Trade, Technology and the Environment: Why Do Poorer Countries Regulate Sooner?

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Abstract

While there has been a proliferation of work on environmentally-friendly innovation, nearly all of these studies have focused on highly-developed economies. These countries perform most of the world's R&D and are typically the first to enact new environmental regulations. However, while environmental policy in high income is likely to induce *new* innovations needed to comply with more stringent regulations, for other countries, the technologies needed to comply with new regulations will already be in use elsewhere in the world when the decision to regulate is made. Thus, rather than asking to what extent environmental regulation induces new environmental innovation, we instead ask to what extent the availability of new technology influences the adoption of new environmental regulations. We begin with a general equilibrium model of a small, open economy, focusing on the political economy decision to regulate emissions. Using a newly-created data set of emission regulations for coal-fired power plants, we test the model's predictions using a hazard regression of the diffusion of environmental regulation across countries. We show that advances in available pollution control technology do lead to earlier adoption, *ceteris paribus*, of regulation in developing countries. Moreover, this result is stronger for more open economies, suggesting that free trade increases access to environmentally-friendly technologies. In addition, political economy variables, such as the size of the domestic coal industry, are also important.

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Technological advances are often seen as a potential panacea for environmental problems. In recent years, several papers have studied the potential for environmental policy to induce environmentally-friendly innovation. Nearly all of these studies have focused on highly-developed economies. This is not surprising, as most R&D expenditures occur in these countries. In 2000, global R&D expenditures were at least $729 billion. Half of this R&D was done in the U.S. and Japan. 82 percent of this was done in the OECD, and half was performed by the United States and Japan alone (National Science Board, 2006). Moreover, as demand for environmental quality is considered a normal good, these countries are typically also the first to enact new environmental regulations.

When considering the links between environmental policy and technological change outside of these advanced economies, it may be appropriate to consider links flowing in the reverse direction. That is, while environmental policy in leading economies is likely to induce *new* innovations needed to comply with more stringent regulations, for other countries, the technologies needed to comply with new regulations will already be in use elsewhere in the world when the decision to regulate is made. Thus, in this paper, rather than asking to what extent environmental regulation induces new environmental innovation, we instead ask to what extent the availability of new technology influences the adoption of new environmental regulations. We do so by examining the diffusion of environmental *regulation* across countries.

The research question is motivated by two observations. First, the diffusion of air pollution control technologies is strongly linked to changes in regulatory pressure. End-of-the-pipe environmental controls increase costs for plants without providing increases in output. Thus, these technologies are unlikely to be adopted without regulatory stimulus.[1] Anecdotal

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[1] Studies supporting the importance of regulation for diffusion of environmental technologies include Gray and Shadbegian (1998), Kerr and Newell (2003), Snyder *et al*. (2003), and Popp (2006b).

evidence suggests that adoption of environmental technologies does not occur until regulations are in place. For example, most power plants in China have controls for particulate matter (PM), while only the newest plants control nitrogen oxides (NO_X) and sulfur dioxide (SO_2), since PM regulations appeared much earlier than NO_X and SO_2 controls.[2] Second, despite the predictions of the environmental Kuznets curve literature, which links better environmental performance to economic growth, many developing countries have air quality standards that are more stringent than developed countries had at similar levels of economic growth. This suggests that early adopters of environmental regulation provide an advantage to countries that adopt these regulations later, presumably through advances in technology made by these early adopters. Thus, we play particular attention to the links between technological advancement and environmental regulation, by asking what role the global technological frontier plays in the setting of environmental regulations.

The questions addressed in this project can be tied to several branches of environmental economics research. In recent years, much research in economics has focused on various links between economic growth, trade, or technological change, and environmental quality. However, few papers have linked these topics. For example, researchers such as Copeland and Taylor (2003) ask whether increased trade improves or degrades environmental quality in developing countries. Opponents of globalization argue that freer trade entices polluting activities to shift to developing countries and increases the scale of economic activity, resulting in more waste and more pollution. In response, many economists argue that as countries grow, they can afford newer, cleaner technologies that reduce pollution despite increases in production. Similarly, research on the environmental Kuznets curve (EKC) explores the relationship between income

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[2] Data are taken from the CoalPower 4 database, available from the International Energy Agency (IEA) Coal Research Programme.

and environmental quality. In several cases, these studies find evidence of a positive correlation between income and environmental quality, suggesting that countries could grow their way out of environmental problems. However, EKC studies typically focus on the correlation of these variables, rather than the causal forces explaining why the relationship holds. Similarly, a growing body of literature examines the links between environmental policy and technological change. While much of this research focuses on developed countries, some researchers (e.g. Lanjouw and Mody 1996) have looked at flows of environmental technologies to developing countries.

In this paper, we look at the decision to adopt pollution control regulations for coal-fired power plants. We use a data base of regulations for SO_2 and NO_X for 45 countries constructed for this paper. For each country, we know the year in which these regulations were first enacted. Using the regulatory history of these particular regulations allows us to focus on a specific set of explanatory variables important to coal-fired plants, permitting us to identify political economy effects more carefully than if a broader index of regulation were used. In addition, using regulations, rather than emissions, differs from the types of analyses done in the EKC literature, in which per capita emissions are the usual dependent variable. Our analysis is not an attempt to explain the overall level of emissions in a country, but rather to explain one determinant of the level of emissions – the presence or absence of environmental regulation.

We begin with a general equilibrium model of a small, open economy that focuses on the political economy decision to regulate emissions. From this, we develop several testable hypotheses that we examine using the aforementioned data. We show that advances in available pollution control technology do lead to earlier adoption of regulation in developing countries. Moreover, this result is stronger for more open economies, suggesting that global engagement does increase access to environmentally-friendly technologies. In addition, political economy variables, such as the magnitude of the coal industry in a country, are also important.

I. Theoretical Framework

To provide a framework for our empirical analysis, we consider a general equilibrium model of a small, open economy that uses electricity in the production of a tradable manufactured good. Electricity is generated by the burning of domestically mined coal or internationally traded natural gas, in shares determined by the profile of the country's power infrastructure. Domestic consumers benefit from goods consumption but experience disutility from emissions generated by coal-fired power plants. The allowable level of emissions from coal-fired plants is endogenously determined by a government that maximizes a weighted sum of social welfare and contributions from organized interest groups.

i. Production

To capture the importance of coal to downstream sectors, we posit a model with four production sectors, each of which uses labor as a factor of production. These sectors are agriculture, which serves as numeraire, coal mining, electricity generation, and manufacturing. Of these, agriculture and manufacturing are traded on international markets, with prices given to this small, open economy. Labor is perfectly intersectorally mobile. The production of coal, electricity, and manufacturing also require the use of sector-specific capital. The owners of these sector-specific factors engage in lobbying to influence the level of pollution regulation chosen by the government.[3]

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[3] Specific-factor models are used frequently in endogenous policy analyses. Because these models imply the existence of factor rents, they provide a mechanism by which agents have resources to expend in an attempt to influence government policy. Hillman (1989) provides a useful overview in the context of trade policy.

The economy contains L workers, each of which inelastically supplies one unit of labor. Agriculture, or the traditional sector, is modeled simply as a tradable sector that uses labor only in a constant returns technology. We choose units so that $P_A = 1$. We assume that the aggregate labor supply, L, is large enough so that there is always a positive supply of locally produced agricultural products. Consequently, $w = 1$.

The other traded sector, manufactures, uses sector-specific capital, K_M, and labor in combination with electricity. Each unit of manufactures requires one unit of electricity to produce. The production technology for manufactures can be expressed as

$$M = \min\left[f_M\left(K_M, L_M\right), E\right], \tag{1}$$

where L_M is the amount of labor used in manufacturing and E is the quantity of electricity used in manufacturing. The function $f_M\left(K_M, L_M\right)$ exhibits constant returns to scale, but because manufacturing capital is fixed in supply, there are diminishing returns to labor input.

Electricity is produced by two types of power plants: coal fired and gas fired. To keep the model simple, we assume that the cost of electricity to manufacturers is a weighted average of the cost of these two types of electricity.[4] Moreover, we assume that the price of electricity from gas-fired power plants is fixed.[5]

Electricity from coal-fired plants is produced with labor and sector-specific capital using the technology $E_C = \min\left[f_{EC}\left(K_{EC}, L_{EC}\right), C\right]$. L_{EC} is the amount of labor used by coal-fired

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[4] Manufacturers often have limited scope for choosing among electricity suppliers. Consequently, electricity prices often vary widely within the same country. To avoid having to distinguish manufacturers by their electricity supplier, we treat the cost of electricity to the manufacturing sector as the average of prices charged by both gas-fired and coal-fired power plants.

[5] Alternatively, we can assume that gas-fired electricity is produced with labor, sector-specific capital, and one unit of natural gas per unit output. In this case, owners of gas-fired plants will also lobby for lower abatement standards because stringency reduces demand for electricity of both types from the manufacturing sector and, hence, their return.

power plants and C is the quantity of coal burned in the plants. The function $f_{EC}\left(K_{EC}, L_{EC}\right)$ exhibits constant returns to scale, but again power generation facilities are in fixed supply so there are diminishing returns to labor input.

Each unit of coal burned generates one unit of emissions. Electricity producers may be required to abatement these emissions from coal burning. The regulatory standard requires electricity plants to apply A units of abatement services per unit of coal burned, resulting in an A% reduction in the volume of emissions. These services can be obtained only from the installation of imported pollution abatement equipment. The domestic lease price of this equipment, which is freely traded on international markets, is $P_A(t)$, where t indicates the level of technology embodied in the abatement equipment and $P_A'(t) < 0$. If the country levies a tariff on imported equipment, the domestic price of abatement services exceeds the world price in proportion to the tariff rate. The total return to owners of coal-fired power plants is

(2) $$\pi_{EC} = P_{EC}E_C - (P_C + P_A(t)A)C - wL_{EC},$$

where P_{EC} is the price per unit of electricity from coal-fired plants, and P_C is the price of coal, both of which are endogenously determined. Equilibrium in the electricity market requires that domestic demand for electricity from coal-fired power plants, which comes from the manufacturing sector, equal domestic supply of electricity from coal-fired power plants.

To reflect the fact that manufacturing plants typically have limited choice of electricity supplier, we assume that there is no substitution between coal-fired electricity and gas-fired electricity by the manufacturing sector. A share, δ, of electricity is purchased by manufacturers from coal-fired plants. Consequently, the total earnings of capital owners in the manufacturing sector are

(3) $$\pi_M = P_M M - [\delta P_{EC} E_C + (1-\delta) P_{EG} E_G] - wL_M .$$

Because manufactured goods are traded and the economy is small, P_M is exogenous.

Coal is mined by the application of labor to coal reserves. These reserves are the specific assets of the coal sector. The technology for coal production, $C = f_C(K_C, L_C)$, exhibits constant returns to scale. Because coal reserves, K_C, are in fixed supply, there are diminishing returns to labor in this sector. Coal is elastically supplied and demanded locally. Denoting the price of coal by P_C, the total return to owners of coal reserves are

(4) $$\pi_c = P_C C - wL_C .$$

Equilibrium in the production sector is defined as a vector of domestic prices, factor rewards, and output levels for which the value marginal product of labor is equal across all sectors, the supply of coal and electricity equals the demand for coal and electricity, respectively, and the total amount of labor demanded equals labor supplied, given world prices. In equilibrium, the return to specific factors in sector i is a function of the world price of manufactures and of abatement services, the stocks of specific capital, and the level of abatement stringency: $\pi_i = \pi_i(p_m, p_A(t), K_M, K_{EC}, K_C, A)$.

ii. Who Bears the Cost of a Higher Abatement Standard?

The model provides for a stark characterization of how the burden of higher abatement standards is distributed among workers and specific factor owners. Workers, who do not own any of the specific assets of the economy, are not affected by higher standards. They earn the agricultural wage, which is set at unity, due to our assumption of perfectly intersectorally mobile labor. Moreover, international trade prevents the relative price of manufacturing from rising, ensuring that workers' real incomes are not affected by higher standards. In contrast, the nominal, and hence real, incomes of specific-capital owners in manufacturing, electricity, and coal mining are reduced when standards are raised. This can be shown by total differentiation of the model, solving for the effect of a higher level of A, the abatement standard, on R_M, R_{EC}, R_{EG} and R_C, the return per unit of capital in each affected industry. This analysis leads to the following proposition:

Result 1: Burden of Higher Abatement Standards. The burden of higher abatement standards is borne by specific capital owners in manufacturing, coal-fired electricity generation, and coal mining, all of whom experience a decrease in their real factor rewards. The marginal impact of a higher standard on capital returns is an increasing function of the price of abatement services. The real return to labor is not affected by a higher standard. [Proof to be provided as an appendix.]

Because this economy is too small to influence world prices, the manufacturing sector cannot pass higher electricity prices through to consumers. Consequently, to offset the higher cost of electricity, manufacturers decrease per unit cost by reducing the level of output, thereby raising labor's marginal productivity in the sector. The downsizing of manufacturing feeds back into electricity generation and coal mining, both of which experience lower prices and reduced output. Capital owners in manufacturing, electricity, and coal earn lower returns. The agricultural sector expands to absorb the labor freed from the manufacturing sector.

iii. Political Economy

Because capital owners bear the burden of regulation, they will expend real resources lobbying the government to avoid it. We assume capital owners in the coal mining, electricity and manufacturing sector solve the collective action problem and form an organized lobby, which distributes the costs and benefits of organized action among its members. We now consider how the level of required abatement is set by a government that accepts contributions (or bribes) from this coal lobby. The abatement standard is the outcome of a non-cooperative, complete-information game played between the government, which sets the standard, and the organized lobby, which offers a contribution to the government to influence policy. In the first stage, the lobby chooses a contribution schedule, *S(A)*, which is contingent on the abatement standard chosen by the government. In the second stage of the two-stage game, the government chooses an abatement level optimally, given the payments functions offered by the owners' lobby. Subsequently, firms choose production taking the regulatory standard as given.

Following Hillman (1989) and Grossman and Helpman (1994), we assume the government chooses the regulatory standard to maximize a weighted sum of contributions and aggregate social welfare. Social welfare is the sum of workers' welfare and the welfare of specific factor owners. Denoting the sum of individual utilities by $W(A)$, the government's objective function is

$$G(A) = S(A) + \alpha W(A), \tag{5}$$

where $\alpha > 0$ is the weight placed by the government on social welfare relative to contributions.

We abstract from distributional concerns by assuming workers care about the environment as well as consumption and have quasi-linear preferences of the form[6]

$$U = D_A + u(D_M) - \theta(\rho)(1-A)(C/L), \tag{6}$$

where D_A is consumption of the agricultural good, and D_M is consumption of the manufactured good. Per-worker damage is proportionate to per-worker unabated coal burning, $(1-A)(C/L)$. This damage, θ, is a increasing function of population density, ρ.

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[6] Quasi-linear preferences simplify treatment of the political equilibrium and are used by Grossman and Helpman (1994) and Damania, et al (2003). Dixit, Grossman, and Helpman (1997) discuss the drawbacks of the method and develop a model with common agency and general preferences with nontransferable utility.

Given this utility function, the indirect utility of a worker is

$$V(p_m, A, w) = w - p_M d_m(p_M) + U(d_M(p_M)) - \theta(\rho)(1-A)(C(A)/L). \tag{7}$$

An increase in the abatement standard benefits workers, with the marginal benefit to each worker given by $\partial V/\partial A = \theta(\rho)C/L.$

As discussed above, the incomes of specific-factor owners are strictly decreasing in the level of the abatement standard. The preferences of the coal lobby are given by $\pi(A) = \pi_M(A) + \pi_{EC}(A) + \pi_C(A),$ as the abatement standard affects their nominal income but not consumption goods prices. Specific-factor owners dislike paying contributions. We also assume that specific factor owners do not receive disutility from emissions.

A key question is how the lobby determines the contribution schedule it offers to the government. The Grossman-Helpman approach uses the result of Bernheim and Whinston (1986), who find that in the Nash equilibrium of the political game lobbies can do no better than to select a contribution schedule that truthfully reflects the true welfare level they receive for various actions by the government. In the present case, this schedule takes the form:

$$S(A) = \max\{0, \pi(A) - B\}, \tag{8}$$

where B is a constant. Bernheim and Whinston argue that a truthful Nash equilibrium is among the equilibria of the game. Substituting this schedule into the government's objective function yields

$$G(A) = (1+\alpha)[\pi(A) - B] + \alpha LV(A). \tag{9}$$

The first-order condition for maximizing the government's objective, allowing for complementary slackness, is:

$$\alpha\beta(\rho)C + (1-\alpha)\left[\frac{\partial\pi_M}{\partial A} + \frac{\partial\pi_{EC}}{\partial A} + \frac{\partial\pi_C}{\partial A}\right] \le 0 \le A. \tag{10}$$

This expression provides the decision rule for the government's cost-benefit calculation. The first term on the left-hand side of (10) gives the (weighted) marginal benefit of cleaner air. The next term gives the (weighted) marginal cost, in terms of reduced contributions for the government from the three industries producing and using coal, of raising the regulatory standard. If a positive standard is chosen, the optimal level of A occurs where the marginal benefit of regulation equals its marginal cost. If marginal benefits do not equal marginal costs at the maximum of the government's objective function, however, the government will choose not to regulate: the politically optimal level of abatement is zero and no regulatory standard will be adopted.

