**Technical Report for DOE grant ER63467-1020269-0008388**
**"International Innovation & Diffusion of Environmental Technologies: The Case of $NO_X$"**
**Submitted by David Popp, Syracuse University**

This research traces the development of nitrogen dioxide ($NO_X$) and sulfur dioxide ($SO_2$) pollution control devices for coal-fired power plants in the United States, Japan, and Germany. This is of particular interest because of the timing of regulation in each country. While the US was an early adopter of $SO_2$ regulations, it did not adopt stringent $NO_X$ regulations until the 1990s. Both Japan and Germany adopted stringent $NO_X$ regulations earlier. As such, advanced control techniques such as selective catalytic reduction (SCR) were first developed in Japan and Germany. In contrast, US firms were more active in the development of $SO_2$ control devices. This study uses patent data from the three countries, as well as adoption data for individual plants, to trace the development of these technologies.

Of particular interest is the role of technology transfer. Figure 1 highlights the paths through which technology may be transferred across countries. In this figure, solid lines represent links already established in the literature. Dashed lines were the focus of this research project. The ultimate goal is adoption of a new technology, as shown in the box on the left. This adoption decision is influenced by the menu of technologies available for the firm to choose from. Integrated assessment (IA) models that include endogenous links between policy and research and development (R&D) allow this knowledge stock to evolve in response to policy. Thus, understanding both the role of this knowledge stock on adoption, and the factors that influence its development, are important. While we know from previous research that firms respond to new regulations in their own country with new innovations, we do not know the extent to which firms respond to regulations in foreign countries. Moreover, we know little about how innovations developed abroad enter the domestic knowledge base. For example, do firms make direct use of knowledge developed in foreign countries, or is domestic R&D necessary to adapt these innovations to local conditions. Understanding such trends is important, as it affects both the speed at which technology will diffuse, and the cost of technology transfer.

To address these issues, this research compares the role that domestic and foreign knowledge play in the decisions of firms to adopt new environmental technologies. I begin by using patent and regulatory data from the U.S., Japan, and Germany to study the links between both domestic and foreign environmental policy and innovation. I show that innovative activity responds to domestic environmental policy pressures, but not to foreign pressures. Moreover, even countries that adopt regulations late, such as the U.S. in the case of $NO_X$, increase innovative activity in response to new domestic regulations. Thus, firms do not simply take advantage of technologies developed abroad. Next, I use these patent data to study the links between available technology and adoption of $NO_X$ pollution control technologies at U.S. coal-fired power plants. By far the most important factor influencing adoption is regulatory pressure. Simply having a new technology available is not enough to encourage adoption. Moreover, technological progress only increases adoption rates for the most advanced technologies. Since regulations are still the primary force driving adoption, more readily available techniques are chosen unless newer ones are sufficiently advanced to justify the extra cost. Moreover, as many of these techniques were first developed abroad, adaptive R&D occurs in the US before adoption. Such R&D can be expected to slow the pace of international technology transfer of new environmental technologies. Below I describe these results in greater detail.

