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Learning curves for environmental technology and their importance for climate policy analysis

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Abstract

We seek to improve the ability of integrated assessment (IA) models to incorporate changes in CO_2 capture and sequestration (CCS) technology cost and performance over time. This paper presents results of research that examines past experience in controlling other major power plant emissions that might serve as a reasonable guide to future rates of technological progress in CCS systems. In particular, we focus on US and worldwide experience with sulfur dioxide (SO_2) and nitrogen oxide (NO_x) control technologies over the past 30 years, and derive empirical learning rates for these technologies. Applying these rates to CCS costs in a large-scale IA model shows that the cost of achieving a climate stabilization target are significantly lower relative to scenarios with no learning for CCS technologies.

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1. Introduction

Large-scale energy-economic models used to study global climate change and carbon management options often ignore the impacts of environmental technology innovation and diffusion, or they use simple representations such as exogenously specified (often arbitrary) rates of change in cost or efficiency over time. The predicted impacts of proposed environmental or energy policy measures can depend critically upon these assumptions. Thus, better methods are needed to model technological change induced by government policy. This is especially true for CO_2 capture and sequestration (CCS) technology, an important new class of environmental technology

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with the potential to allow continued use of fossil fuels without significant greenhouse gas emissions to the atmosphere. Research efforts are underway worldwide to develop this technology and evaluate its effectiveness. Large-scale energy-economic and integrated assessment models are also being used to evaluate the potential of CCS in competition with other options for CO_2 control.

We seek to improve the ability of such models to represent and quantify the changes in CCS technology cost as a function of pertinent variables that are influenced by government actions or policies. Toward this end, this paper presents results of new research that examines past experience in controlling other major power plant emissions that might serve as a reasonable guide to future rates of technological progress in CCS systems. In particular, we focus on US and worldwide experience with sulfur dioxide (SO_2) and nitrogen oxide (NO_x) control technology over the past 30 years, seeking answers to the following related questions: (1) How did the deployment and cost of these environmental technologies change over time? (2) How were these changes and technological innovations related to government actions and policies?

2. Experience with environmental technologies

Two widely used emission control technologies at coal-fired power plants are flue gas desulfurization (FGD) systems used to control SO_2 emissions and selective catalytic reduction (SCR) systems used to control NO_x emissions. Both technologies are post-combustion control systems applied to the flue gas stream emanating from a coal-fired boiler or furnace. In contrast to environmental controls that are applied either prior to or during combustion, FGD and SCR systems represent the technologies having the highest pollutant removal efficiencies currently available for coal-burning plants. They are also the most expensive technologies for emissions control, and for this reason requirements for their use have been highly controversial.

2.1. Historical deployment of FGD systems

FGD systems (also known as scrubbers) encompass a variety of technologies that have been extensively described and discussed in the literature, which is summarized elsewhere [1]. By far the most prevalent technology, accounting for approximately 86% of the world market, are so-called “wet” FGD systems employing limestone or lime as a chemical reagent. These systems can achieve the highest SO_2 removal efficiencies (historically around 90%, but today as high as 98–99%), but they generate a solid residue that must either be transformed into a useful byproduct (such as gypsum) or disposed as a solid waste. So-called “dry” FGD systems typically use lime as the reagent in a spray dryer system that is less efficient than wet FGD systems but adequate to achieve the less restrictive SO_2 removal requirements for low-sulfur coals allowed by the US New Source Performance Standards (NSPS). Because of their limited applicability, lime spray dryers and other forms of dry SO_2 removal account for less than 8% of the total FGD market [2].

Fig. 1 depicts the worldwide growth in FGD installations over the past three decades [2]. The *y*-axis measures the total electrical capacity of power plants whose flue gases are treated with wet lime or limestone scrubbers. Fig. 1 also shows that the United States has led in the deploy-

