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TRADE, TECHNOLOGY, AND THE ENVIRONMENT:
WHY HAVE POOR COUNTRIES REGULATED SOONER?

Mary Lovely
David Popp

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ABSTRACT

Countries who adopted regulation of coal-fired power plants after 1980 generally did so at a much lower level of per-capita income than did early adopters – poor countries regulated sooner. This phenomenon suggests that pioneering adopters of environmental regulation provide an advantage to countries adopting these regulations later, presumably through advances in technology made by these first adopters. Focusing specifically on regulation of coal-fired power plants, we ask to what extent the availability of new technology influences the adoption of new environmental regulation. We build a general equilibrium model of an open economy to identify the political-economy determinants of the decision to regulate emissions. Using a newly-created data set of SO_2 and NO_X regulations for coal-fired power plants and a patent-based measure of the technology frontier, we test the model's predictions using a hazard regression of the diffusion of environmental regulation across countries. Our findings support the hypothesis that international economic integration eases access to environmentally friendly technologies and leads to earlier adoption, ceteris paribus, of regulation in developing countries. By limiting firms' ability to burden shift, however, openness may raise opposition to regulation. Our results suggest that domestic trade protection allows costs to be shifted to domestic consumers while large countries can shift costs to foreign consumers, raising the likelihood of adoption. Other political economy factors, such as the quality of domestic coal and election years, are also important determinants.

Mary Lovely
Syracuse University
The Maxwell School
110 Eggers
Syracuse, NY 13244
melovely@maxwell.syr.edu

David Popp
Syracuse University
The Maxwell School
426 Eggers
Syracuse, NY 13244-1020
and NBER
dcpopp@maxwell.syr.edu

With mounting environmental costs of economic growth, the world looks to technology for an exit ramp from what seems to be a crash course to ecological disaster. Indeed, China, a prominent example of break-neck growth amid rising domestic damage, recently held its first national conference on technology and the environment, declaring scientific innovation the key to "historic transformation of environmental protection" and "leap-frog development."[1,2] For China and other rapidly growing countries, technology seems to offer a panacea for the environmental problems accompanying their economic development.

If technology is a panacea, it is not a costless one. Installation and use of pollution-control technologies are costly and these technologies are rarely adopted without regulatory stimulus.[3] Thus, to understand the diffusion of costly pollution-control technologies, we need to understand the diffusion of regulation. In this paper, we examine the diffusion across countries of coal-fired power plant regulation. Not only is the diffusion of power plant regulation important in its own right, given the rapid construction of these plants across the developing world, its study illuminates the determinants of regulation adoption and thus offers useful lessons for promoting diffusion of other emission-control technologies.

The research question is motivated by two observations. First, the diffusion of air pollution-control technologies is strongly linked to changes in regulatory pressure. 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). This sequence reflects the earlier appearance in China of PM regulations than of NO_X and SO_2 controls.[4] Second, despite

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[1] For a description of the environmental costs of growth in China, see World Bank (2001).
[2] For a brief overview of the National Conference on Environmental Science and Technology, held August 18-19, 2006, see State Environmental Protection Agency (2007).
[3] 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).
[4] Data are taken from the CoalPower 4 database, the International Energy Agency (IEA) Coal Research Programme.

predictions of the environmental Kuznets curve literature, which suggests an inverted-U relationship between environmental performance and economic growth, countries who adopted regulation of coal-fired power plants after 1980 generally did so at a much lower level of per-capita income than did early adopters – poor countries regulated sooner. This phenomenon suggests that early adopters of environmental regulation provide an advantage to countries adopting these regulations later, presumably through advances in technology made by these pioneering adopters.

We attempt to understand why poorer countries adopt sooner, focusing on the link between the global technological frontier and environmental regulation. Environmental controls in advanced economies are likely to induce *new* innovations needed to comply with regulation. However, for other countries, the technologies needed to comply with regulations are already 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, as in previous studies of early adopters, we instead ask to what extent the availability of new technology influences the adoption of environmental regulation by non-innovating countries.[5]

Our approach considers carefully the role of international markets and trade policies in transmitting both knowledge and cost shocks across economies. Previous studies suggest that access to international markets influences firms' ability to use new technology. Reppelin-Hill (1999) finds that adoption of new technology in the steel industry is positively correlated with trade openness. Acharya and Keller (2007) estimate that the contribution of international technology transfer to productivity growth exceeds that of domestic R&D and that imports are a

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[5] 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 these countries were the first to enact environmental protections and most R&D expenditures occur in these countries. In 2000, global R&D expenditures were at least $729 billion. 82 percent of this was done in the OECD and half was performed by the United States and Japan alone (National Science Board, 2006).

major channel for these spillovers. Consequently, we investigate the possibility that low trade barriers ease access to new technology, and thus increase the likelihood of domestic regulation.

We acknowledge the double-edged nature of openness, however, in that the global market constrains domestic firms' ability to pass along higher abatement costs. To the extent that local firms are protected from such competition through trade restrictions, their ability to shift the regulatory burden to domestic consumers may be larger and their opposition to regulation lessened. We also consider the size of the domestic economy relative to the world market, reflecting the ability of local producers to pass costs through to foreign consumers.

To focus directly on the decision to adopt pollution control regulations, we constructed a data base of coal-fired power plant regulation for SO_2 and NO_X across 45 countries. For each country, we identify the year in which these regulations were first enacted. Using the history of these particular regulations allows us to focus on a specific set of explanatory variables important to coal-fired plants and permits us to identify political economy concerns more precisely than if a broad index of regulation were used. Narrowing our study to a specific set of regulations also allows us to more precisely define the relevant technological frontier. We measure innovation using patents on pollution control devices specific to the reduction of SO_2 and NO_X emissions.

We begin with a general equilibrium model of an open economy and we analyze the political economy decision to regulate emissions. From this, we develop several empirical predictions that we examine using our panel of regulation data. Our findings support the hypothesis that international economic integration eases access to environmentally friendly technologies and leads to earlier adoption, *ceteris paribus*, of regulation in developing countries. Our results are also consistent with the view that domestic trade protection allows costs to be shifted to domestic consumers while large countries can shift costs to foreign consumers, raising the likelihood of adoption. Other political economy factors, such as the quality of domestic coal and election years, are also important determinants.

I. Theoretical Framework

To provide a framework for our empirical analysis, we consider a general equilibrium model of an economy that uses electricity to produce a tradable good. Electricity is generated by burning domestically mined coal. Domestic consumers benefit from consumption but experience disutility from emissions generated by coal-fired power plants. The allowable level of such emissions is endogenously determined by a government that maximizes a weighted sum of social welfare and contributions from organized interest groups. The country does not engage in pollution control R&D, instead purchasing abatement services from international suppliers.

i. Production

To capture the importance of coal to downstream sectors, we posit a model with four production sectors: agriculture, which serves as numeraire, coal mining, electricity generation, and manufacturing. Each sector uses intersectorally mobile labor as a factor of production while coal, electricity, and manufacturing production 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.[6]

The economy contains L workers, each of which inelastically supplies one unit of labor. Agriculture serves as numeraire and is modeled as a tradable sector with a constant-returns technology. We choose units so that one unit of output requires one unit of labor input, tying the

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[6] 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.

wage at unity. We assume that aggregate labor supply, $\bar{L}$, is large enough so that there is always a positive supply of locally produced agricultural products.

Electricity from coal-fired plants is produced with labor, sector-specific capital, and coal, using the technology $E = \min\left[f_E\left(K_E, L_E\right), C_E \right]$. L_E measures the labor used by power plants and C_E is the quantity of coal burned. The function $f_E\left(K_E, L_E\right)$ exhibits constant returns to scale, but capital services of power facilities, K_E, are in fixed supply. Electricity is not traded, so its price is determined on the domestic market.

Each unit of coal burned by electricity producers generates one unit of emissions and plants may be required to abate these emissions. A 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 price of abatement services, which reflects the lease price of imported abatement equipment, is $P_A(T)$, where T indicates the level of technology embodied in abatement devices. We posit that the price of abatement is driven by innovation and that advances in the knowledge stock reduce the price of abatement: $\partial P_A / \partial T < 0$.

The return to owners of coal-fired power plants is

$$\pi_E = P_E E - (P_C + P_A A) C_E - wL_E = P_E^N E - wL_E, \tag{1}$$

where P_E is the price of electricity and P_C is the price of coal. To obtain the last term, note that one unit of electricity requires one unit of coal and define the net price of electricity as $P_E^N = P_E - P_C - P_A A$. We assume that coal is not traded; its price is endogenously determined.[7]

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[7] An alternative specification, allowing the price of coal to be exogenously determined, yields the same empirical predictions, with the exception of the effect of larger coal reserves on the political equilibrium.

Coal is mined by the application of labor to coal reserves. The technology for coal production, $C = f_C(K_C, L_C)$, exhibits constant returns to scale. However, coal reserves, K_C, are in fixed supply. The return to owners of coal reserves is

$$\pi_c = P_C C - wL_C. \tag{2}$$

Manufactures are internationally traded and produced using sector-specific capital, K_M, and labor, L_M, in combination with electricity. The production technology for manufactures can be expressed as $M = \min\left[f_M\left(K_M, L_M\right), E_M \right]$, where E_M is the quantity of electricity used in manufacturing. The function $f_M\left(K_M, L_M\right)$ exhibits constant returns to scale, but manufacturing capital is in fixed supply. Letting P_M denote the domestic price of manufactures, earnings of manufacturing capital owners are

$$\pi_M = P_M M - P_E E - wL_M = P_M^N M - wL_M, \tag{3}$$

where we use the requirement for one unit of electricity per unit of manufactures and define the net price of manufactures as $P_M^N = P_M - P_E$.

As detailed in Appendix A, equilibrium in the production sector is defined as a vector of domestic product prices, factor rewards, and output levels for which the value marginal product of labor is equal across all sectors, the domestic supply of electricity and coal equals the domestic demand for electricity and coal, respectively, and labor demanded equals labor supplied, given world prices and the emissions abatement level chosen by the government.

ii. How are profits affected by a stricter abatement standard?

Profits of specific factor owners are affected by the abatement level chosen by the government. The extent to which profits fall when standards are tightened depends on the ability of firms to pass these costs through to consumers. This pass-through ability is determined by both international and domestic market conditions. Consider first a country pursuing free trade. Firms may pass through some cost increases to foreign consumers if local supply changes influence the world price – that is, if the country is large enough to influence its terms of trade. The ability of local producers to pass through regulatory costs depends on the elasticity of the excess demand for manufactures facing the home country. If the country is small on world markets, it faces an infinitely elastic excess demand curve and it has no pass-through ability.

Even in small countries with no international market power, however, restrictive trade policies may confer on producers an ability to pass through costs to consumers.[8] A simple way to see this is to consider a small economy that uses a binding import quota. Domestic demand beyond the quota amount is met by domestic producers. The ability to pass regulatory costs to consumers, therefore, depends on the local excess demand elasticity. This elasticity may reasonably be considered a function of the quota level: the more restrictive the quota, the more distorted is consumption compared to the free-trade level and the less elastic the demand curve. If this relationship holds, producers in countries with more restrictive trade policies will be able to pass through a larger share of the regulatory burden to consumers.

We denote excess demand by $X_M(P_M)$ and interpret this as excess world or excess (above quota) domestic demand, depending on the case. In equilibrium, domestic supply must equal excess demand, $M = X_M(P_M)$. Using this condition, changes in domestic supply affect price to the extent permitted by the slope of the excess demand curve: $\frac{dP_M}{dM} = \frac{1}{\partial X_M / \partial P_M} \equiv -\chi_{MM}$.

Total profits for specific-capital owners are $\pi_M + \pi_E + \pi_C$. Noting that the price of labor is not affected by regulation and using (1) to (3), the change in profits from stricter regulation is:

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[8] As in Damania et al. (2003), we take trade policy as independent of regulatory policy as the former is set through multilateral negotiation.

(4) $$\frac{\partial \pi}{\partial A} = \frac{\partial \pi_M}{\partial A} + \frac{\partial \pi_E}{\partial A} + \frac{\partial \pi_C}{\partial A} = -\left[P_A E + M \chi_{MM} M_A \right] < 0.$$

The first term in brackets is the direct cost of the additional regulation. The second term is the addition to profits from a higher equilibrium price when the local supply curve shifts. Appendix A shows that in general equilibrium $M_A \equiv \partial M / \partial A < 0$ and that $\partial \pi / \partial A < 0$.

Result 1: *Effect of a Stricter Abatement Standard on Profits.* The incomes of specific-factor owners are decreasing in the level of the abatement standard. Specific factor owners bear a larger regulatory burden the more limited their ability to pass costs through to consumers.

iii. How are consumers affected by a stricter abatement standard?

We assume consumers care about the environment as well as consumption and have quasi-linear preferences of the form[9]

(5) $$U = D_A + u(D_M) - \varphi(1-A)E,$$

where D_A is agricultural good consumption, and D_M is manufactures consumption. Damage from emissions is proportional to unabated coal burning by electricity generation, $(1-A)E$. Marginal damage, φ, is assumed to be a function of exogenous country characteristics, such as population density. Consumers each supply one unit of labor and have an income of w.

This utility function implies that the marginal utility of income is unity, given positive consumption of the agricultural good. Consequently, each consumer's demand for the manufactured good, denoted by $D_M(P_M)$, is the inverse of $\partial u(D_M)/\partial D_M$. Consumer surplus is given by $S(P_M) = u(D_M(P_M)) - P_M D_M(P_M)$. Indirect utility, our measure of consumer welfare, is:

(6) $$V(P_M, A, E) = w + S(P_M) - \varphi(1-A)E$$

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[9] 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 general preferences and nontransferable utility.

The effect of a stricter standard on consumer welfare is

$$(7) \qquad \frac{dV}{dA} = \frac{\partial V}{\partial P_M}\frac{\partial P_M}{\partial A} + \frac{\partial V}{\partial A} + \frac{\partial V}{\partial E}\frac{\partial E}{\partial A} = \varphi E - \varphi(1-A)E_A + D_M(P_M)\chi_{MM}M_A.$$

Appendix A shows that $E_A \equiv \partial E / \partial A < 0$. The environmental effect of regulation, the first two terms on the right-side of (7), unambiguously raises consumers' welfare, directly by reducing emissions and indirectly by reducing electricity generation. The last term in (7) indicates that consumers' welfare is influenced by regulation's impact on P_M. Because a stricter abatement standard leads to a backward shift in the local supply curve, P_M rises and consumer surplus falls if firms have any pass-through ability. In sum, a stricter abatement standard has benefits and possible costs for consumers: it reduces emissions but it also may raise the price of consumption.