II. Empirical strategy

Our empirical analysis examines when a country first adopts emissions regulations for coal-fired power plants. In addition, to examine how long it takes for countries to adopt *stringent* regulations, we examine how long it takes to adopt regulations above a certain threshold. Thus, the dependent variable is a binary variable indicating whether a country has enacted emission standards (for a specific pollutant) as of year *t*. A country drops out of the sample the year after adoption. We begin the discussion of our empirical strategy by describing the regulatory determinants suggested by our theory and how we measure them. Next, we discuss construction of the dependent variable, followed by a description of the construction of our key explanatory variable, knowledge stocks, which influence the price of abatement. We end this section with depictions of trends in our data.

i. Regulatory Determinants

Using (10), we can express the politically optimal regulatory standard as $A^* = A^*\left(p_A(t), p_M, K_M, K_{EC}, K_C, \rho, \alpha\right) \geq 0$. In our empirical work, we attempt to control for the exogenous determinants of the regulation decision, using the theory to make predictions about the effect of each influence on the likelihood that a country will adopt a regulatory standard for coal-fired power plants, *ceteris paribus*.

The first influence we consider is the price of abatement services, $P_A(t)$, which we posit is a decreasing function of the technological frontier. A lower abatement price reduces the impact of regulation on incomes in the coal sector and, so, reduces the coal lobby's willingness to pay to avoid regulation. Therefore, we predict that advances in the technology frontier raise the likelihood that a country will adopt a regulatory standard. We capture technological advance using a stock of knowledge, defined below.

Because most pollution control technologies are developed in just a few countries, international trade should increase knowledge of and access to new technologies, making adoption more likely. Consequently, we interact the knowledge stock with openness, which we measure as the ratio of the total value of imports to GDP. This tests whether openness improves access to technology. However, we do note that there is some reason to expect that openness can slow adoption of regulation. For example, opponents of globalization argue that developing countries engaging in trade may see weak environmental regulations as a means of attracting foreign firms to the country, suggesting a negative effect for openness. Thus, while we expect the interaction term to be positive, the sign of the direct effect of openness is ambiguous.

Several case studies of the use of pollution abatement equipment in developing country contexts indicate that local users must have sufficient skills to use the equipment. If local users cannot use the equipment, the net cost of such equipment is very high as no benefits are obtained. To capture this, we also include measures of the average education level of the local population.

Our next consideration is the output price of the energy-intensive sector, p_M. A higher domestic price for this sector raises the cost of abatement for the government because the coal lobby is willing to pay more to prevent regulation. Because the output of this sector is tradeable, the domestic price varies across countries only in relation to the level of trade frictions. Consequently, we control for a country's trade protection in our empirical work and we predict that higher levels of protection reduce the likelihood that an abatement standard will be adopted.

Next we consider the impact of increases in the capital invested in the coal mining and coal using sectors. The more capital invested in these sectors, the larger these sectors will be as a share of the economic activity. Increases in the regulatory standard, therefore, will negatively impact a wider portion of the economy, increasing the amount the sector is willing to pay to avoid regulatory. In our empirical work, we use two measures to capture the size of the coal sector: the share of electricity produced from coal and coal production per capita.[7] We expect larger coal production to reduce the likelihood that a standard will be adopted. A larger share of electricity from coal raises the cost of abatement and, hence, the resources used to avoid regulation. However, the larger the share of electricity produced from coal, the larger the marginal benefit of abatement. If sufficiently heavy weight is placed on social welfare, a larger share of electricity from coal could promote regulation.

Finally, we include several measures that capture the strength of citizen's desire for cleaner environments and their ability to make these views known to the government. The first of these measures is GDP per capita, which has been shown in previous studies to have a consistently positive influence on the timing of regulation adoption. The second measure is population density, with the expectation that more densely populated countries will regulate

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[7] Data on coal production comes from http://www.eia.doe.gov/emeu/international/coal.html.

sooner, all else equal, because of the proximity of residences to power plants. The third measure is a democracy index, reasoning that more democratic governments place a higher weight on social welfare (the α term in the government's objective function.) We use data from Freedom House (http://www.freedomhouse.org/) as an index of political freedoms within a country.

ii. Regulations

To begin our analysis, we need data on coal-fired power plant regulations across countries. This is a challenge, as no single source of such information exists. We began by consulting a series of publications by the International Energy Agency (IEA) Clean Coal Centre (Vernon 1988, Soud 1991, McConville 1997, and Sloss 2003). These books provide detailed information on coal-fired power plant regulations in most developed countries, as well as some information on developing countries, primarily in southeast Asia and eastern Europe. We supplemented this information with additional sources on specific countries where necessary.[8] To narrow the search to a reasonable number of countries, we searched for additional regulatory information only for countries that get at least 10 percent of their electric power from coal.[9] In some cases we were unable to identify when, if at all, regulations were put in place, leaving us with regulatory data for 45 of the 50 countries that get at least 10 percent of electricity from coal.[10] In each case, we identify the year in which emissions restrictions on coal-fired power plants were enacted for both: SO_2 and NO_X. When possible, we also identify the level of these regulations.[11]

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[8] These sources are listed separately at the end of the references.

[9] Percentage of electricity from coal comes from the World Development Indicators. We choose countries that get at least 10 percent of power from coal in at least one year between 1980 and 2001. In addition, we also include two major developed countries that are an important source of environmental technology, even though they do not generate much power from coal: Switzerland and Sweden.

[10] The five missing countries are Luxembourg, Russia, North Korea, Dominican Republic, and Moldova.

[11] Our goal is to find regulations that provide firms incentives to install pollution control devices, such as flue gas desulfurization (FGD) units to remove SO_2 emissions. Thus, we are looking for the enactment of specific emissions regulations for power plants, rather than general legislation on ambient air quality. In one case, Israel, the country

Looking at the adoption data supports the notion that adoption of *regulation*, rather than adoption of the technology itself, is the first step in studying the diffusion of environmental technologies. Figure 1 shows, by year, the percentage of countries that have adopted a regulation.[12] Note the S-shaped pattern that is typical of traditional studies on adoption of technology. Each regulation has a few early adopters, who are typically the technology leaders (e.g. Japan and the U.S.). This is followed by a period of more rapid adoption which, for these policies, occurs in the mid-1980s. A period of slower adoption among the remaining countries follows. As plants will not typically adopt the control technologies used to reduce SO_2 and NO_X without regulatory incentive, understanding the pattern of adoption of these regulations is the first step towards understanding the international diffusion of these environmental technologies.

iii. Knowledge stocks

Our goal in this paper is to test the extent to which technological advances increase the likelihood of adopting environmental regulation. For this, we use patents on pollution control devices as a measure of innovation. We accumulate these patents over time in a knowledge stock designed to capture the level of technology in any given year. Below we describe how the international patent system works and briefly describe construction of the patent dataset used in this paper. Popp (2005) discusses the advantages and disadvantages of using patent data when studying environmental technologies.[13]

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never adopts specific regulations. Instead, Israel controls emissions from power plants using licenses negotiated with plants on an individual basis. As such, we drop Israel from our sample. In a second case, Mexico did enact an SO_2 standard for power plants in 1993. However, the allowable level of emissions are so high that plants do not need to install FGD equipment (Asia-Pacific Economic Cooperation, 1997).

[12] The figure only includes the 38 countries that remain in our sample after merging with other data sources, as described in subsection iii below.

[13] Among the disadvantages, note that not all successful innovations are patented, as inventors may choose to forgo patent protection to avoid disclosing proprietary information. Levin *et al* (1987) report significant differences in the propensity to patent across industries. Fortunately, this is less problematic when studying the development of a single technology than when using patents to study inventive activity across technologies, as the only assumption needed is that the propensity to patent within the industry has remained similar. Moreover, note that the quality of

Patents are granted by national patent offices in individual countries. Patent protection is only valid in the country that grants the patent. An inventor must file for protection in each nation in which protection is desired. Nearly all patent applications are first filed in the home country of the inventor. The date of the initial application is referred to as the *priority date*. If the patent is granted, protection begins from the priority date. If the inventor does file abroad within one year, the inventor will have priority over any patent applications received in those countries since the priority date that describe similar inventions.

These additional filings of the same patent application in different countries are known as *patent families*. Because of the additional costs of filing abroad, along with the one-year waiting period that gives inventors additional time to gauge the value of their invention, only the most valuable inventions are filed in several countries. Moreover, filing a patent application in a given country is a signal that the inventor expects the invention to be profitable *in that country*. Because of this, researchers such as Lanjouw and Schankerman (2004) have used data on patent families as proxies for the quality of individual patents. Lanjouw and Mody (1996) use such data to show that environmental technologies patented by developed country firms are more general than similar inventions from developing countries, as the developed country inventions have larger patent families.

Because we are using patents to identify the technological frontier for pollution control devices, we take advantage of patent families to find the most important patents. We begin by selecting all relevant patents granted in the United States since 1969. We choose the U.S. because it is a major supplier of pollution control equipment and, because of the importance of the U.S. market, many foreign companies choose to patent in the U.S. To identify the most

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individual patents vary greatly. To address this, we use patent families to focus on the highest quality inventions, as discussed below.

important patents, we only keep patents with at least one foreign patent family member – that is, patents that have been sought in multiple countries.

To identify relevant patents, we use patent classifications. When a patent is granted, it is given a technological classification by various patent offices. Traditional classification systems, such as the International Patent Classification (IPC) system or the US patent classification system, do not provide enough detail to distinguish among technologies at the level of detail needed for this paper. Instead, we used the European Classification System (ECLA), which is an extension of the IPC that provides additional detail necessary to distinguish between the types of pollution controlled by various technologies. ECLA classifications are assigned to patent examiners at the European Patent Office (EPO). The EPO provides a searchable on-line database, esp@cenet, that includes ECLA classifications for all US patents granted since 1920.[14]

Relevant technologies include those that reduce SO_2 or NO_X emissions. These includes flue gas desulfurization (FGD) units to remove SO_2 emissions, combustion modification techniques, such as low NO_X burners, designed to reduce the formation of NO_X in the combustion process, and equipment such as selective catalytic reduction (SCR) units designed to remove NO_X emissions from a plant's exhaust (post-combustion treatment). Appendix A lists the relevant ECLA codes for these technologies. In choosing relevant classifications, particular care was taken to avoid classifications that were too broad – that is, where some patents in the class pertained to pollution control, but most did not. Using the on-line databases, we downloaded a list of patent numbers for documents published in the US.[15] Once the relevant

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[14] The database can be found at http://ep.espacenet.com/

[15] These data are also used in Popp (2006a), and are described in more detail there.

patents had been obtained, descriptive information on these patents was downloaded from Delphion, an on-line database of patents.[16]

Descriptive data downloaded include the application, priority, and issue date for each patent, the home country of the inventor, and data on patent families. We use patent family data to identify patents with multiple family members. These patents were then sorted by priority year, as this date tends to correspond most closely with the actual inventive activity. In addition, using priority dates, rather than the date of grant, removes noise that may occur due to variations in the length of the patent application process. Because only granted patents were published in the US until 2001, the data only includes patent applications that were subsequently granted. Figure 2 shows the number of U.S. patents with multiple family members for each of three technologies: SO_2, NO_X combustion modification techniques, and NO_X post-combustion treatment.

We use these patents to construct a stock of knowledge for each year. Using β_1, the rate of decay, to capture the obsolescence of older patent and β_2, the rate of diffusion, to capture delays in the flow of knowledge, the stock of knowledge at time t for technology j is written as:

$$K_{j,t} = \sum_{s=0}^{\infty} e^{-\beta_1(s)}(1 - e^{-\beta_2(s+1)})PAT_{j,t-s}\ . \tag{11}$$

The rate of diffusion is multiplied by s+1 so that diffusion is not constrained to be zero in the current period. The base results presented below use a decay rate of 0.1, and a rate of diffusion of 0.25 for each stock calculation.[17] Figure 3 illustrates these stocks. Note that the value of the stock for SO_2 progresses rather smoothly through time, whereas both NO_X technologies

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[16] This database is available at http://www.delphion.com.

[17] These rates are consistent with others used in the R&D literature. For example, discussing the literature on an appropriate lag structure for R&D capital, Griliches (1995) notes that previous studies suggest a structure peaking between 3 and 5 years. The rates of decay and diffusion used in this paper provide a lag peaking after 4 years. Appendix B presents sensitivity analysis with respect to the rates of decay and diffusion.

experience periods of growth after major environmental regulations. For example, both Germany and Japan pass stringent NO_X regulations in the 1980s that led to the development of new SCR technologies (Popp 2006a).

iv. Additional data and trends

To estimate the effect of knowledge on regulatory adoption, we of course need to control for other country characteristics. We focus on four types of variables. Economic variables include openness to trade and per capita GDP. Education variables include the percentage of the population with high school and college degrees. Because the data are only available in five year increments, we extrapolate missing variables for other years. Demographic variables include population density and the percentage of the population living in urban areas. We control for the importance of the coal sector by considering both coal production and the percentage of electricity from coal. We include overall coal production and production of lignite coal. Lignite coal is the lowest quality coal, and is dirtier than other types of coal. We expect countries with more lignite to be more likely to adopt regulations, as reducing emissions will be more important in these countries. Political variables include the Freedom House index of Political Rights, dummy variables for whether the country is lead by a liberal or conservative party,[18] and a dummy variable for whether an executive branch election was held in a given year.

We use two measures of the openness of the economy, each of which captures different aspects of a country's access to imported technology. To measure dependency on imports, we use import shares, defined as imports divided by GDP. While this number is expected to be higher for more open economies, size effects complicate its interpretation. For example, large, diversified economies such as the United States will have lower import shares than smaller

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[18] Here, a middle-of-the-road (center) party is the excluded category. If the country has a chief executive, the party of that person is used here. If not, the majority party in the legislative branch is used.

economies. Thus, we view import shares as a measure of *dependency* on foreign technologies. Our second measure, trade policy, is an index introduced in Dreher (2006). Dreher creates an index of globalization that combines economic, political, and cultural phenomenon. We use the portion of the index that measures trade restrictions. The index ranges from 0-10, with 0 representing the most restrictive trade policy, and 10 representing the most open trade policy.[19] Whereas import shares measures dependency on other economies, trade policy measures the effect of policy choices on the access of technology.

Table 1 describes the variables in greater detail, and provides the source of each technology. Note that, in a few cases, we are missing data for the countries identified in section *ii* above. Thus, the final sample includes data from 1980-2000 on 38 countries.[20,21] Table 2 provides descriptive data for each of these variables for the 38 countries used in the empirical analysis.

Before proceeding with the empirical analysis, we take a first look at some correlations between key explanatory variables and adoption. First, Figures 4-6 show per capita GDP, in 1995 US dollars, in the year of adoption of regulations for SO_2 and NO_X. As mentioned earlier, stringent NO_X regulations refers to regulations strong enough that plants would likely use SCR technology to reduce emissions. Along the *x*-axis, countries are sorted by the year in which they adopted. Consider first Figure 4, which shows this relationship for SO_2. The figure is divided into three segments. The first segment includes 6 countries that adopt before 1980, the first year

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[19] Dreher's (2006) trade policy index includes four components: 1) presence of hidden trade barriers, 2) the mean tariff rate, 3) taxation on international trade, and 4) capital account restrictions.

[20] The countries with missing data are Vietnam (no data in WDI), Poland, Czech Republic (no data in WDI until after the country adopts regulation), Hong Kong (no political data), Morocco and Ukraine (no education data). In addition, we do not have trade data for Romania until 1990, and so delete Romanian observations earlier than 1990. This is consistent with our treatment of other Eastern European countries, where we only consider adoption decisions made in the post-Communist era.

