ESSAYS ON ENVIRONMENTAL POLICIES AND INTERNATIONAL COMPETITIVENESS

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ABSTRACT

As awareness about the existence and the effects of climate change and local pollution rises, governments increasingly enact environmental policies. These policies are not without consequence for an economy, but empirical evidence of these effects is limited. My thesis sheds light on the relationship between environmental policies and international competitiveness.

In the first chapter, I address the claim that environmental policies stimulate domestic economies. I parse the claim into two sequential parts: the effect of policies on innovation and the effect of that innovation on manufacturing production. Innovation and manufacturing can either take place at home or abroad, and where they take place determines the consequences for the domestic economy. The empirical evidence is based on measures of policy, patent activity, and trade in the renewable energy sector of 27 OECD countries between 1988 and 2003. The results suggest that an additional policy is associated with a significant rise in the adoption of foreign technologies, but few new inventions at home. In turn, however, the increase in patent filings is associated with a significant growth in manufacturing production, suggesting that at least some portion of the inputs into renewable technologies are produced domestically. Therefore, there is evidence that renewable energy policies stimulate domestic economies through manufacturing, but less through innovation.

My second chapter focuses on another widely debated consequence of environmental policies: the industrial flight of polluting industries. Between 1995 and 2008, the European Union raised environmental standards and concurrently experienced important reductions in emissions from manufacturing despite a rise in output. This chapter provides the first analysis of the pollution intensity of EU imports and manufacturing production to examine which forces drove the EU cleanup. I find that emission reductions in EU manufacturing were not due to the industrial flight of polluting industries, but instead can be attributed to large improvements in production techniques.

The final chapter, co-authored with Arik Levinson, identifies the data and conceptual challenges of measuring the stringency of environmental policies, a central issue for any paper that studies the effects of environmental policies. In this paper, we also propose an improved emissions-based measure of stringency.

INDEX WORDS: Environmental Policies, Environment and growth, Technological innovation, Trade, Globalization, Renewable energies.

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Chapter 1

Green Innovation and Green Manufacturing: Links between Environmental Policies, Innovation, and Production

1.1 Introduction

As countries attempt to grow and compete in an increasingly global economy while tackling environmental challenges, the so-called "green economy" has become an appealing way of addressing both concerns. Policy discussions regarding the relationship between the environment and growth used to focus on the trade-off between environmental protection and economic growth. But in many countries these discussions now emphasize the potential complementarities between addressing environmental issues and stimulating economic growth. Politicians make grand claims about a 'win-win' scenario where environmental policies contribute not only to improving the environment but also to encouraging firms to innovate and produce green technologies.[1] In March 2009, then-Director of the National Economic Council Lawrence Summers stated: "The evidence is clear: we can choose to lead [green] industries, with all the commensurate economic and political and environmental benefits, or we can choose to lose out on these jobs and these opportunities" (White House, 2009). On multiple occasions, President Obama has addressed the need to switch to renewable energy sources claiming that "America cannot resist this transition, we must lead it" (White House, 2013), and that he expected "those new energy sources to be built

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[1] This argument is related to the Porter Hypothesis (Porter 1991).

right here in the United States" (White House 2012). These claims represent just a few examples of a widespread rhetoric which asserts that a country that implements environmental policies will benefit from increased output and job creation at home, and will then export environmental technologies to other countries that adopt similar policies later on.

While the environmental goal is laudable, the link between environmental policies and domestic economic stimulus remains uncertain. In fact, this link relies crucially on green technologies being developed domestically and inputs into those technologies being manufactured at home. But economists are often skeptical that environmental policies will necessarily lead to domestic innovation and manufacturing. On the one hand, trade theory suggests that green technologies should be produced in countries that have a comparative advantage, be it through policies or other inherent characteristics of their economy. On the other hand, empirical work documents a home bias in production and trade which suggests that environmental technologies might be disproportionately produced at home.

To evaluate the claim that environmental policies stimulate the domestic economy through innovation and the production and trade of technologies, I provide empirical evidence focusing on the renewable energy sector of OECD countries. The results suggest that environmental policies lead to a rise in the adoption of foreign technologies but few new inventions at home. Through this innovation channel, policies are in turn associated with around a significant rise in the domestic production of renewable technologies. Therefore, renewable energy policies appear to boost domestic economic activity through the manufacturing of renewable energy technologies, but much less through innovation.

I identify four potential outcomes of policies. These outcomes are combinations of two activities – innovation and manufacturing – and two locations where activities can take place – domestic or foreign (Figure 1.1). To be adopted on the domestic market, a technology can either be developed by a domestic firm ('domestic technology'), or developed abroad and patented in the domestic market ('foreign technology'). Foreign technologies can be new technologies created in response to a domestic policy, or transfers of existing technologies that were previously developed perhaps in response to a policy change in a foreign country. In either case, the domestic market is adopting a foreign technology rather than innovating at home. The link between environmental policies and innovation has been studied, but the literature that touches on the differences between domestic and foreign technologies is limited. In the first part of this paper, using patent data as a measure of innovation and technology adoption, I present evidence of the degree to which environmental policies stimulate the development of domestic technologies compared to the licensing of foreign technologies. I test the robustness of my results with different measures of policies: an overall measure, a measure by policy type, and a measure which quantifies differences across countries for a specific policy.

When a technology is patented in a country, the technology and its inputs can either be produced at home or imported from other countries. If the technologies are produced at home, manufacturing output increases. If the equipment and inputs are produced abroad and imported, environmental policies could potentially have little effect on manufacturing output. To identify renewable energy technologies and their inputs requires data using a detailed classification of manufacturing production, which is not available for all the countries in my dataset. Therefore, I proxy manufacturing production with exports to examine whether technological innovation led to an increase in the domestic production of renewable technologies or the inputs into those technologies. The effect of innovation on exports also allows me to address the part of the claim which suggests that environmental policies and increased innovation will improve competitiveness. To fully address the competitiveness angle, I compare the effect of innovation on exports to the effect on imports.

To date, few papers examine the effect of environmental policies on trade, and no paper attempts to estimate whether environmental policies can stimulate the trade of environmental technologies through innovation. Hence, the second part of this project fills an important gap in the literature by estimating how exports and imports of technology-specific inputs respond to a change in environmental patents. Policies could also affect the production of technologies directly without going through innovation, and I test this direct channel as well. Finally, examining the effect of innovation on production allows me to address a potential concern of patents as a measure of innovation and technology adoption. Patents could be filed for strategic rather than commercial reasons in order to stifle competition. If that was the case, I should observe no effect of a rise in innovation on manufacturing production.

Combining the two steps allows me to identify the relative importance of each of four scenarios that might occur as a result of additional environmental policies. 1) The technology was developed at home, and the inputs were manufactured at home. This scenario would provide strong evidence that enacting environmental policies stimulates the economy in environmental sectors. 2) The technology was licensed from abroad, and the inputs imported from abroad. This channel would imply that policies create little direct domestic stimulus, despite the environmental benefits and potential positive spillovers from foreign innovation and imports. 3) The technology was developed domestically but the inputs were imported. 4) Or the technology was developed abroad and the imports were manufactured at home. The last two channels would provide only partial evidence that environmental policies stimulate the economy and differ importantly in what sector and types of occupations benefit.

The questions I pose can be answered by examining the renewable energy sector, which includes solar, wind, biomass, and geothermal, for 27 OECD countries from 1988 to 2003. OECD countries offer an interesting sample because they provide ample variation in environmental policy stringency, renewable energy capacity, innovative activity, and level of economic development. Focusing on one sector allows me to identify specific technologies, the inputs into their production, and the policies that regulate the sector, all of which are necessary to complete the proposed analysis.

While this study focuses on the renewable energy sector, the framework is easily replicable and the conclusions may contribute to the wider debate on the effect of policies on innovation, production and trade. However, renewable energy policies and environmental policies generally differ from other types of policies aimed at promoting the development of local industries. Because the deterioration of the environment is a global and long-term concern, the trend towards environmentally sustainable production practices will only intensify. Countries that move first and develop the technologies early may have a competitive advantage to export these technologies once other countries follow suit. This competitiveness gain is an important element of the green economy strategy.

Finally, it is worth noting the limits of this study. I do not provide a welfare analysis of environmental policies. There could be substantial spillovers of foreign innovation and foreign production into the domestic economy. Or innovation and manufacturing in renewables could be crowding out activity in other sectors. Neither channel is captured in this analysis. Moreover, I am not making a judgment on the environmental benefits of these policies. The renewable energy policies I study in this paper could succeed or fail in achieving their environmental goals. My objective in this paper is to evaluate the policy claims that renewable energy policies will lead to increased domestic innovation and manufacturing of renewable energy technologies.

These claims are abundant in policy debates, and in fact the supposed economic benefits are sometimes presented as the primary goal of environmental policies, yet empirical evidence of the veracity of the claims is limited.

1.2 Context and Existing Literature

1.2.1 Links to the Porter Hypothesis

The question I pose in this paper is related to the Porter Hypothesis. In its “weak” version, the Porter Hypothesis claims that properly-designed environmental regulation may spur innovation, be it in the form of new technologies or changes to production processes. This version does not take a stance on whether the innovation will make firms more competitive, it simply states that some policies could lead to increased innovation. In the first portion of the paper, I contribute to the evidence on the “weak” Porter Hypothesis by asking how innovation responds to environmental policies depending on the origin of the inventor. Determining the origin of innovation allows me to specifically address claims that innovation spurred by environmental regulation will be domestic.

In the “strong” version, the Porter Hypothesis suggests that the benefits from policy-induced innovation will offset the cost of regulation and increase the competitiveness of companies. If firms are unaware of profit-maximizing opportunities in pollution reductions, environmental regulation might help them identify inefficiencies and encourage them to address these inefficiencies through the production and dissemination of technologies. Firms might not identify or implement profitable pollution abatement opportunities if managers have motivations and objectives other than profit-maximization. Similarly, asymmetric information, R&D spillovers, and imperfect competition may lead to sub-optimal investment in innovation (Ambec et.

al. 2013). In the second portion of the paper, I ask whether a rise in innovation translates into increased domestic production or imports, which addresses the global competitiveness portion of the hypothesis at the country-level.

1.2.2 Incorporating the Origin of Inventions into a Vast Literature

A policy could potentially affect three types of technology adoption: innovation in the country where the policy is implemented, innovation in other countries, and the transfer of technologies across countries. The first channel has been studied extensively using various measures of policy stringency and innovation. For example, Lanjouw and Mody (1996), Jaffe and Palmer (1997), and Brunnermeier and Cohen (2003) use pollution abatement costs as a measure of policy stringency to study the effect of policies on innovation. The results suggest that environmental policies do not have an effect on total R&D expenditure (Jaffe and Palmer 1997), but do significantly increase filings of environmental patents (Lanjouw and Mody 1996, Brunnermeier and Cohen 2003). Other papers use energy prices as a measure of stringency and find that higher energy prices induce innovation in energy-efficient technologies (Newell et al. 1999; Popp 2002; Crabb and Johnson, 2010). Alternatively, Johnstone et al (2010) studies the effect of different policy types on innovation and generally shows that more stringent environmental public policies spur patenting activity in renewables. These papers, however, look at total patent filings in a country without distinguishing between innovation that is developed by domestic or foreign inventors. Therefore, they cannot address the policy claim that policies will spur innovation by domestic inventors.

Patents owned by foreign inventors can represent a very large proportion of total patent filings in a country, even in highly innovative economies. Yet relatively few papers examine the links between domestic policies and either new foreign innovation or transfers of existing foreign technologies. Evidence on whether foreign inventors respond to domestic policies is mixed. Comparing the patterns of policy enactment with the patterns of patenting activity, Popp (2006) does not find that domestic regulation on air pollution control encourages patenting in foreign countries. Peters et al. (2012) suggests that some types of regulation spur foreign innovation in the solar industry. Dechezleprêtre and Glachant (2012) concludes that domestic regulation can spur innovation filed abroad, but the effect of domestic regulation on patents filed at home is 25 times higher than on patents filed abroad.

Still, if some countries have already developed relevant technologies, perhaps in response to their own regulation, other countries can license these technologies or build on this innovation. Popp (2006) finds US pollution control innovation was more likely to build on earlier Japanese and German patents when the United States introduced emissions standards later than Japan and Germany. Dechezleprêtre et al. (2013) finds that the stringency of renewable energy policies - proxied by installed capacity of renewable energies - has a small but positive effect on the transfers of patents across countries.

Only one paper distinguishes patents based on the origin on the inventor. Lee et. al. (2011) studies the effect of US automobile performance standards on firm-level innovation, where regulatory stringency is proxied by regulatory expenditures for the industry. In this context, the authors interact the stringency measure with a dummy for domestic firms and find mixed results. In the beginning of their time period, domestic firms appear to be more responsive to regulation than foreign firms, while at the end there is no significant difference between domestic and foreign patenting responses. The broader applicability of their study may be limited, however, due to data constraints that require the authors to restrict the analysis to the top 15 innovative auto companies in the US patent office.

In the first part of this paper, I provide the first cross-country study of the effect of environmental policies on patent filings comparing the effect on patents filed by domestic inventors to those filed by foreign inventors. In sum, this portion combines existing branches of the literature on the effect of policies on different kinds of innovation to create a framework which allows me to test the claim that environmental policies will increase domestic innovative output.

My approach has several advantages over existing work. First, the number of environmental policies enacted in one country in one year in one industry is low, and thus limiting the analysis to one country may not provide enough identifying variation. I exploit variation across time and countries to identify the effect of policies on innovation. Second, most existing work – with the exception of Lanoie et al. (2008) – only examines the contemporaneous effects of policies. Since firms might respond to policies with a lag, I estimate the longer-term effects of policies on innovation. Last but not least, the literature to date generally does not address the endogeneity of environmental policy stringency measures. For example, political economy factors such as the rise of a green party to power could be the source of simultaneous causality. In some robustness checks, I examine the consequences of treating the stringency measure as endogenous.

1.2.3 Sparse Evidence on the Links between Environmental Innovation and Trade

Empirical studies of the links between environmental policies and the competitiveness of firms or industries can be divided into two groups. On the one hand, most papers interested with country-level competitiveness investigate the opposite of the Porter Hypothesis: the claims that environmental policies will impose on companies costs that are high enough to lead them to offshore production to countries with laxer environmental standards (Clark, Marchese, and Zarrilli 2000, Xing and Kolstad 2002, Copeland and Taylor 2004, Brunnermeier and Levinson 2004). On the other hand, evidence of the “strong” version of the Porter Hypothesis focuses on firm-level analysis of the effect of policies on productivity and business performance (see for example Gollop and Roberts 1983, Berman and Bui 2001, Greenstone 2002). But few of these studies identify the source of the change in business performance (Ambec et. al. 2013). In the second part of the paper, I study specifically whether the effect of environmental policies on manufacturing production and trade occurs through innovation or other sources.

Lanoie et. al. (2011) stands out as the only paper to examine the channels through which environmental policies affect firm performance. Using a survey of firms in seven OECD countries which includes perceived environmental stringency and estimated environmental R&D expenditures as a measure of innovation, Lanoie et. al. (2011) provides a comprehensive analysis of the different versions of the Porter Hypothesis. This paper finds that policies spur innovation, and policy-induced innovation has a positive effect on business performance. Given the cross-sectional nature of the data, the authors are not able to control for unobservable firm heterogeneity and are restricted to binary measures of environmental innovation and business performance.

I focus on country-level competitiveness. Having identified the domestic and foreign innovation responses to environmental policies in the first section, I then turn to evaluating the links between environmental innovation and trade. Generally, studies of the relationship between environmental innovation and trade focus on the potential for trade as a vehicle for technology transfer (for a review, see Keller 2004). In a more recent example, Bloom et al. (2011) establishes that EU sectors that were most affected by import competition from China were more innovative. Batrakova and Dechezleprêtre (2013), on the other hand, finds that “dirty” imports from China decreases firms' propensity to innovate in Ireland. However, to the best of my knowledge no paper attempts to estimate how environmental innovation stimulates the trade of environmental technologies. I fill that gap in the literature by examining the links between innovation and the trade of renewable technologies. Combining the two sections of my paper will provide the first evidence of the causal chain between environmental policies and trade.

1.3 Environmental Regulation and the Origin of Technologies

To estimate the links between environmental policies and the adoption of technologies, I need a measure of innovation and a measure of environmental policies. The next subsections describe how those variables are created. I then explain the estimation procedure and present the results.

1.3.1 Policy Measure

For this analysis, I need a measure of the policies specific to renewable energies which varies across countries and time. As shown in Brunel and Levinson (2015), there are many obstacles to measuring policies and all currently used measures have their own drawbacks. For example, many previous studies use pollution abatement costs, but countries or states with more polluting industries will spend more on pollution abatement even if each has implemented the same policy. Few measures are available across countries, vary over time, and are technology specific. As a result, and consistent with a number of papers in the literature, I start with a simple count of the number of policies enacted in country i at time t that are aimed at developing renewable energy sources.[2]

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[2] European Union countries get an extra count for each policy implemented at the European Commission level.

The IEA/IRENA Global Renewable Energy Policies and Measures Database provides a record of such measures for all OECD countries. These measures can be research and development (R&D) incentives, investment incentives, taxes, tariffs, voluntary programs, obligations, and tradable permits. Apart from R&D policies, most policies do not explicitly provide incentives for innovation. However, the policies decrease the relative price of the use of renewables compared to fossil fuels, or increase demand for renewable energy. In doing so, the policies supply implicit incentives for innovation.

The simple count has the advantage of being transparent, but it weighs each policy type equally so I also present results breaking down this total count into different policy type to allow for tax incentives and R&D incentives to have different effects. Figure 1.2 presents a graphical representation of the introduction of relevant policy measures in the OECD until 2003. Each point on the graph represents the time of introduction of a measure in a particular country. Clearly, countries vary both in the timing and the type of policy instruments used. Table 1.1 presents the summary statistics of the policy stringency variable. On average, countries enact 0.635 policies aimed at promoting the use of renewable energies each year. Most of these policies are economic instruments, and to a lesser extent policy support and regulatory instruments.

However, even the breakdown by policy is an imperfect measure. The same policy can vary significantly across countries. For example, in 2000 Denmark implemented a feed-in-tariff for wind production of 0.058 euros per kilowatt-hour. In the same year, Germany set up a feed-in-tariff of 0.091 euros per kilowatt-hour of wind. The count measure assigns the same weight to both. In an attempt to quantify these differences across countries, I use data on wind feed-in-tariffs for seven countries in my dataset: Austria, Denmark, France, Germany, Slovak Republic, Spain, and Switzerland. [3]

1.3.2 Innovation and Adoption of Technologies

In addition to the measure of policies, for this analysis I need a measure of innovation. I use patent data to measure innovation and adoption of new technologies in each OECD country. The data come from the PATSTAT database (EPO 2012) which includes all patent applications filed at the national patent offices of the 27 OECD countries as well at the European Patent Office (EPO).[4] A patent grants protection for a technology only in the country where it is filed, so inventors will file in as many countries as they desire protection. Domestic patents in country i are defined as the count of renewable energy patents that were filed in the patent office of country i by an inventor residing in country i. Foreign patents are measured as the count of renewable energy patents filed in the patent office of country i by a resident of any other country. For both domestic and foreign patents, I distinguish between patents that represent new inventions - patents that were never filed anywhere else in the world - and patents that are transfers of existing technologies - patents that were first filed abroad.

Patents that seek protection in the European Union can be filed in one of the national patent offices or at the EPO. Until 2004, EPO applications required inventors to specify in which EU member states the patent would be applicable. The cost increased proportionally to the number of countries, providing an incentive for inventors to designate only the countries where the patent would be used. The designation

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[3] The data were compiled by Fan Zhang and Louis Preonas for a project sponsored by the World Bank.

[4] Data extracted from EPO World Patent Statistical Database (PATSTAT) based on extractions developed by Ivan Hascic and colleagues at the OECD Environment Directorate and used in Popp, Hascic and Mehdi (2011).

of states is crucial for my study as I need to assign each patent to individual EU member states. However, designation is only mandatory until the end of 2003, hence my analysis ends in 2003. Data on designated states are no longer part of PATSTAT. I collected this data by hand for over 5,000 EPO patents.