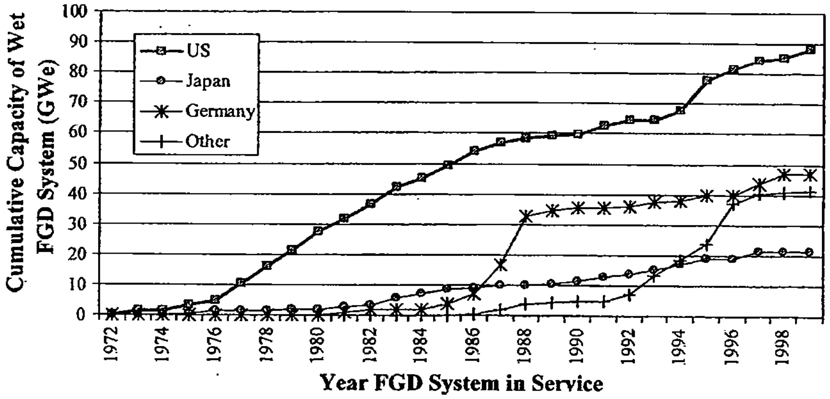

Fig. 1. Cumulative installed capacity of wet lime or limestone FGD systems in the US, Japan, Germany, and rest of the world.

ment of this technology. Today, approximately 30% (90,000 MW) of US coal-fired capacity is equipped with FGD systems, most of which are wet scrubbers.

2.2. Influence of SO_2 control requirements

The onset and growth of FGD use in each country reflects the adoption of national (and in some cases international) regulations that were sufficiently stringent so as to require or encourage the use of FGD as an emissions control strategy. In the United States, stringent requirements for SO_2 control can be traced to the Clean Air Act Amendments (CAAA) of 1970 and 1977. Many existing power plants chose to retrofit FGD systems in order to meet state and local emission regulations designed to achieve the national ambient air quality standards for SO_2 established under the 1970 CAAA. For new power plants, the NSPS criteria set by the US Congress required the use of "best available control technology" (BACT). The first NSPS for coal-fired power plants, established in 1971 by the US Environmental Protection Agency (EPA), defined BACT as a performance-based standard limiting SO_2 emissions to 1.2 lb/MBtu of fuel energy input to the boiler. This emission standard corresponded to roughly a 75% reduction from the average emission rates at the time, but allowed new plants to comply either by burning a sufficiently low sulfur coal, or by installing an FGD system while burning high-sulfur coals.

In 1979, a revised NSPS was promulgated that replaced the performance-based standard with a technology-based standard requiring all new coal-fired plants built after 1978 to employ a system of continuous emission reductions achieving between 70% and 90% SO_2 removal, with the percentage depending upon the sulfur content of the coal being burned. Effectively, this meant the use of an FGD system on all new coal-fired plants. The lower removal efficiency limit applied to plants burning low-sulfur coals typical of those in the western United States, while the higher limit of 90% removal applied to plants burning higher sulfur coals characteristic of the midwest and eastern US.

More recently, the 1990 CAAA established a national emissions cap for SO_2 to address the problem of acid deposition. To achieve this limit, existing power plants were required to further reduce their SO_2 emissions by roughly 40% below their 1990 levels by the year 2000 (with intermediate requirements for 1995). Power plants could comply in a variety of ways (including emissions trading), but owners of some plants chose to install FGD systems.

In other countries, stringent controls on SO_2 emissions were implemented initially in Japan and later in Germany. The first modern utility-scale FGD systems were installed on Japanese power plants in the late 1960s and served as benchmarks for early FGD adoptions in the United States. In 1983, in response to growing concerns about the destruction of German forests from acid rain, Germany enacted stringent new regulations requiring the installation of FGD systems on all large coal-fired plants already in service. Subsequently, other European nations also adopted regulations requiring FGD on coal-fired power plants.

2.3. Learning curve formulation

The deployment of FGD systems over the past several decades has been accompanied by improvements in performance and reductions in the cost of this technology. We use the concept of a "learning curve" (or experience curve) to characterize these reductions in cost. Such curves have been discussed extensively in the literature for a wide range of technologies, including energy technologies [3–7]. Cost reductions are typically described by an equation of the form:

$$y_i = ax_i^{-b} \tag{1}$$

where y_i is the cost to produce the ith unit, x_i the cumulative production through period i (commonly taken to be the cumulative installed capacity for power plants), b the learning rate exponent, and a a coefficient (constant). According to this equation, each doubling of cumulative production results in a cost savings of $(1 - 2^{-b})$, which is defined as the learning rate, while the quantity 2^{-b} is defined as the progress ratio.