[21] In the case of the Eastern European countries, we only consider adoption decisions made in the post-Communist era. This is due both to data availability and because under the Communist regime, many of these countries had stringent environmental laws on the books that were not enforced

of data in our regression. With the exception of the Philippines, each of these countries adopts at a per capita income roughly between \$15,000 and \$20,000. Of the countries that adopt between 1980-2000, we see a strong trend of countries adopting at lower incomes over time. This trend suggests that the availability of technologies, produced by countries that first chose to adopt SO_2 regulations, has lowered the costs of adoption sufficiently for more countries to choose to adopt. This is also shown in the scatter plot in Figure 7A. Finally, the third segment of Figure 4 includes countries that have yet to adopt SO_2 regulations. In general, these are all low income countries. The exceptions are Australia and New Zealand. In both cases, this is because the coal found in these countries is generally low in sulfur (Soud 1991, McConville 1997). Similar trends hold for NO_X, as shown in Figure 5. In comparison, for stringent NO_X regulations (Figure 6), there are still several countries that have not adopted such regulations. Those that have are generally high income countries, although there are some exceptions. In most cases, these exceptions are Eastern European countries.

Figure 7B shows the correlation between the percentage of high school graduates in a country and the year in which the country adopts regulation for the 24 countries adopting SO_2 regulations from 1980-2000. As expected, countries with lower education levels adopt more slowly, although the relationship is not as strong as with income. Finally, Figure 7C shows the correlation between trade policy openness and year of adoption of SO_2 regulations for the same set of countries. Openness introduces more to the economy than new technology, so there are competing hypotheses about the influence of lower trade barriers. Openness increases access to new technologies, which should make countries more willing to adopt regulation. At the same time, countries that rely more on international trade may resist environmental regulations so that domestic firms remain competitive in international markets. The scatter plot suggests that both effects may be present, as there is little discernable relationship between openness and adoption. Thus, we turn to the regression analysis to separate these effects and provide more information on the relationship between openness and environmental regulation.

III. Regressions

We use a hazard model to estimate the effects of both technology and individual country characteristics on the adoption of environmental regulation. We follow the approach used by economists studying the adoption of technology and use a duration model that captures both a baseline hazard and country-specific effects methods (e.g. Hannan and McDowell 1984, Rose and Joskow 1990, Karshenas and Stoneman 1993, Kerr and Newell 2003, Snyder *et al*. 2003, Popp 2006b). These models separate the hazard function into two parts, allowing for the possibility of a baseline hazard, $h_0(t)$, that does not vary by country. This yields a hazard function to be estimated of the form:

$$h(t,\mathbf{X_t},\boldsymbol{\beta}) = h_0(t)\exp(\mathbf{X_t}'\boldsymbol{\beta}). \tag{12}$$

Here, $\mathbf{X_t}$ is a vector of explanatory variables, $\boldsymbol{\beta}$ is the vector of parameters to be estimated, and t represents time.

To estimate equation (12), the baseline hazard h_0 must be specified. Various specifications have been used in the adoption literature. Among the most common are the exponential, Weibull, and Gompertz distributions. The exponential distribution assumes the baseline hazard is constant over time, whereas the others assume that the baseline hazard is a function of time. Thus, the exponential distribution assumes that learning effects are insignificant, and that other time-varying effects are captured by the explanatory variables $\mathbf{X_t}$. In the results that follow, we begin with the exponential distribution, and consider sensitivity of the results to other specifications.

Once the baseline hazard is specified, estimation of equation (12) is completed using maximum likelihood estimation.[22] To aid interpretation, we normalize all continuous variables so that a one unit change in the normalized variable is equivalent to a ten percent change from its mean value. In the hazard model, exp(β) gives the change in the probability of adoption for each variable. Thus, with the normalized data, this can be interpreted as the percentage change in adoption due to a 10 percent change for each continuous variable.[23] We estimate the hazard model for the adoption of SO_2 regulation, of NO_X regulation, and of stringent NO_X regulations that require the use of post-combustion control techniques.

i. SO_2 Results

In the case of SO_2, our data include six countries that adopt prior to 1980, which is the first year in our data set. We drop these six countries from the regression analysis.[24] Table 3 presents results of four model specifications using an exponential hazard.

The first three columns check for sensitivity to different measures of openness. Column one uses import shares as a measure of openness. Most results are as expected. Access to knowledge increases likelihood of enacting SO_2 regulations for coal-fired power plants. However, it is likely that, in the exponential model, the knowledge stock also picks up other

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[22] For an introduction to duration data see Cox and Oakes (1985), Kiefer (1988), and Lancaster (1990).

[23] The normalization first divides each continuous variable by its mean, multiplies by 10, and then takes deviations from the mean by subtracting 10. This procedure is introduced in Kerr and Newell (2003), and results in normalized variables that have a mean of 0.

[24] Another alternative is to add a term to the likelihood function to account for the six early adopters (see, for example, Popp (2006b). One drawback of such an approach is that it assumes that early adopters are influenced by the same forces as later adopters. This seems unlikely, as early adopters tend to be innovators of environmental technology, rather than adopters of environmental technology. That is, access to existing technology should not be important for early adopters. Nonetheless, to check sensitivity of the model to excluding these countries, we did run a model with the modified likelihood function and the early adopters. Such a model does not converge using the exponential hazard, but does using the Weibull. The results under the Weibull are virtually unchanged when the early adopters are included.

unmeasured factors varying over time, as the magnitude of this effect is quite large. A ten percent increase in knowledge increases the likelihood of adoption by 303 percent. Alternatively, one can gauge the effect of knowledge by looking at the predicted increase in adoption rates based on the actual values of the knowledge stock.[25] On average, new increments to knowledge increase the likelihood of adoption by 29 percent per year. We explore this further in our sensitivity analysis, in which we look at results using other specifications of the baseline hazard.

While the magnitude of the effect of knowledge is large, the interaction between knowledge and openness appears more reasonable. As expected, openness appears to increase access to technology, and thus increase the likelihood of adopting regulations. A 10 percent increase in this interacted variable (e.g. a 10 percent increase in knowledge and import shares) increases the likelihood of adoption by 11 percent. Moreover, note that the coefficient on import shares itself is negative. This suggests that the concern that more open countries may be less likely to regulate, fearing that regulation may decrease the competitiveness of domestic firms, may be correct.

We therefore see two effects of openness using the import shares measure. For most of the countries in our sample, the technologies to control SO_2 emissions are produced abroad. In such cases, higher import shares indicate greater access to technology, making countries more willing and able to adopt environmental regulation (*access effect*). At the same time, increased openness means that domestic firms need to compete with foreign firms. Thus, environmental regulations may be seen as an added burden to local firms (*competitive effect*). An important question is which of these two effects dominate. Recall that the variables are normalized so that

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[25] The calculation is the average of $\exp(\mathbf{K(t)}'\beta) - \exp(\mathbf{K(t\text{-}1)}'\beta)$, where **K** represents the knowledge stock, and β is the estimated coefficient. We ignore the interaction with openness (which increases the likelihood of adoption), so that the calculation is for a country with mean levels of openness.

the mean value of each variable equals 0. Thus, if the knowledge stock is below average, the competitive effect clearly dominates. When knowledge is above average, which term dominates depends on the level of knowledge. Here, the access effect dominates when knowledge is at least 18.2 percent above average.[26] Given this, the net effect of openness in our sample is not positive until 1994. Indeed, of the countries in our sample that never adopt, only New Zealand and Mexico have above average levels of import shares by 2000, and the average level of import shares for each of these countries across the 1980-2000 period is below the average of the sample as a whole.

In contrast to using import shares, using the index of trade policy (column 2) provides less favorable results. The signs and magnitudes of both the interaction and the trade policy variable are the same as when we use import shares as a measure of openness. However, unlike the import share results, these effects are insignificant.[27] Column 3 includes both measures of openness. The results remain unchanged, although the import share*knowledge interaction is only significant at the 10 percent level. Finally, column 4 shows the effect of removing the knowledge/openness interaction. Doing so reduces the magnitude of the effect for both knowledge and import shares, but does not change the signs of either coefficient.

Turning to other variables, note that there are no significant differences across the various specifications. Given this, we focus on the results in column 1. The results verify the relationship between per capita GDP and adoption of regulation. A ten percent increase in per capita income increases adoption rates by 36%. This supports other results finding that environmental quality is a normal good. Education appears to have less impact. A ten percent

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[26] The requirement here is that $\exp(\beta_{\text{open}} + \beta_{\text{interact}}K) > 1$, so that $\beta_{\text{open}} + \beta_{\text{interact}}K > 0$. This holds when $K > -\beta_{\text{open}}/\beta_{\text{interact}}$.

[27] One reason for the difference may be that there is less variation in the trade policy index than in import shares, as shown in Table 2.

increase in the share of the population with a high school degree increases adoption by 18 percent, but the effect is insignificant. Completing college has a negative but insignificant effect.[28] As expected, more densely populated countries adopt more quickly, as pollution problems are likely be more severe when population is concentrated and more people are exposed to pollution. However, the percentage of population in urban areas is consistently insignificant.

Our first set of political economy variables deal with the importance of the coal sector. As expected, regulation is less likely when the coal sector is important. Coal production per capita has a negative effect on adoption. A country producing 10 percent more coal per capita than average is 16 percent less likely to adopt SO_2 regulations for coal-fired power plants. However, if a country has a greater share of dirty coal, they are more likely to adopt, as the pollution problems will be greater. Countries producing 10 percent more lignite coal than average are 7 percent more likely to adopt. Note, however, that the net effect of the two coal variables remains negative. Thus, countries with dirtier coal are more likely to adopt than a country producing a similar amount of cleaner coal, but remain less likely to adopt than the typical country. Finally, we find that the percentage of electricity from coal is insignificant. As discussed in the theory section, there are two competing effects. Having more power come from coal makes the need to regulate greater, as the overall level of pollution from coal-fired power plants will be higher. However, assuming that the costs of pollution control are passed through the economy due to higher electric prices, the costs of adopting regulation will also be higher.

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[28] The sign on a college education remains insignificant even if the share of the population with a high school degree is dropped from the equation. We also tried regressions using average years of schooling, rather than percentage with degrees. The average schooling variable is always insignificant using this variable as well. We use the percent graduating as we occasionally find significant results for these variables in the other results that follow. The significance of these percentages, but not the average schooling variable, suggests a threshold effect. Completing high school is more important than increasing average education levels from a fourth to fifth grade level, for example.

Our more general set of political variables yield mixed results, as most are insignificant. One striking finding is the strong negative effect of an executive branch election year. No country enacted SO_2 regulations in an executive branch election year. Political rights, measured using the Freedom House index, are insignificant. For political parties, both liberal and conservative governments are less likely to adopt SO_2 regulations than middle-of-the-road governments. However, the results are only significant for liberal governments, and only when using the specifications in columns 3 or 4. Although this may be a surprise given that liberal governments are typically seen as environmentally friendly, this is less likely the case in lower income countries, where liberal governments may resist regulation in order to protect the interests of low-income laborers.[29]

ii. Sensitivity to baseline hazard

Table 4 shows results of the base model with three alternative baseline hazards: exponential, Weibull, and Gompertz. One striking result from this table is that it is difficult to separately identify the effect of the knowledge stock from the baseline hazard. Thus, we also run each model without the knowledge stock, although we do include the interaction between knowledge and openness in each model. We present results using both measures of openness, although the findings are similar when we use only a single measure of openness.

Other than the knowledge variable, there is little change in the coefficients across specifications.[30] The separate knowledge variable, however, experiences wide swings in value under different hazard assumptions. In the Weibull model, knowledge has a negative effect. A

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[29] The role of political ideology on standard political economy predictions has been explored in the case of trade restrictions. Dutt and Mitra (2005) find empirical support for the proposition that the ideology of the government in power influences the restrictiveness of trade policy.

[30] One exception is the exponential model without a knowledge stock. Because the exponential baseline hazard assumes constant time effects, without knowledge, the model (incorrectly) does not allow for increasing probability of adoption over time, thus confounding the other parameter estimates.

ten percent increase in knowledge reduces adoption by 29 percent. This magnitude appears unrealistically large, as the average *annual* contribution of knowledge is to reduce the likelihood of adoption by 411 percent. This is counteracted, however, by a strongly positive baseline hazard, suggesting that the knowledge stock and baseline hazard are collinear. Thus, we re-estimate the model without the separate knowledge stock. The duration dependence parameter of the Weibull distribution falls, but is still positive, capturing the increased likelihood of adoption over time. Other parameters are virtually unchanged. Most importantly, the interaction between openness and knowledge is virtually the same in each model (0.1017 vs. 0.0949). Moreover, this result is not significantly different from the interaction effect in the exponential model. One notable difference is that, while the magnitudes of the coefficients are the same, the interacted effect of knowledge and import shares is now significant even when both measures of openness are used. The same holds for the last two columns, which present results for the Gompertz baseline hazard. Here, knowledge has a separate positive effect, although it is smaller than in the baseline hazard. More importantly, the interaction effect remains unchanged. Thus, while we are unable to separately identify the overall effect of knowledge with confidence, we are confident in our finding that openness, particularly measured by dependence on imports, increases the impact of knowledge.

iii. NO_X Pre-combustion results

Next, we look at the adoption of any NO_X regulations by the countries in our sample. In most cases, initial regulation levels are weak enough that pre-combustion modifications are sufficient to comply with the regulations. Table 5 presents the results for each of the three baseline hazards, using the model with both measures of openness.[31] In general, access to knowledge through international trade appears less important here than for sulfur dioxide.

As before, knowledge has a positive effect in the exponential model.[32] Also as before, this result does not hold when allowing for time effects in the baseline hazard. In all cases the interaction between knowledge and import shares is positive, although it is insignificant in the Weibull model that includes a separate knowledge stock. The direct effects of both higher import shares and trade policy are similar to before, and are only significant in the exponential model.

As for other variables, the results are very similar to the case of SO_2. GDP, percentage of the population with a high school degree, and population density all increase adoption rates. The political influences of the coal industry are still important. However, in the Weibull and Gompertz specifications, coal production per capita is only significant when omitting the knowledge stock.

iv. NO_X Post-Combustion

To this point, we have looked at the decision to first adopt a regulation, but have said nothing about the stringency of these regulations. Here, we consider stringency by considering the decision to adopt NO_X regulations stringent enough to require post-combustion treatment of the flue gas.[33] Such treatment requires expensive capital equipment (typically a selective catalytic reduction unit, or SCR), making such regulations less prevalent, particularly among

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[31] We omit the table investigating the various specifications of openness, as once again the results are similar across all specifications.

[32] While the magnitude of this effect appears smaller (here, a 10 percent increase in knowledge only increases the likelihood of adoption by 32 percent), there is greater variation in the level of the knowledge stock for pre-combustion technologies, so that the net effect of knowledge is actually higher here than for SO_2. For the pre-combustion technologies, the average effect of new knowledge is to raise the probability of adoption by 48 percent.

[33] We classify all regulations restricting NO_X emissions to 410 mg/m^3, which is the regulation introduced in Japan when they tightened NO_X emission limits in 1986.

developing countries. As shown in Figure 6, most countries adopting stringent NO_X regulations are rich countries. Exceptions are Indonesia and several Eastern European countries.

Once again, we present regression results comparing three separate baseline hazard specifications, which are found in Table 6. As before, identifying the effect of knowledge by itself is difficult, as the knowledge variable is only significant in the exponential model. Of particular note here, however, is that the interaction between knowledge and trade is also insignificant.[34] Because it is mainly leading economies that are adopting stringent NO_X regulations and making use of SCR technology, access to technology from abroad appears less important – countries adopting stringent regulations are generally those capable of producing SCR technology on their own.

There are also notable differences between stringent NO_X regulations and the other regressions for other variables. First, education is never significant. Second, the political power of the coal industry is unimportant, as all of the coal variables are insignificant. While the coal industry may play an important role in influencing whether or not a regulation is put in place, once a regulation is in place it appears to have less power influencing the decision to strengthen NO_X regulations. Instead, political parties appear more important, as middle of the road governments are more likely to tighten regulations than either liberal or conservative governments.

Finally, the most notable difference is that, controlling for other country characteristics, the Eastern European countries are much more likely to pass stringent NO_X regulations than other countries. Here, the influence of the European Union (EU) is important, as countries wishing to join the EU must comply with EU environmental standards. Desires to join the EU

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[34] This is also true for models including only one of the two interactions with openness. T-stats from the exponential baseline hazard for the individual interactions are -0.672 for the model only using import shares, and -0.414 for the model only using trade policy.

push these Eastern European countries to enact regulations more stringent than would otherwise be chosen for their level of development.[35]

IV. Conclusions

In debates on the effect of globalization and the environment, several possible effects have been hypothesized. Three commonly cited effects are scale effects (more consumption leads to more pollution), composition effects (a change in the mix of economic activity), and technique effects (cleaner technologies are used as countries grow and trade expands).[36] One challenge in empirically studying these effects is separately identifying the role of each. In this paper, we focus on the technique effect. Using the adoption of environmental regulations, rather than a generic measure of environmental quality, as our dependent variable, we show that increased access to technology via trade increases the likelihood that a country will adopt environmental regulation. While we do find that richer countries adopt regulation first, developing countries adopt environmental regulation at earlier stages of development than did developed countries, as they can take advantage of off-the-shelf technologies to carry out emission reductions. Thus, the fixed costs of developing new solutions to environmental problems are avoided.