Patent data have the advantage of being classified based on the end-use of the technology in a highly disaggregated form, allowing me to determine exactly which patents are used for the development of each of the four renewable energies. I use the International Patent Classification (IPC) codes presented in Table 1.2 (Popp 2011). It is possible that some codes might include irrelevant technologies, while others might exclude relevant technologies. However, Popp (2011) estimates that these errors are small for renewable energies.

Patents imperfectly measure innovation for several reasons. First, the value of a patent is difficult to estimate. A patent grants the inventor the exclusive right to use the technology, but some patent owners do not exercise that right, while others make abundant use of it domestically and expand protection abroad. Following the literature, I weight each patent by the number of countries in which that invention is patented, also called family size. A patent family is a set of patents taken in various countries to protect a single invention. More valuable inventions are more likely to be part of larger families. This is especially important in my case because domestic and foreign patents could have different values. Figure 1.3 however shows that although the number of foreign patents is higher overall, the distribution of family size follows the same shape for domestic and foreign patents.[5] Second, it is possible for valuable innovation to not be patented. Filing a patent involves publicly disclosing information on the technology. To maintain the secrecy of their innovations, inventors could opt

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[5] There are other ways of accounting for the value of patents. Citations data are another popular measure. Both have been proven to be significantly correlated with patent value, but family size is the main measure used in the literature.

to refrain from patenting their products. Dernis and Khan (2004) show, however, that few valuable innovations are not patented. In spite of the downsides, patents have been found to be an accurate indicator of the knowledge available in a country (Griliches 1990).

Table 1.3 presents the summary statistics for patent counts weighted by family size: total, domestic, and foreign. The mean number of domestic patents is much lower than the mean of foreign patents. This is the case even on a country-by-country basis since large economies that have high innovative capacities also attract a large amount of foreign inventions. And the standard deviations are large for all groups, with many country-year observations at zero, especially for the smaller economies. Figure 1.4 shows the evolution of foreign and domestic patent counts over time for each of the four renewables in my country group. The correlation of domestic and foreign patent counts lie between 0.2 and 0.6 depending on the renewable energy, which indicates that policies might affect domestic and foreign patents differently.

1.3.3 Estimation Procedure

To examine the link between renewable energy policies and innovation distinguishing between domestic and foreign innovation, I estimate the following equations:

$$DomesticPatents_{it} = \beta_1^H POL_{it} + \beta_2^H \boldsymbol{X_{it}} + \gamma_i^H + \delta_t^H + \epsilon_{it}^H \tag{1.1}$$

$$ForeignPatents_{it} = \beta_1^F POL_{it} + \beta_2^F \boldsymbol{X_{it}} + \gamma_i^F + \delta_t^F + \epsilon_{it}^F \tag{1.2}$$

where $DomesticPatents_{it}$ and $ForeignPatents_{it}$ measure adoption of domestic or foreign renewable energy technologies in country i at time t, POL_{it} is one of the three policy measures for country i in year t, $\boldsymbol{X_{it}}$ contains other controls detailed below, and γ_i and δ_t represents country and time fixed effects respectively. The key parameters are β_1^H and β_1^F, which represent the effect of policies on domestic and foreign patent filings respectively. I am interested in comparing these two effects to determine whether environmental policies boost domestic innovation or the licensing of foreign technologies.

The vector $\boldsymbol{X_{it}}$ includes a number of controls. The first two relate to the electricity market. First, according to the induced innovation hypothesis, as the price of substitute factor inputs increases incentives to innovate in the area of renewable energies should increase. To account for the induced innovation channel, I control for the price of electricity obtained from the IEA Energy Price and Taxes Database (IEA 2006a). Because prices for electricity vary depending on whether the electricity is consumed by industry or households, I construct the price variable by weighting the price indices for residential and industrial use by their respective consumption levels as in Johnstone et. al. (2010). Since renewable sources represent a relatively small proportion of total electricity generation over my time period, the price of electricity can be considered exogenous in this context. For the same reason, I do not consider the overall electricity price to be a function of renewable energy policies. Second, I control for potential market size since returns on innovation, and therefore incentives to innovate, are affected by potential demand. For renewables, potential market size can be proxied by electricity consumption, obtained from the IEA Energy Balance Database (IEA 2006b). Again, due to the small proportion of renewables in total electricity production, electricity consumption is assumed to be exogenous.

Other domestic and foreign factors could be affecting patent filings. Patents could be responding to a change of policy abroad. For example, an inventor could develop a technology in response to a policy in another country, and since inventors tend to file in their home countries before filing abroad, domestic patents would increase. Similarly if other countries implement renewable energy policies, that could affect innovation abroad and therefore could change the stock of foreign patents that are available for transfer. Therefore, I include a variable for the count of policies in all countries but the domestic country.[6] Moreover, whether country i invents new technologies or adopts existing technologies depends on how many relevant technologies exist in the world to date and how many have already been adopted in country i. The time fixed effects control for the world stock of renewable energy patents every year. Country fixed effects control for the stock of existing renewable energy patents in each country at the beginning of the time period.

More generally, the time fixed effects control for world trends to shift towards renewable energies in terms of innovation or production. Country fixed effects account for differences in propensity to patent across countries. For example, larger, more developed economies will generally have more domestic capacity for innovation while smaller, less developed economies might rely more intensively on licensing foreign innovation. The number of patents filed in a country could also depend on business climate: countries with more stringent intellectual property rights could have higher number of patents than countries where property rights do not exist or are not enforced.[7]

Finally, I control for time-varying cross-country differences which might affect patenting activity by including a linear country-specific patenting trend. The trend variable accounts for all differences across countries which are relevant to innovation

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[6] Since EU Commission level policies apply to multiple countries, in the case of an EU country a policy implemented at the EU level will count both in the policy variable of country i and in the policy count of all other countries. Therefore, the policies of country i and the policies of all other countries can add up to more than the total number of policies in any given year. As a consequence, time fixed effects are not appropriate to control for policies in foreign countries. The policy count of foreign countries is therefore identified by EU policies.

[7] Evidence on the links between intellectual property rights protection and innovation or technology diffusion is mixed. See Maskus (2010) for a review.

and vary over time. This could be a country-specific shock to economic growth which affects all innovation or a change in intellectual property rights regulation. The trend is calculated as the sum of all patents in country i at time t, excluding energy patents – renewables and otherwise – to limit endogeneity issues.

Despite the abuse of the linear form, I estimate equations (1.1) and (1.2) using a negative binomial since my dependent variable is an overdispersed non-negative count variable. The error terms in equations (1.1) and (1.2) might be contemporaneously correlated. Even though both equations contain the same set of regressors, estimating the two equations separately leads to efficiency losses in the case of count models (King 1989). Therefore, I use a seemingly unrelated negative binomial estimation method as developed by Winkerlmann (2000).

1.3.4 RESULTS

First, I run equations (1.1) and (1.2) on a contemporaneous measure of policy which is the total count of policies enacted in country i in year t (Table 1.4, columns 1 and 2). Before diving into the interpretation of the main coefficient of interest, note that the coefficients on the covariates generally comport with intuition. An increase in the price of electricity or in the demand for electricity have a positive and significant relationship to patent filings. More policies in other countries will increase the number of patent filings at home. This could be because domestic inventors create technologies in response to foreign policies but file at home before transferring their inventions abroad, or it could be that foreign policies spur innovation abroad and thereby boost the number of potential inventions that can be transfered to country i following a policy in country i. Later specifications will shed some light on this question. The coefficient on the patenting trend is negative and significant. One explanation might be that higher innovation in other sectors crowds out innovation in renewables since investment resources are limited.

More central to the question of interest, I find that an additional domestic renewable energy policy is associated with positive but not statistically significant increases of 4.5 percent and 2.3 percent in patent filings by domestic and foreign inventors respectively. The fact that inventors need some time to respond to a policy might explain the small magnitude of these effects. Moreover, contemporaneous policies could be endogenous as firms that have already innovated could lobby for additional environmental policies to promote the use of their technologies. Since firms cannot lobby for past policies and to account for a lag in the response, I run the same regressions with environmental policies at time t-1 (Table 1.4 columns 3 and 4).

I find that the coefficient on renewable energy policies is positive and significant for foreign patents, but small and not statistically significant for domestic patents. An additional environmental policy at time $t-1$ is associated with a 36.8 percent increase in patent filings by foreign inventors, and only 2.2 percent by domestic inventors. Given the mean of the policy count is 0.673, one additional policy represents a large increase, which explains the large magnitude of the foreign effect and impresses further the lack of effect on the domestic inventor side. Evaluated at the mean, these figures translate into 209 additional value-weighted patents owned by foreign inventors, and less than one additional patent held by domestic inventors. Given the average family size over the period, 50 new patents are filed following the implementation of a new renewable energy policy in the OECD, and these patents are owned by foreign inventors. The results suggest at this point that there is no effect on domestic inventors. The remainder of this sections uses the lagged policy as the main regressor of interest.

Despite the current controls and lagged variable, some endogeneity might remain. If there is persistence in the number of policies enacted each year, the lagged policy measure does not entirely remove the previously mentioned source of endogeneity whereby firms that have innovated lobby for more policies. Moreover, omitted political economy variables such as the rise of the green party to power could be positively affecting both the enactment of additional renewable energy policies and the development of the renewable energy industry, leading to a positive bias. And some shocks to economic growth might affect environmental technologies differently than other types of innovation so they would not be controlled for by the patenting trend. Such a shock might lead to more environmental policies being implemented in the hopes of stimulating the economy but less innovation as firms are financially constrained, thus creating a negative bias.

To account for these additional sources of endogeneity, I employ the Hausman and Taylor (1981) method which makes use of the panel dimension of the data to instrument for the endogenous variable using lagged values of the variable. Consistent with the literature, I remove the first two lags from the instruments to avoid further issues related to the persistence of policies. Table 1.4 shows that accounting for endogeneity, an additional policy at time $t-1$ is associated with a 9.8 percent increase in foreign patents (column 6), but also a 14.9 percent increase in domestic patents (column 5). In line with intuition, the increase in the domestic patents coefficients indicates that the negative bias from omitted economic shocks affected domestic inventors more so than foreign inventors. On the other hand, foreign patents appeared to suffer from the positive bias due to omitted political economy variables. Since most foreign patents are transfers of existing technologies, they can respond immediately to the green party rising to power as they anticipate more environmental policies. The coefficients are both significant and not statistically different from one another. Nonetheless, since the majority of patents are foreign, the economic magnitude of the coefficients differ significantly: these percentages evaluated at the mean and accounting for family size represent only 8 additional domestic patents but 54 new foreign patent filings.

Table 1.5 provides evidence that the results are robust to using alternative measures of policy. Columns (1) and (2) present results for the count of policies separated by policy types. For all types, with the exception of voluntary contributions, foreign patent filings respond more to policies than domestic patents do. Economic instruments are the only policies that appear to affect both domestic and foreign patent filings. Columns (3) and (4) use a stock of policies rather than a flow. The last two columns are run on a subset of data for wind policies and technologies in seven OECD countries. Again, the economic magnitude of the effect is highest for patents filed by foreign inventors.

The large number of foreign patents filings does not imply that foreign inventors are developing new technologies in response to domestic policies. This figure could instead represent adoption of existing technologies. Table 1.6 separates patent counts between transfers of existing technologies measured as patents that were previously filed in another country, and new inventions which are patents that were not previously filed elsewhere. Columns (1) and (2) show that policies do not spur new inventions by foreign inventors, but rather incentivize foreign inventors to transfer their existing technologies to the country in question. Foreign transfers represent over three quarters of total foreign patents, so the effect of policies on patent transfers is large.

Finally, a country by country analysis shows that only in Japan and Germany, two countries that have high innovation levels overall, do policies significantly stimulate more domestic than foreign innovation (Table 1.7). These results would support the idea of the first-mover advantage since Germany is also the first country in my dataset to have implemented policies favoring the use or development of renewable energy technologies. The case of Japan, that implemented policies later, might suggest that overall innovative capacity played a key role in positioning Japan as a center of innovation for renewables.

The next few tables provide some additional results and checks. Table 1.8 includes multiple lags of the policy variable and finds that patents respond to policies up to 3 years after enactment. Table 1.9 shows that the conclusion that foreign patent filings respond more to policies than domestic patent filings are robust to specifications including different sets of controls.

In sum, I find that policies which aim to foster the development and use of renewable energies are associated with a significant increase in patent filings of around 10 percent, but outside of highly innovative economies such as Germany or Japan, the vast majority of these patents are transfers of existing foreign technologies rather than new domestic inventions or even new foreign inventions. This result holds with different measures of policy stringency and accounts for potential endogeneity issues. The claim that renewable energy policies stimulate innovation in renewable energy technologies therefore does not appear to be substantiated in OECD countries between 1988 and 2003. However, policies could still stimulate the domestic economy if these foreign transferred technologies spur manufacturing production.

1.4 TECHNOLOGY ADOPTION AND THE PRODUCTION OF TECHNOLOGY-SPECIFIC INPUTS

An inventor will file a patent to protect his invention in a country because he plans to market the invention in that country. On the one hand, the technology or the inputs into that technology can be produced in the country where the patent was filed: a domestic inventor could produce locally, a foreign inventor could engage in foreign direct investment to produce the technology in the country where he filed, or a domestic manufacturer could license the right from the foreign innovator to produce the good locally. On the other hand, the technology or the inputs can be produced abroad and imported to be sold in the country where the patent is filed. Environmental policies will only increase domestic manufacturing if technology-specific goods and inputs are produced domestically, not if they are imported. In this section I examine how the rise in patent filings discussed above – both domestic and foreign – affected the production of the technologies, comparing the effect on the domestic manufacturing of technologies to the effect on the imports of technologies.

Unfortunately, manufacturing production data are not available for all countries at a level of detail which would allow me to identify inputs used exclusively for renewable technologies, so I use exports as a proxy for domestic production. While exports are an imperfect proxy for manufacturing production, they do allow me to examine the competitiveness portion of the claim. As mentioned in the introduction, policymakers state that the technologies that are developed and manufactured in response to environmental policies will then be exported to other countries that implement similar policies later on. But if the rise in exports if trumped by a large inflow of imports, there could be little gains in competitiveness. To test whether policies do in fact improve competitiveness, I examine how policy-induced innovation affects both exports and imports. This section therefore compares the effect of patents on exports and imports to determine whether adopted technologies are primarily produced at home or abroad, and whether the domestic economy experiences a gain in global competitiveness. The following subsections describe the data sources, estimation procedure, and results.

1.4.1 DATA

The measure of technology adoption is patents as in the first part of the paper, but I no longer need to distinguish between domestic and foreign inventors. I assume that a firm in country i that wants to make use of a renewable technology will chose from the set of available technologies as proxied by the technologies which have been patented in this country, regardless of the country of residence of the inventor. Available technologies are not only the technologies patented in year t but all technologies patented up until year t. Thus while the first part of the paper focused on the flows of new patents, this section requires a measure of the stock of knowledge accumulated in each country in renewable energies. Here I assume that patents provide an opportunity to manufacture and sell a technology. If instead patents are filed strategically to impose a barrier on domestic production, then I should observe no effect in this section.

Aggregating patents into a stock by simply adding the count of patents of previous years is problematic for two reasons. First, patents become obsolete with time as new better technologies are introduced. Second, there might be a lag between the time when the patent is filed and the time when it is actually used in the economy. As a result, I aggregate patents into knowledge stocks following standard methods (Popp, Hascic and Mehdi, 2011):

$$\widehat{K}_{it} = \sum_{s=0}^{\infty} e^{-\omega_1 s}(1 - e^{-\omega_2 (1+s)}) * PAT_{i(t-s)} \tag{1.3}$$

where ω_1 is the decay rate allowing for older patents to become less relevant over time. And ω_2 corresponds to the rate of diffusion since a patent might not be utilized right away. The stock aggregates all previous years' patent counts by multiplying each year's count by a function of these decay and diffusion rates. Following Popp, Hascic and Mehdi (2011), I use a patent rate of decay of 0.1, and a rate of diffusion of 0.25. This stock represents the set of available technologies in country i at time t.

For the trade data, the difficulty lies in identifying relevant product categories for renewable energies. Using information from the Organization for Economic Cooperation and Development (Steenblik 2005), the International Trade Commission (USITC 2005, 2009), and the International Center for Sustainable Trade and Development (ITCSD 2009), I compile a list of product categories including primary renewable products and technologies as well as common components of renewable energy based systems. Table 1.10 presents the resulting list of products based on the Harmonized System commodity classification (HS code) at the 6-digit level. The lists has some drawbacks. Some product categories are not exclusively used for renewable energy and some subcategories are not relevant for renewables. In the robustness checks, I present results using a more conservative list of products for solar energy. I obtain export and import data at the HS 6-digit level from the United Nations COMTRADE database.

1.4.2 Estimation Procedure

Using trade data and the stock of patented technologies, I explore the effect of technology adoption on renewable technology exports and imports using a standard gravity model modified to include a measure of technology. Gravity models predict bilateral trade flows based on country characteristics and trade costs between country pairs. These costs are related to distance as well as common features such as a border, language, or trade agreement. Although the gravity model originated as an empirical exercise, trade theorists have since established the theoretical underpinnings of the model, and evidence suggests that gravity models have been successful in predicting trade flows (Frankel 1997, Head and Mayer 2013).

I estimate gravity equations augmented with a measure of available technologies in the following way:

$$ln(Exports_{ijt}) = \beta_1^X ln(K_{it}) + \beta_2^X X_{ijt} + \gamma_i^X + \delta_j^X + \omega_t^X + \nu_{ijt}^X \tag{1.4}$$

$$ln(Imports_{ijt}) = \beta_1^M ln(K_{it}) + \beta_2^M X_{ijt} + \gamma_i^M + \delta_j^M + \omega_t^M + \nu_{ijt}^M \tag{1.5}$$

where $ln(Exports_{ijt})$ and $ln(Imports_{ijt})$ represent log exports and imports between countries i and j at time t. I am interested in exports from the 27 OECD countries but destined for any country in the world. Similarly, the import equations includes imports from the 27 OECD countries originating from anywhere in the world. Thus in both equations, country i is one of the 27 countries in my dataset, while country j can be any country which trades with country i. For simplicity, I will call country i the “patenter", and country j the “partner".

K_{it} is the stock of knowledge related to renewable energies in country i at time t described above. X_{ijt} contains the gravity model variables from the CEPII gravity model dataset (Head and Mayer 2010): log population in patenter and partner, log GDP per capita in patenter and partner, the log of distance between patenter and partner, and indicators for whether the pair shares a common border, a common language, colonial ties, or a regional or bilateral trade agreement. Finally, γ_i and δ_j and ω_t are patenter country, partner country, and time fixed effects respectively. Comparing the magnitude and significance of β_1^M and β_1^X will determine whether an increase in technology adoption is mostly associated with a rise of domestic production proxied by exports or an increase in imports.

Santos Silva and Tenreyro (2006) shows that under heteroskedasticity, log linearized gravity models can lead to substantial biases. The authors propose using a Poisson pseudo maximum likelihood (PPML) estimation instead to obtain consistent estimates. This method is also more appropriate for dealing with zero values in the dependent variable, which are common and create additional issues in log linearized models. I estimate the gravity equations using PPML and provide robustness checks using two other popular methods: ordinary least squares (OLS) dropping pairs with zero trade flows, and OLS with a transformed dependent variable (OLS+1): $ln(Imports_{ijt} + 1)$ and $ln(Exports_{ijt} + 1)$.

Table 1.11 provides the summary statistics for trade flows and the renewable patent stock. On average across OECD countries and years, imports of renewable energy technology inputs total \$11 million and exports \$12 million between 1988 and 2003. The range varies greatly across countries. Germany is the largest exporter with an average of \$63 million per year. Not far behind, Japan and the United States export on average \$45 million per year. The United States is not only one of the top exporters but also by far the main importer of renewable technology inputs: its mean import value across the time period is \$56 million.

