Public policy for energy technology innovation
A historical analysis of fluidized bed combustion development in the USA

Santiago Bañales-López*, Vicki Norberg-Bohm

Abstract

This paper analyzes the role of public policy in the development of atmospheric fluidized bed combustion (AFBC) of coal for power generation in the United States. AFBC is at present a mature technology for power generation up to the size of 250 MW. The technology has mainly been used by cogenerators and independent power producers, rather than by utilities. The trends in development are explained by an interaction of supply and demand factors. On the supply side, the two key factors were the early government-sponsored demonstration plants and the subsequent introduction of advanced designs by the private sector. On the demand side, the key elements were the enactment of the Public Utilities Regulatory Policy Act and the characterization of AFBC as one of the best available technologies to comply with environmental standards. However, these combined with two other public policies—government funding of utility size demonstration units and the incentives provided by the Clean Air Act for clean coal repowering—have not been enough to spur a sustained demand for the technology in the utility sector. We conclude that investments in demonstration should be made only when there is likely to be a sustained market, either a private market that can take-off once there is proof-of-concept or a publicly created market to address the public goods aspects of energy production. Furthermore, given that assessments of future markets is made under uncertainty about the success of the technology in question as well as the evolution of competing technologies and costs of alternative fuels, it is important to have mid-stream reassessment of demonstration programs. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Public policy; Innovation; Fluidized bed combustion

1. Introduction

Promoting technology innovation is a necessary component of a coherent energy policy. At present, the main policy driver in the power sector is the promotion of wholesale and retail electricity competition. However, energy technologies must achieve other important policy goals, particularly environmental protection. The challenge from a public policy perspective is to create incentives in such a way that the path of innovation helps to achieve the full range of public goods associated with energy production and use. Through a retrospective analysis of one particular technology, atmospheric fluidized bed combustion (AFBC) for power applications, this paper draws lessons on the design of policy to promote energy technology innovation. AFBC has a relatively long history of technological and commercial development, a history that has been influenced by a number of public policies, making it a good case for historical research on public policy in energy technology development.

Since the mid-1960s, different US agencies have been involved in the development of fluidized bed as an option for power generation.1 The chemical industry

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1 The main public policies considered in this paper are the DOE atmospheric fluidized bed combustion program (1965–1992), the DOE
was the first to apply fluidized bed technology (Ehrlich, 1975). It was not until the 1960s that researchers realized the potential security, economic and environmental advantages of using this combustion process to raise steam and produce electricity from coal or low quality fuels. Governments, first in England and then in the US, sponsored fluidized bed combustion RD&D in an effort to move this technology through commercialization in the power sector and thus capture its potential advantages.

The paper is organized as follows. In Section 2, we provide the necessary technical background to understand the merits and challenges of atmospheric fluidized bed combustion as an option for power generation. Section 3 describes the commercial evolution of the technology. This sets the stage for Section 4, which analyzes how public and private initiatives shaped the commercial evolution of AFBC. Finally, Section 5 provides a summary of the main conclusions of the study and puts forward a set of recommendations for future public policy for energy technology innovation.

2. Technical background

In a fluidized bed boiler, the combustion air is introduced at the bottom of the furnace, distributed across the chamber by a porous base or air distributor and flown upward through a bed composed of inert particles such as coal ash and limestone byproducts and, in a much lower proportion, fuel particles. Initial increase in the air velocity results in an increase of the pressure drop in the bed. When the pressure drop in the bed is sufficient to offset the weight of the bed, the bed particles start to behave as particles of fluid. At this point, the velocity of the air is called “fluidizing velocity.” A further increase in air velocity produces an expansion of the bed and bubbles of gas rise through the bed (Howard, 1989).