In addition to the links between trade and technology, we also find that political economy forces are important. Factors affecting demand for regulation, such as population density and education, increase the likelihood of regulation. Moreover, regulations that negatively affect the coal sector are less likely in countries where coal is an important part of the economy.

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[35] See, for example, "Eastern Europe's environment: Clean up or clear out," *The Economist*, December 11, 1999, p. 47.

[36] Esty (2001) provides a review of this literature. Copeland and Taylor (2003) provide a rigorous theoretical analysis of these effects in the context of an open economy.

Regulations are never adopted in an election year for the executive. Finally, the politics of globalization appear important, as eastern European countries have passed more stringent regulations than other countries at similar levels of development. This enables these countries to comply with European Union standards as they progress in toward joining the EU.

Studying the adoption of environmental regulation is important because it is the first step to the diffusion of environmental technologies. This is particularly true for end-of-the-pipe technologies like those studied in this paper, as these technologies impose costs on firms while only providing the benefit of compliance with existing regulations. Our work suggests that free trade can enhance the diffusion of these technologies, but that this diffusion comes indirectly, with the decision to regulate preceding a plant's decision to adopt clean technology. Moreover, given these links, it is worth considering when other influences might encourage adoption, so that clean technologies could be adopted in countries that do not regulate emissions. One such case is when the technologies offer firms benefits other than simply complying with regulation. For example, in considering the spread of technologies to reduce carbon emissions, technologies that increase fuel efficiency, and thus potentially reduce consumption of fossil fuels, could diffuse without regulation, as firms using them could still benefit from lower energy costs. Nonetheless, regulation would be needed for such diffusion to reach a socially optimal level. A second possibility for diffusion of clean technologies without regulation is when consumer demand for environmentally-friendly products encourages firms to adopt and market green production techniques. An example is diffusion of chlorine-free bleaching technologies for paper (Reinstaller 2005). We leave the study of diffusion of clean technologies under such conditions to future work.

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Table 1 – Data Definitions and Sources

variable	**Description**	**Source**
Economc Variables		
Import Shares	(Imports)/GDP	WDI
Trade Policy	0 (closed) to 10 (open) index of openness of trade policy	Dreher
GDP Per Capita	Per capita GDP in constant 1995 US $	WDI
Education variables		
% complete Post Second. Ed.	% of population completing post-secondary education	Barro & Lee
% complete Secondary Ed.	% of population completing secondary education	Barro & Lee
Demographic patterns		
Population Density	People per square km	WDI
% Urban Population	% of total population in urban areas	WDI
Political Economy -- Importance of Coal		
% Electricity from Coal	% of electricity production from coal sources	WDI
Coal Production Per Capita	Total coal production, in quadrillion BTU, per person	EIA/WDI
Lignite Production Per Capita	Production of lignite coal, in million short tons, per person	EIA/WDI
Political Economy -- Other		
Election Year	Dummy = 1 if executive branch election held that year	DPI
Political Rights	Index of political rights, from 1 (free) to 7 (not free)	FH
Liberal	Dummy = 1 if country led by a liberal party	DPI
Conservative	Dummy = 1 if country led by a conservative party	DPI

Sources:
WDI: *World Development Indicators*
Barro & Lee: International Data on Educational Attainment (Barro & Lee 2001)
EIA/WDI: Coal data from Energy Information Administration *International Energy Annual 2003,* available at:
http://www.eia.doe.gov/iea. Population data from WDI.
FH: Index produced by Freedom House (http://www.freedomhouse.org)
DPI: Databaes of Political Institutions (Keefer 2005)
Dreher: Data on restrictions component of the globalization index in Dreher (2006).

Table 2 – Descriptive Data

variable	N	mean	sd	min	p50	max
Knowledge Stock: SO2	21	344.288	83.912	180.918	375.265	433.980
Knowledge Stock: NOXPre	21	74.007	38.588	29.410	59.671	133.485
Knowledge Stock: NOXPost	21	217.068	84.212	103.497	233.285	312.251
Import shares	750	30.561	14.602	6.855	27.792	84.398
Trade Policy	750	6.799	1.613	2.670	7.020	9.540
GDP Per Capita	750	14073.550	12132.530	166.746	11843.440	46815.500
% complete Post Second. Ed.	750	8.230	4.856	0.3	7.86	30.3
% complete Secondary Ed.	750	30.410	16.469	1.3	29.0	76.9
Average Schooling	750	7.591	2.391	2.72	8.122	12.25
Population Density	750	125.061	115.877	1.912	96.368	476.127
% Urban Population	750	64.409	20.097	17.041	66.950	97.335
% Electricity from Coal	750	33.436	26.065	0.000	27.535	99.474
Coal Production Per Capita	750	2.23E-08	4.52E-08	0	5.98E-09	3.47E-07
Lignite Production Per Capita	750	0.0006	0.0014	0	1.13E-07	0.0067
Election Year	750	0.059	0.235	0	0	1
Political Rights	750	2.195	1.765	1	1	7
Liberal	750	0.383	0.486	0	0	1
Conservative	750	0.443	0.497	0	0	1
Conservative	750	0.104	0.305	0	0	1

Table 3 – Regression Results: Adoption of SO_2 Regulations

Variable	Import Shares	Trade Policy	Both	Drop Interaction
Knowledge Stock	1.1389	1.1613	1.1108	1.0231
	(3.929)	(3.496)	(3.668)	(3.670)
Knowledge*Import Shares	0.1057		0.1092	
	(2.419)		(1.793)	
Knowledge*Trade Policy		0.1011	0.0163	
		(0.999)	(0.163)	
Import Shares	-0.1931		-0.2183	(-0.066)
	(-2.346)		(-1.687)	(-1.594)
Trade Policy		-0.1671	0.1461	
		(-1.190)	(0.618)	
GDP Per Capita	0.3068	0.3314	0.2933	0.2683
	(3.959)	(3.758)	(4.025)	(3.785)
% complete Post Second. Ed.	-0.2656	-0.3132	-0.2754	-0.2577
	(-1.372)	(-1.924)	(-1.180)	(-1.880)
% complete Secondary Ed.	0.1678	0.1375	0.1793	0.1242
	(1.247)	(1.230)	(1.224)	(1.113)
Population Density	0.0581	0.0482	0.0684	0.0318
	(2.274)	(1.439)	(2.200)	(1.165)
% Urban Population	0.1097	0.0767	0.0629	0.1002
	(0.731)	(0.536)	(0.460)	(0.687)
% Electricity from Coal	0.0520	0.0265	0.0631	0.0399
	(1.443)	(0.720)	(1.311)	(1.107)
Coal Production Per Capita	-0.1707	-0.1272	-0.1766	-0.1312
	(-2.299)	(-1.845)	(-2.361)	(-2.018)
Lignite Production Per Capita	0.0690	0.0707	0.0687	0.0652
	(2.866)	(2.743)	(2.709)	(2.899)
Election Year	-16.0040	-15.5760	-15.6771	-17.5001
	(-15.589)	(-13.660)	(-16.028)	(-21.467)
Political Rights	0.1440	0.1072	0.1858	0.0034
	(0.756)	(0.542)	(0.887)	(0.024)
Liberal	-0.7842	-0.6827	-0.9173	-0.9300
	(-1.592)	(-1.275)	(-1.749)	(-1.874)
Conservative	-0.1736	-0.1875	-0.2885	-0.3819
	(-0.289)	(-0.341)	(-0.515)	(-0.726)
Eastern Europe	0.3030	0.1304	0.5675	0.5976
	(0.420)	(0.178)	(0.660)	(0.786)
Constant	-3.1107	-2.7916	-3.1663	-2.4822
	(-3.106)	(-2.722)	(-2.860)	(-2.896)
N	369	369	369	369
log-likelihood	-62.724	-64.829	-62.542	-65.096
chi2	423.867	533.409	472.347	651.187
fix likelihood ratios:	159.448	163.657	163.083	162.193

The table presents regression results using an exponential baseline hazard. T-stats in parentheses.

Table 4 – Regression Results – Alternative Baseline Hazards for SO$_2$ Adoption

Variable	Exponential		Weibull		Gompertz	
Knowledge Stock	1.1108		-0.9299		0.7150	
	(3.668)		(-1.728)		(2.665)	
Knowledge*Import Shares	0.1092	0.0520	0.1017	0.0949	0.0889	0.0760
	(1.793)	(1.768)	(2.608)	(2.365)	(2.055)	(2.419)
Knowledge*Trade Policy	0.0163	-0.0442	0.0597	0.0785	0.0674	0.0419
	(0.163)	(-0.814)	(0.442)	(0.562)	(0.602)	(0.542)
Import Shares	-0.2183	-0.1377	-0.1202	-0.1228	-0.1516	-0.1208
	(-1.687)	(-2.665)	(-1.632)	(-1.457)	(-1.577)	(-1.794)
Trade Policy	0.1461	0.5038	0.0919	-0.0371	0.0538	0.1854
	(0.618)	(1.869)	(0.386)	(-0.167)	(0.247)	(0.697)
GDP Per Capita	0.2933	-0.0112	0.3277	0.3919	0.3324	0.2383
	(4.024)	(-0.178)	(2.610)	(3.260)	(3.331)	(2.645)
% complete Post Second. Ed.	-0.2754	-0.0448	-0.3784	-0.3940	-0.3106	-0.2447
	(-1.180)	(-0.283)	(-1.699)	(-1.765)	(-1.420)	(-1.279)
% complete Secondary Ed.	0.1793	0.1796	0.2002	0.2056	0.1544	0.1185
	(1.224)	(1.506)	(1.482)	(1.504)	(1.139)	(0.883)
Population Density	0.0684	0.0624	0.0631	0.0663	0.0689	0.0624
	(2.200)	(3.049)	(1.585)	(1.720)	(1.953)	(1.611)
% Urban Population	0.0630	-0.1640	0.1031	0.1003	0.0829	0.0701
	(0.460)	(-1.778)	(0.663)	(0.596)	(0.607)	(0.550)
% Electricity from Coal	0.0631	0.0828	0.0484	0.0450	0.0543	0.0572
	(1.311)	(2.453)	(0.948)	(0.940)	(1.168)	(1.185)
Coal Production Per Capita	-0.1766	-0.1102	-0.1479	-0.1508	-0.1795	-0.1721
	(-2.361)	(-2.603)	(-1.824)	(-1.954)	(-2.220)	(-1.959)
Lignite Production Per Capita	0.0687	0.0286	0.0691	0.0755	0.0741	0.0642
	(2.709)	(2.596)	(2.452)	(2.634)	(2.447)	(2.130)
Election Year	-17.504	-17.012	-18.165	-18.511	-18.623	-17.565
	(-17.894)	(-13.943)	(-31.281)	(-27.437)	(-22.996)	(-25.761)
Political Rights	0.1858	-0.0161	0.1668	0.2268	0.1872	0.0891
	(0.887)	(-0.099)	(0.509)	(0.846)	(0.863)	(0.419)
Liberal	-0.9173	-1.0697	-0.7828	-0.5177	-0.7995	-1.0431
	(-1.749)	(-1.920)	(-1.439)	(-1.001)	(-1.655)	(-2.314)
Conservative	-0.2885	-0.7100	-0.5607	-0.1553	-0.3409	-0.7438
	(-0.515)	(-1.132)	(-1.038)	(-0.287)	(-0.655)	(-1.436)
Eastern Europe	0.5675	1.1782	1.5653	1.0862	0.9594	1.3991
	(0.660)	(1.592)	(1.331)	(1.070)	(1.019)	(1.280)
Constant	-3.1664	-2.4830	-21.0711	-16.0131	-5.2364	-6.2731
	(-2.860)	(-3.296)	(-3.712)	(-3.230)	(-2.861)	(-3.511)
Duration dependence parameter			2.1213	1.7937	0.2013	0.3465
			(8.633)	(6.805)	(2.275)	(3.790)
N	369	369	369	369	369	369
ll	-62.542	-75.559	-52.280	-53.583	-60.478	-62.741
chi2	543.749	477.896	1550.716	1119.683	828.282	911.405
aic	55.118	79.153	36.596	37.201	52.991	55.517

The table presents regression results using alternative baseline hazards. T-stats in parentheses.

Table 5 – Regression Results – Alternative Baseline Hazards for NO$_X$ Adoption

Variable	Exponential		Weibull		Gompertz	
Knowledge Stock	0.2778		-0.2507		-1.0374	
	(2.669)		(-1.317)		(-3.351)	
Knowledge*Import Shares	0.0327	0.0361	0.0241	0.0197	0.0302	0.0227
	(2.980)	(2.609)	(1.694)	(1.917)	(1.924)	(2.219)
Knowledge*Trade Policy	0.0190	-0.0263	0.0255	0.0512	0.0283	0.0643
	(0.641)	(-1.163)	(0.526)	(1.304)	(0.562)	(1.417)
Import Shares	-0.1294	-0.1209	0.0740	0.0485	0.0918	-0.0162
	(-2.224)	(-2.364)	(1.121)	(0.855)	(1.459)	(-0.292)
Trade Policy	0.5414	0.5780	0.0883	0.1565	0.1194	0.3239
	(2.188)	(2.414)	(0.296)	(0.628)	(0.454)	(1.360)
GDP Per Capita	0.0726	-0.0422	0.1682	0.2039	0.1606	0.2130
	(1.440)	(-0.668)	(2.442)	(3.132)	(2.145)	(2.384)
% complete Post Second. Ed.	-0.2251	-0.0690	-0.4251	-0.4620	-0.4296	-0.4270
	(-1.143)	(-0.443)	(-1.747)	(-2.139)	(-1.721)	(-1.920)
% complete Secondary Ed.	0.1589	0.1932	0.1953	0.1916	0.1831	0.1418
	(1.835)	(1.853)	(1.620)	(1.916)	(1.518)	(1.504)
Population Density	0.0988	0.0770	0.0813	0.0957	0.0839	0.1067
	(3.824)	(3.720)	(2.465)	(3.177)	(2.506)	(2.916)
% Urban Population	0.0075	-0.1225	0.1790	0.1557	0.1836	0.1039
	(0.067)	(-1.362)	(0.476)	(0.550)	(0.504)	(0.696)
% Electricity from Coal	0.0749	0.0798	0.0424	0.0480	0.0556	0.0681
	(1.654)	(2.400)	(0.325)	(0.438)	(0.444)	(0.955)
Coal Production Per Capita	-0.1813	-0.1234	-0.0774	-0.1263	-0.0990	-0.2009
	(-2.170)	(-2.707)	(-1.031)	(-1.972)	(-1.136)	(-2.206)
Lignite Production Per Capita	0.0590	0.0333	0.0665	0.0764	0.0670	0.0824
	(2.159)	(2.755)	(2.658)	(2.665)	(2.251)	(2.358)
Election Year	-18.414	-17.293	-17.658	-19.383	-17.952	-17.636
	(-20.52)	(-16.80)	(-26.37)	(-29.46)	(-23.61)	(-27.89)
Political Rights	0.1313	0.0568	0.0708	0.1165	0.0582	0.1652
	(0.787)	(0.377)	(0.365)	(0.675)	(0.286)	(0.843)
Liberal	-1.1908	-1.1193	-0.6896	-0.7212	-0.6354	-0.9205
	(-2.805)	(-2.221)	(-1.113)	(-1.443)	(-0.978)	(-2.268)
Conservative	-1.0334	-0.9213	-0.5795	-0.6623	-0.5338	-0.8553
	(-1.633)	(-1.351)	(-0.731)	(-1.089)	(-0.638)	(-1.606)
Eastern Europe	0.8716	0.9742	0.2099	0.3502	0.7986	1.0303
	(0.972)	(1.374)	(0.172)	(0.288)	(0.682)	(0.894)
Constant	-2.6739	-2.6248	-17.9660	-14.3491	-17.0575	-7.9102
	(-2.704)	(-3.175)	(-3.925)	(-4.433)	(-4.924)	(-3.171)
Duration dependence parameter			1.9399	1.6903	1.2898	0.4481
			(7.418)	(8.682)	(4.613)	(3.441)
N	359	359	359	359	359	359
ll	-74.714	-79.811	-57.880	-59.161	-54.561	-63.504
chi2	554.419	463.876	1055.394	1268.659	969.965	1082.506
aic	67.768	75.962	36.100	36.661	29.460	45.348

The table presents regression results using alternative baseline hazards. T-stats in parentheses.