1.4.3 RESULTS

The results are presented in Table 1.12. The coefficients on the standard gravity model variables are in line with intuition. Across all specifications, all controls have positive and significant effects on trade, except distance. The coefficient on the variable of interest, the stock of renewable technologies, is also positive and significant for both imports and exports in all three functional forms. In the PPML regressions a 1 percent increase in the stock of renewable energy patents is associated with a 0.232 percent rise in imports, and a 0.352 percent rise in exports. Hence, the evidence suggests that while some technologies are imported, some technologies are at least partly produced domestically.

However, it could be that inventors build on the technology embodied in imports to create new technologies, which would lead to an overestimation of the importelasticity of innovation. Or a high level of the trade of renewable technologies might mean that existing technologies are appropriate in which case there would not be the need to innovate further, which would negatively bias the coefficients. To address these concerns, I instrument for the stock of knowledge in renewable technologies with the stock of knowledge in all other non-energy technologies. The instrument is relevant since there is a common patenting trend in each country. And it is exogenous because non-energy patents are unlikely to be directly related to the trade of renewable technologies. I estimate equations (1.4) and (1.5) using an instrumental variable approach. The results from the linear first stage are presented in Table 1.13 and show that the instrument is highly relevant. Accounting for endogeneity, a 1 percent increase in the stock of renewable energy patents is associated with a 0.627 percent increase in imports and a 0.679 percent increase in exports Table 1.14, columns 1 and 2). Again, the results are robust to using OLS or OLS+1.

Still, exports are an imperfect proxy for domestic production. Since the results show that exports and imports both increase, it is possible that there would be no net effect on domestic production. Production of exported goods could be increasing at the expense of production of goods that are now imported. This would indicate a classic trade theory specialization story and would generate gains from trade, but would not represent an increase in manufacturing output. Column 7 therefore examines the effect of the patent stock on net exports. The coefficient on the patent stock is positive and significant, indicating that the rise in patent filings does boost net exports. This specification confirms that increased patents will be associated with a rise in domestic manufacturing production.

Table 1.15 provides some robustness checks. Since the majority of exports of renewable energy technologies from my sample originate in Germany, Japan or the United States, the positive and significant coefficient on exports could be driven only by these three countries, which are highly innovative nations in all industries. Columns (1) and (2) present the regressions removing Japan, Germany and the United States for the sample. For simplicity, only PPML estimates are reported. The coefficients on imports and exports remain significant and roughly of the same magnitude. Therefore, the rise in exports following an increase in the knowledge stock is not limited only to the main exporters. In all countries, some components of the technologies are produced domestically and exported.

As mentioned previously, the set of product codes identified as renewable energy technology inputs is not exact.[8] In Table 1.15 columns (3) and (4), I restrict the solar trade data to photovoltaic cells and modules only. The results remain that the stock of knowledge has a positive and significant effect on exports, although the effect on imports is twice as large.

The above results allow the 27 OECD countries to trade with any country in the world. As a result, I include only the knowledge stock of the patenter and not the knowledge stock of the trading partner since I do not have that data for non-OECD countries. My estimation strategy therefore deviates from standard gravity models which includes all variables in both origin and destination countries. As a check, I restrict trading partners to OECD countries only. Table 1.16 columns (1) and (2) present the same regression as above but limited to OECD countries. An increase in the patenting stock in country i has a positive and significant effect on export, but no effect on imports. Comparing these results to those in Table 1.14 suggests that the effects on imports originates mostly from non-OECD countries. Furthermore, columns (3) and (4) suggests that after controlling for the patent stock in the partner country,

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[8] For example, the two codes for solar energy are: 8541.40 - photovoltaic cells and modules, and 8504.40 - static converters. The first is exclusively solar PV technologies; the second includes both inverters for solar panels and other kinds of converters not used in renewables

the higher the patent stock in country i, the larger the exports and the lower the imports.

Therefore, the results show that renewable energy innovation lead to a rise in exports so that at least some inputs and technologies are produced domestically. In the first part of the paper, the results suggested that one environmental policy was associated with a 10 percent increase in patents. Combining the two sections of the paper, I conclude that an environmental policy is associated with a 6.79 percent increase in exports of renewable energy technologies.[9] These figures represent only the effect of policies on trade through the technology adoption channel. Table 1.17 includes the policy count from part I of the paper in the gravity model regression to examine whether policies have an additional direct effect on trade. The coefficient on the policy variable does not appear to be significant in either regression, suggesting that there is little additional effect of policies on trade beyond the technology adoption channel.

1.5 Conclusion

The sheer magnitude of the political and monetary capital being invested into greening the economy around the world suggest the need for academic research on the links between environmental regulation, green innovation, and green manufacturing. However, the theory is inconclusive so the question of whether environmental policies stimulate the domestic economy is mainly an empirical one.

The framework I devise to identify those links is straightforward. Environmental policies affect two main levels of economic activity: innovation and manufacturing. These activities can take place at home or abroad, allowing for four possible scenarios:

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[9] These “back of the envelope" figures are calculated multiplying the effect of the first part (10 percent) by the effect of the second part (0.679 percent for exports).

both innovation and manufacturing occur domestically, both happen abroad, only innovation is domestic, or only manufacturing is produced at home. I identify which scenario is most prominent in two steps, each posing a different question and requiring different data and estimation techniques.

In the first step, using patent data as a proxy for innovation and a measure of policy stringency specific to renewable energies, I find that renewable energy policies result in a 10 percent increase in patent filings, but very few of these are developed by domestic inventors. Only in historically innovative economies such as Japan and Germany do domestic inventors respond significantly to the implementation of a policy. In the rest of the OECD, including in the United States, adopted technologies are largely licensing of foreign technologies rather than new technologies developed at home. In the estimation, I account for the endogeneity of environmental policies and test the robustness of the results to different measures of policies.

In the second step, I ask whether the increase in technology adoption led to a spike in domestic manufacturing production or to a rise in imports. I find that domestic production - proxied by exports - increase significantly following technology adoption. At least some of the technologies or the inputs into these technologies are manufactured domestically. Combining the two steps of the paper, an additional renewable energy policy in the OECD is associated with a 6 percent rise in domestic production. Therefore, the evidence suggests that renewable policies in the OECD stimulate the economy through manufacturing in the renewable energy sector but have little effect on the innovative sector outside of Germany and Japan.

1.6 FIGURES

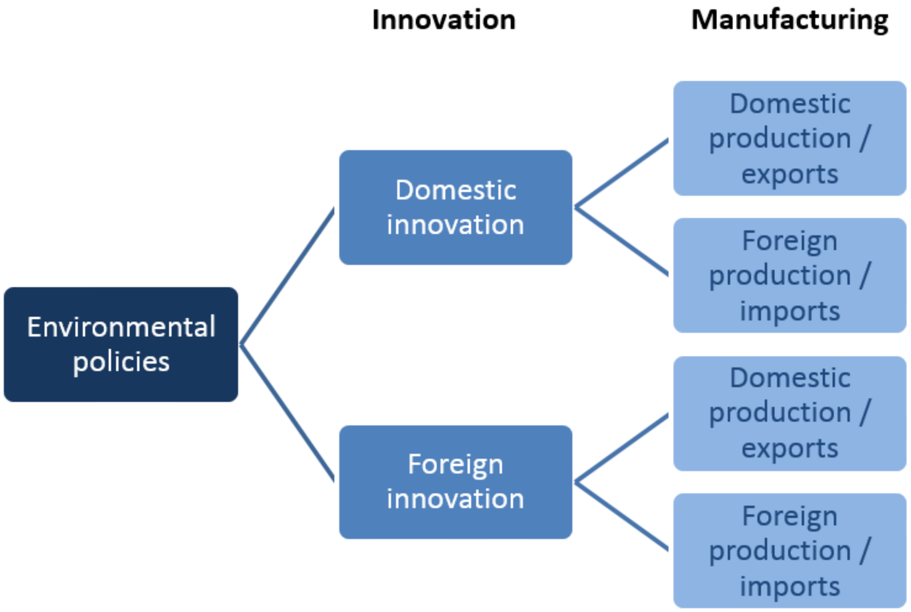
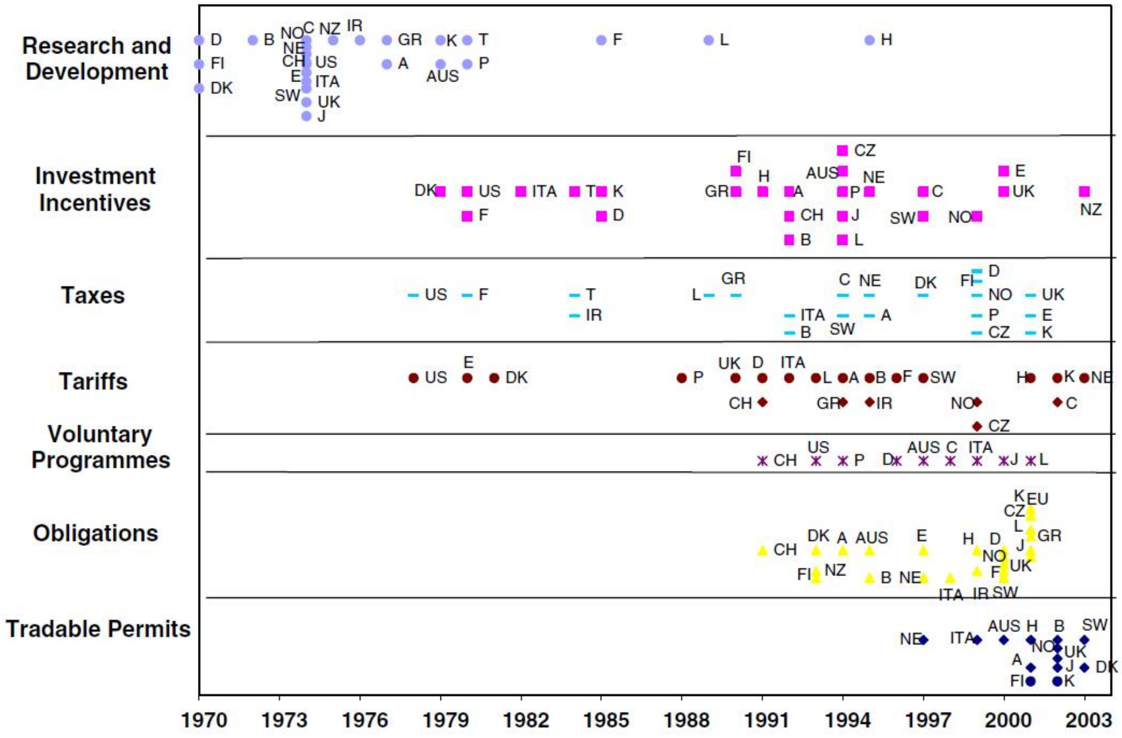


Figure 1.1: Channels from Environmental Policies to Innovation and Manufacturing



Source: IEA (2004)

Note: AUS Australia, C Canada, FI Finland, GR Greece, ITA Italy, L Luxembourg, NO Norway, SW Sweden, UK United Kingdom, A Austria, CZ Czech Rep., F France, H Hungary, J Japan, NE Netherlands, P Portugal, CH Switzerland, US United States, B Belgium, DK Denmark, DE Germany, IR Ireland, K Korea, NZ New Zealand, E Spain, T Turkey.

Figure 1.2: Introduction of Renewable Energy Policies by Type in Selected OECD Countries, 1970-2003

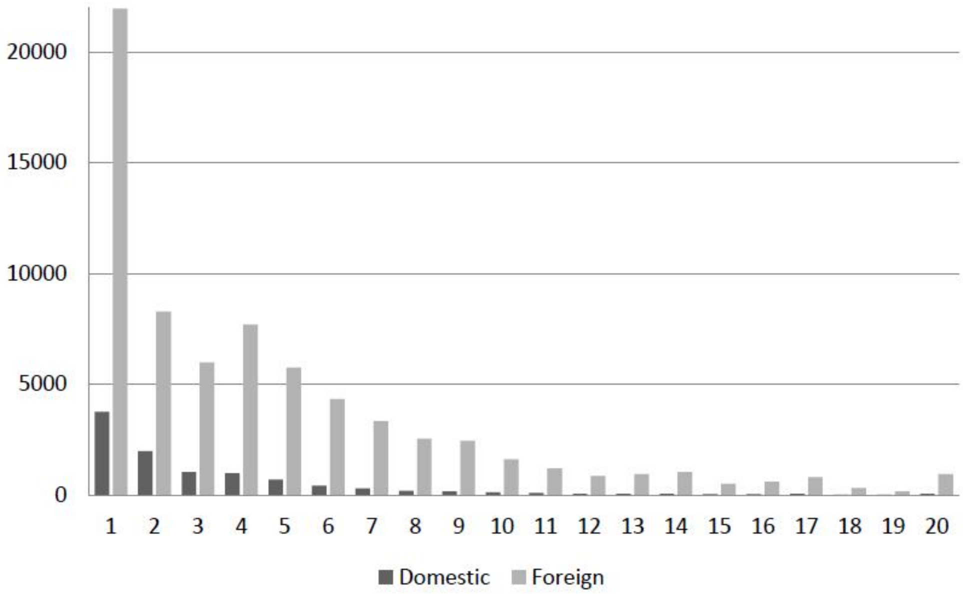


Figure 1.3: Frequency Plot of Patent Family Size by Origin

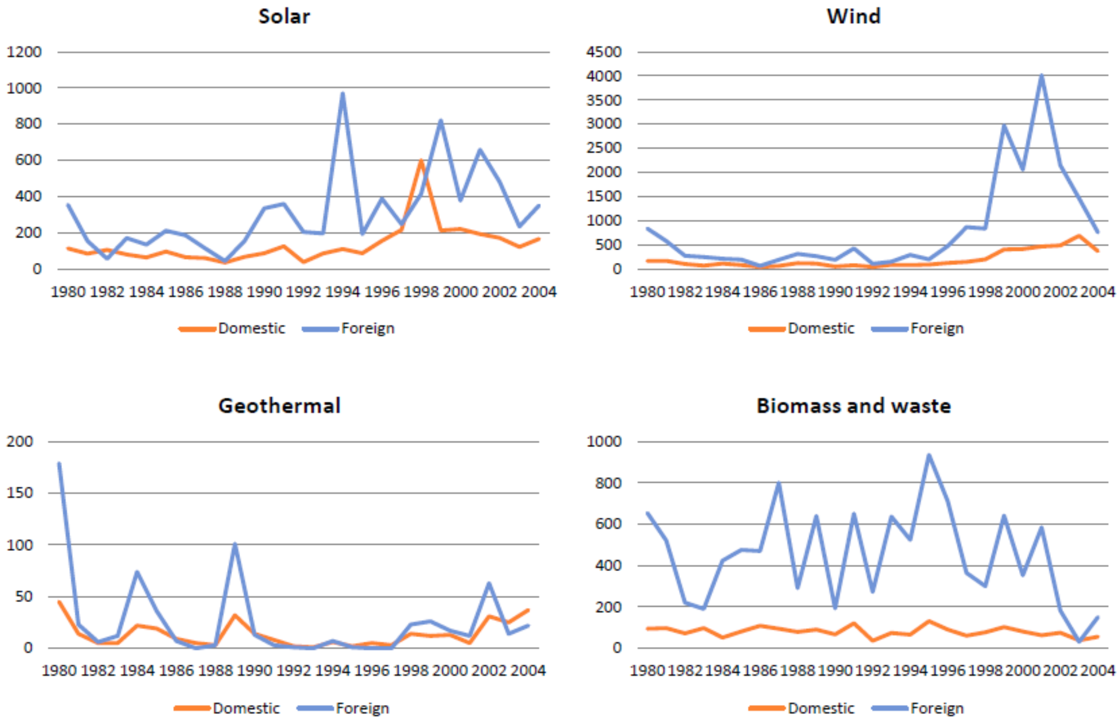


Figure 1.4: Renewable Patents in OECD countries, by Technology

1.7 TABLES

Table 1.1: Summary Statistics of Policy Stringency Measure

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Policy	0.635	1.522	0	10
Economic instruments	0.240	0.603	0	5
Regulatory instruments	0.115	0.363	0	2
Research and Development	0.035	0.197	0	2
Policy support	0.125	0.353	0	2
Information and education	0.070	0.283	0	2
Voluntary contributions	0.050	0.218	0	1

Table 1.2: Patent Classes of Renewable Energy Technologies

Patent classification description	IPC code
WIND	
Wind motors	F03D
SOLAR PHOTOVOLTAICS	
Semiconductor devices sensitive to infrared radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation and specially adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation – adapted as conversion devices, including a panel or array of photoelectric cells, e.g., solar cells	H01L 31/04-058
Generators in which light radiation is directly converted into electrical energy	H02N 6/00
Devices consisting of a plurality of semiconductor components sensitive to infrared radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation – specially adapted for the conversion of the energy of such radiation into electrical energy	H01L 27/142
GEOTHERMAL	
Other production or use of heat, not derived from combustion – using natural or geothermal heat	F24J 3/08
Devices for producing mechanical power from geothermal energy	F03G 4/00-06
BIOMASS and WASTE	
Solid fuels essentially based on materials of nonmineral origin – animal or vegetable substances; sewage, town, or house refuse; industrial residues or waste materials	C10L 5/42-48
Engines or plants operating on gaseous fuel generated from solid fuel, e.g., wood	F02B 43/08
Liquid carbonaceous fuels	C10L1
Gaseous fuels	C10L3
Solid fuels	C10L5
Dumping solid waste	B09B1
Destroying solid waste or transforming solid waste into something useful or harmless	B09B3
Incineration of waste; incinerator constructions	F23G5
Incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels, e.g., chemicals	F23G7
Plants or engines characterized by use of industrial or other waste gases	F01K 25/14
Incineration of waste – recuperation of heat	F23G 5/46
Plants for converting heat or fluid energy into mechanical energy; use of waste heat	F01K27
Use of waste heat of combustion engines – profiting from waste heat of combustion engines	F02G5
Machines, plant, or systems, using particular sources of energyâĂŤusing waste heat, e.g., from internal-combustion engines	F25B 27/02

Source: Popp (2011).

Table 1.3: Summary Statistics of Weighted Patent Counts

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
All patents	604	741	0	3851
Domestic patents	54	170	0	2018
Foreign patents	550	665	0	3341

Table 1.4: Effect of Policies on Innovation

	Negative Binomial				IV - GMM	
	(1) Domestic	(2) Foreign	(3) Domestic	(4) Foreign	(5) Domestic	(6) Foreign
Policy_t	1.045	1.023				
	(0.101)	(0.059)				
World policy_t	1.116	1.098				
	(0.116)	(0.070)				
Policy_{t-1}			1.022	1.368^{***}	1.149^{***}	1.098^{***}
			(0.059)	(0.100)	(0.019)	(0.006)
World policy_{t-1}			1.067	1.582^{***}	1.062^{***}	1.121^{***}
			(0.078)	(0.135)	(0.004)	(0.004)
Elec. cons.	1.020	1.115^{***}	1.017	1.105^{***}	1.233^{***}	1.009^{***}
	(0.013)	(0.024)	(0.012)	(0.021)	(0.005)	(0.008)
Elec. price	1.007^{*}	1.042^{***}	1.007^{*}	1.037^{***}	1.041^{***}	1.011^{***}
	(0.003)	(0.005)	(0.003)	(0.004)	(0.002)	(0.002)
Patenting trend	0.989^{*}	0.960^{***}	0.990^{*}	0.965^{***}	1.088^{***}	0.995^{***}
	(0.004)	(0.007)	(0.004)	(0.006)	(0.002)	(0.002)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors in parentheses; N=400

All regressions include country and time fixed effects.

