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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.


## 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-