Table 1 summarizes the potential advantages of AFBC over more traditional coal technologies. These

<table>
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<tr>
<th>Economic advantages</th>
<th>Fuel flexibility (low-grade fuels)</th>
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<tr>
<td>Smaller burner for same heat output</td>
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<td>Coal preparation cost reduction</td>
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<td>No end-of-pipe environmental controls</td>
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Environmental advantages

- In bed capture of SO$_2$
- Intrinsic reduction of NO$_x$ emissions

potential advantages come from two technical features of the fluidized bed boiler: (1) a higher heat transfer rate, which implies a lower combustion temperature (around 850°C, approximately half the temperature of an entrained flow pulverized coal boiler), and (2) a good mixing of air, inert particles and fuel. The lower combustion temperature means that the formation of thermal NO$_x$ is largely reduced. The good mixing properties in the furnace allow the use of low-grade fuels difficult to burn in traditional coal burners. Another advantage of fluidized bed combustion is the retention of sulfur dioxide in the combustion chamber. The good mixing properties of the fluidized bed combustion chamber and the low combustion temperature are optimal for capturing of SO$_2$ with limestone or dolomite in the furnace. Therefore, a fluidized bed boiler does not need downstream scrubbers to clean up the effluents, with the consequent potential reduction in capital cost.

The achievement of these potential advantages has been constrained by several technical barriers. The main barriers have been: the scale-up of the technology, the reliability of auxiliary systems (mainly fuel feeding systems), and the disposal of solid waste material.

The circulating version of the AFBC has successfully addressed some of these technical barriers. The main difference between a circulating and a bubbling design is the air velocity of the fluidizing air. Typical velocities in circulating AFBC are 5–10 m/s, whereas typical velocities in bubbling AFBC are 1–3 m/s. The circulating design has several advantages over the bubbling design (Basu and Fraser, 1991; Howard, 1989; Yerushalmi, 1985) including higher combustion efficiency, more efficient sulfur removal, smaller furnace cross section, and fewer feed points.

3. Commercial adoption of AFBC

AFBC technology for power applications has mainly been introduced in the non-utility sector for cogeneration purposes and, in a lesser extent, for independent power generation. In this section we present the relevant facts concerning the deployment of AFBC technology for power applications in both the utility and the
non-utility sectors. Fig. 1 shows the electrical capacity of new units in the US non-utility sector with an atmospheric fluidized-bed combustor by year of start-up in the period 1980–1998.

Although the first pilot and demonstration AFBC units are introduced in the 1960s and 1970s, AFBC technology can be considered commercially mature in the mid-1980s. Fig. 1 shows how the technology takes off in the mid-1980s and the number of units installed reaches a maximum in the early 1990s. Capacity of newly installed AFBC units significantly decreases in the 1990s.

AFBC capacity accounts for a moderate share of non-utility new additions: the percentage of AFBC capacity in the non-utility sector fluctuated between 0% and almost 12% in the 1980–1998 period. AFBC capacity represented around 3.7% of the total cumulative non-utility operational capacity at the end of 1999 (EIA, 2000a). In the United States, AFBC has been adopted mainly by independent power producers and cogenerators qualified under Public Utilities Regulatory Policy Act (PURPA).

Circulating design has been more popular than the bubbling design in the United States both in terms of units and cumulative capacity. The National Research Council (1995) estimated that 75% of the units installed by 1995 were of circulating design. Our estimate, made from the installation list of the main manufacturers, is that around 80% of the units and 90% of the capacity installed in the United States is of circulating design (Bañales and Norberg-Bohm, 1998).

As far as the utility market is concerned, the penetration of AFBC units has been almost negligible. There have been six AFBC units commissioned by utilities in the United States4; the cumulative capacity of these units is around 660 MW, which is a very small figure compared with the total installed capacity of the utility sector of around 640,000 MW by the end of 1999 (EIA, 2000b).

Three factors: scale-up, cost and attitude towards risk explain these differences in utility and non-utility adoption of AFBC. In order to measure the impact of scale-up on investment decisions, it is useful to look at the capacity chosen by utility investors in the period of 1970–1996. The capacity of newly installed coal-based utility central stations has been declining in the period 1970–2000, as Fig. 2 shows. The average capacity of the units installed in this period varies between 400 and 600 MW.

The maximum commercially available size of AFBC to date is 250 MW and AFBC manufacturers have been able to offer an acceptable size for utility applications (over 100 MW) only since 1985, when the market for new coal-based power generation was in evident decline.5 Therefore, scale-up of the technology has been an important issue in the lack of AFBC penetration in the utility sector. On the other hand, it is interesting to note that the size of the AFBC steam prime mover is on average larger than the other prime movers among the non-utility generators (EIA, 1993). This evidence indicates that the scale-up has not been a barrier in the non-utility sector.