Table 1.5: Effect of Alternative Measures of Policy on Innovation

	All technologies				Wind only	
	(1) Dom.	(2) Frgn	(3) Dom.	(4) Frgn	(5) Dom.	(6) Frgn
Research and Development$_{t-1}$	1.514	2.757***				
Policy support$_{t-1}$	0.976	1.282				
Information and education$_{t-1}$	1.033	1.244				
Regulatory instruments$_{t-1}$	1.144	1.785***				
Economic instruments$_{t-1}$	1.354*	1.711**				
Voluntary contributions$_{t-1}$	0.581**	0.702				
Stock of policies$_{t-1}$			1.110*	1.378***		
Stock of world policies$_{t-1}$			1.160**	1.600***		
Feed-in-tariff$_{t-1}$					1.138*	1.102**
Policy$_{t-1}$					1.039	1.38
World policy$_{t-1}$	1.249*	1.872***			1.12	1.456*
Elec. cons.	1.018	1.104***	1.005	1.041***	1.354*	1.611***
Elec. price	1.006	1.036***	1.001	1.014***	1.007	1.040***
Patent trend	0.991*	0.965***	0.997	0.995	1.017**	1.006
N	400	400	400	400	112	112

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Country and time fixed effects.

Table 1.6: Effect of Policies on Innovation – New Filings or Transfers of Existing Patents

	(1) Foreign transfers	(2) Foreign new
Policy$_{t-1}$	1.104**	0.387***
	(0.033)	(0.061)
World policy$_{t-1}$	1.134***	1.102***
	(0.016)	(0.007)
Elec. cons.	1.024*	0.867***
	(0.009)	(0.005)
Elec. price	0.989*	1.003*
	(0.005)	(0.003)
Patenting trend	0.990**	1.094***
	(0.003)	(0.004)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Robust standard errors in parentheses; N=400
All regressions include country and time fixed effects.

Table 1.7: Effect of Policies on Innovation – Germany and Japan only

	(1) Domestic patents	(2) Foreign patents
Policy$_{t-1}$	1.241***	1.006
	(0.023)	(0.014)
World policy$_{t-1}$	1.066	0.998
	(0.040)	(0.060)
Elec. cons.	1.135***	1.050*
	(0.036)	(0.026)
Elec. price	0.985	1.025**
	(0.010)	(0.009)
Patenting trend	1.027***	1.025***
	(0.003)	(0.002)

$^{+}$ $p < 0.10$, * $p < 0.05$
Robust standard errors in parentheses; N=400
All regressions include country and time fixed effects.

Table 1.8: Effect of Policies on Innovation – Multiple Lags

	(1) Domestic patents	(2) Foreign patents
Policy_{t-1}	1.029	1.298^{***}
	(0.056)	(0.068)
Policy_{t-2}	1.081	1.323^{***}
	(0.081)	(0.103)
Policy_{t-3}	4.107^{***}	6.811^{***}
	(1.058)	(1.551)
Policy_{t-4}	1.704	1.387
	(0.799)	(0.351)
$\text{World policy}_{t-1}$	1.005	1.370^{***}
	(0.073)	(0.081)
$\text{World policy}_{t-2}$	1.114	1.572^{***}
	(0.103)	(0.137)
$\text{World policy}_{t-3}$	4.215^{***}	7.744^{***}
	(1.080)	(1.713)
$\text{World policy}_{t-4}$	1.630	1.515
	(0.742)	(0.380)
Elec. cons.	1.002	1.040^{***}
	(0.008)	(0.010)
Elec. price	0.996	1.014^{***}
	(0.003)	(0.003)
Patenting trend	0.996	0.984^{***}
	(0.004)	(0.004)

$^{+}$ $p < 0.10$, * $p < 0.05$

Robust standard errors in parentheses; N=400

All regressions include country and time fixed effects.

Table 1.9: Effect of Policies on Innovation – Various Controls

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	D	F	D	F	D	F	D	F	D	F	D	F
Policy$_{t-1}$	0.967	0.889	1.065	5.272**	1.052	5.323**	1.050	1.745***	1.018	1.408***	1.022	1.368***
	(0.032)	(0.060)	(0.070)	(3.251)	(0.066)	(3.315)	(0.064)	(0.279)	(0.058)	(0.122)	(0.059)	(0.100)
World policy$_{t-1}$			1.149	7.055***	1.118	7.023**	1.111	2.202***	1.062	1.639***	1.067	1.582***
			(0.096)	(4.150)	(0.090)	(4.187)	(0.087)	(0.402)	(0.076)	(0.165)	(0.078)	(0.135)
Elec. cons.							1.027*	1.229***			1.017	1.105***
							(0.013)	(0.048)			(0.012)	(0.021)
Elec. price									1.008*	1.048***	1.007*	1.037***
									(0.003)	(0.005)	(0.003)	(0.004)
Patenting trend					0.993**	0.990**	0.986***	0.932***	0.994*	0.992**	0.990*	0.965***
					(0.002)	(0.004)	(0.004)	(0.012)	(0.002)	(0.003)	(0.004)	(0.006)
Observations	400	400	400	400	400	400	400	400	400	400	400	400

Exponentiated coefficients; Country and time fixed effects; D= Domestic, F= Foreign.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.10: List of Renewable Energy Technology Inputs

HS code	Product description
2207.10	Ethanol
2905.11	Methanol
3824.90	Biodiesel and waste fats and oil suitable as a fuel
4401.10	Fuel wood, in logs, in billets, in twigs, in faggots or in similar forms.
4401.30	Artificial logs made from pressed sawdust; wood waste suitable as a fuel
4402.00	Wood, shell or nut charcoal used for fuel
7308.20	Towers and lattice masts of iron and steel
8402.11	Water-tube boilers with a steam production exceeding 45 tonnes per hour.
8402.12	Water-tube boilers with a steam production not exceeding 45 tonnes per hour.
8402.19	Other vapour-generating boilers, including hybrid boilers
8412.80	Windmills
8412.90	Parts of Other Engines and Motors
8413.50	DC-powered water pumps
8413.70	DC-powered submersible water pumps
8413.81	Windmill pumps
8416.30	Mechanical stokers and related appliances used for burning biomass
8416.90	Parts for mechanical stokers and related appliances used for burning biomass
8501.31	DC generators âĂŤ Of an output not exceeding 750 W
8501.61	AC generators (alternators) âĂŤ Of an output not exceeding 75kVA
8502.31	Electric generating sets and rotary converters - Wind powered
8504.40	Static converters (inverters)
8541.40	Photovoltaic cells and modules
9026.80	Anemometers

Source: OECD (2005), USITC (2005, 2009), ITCSD (2009)

Table 1.11: Summary Statistics for Trade Flows and Renewable Patent Stock

Variable	Mean	Std. Dev.	Min.	Max.
Exports in millions USD	12.148	101.869	0	5317.644
Imports in millions USD	10.641	104.022	0	5015.063
Renew. pat. stock (in 1,000)	6.019	6.549	0	37.763

Table 1.12: Effect of Innovation on Trade

	PPML		OLS		OLS (T+1)	
	(1) Exports	(2) Imports	(3) Log(X)	(4) Log(M)	(5) Log(X+1)	(6) Log(M+1)
Log R.E. patent stock	0.352^{***}	0.232^{***}	0.150^{***}	0.065^{*}	0.099^{***}	0.090^{***}
	(0.028)	(0.030)	(0.022)	(0.028)	(0.007)	(0.006)
Log pop. in origin	3.198^{***}	2.188^{***}	1.322^{**}	2.439^{***}	1.180^{***}	2.020^{***}
	(0.637)	(0.557)	(0.416)	(0.500)	(0.101)	(0.099)
Log pop. in destination	0.066	2.081^{***}	0.905^{***}	0.039	0.142^{**}	0.699^{***}
	(0.168)	(0.374)	(0.148)	(0.224)	(0.046)	(0.036)
Log GDP p.c. in origin	0.658^{***}	0.701^{***}	0.405^{***}	0.623^{***}	0.374^{***}	0.407^{***}
	(0.078)	(0.090)	(0.069)	(0.091)	(0.023)	(0.020)
Log GDP p.c. in destination	0.678^{***}	0.932^{***}	0.891^{***}	0.600^{***}	0.370^{***}	0.281^{***}
	(0.051)	(0.062)	(0.041)	(0.062)	(0.012)	(0.010)
Log distance	-0.744^{***}	-0.536^{***}	-1.602^{***}	-1.167^{***}	-0.416^{***}	-0.217^{***}
	(0.021)	(0.026)	(0.018)	(0.023)	(0.009)	(0.008)
Common border	0.483^{***}	0.459^{***}	0.097	0.548^{***}	0.657^{***}	0.792^{***}
	(0.034)	(0.038)	(0.054)	(0.054)	(0.056)	(0.055)
Common language	0.326^{***}	0.331^{***}	0.734^{***}	0.364^{***}	0.083^{***}	0.004
	(0.035)	(0.039)	(0.031)	(0.043)	(0.014)	(0.013)
Colonial ties	0.206^{**}	0.204^{*}	1.881^{***}	0.893^{***}	0.563^{***}	0.149^{***}
	(0.072)	(0.081)	(0.056)	(0.079)	(0.033)	(0.028)
RTA	0.722^{***}	0.873^{***}	0.045	0.254^{***}	0.487^{***}	0.367^{***}
	(0.050)	(0.056)	(0.034)	(0.043)	(0.020)	(0.021)
Observations	74,095	74,095	44,440	29,366	74,095	74,095

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Origin, destination, and time fixed effects.

Table 1.13: Instrumental Variable - First Stage

	(1) Log R.E. patent stock
Log non-energy patent stock	0.208^{***}
Log population in patenter	0.398^{***}
Log population in partner	-0.00882^{***}
Log GPD p.c. in patenter	0.878^{***}
Log GDP p.c. in partner	-0.0244^{***}
Log distance	-0.0681^{***}
Common border	-0.111^{***}
Common language	-0.153^{***}
Colonial ties	0.163^{***}
RTA	0.180^{***}
Constant	-2.623^{***}
N	$74,095$

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 1.14: Effect of Innovation on Trade – Instrumental Variable Approach

	PPML		OLS		OLS (T+1)		
	(1) Exports	(2) Imports	(3) Log(X)	(4) Log(M)	(5) Log(X+1)	(6) Log(M+1)	(7) Log(X-M)
Log R.E. patent stock	0.679***	0.627***	0.257***	0.104*	0.395***	0.297***	0.304***
	(0.152)	(0.097)	(0.042)	(0.047)	(0.016)	(0.014)	(0.017)
Log pop. in origin	0.451***	0.508***	2.583***	3.754***	0.157***	0.026	0.132***
	(0.105)	(0.072)	(0.083)	(0.130)	(0.028)	(0.025)	(0.028)
Log pop. in destination	0.812***	0.985***	−1.568***	−0.814***	−0.472***	−0.862***	−0.178**
	(0.012)	(0.022)	(0.158)	(0.200)	(0.058)	(0.051)	(0.058)
Log GDP p.c. in origin	0.142	0.04	0.440***	0.538***	−0.04	0.128***	−0.079**
	(0.231)	(0.132)	(0.081)	(0.107)	(0.031)	(0.027)	(0.030)
Log GDP p.c. in destination	0.894***	1.547***	0.673***	0.447***	0.326***	0.275***	0.245***
	(0.018)	(0.031)	(0.036)	(0.051)	(0.013)	(0.011)	(0.013)
Log distance	−0.859***	−0.557***	−1.529***	−1.075***	−0.421***	−0.219***	−0.340***
	(0.043)	(0.039)	(0.017)	(0.022)	(0.007)	(0.006)	(0.007)
Common border	1.084***	1.548***	0.176**	0.649***	0.661***	0.794***	0.339***
	(0.077)	(0.110)	(0.061)	(0.069)	(0.027)	(0.024)	(0.029)
Common language	0.689***	0.534***	0.706***	0.303***	0.084***	0.004	0.079***
	(0.077)	(0.110)	(0.031)	(0.042)	(0.013)	(0.011)	(0.013)
Colonial ties	1.679***	0.692***	1.862***	0.872***	0.558***	0.146***	0.586***
	(0.133)	(0.175)	(0.059)	(0.074)	(0.025)	(0.022)	(0.025)
RTA	−0.459***	0.355***	0.043	0.332***	0.425***	0.341***	0.299***
	(0.076)	(0.093)	(0.039)	(0.046)	(0.017)	(0.015)	(0.018)
Observations	74,095	74,095	44,440	29,366	74,095	74,095	68,341

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Origin, destination, and time fixed effects.

Table 1.15: Effect of Innovation on Trade – Robustness Checks

	Excl. top 3 exporters		Restricted solar codes	
	(1) Exports	(2) Imports	(3) Exports	(4) Imports
Log R.E. patent stock	0.633^{***}	0.575^{***}	0.583^{**}	1.119^{***}
	(0.155)	(0.107)	(0.182)	(0.144)
Log pop. in origin	0.413^{**}	0.484^{***}	0.642^{***}	-0.166
	(0.129)	(0.093)	(0.186)	(0.179)
Log pop. in destination	0.800^{***}	0.973^{***}	0.760^{***}	1.020^{***}
	(0.014)	(0.024)	(0.034)	(0.065
Log GDP p.c. in origin	0.145	0.042	0.769^{**}	-0.709^{***}
	(0.256)	(0.166)	(0.281)	(0.131)
Log GDP p.c. in destination	0.875^{***}	1.513^{***}	0.955^{***}	1.594^{***}
	(0.021)	(0.031)	(0.036)	(0.066)
Log distance	-0.846^{***}	-0.541^{***}	-0.869^{***}	0.057
	(0.049)	(0.042)	(0.083)	(0.143)
Common border	1.109^{***}	1.585^{***}	0.852^{***}	1.292^{***}
	(0.209)	(0.237)	(0.237)	(0.226)
Common language	0.695^{***}	0.483^{***}	0.647^{***}	-0.661^{***}
	(0.075)	(0.128)	(0.147)	(0.190)
Colonial ties	1.705^{***}	0.645^{***}	1.318^{***}	1.033^{**}
	(0.120)	(0.190)	(0.225)	(0.366)
RTA	-0.401^{***}	0.392^{***}	-1.170^{***}	-1.676^{***}
	(0.080)	(0.092)	(0.140)	(0.285)
Observations	65,483	65,483	43,819	43,819

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; Origin, destination, and time fixed effects.

Table 1.16: Effect of Innovation on Trade – OECD Only

	PPML - IV(GMM)			
	(1) Exports	(2) Imports	(3) Exports	(4) Imports
Log R.E. patent stock in i	1.438^{***}	-0.065	1.516^{***}	-0.214^{**}
Log R.E. patent stock in j			-0.473^{***}	0.379^{***}
Log population in i	-0.078	0.810^{***}	-0.079	0.891^{***}
Log population in j	0.762^{***}	0.920^{***}	1.088^{***}	0.708^{***}
Log GDP p.c. in i	-0.757^{*}	0.802^{***}	0.862^{**}	0.969^{***}
Log GDP p.c. in j	0.643^{***}	1.310^{***}	1.216^{***}	0.740^{***}
Log distance	-0.534^{***}	-0.450^{***}	-0.695^{***}	-0.509^{***}
Common border	2.374^{***}	1.518^{***}	2.088^{***}	1.484^{***}
Common language	0.214^{*}	-0.023	0.313^{**}	0.011
Colonial ties	0.883^{***}	0.835^{***}	0.361^{*}	0.708^{***}
RTA	0.211	0.729^{***}	0.019	0.506^{***}

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; N=11,618; Origin, destination, and time fixed effects.

Table 1.17: Effect of Innovation on Trade – With Policy Measure

	PPML - IV(GMM)	
	(1) Exports	(2) Imports
Log R.E. patent stock	0.724^{***}	0.577^{***}
	(0.193)	(0.109)
Policy	-0.026	0.052
	(0.025)	(0.028)
Log pop. in origin	0.423^{**}	0.535^{***}
	(0.13)	(0.078)
Log pop. in destination	0.812^{***}	0.984^{***}
	(0.012)	(0.022)
Log GDP p.c. in origin	0.086	0.099
	(0.283)	(0.142)
Log GDP p.c. in destination	0.895^{***}	1.542^{***}
	(0.018)	(0.031)
Log distance	-0.859^{***}	-0.558^{***}
	(0.043)	(0.039)
Common border	1.110^{***}	1.538^{***}
	(0.248)	(0.239)
Common language	0.691^{***}	0.533^{***}
	(0.079)	(0.111)
Colonial ties	1.669^{***}	0.683^{***}
	(0.138)	(0.168)
RTA	-0.465^{***}	0.339^{***}
	(0.078)	(0.091)
Observations	$74,095$	$74,095$

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Robust standard errors; N=74,095; Origin, destination, and time fixed effects.

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Chapter 2

Pollution Offshoring and Emission Reductions in EU and US Manufacturing

2.1 Introduction

EU and US emissions of sulfur dioxide from manufacturing fell 59 percent and 63 percent respectively between 1995 and 2008. One potential explanation could be that emissions decreased following a fall in output. However, over the same time period, EU manufacturing production rose 39 percent and US manufacturing production grew 31 percent. Both the United States and the European Union managed to cleanup their production despite a rise in output. There are three potential sources for this cleanup. First, technological progress could have led to cleaner production processes, be it in the form of cleaner fuels, better energy efficiency or end-of-pipe pollution abatement. Second, EU and US consumers could have increasingly demanded cleaner goods as preferences evolved. Third, changing patterns of international trade could have resulted in pollution offshoring: the European Union and the United States could have specialized in the production of cleaner goods at home, while importing the more pollution-intensive goods from abroad. Looking at the United States between 1987 and 2001, Levinson (2009) shows that the cleanup of US manufacturing was largely the result of changes in technique, while the consumption and trade channels played only a small role. In this paper, I provide the first decomposition of EU production and imports to determine whether US results are generalizable, and I update the US results for comparison.

The main difference between the United States and the European Union lies in the compositional changes – changes in the mix of goods produced resulting from the consumption and trade channels. While compositional changes were small in the United States, EU manufacturing exhibited an important shift, in a direction counter to the pollution offshoring story. After 2001, EU manufacturing increasingly specialized in the production of more pollution-intensive goods – a “brown" shift. This puzzling pattern cannot be explained by price inflation, the activity of a few select industries, or EU enlargement. Some of the brown shift might have been due to a rise in foreign demand for EU pollution-intensive goods: depending on the pollutant, between a quarter and two-thirds of the brown shift of EU production can be matched by increased net exports of pollution-intensive goods. The remainder can be attributed to an increase in domestic demand for more pollution-intensive goods. Meanwhile, total EU imports were increasingly specializing in less pollution-intensive goods – a “green" shift. And imports from low-income countries, which supposedly would have more lax environmental regulation and therefore would be prime destinations for the offshoring of pollution, were becoming cleaner at a faster pace than overall imports. Therefore, between 1995 and 2008, the patterns of EU specialization – brown shift of production and green shift of imports – were exactly opposite to what pollution offshoring would suggest. However, I do find some evidence of offshoring in a few select industries: primary aluminum, and electrometallurgical products, except steel.

On the other hand, updated US results show that US imports from lower-middle-income countries exhibited a brown shift, which suggests pollution offshoring might have occurred from the United States to this group of countries. But trade comprises a small portion of a compositional shift which is itself small, confirming the conclusion from Levinson (2009) that pollution offshoring does not play a large role in the cleanup of US manufacturing. In sum, I find little to no evidence of pollution offshoring in either the European Union or the United States. And in both regions trade and composition effects were overwhelmed by the concurrent improvements in technology that explain most of the cleanup of EU and US manufacturing.

Identifying which forces drive the cleanups can help the European Union and the United States develop policies for a continued cleanup of the manufacturing sector or other sectors, and can provide interesting lessons for countries that might want to emulate the cleanup. If the trade channel is significant then governments might be justified in implementing policies to counteract the effects of pollution offshoring. If the consumption channel dominates, then cleaning up a sector or an economy may involve raising environmental awareness in society. While if the result is driven by changes in technique, emulating the EU or US manufacturing cleanup in another sector or another country would entail policies to promote innovation in pollution abatement technologies. Most likely, countries would have to consider a combination of those policies. This study provides an indication of the relevance of each channel in two developed regions. It does not, however, imply that the policies that have been implemented to date are necessarily optimal or should be repeated. In fact, the methodology is an accounting exercise which does not allow me to determine whether these changes were caused by environmental policies (EU Emissions Trading Scheme, Kyoto), industrial policies, or trade policies.