**Figure 1 – Theoretical Framework**

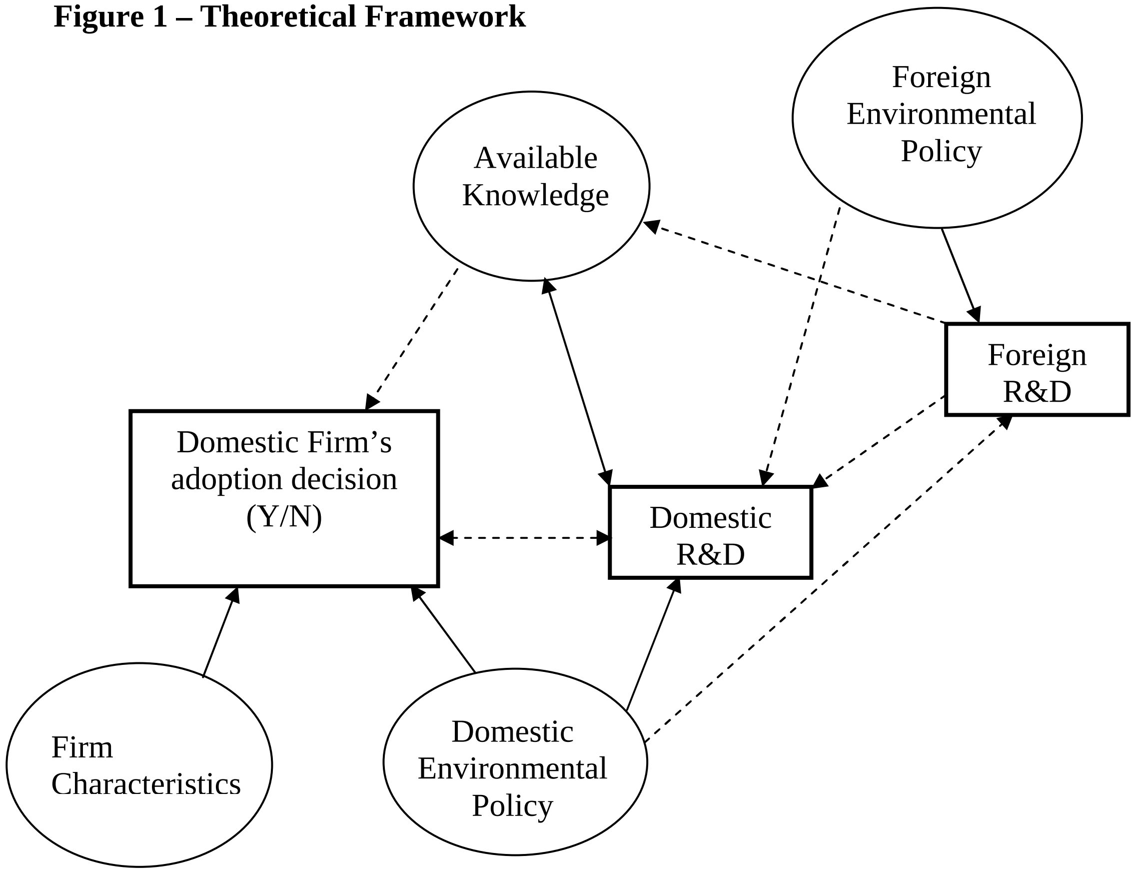


Figure 1 presents a schematic of the theoretical framework for this proposal. In the diagram, boxes represent endogenous variables chosen by firms and circles represent exogenous variables. Solid lines represent linkages well-established in the literature. Broken lines are links that are less established, and are thus the focus of this study.

The study includes two main parts. The first is a look at patenting behavior in these three countries. The manuscript from this research, "International Innovation and Diffusion of Air Pollution Control Technologies: The Effects of $NO_X$ and $SO_2$ regulation in the U.S., Japan, and Germany," is currently under review at the *Journal of Environmental Economics and Management*, and is available as National Bureau of Economic (NBER) Working Paper #10643. Key results include the following:

- As expected, the stringency of regulation affects technology adoption. $NO_X$ emissions can be controlled via modifications to the combustion process or by treatment of flue gas after combustion. Post-combustion techniques are more effective, and can reduce emission by as much as 80-90%, compared to just 30-40% for combustion modification. However, post-combustion techniques are more expensive. Thus, it is the technology of choice for plants facing tight $NO_X$ emissions restrictions, such as in Germany and Japan. Using funds from the grant, a database of coal-fired power plants from around the world was purchased from the International Energy Agency Coal Research Program. Of the 87 Japanese coal-fired power plant units listed in the database that were in operation as of 2000, 51 (59%) use post-combustion techniques to control $NO_X$ emissions. Similarly, 118 of 228 (52%) such plants in Germany use post-combustion methods. In contrast, just 41 post-combustion treatment techniques were in use in 1150 US units (3.6%), although another 85 were planned or under construction in response to strengthened $NO_X$ regulations in the late 1990s.

- Innovation appears to be driven primarily by *domestic* regulations. I analyze patent data from each country, sorting patents by both their application date and the country of origin. Detailed data on patents for $NO_X$ post-combustion control techniques filed in the US and Germany are presented in Figures 2 and 3 at the end of this report. Figure 2 displays these patents for the United States. Beginning in 1974, when stricter Japanese $NO_X$ limits took effect, until 1989, when the 1990 Clean Air Act (CAA) was being debated in Congress, as many or more successful $NO_X$ post-combustion patent applications filed in the US came from foreign sources as domestic sources in all but three years (1978, 1980, and 1981). These trends are driven in large part by stricter regulations in Japan and Germany. $NO_X$ post-combustion patents from Japan increase after passage of stricter $NO_X$ regulations in 1973, and German patents peak after passage of $NO_X$ regulations in 1984. Japanese patents also reach a second, lower peak after Japanese standards were tightened in 1987. In fact, at the peak level of patenting for each country, the number of patents from each country is greater than the number from US applicants in the same year! Furthermore, neither German nor Japanese patenting activity respond to the 1990 CAA. In contrast, domestic (US applicant) and total foreign patents do respond to the 1990 CAA. Domestic patents increase by a factor of 11 from a post-CAA low of 6 in 1982 to a peak of 82 in 1990.[1]