Result 2: Effect of a Stricter Abatement Standard on Consumers. A stricter standard increases consumers' welfare by reducing damage from emissions. There is a consumer surplus loss from stricter regulation, however, if it raises the relative price of manufactures. Consumer surplus loss is larger the greater firms' ability to pass through compliance costs to consumers.

iv. Political Economy

Because specific-factor owners bear some 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 sectors solve the collective action problem and form an organized "coal lobby," which distributes the costs of organized action among its members. The abatement standard is set by a government that values social welfare and contributions (or bribes) from this coal lobby. It 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, *B(A)*, that maximizes its members' net welfare contingent on the abatement standard chosen by the government. In the second stage of the game, the government chooses an abatement standard to maximize a weighted sum of contributions and aggregate social welfare. Denoting social welfare by $W(A)$, the government's objective function is

$$G(A) = \alpha W(A) + (1-\alpha)B(A), \tag{8}$$

where $\alpha, 0 \leq \alpha \leq 1,$ is the weight placed by the government on social welfare.

An equilibrium of the game is a subgame-perfect Nash equilibrium in the contribution schedule and the chosen abatement standard. We confine ourselves to equilibria in truthful contribution schedules, which take the form:

$$B(A) = \max\{\pi(A) - b, 0\}, \tag{9}$$

where b is a constant. Bernheim and Whinston (1986) argue that a truthful Nash equilibrium is among the equilibria of the game.[10]

The coal lobby ignores consumer surplus and environmental damage and, thus, the preferences of the lobby are given by $\pi(A) = \pi_M(A) + \pi_E(A) + \pi_C(A).$ Substituting (9) into the government's objective function and noting that social welfare gross-of-contributions is the sum of profits, labor income, and consumer surplus, minus the damage from coal burning, yields:

$$G(A) = \alpha[w + S(P_M(A)) - \varphi(1-A)E(A)] + \pi(A) - b. \tag{10}$$

Using results 1 and 2, the first-order condition for maximizing the government's objective, allowing for complementary slackness, is:

$$\alpha\left[\varphi E - \varphi(1-A^*)E_A + D_M \chi_{MM} M_A\right] - \left[P_A E + M \chi_{MM} M_A\right] \leq 0; if < 0, A^* = 0. \tag{11}$$

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[10] A locally truthful contribution schedule has the property that $\partial B(A)/\partial A = \partial \pi(A)/\partial A$ at the equilibrium point. Grossman and Helpman (1994) provide an application to trade policy, Damania et al. (2003) an application to environmental policy and Fredriksson and Wollscheid (2008) an application to abatement technology investment.

This expression characterizes the political-equilibrium abatement standard. The first term on the left-hand side of (11) gives the (weighted) marginal benefit of regulation. This marginal benefit is the sum of three impacts: the direct effect of on emissions, the indirect benefit from reduced coal-fired electricity use, and the possible reduction in consumer surplus. The second term gives the marginal cost for the government, in terms of reduced contributions from the coal lobby.

When a non-negative standard is chosen, the marginal benefit of regulation to the government equals its marginal cost. If firms have no ability to pass through cost increases, from (11) the political-equilibrium level of abatement is $A^* = 1 + \frac{E}{\alpha\varphi E_A}\left(P_A - \alpha\varphi\right)$. If the government chooses an abatement standard that does not require the complete abatement of emissions $(A^* < 1)$, it must be that $P_A - \alpha\varphi > 0$. Thus, the politically chosen abatement standard is weaker the larger the cost of abatement relative to the value of cleaner air to the government.[11]

When firms do face an elastic excess demand curve, either because of international market power or domestic trade protection, the politically optimal abatement level is

$$(12) \qquad A^* = 1 + \frac{1}{\alpha\varphi E_A}\left\{(P_A - \alpha\varphi)E + \alpha(M - D_M)\chi_{MM}M_A + (1-\alpha)M\chi_{MM}M_A\right\}.$$

The first term in brackets reflects the balance between direct regulatory costs and the value to consumers of lower emissions. The second and third terms in brackets reflect the consequences of firms' ability to shift costs forward to consumers. As measured by the second term in brackets, producer revenue gained through the price rise is offset by lost consumer surplus. If the country is a net exporter of manufactures and can influence its terms of trade, the gain to producers must exceed lost domestic consumer surplus as foreign consumers bear some of the

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[11] The abatement rate that maximizes social welfare for a small country is given by (11) when $\alpha = 1$. It is readily seen that the socially optimal level exceeds the politically optimal level when a non-zero standard is chosen.

burden. If the country is a net importer but imports are relatively small, perhaps as a consequence of trade restriction, this term will also be relatively small. The last term in brackets gives the extra weight placed on producer revenue gains, indicating that a producer price increase, whether from international or domestic market power, reduces the government's regulatory cost in terms of lost contributions and leads to adoption of a stricter standard.

Finally, because we are looking at countries that have not regulated, we note that the government may choose not to regulate. The government will not enact an abatement standard if the benefits of abatement are not large enough to offset the cost of lost contributions, either because the relative marginal disutility of emissions (φ) is small or the cost of abatement is high.

II. Empirical strategy

Our empirical analysis examines when a country first adopts emissions regulations for coal-fired power plants. In addition, to understand the determinants of *stringent* regulation, 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 discussion of our empirical strategy by deriving predictions about the relationship between adoption and the determinants identified by our theory. Next, we discuss construction of the dependent variable, followed by a description of the construction of our key explanatory variable, knowledge stocks. We end this section with depictions of trends in our data.

i. Empirical Predictions

In this section, we explore the effect on the politically determined abatement standard of changes in our exogenous variables: the price of abatement services, the country's pass-through ability, domestic coal reserves, the value consumers place on clean air, and the weight placed by the government on social welfare. We consider a country for which the first-order condition (11) and the second-order condition $G_{AA} < 0,$ hold at a non-negative level of A^*.[12]

Prediction 1: A reduction in the price of abatement services tightens the political equilibrium abatement standard when there is no abatement.

Proof: Total differentiation of (11), evaluated at $A^* = 0$, yields

$$\frac{dA^*}{dP_A} = \frac{E}{G_{AA}} < 0. \tag{13}$$

The sign follows from that assumption that the second-order condition holds.

Because most pollution control technologies are developed in just a few countries, international trade increases access to new technologies, effectively reducing the user cost of advanced abatement equipment and making adoption more likely.[13] Therefore, in our hazard analysis we interact the knowledge stock, representing the available new technologies, with alternative measures of openness. Equation (13) suggests that the sign of the estimated coefficient for this interaction will reflect a higher adoption probability in more open economies when the knowledge stock grows. Support for this form of "access effect" is consistent with technology embodied in imported goods or imports-related learning.

We employ two alternative measures of trade openness for our estimation. First is the ratio of the total value of imports to GDP.[14] This measure has been used in many prior studies on technological diffusion and it has the distinct advantage of being available for all countries in

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[12] We follow the literature and ignore effects that involve third derivatives of production functions as we have no economic interpretation for these effects and because the specific factor model does not place restrictions on them.

[13] The producers of nearly all the SO_2 scrubbers listed in the IEA's CoalPower 4 database are headquartered in the U.S., Japan, Germany, or Switzerland. All of the listed FGD units installed in China come from foreign suppliers.

[14] We use import share to measure openness because most countries in our sample are abatement equipment importers. The most commonly used measure of openness is exports plus imports as a share of GDP. This alternative measure is highly correlated with the imports-to-GDP ratio.

our sample for most years. However, this ratio is also influenced by factors other than trade policy, most notably country size, limiting our ability to isolate an "access effect" of openness from the ability to pass-through regulatory costs to foreign consumers.[15] Consequently, we employ an alternative measure that controls for country characteristics, including the size of the economy, the Hiscox-Kastner trade policy orientation index (TPOI). This index is constructed from the residuals of a gravity model of bilateral trade flows, expressed relative to the sample maximum intercept. The numbers represent the percentage reduction in imports in each year due to deviations of trade policy from a free-trade benchmark. As such, higher values indicate more "missing trade" and, thus, measure a country's barriers to trade not accounted for by distance, remoteness, and other controls used in the gravity estimation.[16]

Prediction 2: In the political equilibrium, greater ability by producers to pass compliance costs through to consumers leads to a stricter standard.

Proof: Totally differentiating (11) and rearranging yields:

$$\frac{dA^*}{d\chi_{MM}} = \frac{[\alpha(M - D_M) + (1-\alpha)M]}{G_{AA}} M_A. \tag{14}$$

We consider the effect of international market power, conveyed by country size relative to the world economy, separately from the market power conveyed on domestic producers from trade restrictions. First, if the country has some ability to influence the international terms of trade and it is a net exporter of manufactures, the term in brackets is positive and the total derivative is

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[15] Using direct policy measures is also problematic. Average tariff rates underestimate the level of protection as the weights used reflect distorted trade flows and do not measure non-tariff barriers. Non-tariff barrier measures are available for only isolated years. Commonly used alternatives, such as tariff revenue as a share of total imports, have disadvantages shared by average tariff rates.

[16] Hiscox and Kastner (2002) describe the gravity model used to estimate the residuals and the index as well as provide a discussion of the advantages and disadvantages of the index. The Hiscox-Kastner index is available for most countries in our sample, with the exception of Eastern European countries and Zimbabwe, for all years in the sample. We thank Scott Kastner for providing updated data. The correlation between the Hiscox-Kastner index and import shares is -0.4383, suggesting that the two measures pick up different effects.

positive. In this case, greater pass-through of compliance costs unambiguously increases the politically determined standard as the impact on producers' contributions exceeds the weight given to that on consumer surplus. Moreover, if the country is a net importer of manufactures but these are relatively small, defined as $(D_M - M)/M < (1-\alpha)/\alpha,$ the term in brackets is positive and the total derivative is positive. These considerations imply that our empirical analysis of the adoption decision should control for the size of the domestic economy relative to the world economy, which we measure as merchandise exports as a share of world merchandise exports. Data for this measure is drawn from the World Development Indicators.

Even in a country too small to influence its terms of trade, producers may be able to pass regulatory costs along to consumers if trade policy is sufficiently restrictive. For this reason we also include the direct effect of our two alternative openness measures defined above: the total value of imports relative to GDP and the Hiscox-Kastner trade policy orientation index.

Prediction 3: Holding the world price of manufactures and all other factor endowments fixed, larger coal reserves weaken the political equilibrium abatement standard.

Proof: Totally differentiate (11) to obtain:

$$\frac{dA^*}{dK_C} = \frac{(P_A - \alpha\varphi)}{G_{AA}} \frac{\partial E}{\partial K_C} < 0. \tag{15}$$

As shown in Appendix A, a larger coal sector reduces the domestic price of coal and increases coal-fired electricity generation: $\partial E / \partial K_C > 0$. The term in brackets is positive is the government chooses a standard that is less than full abatement, as discussed for the small-country case.[17]

In our empirical work, we capture the size of specific investments in coal using coal production per capita and the share of electricity produced with coal.[18] We expect larger coal

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[17] If we amend the model so that coal is freely traded, policy does not depend on the size of domestic coal reserves.
[18] Data on coal production comes from http://www.eia.doe.gov/emeu/international/coal.html.

production to be associated with a lower probability of regulating emissions from coal-fired plants. We also control for lignite production per capita. 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 regulation, as the marginal benefit of abatement is higher.

Prediction 4: An increase in the disutility consumers experience from coal burning leads to a stricter abatement standard in the political equilibrium.

Proof: Totally differentiate (11) to obtain:

$$\frac{dA^*}{d\varphi} = \frac{[(1-A)E_A - \alpha E]}{G_{AA}} > 0. \tag{16}$$

The sign of the numerator is negative and, thus, the derivative is positive.

In our hazard analysis, we include several measures that capture the marginal benefit of a cleaner environment, φ. The first of these measures is GDP per capita. If environmental quality is a normal good, richer consumers will place a higher weight on environmental quality relative to consumption, and thus should regulate sooner. The second measure, population density, also relates to the term φ in our theoretical model. We expect that more densely populated countries will regulate sooner, all else equal, because of the proximity of residences to power plants.

Prediction 5: An increase in the weight placed on social welfare relative to contributions leads to a stricter political equilibrium abatement standard.

Proof: Totally differentiate (11) to obtain:

$$\frac{dA^*}{d\alpha} = -\frac{[\varphi E - \varphi(1-A)E_A + D_M \chi_{MM} M_A]}{G_{AA}} > 0. \tag{17}$$

The sign of the term in brackets, which captures the marginal benefit to consumers of abatement, must be positive if a non-negative level of abatement is chosen. The denominator is negative by assumption, so the derivative is positive.

To capture the α term in the government's objective function, we include measures of a citizen's ability to make his or her views known to the government. The first measure is the Freedom House index of political rights, reasoning that more democratic governments place a higher weight on social welfare. The second measure is whether or not it is an election year. The government will place a higher weight on political contributions when an election is near. We also include measures for the ideology of the ruling party, controlling for whether the government is liberal or conservative, as opposed to centrist.[19]

ii. Regulations

No single source of information on coal-fired power plant regulations exists. By consulting a series of publications by the International Energy Agency (IEA) Clean Coal Centre (Vernon 1988, Soud 1991, McConville 1997, and Sloss 2003), we collected detailed information on coal-fired power plant regulations in most developed countries, as well as some developing countries, primarily in Southeast Asia and Eastern Europe. We supplemented this information with country-specific sources where necessary.[20] To narrow the task, we searched for additional regulatory information only for countries that get at least 10 percent of their electric power from coal.[21] In some cases we were unable to identify when, or if, 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.[22] For each, we identify the year in which emissions restrictions on coal-fired power plants were enacted for both SO_2 and NO_X.[23] Additionally, for NO_X we identify both the initial

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[19] 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.

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

[21] These countries get at least 10 % of power from coal in at least one year between 1980 and 2001. We also include Sweden, an environmental technology source, even though it does not generate much power from coal.

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

[23] Our goal was to find regulations that provide incentives to install pollution control devices, such as flue gas desulfurization (FGD) units to remove SO_2 emissions. Thus, we sought the enactment of specific emissions regulations for power plants, rather than general legislation on ambient air quality. One case, Israel, never adopts

regulation and the adoption of rules stringent enough to necessitate the use of the more expensive post-combustion abatement techniques described in the next section.[24]

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.[25] 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

A key goal of this paper is to estimate the extent to which access to technological advances increase the likelihood of adopting environmental regulation. For this, we use pollution-control device patents 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.[26]

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specific regulations, using licenses negotiated with plants on an individual basis instead, and so we drop it from our sample. In a second case, Mexico enacted an SO_2 standard for power plants in 1993, but the allowable level of emissions is so high that plants do not need to install FGD equipment (Asia-Pacific Economic Cooperation, 1997).

[24] We define stringent regulations as those restricting NO_X emissions to 410 mg/m^3 or less, which is the regulation introduced in Japan when they tightened NO_X emission limits in 1986.