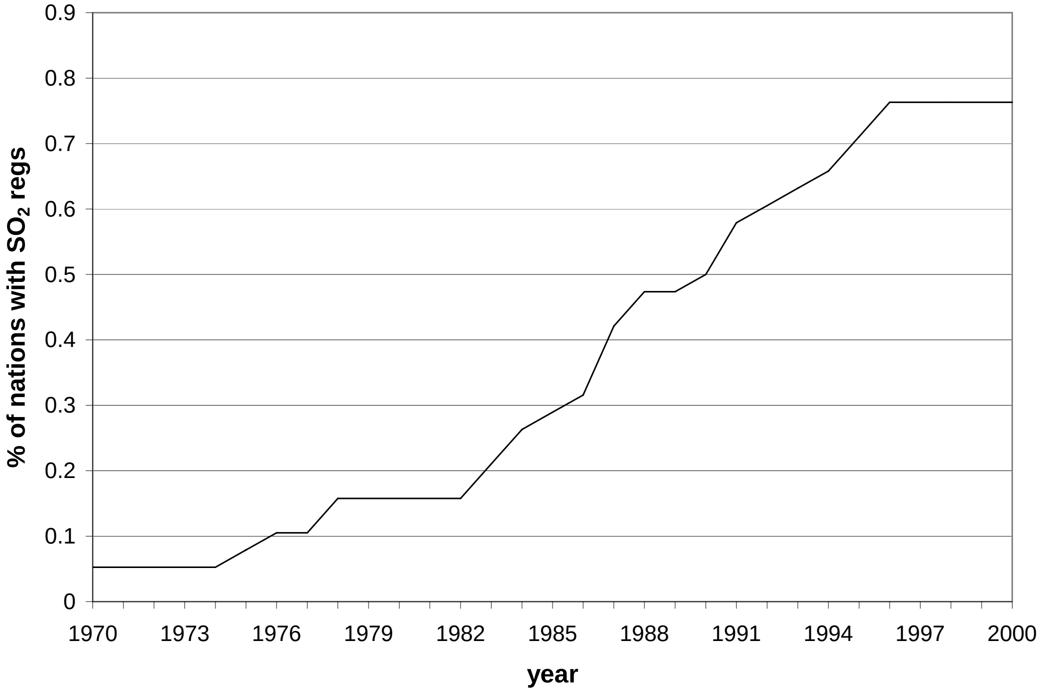
Table 6 – Regression Results – Alternative Baseline Hazards for Stringent NO_X Adoption

Variable	Exponential		Weibull		Gompertz	
Knowledge Stock	0.3226		-0.1917		0.1043	
	(2.120)		(-0.783)		(0.709)	
Knowledge*Import Shares	0.0080	0.0019	0.0038	0.0065	0.0059	0.0040
	(0.383)	(0.120)	(0.142)	(0.252)	(0.273)	(0.196)
Knowledge*Trade Policy	-0.0528	0.0421	-0.0729	-0.0836	-0.0637	-0.0567
	(-0.637)	(1.169)	(-0.775)	(-0.863)	(-0.739)	(-0.777)
Import Shares	-0.1941	-0.1592	-0.1571	-0.1699	-0.1848	-0.1784
	(-2.259)	(-2.848)	(-1.746)	(-1.902)	(-2.091)	(-2.268)
Trade Policy	0.4599	0.6125	0.4278	0.4357	0.3954	0.3786
	(1.350)	(2.260)	(1.233)	(1.162)	(1.107)	(1.116)
GDP Per Capita	0.3313	0.2249	0.3421	0.3554	0.3354	0.3249
	(3.588)	(3.449)	(3.207)	(3.495)	(3.301)	(3.460)
% complete Post Second. Ed.	-0.0189	-0.0414	-0.0597	-0.0482	-0.0268	-0.0305
	(-0.181)	(-0.513)	(-0.361)	(-0.308)	(-0.219)	(-0.250)
% complete Secondary Ed.	-0.1304	-0.0026	-0.0844	-0.1103	-0.1363	-0.1265
	(-0.975)	(-0.026)	(-0.527)	(-0.738)	(-0.921)	(-0.893)
Population Density	0.0782	0.0841	0.0818	0.0823	0.0710	0.0680
	(2.206)	(2.466)	(2.658)	(2.575)	(2.040)	(1.973)
% Urban Population	-0.0655	-0.1370	-0.1374	-0.1062	-0.0423	-0.0438
	(-0.303)	(-0.825)	(-0.592)	(-0.507)	(-0.188)	(-0.197)
% Electricity from Coal	0.0408	0.0477	0.0328	0.0335	0.0465	0.0483
	(0.805)	(1.264)	(0.555)	(0.552)	(0.817)	(0.840)
Coal Production Per Capita	-0.0129	-0.0138	-0.0077	-0.0087	-0.0130	-0.0132
	(-1.057)	(-1.195)	(-0.632)	(-0.737)	(-1.083)	(-1.096)
Lignite Production Per Capita	0.0187	0.0103	0.0204	0.0213	0.0166	0.0152
	(1.124)	(0.659)	(0.989)	(1.075)	(0.995)	(0.911)
Election Year	-18.897	-17.364	-16.146	-16.458	-17.392	-17.530
	(-23.00)	(-16.25)	(-22.84)	(-21.06)	(-21.86)	(-22.53)
Political Rights	0.2405	0.0466	0.1582	0.1863	0.1614	0.1333
	(1.273)	(0.194)	(0.663)	(0.831)	(0.736)	(0.576)
Liberal	-2.7945	-3.0209	-2.3447	-2.4249	-2.5816	-2.5405
	(-3.612)	(-4.293)	(-2.872)	(-2.941)	(-2.909)	(-2.856)
Conservative	-2.5271	-2.4973	-2.1388	-2.2501	-2.3536	-2.2888
	(-2.912)	(-2.913)	(-1.991)	(-2.190)	(-2.288)	(-2.254)
Eastern Europe	4.5312	5.0231	4.9363	4.8798	4.9163	4.9807
	(3.061)	(3.434)	(3.087)	(2.865)	(3.067)	(3.096)
Constant	-3.5043	-2.9769	-12.4557	-10.1678	-5.0863	-5.5036
	(-4.339)	(-4.398)	(-3.672)	(-2.793)	(-3.610)	(-3.497)
Duration dependence parameter			1.4648	1.2171	0.1519	0.1992
			(5.104)	(3.610)	(1.999)	(2.423)
N	597	597	597	597	597	597
ll	-54.146	-57.777	-50.576	-50.844	-53.274	-53.390
chi2	3014.713	494.610	2709.846	3774.537	2796.233	2221.950
aic	64.798	70.059	59.658	58.195	65.054	63.285

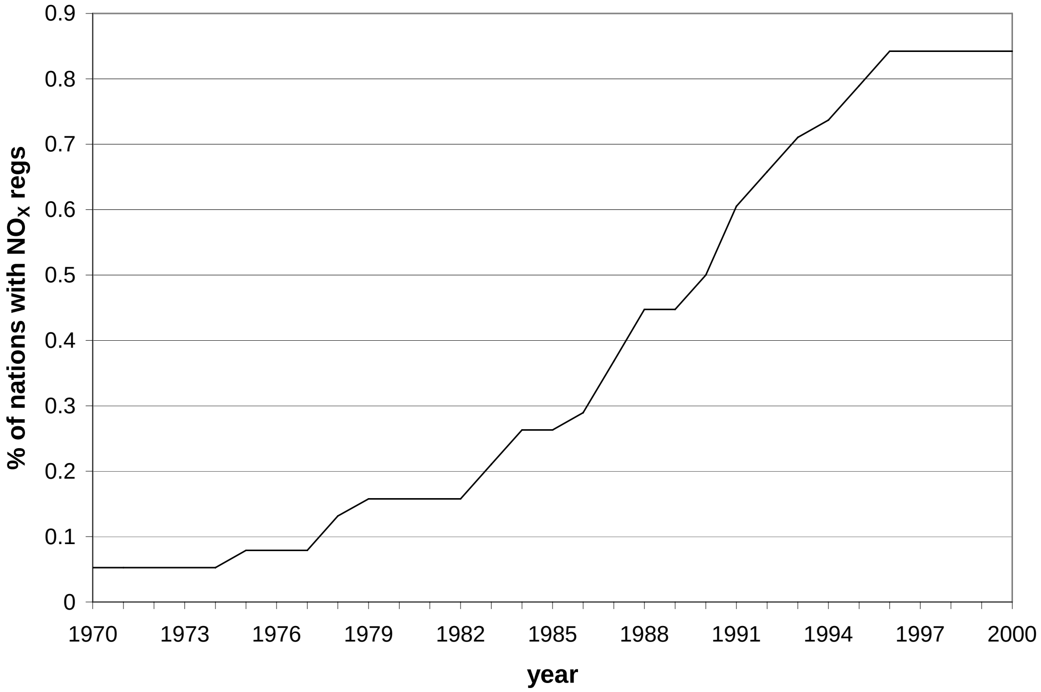
The table presents regression results using alternative baseline hazards. T-stats in parentheses.

Figure 1 – Adoption of Environmental Regulations Over Time

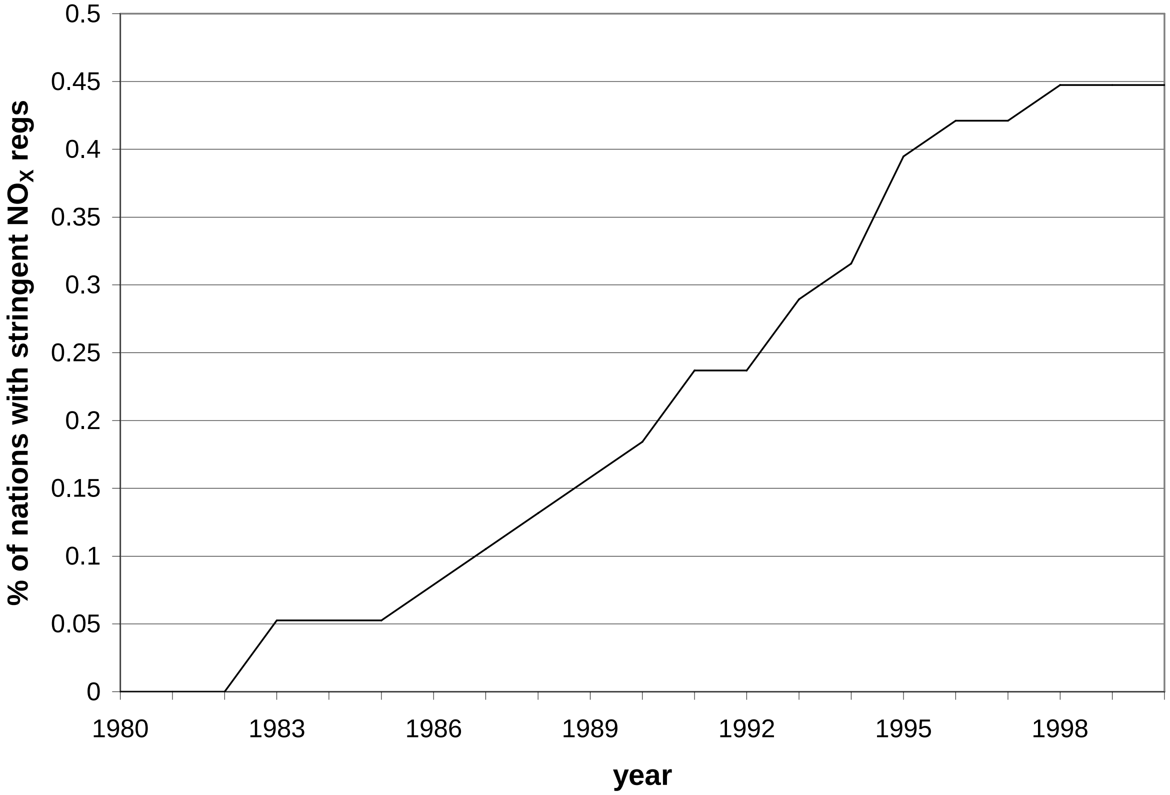
A. Sulfur Dioxide



B. Nitrogen Dioxide

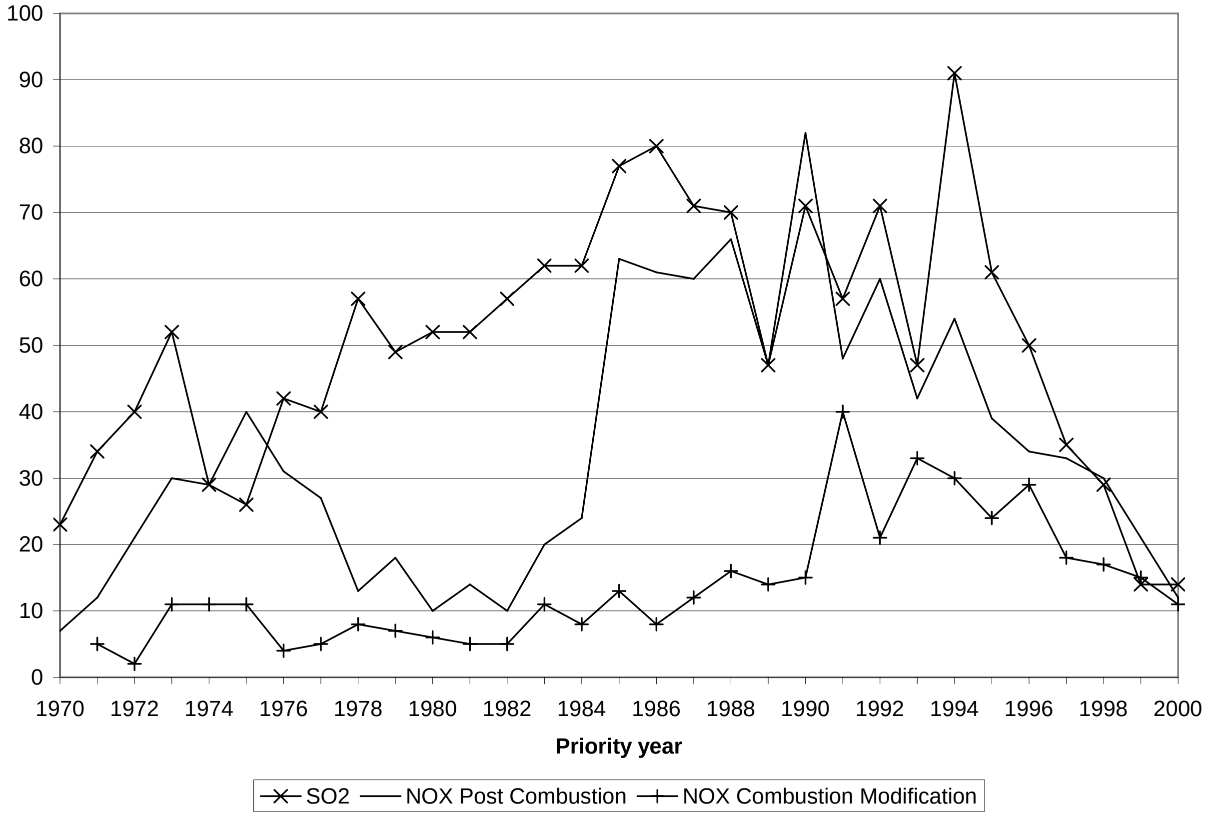


C. Stringent NO_X Regulations



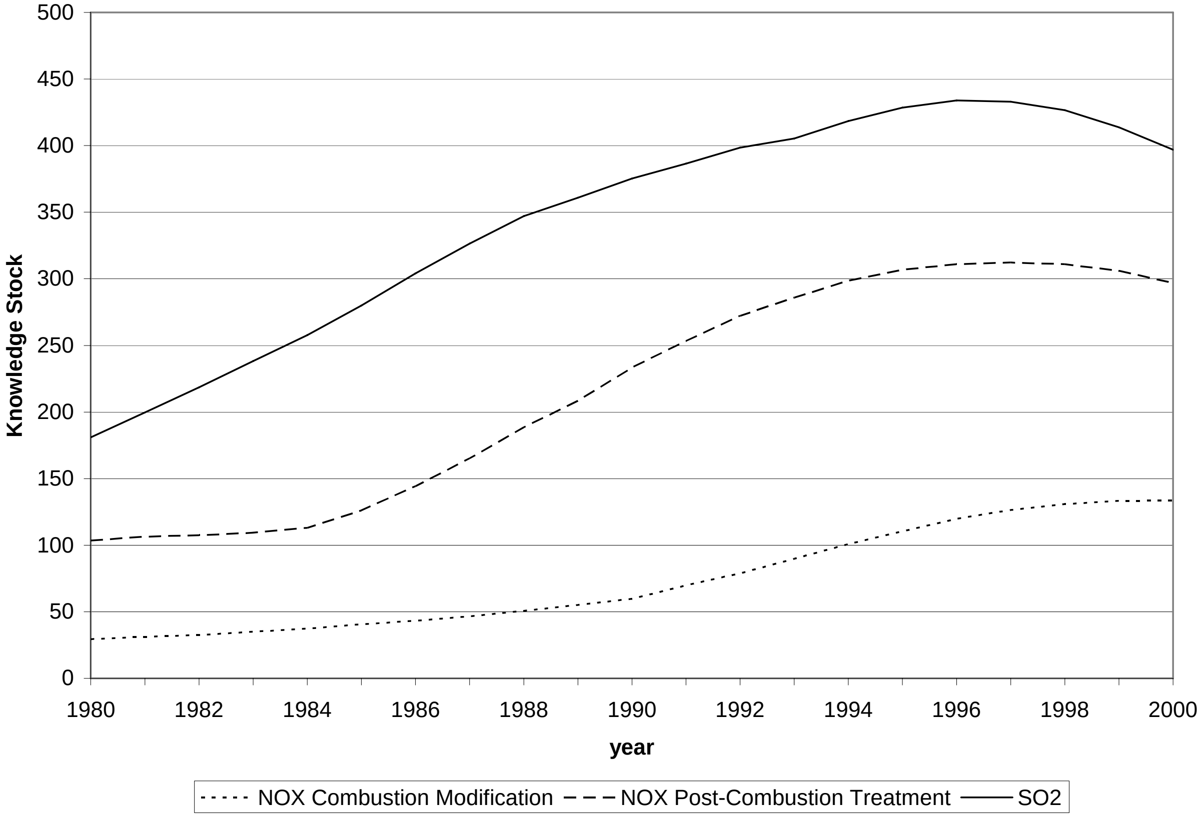
The figures show the cumulative percentage of countries that have adopted each regulation by the year on the *x*-axis. In each case, note the S-shaped diffusion pattern that is typical for studies of technology adoption. Note also that adoption of stringent NO_X regulations has, to date, leveled off with fewer countries adopting than for the other regulations.

