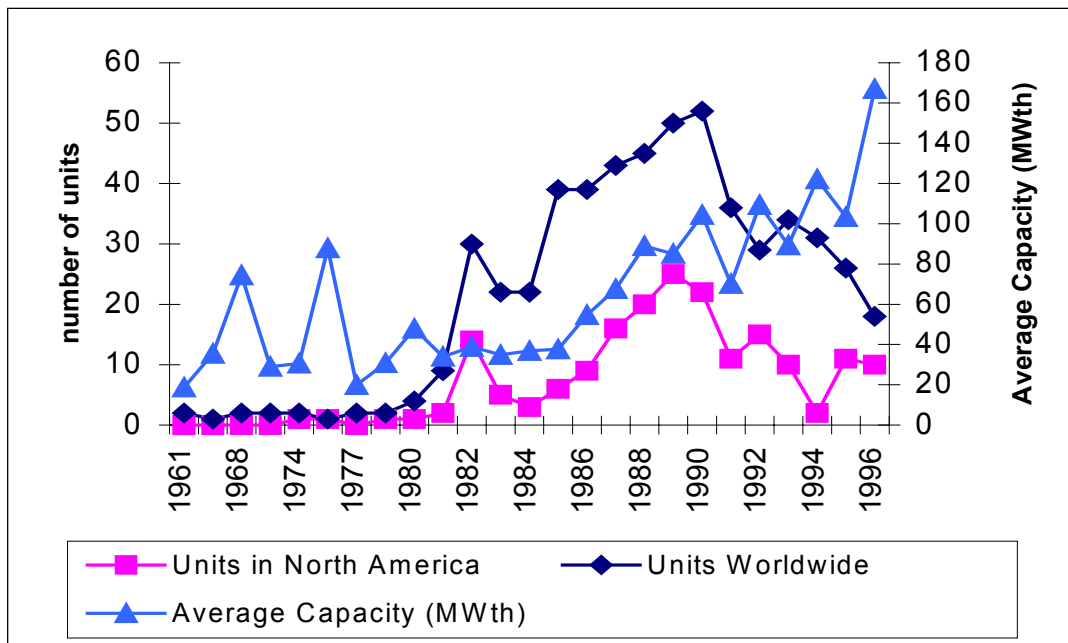
been to increase attention to manufacturing issues and to increase public-private partnerships, including growth in the level of private sector cost sharing. Recently, programs such as the Thin-Film Partnership and the PV Manufacturing Program have been developing collaborations between the firms in the industry.

*Atmosphere Fluidized Bed Combustion (AFBC)<sup>xiv</sup>*

Coal is the most abundant fuel in United States, currently accounting for 55 percent of primary energy use [42]. Since the 1960s, the U.S. government has supported the development of energy technologies that can use coal in an environmentally compatible manner. AFBC is one of the technologies in this “clean-coal” portfolio.

AFBC is at present a commercially available technology, in sizes up to 250 MW. The principal users of the technology are co-generators and independent power producers. In 1995, there were a total of 179 units in the United States, with an installed capacity of about 6700 MW. This capacity represents roughly 10 percent of the non-utility market in the United States but less than 1 percent of total generation. The market for AFBC took off in 1980, grew steadily for a decade and has fallen off somewhat in the 1990's. During the 1990s fewer units were ordered but these units had a higher capacity, as shown in Figure 3.

**Figure 3<sup>xv</sup>**



Government R&D programs were instrumental in the transfer of AFBC technology from the chemical industry to the power sector [51]. The chemical industry introduced the use of fluidized bed combustion technology in the 1920s. Research on the use of AFBC for electricity generation originated in the United Kingdom in 1960, motivated by the increasing competition that coal was facing from other fuels. By the mid-1960s, the U.S. federal government, through the Office of Coal Research of the National Air Pollution Control Administration and the United States Bureau of Mines, began funding the development of AFBC technology. In both the United States and the United Kingdom, early support took two forms: in-house R&D and contracts with private industry to design and build demonstration units. In addition, by 1968, these institutions had begun an international, biannual conference, which served as an important avenue for transferring technological knowledge.

The goal of the early U.S. R&D program was to create a coal technology for electricity generation that was both lower cost than traditional pulverized-coal boilers and could minimize the environmental damages caused by coal combustion. To achieve the cost-reduction goals, R&D focused on: reducing fouling, corrosion and erosion of handling systems; temperature control systems (turn down systems); reliability of auxiliary systems, especially fuel feeding systems; and scale-up of the technology. To achieve the environmental goals, research focused on efficient use of limestone for capturing SO<sub>2</sub>, and disposal of solid waste material. These early efforts, while not resulting in an utility scale boiler, were sufficiently successful to convince both government and industry that they were pursuing reasonable technological goals.