  Figure 3 displays the same data for Germany. Here, the links between *domestic* regulation and innovation are even more apparent. Domestic $NO_X$ post-combustion patent applications increase by a factor of 5.5 between 1983 and 1985, from 27 to 149. In contrast, total foreign applications merely double from just 12 in 1983 to 24 in 1985. Regulations passed in Germany in 1984 were significantly more stringent than $NO_X$ regulations elsewhere. Thus, new innovations were needed to achieve these goals. A look at international patenting activity of German inventors supports the notion that important innovations were taking place in response to these innovations. Since a patent is only valid in the granting country, a patent must be obtained in each nation that the inventor desires protection. Because each filing entails additional costs, inventors typically file for protection in their home country first, and file abroad only for the most valuable inventions. Researchers use these foreign filings, known as patent families, as proxies for the quality of a patent. For German $NO_X$ post-combustion patents, an average of 30% were also filed in Japan

[1] Note that the growth in US post-combustion patents also begins in the mid-1980s. This is likely in response to new standards passed for industrial sources of $NO_X$, rather than the German regulations. If these patents were in response to German regulations, we would expect to see a similar increase of US patent applications in Germany. However, as the paper shows, this was not the case.

between 1970 and 2000, and 24% were also filed in the United States. However, the patents granted in the mid-1980s were more likely to file in Japan. In 1982, just 30.8% such patents also sought protection in Japan. This figure rises to 37.0% in 1983, 45.1% in 1984, and 46.3% in 1985. It drops back to 26.7% in 1986, suggesting that the prospects for truly important discoveries began to fall.

- Transfer of knowledge between countries appears to be indirect, rather than direct. That is, plants in countries that enact regulations later do not purchase control technologies directly from foreign firms. Rather, domestic innovation takes place after passage of the regulation, *but this innovation builds on the results of foreign R&D.* Thus, knowledge spillovers occur. Evidence of this comes from patent citation data. This paper includes a regression that looks at the probability of US patents citing patents from other countries. In general, US patents cite Japanese and German patents about 40% less frequently than other US patents. However, US patents for $NO_X$ post-combustion technologies are just 5% less likely to cite Japanese patents than US patents. Moreover, early Japanese $NO_X$ innovations (those patents granted before 1990) are 91% *more likely* to be cited than U.S. $NO_X$ post-combustion patents. Finally, in this work, $SO_2$ patents serve as a useful control. Because US regulations concerning $SO_2$ emissions from power plats were as stringent (if not more so) than other nations, more $SO_2$ patents emerged directly from the US. In this case, the typical pattern of patent citations coming primarily within a country prevails.

This first paper addresses the sources of technology available to a firm facing new environmental regulations. The second part of the study asks how this available knowledge affects adoption decisions. This research has resulted in a second working paper, entitled "Exploring Links Between Innovation and Diffusion: Adoption of NOX Control Technologies at U.S. Coal-fired Power Plants." In this paper, I use a hazard model to estimate the probability of adoption for either combustion modification or post-combustion treatment techniques at these power plants. As this is the first paper to explicitly include the level of technology as an explanatory variable, the paper begins by developing a theoretical framework for the econometrics. The model shows that both the level of technological advancement, and expectations of future advances, are important. Moreover, since the paper considers two competing technologies, the state of technological advancement for *both* can affect adoption of either technology.