These cost reductions reflect not only the benefits from "learning by doing" at existing facilities that install environmental technologies, but also the benefits derived from investments in research, development and demonstration (RD&D) that produce new knowledge and new generations of a technology. Ideally, the learning curve equation would explicitly include the effects of additional factors like RD&D expenditures. While some studies have sought to develop or propose such two-factor models of learning [8], in practice, such relationships are extremely difficult to develop and validate because of data limitations. Thus, in the single-factor model (Eq. (1)) commonly used to characterize learning rates, cumulative production or capacity is a surrogate for total accumulated knowledge gained from many different activities whose individual contributions cannot be readily discerned or modeled.

In this formulation of the learning curve, the cumulative installed capacity of a technology (like FGD systems) is also the variable that is directly influenced by alternative environmental policies. A detailed study of the innovation response to SO_2 control requirements in the US found that the stringency of government regulations appeared to be a key factor driving both the direction and magnitude of inventive activities, as well as the communication processes underlying knowledge transfer and diffusion [1]. Other factors, such as the timing and scope of policy requirements (e.g. market-based approaches vs. traditional "command-and-control" regulations) also may affect the nature and rate of technology innovation [9]. Data limitations again preclude the explicit incorporation of these factors into a quantitative model of learning rates. The empirical learning rates derived in this paper thus reflect the aggregate outcome of these complex processes.

2.4. Trend in FGD capital cost

The development of a learning curve for FGD systems is not straightforward because many of the factors that influence cost are not directly related to improvements in the FGD technology. For example, FGD costs vary significantly with coal sulfur content, emission reduction requirements, and power plant size [10]. To obtain a more accurate picture of real FGD cost reductions, we use a series of studies performed by the same organizations over a period of years using a consistent set of design premises as the basis for FGD cost estimates [1]. These studies reflect the contemporaneous designs and costs of FGD systems installed at US power plants.

Fig. 2 shows the resulting trend for FGD capital cost. All costs are adjusted to a common basis for a standardized 500 MW power plant burning a high-sulfur (3.5% S) US coal with a wet limestone FGD system that achieves 90% SO_2 removal. Thus, we compare the costs of an FGD system that does the same "job" at different points in time. Adjusted costs in constant 1997 dollars were then normalized on the initial (1976) value to obtain Fig. 2. Total capital costs exhibit a significant decline over time. A learning curve of the form given by Eq. (1) yields a progress ratio of 89%, corresponding to a learning rate of 11% (i.e. a decrease in capital cost of 11% for each doubling of installed FGD capacity). This value is similar to the learning rates found for other large-scale energy technologies [6,11].

Many of the process improvements that contributed to lower FGD costs (especially improved understanding and control of process chemistry, improved materials of construction, simplified absorber designs, and other factors that improved reliability) were the result of sustained R&D programs and inventive activity, as documented and described elsewhere [1]. Increased competition among FGD vendors also may have been a contributing factor. Such influences are

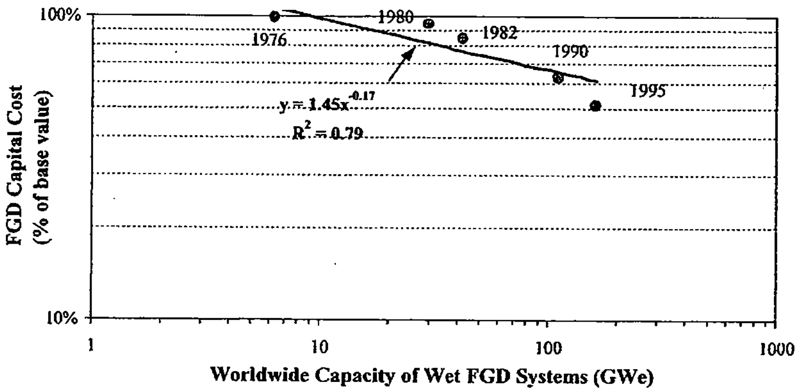

Fig. 2. FGD capital costs for a standardized coal-fired plant (500 MW, 3.5% S coal, 90% SO_2 removal) vs. cumulative installed FGD capacity worldwide. All data points normalized on an initial (1976) value of US$ 254/kW in constant 1997$.

difficult to discern in most studies of experience curves because the available data typically represent the cost to technology users (i.e. technology prices) rather than the cost to technology developers. This is one of the many limitations inherent in the development of learning curves, as elaborated by others [11,12]. However, a careful look at the underlying technological changes over several decades indicates that the FGD cost reductions shown here primarily reflect the fruits of technology innovation.