Cost (capital cost and cost of electricity) is probably the most important factor for energy technology choice and AFBC did not offer general cost advantages for utilities. In preliminary cost assessments of the

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4The three bubbling design units are: Black dog—Northern States Power Corporation, Heskett 2—Montana–Dakota Utilities, Shawnee—Tennessee Valley Authority, and the three circulating design units are: TNP (2 units)—Texas–New Mexico Power Corporation and Nucla—Colorado–Ute.

5The average capacity of the units installed increases over time, but this capacity remains small compared to full-size utility units (Simbeck et al., 1994b). The biggest unit installed is a 250 MW unit in France; two more units of the same size are planned in Red Hills, Mississippi.
technology, experts expected AFBC to achieve a cost equivalent to conventional pulverized coal (PC) technology without scrubbers. This would result in lower costs than PC in cases where scrubbers were necessary to meet clean air requirements. Had this cost been achieved, AFBC would have had a competitive advantage compared to more traditional alternatives. However, this hope turned out to be only partially true. Under certain conditions, AFBC has a higher capital cost than PC, although the cost range is too wide to state that AFBC has always a higher capital cost than PC. According to the International Energy Agency (IEA, 1996), AFBC cost for the range of 50–350 MW is reported to be between $1000 and $1600/kW. IEA reports a range of cost for advanced PC between $950/kW and $1300/kW for a range of electrical output of 50–1000 MW. Therefore, according to IEA, both technologies can have the same capital cost, with a broader range and potentially higher cost for fluidized bed technology. In financial evaluations taking into account both capital and operational cost, AFBC can be more competitive than PC when low-grade or high-sulfur coal is available. AFBC has in general a higher capital cost than PC boilers but this higher capital cost can be offset by lower operational cost when less expensive, low-grade fuel, which is impossible to use in a PC boiler, is available (Johns, 1989). The private sector AFBC adoption into the non-utility market reflects these advantages. However, the technology has not achieved its initial promise of lower capital cost than more conventional coal-based technologies, providing no incentive for utilities to choose this less proven technology.

Third, risk aversion of utilities has been pointed out as a potential barrier to further acceptance of AFBC. Typically, the first commercial units of new technologies have operational problems and that was the case of AFBC. However, as engineering experience has grown, the reliability of AFBC units has approached the reliability of other mature technologies. IEA (1996) reports very similar availability factors for PC with flue gas desulfurization (FGD) and AFBC. Despite the fact that most of the problems had been overcome by 1985 when manufacturers offered commercially guaranteed units of the size required for utility applications, it remains a technology without long-term demonstration of large-scale units (IEA, 1996). Several sources suggest the conservatism of the traditional utility business works against taking risks with new technologies: both IEA (1996) and the consulting firm SFA Pacific (Simbeck et al., 1994a) state that one of the factors contributing to the take-off of AFBC in the non-utility sector has been the less risk-averse culture of independent generators.

4. Policy drivers of AFBC development and adoption

In this section, we assess to what extent public policies influenced the pattern of commercial adoption outlined in the previous section. We first examine supply push policies, including government sponsored applied research and demonstration. We then turn to two sets of demand-pull policies, utility regulation and environmental legislation. For each of these topics, the main policies are described and their impacts on AFBC commercial development are analyzed.

4.1. Government sponsored research, development and demonstration (RD&D)

Several US federal agencies and administrations have been implementing RD&D policies for AFBC development in the power sector since the early sixties. The outcomes of these programs can be divided into three main categories: (1) design prototypes, (2) small-scale demonstration plants for the power/industrial sector and (3) demonstration plants for the utility power sector. The Department of Energy, the Environmental Protection Agency (EPA) and its predecessors implemented policies aimed at developing workable AFBC designs as a new way of burning coal that would be competitive with oil and gas alternatives and able to meet the new environmental challenges. The main outcomes of these policies were in-house basic research, such as the experimental work on fluidized combustion at the Morgantown and Pittsburgh Research Centers of the US Bureau of Mines (Skinner, 1970), and design prototypes developed by industrial contractors, like Battelle’s design (Nack et al., 1977).