In 1977, the U.S. Department of Energy (DOE) was formed and became responsible for all federal energy-related R&D. The work on AFBC continued to include in-house research, as well as sponsorship of private sector R&D and demonstration plants. The demonstration plants were the larger part of this program, and also the most influential. These demonstration plants were used to test specific innovations such as feeding systems, the use of alternative fuels, methods for sulfur retention, and most importantly scale-up. The scaling up from pilot to commercial size was a critical issue for AFBC technology, as it could not be adequately modeled. Thus, successful demonstration was key to future commercial acceptance. The demonstration program had two separate foci: (1) industrial demonstrations that were sponsored by DOE, and (2) utility scale demonstrations that were sponsored not only by DOE but also by the Tennessee Valley Authority (TVA) and Electric Power Research Institute (EPRI) [52, 53, 54].

There are two main approaches to AFBC technology, bubbling designs and circulating designs. For industrial application, the publicly sponsored demonstration plants were all of the bubbling technology. The firms involved in these demonstrations all later commercialized bubbling AFBC boilers. The U.S. government did not sponsor any circulating designs. The circulating design has proven by far the most popular choice in the U.S. market. It was demonstrated in Europe in the early 1980s and transferred to U.S. market in the mid-1980s.

The TVA, in conjunction with EPRI, sponsored the initial utility applications. After successful operation of a 20MW pilot plant, they partially sponsored, along with the two private companies, a 160 MW retrofit. The retrofit had adequate environmental performance, however it did not meet the TVA's operation and maintenance expectations. These pilots were based on the bubbling design. As with the industrial boilers, the circulating design looks more promising for large power sector applications. The largest circulating fluidized boiler and first utility application of this technology was a 110 MW retrofit at the NUCLA power station in Colorado, completed in 1984. Through its clean-coal program, the DOE sponsored the testing and evaluation of the economic, environmental, and operational characteristics of this boiler. The tests were carried out from 1988 to 1991. NUCLA proved a successful scale-up of circulating technology, and the company, Ahlstron Pyropower, has built additional units of this size.

In summarizing the role of the government on the supply side for AFBC, we note that it played a catalytic role in creating the AFBC industry, but had limited impact on the eventually dominant technology. The early government R&D efforts were instrumental in transferring AFBC from the chemical industry to the electric power sector. Each of the private sector firms that participated in the government-sponsored pilot and the demonstration plants commercialized the bubbling technology. This experience with bubbling technology created companies interested in AFBC technology, who later pursued the circulating technology through licensing or acquisition once it proved to be the better technology. Because there has been limited penetration of the circulating technology for re-powering, it is difficult to suggest that government involvement in testing it had a significant impact.

AFBC technology was a successfully demonstrated, commercially available technology by the mid-1980s. It was well poised to take advantage of the opening created by PURPA. Because of PURPA, AFBC was able to capture a niche in the co-generation market. Specifically it was cost-effective when low-grade fuels were available or coal was abundant.

Although environmental concerns were one of the drivers of public investment in AFBC R&D, environmental regulation neither created a strong market for this technology, nor hindered its diffusion. During the 1980s, AFBC was identified as one of the "best available technologies" to comply with SO<sub>2</sub> standards, as was conventional pulverized coal combustion equipped with scrubbers. Thus, the Clean Air Act regulations provided neither advantages nor disadvantages. The 1990 amendments to the Clean Air Act promoted re-powering with clean-coal technologies, including AFBC, by providing longer time frames for compliance for plants that chose to re-power with clean-coal technologies. However, no utilities chose to comply with the Clean Air Act amendments in this way. While the 1990 amendments provided a potential opening for AFBC, less expensive options were available for compliance (e.g. fuel switching) and with the utility sector undergoing restructuring, utilities did not want to commit to large capital investments.

The following counter-factual is worth exploring as a way of highlighting the role of regulation and the shortcomings of addressing one pollutant at a time. For SO<sub>2</sub> emissions, AFBC has comparable environmental performance to conventional pulverized coal boilers equipped with scrubbers or using low-sulfur coal. In terms of NO<sub>x</sub> reduction, AFBC is superior. Concern over NO<sub>x</sub> emissions is now growing, and the power sector may face more stringent NO<sub>x</sub> standards in the future. If environmental regulation had taken on both SO<sub>2</sub> and NO<sub>x</sub> simultaneously, it may have created a greater demand for this technology. Alternatively, if regulation had addressed CO<sub>2</sub> emissions as well, other clean-coal technologies would look more promising than AFBC.