Figure 2 – U.S. Pollution Control Patents



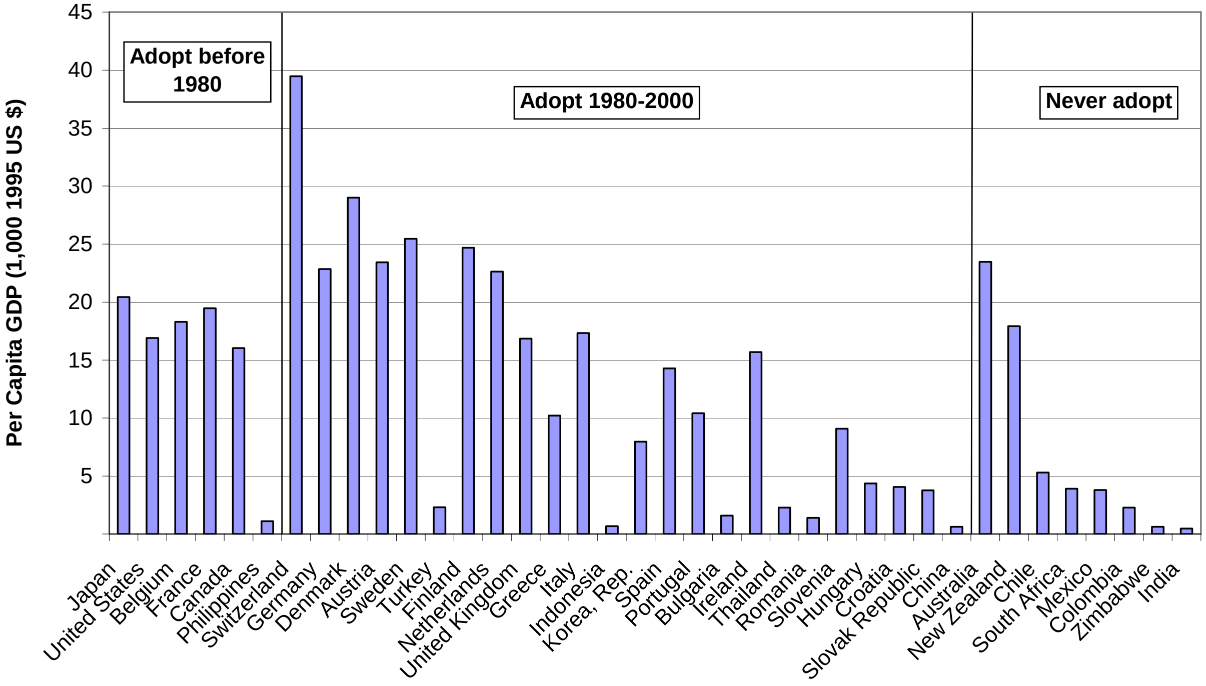
The figure shows patents granted in the U.S. with at least one foreign patent family member for each of three pollution control technologies.

Figure 3 – Knowledge Stocks



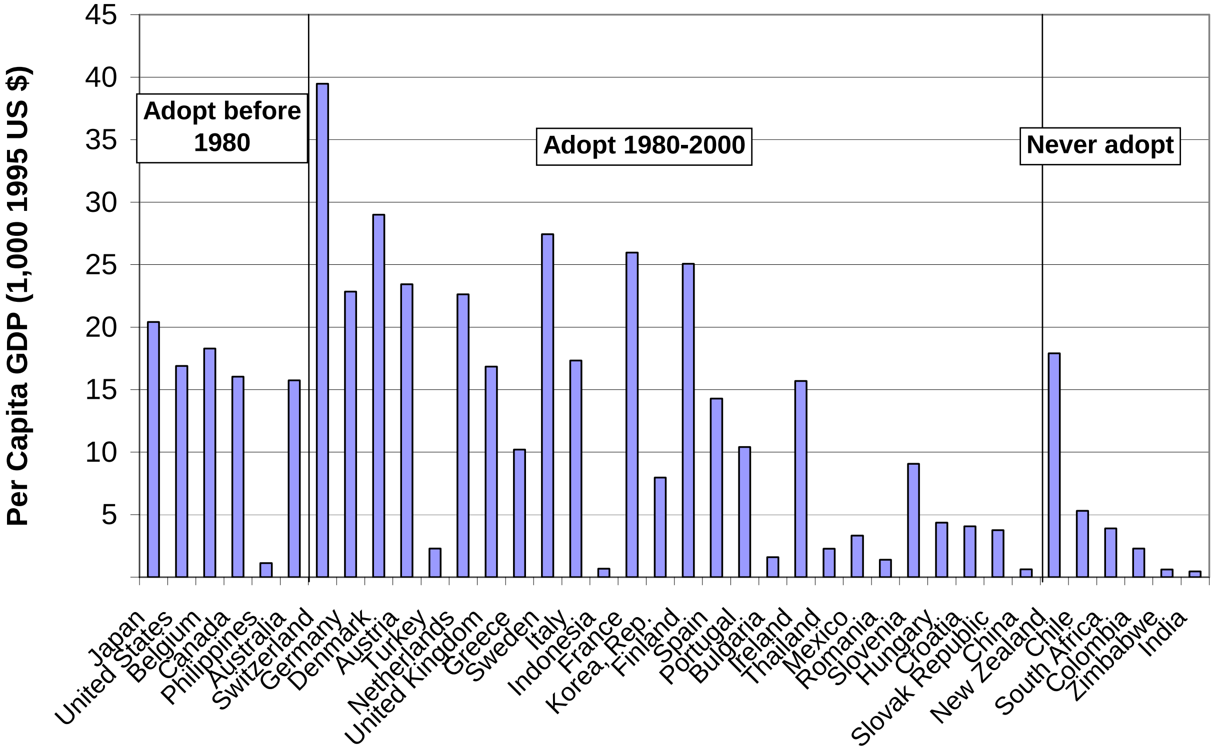
The figure shows the value of the knowledge stocks constructed for this paper for each of the three technologies. Note that the value of the stock for SO_2 progresses rather smoothly through time, whereas both NO_X technologies experience periods of growth after major environmental regulations.

Figure 4 – Per Capita GDP in the Year of Adoption: SO_2



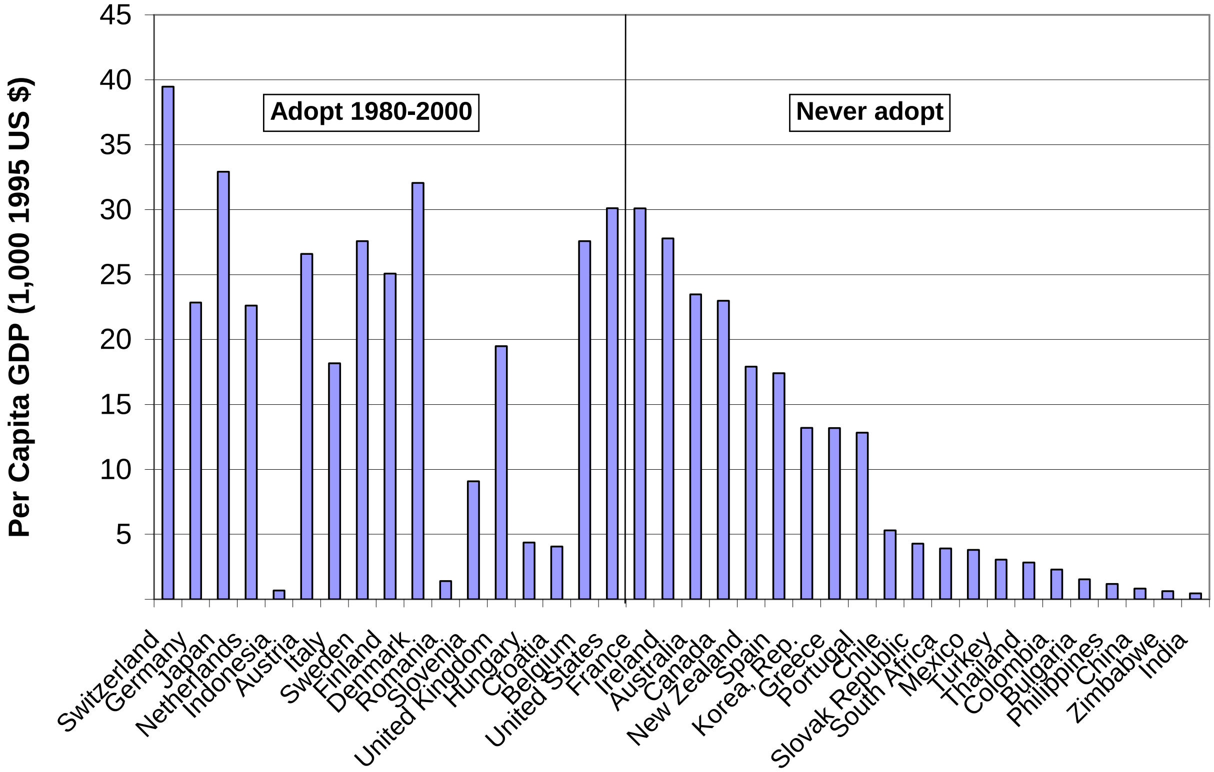
The figure shows the per capita GDP (in constant 1995 U.S. dollars) of each country in the year in which it adopts SO_2 regulations for coal-fired power plants. Countries are sorted from left to right along the *x*-axis by the order in which regulations were enacted. The first two countries, Japan and the U.S., enacted regulations in 1970. Three groups are presented. The first six countries adopted regulations before 1980, and are thus not included in the regressions that follow. The last eight countries never adopt regulation. With the exception of Australia and New Zealand, who have stocks of relatively clean coal, these are all low income countries. The remaining countries adopt during the time frame used in the regression for SO_2 (1980-2000).

Figure 5 – Per Capita GDP in the Year of Adoption: NO_X



The figure shows the per capita GDP (in constant 1995 U.S. dollars) of each country in the year in which it adopts NO_X regulations for coal-fired power plants. Countries are sorted from left to right along the *x*-axis by the order in which regulations were enacted. The first two countries, Japan and the U.S., enacted regulations in 1970. Three groups are presented. The first six countries adopted regulations before 1980, and are thus not included in the regressions that follow. The last six countries never adopt regulation. With the exception of New Zealand, who has a stock of relatively clean coal, these are all low income countries. The remaining countries adopt during the time frame used in the regression for NO_X (1980-2000).

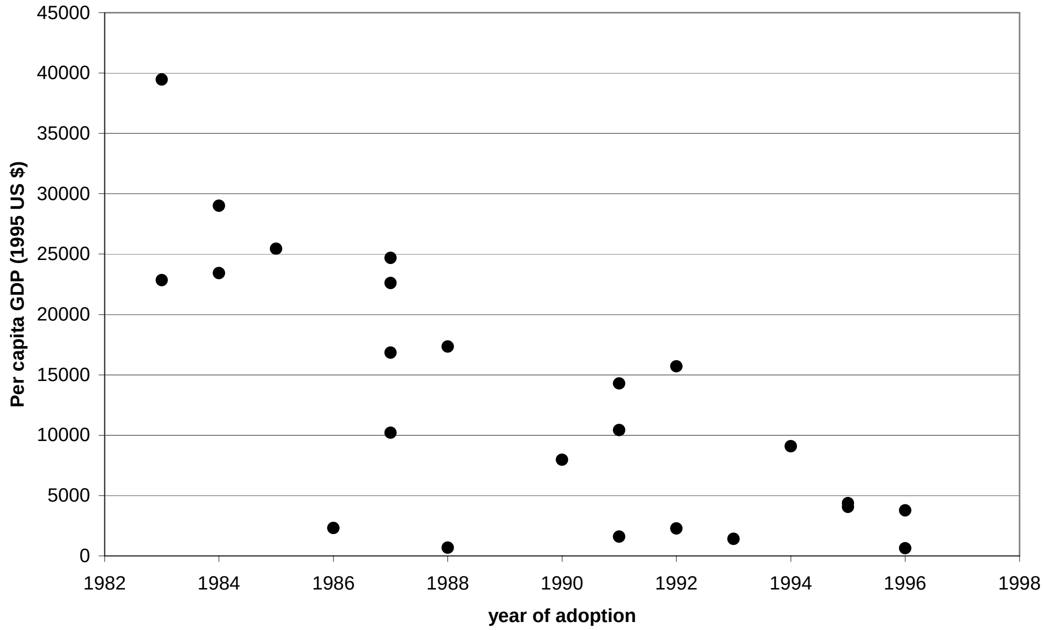
Figure 6 – Per Capita GDP in the Year of Adoption: Stringent NO_X Regulations



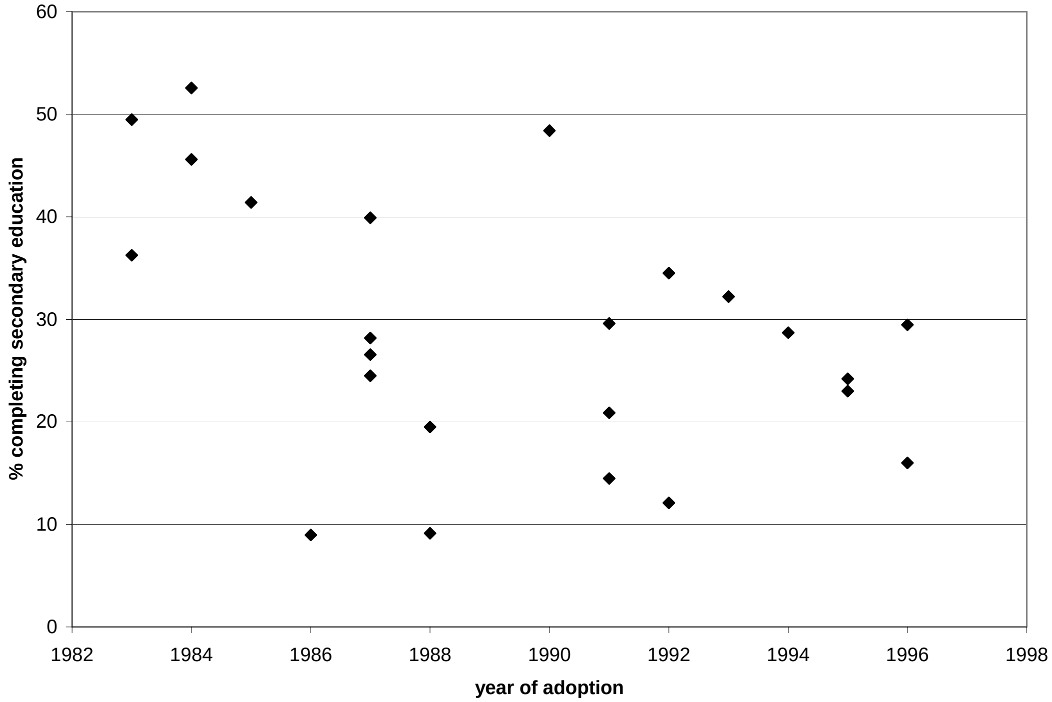
The figure shows the per capita GDP (in constant 1995 U.S. dollars) of each country in the year in which it adopts stringent NO_X regulations for coal-fired power plants. Countries are sorted from left to right along the *x*-axis by the order in which regulations were enacted. Two groups are presented. Those on the left are countries that adopt stringent NO_X regulations between 1980 and 2000. The first country two countries, Switzerland and Germany, adopt in 1983. Those countries on the right have not adopted stringent NO_X regulations as of 2000.