As with many studies of learning curves, uncertainties are introduced by the limited number of observations. The R^2 value of 0.79 shown in Fig. 2 offers another indicator of uncertainty, typical of the values found in other studies [11]. The assumption of a constant learning rate implied by Eq. (1) imposes additional uncertainty in cases where a different functional form better fits the available data. Nor does this methodology reflect the cost impacts of FGD design improvements that allow current systems to achieve higher SO_2 removal efficiencies than in the past (a different "job" than the 90% removal modeled here). All of these issues merit further discussion and research, but are beyond the scope of the present paper.

2.5. Historical deployment of SCR systems

Fig. 3 shows the historical trend in the worldwide growth of SCR capacity. Here, the earliest use of SCR is seen in Japan beginning in the 1970s, followed by widespread adoption in Germany in the mid-1980s. The US has been the laggard in SCR use, with the first units on coal-fired plants installed only in 1993. By 2004, however, US capacity of SCR systems is expected to grow to over 90 GW in response to recently enacted NO_x control regulations. SCR systems also have been installed on electric power plants burning oil and natural gas since these systems also produce NO_x during combustion. The total capacity of SCR systems on non-coal utility systems for US power plants was approximately 11.5 GW in 1996 [13], most of which was installed only in the last decade.

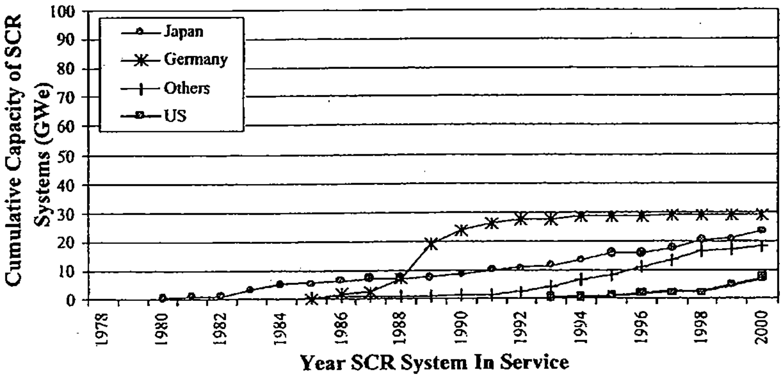

Fig. 3. Cumulative installed capacity of SCR systems on coal-fired power plants in the US, Japan, Germany, and rest of the world.

2.6. Influence of NO_x control requirements

As with FGD systems, the growth trends in SCR capacity reflect the impact of different policies for NO_x control in different countries. In the United States, limits on power plant NO_x emissions initially followed the same timetable and regulatory approach as for SO_2. The key difference was in the stringency of emission reduction requirements. Under the 1970 CAAA, existing power plants were largely unaffected by state-level regulations for achieving NO_2 air quality standards. For new sources, the 1971 NSPS imposed only modest emission reduction requirements that could be met at low cost using low-NO_x burners (LNB) for combustion in utility boilers.

While SO_2 emission restrictions grew more stringent (and more costly) during the 1970s and 1980s, NO_x emission requirements for US coal plants did not change appreciably until the 1990s. At that time, the acid rain provisions of the 1990 CAAA required many existing coal-fired plants to install “reasonably available control technology” in the form of LNB and other combustion modifications. Then, in 1994, EPA established much more stringent requirements for existing power plants (emission reductions averaging about 85%) as part of a regional strategy to attain the health-related air quality standards for ground-level ozone. Achieving these stringent NO_x reductions required retrofitting SCR systems at many existing power plants. A massive expansion in SCR installations is thus now underway in the United States. A 1997 revision to the Federal NSPS now also requires a high level of NO_x control that is currently achievable only with SCR systems in most cases.

In contrast to the US situation, the use of SCR in other industrialized countries began many years earlier in response to stricter NO_x emission limits. Japan first enacted strict requirements in the 1970s and pioneered the development of SCR technology for power plant applications. In the mid-1980s, Germany required the use of SCR systems on large coal-fired power plants as part of its acid rain control program. Subsequently other European countries also began to adopt this technology, as seen in Fig. 3.