In sum, although AFBC is now a mature technology, it has had limited penetration of the electricity generation market. On the supply side, government played a key role by funding the initial demonstrations of AFBC for power generation, although this funding continued longer than necessary, as evidenced by concurrent private sector investment in new AFBC plants. After initial demonstrations, the private sector was largely responsible for subsequent introduction of advanced designs. On the demand side, demonstration programs, deregulation in the power sector and environmental regulation did not create a vibrant market for AFBC. Except in niche markets, AFBC did not develop economic advantages over its competitors, which included gas turbines and pulverized-coal boilers. Furthermore, while environmental regulations were inclusive of AFBC, they did not create advantages for AFBC over its competitors.

### *Gas Turbines<sup>xvi</sup>*

Gas turbines are currently the least expensive technology for electricity generation; the majority of electricity capacity added in the United States over the next decade is expected to be from gas turbines. The advantages of gas turbines include not only their competitive cost, but also modularity, low capital costs, dispatchability, and low pollution compared to other fossil-fuel generating technologies. All these characteristics have contributed to the attractiveness of gas turbines in the emerging competitive power generation market.

The basic R&D underlying gas turbine technology was carried out for military jet engines during World War II. The technology was adopted in the power sector in the 1960s. With this transfer of turbine technology to a civilian application, firms began to create separate divisions and separate R&D programs for their power sector gas turbines. Nonetheless, over the past three decades, firms have continued to draw on advances in military jet engines as sources of the technology for stationary gas turbines. While government-sponsored military R&D and private sector R&D for stationary gas turbines were the largest sources of innovation, government-sponsored R&D directed specifically to gas turbines and transfers from NASA have also contributed to the evolution of gas turbines.

The early power applications were not highly efficient, and could not compete with the cost of base load coal or oil generation. They were thus used only for peaking power. Considerable technological innovation over the last several decades has put gas turbines in their current position of being the most

attractive technology for new power generation in the deregulated marketplace. Simple gas turbines have doubled their efficiency over this period, and the introduction of combined cycles tripled efficiency. These efficiency gains depended on increases in the firing temperatures, innovations in aerodynamics, and perfection of the combined cycle.

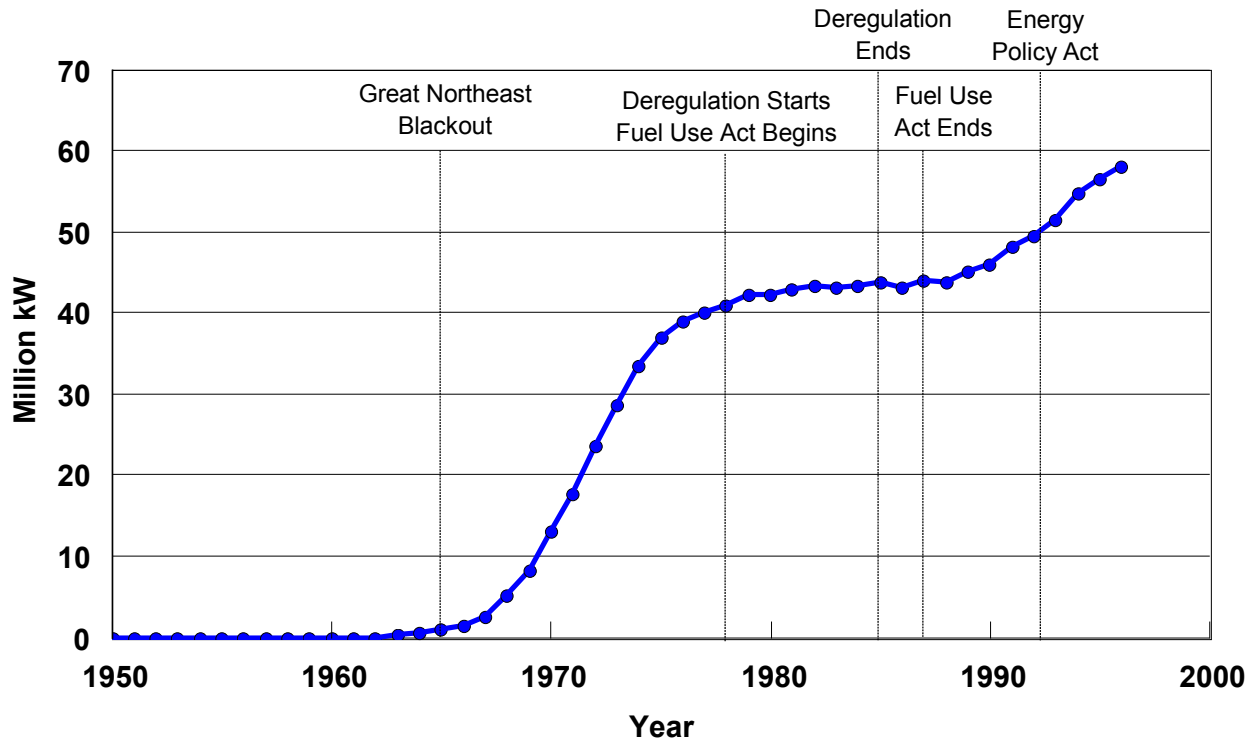
R&D proceeded along two lines in order to make higher temperatures possible: material improvements and cooling systems. In the 1960s, the material trajectory of jet engine gas turbines and stationary gas turbines largely diverged. Unlike jet engines, stationary turbines did not need to operate in pristine environments or be lightweight; rather they needed to operate with more corrosive fuels and operating environments. Some of the advances in materials were done independently by power generation engineering groups, such as those for improved heat tolerance and distribution for turbine inlet components. Others such as protective coatings on high temperature components stemmed from both power and aviation engineering groups. In the mid-1960s, private firms introduced cooling to stationary gas turbines. This technology was transferred initially from military turbine jet engines. A later source of the cooling technology was the drilling industry. NASA was also an important source of analytical techniques for cooling design; finite element analysis generated for space applications allowed for more complex and faster development of cooling designs. Building on these transferred technologies, the private sector invested in cooling research that led to design innovations. In addition to the dual-use programs (military jet engines and NASA) discussed above, during the decade following the oil crisis, the U.S. government also invested directly in stationary gas turbine research through the High Temperatures Technology Program. This program contributed technologies for both cooling and material coatings.