To date, empirical literature on pollution offshoring has typically focused on the United States before the year 2000. Levinson (2009) finds that, from 1987 to 2001, 90 percent of the US manufacturing cleanup was due to improvements in technique. Of the remaining 10 percent, less than half could be accounted for by an increase in net imports of polluting goods. But are those results unique to the United States or do they hold true for other developed regions? To inform the debate about the external validity of the US results, I develop the first detailed analysis of the pollution intensity of EU production and imports. A study of the European Union is particularly interesting because, like the United States, it has been a front runner in the design and implementation of environmental policies. As a result, questions about the consequences of those policies for competitiveness and the offshoring of industries feature prominently in environmental policy debates, but there is little empirical evidence to support either side of the argument. For comparison purposes, I update the US analysis to 2008. While not the focus of this paper, the update is interesting as a standalone component because while the 1990s was a decade of economic expansion, the early 2000s were characterized by a slow-down of economic activity. This shift could have been reflected in changing trends of industrial specialization and household consumption.

I replicate the methodology developed in Levinson (2009) to determine whether EU manufacturing production and imports were becoming more or less pollution-intensive. The key to this method lies in the creation of an index of pollution intensity for a detailed decomposition of industries. Ideally, one would construct the EU index using EU data on emissions, industry structure and industry composition. Unfortunately, those data are not available. This paper proposes a reasonable proxy. I construct a pollution intensity measure for 350 industries in the EU manufacturing sector using US emissions inventory, US input-output tables, and EU industry composition. Using the index developed by Levinson for US manufacturing, I update the US results to cover the period from 1995 to 2008.

2.2 Decomposition of Manufacturing Emissions

2.2.1 Method and Data

The analysis in this paper follows Levinson (2009). The total amount of pollution from EU manufacturing (P) can be written as:

$$P = \sum_i p_i = V \sum_i \frac{v_i}{V} * \frac{p_i}{v_i} = V \sum_i \theta_i z_i \tag{2.1}$$

where $i = 1, \ldots, k$ indexes manufacturing industries. V is total manufacturing output, z_i is the amount of pollution per dollar of value shipped in that industry ($z_i = \frac{p_i}{v_i}$), and θ_i is the industry's share of total output ($\frac{v_i}{V}$). In vector form, equation (2.1) becomes:

$$P = V\mathbf{z}\boldsymbol{\theta} \tag{2.2}$$

Totally differentiating equation (2.2), one can identify the three sources of a change in emissions:

$$dP = \boldsymbol{\theta'}\mathbf{z}dV + V\mathbf{z}'d\boldsymbol{\theta} + V\boldsymbol{\theta'}d\mathbf{z} \tag{2.3}$$

The first term is the “scale effect", which measures how emissions increase as a result of an increase in production V, everything else held constant. The second term is the “composition effect", which captures whether the structure of production (θ) has switched towards cleaner goods. And the third term is the “technique effect", which assesses the effect of changes in pollution intensity (z). Using data on pollution levels P, manufacturing output V, and emission intensities z, I isolate the sources of changes in emissions. The remainder of this section describes data sources and issues.

For the European Union, I obtain times series data on total and industry-level manufacturing (dV and $d\theta$) from Eurostat.[1][2] The Environmental Database from Eurostat provides data on total manufacturing emissions by pollutant (dP), notably for the three pollutants of interest: sulfur dioxide (SO2), nitrogen dioxide (NO2) and volatile organic compounds (VOCs).

I use a proxy for EU emissions by industry (z) as current data are unfortunately not appropriate for this analysis. The European Pollutant Emissions Register (EPER), available for 2001 and 2004, divides manufacturing into just 14 sectors. The high level of aggregation is problematic for two reasons. First, a sector is comprised of a variety of industries and products, some of which might be clean even if the sector appears highly pollution-intensive on average. For example, SIC sector 32, “Stone, clay, glass and concrete products" is one of the top polluting sectors in terms of SO2 emissions; but industry 3261, “vitreous plumbing fixtures", is among the least polluting industries. Therefore, using a rough division of economic activities may hide important pollution variation within sectors. Second, the high level of aggregation could overstate the role of technique because within-sector compositional changes would be recorded as technique.

Starting in 2007, the EPER became the European Pollutant Release and Transfer Register (E-PRTR), which contains emissions data at the 4-digit level. However, the data still present substantial challenges. Facilities below certain thresholds, which vary by industry, are not required to report emissions, resulting in incomplete data.[3]

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[1] To avoid issues related to enlargement of the European Union, the study is restricted to the “EU-15": Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

[2] EU manufacturing data are classified using the Nomenclature Générale des Activités Economiques de la Communauté Européenne (NACE rev 2). With the use of concordances provided by Eurostat and the US Census Bureau, NACE rev 2 can be converted into US SIC 1987 classification.

[3] The reporting guidelines are available in European Commission (2006).

For SO2, more than 80 percent of EU manufacturing industries do not report emissions. In contrast, in US data only about 35 percent of manufacturing industries report zero or missing data for SO2 emissions. Moreover, examining EU production patterns between 1995 and 2008 using 2007 technology is problematic for my study. As technology improves over time, the range of pollution intensity narrows so there is less room for reducing emissions by switching production to less polluting goods.[4] Therefore, using 2007 technology would understate compositional changes relative to using earlier technology, and the difference between the observed and the true compositional changes would be mistakenly recorded as technique.

For these reasons, I proxy EU emissions by industry using US emissions from the World Bank IPPS data by 4-digit SIC code for 1987 (Hettige et al. 1995). Emission levels are not always the same between US and EU industries, but they are highly correlated. Using the 4-digit level data available for the European Union for 2007, the correlation in pollution intensities for SO2 is 0.71 overall. Considering the different reporting rules and the amount of missing EU data, this correlation is quite high. Moreover, the correlation in pollution intensities is 0.95 among the top ten polluting industries, which drive most of the results. But if pollution intensities evolve differently over time across the two regions, this one-year comparison might not be convincing enough. Comparing pollution intensities of the 14 industries available from the EPER for 2001 and 2004, the correlation with aggregated US data is 0.82. Although the relationship between emission levels is not exact, these correlations suggest that the most highly polluting industries are generally the same in Europe and the United States, even across different years. Since I study the evolution of pollution inten-

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[4] If a new technology allows for the same production process to emit 10 percent less SO2, the magnitude of the decrease will be large for industries with high pollution intensities (level of emission per unit of output), and small for industries with low pollution intensities. Therefore, the range of pollution intensity narrows.

sity over time compared to fixed 1995 levels, ultimately I am concerned with relative rather than absolute levels of emissions, so US technology provides a reasonable proxy to consider pollution patterns in EU manufacturing production.

I construct pollution intensity coefficients (z) for 361 manufacturing industries by dividing IPPS pollution levels of SO2, NO2 and VOCs by EU industry-level manufacturing output.[5] I can only calculate pollution coefficients for 1987, so I cannot directly measure changes in pollution intensity. Thus I compute the technique effect (dz) as the difference between actual pollution and the pollution predicted by the scale and composition effects. As a residual, the technique effect essentially sums up any effect that is not already captured by scale or composition, which includes all changes to production processes from the introduction of new pollution abatement technologies to a change in capital or energy intensities.

As in Levinson (2009), I obtain data on US manufacturing from the NBER Manufacturing Productivity Database (Bartelsman and Gray 1996). The National Emissions Inventory (NEI) provides data on total US manufacturing pollution in terms of sulfur dioxide (SO2), nitrogen dioxide (NO2) and volatile organic compounds (VOCs). And I use the World Bank IPPS data to calculate the pollution intensity coefficients.

I adjust all the data for inflation using industry by industry producer price indices (PPI) from Eurostat for EU data and from the NBER Manufacturing Productivity Database for US data. Energy prices were volatile in the 2000s so it is important to consider how energy prices affected each industry depending on the industry's energy intensity. If the price of oil increases, the value of output per unit of emission will increase more for energy-intensive industries such as refineries than for others such as

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[5] The IPPS database also includes data on emissions of carbon monoxide (CO), but these data are not available for the European Union in the Environmental Database of Eurostat so I do not include CO in the analysis.

textiles, holding everything else constant. Using the absolute value of output would therefore overstate the composition effect and understate the role of technique.

One downside of industry-specific PPI is the rapid technological advancement in the computer and electronics industry. The price index of those sectors has decreased significantly, from a baseline of 100 in 1995 to as low as 20 in the European Union and 3 in the United States by 2008.[6] But for this sector the rapid drop in prices captured by the PPI is a result of technological change rather than deflation. Adjusting value shipped and trade flows of computers and electronics by industry-specific PPI therefore overstates the weight of this industry in total output, imports and predicted pollution. Running the analysis with and without computers yields similar results for the European Union but poses a problem for the comparison between Levinson (2009) and the update of the US results provided in this paper. Levinson (2009) uses preliminary estimates of industry-specific PPI after 1997. In the case of the computer and electronics industries, the preliminary estimates differ significantly from the final estimates used in the update, rendering the comparison difficult. Consequently, I exclude the computers and electronics industries from the analysis.

Finally, if manufacturing firms increasingly purchased electricity from utility firms rather than generating their own, emissions from the manufacturing industry would have also shifted to utility firms. That drop would be erroneously attributed to the technique effect. However, purchases of electricity as a share of electricity consumption remained stable in the European Union and the United States over the time period.[7]

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[6] No other sector exhibits such a strong decrease in PPI.

[7] In France, purchases of electricity as a share of electricity consumption remained between 93 and 96 percent from 1996 to 2010 (INSEE 1996, 2010). The same figure for the United Kingdom went from 89 percent in 1996 to 91 percent in 2010 (UK DECC 2011). In Germany, the quantity of electricity produced as a share of consumption for manufacturing and mining went from 22 percent to 23 percent between 2002 and 2009 (Destatis 2002, 2009, AGEB 2002, 2009). Similarly, in the United States, purchases of electricity as a share of net demand of

2.2.2 RESULTS

Figure 2.1 presents the decomposition of the scale, composition, and technique effects for SO2 emissions from EU manufacturing, adjusted for industry-specific inflation.[8] Line (1) represents actual emissions of SO2 from EU manufacturing, which decreased 59 percent between 1995 and 2008. Line (2) depicts the scale effect, which represents the amount of emissions that would have been emitted from EU manufacturing had the composition and technique of production remained constant through time, i.e. had pollution increased one-for-one with manufacturing output. Since real EU manufacturing increased 37 percent between 1995 and 2008, the scale effect predicts that emissions from all pollutants should have also increased 37 percent.[9] The difference between the scale effect and actual emissions is the proportional cleanup from manufacturing.

The next step consists of determining what combination of composition and technique offset the scale effect and led to the cleanup. Line (3) captures the scale and composition effects. It multiplies output in each industry by the emission intensity coefficient z, where z is emissions per dollar of output from the IPPS dataset. The change in emissions due to shifts towards producing more or less pollution-intensive goods – the composition effect – is the difference between lines (2) and (3). The remainder – the difference between lines (1) and (3) – represents the technique effect, the fact that firms can now produce the same unit of output with fewer emissions. Where line (3) is below line (2), emissions predicted by scale and composition were

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electricity in the manufacturing sector were 87 percent in 1998 and 86 percent in 2006 (US EIA 2006).

[8] The graphs and discussion focus on SO2 for simplicity, but the tables include the results for all three pollutants. The results are also summed over all three pollutants as an indication, though the sum of a ton of SO2 and a ton a NO2 does not have an obvious interpretation.

[9] The patterns are the same for 2009 but I end the discussion in 2008 to avoid distortions due to the global financial crisis.

lower than emissions predicted by scale alone. In those instances, the composition of EU manufacturing moved towards less polluting industries – a green shift. Conversely, line (3) being above line (2) denotes a brown shift of production. Prior to 2001, EU compositional changes were small. After 2001, however, the composition of EU production switched towards pollution-intensive goods in a dramatic way. The combined scaled and composition effect together increased emissions by 99 percent – a large brown shift.

The brown specialization of EU production is surprising. It cannot be explained by price inflation since I deflated data by industry-specific price indexes, nor is it driven by a few industries. In fact, I removed two outliers from Figure 2.1 when performing the composition calculations: electrometallurgical products, except steel (SIC 3313), and blast furnaces and steel mills (SIC 3312). Including these two highly polluting industries does not change the conclusion that EU production increasingly specialized in polluting goods, but significantly augments the effect: the predicted emissions from scale and composition rise from 99 percent to 140 percent.[10] But since two industries account for a large portion of that rise, the magnitude of the number is not indicative of the size of the overall brown shift in manufacturing. That is not to say that SIC 3312 and 3313 are not important, but the pattern shown in Figure 2.1 is more representative since it reflects a general and persistent tendency of EU manufacturing to switch towards the production of more pollution-intensive goods between 2001 and 2008.

This brown shift happened over a time period when the European Union implemented a variety of environmental policies and signed the Kyoto Protocol. However, the shift cannot be interpreted as a failure of environmental regulation. The switch

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[10] This large increase could be the consequence of the sharp rise in steel prices in 2004-2005, which also led to an increase in the price of electrometallurgical products commonly used to enhance steel products.

towards polluting industries might have been even more pronounced absent environmental regulation. Moreover, these regulations could have affected the technique of production rather than the choice of goods produced. In fact, as EU manufacturers adopted new techniques that reduced the cost of producing pollution-intensive goods, it is possible that they were able to competitively produce those goods even in an environment with stricter environmental regulations.[11] In other words, progress in technique might have enabled the brown compositional shift of EU manufacturing despite stricter environmental regulation, and in such a way that decreased overall emissions.

Since the EU manufacturing sector increasingly specialized in the production of more pollution-intensive goods since 2001, the technique effect – the gap between lines (1) and (3) – was even larger than the total cleanup of manufacturing – the gap between lines (1) and (2). In fact, Table 2.1 shows that the technique effect was between 1.5 and 2 times as large as the total cleanup for each pollutant. Some caution must be applied here. Within each industry, some firms might have switched to production goods from cleaner sub-industries – a within-industry composition change that is categorized here as technique. The level of aggregation of the data could therefore overstate the effect of technique. Still, given the overwhelming role of technique, those sub-industry movements are unlikely to reverse the conclusion that technique played a crucial role in the cleanup of EU manufacturing.

In the United States, the technique effect was also the main driver of the cleanup of manufacturing, but unlike in the European Union, the composition effect remained small even after 2001. Figure 2.2 traces out the same scale, composition and technique effects for SO2 emissions in the United States. Over time, line (3) oscillates around

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[11] Lu and Pang (2015) show that this induced-innovation channel played a role in the specialization of US manufacturing.

line (2) with no clear persistent shift. That is not to say that there was no movement across industries, but the movement was occurring across industries of similar levels of pollution intensity. Therefore, the composition effect did not play a large role in the cleanup of US manufacturing. Improvements in production technique explain almost all of the cleanup for SO2. Table 2.2 shows that the technique effect accounted for more than 80 percent of the cleanup for SO2 and NO2 (87 percent and 81 percent respectively). Using plant-level data, Shapiro and Walker (2015) confirms the role of falling pollution intensity within narrowly defined products in the decrease in pollution in US manufacturing, and find that much of that decrease can be attributed to environmental regulation. The role of technique is much smaller for VOCs (35 percent) because of significant increases in emissions from petroleum refining industries due to a lower technique effect. Still, the increase in actual emissions (12 percent) was below the increase in emissions predicted by the scale effect (31 percent) so manufacturing production was becoming less pollution-intensive in terms of VOCs as well.

In sum, both the European Union and the United States experienced important cleanups of their manufacturing sector between 1995 and 2008. The main driver of the cleanup in both regions was unquestionably the technique effect. But the role of composition differed between the two regions. In the United States, the composition of goods remained essentially the same over the time period, while in the European Union the manufacturing sector increasingly specialized in the production of more pollution-intensive goods. The next step consists of identifying the role of trade in composition, both to determine whether worries about pollution offshoring are warranted and to shed light on potential explanations for the large brown compositional shift in the European Union.

2.3 The Role of International Trade

2.3.1 Method and Data

This section focuses on the composition effect, particularly the role of international trade in the compositional changes observed in EU and US manufacturing. The composition effect could have been due either to a change in the preferences of consumers, who demanded cleaner goods, or to the fact that instead of producing polluting goods, the European Union and the United States imported them from abroad. Therefore, the composition effect is the combined change in trade and domestic consumption. In this section, I examine the pollution embodied in imports and the share of trade in the composition effect to determine whether pollution offshoring played a large role in the cleanup of manufacturing.

Let P^M denote the amount of additional pollution that would have been emitted within a region if its imported goods were instead produced at home:

$$P^M = \sum_i p_i^M = V^M \sum_i \theta_i^M z_i \tag{2.4}$$

Equation (2.4) is essentially a version of equation (2.1) applied to imports. V^M represents total imports, θ_i^M is the share of imports of industry i in total imports, and z is a measure of the pollution intensity.

I still use IPPS emissions data to measure technology (z) because P^M does not represent the amount of pollution emitted abroad when producing the imports, but rather the amount of pollution that would have been emitted had the imports been produced domestically. To determine whether there is evidence of pollution offshoring, the important metric is not the pollution created abroad, but rather the pollution not emitted at home due to offshoring. The concept is similar to labor offshoring, where one is concerned with the jobs lost at home rather than those created abroad.

Additionally, trade data only account for the goods that cross the border, not for the inputs into those goods. Studies of compositional shifts of imports that work with finished products (Schatan 2003, Khan 2003, Cole 2004) find that the pollution content of imports has fallen dramatically, and much faster than the pollution content of exports. However, accounting for inputs could reduce that difference. For example, assembling a car is a not a pollution-intensive process, however, producing the steel and the rubber used in car parts is pollution-intensive (Levinson, 2009). If imports into the European Union or the United States are dominated by finished products, as is usually the case for industrialized economies, then failure to account for the pollution content of inputs could significantly understate the overall pollution content of imported goods. In fact, accounting for inputs raises emissions embodied in imports 18 percent for EU imports and by 26 percent for US imports. Moreover, Michel (2013) shows that for Belgian firms there is evidence of pollution offshoring for intermediate goods in footloose industries.

To account for inputs to production, I construct a pollution intensity index that embodies the pollution of the entire production chain. This index, denoted z^{**}, is a straightforward application of the Leontief (1970) input-output algebra. Let y_i be the final output, where y_i is a subset of x_i. Total output $\mathbf{x}$ is the sum of output used as intermediate goods and final output:

$$\mathbf{x} = \mathbf{DRx} + \mathbf{y} \tag{2.5}$$

where $\mathbf{x}$ is a vector of k outputs, one from each industry, and $\mathbf{DR}$ is an $k \times k$ matrix of direct requirements coefficients with elements dr_{ij} representing the dollar value of input industry i needed to produce one dollar's worth of industry j output – $\mathbf{DR}$ is the input-output matrix. Trade data give the vector $\mathbf{y}$, but I am interested in $\mathbf{x}$.

Rearranging the above equation and isolating $\mathbf{x}$ gives:

$$\mathbf{x} = [\mathbf{I} - \mathbf{DR}]^{-1}\mathbf{y} \tag{2.6}$$

The matrix $[\mathbf{I} - \mathbf{DR}]^{-1}$ is the Leontief total requirements matrix, which gives the relationship between final demand y and total output x. By the same argument, the total amount of pollution necessary to produce each good is:

$$\mathbf{z}^{*} = \mathbf{z}'[\mathbf{I} - \mathbf{DR}]^{-1} \tag{2.7}$$

However, this vector $\mathbf{z}^{*}$ does not account for the fact that some inputs might have been imported. Therefore, it might overstate the pollution that would have been emitted by producing the good at home. To account for imports, the $\mathbf{DR}$ matrix is pre-multiplied by $diag(\mathbf{d})$, where $\mathbf{d}$ is a $k \times 1$ vector of the share of each input that is supplied by domestic production. The total domestic requirements emissions coefficient is therefore:

$$\mathbf{z}^{**} = \mathbf{z}'[\mathbf{I} - diag(\mathbf{d})\mathbf{DR}]^{-1} \tag{2.8}$$

where $[\mathbf{I} - diag(\mathbf{d})\mathbf{DR}]^{-1}$ is the total domestic requirement matrix.