The DOE and its predecessors sponsored small-scale industrial demonstration plants through the Atmospheric Fluidized Bed Combustion Program between 1965 and 1992 (DOE, 1991, 1993). DOE described the program as a coherent research, development and demonstration program in which private industry contributes a percentage of the cost, reaching 50% or more at the commercial-scale demonstration stage. The main outcome of this program has been several bubbling AFBC industrial plants built by the private sector in the period 1975–1990.

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6 For example, EPRI estimated that AFBC would have a capital cost of $710/kw, compared with a cost of $800/kw for advanced pulverized coal with scrubbers. (Yeager, 1980).

7 The estimated cost of the most recent AFBC utility project in the United States, the 2 × 250 MW generation facility in Red Hills, Mississippi, is $1070/kw (Makansi, 1997).

8 The units are Rivesville, Georgetown University, Great Lakes, Shamokin, Steam Heat Authority Wilkes-Barre and East Stroudsburg.
An analysis of the installation lists of the main manufacturers reveals that risk sharing through the DOE AFBC program helped each of them to introduce their first bubbling designs into the non-utility market. Subsequently, the private sector was instrumental in the introduction of the circulating design, which has been the design of choice in the US market.  

There have been two public programs to demonstrate AFBC technology for utility applications: the DOE Clean Coal Technology Demonstration Program and the Tennessee Valley Authority (TVA) AFBC Program. The Clean Coal Technology (CCT) Demonstration Program started in 1986 and it is expected to end by 2005. Its objective is to demonstrate the most promising clean coal technologies in the marketplace. The program is based on the following principles: (1) At least 50% private cost–sharing is required; (2) Industrial participants are required to repay funds if the project is commercially successful; and (3) Real and intellectual property rights are retained by industry (DOE, 1997). There has been only one completed AFBC demonstration plant under the CCT program, the Nucla CFBC Demonstration Project (DOE, 1995). The Nucla Demonstration Project was a successful retrofit with circulating design. However, the Nucla project was only partially sponsored by DOE with the private sector taking a leading role.  

Retrofit with cleaner technologies has been of increasing interest from a public policy perspective as the US coal plants get older and need either to be re-converted or de-commissioned. There is another AFBC project planned under the CCT program, the expected demonstration of a 235 MW circulating fluidized bed boiler. 

In 1976, the Tennessee Valley Authority in collaboration with the Electric Power Research Institute started a program for AFBC development for utility applications (Falkenberry, 1977). The objective of the program was to have a commercial utility unit in operation in the 1990s (High, 1980). To achieve this objective, TVA planned to operate a pilot plant by 1980, a 200 MW demonstration by 1984, and a full commercial plant by the end of the 1990s. The first two stages of this program went forward, at slightly later dates than planned. A 20 MW pilot plant went into operation in 1982 and a 160 MW demonstration project began operation in 1988. The TVA 160 MW unit, the largest AFBC unit in the world at the time, has had reliability problems, and as a result, the unit has had an operational cost above average and a lower availability than expected (Anderson et al., 1997). This poor performance may have contributed to the lack of demand for bubbling AFBC technology for utility applications. It is interesting to note that the final outcome of the program, the full-scale commercial plant, was never built. 

The public involvement in the demonstration of AFBC technology in the utility sector has not had a positive impact on private sector investment decisions. TVA should be commended for not going forward with its full-scale commercial plant, given the problems with its 1988 demonstrations. But in retrospect, the continuation of a program to demonstrate full-scale bubbling AFBC technology in the early 1980s was already inappropriate taking into account the decline of newly installed coal units in the utility sector and the shift in paradigm in the whole industry after the practical application of PURPA in the early 1980s. As far as the Clean Coal Technology Program is concerned, the public involvement in the NUCLA project has not spurred a greater interest on retrofitting with AFBC technology, even with the Clean Air Act (CAA) incentives discussed in Section 4.3.

4.2. Utilities regulation

Since the decade of the 1970s, regulation in the power sector has undergone a fundamental change as competition in generation has been progressively introduced in the electricity sector. While technological change was one of the factors driving this change in regulation, the regulatory changes have also been shaping the patterns of technology choice. Specifically, new private investors, who were not constrained by traditional utility regulation, had a different attitude towards investment risk and technology choice. 