In the mid-1980s, when the market for gas turbines picked up again, as will be discussed below, turbine firms began developing a new generation of higher-efficiency gas turbines which included perfecting the combined-cycle gas turbine. At this point, firms were able to draw on a large set of untapped innovations in jet engine technology to further increase firing temperatures by improving materials and cooling systems. They also increased efficiency through improvements in turbine aerodynamics. In the mid-1990s, the U.S. government again invested directly in stationary gas turbine technology by sponsoring the Advance Turbine Systems Program, which has a goal of creating the next generation of gas turbines. The participants in this program include 6 U.S. turbine manufacturers, 83 universities, and DOE research centers. Further investigation into this program is necessary to understand its impacts. Watson concluded that this program may give U.S. manufacturers an early competitive lead but that it was not necessary for ongoing innovation in stationary gas turbines [22].

Regulation and deregulation in both the gas and electric sectors have influenced the market for gas turbines. During the 1970s, price controls on natural gas led to shortages. In 1977, deregulation of natural gas began, with all of natural gas deregulated by the year 1985. During the process of deregulation (between 1977 and 1985), the price of natural gas continued to increase; upon completion of deregulation gas prices fell quickly and sharply, making gas a more competitive fuel. During nearly the same period, from 1978 through 1987, the Fuel Use Act restricted the use of natural gas for most new industrial facilities and all new power plants. This was based on the belief that supplies were limited and that natural gas should be saved for use in more critical applications such as residential and commercial heating. During this period, the U.S. market for gas turbines dried up. Similar restrictions in the European Community limited the market there as well.

PURPA created an expanded market for gas turbines. Greater adoption of cogeneration technology was one of the goals of this legislation, and gas turbines were an excellent choice for co-generators. Although states began PURPA implementation in 1983, the use of gas remained constrained by regulated prices (deregulation was not complete until 1985) and the Fuel Use Act. When the Fuel Use Act was lifted in 1987, the gas turbine market took off, as shown in Figure 4. Current deregulation is expected to favor gas turbines over all other technologies.

Figure 4: Electric Utility Net Summer Capability in the United States



There were not specific environmental regulations that forced the use of natural gas. However, as the cleanest fossil fuel, gas turbines were able to meet the requirements of the Clean Air Act without need for additional pollution-control equipment. This contributed cost-competitiveness by keeping capital costs down, reducing operation and maintenance requirements associated with pollution-control, and reducing the need for permits and inspections required by coal power plants with scrubbers. Environmental regulations did force some technological innovation in systems for the control of NOx.