Figure 7 – Scatter Plots

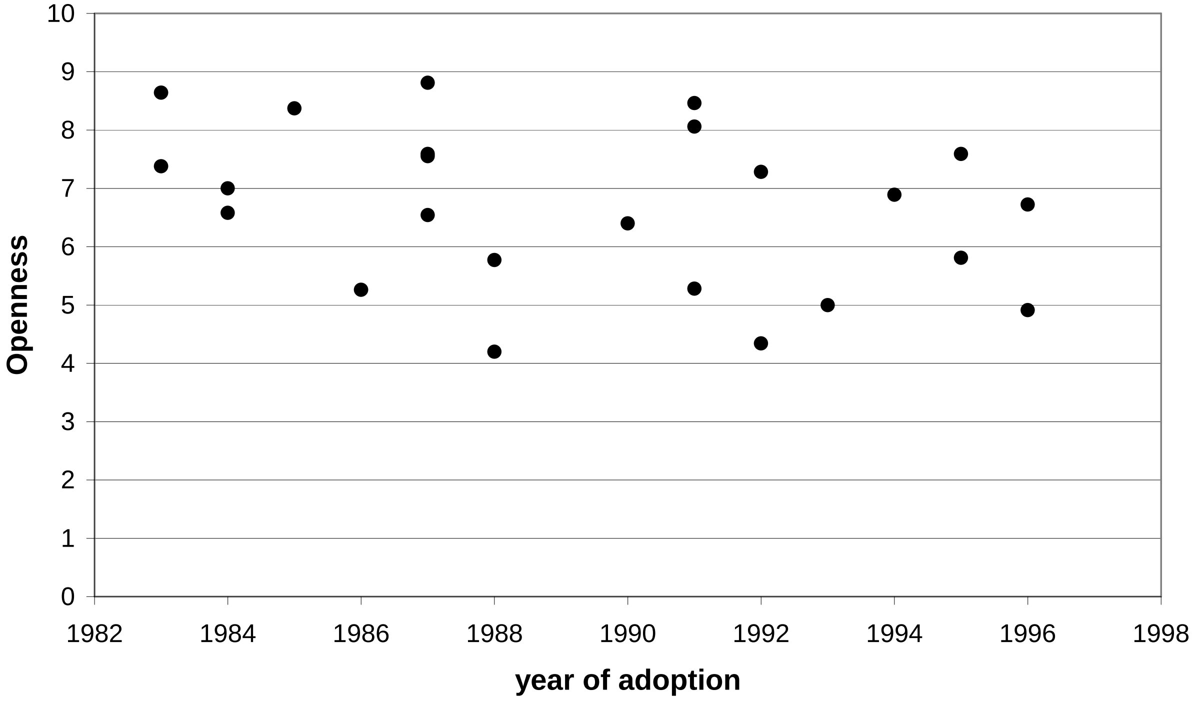
A. Correlation Between Income and Adoption



B. Correlation Between Education and Adoption



C. Correlation Between Openness and Adoption



The figures show the correlation between the year of adoption and various explanatory variables for those countries that adopt regulation between 1980 and 2000. Countries with higher incomes and more people with high school educations adopt regulation faster. There is no strong relationship between openness and adoption.

Appendix A – European Classifications (ECLA) for Pollution Control Patents

I. Nitrogen Dioxide pollution control

Combustion Modification

F23C 6/04B	MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING ENGINES OR PUMPS/COMBUSTION APPARATUS; COMBUSTION PROCESSES/COMBUSTION APPARATUS USING FLUENT FUEL/Combustion apparatus characterised by the combination of two or more combustion chambers/in series connection/[N: with staged combustion in a single enclosure]
F23C 6/04B1	MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING ENGINES OR PUMPS/COMBUSTION APPARATUS; COMBUSTION PROCESSES/COMBUSTION APPARATUS USING FLUENT FUEL/Combustion apparatus characterised by the combination of two or more combustion chambers/in series connection/[N: with staged combustion in a single enclosure]/ [N: with fuel supply in stages]
F23C 9	MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING ENGINES OR PUMPS/COMBUSTION APPARATUS; COMBUSTION PROCESSES/COMBUSTION APPARATUS USING FLUENT FUEL/Combustion apparatus with arrangements for recycling or recirculating combustion products or flue gases

Post-Combustion

B01D 53/56	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/Removing components of defined structure/Nitrogen compounds/Nitrogen oxides
B01D 53/56D	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/Removing components of defined structure/Nitrogen compounds/Nitrogen oxides/[N: by treating the gases with solids]

B01D 53/60	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/Removing components of defined structure/Simultaneously removing sulfur oxides and nitrogen oxides
B01D 53/86F2	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/General processes for purification of waste gases; Apparatus or devices specially adapted therefore/Catalytic processes/ N: Removing nitrogen compounds]/[N: Nitrogen oxides]/
B01D 53/86F2C	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/General processes for purification of waste gases; Apparatus or devices specially adapted therefore/Catalytic processes/ N: Removing nitrogen compounds]/[N: Nitrogen oxides]/[N: Processes characterised by a specific catalyst]
B01D 53/86F2D	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/General processes for purification of waste gases; Apparatus or devices specially adapted therefore/Catalytic processes/ N: Removing nitrogen compounds]/[N: Nitrogen oxides [N: Processes characterised by a specific device]
B01D 53/86G	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/General processes for purification of waste gases; Apparatus or devices specially adapted therefore/Catalytic processes/ [N: Simultaneously removing sulfur oxides and nitrogen oxides]

B01J 29/06D2E	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ CHEMICAL OR PHYSICAL PROCESSES, e.g. CATALYSIS, COLLOID CHEMISTRY; THEIR RELEVANT APPARATUS/ Catalysts comprising molecular sieves/ having base-exchange properties, e.g. crystalline zeolites/ Crystalline aluminosilicate zeolites; Isomorphous compounds thereof/ [N: containing metallic elements added to the zeolite]/ [N: containing iron group metals, noble metals or copper]/ [N: Iron group metals or copper]

II. Sulfur Dioxide pollution control

Sulfur dioxide pollution control techniques

B01D 53/14H8	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/ by absorption/ [N: Gases containing acid components]/ [N: containing only sulfur dioxide or sulfur trioxide]
B01D 53/50	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/Removing components of defined structure/Sulfur compounds/Sulfur oxides Includes 50B, 50B2, 50B4, 50B6, 50C, 50D
B01D 53/86B4	PERFORMING OPERATIONS; TRANSPORTING/ PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL/ SEPARATION/ Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols/Chemical or biological purification of waste gases/General processes for purification of waste gases; Apparatus or devices specially adapted therefore/Catalytic processes/ [N: Removing sulfur compounds]/ [N: Sulfur oxides]

Fluidized bed combustion

F23C 10	MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING ENGINES OR PUMPS/COMBUSTION APPARATUS; COMBUSTION PROCESSES/COMBUSTION APPARATUS USING FLUENT FUEL/ Fluidised bed combustion apparatus

Appendix B – Knowledge Stock Sensitivity Analysis

In this appendix, we examine the sensitivity of the regression results to changes in the rates of decay and diffusion used to calculate the knowledge stock. In addition to the base rates of decay = 0.1 and diffusion = 0.25, we consider three alternative sets of decay and diffusion rates. To aid in interpreting these rates, we note the number of years it takes for a patent to have its maximum effect on the stock under each set of assumptions. For comparison, patents have their maximum effect after 4 years using the base rates.

- decay = 0.25, diffuse = 0.5 (peak = 1 year)
- decay = 0.05, diffuse = 0.5 (peak = 4 years)
- decay = 0.05, diffuse = 0.1 (peak = 10 years)

Tables B1 – B3 present regression results for each decay/diffusion combination for each of the three baseline hazards. Table B1 presents these results for adoption of SO_2 regulation. Table B2 presents results for adoption of NO_X regulation, and table B3 for adoption of stringent NO_X regulation. As discussed in the text, estimation of the direct effect of knowledge is difficult, as it cannot be separately identified from any baseline hazard effects. Thus, estimates of the direct effect vary across specification. However, estimation of the interaction effect of knowledge and the openness variables is consistent both across decay/diffusion rate combinations and across baseline hazard specifications. The one exception is for SO_2 adoption with slow diffusion (decay = 0.05 & diffusion = 0.1). Here, the interacted effect of knowledge and import shares is lower. However, the effect of knowledge with this specification occurs more slowly than is usually assumed in the technological change literature. Supporting this, note that the log-likelihood for this combination is higher, suggesting that this combination is not a good fit for the data.

Turning to other variables, there are also few changes in the main results. The only change across decay/diffusion combinations is on the effect of education. Most notably, note that while the magnitude of the effect of secondary education is consistent across specifications, it is sometimes significant and sometimes insignificant. Similarly, the significance of the negative effect on post-secondary education also varies across specifications. The effects of other variables, such as GDP, coal production, and the Eastern European dummy, remain the same across specifications.

Table B1 – Adoption of SO_2 Regulations: Sensitivity to Decay Rates

Variable	*Exponential*				*Weibull*				*Gompertz*			
	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1
Knowledge Stock	1.1108	1.6331	0.8892	0.5513	-0.9299	0.8908	-3.8417	-3.7386	0.7150	1.4520	0.3690	-1.5600
	(3.668)	(5.203)	(3.328)	(3.244)	(-1.728)	(2.942)	(-2.550)	(-4.396)	(2.665)	(3.836)	(1.528)	(-2.937)
Knowledge*Import Shares	0.1092	0.1523	0.0911	0.0643	0.1017	0.0512	0.1347	0.0974	0.0889	0.0427	0.0731	0.0536
	(1.793)	(1.502)	(2.225)	(2.515)	(2.608)	(0.616)	(2.603)	(2.685)	(2.055)	(0.514)	(2.386)	(2.691)
Knowledge*Trade Policy	0.0163	-0.1215	0.0263	0.0210	0.0597	-0.0922	0.0107	-0.0978	0.0674	-0.0076	0.0583	0.0400
	(0.163)	(-0.865)	(0.336)	(0.425)	(0.442)	(-0.986)	(0.093)	(-0.857)	(0.602)	(-0.065)	(0.687)	(0.684)
Import Shares	-0.2183	-0.2529	-0.2000	-0.1785	-0.1202	-0.0401	-0.1098	-0.0035	-0.1516	-0.0471	-0.1355	-0.0900
	(-1.687)	(-1.709)	(-2.010)	(-2.331)	(-1.632)	(-0.341)	(-1.469)	(-0.044)	(-1.577)	(-0.399)	(-1.761)	(-1.373)
Trade Policy	0.1461	0.2160	0.2132	0.3275	0.0919	-0.2270	0.2702	-0.1868	0.0538	-0.2293	0.1578	0.3888
	(0.618)	(0.999)	(0.932)	(1.317)	(0.386)	(-1.119)	(0.862)	(-0.663)	(0.247)	(-1.146)	(0.686)	(1.026)
GDP Per Capita	0.2933	0.1881	0.2685	0.2092	0.3277	0.4235	0.2787	0.4258	0.3324	0.3792	0.2845	0.1734
	(4.024)	(3.817)	(3.892)	(3.768)	(2.610)	(3.817)	(2.233)	(2.722)	(3.331)	(4.008)	(3.096)	(1.640)
% complete Post Second. Ed.	-0.2754	-0.2832	-0.2729	-0.2402	-0.3784	-0.4675	-0.4589	-0.6197	-0.3106	-0.4225	-0.2906	-0.2827
	(-1.180)	(-1.547)	(-1.164)	(-1.083)	(-1.699)	(-2.368)	(-1.746)	(-2.034)	(-1.420)	(-2.245)	(-1.330)	(-1.178)
% complete Secondary Ed.	0.1793	0.2676	0.1739	0.1593	0.2002	0.2634	0.2970	0.4289	0.1544	0.2486	0.1413	0.1513
	(1.224)	(2.080)	(1.267)	(1.313)	(1.482)	(1.678)	(2.315)	(2.560)	(1.139)	(1.651)	(1.086)	(1.014)
Population Density	0.0684	0.0307	0.0759	0.0835	0.0631	0.0181	0.0681	0.0414	0.0689	0.0199	0.0737	0.0762
	(2.200)	(1.528)	(2.390)	(2.622)	(1.585)	(0.731)	(2.036)	(1.107)	(1.953)	(0.800)	(1.988)	(1.618)
% Urban Population	0.0630	0.0035	0.0422	0.0089	0.1031	0.1830	0.0400	0.0764	0.0829	0.1388	0.0534	-0.0023
	(0.460)	(0.023)	(0.323)	(0.072)	(0.663)	(0.867)	(0.288)	(0.265)	(0.607)	(0.728)	(0.416)	(-0.018)
% Electricity from Coal	0.0631	0.0642	0.0684	0.0755	0.0484	0.0312	0.0545	0.0410	0.0543	0.0358	0.0624	0.0813
	(1.311)	(1.242)	(1.484)	(1.658)	(0.948)	(0.545)	(0.897)	(0.466)	(1.168)	(0.655)	(1.315)	(1.311)
Coal Production Per Capita	-0.1766	-0.0784	-0.1862	-0.1895	-0.1479	-0.0919	-0.1285	-0.0498	-0.1795	-0.0936	-0.1828	-0.1822
	(-2.361)	(-2.329)	(-2.381)	(-2.296)	(-1.824)	(-2.086)	(-1.659)	(-1.872)	(-2.220)	(-1.934)	(-2.164)	(-1.835)
Lignite Production Per Capita	0.0687	0.0404	0.0687	0.0645	0.0691	0.0749	0.0634	0.0723	0.0741	0.0691	0.0704	0.0616
	(2.709)	(4.615)	(2.545)	(2.353)	(2.452)	(3.664)	(2.582)	(4.037)	(2.447)	(3.523)	(2.304)	(1.908)
Election Year	-17.504	-18.518	-17.424	-17.585	-18.165	-17.307	-17.618	-15.954	-18.623	-18.121	-17.849	-18.058
	(-17.894)	(-19.067)	(-18.335)	(-18.709)	(-31.281)	(-22.093)	(-26.155)	(-20.775)	(-22.996)	(-21.152)	(-23.766)	(-29.474)
Political Rights	0.1858	-0.0790	0.1587	0.1049	0.1668	-0.0386	0.0865	0.0939	0.1872	-0.0445	0.1329	-0.0012
	(0.887)	(-0.491)	(0.791)	(0.550)	(0.509)	(-0.272)	(0.228)	(0.379)	(0.863)	(-0.317)	(0.611)	(-0.005)
Liberal	-0.9173	-0.6729	-1.0904	-1.2723	-0.7828	-0.0438	-1.0662	-0.0891	-0.7995	-0.2837	-1.0003	-1.3220
	(-1.749)	(-1.221)	(-2.253)	(-2.680)	(-1.439)	(-0.064)	(-1.262)	(-0.114)	(-1.655)	(-0.497)	(-2.190)	(-2.493)
Conservative	-0.2885	-0.1834	-0.4775	-0.6906	-0.5607	0.6713	-0.5439	1.0427	-0.3409	0.4266	-0.5532	-0.9252
	(-0.515)	(-0.335)	(-0.894)	(-1.300)	(-1.038)	(0.933)	(-0.807)	(1.014)	(-0.655)	(0.714)	(-1.106)	(-1.543)
Eastern Europe	0.5675	1.4019	0.7600	1.0162	1.5653	0.7321	2.4290	1.1628	0.9594	0.8536	1.2389	2.2484
	(0.660)	(1.616)	(0.883)	(1.197)	(1.331)	(0.754)	(1.784)	(1.008)	(1.019)	(0.889)	(1.261)	(1.722)
Constant	-3.1664	-3.3889	-2.9374	-2.6603	-21.0711	-16.6253	-49.3405	-69.3106	-5.2364	-7.6514	-5.4562	-15.6398
	(-2.860)	(-3.593)	(-2.790)	(-2.810)	(-3.712)	(-3.096)	(-3.306)	(-4.856)	(-2.861)	(-3.307)	(-3.102)	(-3.523)
Duration dependence parameter					2.1213	1.8172	3.0276	3.3577	0.2013	0.4029	0.2482	1.2317
					(8.633)	(5.996)	(9.897)	(16.831)	(2.275)	(2.829)	(2.593)	(3.447)
N	369	369	369	369	369	369	369	369	369	369	369	369
ll	-62.542	-61.686	-63.642	-66.264	-52.280	-51.851	-43.076	-34.712	-60.478	-54.166	-61.538	-58.217
chi2	543.749	549.207	540.086	526.521	1550.716	802.387	1621.275	1602.726	828.282	632.853	867.415	1692.045
aic	55.118	53.406	57.318	62.563	36.596	35.737	18.187	1.459	52.991	40.367	55.111	48.469