[25] The figure only includes the 39 countries that remain in our sample after merging with other data sources.

[26] Popp (2005) discusses the advantages and disadvantages of using patent data when studying environmental technologies. Among the disadvantages, 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.

Patents are granted by national patent offices in individual countries and 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 files 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 costs of filing abroad, along with the one-year waiting period that gives inventors additional time to gauge their invention's value, only the most valuable inventions are filed in several countries. Moreover, filing a patent application 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 use patents to identify the technological frontier, we take advantage of patent families to find the most important ones. We begin by selecting all relevant patents granted in the United States since 1969. Relevant technologies include those that reduce SO_2 or NO_X emissions. These include 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).

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.[27] We keep only patents with at least one foreign patent family member.

We use the European Classification System (ECLA) to identify relevant patents, as it provides detail necessary to distinguish between the types of pollution controlled by various technologies.[28] Appendix B lists the relevant ECLA codes for these technologies. Using the European Patent Office's on-line database, esp@cenet, we downloaded a list of patent numbers for documents published in the US.[29,30] We obtained additional descriptive information on these patents from Delphion, an on-line database of patents, including the application, priority, and issue date, the home country of the inventor, and data on patent families, which we use to identify patents with multiple family members.[31] These patents were sorted by priority year, as this date corresponds most closely with the actual inventive activity.[32] 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:

$$(18) \qquad K_{j,t} = \sum_{s=0}^{\infty} e^{-\beta_1(s)}(1-e^{-\beta_2(s+1)})PAT_{j,t-s}$$

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[27] As a robustness check, we constructed a similar stock using patents granted in Germany. See appendix C.
[28] ECLA classifications are assigned by patent examiners at the European Patent Office. Traditional patent classification systems, such as the International Patent Classification system and the US patent system, do not provide enough detail to distinguish among technologies at the level needed for this paper.
[29] The database can be found at http://ep.espacenet.com/.
[30] These data are also used in Popp (2006a), and are described in more detail there.
[31] This database is available at http://www.delphion.com.
[32] In addition, using priority dates, rather than the date of grant, removes noise introduced by variations in 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.

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.[33] Figure 3 illustrates these stocks, with the stock in 1980 normalized to 100 in each case. 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. For example, both Germany and Japan passed stringent NO_X regulations in the 1980s that led to the development of new SCR technologies (Popp 2006a).

iv. Additional data and trends

Table 1 describes the variables and their sources in greater detail. The final sample includes data from 1980-2000 on 39 countries.[34] Table 2 provides descriptive data for each of these variables for the 39 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. 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 of data in our regression. With the exception of the Philippines, each of these countries adopts at a per

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[33] 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 D presents sensitivity analysis with respect to the rates of decay and diffusion.

[34] 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), and Ukraine (no data on merchandise exports). 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. 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.

capita income roughly between \$15,000 and \$20,000.[35] Of the countries that adopt between 1980 and 2000, we see a strong trend of adoption at lower income over time. 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. 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, there are still many countries that have not adopted stringent NO_X regulations (Figure 6). Those that have adopted are generally high income countries, with a major exception being Eastern European countries.

III. Regressions

Following the approach used by economists studying technology adoption, we use a duration model that captures both a baseline hazard and country-specific effects on the adoption of environmental regulation.[36] These models separate the hazard function into two parts, allowing for a baseline hazard, $h_0(t)$, that does not vary by country. Letting $\mathbf{X_t}$ represent a vector of explanatory variables, $\boldsymbol{\beta}$ represent the vector of parameters to be estimated, and t represent time yields a hazard function to be estimated of the form:

$$h(t,\mathbf{X_t},\boldsymbol{\beta}) = h_0(t)\exp(\mathbf{X_t}'\boldsymbol{\beta}). \tag{19}$$

To estimate equation (19), the baseline hazard h_0 must be specified. We present results using three specifications common to the adoption literature: 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. As a further

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[35] Early adoption of regulation in the Philippines is explained by close bilateral relations with the United States, which includes aid for environmental protection.

[36] See, for example, Hannan and McDowell 1984, Rose and Joskow 1990, Karshenas and Stoneman 1993, Kerr and Newell 2003, Snyder *et al*. 2003, and Popp 2006b.

robustness check, we estimate a Cox (1972) proportional hazards model, which uses semi-parametric estimation instead of specifying the baseline hazard. Once the baseline hazard is specified, we estimate equation (19) using maximum likelihood estimation, calculating robust standard errors because we have multiple observations per country.[37] In the hazard model, exp(β) gives the change in the probability of adoption for each variable. To aid interpretation, we normalize all non-interacted continuous variables so that a one unit change in the normalized variable is equivalent to a ten percent change from its mean value.[38] We present results 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.[39] Table 3 presents results using various measures of trade policy. In this table, all results are presented using the Weibull baseline hazard. Our main interest is the interaction of knowledge and trade policy. Column 1 uses import share as a measure of trade policy. Column 2 uses the Hiscox-Kastner trade policy orientation index (TPOI). While TPOI is our preferred policy measure, as import shares may be complicated by scale effects, TPOI is not available for the Eastern European countries in our sample, nor for Zimbabwe. In both cases, note that the interaction between policy and the knowledge stock has the correct sign, as both a larger import share and a lower TPOI signify more open trade policies. While the interacted coefficients appear small,

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

[38] 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. Table 1 indicates the variables that are normalized.

[39] An 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.

recall that the base level of knowledge is 100. Thus, for the base level of technology, a one percent increase in openness increases the likelihood of adoption by 13 to 17 percent. In addition, in each case the direct effect of our trade policy variable, which measures the ability of producers to pass cost increases on to domestic consumers, reduces the probability of adopting a regulation, with a one percent increase in openness reducing the likelihood of adoption by about 30 percent. Both the access effect and the domestic pass-through effect are significant at the 1 percent level using TPOI, but only at the 10 percent level using import shares.

These results suggest two competing effects. First, greater openness provides easier access to technology, making countries more willing and able to adopt environmental regulation. At the same time, increased openness raises domestic firms' need to compete with foreign firms, making it harder to pass cost increases to consumers. In each case, the access effect dominates when the knowledge stock is just over double its 1980 value.[40] Further emphasizing the role of openness, of the nine countries in our sample that never adopt SO_2 regulations, the average level of import shares for each of these countries across the 1980-2000 period is eight percentage points below the average of the sample as a whole and the average TPOI index is 12 percentage points less open than average. Of these nine countries, only New Zealand, Morocco, and Mexico have above average levels of import shares by 2000, and only Australia, New Zealand, Chile, and South Africa have a below average (e.g. more open) TPOI by 2001.[41]

Our third trade-related measure, world export share, captures the ability of a country to pass cost increases on to foreign consumers through a favorable terms-of-trade effect. This

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[40] The access effect dominates when $\exp(\beta_{open} + \beta_{interact}K) > 1$, so that $\beta_{open} + \beta_{interact}K > 0$. This holds when $K > -\beta_{open}/\beta_{interact}$. This occurs for a value of K equal to 221 using import shares, and 203 using TPOI. Knowledge surpasses these values in 1993 and 1990, respectively. Interestingly, it is after this date that the majority of low income countries adopt SO_2 regulations. In Figure 4, countries to the right of Korea adopted regulations after 1990 and those to the right of Romania adopted after 1993.

[41] Recall that New Zealand and Australia do not adopt SO_2 regulations because domestic coal supplies are naturally low in sulfur. Only 2 of the 7 remaining non-adopting countries are more open than average.

effect is positive, suggesting that larger countries with greater market power are more likely to regulate, as regulatory cost increases can be at least partially passed on to foreign consumers. However, the effect is only significant using the TPOI. In this case, a one percentage point increase in world export share increases the likelihood of adoption by 41 percent.

The lower significance of the trade measures using import shares may come from correlations between import shares and the world export share. To investigate this, columns 3 and 4 present results without world export share, and columns 5 and 6 present results without the direct effect of import shares or TPOI.[42] Note from column 3 that dropping world export share does increase the significance of the import share variables. However, dropping the direct effect of import shares or TPOI does not greatly improve the significance of world export share.

Turning to other variables, we again note that there are no significant differences across the various specifications. A ten percent increase in per capita income increases adoption rates by about 36%, supporting other results finding that environmental quality is a normal good. 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, this is only significant in the models without world export share.

Our next set of variables describes the coal sector. As expected, regulation is less likely when the coal sector is important. Coal production per capita has a negative, although not always statistically significant, effect on adoption. When significant, a country producing 10 percent more coal per capita than average is about 15 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

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[42] Another possibility is that the different results occur because of the smaller sample used with TPOI. However, the results in column 1 hold when we omit Eastern Europe and Zimbabwe, as is the case for the regressions using TPOI.

more lignite coal than average are 5 percent more likely to adopt. Note, however, that the net effect of the two coal variables remains negative. While countries with dirtier coal are more likely to adopt than a country producing a similar amount of cleaner coal, they remain less likely to adopt than the typical country. Finally, we find that the percentage of electricity from coal is insignificant. This result may be due to competing effects: Having more power come from coal makes the need to regulate greater, but it also raises the cost of regulation.

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, as are the effect of political parties. 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 consumers.[43]

Finally, Table 4 presents sensitivity to our choice of the baseline hazard. The table presents results for the model using TPOI for each specification of the baseline hazard, including results both with and without the direct effect of knowledge.[44,45] Note first that, except for the direct effect of the knowledge stocks, there are no substantive differences across the various specifications. Of the three parameterized baseline hazards, Aikike's information criterion shows the Weibull to be the best fit. Notably, the Weibull results in column 1 are very similar to the semi-parametric results obtained using the Cox model. However, the Weibull has two

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[43] Dutt and Mitra (2005) find empirical support for the proposition that the ideology of the government in power influences the restrictiveness of trade policy but that the direction of this effect depends on country GDP.

[44] We focus on results using TPOI, as that measure of trade policy is less confounded by country size. Results are similar using import shares and are available from the authors upon requests. The only differences are consistent with those found in Table 3: the knowledge stock/import share interaction is less significant and the effect of coal production per capita is more significant.

[45] For the Cox model, we only include results without the direct effect of knowledge, as the Cox model cannot be estimated when including the knowledge stocks, as this measure only varies across time.

advantages over Cox. One is that it is more efficient (Cleves *et* al, 2004). In addition, because no country adopts regulation in an election year, the Cox model is unable to estimate a coefficient for the election year variable. A concern with parameterizing the baseline hazard is that, if the parameterization is incorrect, the estimated coefficients will be biased. The similar results between the Weibull and the Cox models show that this is not the case here. Given this, we consider the Weibull results in column 1 our preferred specification.[46,47]

ii. NO_X regulation results

Table 5 compares the results across pollutants, using the Weibull model.[48] For NO_X, we distinguish between two classes of regulation. In most cases, initial regulation levels are weak enough that pre-combustion modifications are sufficient to comply with the regulations. The middle columns of Table 5 look at the adoption of these regulations. To consider stringency, we also look at adoption of NO_X regulations stringent enough to require post-combustion treatment of the flue gas. Such treatment requires expensive capital equipment (typically a selective catalytic reduction unit, or SCR), making such regulations less prevalent, particularly among 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. The last two columns of Table 5 focus on the adoption of these more stringent regulations.

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[46] As shown in Table 4, we are unable to obtain precise estimates of the direct effect of knowledge stocks because they only vary by time, not by country. Thus, when we estimate a time-varying hazard, the effect of these stocks is not uniquely identified. Fortunately, the estimates of other parameters do not change when knowledge is dropped. The Weibull and Gompertz results are nearly identical both with and without it. In these models, the knowledge stock essentially provides more detailed parameterization of the baseline hazard, rather than serving as a direct estimate of the overall effect of knowledge. In the exponential model, leaving knowledge stock out of the model results in misspecification, as it assumes that learning effects are insignificant and that all time-varying effects are captured by the explanatory variables. Here, coefficients do change and the log-likelihood decreases when knowledge stock is omitted. In this case, the knowledge stock acts as a proxy for the time-varying hazard, which the other models show to be significant.

[47] Note that we cannot directly compare the log-likelihood from the Cox model and the parameterized models, as the Cox model maximizes a partial log-likelihood function.

[48] As with SO_2, results do not vary using baseline hazard parameterizations and the Weibull model provides the best fit of the baseline hazard parameterizations. Other results are available from the authors by request. Also, as with SO_2, countries that adopt NO_X regulations before 1980 are omitted from our sample.

Looking first at the adoption of any NO_X regulation, we see that the interaction between knowledge and import shares is positive, but that the magnitude is smaller than before. This smaller magnitude is partially offset by greater variation in the knowledge stock for NO_X technologies. Still, at the average value of knowledge, the effect of a one percent increase of import shares is nearly one-third as great as for SO_2. The direct effect of import shares is negative, as expected, but also about one-third as great as for SO_2. Finally, the ability to pass costs on to foreign consumers, measured using world export shares, is insignificant. Because the costs of boiler modifications necessary to meet weaker NOX regulations are lower than the costs of SO_2 controls, technological advances and the ability to pass along cost increases appear less important here than for sulfur dioxide. Finally, note that while these trade policy effects are insignificant using TPOI, this change occurs because of the smaller sample size. If the model using import shares is re-run without observations from Eastern Europe and Zimbabwe, the import share effects are also insignificant.

As for other variables, the results are very similar to SO_2. GDP and population density increase adoption rates. The political influences of the coal industry are generally insignificant, except for our measure of dirty coal, which increases the probability of adoption.

Finally, the last two columns of Table 5 examine the adoption of stringent NO_X regulations. Unlike the initial adoption of SO_2 or NO_X regulations, availability of knowledge is insignificant. 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 and improving SCR technology on their own.

Among other variables, GDP is still important – richer countries are more likely to increase the stringency of NO_X regulations. Unlike previous results, 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. Desire to join the EU pushes these Eastern European countries to enact regulations more stringent than would otherwise be chosen for their level of development.[49]

IV. Conclusions

In debates on the effect of globalization and the environment, commonly cited effects are scale effects (more production leads to more pollution), composition effects (a change in the mix of economic activity can improve or exacerbate emissions), and technique effects (cleaner technologies are used as countries grow).[50] One challenge in empirically studying these effects is separately identifying the role of each. Using the adoption of environmental regulations, rather than a generic measure of environmental quality, as our dependent variable, we provide new evidence on the technique effect, showing 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.

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

[50] 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.

Our results provide new evidence on the role of economic openness in allowing these spillovers to spread across country borders. We posit that openness both eases access to technology and limits domestic firms' ability to pass regulatory costs to consumers. Our findings support the view that small, open economies are least able to transfer these costs away from firms and, thus, are less likely to regulate, *ceteris paribus*. They suggest that international burden shifting is an important factor in the political economy of environmental regulation.