In sum, public policies and private markets were both instrumental in the highly successful commercialization of gas turbines. Government sponsored R&D, particularly military R&D for jet engines, created the initial technology and an ongoing source of technological innovations that private firms relied on as they increased the efficiency of gas turbines. However, private firms also invested significantly in R&D, both for technological breakthroughs and adaptation of jet turbine technology for stationery turbine applications. On the demand side, the need for peaking power provided the first market for stationery gas turbines. Government policy controlling the price and use of natural gas as well as the traditional regulation of utilities as a natural monopoly, created barriers to greater diffusion of this technology. With the removal of these barriers, the technology has been able to penetrate the marketplace without further government subsidies or standards.

### *Summary of the Government Role in Technological Innovation*

The government was active in R&D for all four of these technologies. In each case, government-sponsored R&D played a key role in the initial development of these technologies for power sector applications. Two of the technologies, gas turbines and solar photovoltaics, were dual-use technologies with origins in the military and space programs, respectively. For these technologies, government investments in both basic science and basic technology were fundamental to the founding of these industries. In both cases, the civilian technology eventually broke off from its originating military or space use, taking a technological path that required innovations appropriate to the power sector application. In the case of stationary gas turbines, since the 1960s the private sector has invested in innovation specific to stationary gas turbines, while continuing to draw on military jet engine breakthroughs. For terrestrial solar PV, the government has continued to be the main source of research, both fundamental and applied. For wind turbines, the U.S. government attempted to apply a "big science" approach similar to that which brought success in military and space technology. This effort did not achieve commercial success, and its contributions of some of the key design tools used in the wind turbine industry came at too high a price. By contrast, government investment in component R&D for wind turbines has been responsible for about half of the key wind turbine component innovations. In the case of AFBC, basic R&D was not necessary, as the technology had already been proven effective in the chemical industry. The government role was one of initially sponsoring pilot plants for electricity generation applications and later sponsoring scale-ups for utility applications.

The initial restructuring of the U.S. electric power sector, created by PURPA, played a crucial role in the entrance into the power sector of gas turbines, wind turbines, and AFBC coal plants. Gas turbines and AFBC power plants both found expanding markets for co-generation under PURPA. Gas turbines were on their way to becoming the least-expensive technology for generating electricity and were widely adopted. AFBC plants were cost competitive only in the niche markets of low-grade fuel. Even with PURPA, wind turbines required additional financial initiatives to be attractive investments. These included relatively generous avoided costs, long-term contracts, and investment tax credits. Solar photovoltaics were too expensive to compete in the grid-connected power generation market; even with tax breaks for renewables they were not attractive investments for qualifying facilities under PURPA. In the ongoing restructuring created by deregulation, gas turbines are expected to be the preferred technology for new generation capacity. AFBC is likely to continue to capture only small niche markets. Wind turbines and Solar PV generating capacity will only be added in states that create special incentives for their adoption.

Environmental regulations acted indirectly in the development of these technologies. The growing environmental concerns over air pollutants provided an impetus to investments in R&D for this new set of energy technologies and was one of the rationales for PURPA. The Clean Air Act may have had some impact on the market for alternatives to traditional coal boilers. Gas turbines, and to a lesser degree AFBC, benefited by not needing additional end-of-stack controls for sulfur, thus reducing both capital and O&M costs. However, traditional coal combustion was able to comply with the Clean Air Act through the addition of scrubbers, and remained economically competitive with the alternatives until the dominance of gas turbines in the 1990s.

### **Analysis: Supply-push and Demand-pull Policies for Technology Commercialization**

These cases confirm many well-known lessons about the pitfalls of government intervention in the development of technology. This section begins by reviewing these. It then moves into the more fertile ground of examining insights these cases provide on public policy during the commercialization phase of new energy technologies.

For supply-push, these cases confirm the difficulties governments have in making wise decisions about the development of technologies that will be largely adopted by the private sector. First, public agencies often make poor choices in picking which technologies should be developed, i.e. the problem of the government "picking winners"[57]. These cases present examples of government investments in technological pathways that did not prove to be commercially viable (e.g. large wind turbines) or commercially dominant (e.g. AFBC bubbling). Clearly, some R&D investments will not be successful. Nonetheless, as confirmed by these cases, this problem can be minimized by developing a process for setting R&D priorities that involves both the public and private sector, and requiring cost-sharing by the private sector, and designing processes that require mid-stream review.