For estimation, I combine the U.S. patent data from the first paper with data on the adoption of $NO_X$ pollution control devices by coal-fired electric plants to estimate the effect of new knowledge on the adoption of $NO_X$ pollution control techniques. The patent data are aggregated into knowledge stocks that represent the current state of the art for each technology. To examine the potential of international technology transfer, I include separate stocks for domestic and foreign knowledge, and include a third stock that interacts domestic patenting activity with the foreign knowledge stock. Adoption data come from the US Energy Information Administration's (EIA) Form 767. This survey lists the type(s) of $NO_X$ pollution control used at each plant, along with the $NO_X$ regulations faced by the plant. Figure 3 shows the percentage of plants using either technology from 1990-2002. Form 767 also provides other descriptive data for these plants, such as regulations faced, plant size, and age. Financial data for the utilities owning these plants was assembled from several sources: FERC Form 1, EIA Form 412, and Compustat. Key results of the regressions include the following:

- Regulatory pressures are by far the most important predictor of adoption. For example, plants covered by Ozone Transport Commission (OTC) regulations are twice as likely to adopt combustion modification technology, and ten times as likely to adopt post-combustion treatment. OTC regulations are currently the most stringent faced by coal-fired plants in the U.S. Thus, these plants are by far the most likely to adopt more costly post-combustion treatment. This result is important, as it shows that the availability of a new environmental technology is not sufficient to encourage adoption. Regulatory pressure is also needed.
- The state of technological advancement is important for the newer post-combustion treatment techniques. For post-combustion treatment, one new patent increases adoption by about six percent. Foreign patents are more important, as one foreign patent increases adoption by eight percent. As expected, expectations of future advances slow adoption. Finally, when the interacted knowledge stock described above is included, only the interacted term has a significant positive effect. This result suggests that adaptive R&D is important before technologies first developed abroad are adopted.
- In contrast, the state of technological advancement is not important for combustion modification techniques. When significant, the effect of a new patent on adoption rates is less than one percent. In essence, combustion modification serves as the "default" technology. Because it is cheaper and more fully developed in the U.S., plants facing $NO_X$ regulation choose combustion modification unless the competing post-combustion techniques are advanced enough to suit their needs.
- Although many prior studies show that a firm's financial strength increases adoption rates, here the financial strength of the parent utility only matters for post-combustion techniques. When faced with new regulations, a firm must choose to adopt *something* to comply with the regulation. Increased financial strength simply makes it easier to adopt a *better* technology.

These two papers offer several important lessons for integrated assessment models. First, note that regulatory pressure must be present before environmental technologies are adopted. This suggests that future research should not only concern itself with the diffusion of technologies, but also with the diffusion of regulation. One caveat for climate change is that innovations that reduce carbon emissions by simply improving energy efficiency may be adopted even without regulatory pressure, if the energy cost savings are sufficient to justify the technology's costs. However, any future technologies designed to capture emissions, as well as more expensive renewable energy technologies, are unlikely to be adopted without regulatory pressure.

Second, the role of adaptive R&D suggests domestic and foreign R&D are imperfect substitutes. Thus, it is not enough for IA models to model knowledge stocks as a combination of domestic and foreign innovative activity. Functional forms that require some level of domestic innovation before adoption of foreign technologies should be used.

Finally, it is useful to consider the generalizability of these results. It is particularly striking that even a technological leader like the US does not take direct advantage of foreign technologies. Still, further research on technology transfer between developed and developing countries is needed. We would expect there to be greater differences in technological sophistication between developing and developed countries than between the US, Japan, and Germany. This has two conflicting implications for applying these results to transfer from developed to developing countries. First, greater differences in currently-used technologies suggest that adopting the technology to local circumstances will be even more important for developing countries. However, less technological sophistication in developing countries may hamper the ability to make such modifications, and make developing countries more willing to accept "imperfect fits" of technology, rather than do adaptive R&D. More detailed analysis of technology transfer in a developed/developing country setting would be of great use to both policymakers and economists alike.