In addition to the links between trade and technology, we find that other political economy forces are important. Factors affecting the value placed on abatement, such as population density and income level, increase the likelihood of regulation. Moreover, regulations that negatively affect the coal sector are less likely in countries with large coal reserves, but more likely the larger are reserves of dirty coal. Finally, the politics of globalization appear important, as Eastern European countries have passed more stringent regulations than other countries at similar levels of development in their progress toward joining the EU.

Studying the adoption of environmental regulation is an important step in understanding the diffusion of environmental technologies. Regulation is particularly important 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.[51] 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. Given these links, it is worth considering when other influences might encourage adoption, so that clean technologies can be adopted in countries that do not yet regulate emissions.

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[51] While some green technologies may diffuse without regulation, environmental policy will be needed to encourage socially optimal adoption levels. For example, while technologies that increase fuel efficiency, potentially reducing fossil fuel consumption and the associated carbon emissions, could diffuse without regulation, adopters will consider the private gains from lower fuel costs, but not the social benefits of reduced emissions.

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Table 1 – Data Definitions and Sources

variable	**description**	**source**
Openness		
Trade Policy Orientation Index	Index created by fixed country-year effects in a gravity model of bilateral trade	HK
Import Share	(Imports)/GDP	WDI
International Market Position		
World Export Share	Merchandise exports as share of world merchandise exports	WDI
Political Economy – Marginal Benefit of Abatement		
GDP Per Capita*	Per capita GDP in constant 1995 US $	WDI
Population Density*	People per square km	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, ranging 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

* -- These variables are scaled in the regression so that a one-unit change represents a 10% deviation from the mean.

Sources:
WDI: *World Development Indicators*
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: Database of Political Institutions (Keefer 2005)
HK: Hiscox and Kastner (2002)

Table 2 – Descriptive Data

variable	N	mean	sd	min	p50	max
Knowledge Stock: SO2	21	190.300	46.381	100.000	207.422	239.876
Knowledge Stock: NOXPre	21	251.636	131.207	100.000	202.893	453.873
Knowledge Stock: NOXPost	21	209.733	81.366	100.000	225.402	301.700
Import shares	771	30.574	14.410	6.855	27.873	84.398
Trade Policy Orientation Index	672	31.454	14.861	1.970	27.471	77.978
World Export Share	771	2.120	2.890	0.030	0.924	12.775
GDP Per Capita	771	13724.48	12146.67	166.75	11179.19	46815.50
Population Density	771	123.121	114.878	1.912	93.345	476.127
% Electricity from Coal	771	33.354	25.811	0	27.263	99.474
Coal Production Per Capita	771	2.17E-08	4.47E-08	0	5.19E-09	3.47E-07
Lignite Production Per Capita	771	0.001	0.001	0	5.55E-08	0.007
Election Year	771	0.057	0.232	0	0	1
Political Rights	771	2.258	1.784	1	1	7
Liberal	771	0.379	0.485	0	0	1
Conservative	771	0.431	0.495	0	0	1
Eastern Europe dummy	771	0.101	0.302	0	0	1

Table 3 – Regression Results: Adoption of SO_2 Regulations

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Knowledge Stock	-0.0893	-0.0018	-0.0970	-0.0107	-0.0403	-0.0456
	(-2.499)	(-0.064)	(-3.053)	(-0.406)	(-1.665)	(-1.840)
Knowledge x Import Share	0.0016		0.0019		-0.0001	
	(1.849)		(2.497)		(-0.975)	
Import Share	-0.3554		-0.4233			
	(-1.885)		(-2.507)			
Knowledge x Trade Policy Orientation Index		-0.0012		-0.0009		0.0001
		(-3.009)		(-2.439)		(0.389)
Trade Policy Orientation Index		0.2608		0.1817		
		(3.361)		(2.750)		
World Export Share	0.1618	0.3452			0.3307	0.2363
	(0.927)	(2.193)			(1.926)	(1.574)
GDP Per Capita	0.3094	0.3144	0.3260	0.2836	0.2525	0.2431
	(3.827)	(4.408)	(3.935)	(5.325)	(3.102)	(4.421)
Population Density	0.0534	0.0345	0.0766	0.0658	0.0096	0.0152
	(1.365)	(1.052)	(2.783)	(2.724)	(0.303)	(0.461)
% Electricity from Coal	0.0447	0.0579	0.0375	0.0477	0.0496	0.0385
	(1.123)	(1.700)	(0.993)	(1.653)	(1.258)	(1.271)
Coal Production Per Capita	-0.1545	-0.1165	-0.1259	-0.0608	-0.1549	-0.1050
	(-1.913)	(-1.531)	(-1.859)	(-3.994)	(-1.787)	(-1.386)
Lignite Production Per Capita	0.0529	0.0450	0.0535	0.0452	0.0476	0.0402
	(2.303)	(2.312)	(2.655)	(5.156)	(1.804)	(1.881)
Election Year	-17.080	-15.554	-18.569	-15.952	-17.614	-16.679
	(-23.91)	(-21.74)	(-22.60)	(-20.58)	(-29.23)	(-25.19)
Political Rights	0.0959	0.2396	0.1140	0.2277	-0.0684	0.1184
	(0.375)	(1.136)	(0.423)	(0.939)	(-0.298)	(0.505)
Liberal	-0.6475	-0.4549	-0.9328	-0.8488	-0.4823	-0.5328
	(-0.898)	(-0.589)	(-1.616)	(-1.135)	(-0.724)	(-0.703)
Conservative	-0.5445	-0.6872	-0.7546	-1.2109	-0.7124	-0.6425
	(-0.840)	(-0.798)	(-1.188)	(-1.468)	(-1.098)	(-0.783)
Eastern Europe	1.607		1.437		1.915	
	(2.141)		(2.110)		(2.255)	
Constant	1.302	-16.901	4.108	-11.905	-9.070	-7.348
	(0.209)	(-3.495)	(0.979)	(-3.663)	(-2.169)	(-2.456)
Duration dependence	1.8982	1.8204	1.8661	1.7151	1.8955	1.8067
	(9.062)	(7.731)	(8.689)	(7.087)	(9.204)	(8.291)
N	390	327	390	327	390	327
log-likelihood	-3.408	-5.817	-3.807	-7.396	-5.327	-7.464
chi2	1360.76	1291.35	1169.34	943.91	1434.90	1399.00
aic	38.82	41.63	37.61	42.79	40.65	42.93

The table presents regression results the Weibull baseline hazard; t-stats in parentheses.

Table 4 – SO_2 Regression Results: Sensitivity to Alternative Specifications

Variable	Weibull		Exponential		Gompertz		Cox
Knowledge Stock	-0.0018		0.0795		0.0882		
	(-0.064)		(4.623)		(4.870)		
Knowledge x TPOI	-0.0012	-0.0012	-0.0013	0.0007	-0.0013	0.0001	-0.0009
	(-3.009)	(-3.725)	(-3.901)	(2.961)	(-3.964)	(0.276)	(-2.254)
TPOI	0.2608	0.2648	0.2646	-0.1219	0.2587	0.0156	0.1834
	(3.361)	(3.541)	(4.281)	(-1.943)	(4.168)	(0.300)	(2.054)
World Export Share	0.3452	0.3465	0.3075	0.1901	0.2888	0.2642	0.2071
	(2.193)	(2.193)	(2.024)	(1.053)	(1.969)	(1.388)	(2.168)
GDP Per Capita	0.3144	0.3160	0.2920	0.1697	0.2901	0.1947	0.2873
	(4.408)	(4.423)	(5.496)	(4.932)	(5.632)	(4.637)	(4.334)
Population Density	0.0345	0.0349	0.0333	-0.0091	0.0320	0.0045	0.0299
	(1.052)	(1.085)	(1.019)	(-0.271)	(1.019)	(0.130)	(1.016)
% Electricity from Coal	0.0579	0.0585	0.0654	0.0314	0.0640	0.0376	0.0365
	(1.700)	(1.870)	(2.260)	(1.484)	(2.306)	(1.626)	(1.353)
Coal Production Per Capita	-0.1165	-0.1168	-0.1187	-0.1043	-0.1095	-0.1168	-0.0616
	(-1.531)	(-1.518)	(-1.506)	(-1.408)	(-1.474)	(-1.358)	(-3.271)
Lignite Production Per Capita	0.0450	0.0452	0.0435	0.0314	0.0421	0.0332	0.0394
	(2.312)	(2.281)	(2.329)	(1.380)	(2.478)	(1.180)	(3.296)
Election Year	-15.554	-16.377	-14.515	-16.135	-15.334	-15.371	
	(-21.74)	(-26.06)	(-23.24)	(-36.93)	(-23.82)	(-30.74)	
Political Rights	0.2396	0.2439	0.2726	0.0228	0.2916	0.0247	0.4029
	(1.136)	(1.143)	(1.460)	(0.114)	(1.598)	(0.112)	(2.236)
Liberal	-0.4549	-0.4479	-0.2432	-0.6749	-0.2418	-0.6583	-0.1128
	(-0.589)	(-0.609)	(-0.342)	(-0.961)	(-0.350)	(-0.927)	(-0.186)
Conservative	-0.6872	-0.6831	-0.3090	0.0358	-0.2837	-0.2184	-0.3213
	(-0.798)	(-0.799)	(-0.349)	(0.048)	(-0.323)	(-0.289)	(-0.382)
Constant	-16.901	-17.129	-19.118	-3.597	-19.830	-5.660	
	(-3.495)	(-4.382)	(-4.828)	(-2.316)	(-5.489)	(-3.061)	
Duration dependence	1.8204	1.8117			-0.0842	0.1938	
	(7.731)	(9.948)			(-0.710)	(3.084)	
N	327	327	327	327	327	327	327
log-likelihood	-5.817	-5.818	-10.092	-16.806	-9.973	-15.273	-34.044
chi2	1291.35	1420.39	1583.92	1775.60	1747.71	1313.06	84.00
aic	41.63	39.64	48.18	59.61	49.95	58.55	90.09

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

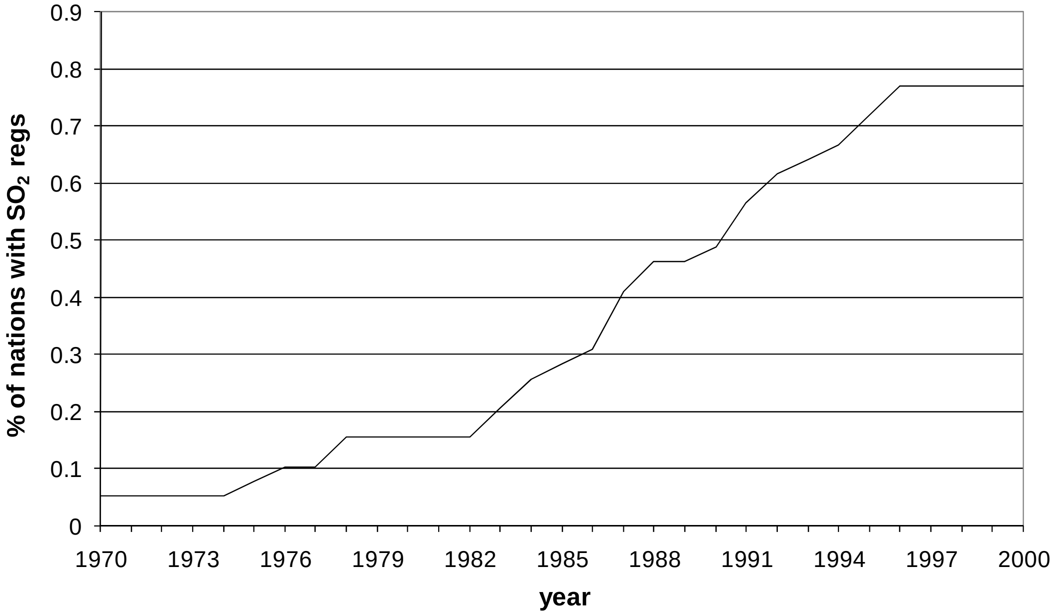
Table 5 – Regression Results: Weibull Results for Alternative Technologies

Variable	SO2		NOX: Any Reg		NOX: Stringent	
Knowledge Stock	-0.0893	-0.0018	-0.0258	-0.0253	-0.0044	-0.0139
	(-2.499)	(-0.064)	(-2.455)	(-2.028)	(-0.477)	(-0.997)
Knowledge x Import Share	0.0016		0.0004		-0.0002	
	(1.849)		(2.198)		(-0.708)	
Import Share	-0.3554		-0.1095		0.0163	
	(-1.885)		(-2.043)		(0.249)	
Knowledge x Trade Policy Orientation Index		-0.0012		0.0002		0.0000
		(-3.009)		(0.451)		(-0.164)
Trade Policy Orientation Index		0.2608		-0.0613		0.0485
		(3.361)		(-0.695)		(0.815)
World Export Share	0.1618	0.3452	0.0709	-0.0095	-0.0022	0.0894
	(0.927)	(2.193)	(0.398)	(-0.055)	(-0.017)	(1.237)
GDP Per Capita	0.3094	0.3144	0.2104	0.2090	0.2935	0.3399
	(3.827)	(4.408)	(2.497)	(2.783)	(3.880)	(5.571)
Population Density	0.0534	0.0345	0.0806	0.0563	0.0545	0.0538
	(1.365)	(1.052)	(2.747)	(1.828)	(1.659)	(1.606)
% Electricity from Coal	0.0447	0.0579	0.0385	0.0333	-0.0313	-0.0293
	(1.123)	(1.700)	(0.650)	(0.595)	(-1.041)	(-1.088)
Coal Production Per Capita	-0.1545	-0.1165	-0.0561	-0.0120	-0.0146	-0.0123
	(-1.913)	(-1.531)	(-1.091)	(-0.285)	(-1.269)	(-1.246)
Lignite Production Per Capita	0.0529	0.0450	0.0452	0.0404	0.0241	0.0374
	(2.303)	(2.312)	(3.619)	(3.882)	(1.011)	(2.494)
Election Year	-17.080	-15.554	-18.879	-17.135	-16.144	-15.255
	(-23.90)	(-21.74)	(-28.34)	(-31.77)	(-20.93)	(-24.97)
Political Rights	0.0959	0.2396	0.0990	0.4292	-0.0265	0.6692
	(0.375)	(1.136)	(0.535)	(1.916)	(-0.087)	(1.354)
Liberal	-0.6475	-0.4549	-0.7493	-0.9087	-2.2733	-2.0885
	(-0.898)	(-0.589)	(-1.423)	(-1.633)	(-2.789)	(-1.905)
Conservative	-0.5445	-0.6872	-0.6917	-1.1804	-2.0196	-1.9066
	(-0.840)	(-0.798)	(-0.969)	(-1.309)	(-2.735)	(-2.057)
Eastern Europe	(1.607)		(0.275)		(4.422)	
	(2.141)		(0.336)		(2.902)	
Constant	1.301	-16.901	-9.627	-10.509	-8.608	-10.420
	(0.209)	(-3.495)	(-2.737)	(-3.003)	(-3.118)	(-4.428)
Duration dependence	1.8982	1.8204	1.8407	1.9109	1.2745	1.3287
	(9.062)	(7.731)	(6.897)	(8.716)	(5.141)	(4.178)
N	390	327	380	317	618	542
log-likelihood	-3.408	-5.817	-3.067	-2.935	-12.337	-9.867
chi2	1360.76	1291.35	3898.39	5266.31	741.31	1372.90
aic	38.82	41.63	38.13	35.87	56.67	49.73