Second, the literature on technology policy has noted a pull for investments in demonstrations rather than in basic R&D, as demonstration projects can provide greater "pork" to congressional constituents [56, 57]. In these cases we saw investments in demonstrations long before a technology was commercially viable (e.g. solar photovoltaics) and also after a technology was commercially successful (e.g. AFBC). Under these circumstances it is hard to make a case for large-scale government-supported demonstrations. Having raised this criticism, it is important to note that these cases also show that demonstrations can play an important role in commercialization. This is not only because they subsidize the cost of first plants that are not cost-competitive (the mountain of death problem), but more importantly because they provide verification of new technologies and thus reduce the risk to potential developers and adopters. The lesson to be drawn regarding demonstrations is that it is appropriate for government to support demonstrations only for first of a kind technologies that are too risky for the private sector to bring through commercialization *and* for which there is a likely commercial market

A final lesson for supply-push policy, as seen in the case of wind turbines, is that inconsistency in funding can lead to loss of technological capability and then subsequent need to rebuild that capacity, resulting in inefficiency and longer time frames for technology development and diffusion.

Turning attention to demand-pull policies, these cases confirm that regulation (or the lack thereof) can have a "lock-in" effect. First, the regulation of electric utilities as natural monopolies prevented the penetration of technologies that were more efficient and smaller scale than the power plants typically adopted by electric utilities. PURPA, by mandating the buyback of electricity from small independent generators, opened the market for a different set of technologies. Second, the lack of internalization of environmental externalities (e.g. SO<sub>2</sub>, NO<sub>x</sub> and CO<sub>2</sub>) dampened the private market for environmentally preferred power generation technologies. Third, single pollutant legislation may not lead to optimal technology choices over the long run, as suggested by the counterfactual exploration of NO<sub>x</sub> and CO<sub>2</sub> control in the AFBC case. Given the longevity of technology in the electric power sector, this is a particular concern.

This analysis now turns to the key focus of this article - the role of government in bringing technology through the commercialization stage. Comparing across these cases is complex. Although only the fossil fuel technologies have become commercially competitive for grid generation, the efficiency increases and price decreases for the renewable technologies have been quite dramatic. Despite the many differences, government involvement in supply-push and demand-pull influenced the path and pace of technology development and commercialization for each of these technologies. From these cases, this analysis identifies five factors that influence the necessary level of government involvement and division of effort between supply-push and demand-pull during the commercialization of environmentally enhancing energy technologies (and other private goods desired for their public good attributes). These include the size, strength and risk of the private market niche; industry structure; firm financial capability; firm technological capability; and sources of innovation.

In the case of gas turbines and AFBC power plants, each were able to capture a market niche prior to being fully competitive with base-load generation technologies. Gas turbines first market niche was based on quick start-up and shut-down capabilities, which made them perfect for peaking power. As the need for peaking power grew in the United States, this niche grew as well, creating incentives for private

sector investments in improving this technology. Due to its comparatively clean environmental characteristics, if it could become cost-competitive with coal, it would have an even larger market, again providing incentives for private sector investment in innovation. Important to the ultimate commercial success of this technology, the gas turbine industry was able to weather an almost decade-long, regulatory-driven, virtual shut-down of its business. This occurred during the years 1978 to 1987 when the Fuel Use Act prevented the adoption of gas turbines for most industrial and utility uses. Several factors contributed to the industry's ability to survive. First the firms in this business were either also producing gas turbines for aviation applications, or were in the steam turbine business. Thus they had other products to which they could apply their human and physical capital during this period. Second, there were reasons to believe this was a temporary setback; at the same time that the purchase of new turbines was restricted, natural gas was being deregulated and PURPA was enacted, suggesting potential future markets. Third, they were able to make some sales to Middle East markets, foreshadowing the opening of developing country markets for gas turbines.

AFBC plants were able to capture a niche market once PURPA opened the market for cogenerators to sell electricity to the grid. This market was limited to applications where low-grade fuel and/or abundant coal was available. Nonetheless, both private firms and government R&D sponsors believed that AFBC could be less expensive than traditional pulverized-coal boilers, and thus be able to compete in a larger industrial and utility market. With a small but growing cogeneration market, continued faith in further technological potential, and a large global market for coal combustion, private firms continued to invest in this technology. As with gas turbines, AFBC were developed and manufactured by large firms with additional power sector products.