The Public Utilities Regulatory Policy Act was one of the statutes of the National Energy Act of 1978. Under PURPA, a new generating unit could be named a qualifying facility (QF) if the unit used renewable energy or cogeneration and if the small power producer had no more than 50% of its equity held by a utility. The incentive to invest in qualifying facilities was twofold. First, utilities were obliged to buy the power produced by the QF at the “avoided cost” of the utility, and second, the owners of the facility would not be regulated under the Public Utilities Holding Company Act. From 1983 to the present, the share of non-utility producers
has increased considerably. With the enactment of the Energy Policy Act (EPAct) of 1992, the possibilities of non-utility production were expanded. In total, there are three different non-utility classifications (EIA, 1993): cogeneration, small power production and independent power producers. Most of the AFBC units qualified under one of these categories (Simbeck et al., 1994a; DOE, 1993).

This explains why AFBC technology took off commercially in the mid-80s, exactly when the enactment of PURPA started to have its practical effects (Mitchell and Hargis, 1995). In the same way, the decline of the market for cogeneration since the early 1990s may be the explanation for the decline of units installed. Taking into account this evidence, PURPA has been a spur for the development and diffusion of circulating fluidized bed in the non/utility market. Fluidized bed is now a mature option in the boiler market and this rapid development would not have been achieved without the spur PURPA provided to the US cogeneration market.

4.3. Environmental legislation

The CAA was introduced in the late 1960s during the same time period as the first RD&D policies for fluidized bed development. The successive amendments of the CAA have regulated the emissions of SO$_2$, NO$_x$ and particulates, all of which are produced in AFBC units, as well as traditional PC coal generation. Therefore, a question to address is whether environmental legislation introduced since 1970 has created incentives for the development of clean coal technologies and, in particular, fluidized bed.

It is out of the scope of this paper to present the different provisions and the complex evolution of the Clean Air Act. For our purposes it is enough to know that most of the AFBC units had to comply with the New Sources Performance Standards which, in its more stringent version, imply an emission cap of 1.2lb/MBTU for SO$_2$ together with a 90% reduction in the sulfur content of the fuel. AFBC had no problems complying with environmental legislation without the addition of control technologies. For SO$_2$, AFBC has the same performance as conventional pulverized coal boilers equipped with wet scrubbers. It is not surprising that the Environmental Protection Agency (EPA), summarizing the results of the environmental characterization program of fluidized bed in 1980, reported that “It is anticipated that both atmospheric and pressurized fluidized bed combustion systems should be capable of meeting the recently revised New Source Performance Standards (NSPS) covering SO$_2$, NO$_x$ and particulates from electric utility steam-generating units” (Henschel, 1980, p. 50). Furthermore, EPA certified AFBC as one of the “best available technologies” for new industrial boilers. The portfolio of technologies considered in the study for the development of the standards were wet and dry FGD systems, fluidized bed and fuel pretreatment technologies. The final standards for industrial boilers are set according to the performance of “conventional control systems: wet FGD, fluidized bed and lime spray drying” (Byrne et al., 1986, pp. 892–893).

In sum, AFBC complied both with SO$_2$ and NO$_x$ federal emissions limitations without additional control technologies. More stringent federal or state regulations can be met with the same additional technologies needed for pulverized coal boilers, dry scrubbers or selective non-catalytic reduction control technologies.

As shown in Fig. 2, the construction of new utility coal plants has been decreasing in the last two decades. There are several reasons for this trend: over-capacity, slow-down of the electricity demand rate, uncertainty created by deregulation, and the cost of environmental compliance in new utility plants after the 1977 amendments of the Clean Air Act. By the late 1980s utility coal plants were aging, opening a new potential market for clean coal repowering.

The CAA 1990 amendments had the explicit objective of serving as a demand-pull for clean coal technology, allowing an extension for compliance for utilities repowering with clean coal technologies. Weth et al. (1991) argued that the 1990 amendments opened an unprecedented opportunity for AFBC repowering of the old US coal power plants. The authors point out that in order to consider AFBC as an option for compliance, the technology should be adequately demonstrated before the deadlines set by the 1990 amendments. However, no utility has chosen to comply with CAA using clean coal advanced power combustion systems (EIA, 1997).