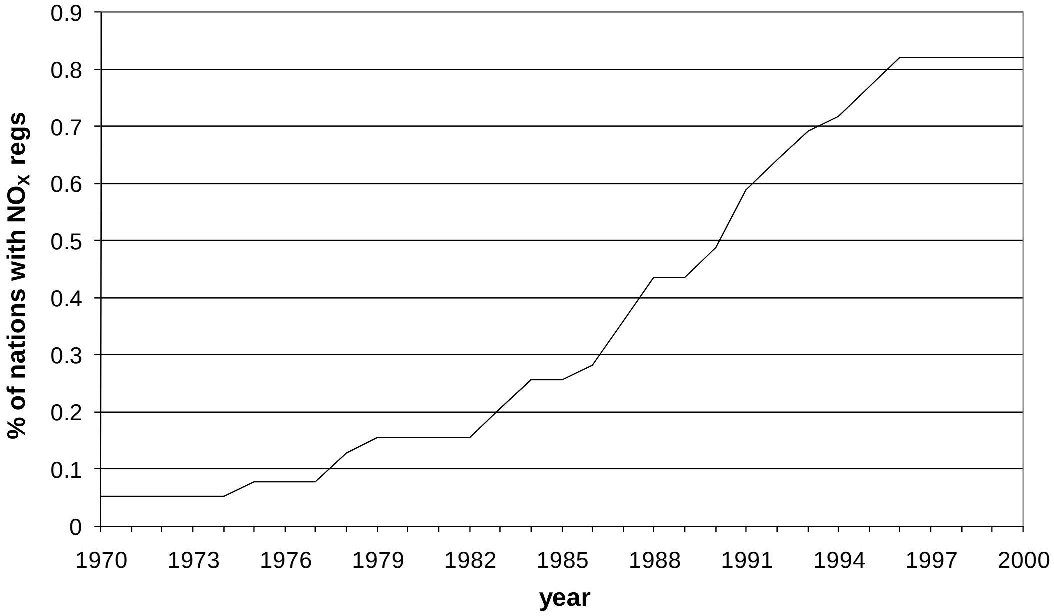
The table presents regression results for alternative regulations, using the Weibull baseline hazard; t-stats in parentheses.

Figure 1 – Adoption of Environmental Regulations over Time

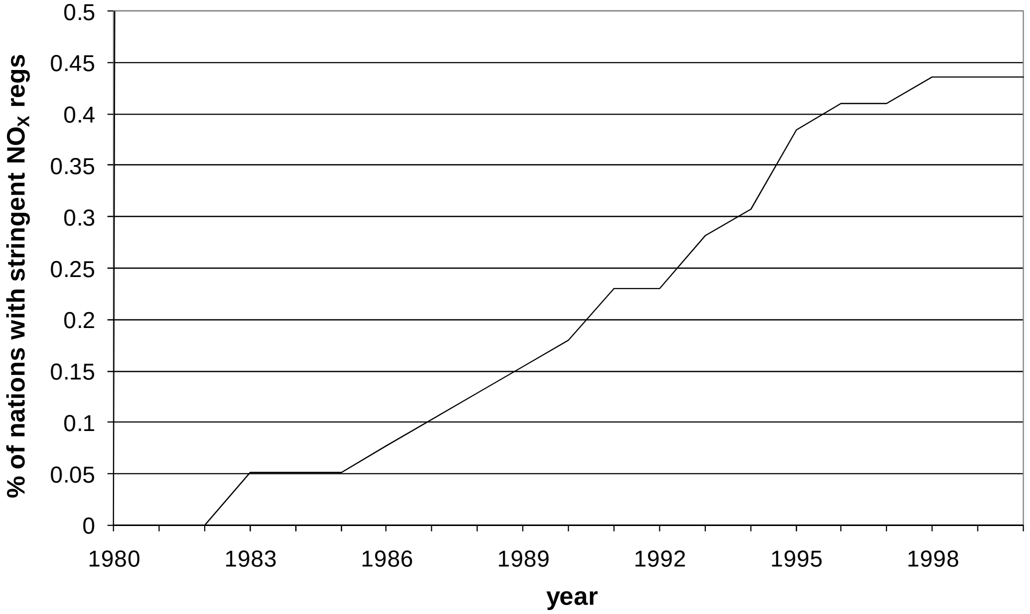
A. Sulfur Dioxide



B. Nitrogen Dioxide

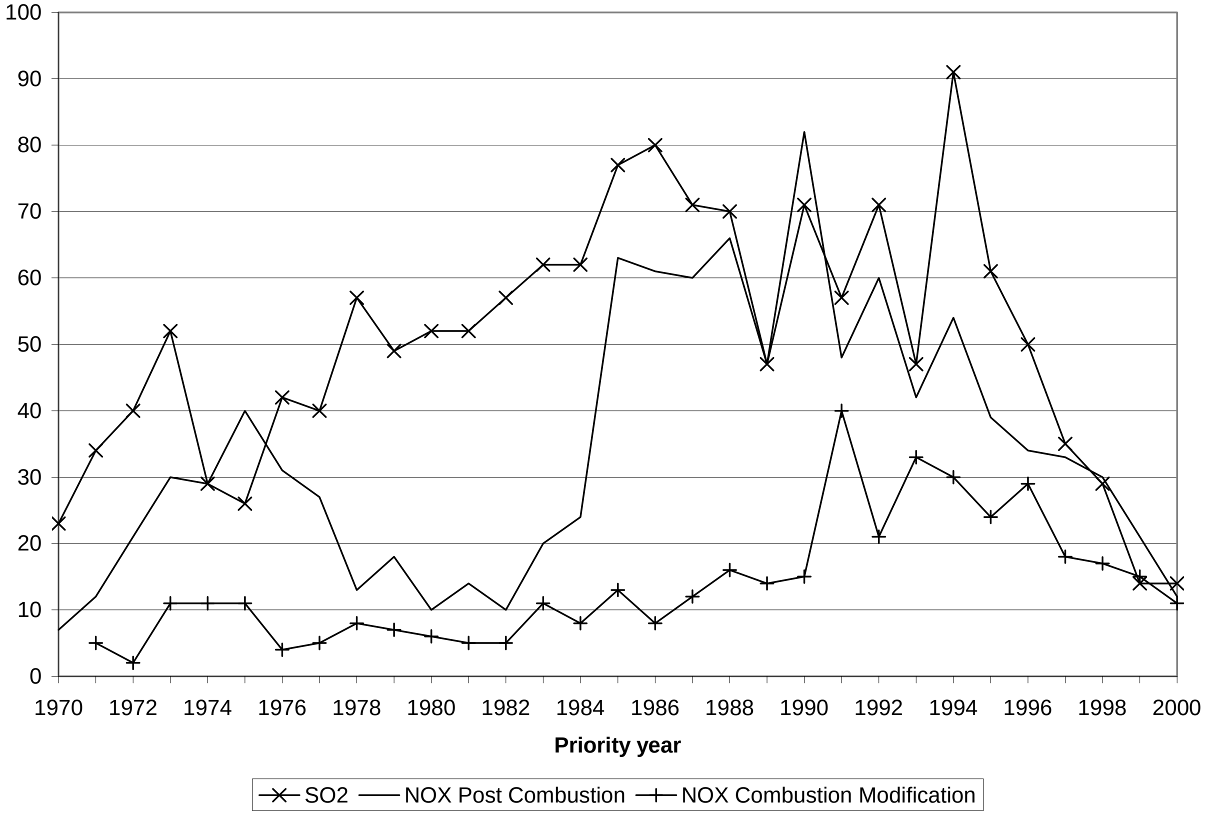


C. Stringent NO_X Regulations



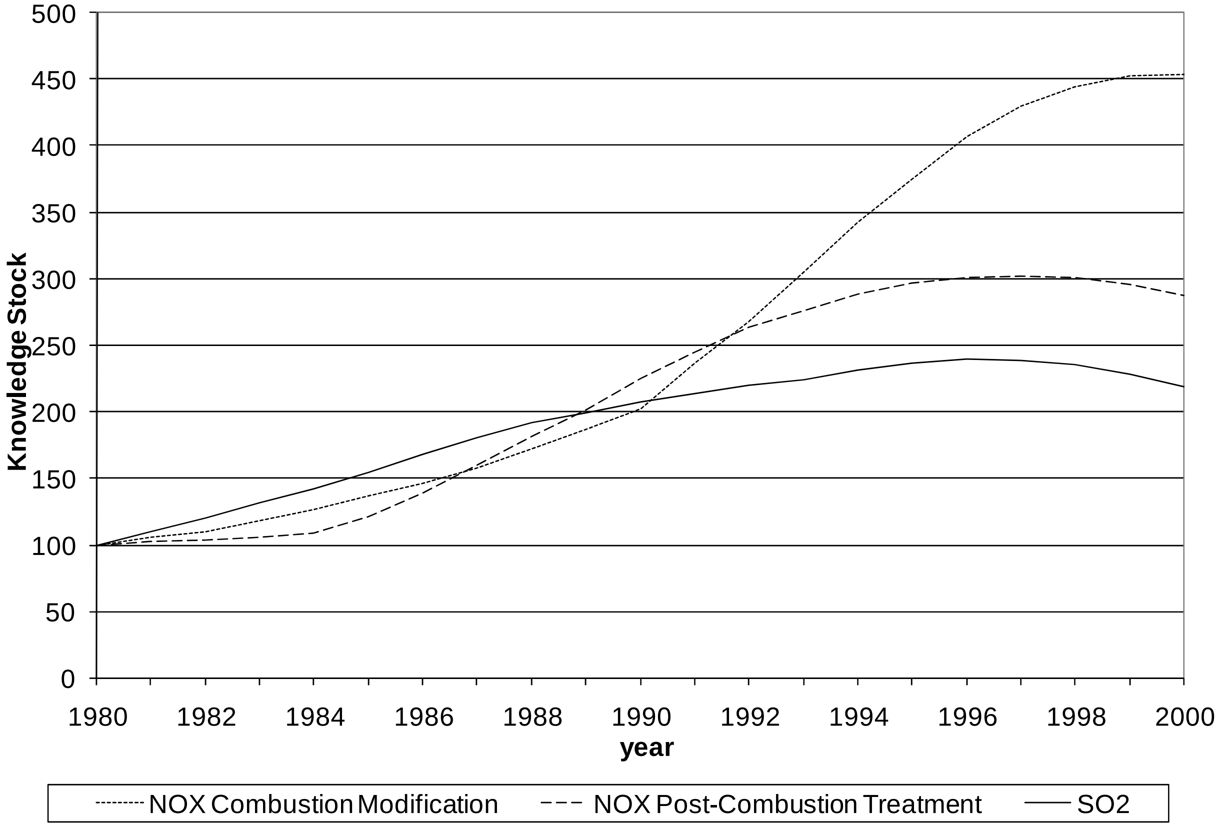
The figures show the cumulative percentage of countries that have adopted each regulation by the year on the *x*-axis. In each case, note the S-shaped diffusion pattern that is typical for studies of technology adoption. Note also that adoption of stringent NO_X regulations has, to date, leveled off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

Figure 2 – U.S. Pollution Control Patents



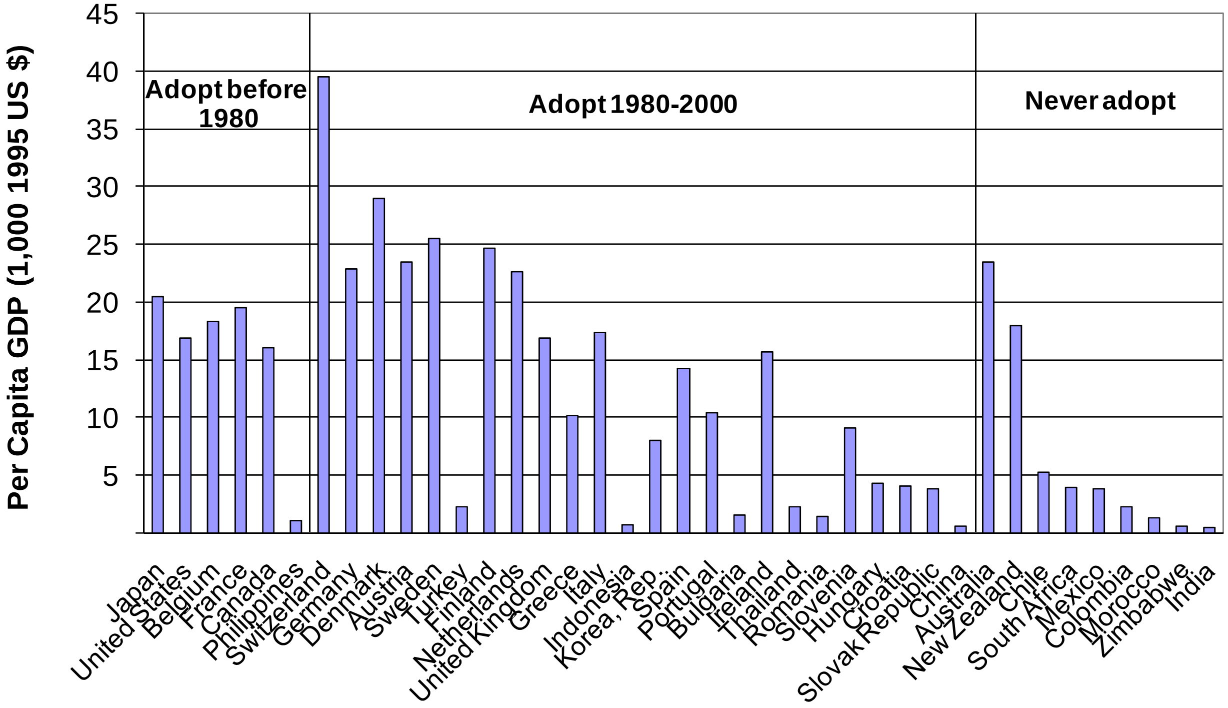
The figure shows patents granted in the U.S. with at least one foreign patent family member for each of three pollution control technologies.