The industrial structure of the wind industry and the solar photovoltaic industry was quite different. The firms involved in this industry were small, their manufacturing techniques were not high-tech, and they were single product firms. While in both cases there was some private sector innovation, government sponsored R&D supported the lions-share of technological breakthroughs. Thus, unlike gas turbine manufacturers who were able to survive the long down-turn in their business, the U.S. wind turbine manufacturers went out of business when the demand-pull policies for wind turbines ended. The key lesson that many observers take from the wind turbine story is that the investment subsidies and tax incentives were too large, leading investors to put up inferior technologies. The more important lesson to learn from this experience is the need for a long-term and consistent market for an emerging technology. During the period of market support, the private sector invested in on-going innovation. As the bottom fell out of this market, so did further development of the technology. Firms were not able to install next generation turbines. More critically, the United States experienced setbacks to its developing technological capability in this area.

In sum, the differences between the path to commercialization for the fossil fuel and renewable technologies examined in this paper are striking, as shown in Table 1. Multiple factors contributed to the commercial success of gas turbines and AFBC. Technologically, they were closer to being competitive than the renewable technologies examined in this paper. But there are other important issues. Both were able to capture private niche markets before they were broadly competitive, both had reason to expect a growing private market if they could reach what appeared to be reasonable technological goals, and both were developed in industries with deep and complementary technological assets in the form of both human and manufacturing capability and in-house resources to invest in R&D. Furthermore, in the case of gas turbines, the more commercially successful technology, public investments in military jet engines provided an on-going source of applied R&D which gas turbine manufactures drew on to improve efficiency and reliability.

In contrast, wind turbines and solar photovoltaics, could not capture large private niche markets. To this day, wind turbines (of the size used for grid-connection) are not cost-competitive with fossil technologies. While PV and micro-wind turbines are cost-competitive for low-density remote applications, this is a limited private market. Much of this niche is in developing countries, where the market risk is higher, energy is often subsidized, and financing and subsidies are often needed to make the technology

affordable [58]. Furthermore, the renewable firms did not have the depth of technological capability and complementary assets that would allow them to weather the long climb to un-subsidized commercialization.

**Table 1: Factors Influencing Development and Diffusion of Renewable and Fossil Technologies<sup>xvii</sup>**

		<b>Renewables</b>	<b>Fossil Fuel</b>
		<b>(Wind and PV)</b>	<b>(Gas Turbines and AFBC)</b>
<b>Industry Structure</b>		<ul style="list-style-type: none"> <li>- Small firms</li> <li>- Single product</li> <li>- Craft production</li> </ul>	<ul style="list-style-type: none"> <li>- Large firms</li> <li>- Multiple-related products</li> <li>- Automated production</li> </ul>
<b>Financial capability</b>		<ul style="list-style-type: none"> <li>- Limited in-house</li> <li>- Limited venture capital</li> </ul>	<ul style="list-style-type: none"> <li>- Significant in-house</li> </ul>
<b>Technological capability</b>		<ul style="list-style-type: none"> <li>- Incremental and radical innovation</li> <li>- Require government funding</li> </ul>	<ul style="list-style-type: none"> <li>- Incremental and radical</li> <li>- Dual-use (gas turbines)</li> </ul>
<b>Sources of innovation</b>		<ul style="list-style-type: none"> <li>- Limited transfer from aero/space (PV)</li> </ul>	<ul style="list-style-type: none"> <li>- On-going transfer from aerospace</li> <li>- Steam turbines</li> <li>- Chemical Industry (AFBC)</li> </ul>
<b>Private market niche</b>		<ul style="list-style-type: none"> <li>- Limited green consumers willing to pay</li> <li>- Remote, low-density</li> </ul>	<ul style="list-style-type: none"> <li>- Peaking power (gas turbines)</li> <li>- Low grade fuels (AFBC)</li> <li>- Co-generation</li> </ul>

## Conclusion

If, due to public good characteristics, we would like to see the diffusion of PV and wind outside the current limited uses where they are cost competitive, policies for supply-push and demand-pull are both necessary. This conclusion would hold for many other emerging environmentally preferred energy technologies as well. Publicly sponsored R&D was an important source of energy technology innovation, even for gas turbines, which had significant in-house technological and financial capabilities. For emerging technologies dominated by small firms, as has been the case in renewables, public funding has been even more important. Investing in R&D is necessary but insufficient; governments must also create markets in which to grow these new industries. Market niches are important not only for firm survival, but because they are crucial for guiding technological developments of the civilian energy R&D programs. During the period spanning pre-commercialization, first commercial use and lead adoption, government must act simultaneously to support both technology development and to create markets.