**Figure 2 – $NO_X$ Post-Combustion Patents in the United States**

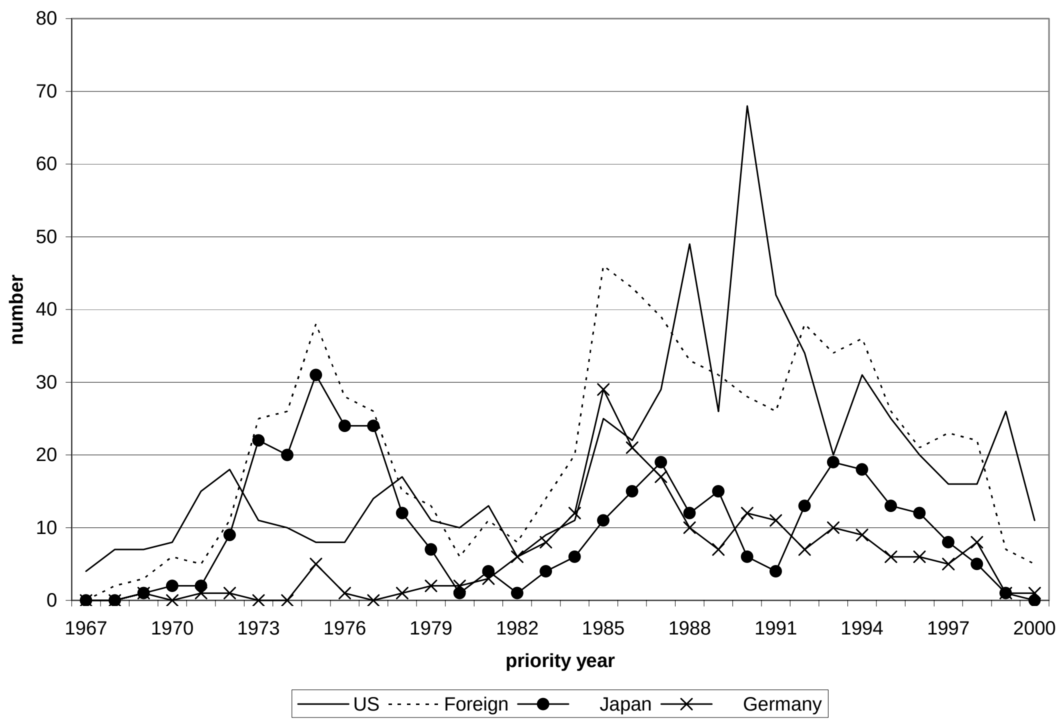

**Figure 3 -- $NO_X$ Post-Combustion Patents in Germany**

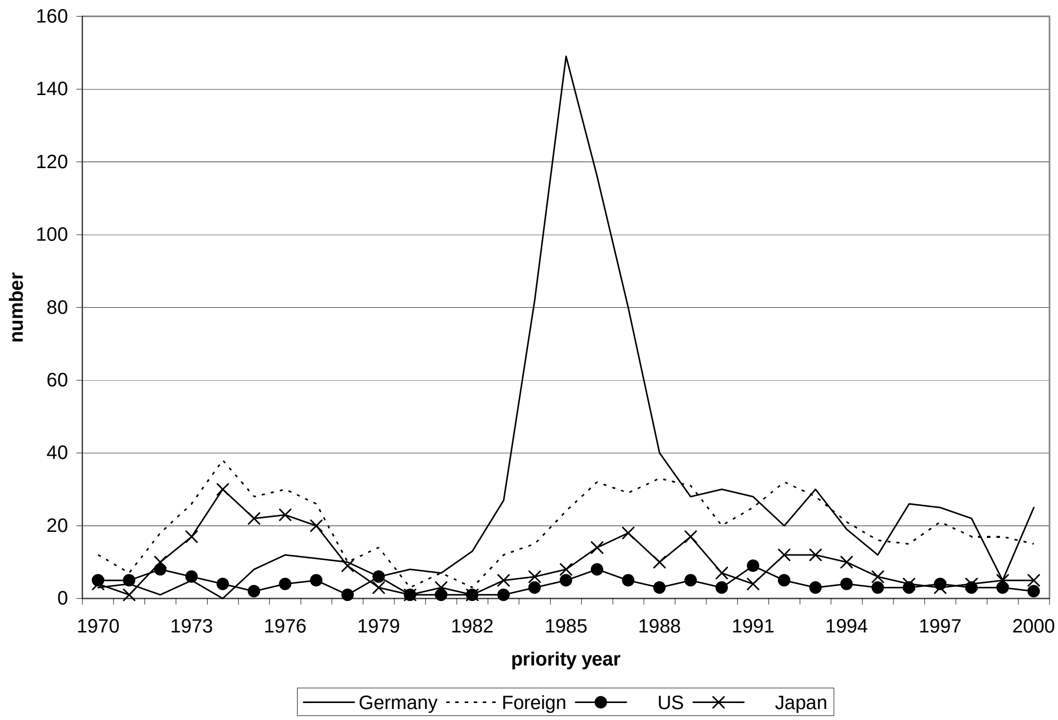


**Figure 4 – Percentage of Plants Adopting $NO_X$ Pollution Control Technologies**