Figure 3 – Knowledge Stocks



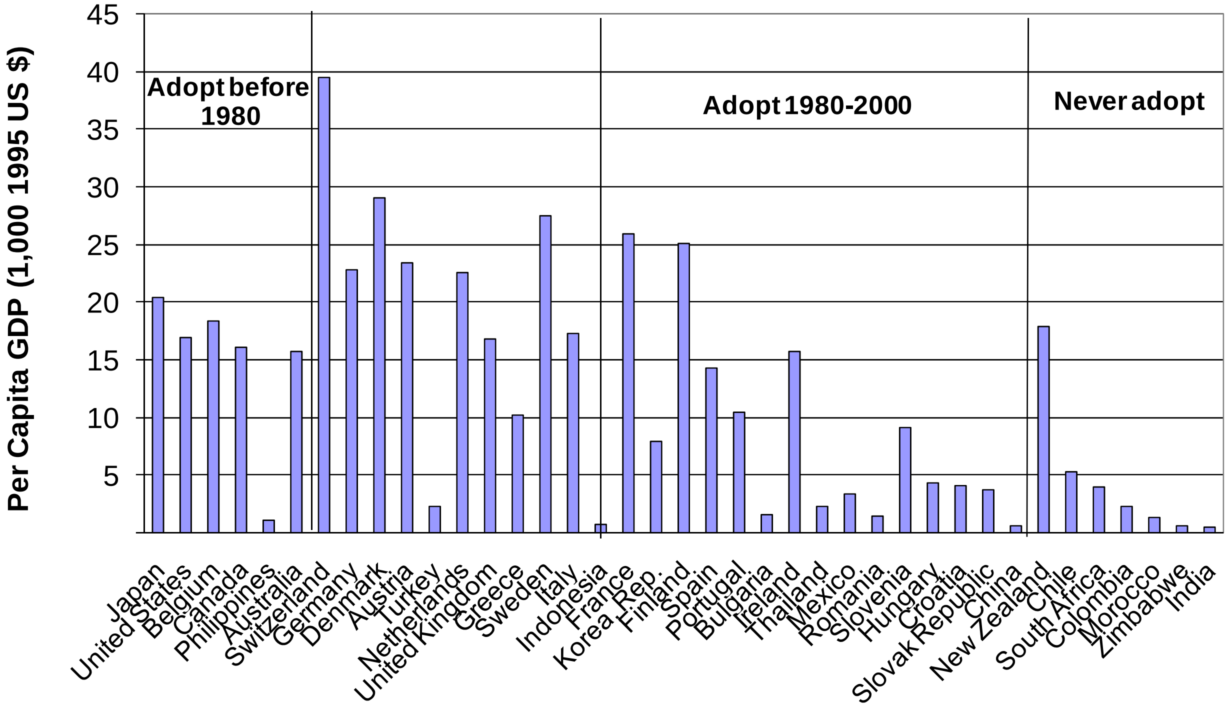
The figure shows the value of the knowledge stocks constructed for this paper for each of the three technologies. Note that the value of the stock for SO_2 progresses rather smoothly through time, whereas both NO_X technologies experience periods of growth after major environmental regulations.

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



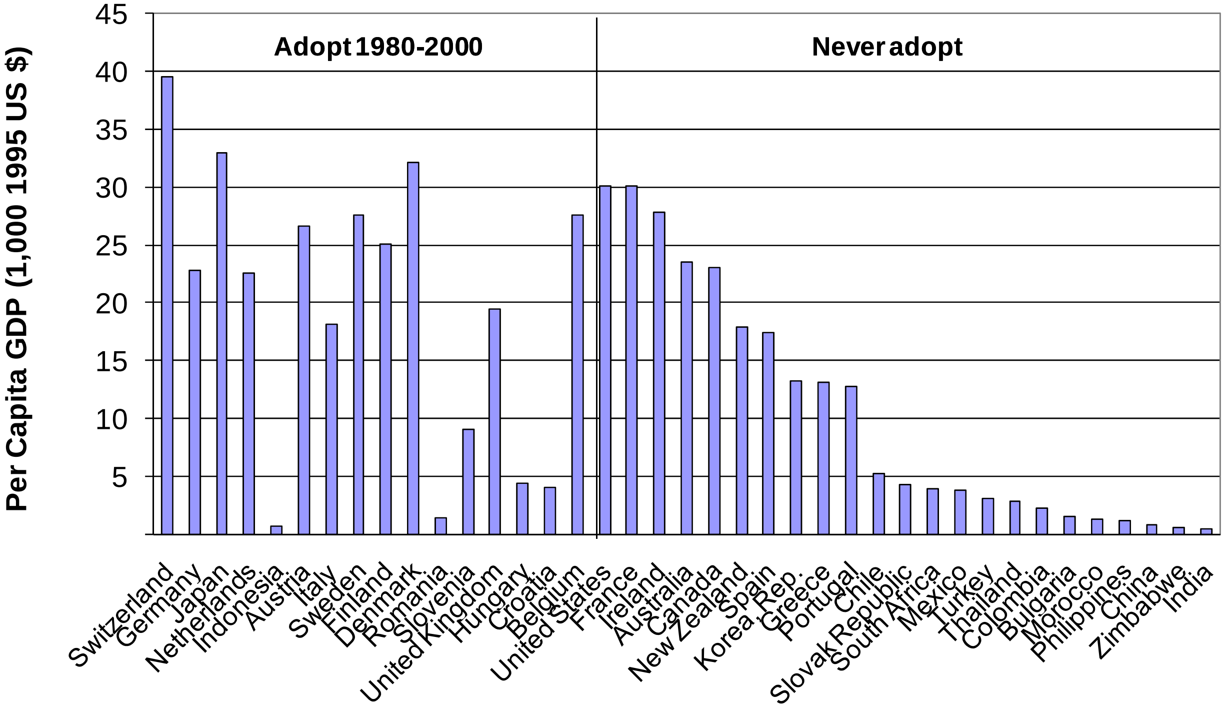
The figure shows the per capita GDP (in constant 1995 U.S. dollars) of each country in the year in which it adopts SO_2 regulations for coal-fired power plants. Countries are sorted from left to right along the *x*-axis by the order in which regulations were enacted. The first two countries, Japan and 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. Germany, the first country to adopt stringent NO_X regulations, did so in 1983. Those countries on the right have not adopted stringent NO_X regulations as of 2000.

Appendix A – Theoretical Model and Solutions

The model we use to understand the effect of emissions regulations is a version of the Ricardo-Viner (RV) model. The RV model posits perfect intersectoral mobility of labor but sector-specific capital. In this way, it captures the short-run interests of capital owners who expend a portion of their production surplus to influence economic policy.

i. Equilibrium Conditions

We consider an economy with four production sectors with technology described in the text: agriculture (A), Manufacturing (M), Electricity Generation (E), and Coal Mining (C). Agricultural and manufacturing goods are traded internationally. Equilibrium in the labor market requires that labor supply equal the sum of labor demand: $\overline{L} = L_A + L_M + L_E + L_C$. Agriculture serves as numeraire and labor productivity is unity, tying the wage at unity. Profit maximization requires that the value marginal product of labor equal the wage in each sector: $P_C f_C'(L_C) = 1; P_E^N f_E'(L_E) = 1; P_M^N f_M'(L_M) = 1$.

Net prices to manufacturing and electricity producers, P_j^N, differ from market prices, P_j, because of intermediate inputs, as defined in the text. The manufacturing sector uses one unit of electricity for each unit produced, implying that in equilibrium, $E = M$. Electricity production requires one unit of coal for each unit of energy generated, implying that emissions are proportional to electricity generation. Power plants must abate A percent of emissions, with these services purchased internationally at the fixed price, P_A.

Firms' ability to raise prices is limited by the elasticity of demand. If the country pursues free trade or uses a tariff only, the relevant elasticity reflects the slope of the world excess demand curve, while if the country is small and uses a binding quota, the relevant elasticity reflects the slope of the domestic excess demand curve. We denote excess demand by

$X_M(P_M)$ and interpret this as excess world or excess domestic demand, depending on the case. In equilibrium, domestic supply must equal excess demand, $M = X_M(P_M)$. Denoting the price elasticity of excess demand by $\varepsilon_M = -(\partial X_M / \partial P_M)(P_M / X_M) \geq 0$, and using the equilibrium condition, $\hat{M} = -\varepsilon_M \hat{P}_M$.

ii. Comparative-Statics Solutions

We use comparative statics to show how changes in exogenous variables affect equilibrium prices, outputs and profits. We totally differentiate the equilibrium conditions of the model and express the effects on endogenous variables as a percentage change.

Stricter Abatement Standard

The percentage change in the share of emissions that must be abated is $\hat{A}$. We define the elasticity of output with respect to labor in sector *j* as η_j, the (negative of the) elasticity of the marginal product of labor with respect to labor in sector *j* as σ_j. Input cost shares are $\theta_{MM} = P_M / P_M^N$, $\theta_{EE} = P_E / P_E^N$, $\theta_{AE} = P_A A / P_E^N$, $\theta_{EM} = P_E / P_M^N$, $\theta_{CE} = P_C / P_E^N$. Finally, we define the parameter $\psi = \eta_C \eta_E \theta_{EE} \left(\sigma_E + \varepsilon_M^{-1} \eta_M \theta_{MM}\right) + \eta_M \theta_{EM} \left(\sigma_E \eta_C + \sigma_C \eta_E \theta_{CE}\right) > 0$. This parameter is larger the more inelastic is excess demand. Using these terms, we can express the effect of a higher abatement standard as:

$$\frac{\hat{P}_M^N}{\hat{A}} = -\left(\frac{\sigma_M \eta_E \eta_C \theta_{AE} \theta_{EM}}{\psi}\right) < 0;$$

(A.1)
$$\frac{\hat{P}_E^N}{\hat{A}} = -\left(\frac{\sigma_E \eta_M \eta_C \theta_{AE} \theta_{EM}}{\psi}\right) < 0;$$

$$\frac{\hat{P}_C}{\hat{A}} = -\left(\frac{\sigma_C \eta_E \eta_M \theta_{AE} \theta_{EM}}{\psi}\right) < 0.$$

Thus, tightening the standard lowers net producer prices. The extent to which total profits for the coal lobby fall depend on how far net producer prices fall:

$$\text{(A.2)} \qquad \frac{\hat{\pi}}{\hat{A}} = \frac{P_M^N M}{\pi}\frac{\hat{P}_M^N}{\hat{A}} + \frac{P_E^N E}{\pi}\frac{\hat{P}_E^N}{\hat{A}} + \frac{P_C C}{\pi}\frac{\hat{P}_C}{\hat{A}} < 0,$$

where we have used (A.1) to sign the derivative. Regardless of the extent to which producers are able to pass through regulatory compliance costs to consumers, profits cannot rise when the standard is tightened.

The effect of increased abatement on pollution depends on how electricity generation responds. We find that a stricter mandate reduces manufacturing and electricity generation:

$$\text{(A.3)} \qquad \frac{\widehat{M}}{\hat{A}} = \hat{E} = -\left(\frac{\eta_M \eta_E \theta_{AE} \theta_{EM}}{\psi}\right) < 0.$$

If domestic producers have any ability to pass through costs, the consumer price of manufactured goods rises:

$$\text{(A.4)} \qquad \frac{\hat{P}_M}{\hat{A}} = -\varepsilon_M^{-1}\hat{M} = \left(\frac{\eta_M \eta_E \theta_{AE} \theta_{EM}}{\varepsilon_M \psi}\right) \geq 0.$$

The price increase is larger the more inelastic is excess demand. It can be shown that $\hat{P}_M < \hat{A}$.

Larger Coal Reserves

In the text we note that larger coal reserves imply a larger manufacturing sector and higher emissions, *ceteris paribus*. Here we provide the proof of this assertion for the case of non-traded coal. Totally differentiating our model and solving yields:

$$\text{(A.5)} \qquad \hat{M} = \hat{E} = \left(\frac{\sigma_C \eta_E \eta_M \theta_{CE} \theta_{EM}}{(\sigma_C \eta_E \theta_{CE} + \sigma_E \eta_C)\eta_M \theta_{EM} + \sigma_M \eta_E \eta_C \theta_{EE}}\right) v_C \hat{K}_C > 0,$$

where $v_C > 0$ is the marginal physical product of capital in the coal sector.

Appendix B – 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 C – U.S. vs. German Knowledge Stocks

In this appendix, we examine the sensitivity of the results to the source of our patent data. Given that the U.S. was an early adopter of most regulations and that U.S. firms are a major source of abatement technology, our base specification uses patents granted in the U.S. Moreover, since we are focusing on patents with multiple family members, the U.S. is a logical choice in that its large market makes it a destination for many foreign patents.

Nonetheless, in this appendix we present results using an alternative knowledge stock, on based on patents granted in Germany. Again, we construct the stock using only those patents filed in multiple countries. As shown in table C1, there are few changes. Results for most explanatory variables are nearly identical when using the German knowledge stocks. One notable exception is the interaction between knowledge and import shares for SO_2. This interaction is nearly zero when using the German stocks. Unlike the U.S., Germany was not an early adopter of SO_2 regulations, waiting until 1983 to first enact SO_2 restrictions for coal-fired power plants. Thus, as shown in Popp (2006a), Germany was not a major destination for SO_2 patents until the mid-1980s.

Interestingly, while we might expect a similar effect for stringent NO_X regulations, that does not appear to be the case. In 1983, Germany was also the first country to pass stringent NO_X regulations. However, using the German knowledge stocks for stringent NO_X regulations does not change the effect of knowledge. The key difference is that, even though the U.S. did not have stringent NO_X regulations at the time, many foreign firms chose to file relevant patents in the U.S. as well. This can be seen in Figure 2 of the text, where NO_X post-combustion patents increase dramatically in 1984. Thus, the importance of the U.S. as a destination for foreign patents supports using U.S. patents as the basis for our knowledge stocks.