This call for government involvement in a well-orchestrated combination of supply-push and demand-pull policies, even in the face of the many pitfalls to effective government action identified in these four cases, suggests a need for attention to the details of policy design. Lessons for policy design come from these cases as well as existing research. In R&D programs, components of effective policy include: public-private partnerships, including private sector involvement in directing research and cost-sharing between the public and private sector; a proper division between basic technological R&D and demonstration,

investing in demonstration only when necessary to verify the performance of the technologies and thus reduce the risk to potential developers and adopters, and when there is a likely private market; consistency in funding as well as a level of funding that matches the public interest in developing new energy technologies; oversight that allows for regular reassessment and redirection, including the canceling of programs mid-stream; and a diverse portfolio pursuing multiple strategies for a single technology as well as multiple technologies.

In terms of demand-pull policies, government created niche markets must not only provide adequate incentives, but also certainty and longevity to be effective in bringing technologies through commercialization [59, 60]. If incentives are in the form of subsidies, a variety of market-based approaches can be used to make policy efficient, in other words to make subsidies only as large as necessary to induce market activity [61, 62]. Furthermore to guard against technology lock-in, regulations should be flexible, multi-pollutant and multi-media, and take a long-term perspective [63].

Despite the risk of some ineffective and inefficient programs, the technologies needed to manage climate change will not be widely commercialized without government policies for both supply-push and demand-pull. If renewables and other promising new energy technologies are going to be a significant part of efforts to manage climate change in the medium-term, we must act now to increase R&D funding and expand niche markets.

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## ENDNOTES

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<sup>i</sup> PCAST, p. 7-15 citing two sources: "Mountain of Death" from the Electric Power Research Institute; "Valley of Death" from Helena Chum, NREL, and Irvine Barash, VenCom Management, Inc., personal communications [2].

<sup>ii</sup> Deregulation, improvements in generation technology, and low-cost fossil fuels appear to be bringing on a new era of falling electricity prices.

<sup>iii</sup> Private sector energy R&D shows similar trends. In the face of electricity sector restructuring, investor owned utilities (IOUs) decreased R&D expenditures by 35 percent between 1994 and 1996, from \$65 to \$403 million. During the same period, the ten largest IOU contributors to the Electric Power Research Institute decreased their support by 47 percent, from \$130 to \$69 million [7]. For an examination of private energy R&D trends, see [8].

<sup>iv</sup> In 1997, President Clinton asked his Committee of Advisers on Science and Technology (PCAST) to review the current national energy R&D portfolio. The PCAST study recommended an increase, over a five-year period, of \$1.1 billion over FY 1997 levels (in current dollars) for applied energy technology R&D. This represents a 61% increase over 1997 levels; the report recommended that 32% of this increase occur in FY1999. PCAST made the following recommendations for R&D priorities: (1) most of the increase should go to energy efficiency and renewable energy technologies, (2) nuclear fission and fusion should receive smaller increases, (3) R&D spending for advanced fossil-fuel technologies should remain roughly constant, but shift to longer-term opportunities [2].

<sup>v</sup> Source: PCAST, Federal Research and Development for the Challenges of the Twenty-First Century, 1997 [2].

<sup>vi</sup> Non-utility generators include independent power producers as well as cogenerators.

<sup>vii</sup> For updated information on utility restructuring in United States, including the information on specific programs to promote the adoption of renewable energy technologies and energy efficiency, see the Web site of the National Association of Regulatory Utility Commissions, <http://ragtime.xenergy.com/Client/NARUC/Production/naruc.nsf>

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<sup>viii</sup> This section is based on Loiter and Norberg-Bohm 1999 [17].

<sup>ix</sup> This picture is changing. More recent government efforts have led to the development of wind farms in other parts of the country [27, 28, 29]. Parsons 1998, Guey-Lee 1998, Giovado 1998).

<sup>x</sup> For updated information on efforts to support renewables in electricity restructuring see [http://www.eia.doe.gov/cneaf/electricity/chg\\_str/pbp.html](http://www.eia.doe.gov/cneaf/electricity/chg_str/pbp.html).

<sup>xi</sup> Source: CEC; Karnøe 1993; Brooks and Freedman 1996 [32, 33, 35].

<sup>xii</sup> This section draws on research by Nilson [21].

<sup>xiii</sup> With the entrance of several large oil companies into the renewables arena in the last couple of years, we may see changes in manufacturing approaches, including increased economies of scale.

<sup>xiv</sup> This section is based on Bañales and Norberg-Bohm [20].

<sup>xv</sup> Source: Simbeck, et al 1994b [50, 51].

<sup>xvi</sup> This section draws on Unger and Herzog 1998 [14] and Watson [22].

<sup>xvii</sup> Unger and Herzog 1998 [14]; using Energy Information Administration data:  
<ftp://ftp.eia.doe.gov/pub/energy.overview/aer/0808.txt>