It can be argued that the technology was not proven at an adequate scale; however, the Nucla project was a successful circulating retrofit of a 110MW unit. Although this size is still lower than the average size of old units, one might expect that the success of Nucla would have triggered some demand for repowering with AFBC had the utilities chosen repowering as an option for 1990 compliance. It is interesting to note that the average capacity of the fossil units proposed for repowering with other than clean coal technologies in the period 1996–2005 is small, typically below 100MW (EIA, 1997). In fact, the lack of AFBC repowering projects is mainly due to the availability of much cheaper options for compliance and the unwillingness of utilities to get involved in heavy capital investments. The Phase II of the CAA 1990 amendments mandates an SO$_2$ emission limit of 1.2lb/MBTU, which is the same that the 1970 NSPS established. Most of the utilities chose to comply with the requirement by switching to low-sulfur content fuel (e.g., coal or natural gas) and installing scrubbers (EIA, 1997).
In sum, environmental legislation has been neither a barrier nor a stimulus to the adoption of AFBC. EPA has considered AFBC as one of the best available technologies to comply with SO2 NSPS standards. Because of this, it has been easy for users to get environmental permits for AFBC units. In that sense, the CAA has created no barriers to the construction of new AFBC units. However, CAA has not been effective in serving as a demand-pull for clean coal repowering, AFBC specifically. Although the 1990 amendments had specific provisions to give extensions for units complying with clean coal technologies, no utility has chosen this option. The main reason for this is the availability of cheaper options for compliance (i.e. fuel switching) rather than lack of technology demonstration. The conservatism of an industry undergoing restructuring is another factor that explains the utilities’ resistance to commit to options implying large capital investments.

5. Conclusions

Energy technology innovation can result on both decreasing electricity prices and improving environmental protection. A sound energy policy can accelerate the pace of invention and innovation and create opportunities that the private sector is not able to pursue without some kind of risk-sharing framework.

The following lessons learned from the fluidized bed experience could be applied in future energy policy. First, government sponsored research, development and demonstration programs especially if undertaken together with the private sector, can be a strong contributor to the introduction of new and promising technologies in the marketplace. Second, investments in demonstration should be made only when there is likely to be a sustained market, either a private market that can take-off once there is proof-of-concept or a publicly created market to address the public goods aspects of energy production.

The interaction of demand and supply factors explains the pattern of innovation and diffusion of AFBC technology. The key factors of the process were: (1) the early, government-supported demonstrations of the technology, (2) the introduction, mostly by private sector, of the circulating design, (3) the early characterization of AFBC as a best available technology for compliance with environmental standards and (4) the development of cogeneration and non-utility generation since 1980. Public policy had an instrumental role in the early demonstration of the technology, in the opportune environmental characterization and in the reform of the utility industry with the enactment of PURPA. These policies, together with the successful technological developments undertaken by the private sector, account for the moderate penetration in the non-utility market, that is, the new generation units that are QF under PURPA or Independent Producers under the Energy Policy Act of 1992.

This synergetic convergence of supply and demand trends did not materialize in the utility sector. The TVA program was not successful in demonstrating the technology at full-scale; furthermore, full-scale demonstration was not what was needed in an industry evolving towards a more decentralized investment decision-making process. The TVA program was wisely stopped after acknowledgment of the poor performance of their medium-size unit in the late 1980s, but there was already enough evidence to put into question the need for a full-scale bubbling design in the early 1980s. Regarding the Nucla project, there was a rational for public involvement in the demonstration of AFBC retrofitting of aging coal plants. However, the project would have probably gone ahead without public support and the government intervention was not enough to support a sustained private interest on the technology. More vigorous demand-pull incentives would have been necessary to create a sustained market for clean coal retrofitting, either for AFBC or for other clean coal technologies, such as integrated gasification combined cycle (IGCC) combined with carbon sequestration, for achieving the carbon reductions needed to manage climate change (PCAST, 1997).

Therefore, investments in demonstration should be based on the likely existence of a sustained market for the technology. Given that assessments of future markets are made under uncertainty about success of the technology in question as well as evolution of competing technologies and costs of alternative fuels, it is important to have mid-stream reassessment of demonstration programs. This reassessment should cover not only technological success but also re-evaluate potential markets in light of competing technologies. Finally, governments can proactively use regulatory reform and environmental policies to develop sustained markets for new technologies.

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