Table B2 – Adoption of NO_X Regulations: Sensitivity to Decay Rates

	Exponential				*Weibull*				*Gompertz*			
Variable	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1
Knowledge Stock	0.2778	0.3485	0.2811	0.2509	-0.2507	-0.0927	-0.2683	-0.3337	-1.0374	-0.2127	-1.1344	-1.4660
	(2.669)	(2.711)	(2.702)	(2.813)	(-1.317)	(-0.501)	(-1.400)	(-1.649)	(-3.351)	(-0.938)	(-3.492)	(-3.014)
Knowledge*Import Shares	0.0327	0.0339	0.0323	0.0315	0.0241	0.0200	0.0240	0.0265	0.0302	0.0268	0.0294	0.0344
	(2.980)	(2.471)	(2.961)	(3.084)	(1.694)	(1.565)	(1.682)	(1.675)	(1.924)	(2.213)	(1.841)	(1.381)
Knowledge*Trade Policy	0.0190	0.0218	0.0201	0.0172	0.0255	0.0375	0.0232	0.0149	0.0283	0.0411	0.0261	0.0064
	(0.641)	(0.600)	(0.683)	(0.700)	(0.526)	(0.695)	(0.481)	(0.313)	(0.562)	(0.835)	(0.518)	(0.094)
Import Shares	-0.1294	-0.1531	-0.1281	-0.1194	0.0740	0.0400	0.0738	0.0848	0.0918	-0.0238	0.0933	0.1153
	(-2.224)	(-2.125)	(-2.211)	(-2.193)	(1.121)	(0.663)	(1.097)	(1.249)	(1.459)	(-0.578)	(1.420)	(1.520)
Trade Policy	0.5414	0.4708	0.5384	0.5483	0.0883	0.1711	0.0849	0.0508	0.1194	0.3707	0.1121	-0.0187
	(2.188)	(1.817)	(2.177)	(2.311)	(0.296)	(0.632)	(0.283)	(0.163)	(0.454)	(1.430)	(0.412)	(-0.057)
GDP Per Capita	0.0726	0.1264	0.0781	0.0624	0.1682	0.1757	0.1666	0.1656	0.1606	0.1459	0.1606	0.1866
	(1.440)	(1.951)	(1.531)	(1.297)	(2.442)	(2.308)	(2.410)	(2.433)	(2.145)	(2.046)	(2.104)	(2.237)
% complete Post Second. Ed.	-0.2251	-0.2274	-0.2342	-0.2355	-0.4251	-0.4377	-0.4237	-0.4085	-0.4296	-0.3706	-0.4315	-0.3877
	(-1.143)	(-0.992)	(-1.175)	(-1.254)	(-1.747)	(-1.841)	(-1.729)	(-1.704)	(-1.721)	(-1.778)	(-1.683)	(-1.421)
% complete Secondary Ed.	0.1589	0.1195	0.1583	0.1703	0.1953	0.2062	0.1959	0.1875	0.1831	0.1768	0.1838	0.1335
	(1.835)	(1.130)	(1.826)	(2.055)	(1.620)	(2.015)	(1.603)	(1.434)	(1.518)	(2.091)	(1.465)	(0.775)
Population Density	0.0988	0.1080	0.1001	0.0970	0.0813	0.0876	0.0809	0.0781	0.0839	0.0902	0.0840	0.0835
	(3.824)	(3.322)	(3.800)	(3.977)	(2.465)	(2.518)	(2.460)	(2.364)	(2.506)	(2.716)	(2.474)	(2.166)
% Urban Population	0.0075	0.0722	0.0137	-0.0014	0.1790	0.1713	0.1785	0.1842	0.1836	0.1289	0.1825	0.2310
	(0.067)	(0.567)	(0.120)	(-0.013)	(0.476)	(0.552)	(0.467)	(0.456)	(0.504)	(0.828)	(0.476)	(0.494)
% Electricity from Coal	0.0749	0.0670	0.0749	0.0770	0.0424	0.0442	0.0421	0.0373	0.0556	0.0587	0.0551	0.0412
	(1.654)	(1.297)	(1.622)	(1.731)	(0.325)	(0.385)	(0.317)	(0.266)	(0.444)	(0.831)	(0.419)	(0.253)
Coal Production Per Capita	-0.1813	-0.2083	-0.1846	-0.1781	-0.0774	-0.1052	-0.0748	-0.0671	-0.0990	-0.1660	-0.0932	-0.0807
	(-2.170)	(-2.163)	(-2.172)	(-2.175)	(-1.031)	(-1.267)	(-1.004)	(-0.919)	(-1.136)	(-1.816)	(-1.081)	(-0.900)
Lignite Production Per Capita	0.0590	0.0700	0.0603	0.0575	0.0665	0.0697	0.0661	0.0656	0.0670	0.0692	0.0666	0.0717
	(2.159)	(2.121)	(2.159)	(2.186)	(2.658)	(2.159)	(2.704)	(2.858)	(2.251)	(2.045)	(2.300)	(2.439)
Election Year	-18.414	-16.540	-16.547	-17.525	-17.658	-19.677	-18.806	-18.519	-17.952	-18.488	-17.922	-17.412
	(-20.516)	(-18.706)	(-18.537)	(-19.793)	(-26.371)	(-25.098)	(-28.111)	(-28.983)	(-23.614)	(-21.937)	(-23.279)	(-24.626)
Political Rights	0.1313	0.2542	0.1361	0.0932	0.0708	0.1388	0.0685	0.0612	0.0582	0.1554	0.0532	0.0975
	(0.787)	(1.275)	(0.810)	(0.579)	(0.365)	(0.609)	(0.352)	(0.319)	(0.286)	(0.563)	(0.262)	(0.460)
Liberal	-1.1908	-1.1573	-1.1808	-1.1613	-0.6896	-0.7756	-0.6930	-0.6611	-0.6354	-1.0532	-0.6481	-0.5616
	(-2.805)	(-2.643)	(-2.803)	(-2.755)	(-1.113)	(-1.416)	(-1.098)	(-0.975)	(-0.978)	(-2.164)	(-0.953)	(-0.641)
Conservative	-1.0334	-0.9347	-1.0264	-1.0192	-0.5795	-0.7907	-0.5798	-0.5201	-0.5338	-1.1123	-0.5397	-0.3094
	(-1.633)	(-1.550)	(-1.645)	(-1.631)	(-0.731)	(-1.223)	(-0.716)	(-0.601)	(-0.638)	(-2.008)	(-0.611)	(-0.291)
Eastern Europe	0.8716	0.1916	0.8750	1.0878	0.2099	0.4188	0.2129	0.0417	0.7986	1.2138	0.8074	-0.0330
	(0.972)	(0.187)	(0.965)	(1.236)	(0.172)	(0.325)	(0.173)	(0.033)	(0.682)	(0.962)	(0.668)	(-0.023)
Constant	-2.6739	-3.0856	-2.7091	-2.6336	-17.9660	-15.0054	-18.3826	-19.5987	-17.0575	-8.4130	-18.2946	-22.5101
	(-2.704)	(-2.649)	(-2.696)	(-2.697)	(-3.925)	(-4.477)	(-3.870)	(-3.806)	(-4.924)	(-3.876)	(-4.850)	(-4.056)
Duration dependence parameter					1.9399	1.7449	1.9648	2.0307	1.2898	0.5203	1.4054	1.7634
					(7.418)	(8.109)	(7.385)	(7.439)	(4.613)	(3.825)	(4.532)	(3.607)
N	359	359	359	359	359	359	359	359	359	359	359	359
ll	-74.714	-73.088	-74.476	-74.941	-57.880	-59.496	-57.729	-57.031	-54.561	-63.835	-53.653	-49.678
chi2	554.419	590.441	460.874	515.074	1055.394	908.680	1189.653	1276.057	969.965	735.569	937.694	946.795
aic	67.768	64.515	67.290	68.222	36.100	39.331	35.797	34.401	29.460	48.008	27.645	19.694

Table B3 – Adoption of Stringent NO_X Regulations: Sensitivity to Decay Rates

	Exponential				*Weibull*				*Gompertz*			
Variable	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.5 Diff.=0.5	Decay=0.5 Diff.=0.1
Knowledge Stock	0.3226	0.3329	0.2978	0.2265	-0.1917	0.1663	-0.4895	-0.8722	0.1043	0.2412	-0.0133	-1.5754
	(2.120)	(3.760)	(2.066)	(1.902)	(-0.783)	(1.419)	(-1.418)	(-1.730)	(0.709)	(2.420)	(-0.081)	(-2.489)
Knowledge*Import Shares	0.0080	0.0064	0.0049	-0.0009	0.0038	0.0083	-0.0019	-0.0036	0.0059	0.0085	0.0007	-0.0135
	(0.383)	(0.561)	(0.256)	(-0.066)	(0.142)	(0.678)	(-0.077)	(-0.182)	(0.273)	(0.719)	(0.035)	(-0.779)
Knowledge*Trade Policy	-0.0528	-0.0270	-0.0506	-0.0391	-0.0729	-0.0263	-0.0712	-0.0450	-0.0637	-0.0252	-0.0585	-0.0482
	(-0.637)	(-0.510)	(-0.673)	(-0.692)	(-0.775)	(-0.425)	(-0.830)	(-0.578)	(-0.739)	(-0.432)	(-0.777)	(-0.799)
Import Shares	-0.1941	-0.1679	-0.1897	-0.1795	-0.1571	-0.1506	-0.1392	-0.0969	-0.1848	-0.1640	-0.1742	-0.1292
	(-2.259)	(-2.466)	(-2.223)	(-2.296)	(-1.746)	(-2.260)	(-1.578)	(-1.159)	(-2.091)	(-2.482)	(-1.962)	(-1.416)
Trade Policy	0.4599	0.5163	0.4399	0.4004	0.4278	0.4452	0.4196	0.5176	0.3954	0.4308	0.3528	0.2956
	(1.350)	(1.773)	(1.316)	(1.327)	(1.233)	(1.437)	(1.320)	(1.872)	(1.107)	(1.328)	(1.000)	(0.973)
GDP Per Capita	0.3313	0.3116	0.3330	0.3285	0.3421	0.3471	0.3557	0.4218	0.3354	0.3433	0.3365	0.3407
	(3.588)	(5.826)	(3.533)	(3.288)	(3.207)	(5.422)	(3.243)	(3.210)	(3.301)	(5.495)	(3.239)	(3.059)
% complete Post Second. Ed.	-0.0189	-0.0179	-0.0160	-0.0104	-0.0597	-0.0726	-0.0603	-0.0705	-0.0268	-0.0520	-0.0225	-0.0321
	(-0.181)	(-0.205)	(-0.159)	(-0.119)	(-0.361)	(-0.475)	(-0.394)	(-0.590)	(-0.219)	(-0.423)	(-0.195)	(-0.244)
% complete Secondary Ed.	-0.1304	-0.0811	-0.1365	-0.1406	-0.0844	-0.0532	-0.0712	-0.0167	-0.1363	-0.0792	-0.1416	-0.0889
	(-0.975)	(-0.814)	(-1.041)	(-1.124)	(-0.527)	(-0.412)	(-0.480)	(-0.154)	(-0.921)	(-0.665)	(-0.975)	(-0.631)
Population Density	0.0782	0.1017	0.0745	0.0642	0.0818	0.1145	0.0831	0.1381	0.0710	0.1086	0.0647	0.0558
	(2.206)	(2.783)	(2.160)	(1.959)	(2.658)	(2.610)	(2.919)	(3.380)	(2.040)	(2.504)	(1.908)	(1.946)
% Urban Population	-0.0655	-0.1769	-0.0556	-0.0391	-0.1374	-0.2443	-0.2014	-0.5123	-0.0423	-0.2088	-0.0342	-0.1596
	(-0.303)	(-1.002)	(-0.253)	(-0.169)	(-0.592)	(-1.377)	(-0.800)	(-1.464)	(-0.188)	(-1.243)	(-0.148)	(-0.602)
% Electricity from Coal	0.0408	0.0198	0.0422	0.0468	0.0328	0.0258	0.0267	0.0038	0.0465	0.0293	0.0473	0.0272
	(0.805)	(0.416)	(0.830)	(0.946)	(0.555)	(0.458)	(0.456)	(0.073)	(0.817)	(0.521)	(0.800)	(0.408)
Coal Production Per Capita	-0.0129	-0.0075	-0.0138	-0.0158	-0.0077	-0.0018	-0.0060	0.0078	-0.0130	-0.0044	-0.0139	-0.0113
	(-1.057)	(-0.587)	(-1.133)	(-1.309)	(-0.632)	(-0.154)	(-0.491)	(0.541)	(-1.083)	(-0.385)	(-1.141)	(-0.917)
Lignite Production Per Capita	0.0187	0.0225	0.0184	0.0166	0.0204	0.0209	0.0220	0.0291	0.0166	0.0201	0.0160	0.0201
	(1.124)	(1.372)	(1.107)	(1.004)	(0.989)	(1.115)	(1.004)	(1.229)	(0.995)	(1.156)	(0.941)	(0.885)
Election Year	-18.897	-17.660	-18.900	-17.845	-16.146	-18.560	-16.733	-19.163	-17.392	-17.702	-17.539	-17.753
	(-22.999)	(-23.429)	(-23.126)	(-20.800)	(-22.841)	(-25.999)	(-25.054)	(-26.313)	(-21.859)	(-23.485)	(-23.903)	(-29.444)
Political Rights	0.2405	0.2662	0.2217	0.1641	0.1582	0.2298	0.1264	0.2546	0.1614	0.2235	0.1161	-0.0585
	(1.273)	(1.194)	(1.178)	(0.835)	(0.663)	(0.975)	(0.495)	(1.031)	(0.736)	(0.968)	(0.492)	(-0.174)
Liberal	-2.7945	-2.7266	-2.8050	-2.9205	-2.3447	-2.4941	-2.3253	-2.2185	-2.5816	-2.5884	-2.5882	-2.6821
	(-3.612)	(-3.958)	(-3.536)	(-3.436)	(-2.872)	(-3.198)	(-2.993)	(-3.716)	(-2.909)	(-3.239)	(-2.802)	(-3.007)
Conservative	-2.5271	-2.4615	-2.5205	-2.5786	-2.1388	-2.2673	-2.1134	-2.0738	-2.3536	-2.3417	-2.3517	-2.2772
	(-2.912)	(-3.411)	(-2.811)	(-2.641)	(-1.991)	(-2.785)	(-1.937)	(-2.242)	(-2.288)	(-2.916)	(-2.152)	(-1.716)
Eastern Europe	4.5312	3.9599	4.6362	4.8732	4.9363	4.5464	5.1165	5.2508	4.9163	4.4935	5.0658	5.5441
	(3.061)	(2.857)	(2.999)	(2.870)	(3.087)	(3.176)	(3.043)	(3.189)	(3.067)	(3.091)	(3.016)	(2.811)
Constant	-3.5043	-3.6763	-3.4421	-3.1813	-12.4557	-7.9292	-17.6251	-28.4504	-5.0863	-5.0622	-5.6315	-18.1283
	(-4.339)	(-6.739)	(-4.097)	(-3.793)	(-3.672)	(-4.001)	(-3.216)	(-2.281)	(-3.610)	(-4.706)	(-3.966)	(-3.868)
Duration dependence parameter					1.4648	0.8980	1.8651	2.3652	0.1519	0.1213	0.2159	1.4041
					(5.104)	(3.577)	(5.435)	(5.142)	(1.999)	(1.872)	(2.398)	(3.043)
N	597	597	597	597	597	597	597	597	597	597	597	597
ll	-54.146	-53.486	-54.407	-55.299	-50.576	-50.851	-49.490	-46.514	-53.274	-51.957	-53.236	-48.098
chi2	3014.713	2226.196	2591.550	1398.053	2709.846	2833.520	2494.391	2570.382	2796.233	2732.026	2368.642	1688.947
aic	64.798	63.479	65.320	67.104	59.658	60.208	57.486	51.533	65.054	62.421	64.977	54.701