Table C1 – Sensitivity to Alternative Country for Patent Stocks

Variable	SO2				NOX: Any Reg				NOX: Stringent			
	US		**Germany**		**US**		**Germany**		**US**		**Germany**	
Knowledge Stock	-0.0893	-0.0018	0.0073	0.0634	-0.0258	-0.0253	-0.0418	-0.0432	-0.0044	-0.0139	0.0067	0.0107
	(-2.499)	(-0.064)	(0.297)	(4.567)	(-2.455)	(-2.028)	(-2.369)	(-2.703)	(-0.477)	(-0.997)	(0.491)	(0.895)
Knowledge x Import Share	0.0016		0.0002		0.0004		0.0006		-0.0002		-0.00003	
	(1.849)		(0.214)		(2.198)		(2.180)		(-0.708)		(-0.089)	
Import Share	-0.3554		-0.0676		-0.1095		-0.1633		0.0163		-0.0231	
	(-1.885)		(-0.332)		(-2.043)		(-2.076)		(0.249)		(-0.243)	
Knowledge x Trade Policy		-0.0012		-0.0014		0.0002		0.0001		-0.00005		0.00002
Orientation Index		(-3.009)		(-3.745)		(0.451)		(0.363)		(-0.164)		(0.072)
Trade Policy Orientation Index		0.2608		0.3407		-0.0613		-0.0548		0.0485		0.0575
		(3.361)		(3.947)		(-0.695)		(-0.503)		(0.815)		(0.984)
World Export Share	0.1618	0.3452	0.3083	0.3055	0.0709	-0.0095	0.0696	0.0417	-0.0022	0.0894	-0.0045	0.1305
	(0.927)	(2.193)	(1.598)	(2.647)	(0.398)	(-0.055)	(0.384)	(0.227)	(-0.017)	(1.237)	(-0.038)	(2.157)
GDP Per Capita	0.3094	0.3144	0.3297	0.3799	0.2104	0.2090	0.2237	0.2227	0.2935	0.3399	0.3071	0.3896
	(3.827)	(4.408)	(3.805)	(5.085)	(2.497)	(2.783)	(2.466)	(2.818)	(3.880)	(5.571)	(4.190)	(5.135)
Population Density	0.0534	0.0345	0.0197	0.0241	0.0806	0.0563	0.0801	0.0491	0.0545	0.0538	0.0610	0.0664
	(1.365)	(1.052)	(0.567)	(0.808)	(2.747)	(1.828)	(2.397)	(1.442)	(1.659)	(1.606)	(1.652)	(2.176)
% Electricity from Coal	0.0447	0.0579	0.0587	0.0488	0.0385	0.0333	0.0446	0.0387	-0.0313	-0.0293	-0.0342	-0.0484
	(1.123)	(1.700)	(1.500)	(1.376)	(0.650)	(0.595)	(0.769)	(0.686)	(-1.041)	(-1.088)	(-1.085)	(-1.543)
Coal Production Per Capita	-0.1545	-0.1165	-0.1561	-0.0864	-0.0561	-0.0120	-0.0550	-0.0144	-0.0146	-0.0123	-0.0147	-0.0144
	(-1.913)	(-1.531)	(-1.838)	(-2.239)	(-1.091)	(-0.285)	(-1.170)	(-0.359)	(-1.269)	(-1.246)	(-1.324)	(-1.364)
Lignite Production Per Capita	0.0529	0.0450	0.0531	0.0491	0.0452	0.0404	0.0428	0.0392	0.0241	0.0374	0.0267	0.0448
	(2.303)	(2.312)	(2.501)	(4.590)	(3.619)	(3.882)	(3.809)	(3.850)	(1.011)	(2.494)	(1.273)	(2.796)
Election Year	-17.080	-15.554	-16.444	-16.065	-18.879	-17.135	-18.470	-17.755	-16.144	-15.255	-18.853	-15.900
	(-23.90)	(-21.74)	(-18.32)	(-22.23)	(-28.34)	(-31.77)	(-31.85)	(-30.61)	(-20.93)	(-24.97)	(-22.69)	(-31.40)
Political Rights	0.0959	0.2396	0.1237	0.4245	0.0990	0.4292	0.1051	0.4373	-0.0265	0.6692	0.1017	0.7731
	(0.375)	(1.136)	(0.734)	(2.207)	(0.535)	(1.916)	(0.512)	(1.864)	(-0.087)	(1.354)	(0.389)	(1.665)
Liberal	-0.6475	-0.4549	-0.2850	-0.3420	-0.7493	-0.9087	-0.7319	-0.9653	-2.2733	-2.0885	-2.1842	-2.6443
	(-0.898)	(-0.589)	(-0.511)	(-0.522)	(-1.423)	(-1.633)	(-1.365)	(-1.755)	(-2.789)	(-1.905)	(-3.055)	(-2.338)
Conservative	-0.5445	-0.6872	-0.2935	-0.2211	-0.6917	-1.1804	-0.6640	-1.1846	-2.0196	-1.9066	-1.9978	-2.2110
	(-0.840)	(-0.798)	(-0.492)	(-0.246)	(-0.969)	(-1.309)	(-0.899)	(-1.269)	(-2.735)	(-2.057)	(-3.202)	(-2.372)
Eastern Europe	(1.607)		(1.448)		(0.275)		(0.597)		(4.422)		(4.067)	
	(2.141)		(1.766)		(0.336)		(0.713)		(2.902)		(2.831)	
Constant	1.301	-16.901	-12.609	-23.972	-9.627	-10.509	-8.731	-12.169	-8.608	-10.420	-7.349	-10.505
	(0.209)	(-3.495)	(-1.525)	(-4.727)	(-2.737)	(-3.003)	(-2.475)	(-2.644)	(-3.118)	(-4.428)	(-2.061)	(-4.227)
Duration dependence	1.8982	1.8204	1.4390	1.1326	1.8407	1.9109	2.0724	2.2521	1.2745	1.3287	0.7484	0.3843
	(9.062)	(7.731)	(4.883)	(3.450)	(6.897)	(8.716)	(6.926)	(9.432)	(5.141)	(4.178)	(3.030)	(0.851)
N	390	327	390	327	380	317	380	317	618	542	618	542
log-likelihood	-3.408	-5.817	-5.721	-4.820	-3.067	-2.935	-2.337	-1.857	-12.337	-9.867	-12.768	-10.134
chi2	1360.76	1291.35	815.21	1891.36	3898.39	5266.31	4694.45	4330.89	741.31	1372.90	828.50	3351.72
aic	38.82	41.63	43.44	39.64	38.13	35.87	36.67	33.71	56.67	49.73	57.54	50.27

T-stats below estimates

Appendix D – Knowledge Stock Sensitivity Analysis

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 rates. To aid in interpreting these rates, we note the number of years it takes for a patent to have its maximum effect under each assumption set. 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 D1 – D3 present regression results for each decay/diffusion combination for each of the three baseline hazards, using the Trade Policy Orientation Index. Results are similar using import shares as our measure of trade policy, and are available from the authors upon request. Table D1 presents these results for adoption of SO_2 regulation. Table D2 presents results for NO_X regulation, and table D3 for 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 decay in the Weibull model (decay = 0.05). Here, the interacted effect of knowledge and TPOI is insignificant[52]. However, the effect of knowledge with this specification occurs more slowly than is usually assumed in the technological change literature. Looking at other variables and at the NO_X technologies, we also see few changes in the main results, suggesting our results are robust to the choice of decay and diffusion.

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[52] Alternatively, when using import shares, the interaction becomes positive and significant using a slow decay rate.

Table D1 – Adoption of SO_2 Regulations: Sensitivity to Decay Rates

	Exponential				*Weibull*				*Gompertz*				*Cox*			
	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05
Variable	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1
Knowledge Stock	0.0795	0.1254	0.0570	0.0290	-0.0018	0.0925	-0.1345	-0.1434	0.0882	0.1235	0.0650	-0.0179				
	(4.623)	(5.768)	(4.463)	(4.260)	(-0.064)	(3.247)	(-2.861)	(-3.660)	(4.870)	(4.868)	(4.172)	(-1.084)				
Knowledge x Trade Policy Orientation Index	-0.0013	-0.0014	-0.0009	-0.0005	-0.0012	-0.0017	-0.0004	0.0003	-0.0013	-0.0019	-0.0009	-0.0005	-0.0009	-0.0011	-0.0007	-0.0004
	(-3.901)	(-2.397)	(-3.696)	(-3.255)	(-3.009)	(-2.178)	(-1.003)	(0.371)	(-3.964)	(-2.472)	(-3.740)	(-2.855)	(-2.254)	(-1.235)	(-1.792)	(-1.458)
Trade Policy Orientation Index	0.2646	0.2148	0.2095	0.1386	0.2608	0.2763	0.1285	-0.0549	0.2587	0.2993	0.2084	0.1327	0.1834	0.1715	0.1492	0.1118
	(4.281)	(2.369)	(4.150)	(3.727)	(3.361)	(2.216)	(1.354)	(-0.256)	(4.168)	(2.599)	(4.113)	(3.493)	(2.054)	(1.184)	(1.652)	(1.345)
World Export Share	0.3075	0.1962	0.3100	0.3017	0.3452	0.2516	0.3209	0.3734	0.2888	0.2383	0.2974	0.3376	0.2071	0.1768	0.2045	0.2044
	(2.024)	(1.906)	(1.966)	(1.865)	(2.193)	(2.195)	(2.351)	(1.456)	(1.969)	(2.128)	(1.895)	(1.902)	(2.168)	(1.785)	(2.157)	(2.185)
GDP Per Capita	0.2920	0.2694	0.2621	0.2190	0.3144	0.3315	0.2978	0.3819	0.2901	0.3060	0.2631	0.2046	0.2873	0.2707	0.2833	0.2813
	(5.496)	(5.803)	(5.280)	(5.076)	(4.408)	(5.025)	(3.925)	(4.112)	(5.632)	(5.329)	(5.513)	(4.457)	(4.334)	(4.289)	(4.342)	(4.338)
Population Density	0.0333	0.0033	0.0329	0.0305	0.0345	0.0138	0.0251	-0.0320	0.0320	0.0098	0.0326	0.0256	0.0299	0.0203	0.0297	0.0304
	(1.019)	(0.118)	(0.989)	(0.910)	(1.052)	(0.455)	(0.743)	(-0.627)	(1.019)	(0.332)	(1.001)	(0.711)	(1.016)	(0.683)	(1.014)	(1.037)
% Electricity from Coal	0.0654	0.0479	0.0648	0.0616	0.0579	0.0459	0.0419	0.0275	0.0640	0.0506	0.0646	0.0584	0.0365	0.0291	0.0362	0.0363
	(2.260)	(1.890)	(2.459)	(2.743)	(1.700)	(1.395)	(1.376)	(0.543)	(2.306)	(1.683)	(2.499)	(2.458)	(1.353)	(1.083)	(1.351)	(1.363)
Coal Production Per Capita	-0.1187	-0.0657	-0.1260	-0.1272	-0.1165	-0.0828	-0.0832	-0.0627	-0.1095	-0.0800	-0.1200	-0.1373	-0.0616	-0.0586	-0.0614	-0.0616
	(-1.506)	(-3.011)	(-1.496)	(-1.468)	(-1.531)	(-2.177)	(-1.898)	(-2.568)	(-1.474)	(-2.372)	(-1.442)	(-1.452)	(-3.271)	(-3.294)	(-3.256)	(-3.228)
Lignite Production Per Capita	0.0435	0.0339	0.0413	0.0365	0.0450	0.0441	0.0395	0.0479	0.0421	0.0403	0.0406	0.0351	0.0394	0.0387	0.0390	0.0387
	(2.329)	(5.934)	(1.880)	(1.435)	(2.312)	(4.356)	(3.551)	(5.100)	(2.478)	(4.762)	(1.984)	(1.126)	(3.296)	(3.337)	(3.287)	(3.263)
Election Year	-14.515	-15.204	-15.721	-15.200	-15.554	-15.772	-17.838	-14.111	-15.334	-16.841	-14.813	-15.093				
	-23.239	-21.713	-27.771	-28.598	-21.738	-22.164	-21.753	-16.587	-23.815	-23.935	-23.941	-22.448				
Political Rights	0.2726	0.3433	0.2089	0.1384	0.2396	0.3041	0.2013	0.5986	0.2916	0.2954	0.2251	0.0617	0.4029	0.3530	0.3949	0.3922
	(1.460)	(1.884)	(1.091)	(0.707)	(1.136)	(1.598)	(0.870)	(2.020)	(1.598)	(1.561)	(1.219)	(0.265)	(2.236)	(2.034)	(2.169)	(2.115)
Liberal	-0.243	-0.547	-0.338	-0.481	-0.455	-0.399	-0.885	-0.927	-0.242	-0.428	-0.320	-0.623	-0.113	-0.222	-0.120	-0.121
	(-0.342)	(-1.016)	(-0.470)	(-0.682)	(-0.589)	(-0.596)	(-1.041)	(-1.208)	(-0.350)	(-0.664)	(-0.459)	(-0.824)	(-0.186)	(-0.361)	(-0.198)	(-0.200)
Conservative	-0.3090	-0.2463	-0.3922	-0.4608	-0.6872	-0.2229	-1.0525	-0.1291	-0.2837	-0.1671	-0.3719	-0.5576	-0.3213	-0.2884	-0.3388	-0.3586
	(-0.349)	(-0.333)	(-0.460)	(-0.564)	(-0.798)	(-0.262)	(-1.036)	(-0.114)	(-0.323)	(-0.206)	(-0.437)	(-0.692)	(-0.382)	(-0.345)	(-0.406)	(-0.433)
Constant	-19.1180	-21.9469	-15.4686	-10.8258	-16.9006	-23.5840	-11.1304	-23.0969	-19.8302	-23.5336	-16.2342	-6.1782				
	(-4.828)	(-5.571)	(-4.665)	(-4.556)	(-3.495)	(-4.450)	(-2.592)	(-2.516)	(-5.489)	(-4.892)	(-5.401)	(-2.685)				
Duration dependence					1.8204	1.1655	2.7502	3.1984	-0.0842	0.1489	-0.0804	0.7050				
					(7.731)	(4.112)	(11.665)	(13.707)	(-0.710)	(1.627)	(-0.629)	(2.816)				
N	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327	327
log-likelihood	-10.092	-8.001	-11.834	-14.247	-5.817	-5.654	0.576	7.600	-9.973	-7.047	-11.764	-12.639	-34.044	-34.444	-34.134	-34.166
chi2	1583.915	1867.539	1710.736	1478.017	1291.352	1777.513	1194.520	1159.447	1747.707	2040.908	1507.989	970.675	84.002	77.320	86.470	88.989
aic	48.184	44.001	51.669	56.493	41.634	41.308	28.849	14.799	49.946	44.094	53.527	55.278	90.088	90.888	90.269	90.331