For both regions, I collect trade data at the 4-digit level based on the US SIC classification from the World Bank World Integrated Trade Systems (WITS), and use the 1987 benchmark input-output tables from the US Bureau of Economic Analysis (BEA).[12] Unfortunately, an input-output table of the EU economy is not available at the 4-digit level so I assume that the structure of the EU and US economies are similar and apply the US input-output table to the EU analysis. Despite some differences, a study by Eurostat comparing US and EU I-O tables at an aggregated level shows remarkable similarities in the input coefficients (Remond-Thiedrez, 2013).[13] However,

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[12] Those tables use their own classification but the BEA provides a concordance with US Standard Industrial Classification (US SIC) in 1987.

[13] There could remain catchdifferences across EU countries.

since the share of imported intermediate goods could differ significantly between the European Union and the United States, I separately adjust each region for the share of products supplied domestically. The $\mathbf{z}^{**}$ matrix for the European Union is therefore computed using US emissions and US IO tables, but EU domestic shares.

2.3.2 RESULTS

To determine the role of trade in the composition effect, I first examine the evolution of the pollution intensity of EU and US imports. Figure 2.3 shows the amount of SO2 emissions embodied in EU imports. Line (1) represents the scale effect. Based on the increase in the quantity of imports, the scale effect predicts an increase in the amount of pollution displaced by EU imports of 143 percent between 1995 and 2008.[14] But the composition of imports also changed. Line (2) calculates the amount of pollution displaced by EU imports accounting for the changes in composition. It represents the total amount of pollution that would have been emitted if all imports and their inputs had been produced in the European Union using domestic technology. Pollution displaced by EU imports grew 77 percent between 1995 and 2008. Thus, the composition effect reduced SO2 emissions displaced by imports by 27 percent in the European Union compared to the increase predicted by the scale effect (Table 2.3, column 2).[15] EU manufacturing imports increasingly consisted of relatively cleaner goods between 1995 and 2008 in terms of SO2. Similarly, the green shift of imports resulted in decreases in predicted emissions of 31 percent and 18 percent for NO2 and

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[14] The plot shows a sharp increase in real imports after 2002, in line with renewed economic expansion.

[15] Based on the scale effect, emissions should have increased from a base level of 100 percent in 1995 to 243 percent in 2008. Accounting for changes in composition, emissions actually displaced by imports increased from 100 percent in 1995 to 177 percent in 2008. The composition effect was to change emissions by $\frac{177-243}{243} = -27\%$.

VOCs respectively. These results point to a green shift of imports into the European Union.

The green shift of imports coincided with a brown shift of production, which is exactly the opposite of what pollution offshoring would predict. However, the pollution offshoring argument usually concerns low-income countries that generally implement less stringent environmental standards than the European Union. As such, they constitute prime destinations for EU firms looking to escape stringent domestic environmental standards by offshoring the production of pollution-intensive goods to countries with laxer standards. Pollution offshoring to low-income countries could be masked by other changes in aggregate, so in the last four columns of Table 2.3 I break down the composition effect separately for trading partners of different income groups.[16]

As can be seen in the last four columns of Table 2.3, the green shift of EU imports was present for all groups, and contrary to the pollution offshoring intuition, the shift was in fact most pronounced for low-income country imports. Across all pollutants, the green shift of low-income country imports amounted to over a 50 percent reduction compared to emissions predicted by scale. Lower-middle-income country imports exhibited a smaller green shift (26 percent), of the same magnitude as the green shift of imports from high-income countries (27 percent). EU imports from low and lower-middle-income countries were not specializing in pollution-intensive goods leading up to 2008.

The figures in this table do not include outliers. Low-income country imports exclude primary aluminum (SIC 3334 and SIC 2819) and lower-middle-income country

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[16] The income groups are formed according to the World Bank definitions. For the European Union, the high-income country group excludes EU-15 members so as not to count intra-EU trade.

imports omit electrometallurgical products, except steel. This is because the production of low and lower-middle-income countries is usually labor-intensive, and thus relatively clean when measured using US technology. As a result, the production of just one dirty import can significantly alter the results and obscure the broader patterns.

Including aluminum, EU imports from low-income countries appear to have experienced a much smaller green shift, only 2 percent for SO2. Imports of primary aluminum (SIC 3334 and SIC 2819) grew thirteen-fold between 1995 and 2008. This increase was in part due to the creation of the Mozal aluminum plant in Mozambique in 2000. Electricity amounts to a large portion of the operating costs of producing aluminum and Mozambique had newly secured access to cheaper electricity through the Motraco venture, which created two electricity transmission lines from South Africa (Wells and Bueher 2000). Since primary aluminum is a highly pollution-intensive good, by 2008 it accounted for 82 percent of the pollution content of low-income country imports despite amounting to only 9 percent of their value. Moreover, in 2008 imports of aluminum from Mozambique still represented less than 1 percent of total aluminum imports into the European Union. Therefore, including imports of primary aluminum obscures the large green shift of imports from low-income countries but is not evidence pollution offshoring overall. However, it does suggest pollution offshoring might be occurring for aluminum.

Similarly, accounting for electrometallurgical products, except steel, EU imports from lower-middle-income countries seem to have experienced a brown shift of 18 percent. Imports of electrometallurgical products, except steel, grew by a factor of 11 between 1995 and 2008, accounting for 20 percent of the pollution content of all EU imports from this country group by 2008. But growth in imports of one polluting good is hardly evidence of a broader trend to offshore pollution to low and lower-middle-income countries. The figures reported in Table 2.3 are more representative of the general trend, which points to an important green shift of EU imports from all countries.[17] Therefore, I do not find broad patterns of pollution offshoring from the European Union but there might be some offshoring in the few specific industries described above.

In an attempt to shed light on the reason for the brown shift of EU production, I study the imports of the 12 countries that acceded to the European Union in 2004 and 2007.[18] One hypothesis could be that the brown shift of production in the EU-15 countries was a result of enlargement since the two happened simultaneously. Before accession, the EU-15 could have offshored pollution to their Eastern European neighbors with less stringent environmental standards. As part of the accession process, enlargement countries had to meet EU environmental standards and implement EU environmental regulation. The production of pollution-intensive goods could then have been repatriated to the EU-15 as acceding countries cleaned up their production to adhere by EU standards. If that hypothesis holds, the composition of enlargement countries imports into the EU-15 should have changed towards less pollution-intensive goods around the time of accession. The green shift of imports from enlargement countries was about 60 percent between 1995 and 2008, larger than those of the income groups they belong to (high-income and higher-middle-income). But there does not appear to be a change in the pace of the green shift around the time of accession or at any point between 1995 and 2008, possibly because the accession process occurred gradually and started prior to 1995. In any case, the lack of change in the pace of the

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[17] The results for high- and higher-middle-income country imports are not driven by outliers and so include all goods.

[18] None of these 12 countries are included in this paper's definition of the "European Union", which only looks at the EU-15. The 10 countries that acceded in 2004 are: Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia. Bulgaria and Romania acceded in 2007.

green shift of enlargement country imports invalidates the hypothesis: the enlargement process cannot explain the brown shift of EU production.

Despite the green shift of imports, aggregate emissions displaced by imports increased 77 percent between 1995 and 2008 in the European Union – Figure 2.3. This leaves room for a role of trade in the total cleanup of manufacturing. In Figure 2.1, line (4) estimates the scale and composition effect including net imports. It sums the pollution from the production of manufacturing and the pollution that would have been emitted had the increase in net imports between 1995 and 2008 been produced domestically, everything else held equal. In other words, it represents the amount of pollution embodied in the goods demanded by EU consumers if technology were fixed at 1987 levels.

As shown in Figure 2.1, line (4) is strictly below line (3). The amount of emissions from the goods consumed in the European Union was less that the pollution from EU production. The brown shift in EU manufacturing production would have been reduced by adding net imports. Despite the fact that the value of EU manufacturing imports was larger than the value of its exports, the pollution content of imports was lower than that of exports. EU exports experienced a green shift that was less pronounced than the green shift of EU imports. Therefore, adding back the pollution content of net imports – a negative number – decreases the brown shift of EU manufacturing. In other words, the mix of goods imported by the European Union was increasingly clean compared to domestic production and compared to EU exports.[19] Table 2.4 shows that net EU exports of polluting goods account for a quarter to two-thirds of the brown shift of production depending on the pollutant.

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[19] That is not to say that EU imports were not in fact produced with dirtier technologies than would have been used in the European Union. This paper can only comment on the pollution embodied in goods based on US technology.

In the United States, I find the results to be different from the European Union, but in line with the conclusions from Levinson (2009). Figure 2.4 shows that US imports, like EU imports, exhibited a green shift between 1995 and 2008. The scale effect predicted a 130 percent increase in SO2 emissions embodied in US imports. Accounting for changing composition and inputs, SO2 emissions displaced by US imports were 26 percent lower than the scale effect would predict, indicating a green shift of imports (Table 2.5 column 2). The magnitudes differ but the conclusions hold for NO2 and VOCs as well.

This green shift of US imports was most pronounced for low-income country imports, which goes against the pollution offshoring predictions. Across all pollutants, the green shift of low-income country imports exceeded 80 percent. However, US imports from lower-middle-income countries exhibited a brown shift of 36 percent for SO2. Unlike the EU results, this brown shift cannot be attributed to a single product. The shift was due to smaller but more widely spread increases in imports of polluting industries. Some of those increases concerned polluting industries: power, distribution and specialty transformers (3612), clay refractories (3255), petroleum refining (2911). The rest of the pollution increase was due to a large rise in imports of a variety of industries that are somewhat polluting such as hoists, cranes and monorails (3596), paper industries machinery (3554), plastic materials and resin (2821), and soybean oil mills (2075). The more global nature of this brown shift suggests that pollution offshoring could have been occurring from the United States to lower-middle-income countries. In fact, in a recent paper, Xiaoyang Li and Yue Maggie Zhou find some evidence of pollution offshoring to low- and lower-middle-income countries using plant-level US data.

However, trade does not play a large role in the cleanup of US manufacturing. In Figure 2.2, line (4) is strictly above line (3) because US production would have been more pollution-intensive if net imports were produced at home. For SO2, a little over half of the US compositional shift can be accounted for by net imports of polluting goods (Table 2.6). However, given the small size of the US compositional shift, net imports accounted for a small share of the cleanup. For SO2 and NO2 the share of trade in the total cleanup is less than 10 percent. For VOCs, the cleanup was much smaller than for the other pollutants and so net imports account for almost 50 percent of the cleanup.

To summarize, in the European Union, imports were increasingly composed of less pollution-intensive goods, while manufacturing production exhibited a brown shift, suggesting the opposite of pollution offshoring. Not only did imports not contribute to the cleanup of EU manufacturing, but a significant portion of the brown shift of EU production can be matched by increased exports of pollution-intensive goods. In the United States, there was some evidence of pollution offshoring to lower-middle-income trading partners, but depending on the pollutant, trade only accounted for a small share of the cleanup of US manufacturing production. Pollution offshoring therefore did not appear to be a concern in either the European Union or the United States between 1995 and 2008.

2.4 Conclusion

Over the past several decades, both the European Union and the United States have raised environmental standards and imposed additional regulation on companies. As a result, EU and US manufacturing sectors could have increasingly specialized in the production of clean goods and offshored the production of those polluting goods that are the target of regulations. In fact, despite important increases in output, both the European Union and the United States experienced a significant cleanup of their manufacturing industries between 1995 and 2008. This cleanup may be partially due to offshoring, but could also be the result of improvements in production technology or changes in consumer preferences. While several studies have examined the role of technique, offshoring, and consumer demand in the cleanup of US manufacturing, there is no evidence as to whether these patterns hold true for other developed economies. In this paper, I study the specialization of EU manufacturing production and trade between 1995 and 2008 to identify the relative importance of the technique, offshoring and consumer demand channels for the cleanup of the European Union.

In line with US results, the cleanup of EU manufacturing was largely due to improvements in production techniques that allowed the same goods to be produced with less pollution. However, unlike in the United States where the mix of goods produced did not change significantly, EU production increasingly specialized in the production of more pollution-intensive goods in an important way, even accounting for price inflation and outlier industries. Although the shift coincides with EU enlargement, I do not find a link between the brown shift of production and enlargement. The brown specialization appears to have been due to an increase in the demand for increasingly pollution-intensive goods, both domestically and abroad. In parallel, EU imports increasingly consisted of the less pollution-intensive goods, especially from lower-income countries. Therefore, the patterns of specialization of EU production and imports point to the opposite of pollution offshoring. In the United States, I do find some evidence of pollution offshoring towards lower-middle-income countries, but trade accounts for less than 10 percent of the total cleanup of US manufacturing. Overall, I conclude that there is little support for the pollution offshoring hypothesis either in the European Union or in the United States.

2.5 FIGURES

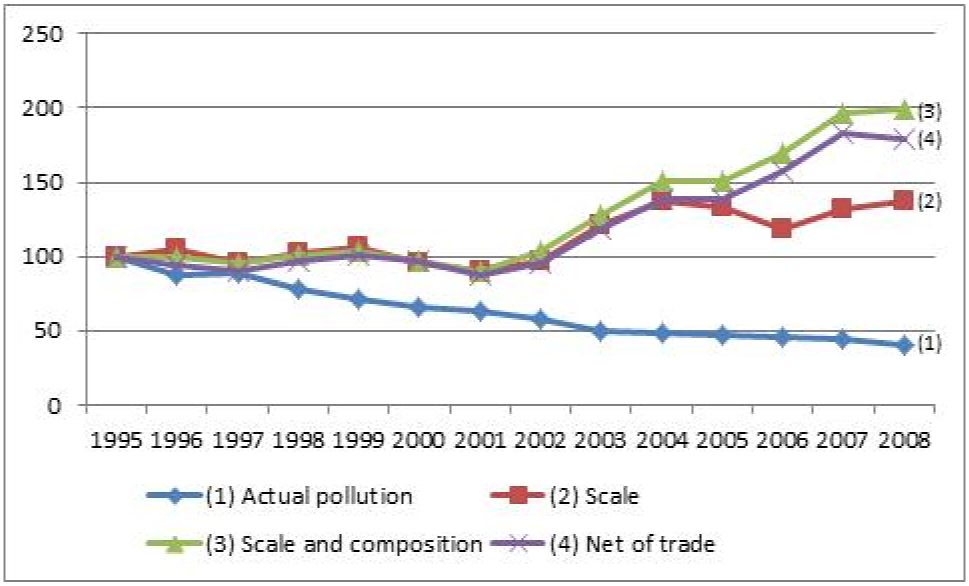

Figure 2.1: SO2 Emissions from EU manufacturing, 1995-2008

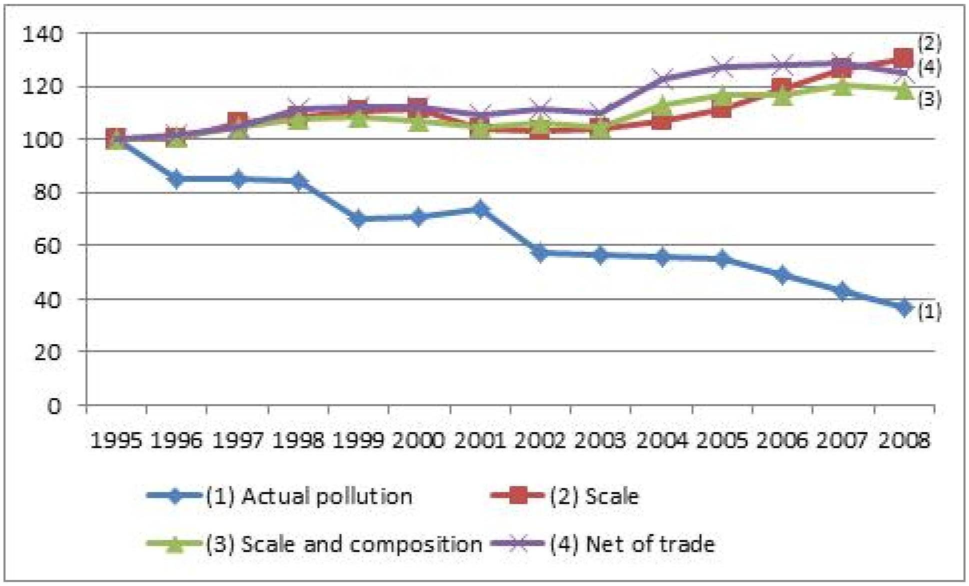

Figure 2.2: SO2 Emissions from US manufacturing, 1995-2008

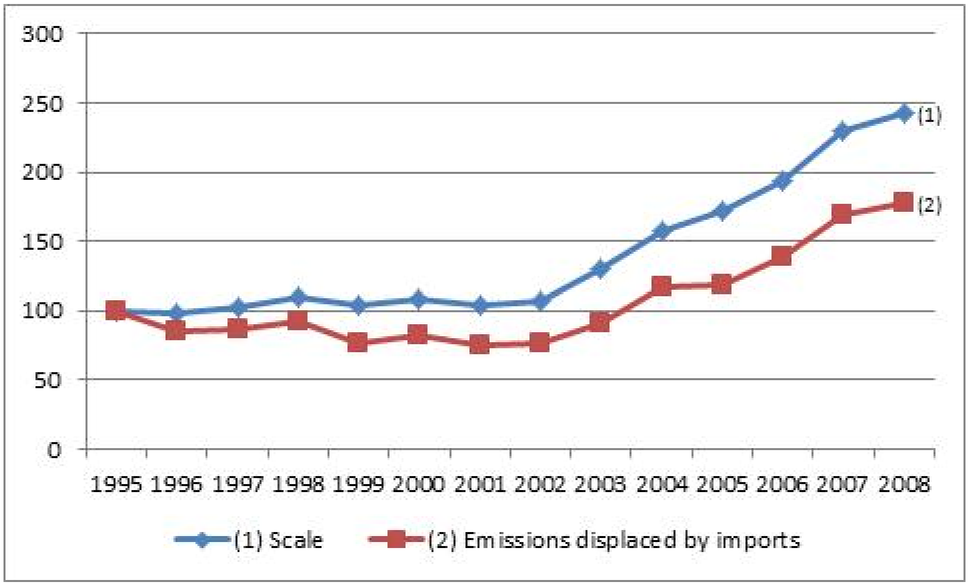

Figure 2.3: EU Imports from All Countries and Displaced SO2 Emissions, 1995-2008

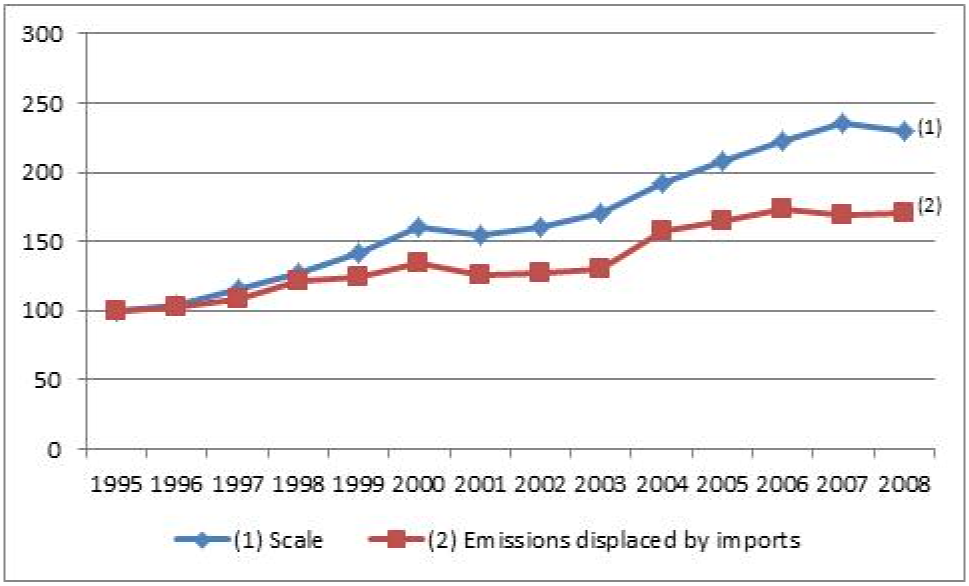

Figure 2.4: US Imports from All Countries and Displaced SO2 Emissions, 1995-2008

2.6 TABLES

Table 2.1: EU Scale Composition and Technique Effects, 1995-2008

	SO2	NO2	VOCs	All3
Actual pollution (1)	−0.59	−0.23	−0.24	−0.39
Scale (2)	0.37	0.37	0.37	0.37
Scale and composition (3)	0.99	0.96	0.95	0.97
Fraction of cleanup due to technique (4)	1.65	1.98	1.96	1.79

Note: $(4) = \frac{(3)-(1)}{(2)-(1)}$

Table 2.2: US Scale Composition and Technique Effects, 1995-2008

	SO2	NO2	VOCs	All3
Actual pollution (1)	−0.63	−0.4	0.12	−0.4
Scale (2)	0.31	0.31	0.31	0.31
Scale and composition (3)	0.19	0.17	0.19	0.18
Fraction of cleanup due to technique (4)	0.87	0.81	0.35	0.82

Note: $(4) = \frac{(3)-(1)}{(2)-(1)}$

Table 2.3: Difference between Pollution Predicted by Total Imports and Industry Specific Production: The Composition Effect in the European Union (1995-2008)

		Imports				
	Manufacturing (1)	All (2)	High -income (3)	Higher-middle -income (4)	Lower-middle -income (5)	Low -income (6)
SO2	0.72	−0.27	−0.15	−0.4	−0.26	−0.66
NO2	0.55	−0.31	−0.17	−0.41	−0.17	−0.64
VOCs	0.46	−0.18	−0.09	−0.28	−0.06	−0.53
All3	0.59	−0.26	−0.14	−0.38	−0.18	−0.64

Notes: Imports from lower-middle-income countries do not include steel, and imports from low-income countries do not include aluminum. A negative number denotes a green shift, and a positive number represents a brown shift.