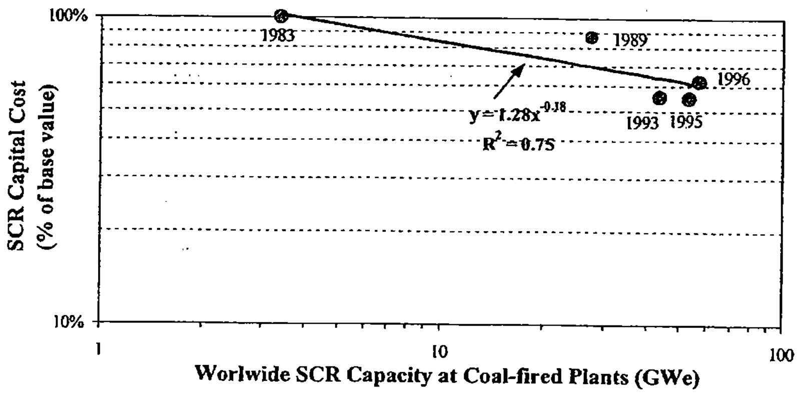

Fig. 4. SCR capital costs for a standardized coal-fired power plant (500 MW, 80% NO_x removal) vs. cumulative installed capacity worldwide. All data points normalized on an initial (1983) value of US$ 105/kW in constant 1997$.

2.7. Trend in SCR capital cost

Learning curves for SCR systems were developed using the same methodology described above for FGD technology, i.e. the use of historical cost studies for a standardized power plant with an SCR system doing the same job (80% NO_x removal) at different points in time. Fig. 4 shows the resulting trend for capital cost. A learning curve fitted to Eq. (1) yields a progress ratio of 88%, or a learning rate of 12%. As with FGD systems, these observed cost decreases reflect the effects of investments in R&D as well as learning by doing and other factors. SCR process improvements have substantially lengthened the average catalyst lifetime, while improvements in catalyst manufacturing methods, as well as competition among catalyst manufacturers, simultaneously lowered catalyst prices by 50% over a recent 10-year period. During this time there was no systematic change in the real price of the principal metals, mainly vanadium and titanium, used for SCR catalysts [14].

3. Application in integrated assessments models

The learning rates of 11% and 12% for FGD and SCR systems, respectively, are similar not only to each other, but also to the average learning rates found in other studies for a wide range of market-based technologies, including a broad array of energy technologies [11,15–17]. We believe these results also provide a quantitative guideline for assessing the influence of technological change on future compliance costs of new emission control requirements for coal-based energy plants. Of particular interest are policies to reduce greenhouse gas emissions, and the role of CCS technologies.

In a preliminary integrated assessment modeling study carried out by researchers at IIASA [18], an average learning rate of 12% (based on the results found above) was used to model the expected rate of capital cost decline for CCS systems deployed to reduce greenhouse gas emissions. The IIASA model simulated endogenous learning for CCS technologies at fossil fuel power plants and related energy conversion facilities (such as plants producing hydrogen or synfuels). Thus, changes in CCS cost over time depended on the policy scenario and its influence on total installed CCS capacity (in competition with other carbon mitigation options). Results were obtained for two different baseline scenarios of future world energy use, and a policy scenario that achieved stabilization of atmospheric CO_2 concentration at 550 ppmv by 2100 in a least-cost (globally optimized) manner. The effective carbon taxes required for this scenario were found to be significantly lower for cases with technological learning compared to cases with no learning (constant costs) for CCS technologies. For example, for the "A2" baseline energy scenario, carbon taxes with CCS learning were lower by 24% in 2020, 67% in 2050, and 1% in 2100 compared to no learning. In these scenarios, the total carbon sequestered by the year 2100 was approximately twice as great with learning as with no learning. Further details of this analysis are reported in Ref. [18].

Future studies will explore the effects of alternative climate policy scenarios on the role of CCS technology and the importance of endogenous learning. A number of methodological issues also remain to be explored further in the context of modeling studies with long time horizons such as the 50- to 100-year time frames commonly used for climate policy analysis. For example, it is unlikely that the learning rates observed during the initial development and deployment of a new technology (like CO_2 capture) would be sustained indefinitely as the technology matures [19]. In addition, there are uncertainties about technology risk and ability to learn, the value of progress ratios and the shape of experience curves [12]. We hope to explore such issues as part of our continuing research in this area.

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