t-statistics below estimates

Table D2 – Adoption of NO_X Regulations: Sensitivity to Decay Rates

	Exponential				*Weibull*				*Gompertz*				*Cox*			
Variable	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.05 Diff.=0.5	Decay=0.05 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.05 Diff.=0.5	Decay=0.05 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.05 Diff.=0.5	Decay=0.05 Diff.=0.1	Decay=0.1 Diff.=0.25	Decay=0.25 Diff.=0.5	Decay=0.05 Diff.=0.5	Decay=0.05 Diff.=0.1
Knowledge Stock	0.0136	0.0207	0.0128	0.0100	-0.0253	-0.0140	-0.0236	-0.0235	-0.0711	-0.0060	-0.0701	-0.0790				
	(2.393)	(2.907)	(2.521)	(2.531)	(-2.028)	(-1.073)	(-2.042)	(-2.102)	(-2.781)	(-0.564)	(-2.791)	(-2.522)				
Knowledge x Trade Policy Orientation Index	-0.0002	-0.0003	-0.0002	-0.0002	0.0002	0.0000	0.0001	0.0001	0.0003	-0.0002	0.0003	0.0004	-0.0003	-0.0004	-0.0003	-0.0002
	(-1.327)	(-1.790)	(-1.422)	(-1.437)	(0.451)	(0.002)	(0.425)	(0.476)	(0.742)	(-0.747)	(0.740)	(0.857)	(-0.781)	(-1.278)	(-0.854)	(-0.786)
Trade Policy Orientation Index	0.0570	0.0769	0.0580	0.0528	-0.0613	-0.0084	-0.0593	-0.0695	-0.1058	0.0455	-0.1084	-0.1500	0.0156	0.0331	0.0189	0.0153
	(1.559)	(2.160)	(1.640)	(1.565)	(-0.695)	(-0.120)	(-0.679)	(-0.716)	(-0.883)	(0.955)	(-0.885)	(-0.964)	(0.202)	(0.532)	(0.252)	(0.199)
World Export Share	0.2330	0.2648	0.2344	0.2248	-0.0095	0.0327	-0.0081	-0.0072	-0.0712	0.1576	-0.0751	-0.0715	0.0199	0.0378	0.0224	0.0185
	(2.202)	(2.202)	(2.227)	(2.238)	(-0.055)	(0.256)	(-0.046)	(-0.039)	(-0.418)	(1.584)	(-0.425)	(-0.359)	(0.170)	(0.333)	(0.193)	(0.159)
GDP Per Capita	0.1441	0.1616	0.1465	0.1427	0.2090	0.2210	0.2095	0.2053	0.2110	0.1813	0.2132	0.2039	0.1836	0.1909	0.1847	0.1834
	(3.649)	(4.232)	(3.705)	(3.615)	(2.783)	(3.486)	(2.762)	(2.649)	(3.014)	(4.576)	(2.952)	(2.629)	(3.661)	(3.729)	(3.675)	(3.669)
Population Density	0.0286	0.0379	0.0300	0.0288	0.0563	0.0584	0.0564	0.0552	0.0601	0.0420	0.0607	0.0600	0.0726	0.0780	0.0735	0.0725
	(1.069)	(1.338)	(1.122)	(1.110)	(1.828)	(1.931)	(1.822)	(1.776)	(2.052)	(1.490)	(2.055)	(2.132)	(2.280)	(2.426)	(2.310)	(2.291)
% Electricity from Coal	0.0470	0.0496	0.0474	0.0476	0.0333	0.0337	0.0339	0.0338	0.0278	0.0351	0.0281	0.0283	0.0454	0.0512	0.0463	0.0452
	(2.374)	(2.215)	(2.365)	(2.468)	(0.595)	(0.729)	(0.600)	(0.580)	(0.494)	(1.183)	(0.485)	(0.423)	(1.533)	(1.773)	(1.569)	(1.526)
Coal Production Per Capita	-0.1079	-0.1265	-0.1092	-0.1050	-0.0120	-0.0292	-0.0117	-0.0117	-0.0091	-0.0872	-0.0076	-0.0120	-0.0323	-0.0358	-0.0328	-0.0319
	(-1.420)	(-1.267)	(-1.412)	(-1.472)	(-0.285)	(-0.700)	(-0.278)	(-0.273)	(-0.205)	(-1.210)	(-0.170)	(-0.268)	(-0.782)	(-0.841)	(-0.792)	(-0.780)
Lignite Production Per Capita	0.0292	0.0348	0.0299	0.0289	0.0404	0.0397	0.0403	0.0407	0.0417	0.0369	0.0422	0.0455	0.0377	0.0379	0.0378	0.0378
	(1.198)	(1.090)	(1.203)	(1.262)	(3.882)	(3.932)	(3.864)	(3.791)	(3.774)	(1.707)	(3.733)	(3.291)	(2.796)	(2.750)	(2.797)	(2.811)
Election Year	-15.0823	-14.4341	-15.0764	-15.0990	-17.1346	-17.7591	-16.8702	-17.6926	-18.3086	-16.1965	-19.4010	-16.8282				
	(-29.416)	(-26.351)	(-29.503)	(-29.838)	(-31.771)	(-35.503)	(-31.164)	(-32.186)	(-33.244)	(-33.858)	(-34.936)	(-28.887)				
Political Rights	0.0964	0.1111	0.0996	0.1037	0.4292	0.3594	0.4316	0.4236	0.5000	0.1814	0.5115	0.4624	0.3357	0.3584	0.3390	0.3352
	(0.538)	(0.597)	(0.553)	(0.584)	(1.916)	(1.675)	(1.912)	(1.856)	(2.103)	(0.893)	(2.105)	(1.949)	(1.732)	(1.822)	(1.748)	(1.738)
Liberal	-0.737	-0.621	-0.732	-0.753	-0.909	-0.877	-0.920	-0.886	-0.969	-0.715	-1.007	-0.871	-0.158	-0.090	-0.150	-0.166
	(-1.078)	(-0.897)	(-1.074)	(-1.106)	(-1.633)	(-1.402)	(-1.645)	(-1.622)	(-1.563)	(-1.046)	(-1.592)	(-1.423)	(-0.295)	(-0.170)	(-0.280)	(-0.310)
Conservative	-0.6401	-0.5830	-0.6483	-0.6674	-1.1804	-1.1891	-1.1922	-1.1452	-1.2399	-0.8048	-1.2765	-1.0643	-1.0445	-1.0608	-1.0481	-1.0455
	(-0.879)	(-0.793)	(-0.889)	(-0.919)	(-1.309)	(-1.367)	(-1.313)	(-1.262)	(-1.267)	(-1.021)	(-1.280)	(-1.118)	(-1.422)	(-1.432)	(-1.427)	(-1.428)
Constant	-6.2063	-7.5837	-6.2449	-5.8621	-10.5093	-10.3516	-10.9468	-11.2173	-0.2848	-5.6261	-0.6283	0.3106				
	(-4.083)	(-3.944)	(-4.136)	(-4.227)	(-3.003)	(-4.376)	(-3.082)	(-2.871)	(-0.073)	(-3.004)	(-0.159)	(0.064)				
Duration dependence					1.9109	1.6724	1.9397	2.0028	1.4319	0.3910	1.5630	1.9369				
					(8.716)	(9.230)	(8.728)	(8.718)	(4.465)	(3.450)	(4.410)	(3.687)				
N	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317
log-likelihood	-18.698	-16.884	-18.442	-18.690	-2.935	-5.996	-2.784	-1.975	-0.502	-12.319	0.276	3.270	-39.754	-39.451	-39.711	-39.756
chi2	1470.263	1392.189	1492.206	1494.090	5266.314	6079.087	5085.732	5425.181	6290.330	2671.893	6956.901	5785.787	76.050	78.289	76.746	76.480
aic	65.396	61.768	64.884	65.381	35.870	41.992	35.567	33.949	31.004	54.639	29.448	23.460	101.508	100.902	101.422	101.511

t-statistics below estimates

Table D3 – Adoption of Stringent NO_X Regulations: Sensitivity to Decay Rates

	Exponential				*Weibull*				*Gompertz*				*Cox*			
	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05	Decay=0.1	Decay=0.25	Decay=0.05	Decay=0.05
Variable	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1	Diff.=0.25	Diff.=0.5	Diff.=0.5	Diff.=0.1
Knowledge Stock	0.0117	0.0190	0.0098	0.0071	-0.0139	0.0089	-0.0255	-0.0354	0.0131	0.0191	0.0070	-0.0636				
	(2.135)	(2.344)	(1.975)	(1.599)	(-0.997)	(0.481)	(-1.529)	(-1.919)	(1.147)	(1.866)	(0.604)	(-2.295)				
Knowledge x Trade Policy Orientation Index	-0.0001	0.0001	-0.0001	-0.0001	0.0000	0.0003	-0.00004	-0.0001	-0.0001	0.0001	-0.0001	-0.0002	0.000003	0.0007	-0.00002	-0.0001
	(-0.892)	(0.228)	(-0.880)	(-0.965)	(-0.164)	(0.412)	(-0.136)	(-0.317)	(-0.935)	(0.201)	(-0.835)	(-0.400)	(0.007)	(0.808)	(-0.049)	(-0.334)
Trade Policy Orientation Index	0.0915	0.0569	0.0906	0.0943	0.0485	-0.0047	0.0383	0.0523	0.0926	0.0575	0.0887	0.0615	0.1107	-0.0514	0.1157	0.1355
	(2.033)	(0.955)	(1.991)	(1.924)	(0.815)	(-0.028)	(0.556)	(0.498)	(1.998)	(0.953)	(1.920)	(0.695)	(1.208)	(-0.283)	(1.279)	(1.618)
World Export Share	0.1469	0.1542	0.1448	0.1439	0.0894	0.1314	0.0751	0.0586	0.1488	0.1543	0.1412	0.0971	0.2348	0.2200	0.2357	0.2400
	(2.729)	(2.900)	(2.717)	(2.689)	(1.237)	(2.062)	(0.896)	(0.459)	(2.573)	(2.965)	(2.488)	(1.184)	(2.525)	(2.270)	(2.536)	(2.571)
GDP Per Capita	0.3278	0.4348	0.3203	0.3006	0.3399	0.4440	0.3550	0.5140	0.3297	0.4346	0.3167	0.3157	0.7267	0.7597	0.7254	0.7199
	(5.786)	(4.572)	(5.976)	(6.251)	(5.571)	(4.468)	(4.912)	(3.035)	(5.541)	(4.585)	(5.898)	(4.632)	(1.792)	(1.672)	(1.803)	(1.851)
Population Density	0.0565	0.0790	0.0550	0.0507	0.0538	0.0768	0.0534	0.0830	0.0569	0.0791	0.0541	0.0415	0.1413	0.1423	0.1415	0.1426
	(1.766)	(2.709)	(1.709)	(1.554)	(1.606)	(2.557)	(1.528)	(1.831)	(1.790)	(2.693)	(1.686)	(1.105)	(1.919)	(1.767)	(1.932)	(1.983)
% Electricity from Coal	-0.0247	-0.0643	-0.0219	-0.0124	-0.0293	-0.0685	-0.0293	-0.0480	-0.0252	-0.0642	-0.0208	-0.0162	-0.1187	-0.1293	-0.1182	-0.1161
	(-0.947)	(-1.875)	(-0.867)	(-0.521)	(-1.088)	(-1.899)	(-1.022)	(-1.304)	(-0.934)	(-1.869)	(-0.807)	(-0.552)	(-1.201)	(-1.145)	(-1.207)	(-1.231)
Coal Production Per Capita	-0.0189	-0.0119	-0.0189	-0.0198	-0.0123	-0.0113	-0.0104	-0.0035	-0.0190	-0.0118	-0.0186	-0.0121	-0.0123	-0.0088	-0.0124	-0.0131
	(-1.452)	(-1.068)	(-1.473)	(-1.479)	(-1.246)	(-1.094)	(-1.022)	(-0.285)	(-1.423)	(-1.046)	(-1.487)	(-1.088)	(-0.614)	(-0.480)	(-0.618)	(-0.644)
Lignite Production Per Capita	0.0345	0.0526	0.0333	0.0298	0.0374	0.0535	0.0405	0.0658	0.0348	0.0526	0.0327	0.0359	0.0911	0.0936	0.0910	0.0905
	(2.706)	(2.787)	(2.704)	(2.661)	(2.494)	(2.780)	(2.285)	(2.179)	(2.698)	(2.790)	(2.690)	(2.053)	(1.565)	(1.468)	(1.575)	(1.615)
Election Year	-14.9902	-15.7237	-15.2255	-14.5779	-15.2547	-16.5188	-16.0579	-15.1527	-16.4804	-16.5448	-15.8176	-15.6594				
	(-28.785)	(-30.328)	(-28.898)	(-26.905)	(-24.973)	(-31.592)	(-24.264)	(-17.469)	(-33.165)	(-31.202)	(-30.814)	(-23.207)				
Political Rights	0.4780	0.8923	0.4495	0.3517	0.6692	0.9576	0.7721	1.4017	0.4811	0.8914	0.4436	0.6608	1.8426	1.9809	1.8340	1.7934
	(0.959)	(1.823)	(0.891)	(0.658)	(1.354)	(2.043)	(1.375)	(1.654)	(0.966)	(1.855)	(0.888)	(1.037)	(1.239)	(1.232)	(1.241)	(1.249)
Liberal	-2.402	-3.171	-2.339	-2.233	-2.089	-3.007	-2.127	-2.989	-2.435	-3.174	-2.280	-1.881	-4.629	-4.776	-4.621	-4.585
	(-2.259)	(-3.047)	(-2.209)	(-2.137)	(-1.905)	(-2.672)	(-1.906)	(-2.528)	(-2.182)	(-3.030)	(-2.058)	(-1.577)	(-1.988)	(-1.824)	(-1.999)	(-2.040)
Conservative	-1.9210	-2.8491	-1.8640	-1.8029	-1.9066	-2.7095	-2.1587	-3.6638	-1.9593	-2.8542	-1.7992	-1.8815	-4.2242	-4.3725	-4.2211	-4.2131
	(-2.306)	(-3.278)	(-2.228)	(-2.102)	(-2.057)	(-2.800)	(-2.034)	(-2.236)	(-2.116)	(-3.217)	(-1.944)	(-1.553)	(-2.249)	(-2.117)	(-2.260)	(-2.307)
Constant	-8.7548	-10.8984	-8.4417	-7.7553	-10.4197	-10.6116	-12.1625	-20.3600	-8.8779	-10.9064	-8.1972	-4.0325				
	(-4.484)	(-3.854)	(-4.526)	(-4.403)	(-4.428)	(-2.879)	(-4.696)	(-2.970)	(-4.144)	(-3.839)	(-4.041)	(-1.081)				
Duration dependence					1.3287	0.4738	1.7494	2.3373	-0.0169	-0.0019	0.0401	1.4694				
					(4.178)	(1.225)	(5.408)	(6.238)	(-0.127)	(-0.027)	(0.243)	(2.903)				
N	542	542	542	542	542	542	542	542	542	542	542	542	542	542	542	542
log-likelihood	-12.239	-9.368	-12.457	-13.107	-9.867	-8.903	-8.714	-4.509	-12.234	-9.368	-12.439	-7.511	-20.563	-20.361	-20.563	-20.547
chi2	1403.420	2480.548	1374.423	1147.671	1372.902	3216.914	1522.633	1372.034	2243.544	2895.016	1754.371	1548.240	82.794	70.432	83.343	85.827
aic	52.477	46.736	52.914	54.215	49.734	47.806	47.428	39.019	54.467	48.736	54.879	45.022	63.127	62.722	63.126	63.095

t-statistics below estimates