Table 2.4: Share of EU Cleanup Explained by Trade, 1995-2008

	Share of composition change	Share of total cleanup
SO2	0.37	−0.16
NO2	0.62	−0.24
VOCs	0.25	−0.05
All3	0.33	−0.15

Note: Parentheses indicate that the effect of trade goes against the cleanup.

Table 2.5: Difference between Pollution Predicted by Total Imports and Industry Specific Production: The Composition Effect in the United States (1995-2008)

		Imports				
	Manufacturing (1)	All (2)	High -income (3)	Higher-middle -income (4)	Lower-middle -income (5)	Low -income (6)
SO2	−0.09	−0.26	−0.19	−0.36	0.36	−0.8
NO2	−0.1	−0.28	−0.22	−0.34	0.12	−0.81
VOCs	−0.09	−0.17	−0.11	−0.16	0.04	−0.82
All 3	−0.1	−0.24	−0.18	−0.31	0.22	−0.81

Notes: A negative number denotes a green shift, and a positive number represents a brown shift.

Table 2.6: Share of US Cleanup Explained by Trade, 1995-2008

	Share of composition change	Share of total cleanup
SO2	0.56	0.07
NO2	0.32	0.06
VOCs	0.73	0.48
All3	0.52	0.09

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CHAPTER 3

EVALUATING MEASURES OF ENVIRONMENTAL REGULATORY STRINGENCY

3.1 INTRODUCTION: OBSTACLES AND APPROACHES

Important policy debates often hinge on measures of jurisdictions' environmental regulatory stringency. The US Clean Air Act was enacted in part to prevent individual US states from lowering their environmental standards in a "race to the bottom" to attract investment (Portney, 1990). The EU has long debated whether "harmonization" of regulatory stringency should be a prerequisite for more European unification (Bhagwati and Hudec, 1996). Opponents of strict regulations cite their costs in terms of lost productivity, lower labor demand, and reduced investment; proponents cite Porter's (1991) hypothesis that strict regulations encourage innovation and investment. And more subtle arguments note that lax environmental regulations can substitute for protectionist tariffs (Ederington and Minier, 2003). Most recently, international climate negotiators have struggled with concerns that greenhouse gas emissions capped in one country will be emitted instead by nonparticipating countries. The jargon has proliferated along with the policy debates: pollution havens, industrial flight, environmental dumping, race-to-the-bottom, NIMBY, harmonization, and leakage. These varying policy concerns share a unifying feature: assessing them requires measuring the relative stringency of environmental regulations over time or across different states or countries. This paper identifies the main obstacles to measuring environmental regulatory stringency, and evaluates existing measures in terms of how accurately they embody stringency and how well they enable researchers to answer these policy questions.

Perhaps because these questions are so important, the number of papers in this literature is vast. Many read as though the chief obstacles to measuring stringency involve data collection, as though if we gave the appropriate agencies enough resources they could simply collect the right information. But the obstacles to using those measures for policy analysis involve a much deeper set of conceptual and econometric problems. Broadly speaking, there are four: (1) multidimensionality – environmental regulations cannot easily be captured by one measure of "stringency"; (2) simultaneity – jurisdictions with strong economies or bad pollution problems may impose the most stringent regulations; (3) industrial composition – in places where the mix of industries is more pollution-intensive, the average business automatically faces more stringent regulations; and (4) capital vintage – regulatory standards are typically tighter for new sources of pollution, with implications for the environment, the economy, and measures of regulatory stringency.

Because those conceptual problems are so challenging, the number of approaches papers have taken to attempt to measure stringency has also been vast. We break those approaches down into five categories: (1) private sector abatement costs, (2) direct assessments of the regulations themselves, (3) composite indexes meant to compress the multidimensional problem down to one number, (4) measures based on pollution or energy use, and (5) measures based on public sector expenditures or enforcement. In the pages that follow we discuss empirical work that has taken each of the five approaches and consider their strengths and weaknesses in light of the obstacles faced. At the end we find that the concept of stringency used in stylized theoretical models is difficult to implement empirically, and that measures used to date fall short on numerous dimensions. Finally, we propose a new measure of our own, a hybrid of the emissions and cost-based approaches

Section 3.2 describes the four conceptual obstacles to measuring and interpreting stringency measures; Section 3.3 discusses the five categories of approaches and reviews the advantages and drawbacks of representative literature for each type; Section 3.4 present our new hybrid measure; and Section 3.5 concludes.

3.2 Four Conceptual Obstacles to Measuring Environmental Regulatory Stringency

In most cases, researchers are interested in forecasting the consequences of changing regulations. For that purpose, the ideal measure of stringency would be a panel, varying both across jurisdictions and within jurisdictions over time. Unfortunately, many available measures of stringency involve comparisons across countries or states in a single year. That limitation complicates even further our four obstacles – multidimensionality, simultaneity, industry composition, and capital vintage – as we discuss in this section.

3.2.1 Multidimensionality

The "environment" is a complex multidimensional problem, and so are its associated regulations. Governments regulate various media – air, water, hazardous waste – and pollutants into those media – sulfur dioxide, sewage, toxic chemicals, etc. Some regulations target households while others target industries. Regulations set standards for total emissions, emissions concentrations, ambient environmental quality, and the technologies employed by producers. Finally, regulations only matter if they are enforced.

Challenges of Multidimensionality

This multidimensionality poses challenges. The simplest involves matching the regulation to the policy question being asked. If we are interested in whether regulations cause industrial flight from strict countries, neither the lead content of automotive gasoline nor the incentives to recycle household waste will directly affect industries' profitability in various locales. Some regulations target emissions when ambient quality matters or vice versa. The US Clean Air Act sets uniform National Ambient Air Quality Standards (NAAQS). So in terms of ambient standards, every air quality control region (typically a county) faces the same level of stringency. But in order to meet those standards, some counties must impose costly emissions requirements while others do not. In Los Angeles, where the local mountains trap air pollution over the city, the NAAQS are costly to meet. In Honolulu, where winds quickly blow air pollution out over the Pacific, the NAAQS are easily met. If the “regulation" being studied is the local ambient standard, then both cities have equally stringent rules. But if the “regulation" is the control technologies manufacturers must adopt, Los Angeles is more stringent. So are Los Angeles's regulations more stringent? The answer depends on the context.

A second obstacle is that complex regulations are not easily comparable. The new US standards for industrial boilers limit toxic emissions to 2.0-3.0 tons per year of mercury and 580,000 tons per year of sulfur dioxide. Which is more stringent? In 1987 the US EPA set the NAAQS for particulate matter at 150 $\mu g/m^3$ of particles smaller than 10 micrometers in diameter, averaged over 24 hours, not to be exceeded more than once per year over three years. In 1997 that was changed to 65 $\mu g/m^3$ of particles smaller than 2.5 micrometers in diameter, at the 98th percentile, averaged over three years.[1] Which is more stringent? The answer depends on the compliance costs for industry, the health consequences to people, and the context in which the question is asked.

How Multidimensionality Has Been Addressed to Date

Researchers have dealt with the multidimensionality and complexity of regulations in one of two ways. Some avoid multidimensionality by focusing on one particular narrow environmental problem with directly comparable stringency measures. Berman and Bui (2001) study air pollution regulations as they affect oil refineries in Los Angeles. They use confidential plant-level data from the Census of Manufactures, and a painstaking, line-by-line reading of the local air pollution regulations. Berman and Bui know the exact dates on which specific regulatory changes affected particular refineries, how those refineries responded, and what costs they incurred. Levinson (1999a) similarly narrows the multidimensionality by focusing on hazardous waste disposal taxes, a single dimension of state law that is easily measurable, comparable, and clearly targeted. The advantage of these focused approaches is clear: accuracy in identifying the appropriate regulations and comparability across regulations. The disadvantage is that the results might not be generalizable.

Other researchers address multidimensionality by constructing composite indexes or proxies for environmental stringency. Smarzynska and Wei (2004) use the number of international environmental treaties joined and the number of active environmental NGOs as indicators of countries' environmental regulatory stringency. Cole and Elliott (2003) use an index based on a survey sent to each UN member country asking for details about its environmental policies, legislation and enforcement. Kellenberg (2009) and Kalamova and Johnstone (2011) use the World Economic Forum (WEF)

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[1] `www.epa.gov/ttn/naaqs/standards/pm/s_pm_history.html`

surveys, which ask business executives in many countries about the stringency and enforcement of the regulations their companies face. Fredriksson and Millimet (2004) combine composite indexes, including an early version of the Yale Environmental Performance Index that ranked countries on 68 measures, including pollution levels, resource endowments, and public and private abatement efforts.

These proxies are meant to summarize multidimensional regulations in one number, to apply broadly to entire economies, and to be inherently generalizable. The disadvantage is that while they may successfully rank countries' stringency levels, they cannot assess their magnitude – they are ordinal rather than cardinal. Does signing twice as many treaties or having twice as many NGOs mean a country is twice as stringent? What does it mean that Germany's WEF index is above 6.5 while Argentina's is below 3.5? Research using these indexes may be able to answer questions about the direction and statistical significance of the effect of the regulations, and may be able to describe different outcomes when the indexes are relatively high or low, but cannot say how those indexes translate into real costs for regulated industries.

As limiting as these workarounds may seem, multidimensionality may be the smallest obstacle to evaluating measures of stringency. A larger conceptual obstacle is simultaneity.

3.2.2 Simultaneity

With any measure of stringency, applying and interpreting that measure can be tricky. Researchers want to assess the consequences of regulatory stringency on pollution, labor demand, trade, economic growth, etc. Unfortunately, each of those consequences may also simultaneously help to determine regulatory stringency. Environmental and economic conditions may influence stringency even as researchers attempt to measure the causality in the opposite direction. In a widely cited example, Grossman and Krueger (1991) find that in some cases US “imports from Mexico appear to be lower in …sectors where US pollution abatement costs are relatively high," a counterintuitive result they attribute to an unnamed omitted variable. A natural candidate for that omitted variable would be some source of comparative advantage that US industries have that is correlated with pollution intensity: skilled labor, physical capital, access to inexpensive energy, etc.

Natural Experiments as a Solution to Simultaneity

Researchers deal with the simultaneity of regulations in two closely related ways: natural experiments and instrumental variables.[2] Natural experiments involve some external force determining the stringency of regulations. The best example of this approach was first provided by McConnell and Schwab (1990) and Henderson (1996) and followed by numerous researchers since. They use the US Clean Air Act, which imposed uniform national ambient standards (the NAAQS mentioned earlier) on every county in the US. States are responsible for ensuring that air quality in all their counties attains those standards. As a consequence, a county whose air quality falls below the NAAQs faces stringent standards, while a county whose air quality meets or exceeds the standards faces less stringent regulations. Because those NAAQs are set federally and apply nationally, they are not caused by or correlated with the economic activity in particular counties: in other words they are plausibly exogenous. Researchers using this measure of stringency can defensibly interpret changes in local

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[2] If the source of the simultaneity is time-invariant, the problem can also be addressed with panel data and fixed effects. But it is easy to imagine sources of simultaneity that change over time: demographic changes, technology trends, etc. In that case, fixed effects cannot solve the problem.

economic activity that follow federal law changes as causal consequences of changes in regulatory stringency.

Similarly, in Levinson (1999a) the natural experiment involves a 1992 US Supreme Court ruling that prohibited states from charging higher fees for disposing of waste imported from other states. Before 1992 this was common practice. Because the fee changes resulting from the 1992 ruling were not the result of individual states' decisions or disposal quantities, changes in interstate shipments of waste following the 1992 ruling could reasonably be interpreted as the consequence of the externally-imposed fee changes.

The problem with natural experiments as solutions to the simultaneity problem is that they are scarce. It is difficult to think of examples where states or countries have been forced by outside circumstances to alter or adopt regulations with varying levels of stringency. And the few examples that exist may not be representative of regulatory effects in general.

Instrumental Variables as a Solution to Simultaneity

Instead of natural experiments, researchers have turned to a statistical approximation for those experiments: instrumental variables. The idea is to find a characteristic of jurisdictions or industries that is correlated with regulatory stringency but uncorrelated with the relevant measure of economic activity, except indirectly through its relationship to stringency. Unfortunately, good examples of such instrumental variables are also scarce.

Millimet and Roy (2012) provide an excellent review of research using instrumental variables for stringency. Xing and Kolstad (2002) use infant mortality and population density. Ederington and Minier (2003) use instruments motivated by political-economy theories: unionization rates, concentration ratios, etc. Levinson and Taylor

(2008) use the geographic distribution of industries across US states and the pollution abatement costs incurred by other industries in those states. Kellenberg (2009) uses lagged values of countries' corruption, income, urbanization and education. Jug and Mirza (2005) use prior years' wages and investment in environmental equipment. In addition to their survey of the literature, Millimet and Roy make two contributions. Their first is an instrument that relies on the fact that environmental regulatory stringency imposes higher costs on more pollution-intensive industries, whereas other local business conditions affect all industries equally. Their second strategy avoids the use of instruments altogether and exploits assumptions about heteroskedasticity of the errors in the estimating equation.

Several problems confront these approaches to addressing simultaneity. Most obviously, readers have good reasons to question the underlying assumptions. Infant mortality may be a consequence of pollution and motivate stringent regulations; industry concentrations may affect regulatory stringency and be affected by those regulations. Moreover, the key assumption underlying instrumental variables techniques – that the variable being used as an instrument affects the outcome only through its effect on regulations – is not easily testable. Examples of good instruments that stand up to this scrutiny – especially ones that vary across jurisdictions and over time – are in short supply.

The next two obstacles to measuring regulatory stringency – industrial composition and capital vintage – can be thought of as special cases of simultaneity. But they are central to evaluating stringency and to the research questions analysts want answered, and so they are worth discussing separately.

3.2.3 INDUSTRIAL COMPOSITION

Because states and countries differ in their industrial compositions, some measures of stringency will appear different even for jurisdictions whose regulations are identical. For example consider two states: one producing cement, which creates pollution as a by-product, and a second producing textiles, which is responsible for much less pollution. Even if the two states have identical laws, the average manufacturer in the first jurisdiction will incur more environmental costs than the average manufacturer in the second. Abatement costs, surveys of business executives, and pollution emitted per dollar of sales will differ for reasons having nothing to do with regulatory stringency. Depending on how we measure stringency, industrial composition could thus result in misleading inferences.

This problem – differing industrial compositions across jurisdictions – poses especially acute challenges for interpreting measures of stringency based on pollution abatement costs. Jurisdictions that are home to pollution-intensive industries will have relatively high average pollution abatement costs even if the regulations are nor more stringent than in other jurisdictions. And if concentrations of polluting industries lead jurisdictions to enact more stringent regulations, to address the resulting pollution problems, that simultaneity further complicates the analysis. A researcher who is not careful about this might conclude that environmental stringency attracts pollution-emitting industries, or at least that stringency does not deter those industries. The solution, which we detail in Section 3, involves measuring jurisdictions' pollution costs independent of their industrial compositions.

3.2.4 Capital Vintage

The final obstacle to measuring regulatory stringency involves a particular feature of many environmental regulations: they are “grandfathered" or “vintage-differentiated," meaning they are stricter for new sources of pollution than for existing sources. For obvious practical reasons, regulations do not require manufacturers to retrofit existing facilities to meet the same strict standards as newly constructed facilities. One prominent example of grandfathered regulations is the US Clean Air Act, which prescribes “New Source Performance Standards" for large industrial sources of pollution that are new or significantly modified. Ironically, this can protect existing industries from potential competition, extend the profitable life of older equipment, and result in higher aggregate emissions.[3]

Depending on how we measure regulatory stringency, grandfathering could significantly bias those measurements. For example, suppose our measure is based on pollution abatement costs incurred. A stringent regulation that grandfathers existing sources may result in no new development and low abatement costs. A less stringent regulation or one that does not grandfather existing sources might result in more new development and higher abatement expenditures. Perversely, vintage-differentiated regulations can result in stringent places appearing lax and vice versa. Or, suppose our stringency measure is based on emissions, where low emissions are interpreted as the result of strict regulations. A strict vintage-differentiated regulation that deters new investment in cleaner production might be misinterpreted as a lack of stringency because emissions from existing production would remain high.

These four obstacles do not necessarily mean that measuring environmental regulatory stringency is impossible. They just mean that we must interpret results from

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[3] Buchanan and Tullock (1975) pointed this out long ago. See Stavins (2006) for a recent discussion.

research using those measures carefully. The next section describes how researchers have constructed measures of stringency, and evaluates their success at surmounting the four obstacles.

3.3 Approaches to Evaluating Stringency

We divide methods used to measure stringency into five categories: (1) private-sector pollution abatement expenditures; (2) direct assessments of the regulations themselves; (3) composite indexes; (4) measures based on ambient pollution, emissions, or energy use; and (5) pollution control efforts by governments. Under each heading we list a few representative citations to research using the approach. For a more complete tabulation of papers in each category, see Appendix A.

3.3.1 Private-sector Cost Measures

Pollution Abatement Costs

The earliest and most comprehensive of these data come from the US Pollution Abatement Costs and Expenditures (PACE) survey, conducted annually by the US Census Bureau from 1973 until 1994, and then intermittently in 1999 and 2005. Researchers have taken various approaches to the simultaneity, industrial composition, and capital vintage problems with the PACE data. To address industry composition, Levinson (1996) uses the confidential establishment-level data to regress each plant's abatement operating costs on other characteristics, including age of the facility and dummies for each industry and state. The age coefficient controls for capital vintage and the industry dummies account for industrial composition. A high state dummy coefficient indicates that manufacturers in that state that are observably similar in all other dimensions spend relatively more on pollution abatement.[4] Becker (2011) follows a similar approach using establishment-level data and controlling for capital vintage and industry composition to create a county-level index of compliance costs.

Because most researchers do not have access to confidential establishment-level PACE data, Keller and Levinson (2002) construct an industry-adjusted, cost-based measure using published average annual PACE data by industry and state. They calculate the total costs per dollar of gross state product: $S_{st} = \frac{P_{st}}{Y_{st}}$, where P_{st} is the pollution abatement cost in state s in year t, and Y_{st} is the gross state product in state s in year t. They compare that to the predicted abatement costs, $\widehat{S_{st}}$, which is simply a weighted average of the national pollution abatement costs for each of 20 two-digit SIC industry codes, where the weights are the industries' shares of output in state s, $\frac{Y_{sit}}{Y_{it}}$. Keller and Levinson's measure of stringency is just the ratio of actual over predicted costs, $\frac{S_{st}}{\widehat{S_{st}}}$. When this ratio is greater than one, pollution abatement costs are larger than would be expected given the state's industrial composition, and Keller and Levinson infer that the state's regulations are relatively stringent.

On the surface, the PACE survey sounds like exactly the data needed to measure stringency because it directly asks managers at industrial facilities how much their establishments spent abating pollution. However, one drawback of using PACE data is that it includes abatement costs of all types, not only those due to regulatory stringency. States with the same regulatory stringency could have different abatement costs if the inputs to pollution abatement cost more in some states than others; for example if low-sulfur coal has to be shipped farther or if environmental engineers

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[4] As constructed by Levinson (1996) the measure does not vary over time, only across states. A version could be estimated using annual cross-sections of establishment-level pollution abatement cost data, and by including state dummies, year dummies, and the interactions between the two. The coefficients on the interaction terms would indicate whether each state became more or less stringent relative to the national trend.

are higher-paid. So the PACE data serve as a measure of a jurisdiction's overall environmental costs, not just those related to regulatory stringency.

A more important drawback of PACE data, however, is that its central survey question has become increasingly difficult for environmental managers to answer. Consider the instructions accompanying the 1994 PACE survey:

> "For this survey, only expenditures with the primary purpose of protecting the environment are included. This survey does not ... include expenditures that abate pollution when the primary purpose is to increase profits or cut costs, and the environmental protection is a side benefit."[5]

This survey question might be relatively easy to answer for end-of-pipe technologies that modify existing production processes in response to new regulations. It is much less clear when process or product changes have evolved in response to regulations that have been enforced for decades. If a manufacturer installs capital equipment enabling it to begin using recycled materials, is that an environmental investment? Does it matter if doing so also increases profits? If an electricity generator switches from coal to natural gas and saves money partly because environmental regulations have made burning coal more costly and partly because natural gas prices have fallen, how much of that process change should be counted as environmentally motivated? Just because a government agency asks survey respondents these questions does not mean researchers can accept their answers as meaningful.

Several studies have evaluated the answers collected by the PACE survey. Gray and Shadbegian (2003) study abatement costs in pulp and paper mills. Accounting for differences in technologies across plants, they find that the true abatement costs

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[5] Current Industrial Reports, Pollution Abatement Costs and Expenditures: MA200(94)-1. US Census Bureau. Washington, DC, 1994.

could be more than 3 times the reported costs. Joshi et al. (2001) interview accountants at 55 US steel mills and conclude that every $1 of reported environmental costs is associated with $9-10 of unreported environmental costs – overhead and process changes that are difficult to separately identify as being primarily for environmental purposes. Morgenstern et al. (2001) add to this list, noting that grandfathered regulations mean that reported abatement costs of existing facilities understate the costs faced by manufacturers expanding or opening new facilities. But Morgenstern et al. also identify reasons why surveys may overstate costs, including complementarities between environmental objectives and other purposes.

About the time the US stopped collecting PACE data, Canada and the EU began. Pasurka (2008) documents these efforts around the world, including Canada's Survey of Environmental Protection Expenditures (SEPE) and the joint OECD/Eurostat Questionnaire on Environmental Protection Expenditure and Revenues. As he notes, it is sometimes difficult to compare surveys across countries. Germany's data focus on end-of-pipe expenditures from 1996 to 2002, while other countries' surveys include all abatement costs. The US survey includes capital depreciation while Canada's does not. Country surveys differ in their industry classification systems and industry coverage, making it difficult to account for countries' differing industrial compositions.

Lest this all sound overly negative about the merits of these abatement costs surveys, note that in aggregate reported abatement costs vary over time, across industries, and across jurisdictions in ways that comport with intuition. The industries we expect to have high abatement costs come out on top of the list; countries and US states we expect to have low abatement costs rank towards the bottom; and changes in pollution regulations appear to be reflected in reported abatement costs (Becker, 2005). We are not claiming those surveys contain no information; we are only noting that the responses need to be treated cautiously and understood as speculative answers to increasingly difficult abstract questions that are not limited to regulatory costs and are not necessarily applicable to new sources.

SHADOW COSTS

Several researchers have avoided the conjectural nature of cost surveys by using economic theory and choices made by firms to calculate the “shadow price" of pollution indirectly. Van Soest et al. (2005) define the shadow price of an input as “the potential reduction in expenditures on other variable inputs that can be achieved by using an additional unit of the input under consideration (while maintaining the level of output)." Assume for simplicity that a firm has two inputs – emissions and another generic input X – and the firm wants to maintain a certain level of output.[6] When there is no regulation, the price of emissions is low, or even zero, and profit-maximizing firms will choose to use relatively more emissions and less of other inputs. When the price of emissions is higher, maybe because regulations are stringent, the firm will choose lower emissions.

The key to this approach is that all of the prices and quantities in the analysis except the price of emissions can be looked up in government statistical tables and reports, although the level of detail will depend on the data availability which varies by pollutant and the country of interest. If firms are profit maximizing, and if we know the output, the amounts of all inputs used, emissions, and the prices of all the other inputs, then we can calculate the implicit or “shadow" price of emissions, which will be higher in jurisdictions where the cost of abatement is higher. Like the cost

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[6] Economists consider pollution an “input" to production, even though it physically emerges from smokestacks or wastewater pipes, because it is an activity undertaken in order to generate the main product of the firm. Relabel emissions “waste disposal services" if that seems clearer.

survey approaches, the shadow price approach interprets higher costs as a result of more stringent regulation.

This shadow cost approach to measuring environmental regulatory stringency has a number of advantages. It summarizes multidimensional environmental regulations into one cardinal measure of costs. It controls for capital vintage and industrial composition. And it can be estimated across countries, industries, years, and pollutants. Of course the shadow price approach also has drawbacks. Shadow prices will depend in part on the functional forms chosen for cost functions or production functions, and on the set of other inputs used in their estimation, which might itself depend on which inputs have readily available price and quantity data. Like the abatement expenditures reported to cost surveys, shadow prices measure expenditures that are not necessarily the result of regulatory stringency.

An alternative to using the costs imposed by the regulations as a measure of stringency is to use some direct assessment of the regulation itself.

3.3.2 Regulation-based Measures

Regulation-based measures of stringency face two main difficulties: multi-dimensionality and simultaneity. Accordingly most studies that use this approach ask very narrow questions about particular pollutants and try to circumvent the simultaneity by using an instrumental variable or natural experiment.

Addressing Simultaneity Through Natural Experiments

One widely-used strategy in this category takes advantage of the US Clean Air Act, because its national ambient air quality standards (NAAQS) address both problems. The NAAQS set a maximum allowable ambient concentration level for six common air pollutants, and so can be seen as a general measure of multidimensional stringency;

and the standards are set federally and apply to every county in the US, so they can be seen as exogenous to any one county's economic or environmental conditions. But using county attainment status as a measure of stringency has two drawbacks. First, it's difficult to translate NAAQS attainment into a cardinal measure of stringency, and therefore difficult to assess magnitudes or to draw general conclusions about the consequences of regulations. And second, any economic consequences can only be assessed as the outcomes in stringent non-attainment counties relative to the outcomes in less stringent attainment counties. If regulations cause investment to shift from non-attainment to attainment counties, this approach cannot tell the overall effect of the regulations on investment, just the difference between the two sets of counties. Researchers have to be careful not to double-count the regulations' effect by interpreting that total difference as the effect of the regulations in non-attainment counties.

Henderson (1996) and Becker and Henderson (2000) use this approach and show that the more stringent regulations in nonattainment counties improve air quality and reduce the number of new polluting manufacturing plants locating there. Recent adopters of this approach study industry location and employment (Greenstone, 2002), housing prices (Chay and Greenstone, 2005), pollution (Greenstone, 2004), new manufacturing plants (List et al., 2004), and mortality (Chay, et al. 2003). As thorough as all of this research has been about the effects of those US air quality standards, the results cannot necessarily be applied to standards imposed for other pollutants or by other countries.

Narrow Approach to Regulation-based Measures

An alternative regulation-based approach uses a specific regulation as an indicator for overall environmental regulatory stringency. One example is the maximum allowable amount of lead per gallon of gasoline as a proxy for countries' overall level of environmental concern. While this measure only applies directly to the transportation sector, Damania et al. (2003) show that gasoline lead is correlated with three other composite indexes of regulatory stringency. Cole et al. (2006) and Cole and Fredriksson (2009) use this measure to study the relationship between foreign direct investment and environmental regulations.

Other research has also used specific regulations to study narrow policy questions relevant to those regulations. Berman and Bui (2001) study the regulations applicable to particular petroleum refineries in Los Angeles. Refineries not subject to those rules, because they use different technologies or are located elsewhere, are used as a comparison group. Other examples include McConnell and Schwab (1990), who use states' standards for the maximum amount of volatile organic compounds in automobile paint, and Levinson (1999b) which uses indicator variables for whether or not the states' toxic air pollution rules grandfathered existing sources of pollution. Hascic and Johnstone (2011) examine the effect of fuel taxes and fuel efficiency standards on innovation aimed at alternatively fueled vehicles. All of these studies have the same limitation: results cannot be generally applied beyond the conditions and outcomes of the particular examples they explore.

That concern leads us to the next batch of measures: composite indexes meant as comprehensive indicators of countriesâĂŹ overall environmental regulatory stringency.

3.3.3 General Composite Indexes

Composite indexes attempt to solve the multidimensionality issue, but they are vulnerable to being criticized as arbitrary and their magnitudes can be difficult to interpret. Composite indexes depend on the relative weights of their component dimensions. These weights have little foundation in theory or practice, and small changes in the weights can result in significant differences in the index (Ravallion, 2010).[7] Some of the earliest attempts to quantify regulatory stringency were based on simple indexes constructed from counts of regulations, environmental non-governmental organizations, international treaties signed, and similar easily enumerated characteristics. In the US, researchers have used the voting records of states' congressional delegations (Gray, 1997) and counts of the number of statutes each state has from a list of 50 common laws (Levinson, 1996).

Indexes Based on Surveys of Government Officials

For cross-country comparisons an immense number of these types of indexes have been examined. Among the earliest was a 1976 survey sent by the United Nations Conference on Trade and Development (UNCTAD) to 145 countries, asking government officials details about their environmental policies. Only 40 responded, and the UN ranked their overall responses on a 7-point scale (Tobey, 1990; Walter and Ugelow, 1979).

These cross-country indexes have come a long way since the UNCTAD effort. Dasgupta et al. (2001) randomly selected 31 of the 145 national environmental reports prepared in advance of the first UN Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992. They assessed the answers to 25 questions as they applied to four media (air, water, land, and wildlife) and five economic sectors, resulting in 500 separate scores for each country. This was done separately for five different environmental dimensions: awareness, policies, legislation, control mechanisms, and implementation. And, the ranking can be compiled separately for each

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[7] Other areas of economics have made some progress in understanding the conceptual foundations of existing indexes. Ravallion (2011), for example, discusses the properties of the Human Development Index and the implied trade-offs between its components.

media, industry, or environmental dimension. Not surprisingly, the measure is correlated with economic development. Switzerland ranks first; Mozambique last. Damania et al. (2003) use the Dasgupta approach, along with several others, to try to calculate the causal political-economic relationship between trade policy and environmental policy. Raspiller and Riedinger (2008) use it to estimate the effect of regulations on the location decisions of French multinational firms.

Two problems arise with this method of measuring environmental regulatory stringency. First, the UNCED survey was one single cross section for 1990. There is no way to construct a panel of data and include country fixed effects to control for unobserved country characteristics correlated with both regulatory stringency and economic activity.[8] Second, as sensible and methodical as Dasgupta et al. were in constructing their index, different researchers might have constructed a different index from those same 31 national environmental reports, with different country rankings. None of the studies we are aware of attempt this robustness check, examining whether alternative indexes constructed with the same data deliver similar conclusions.

Indexes Based on Surveys of Business Managers

Instead of surveying government officials about their countries' environmental regulatory stringency, a number of papers have used surveys of business managers. Among

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[8] Raspiller and Riedinger use firm-level data and include country-level fixed effects. But those fixed effects capture unobserved characteristics of the set of firms that choose to locate in a given country, not unobserved characteristics of that country that may be correlated with the Dasgupta index and might be spuriously attributed to the effect of stringency. Damania et al. (2003) try to convert the Dasgupta index into a panel by predicting its values in 1990 using country characteristics that vary over time, such as GDP, population, urbanization, corruption, and industry's share of the work force. They then predict the Dasgupta index for years other than 1990. This assumes that the regressors used to predict stringency are not themselves determined by stringency.

the most widely used is the World Economic Forum (WEF) survey of executives. Kellenberg (2009) focuses on two questions that have been asked consistently since 2000: one about regulatory stringency and another about enforcement. Wagner and Timmins (2009) find that outbound foreign direct investment from Germany is strongly negatively associated with high values of the WEF index for one particular industry, chemical manufacturing. Kalamova and Johnstone (2011) find a more broad-based effect that is relatively small and nonlinear; it diminishes above a certain threshold of stringency.

As Kalamova and Johnstone emphasize, this measure of stringency is based on perceptions, not actual hard data on costs or regulations. Perceptions may correlate with regulatory stringency, but Kalamova and Johnstone cannot say whether the nonlinear relationship they find reveals a true nonlinear relationship between stringency and investment, or a spurious nonlinear relationship between actual and perceived stringency. Moreover, the perception of regulations may be even more simultaneously determined by economic activity than the actual regulations. We know, for example that public support for environmental policies falls when unemployment rates rise (Kahn and Kotchen, 2011). If economic downturns increase perceived stringency, that may be misinterpreted as though actual stringency reduces investment.

Another problem with the surveys of executives involves the industrial composition obstacle. As Albornoz et al. (2009) note, firms that come from more pollution-intensive industries are more likely to report that they incur environmental costs.

Indexes Based on Counts of Regulation

In the same way that the Dasgupta index improves on the UNCTAD index from the early 1970s, indexes based on counts of regulations have also become more sophisticated. Smarzynska and Wei (2004) count whether or not each country signed or ratified one of four international environmental treaties, along with the number of environmental NGOs present in the country. Johnstone et al. (2010) are interested in the degree to which policies towards renewable energy have spurred technological innovation. They create a list of policies including tax incentives, investment subsidies, differentiated tariffs, voluntary programs, quotas, and tradable certificates. Then they document how many of these policies had been implemented in each of 25 countries from 1978 to 2003. While not technically a measure of regulatory stringency, we could imagine such a measure being constructed with that alternative goal in mind.

Other Indexes

One final effort worth highlighting is Cole et al. (2010), which uses an index constructed by the Japanese Research Institute of Economy, Trade and Industry. The index calculates a weighted average of 303 four-digit manufacturing industries within each of 41 two-digit sectors that are governed by 3000 broad industrial regulations. The index represents the share of each sector that is regulated. Like the other indexes, however, we do not know whether slight deviations in its construction might lead to large differences in its rankings and conclusions. And like all such indexes, this one conveys little sense of magnitude. Regulations are weighed equally regardless of the burden they impose.

3.3.4 Emissions, Pollution, or Energy Use

Emissions and Pollution

Some studies have turned the entire concept on its head and used emissions, ambient pollution, or energy use as measures of stringency. On the surface this seems backwards. The regulations whose stringency is to be measured are designed to reduce pollution; so does pollution indicate regulatory stringency or laxity? The answer depends on the situation. Some studies have taken high levels of pollution as evidence that regulations are relatively lax. Xing and Kolstad (2002) use national aggregate SO2 emissions in this way. Others use high pollution as evidence that regulations are stringent, on the grounds that governments will be forced to tighten regulations to deal with the problem. McConnell and Schwab (1990) use the degree to which a US county was out of compliance with national standards as a proxy for the stringency of the regulations the state would have to impose to meet those standards.

Several research projects have used reductions in emissions as indicators of stringency. Smarzynska and Wei (2004) used declines in carbon dioxide, lead, and water pollution as a share of GDP. Gollop and Roberts (1983), in a classic study, conduct a detailed examination of 56 US electric utilities from 1973 to 1979. They construct a measure of stringency that is based on the difference between actual observed emissions and an engineering estimate of what the utility's unconstrained emissions rate would have been absent any regulation. These two approaches represent extremes of aggregation and disaggregation. Smarzynska and Wei use aggregate country-wide emissions reductions. Those could be a consequence of regulatory changes, but they could also result from changes in industrial composition or factor prices involving other trends. Gollop and Roberts use emissions reductions below unconstrained levels for one particular industry in the US. Their application would be difficult to apply to other industries or countries because legal standards and unconstrained emissions would have to be calculated in different ways for each situation.

Energy Use

The last approach in this category involves energy use as a proxy for regulatory stringency. Cole and Elliot (2003) use countries' energy consumption divided by GDP in 1980, along with the change in that variable from 1980-1995. Those two numbers were ranked, the ranks were added together, and the sum was ranked again and divided by the number of countries, resulting in a stringency measure from zero to one. This energy-based measure is highly correlated with the Dasgupta index discussed above ($\rho = 0.77$). Harris et al. (2003) elaborate on this same energy index using two measures of energy (final consumption and primary supply) scaled by population and two alternative measures of GDP (based on purchasing power parity and exchange rates), resulting in six different versions of the index used by Cole and Elliot.

It is hard to tell from these indexes, however, whether the measure of stringency is largely the result of changes in energy use or levels. Both changes and levels could differ across countries for many reasons other than environmental standard stringency: energy prices, industrial composition, trade liberalization, etc. Furthermore, if environmental regulations drive up the price of energy, it is not clear that energy expenditures will decline as a share of GDP.

3.3.5 Enforcement or Public Expenditures

The final category of measures involves public sector environmental efforts as a measure of stringency. Gray (1997) uses US states' budgets for environmental and natural resources. This has the advantage that it includes enforcement, which is an important part of stringency, but it requires caution. Some public sector expenditures relieve the private sector of costs – think of tax incentives and subsidies for clean-up. These could be seen as reducing stringency. Shadbegian and Gray (2012) avoid this concern by focusing on enforcement efforts, and Levinson (1996) uses the number of employees at state environmental agencies. But these are at best remote indicators of stringency. State laws can be made stringent by well-staffed environmental agencies through frequent inspections even without steep punishments for violations, or though infrequent inspections by understaffed agencies if the punishment for violations discovered is sufficiently onerous. Pearce and Palmer (2001) combine this public expenditure approach with the private cost approach we discussed first. They ask whether over time the burden of environmental regulations has shifted from the public sector to the private sector. As they point out, this division is not unambiguous.

In general, public sector effort has not been widely used to measure regulatory stringency, especially recently, probably because its shortcomings outweigh its advantages, and partly because as more emissions and cost data have become available the need for public sector data as a proxy has declined.

3.3.6 Comparing the Measures

As shown, existing measures of environmental stringency vary depending on what they cover and how well they tackle the multidimensionality and simultaneity obstacles, thereby resulting in different rankings. But how correlated are these rankings? And does a low correlation necessarily imply that the measures are failing to accurately measure stringency?

Table 3.1 presents the correlations among eight recent measures of the stringency of US state environmental regulations.[9] These include the share of the population of each state living in counties with air quality that exceeds federal standards; three composite indexes; the League of Conservation Voters evaluation of the voting record of state congressional delegations; and three measures constructed from the 2006 PACE data. The indexes are remarkably uncorrelated.[10] The highest correlations in the table are among the composite indexes, which is not surprising given that they share many components. (Descriptions of the indexes and web links can be found

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[9] The indexes discussed in this section can be found in the appendix.

[10] List and Co (2000) finds similarly low correlations across states' abatement expenditures, regulatory budgets, and a composite regulatory index.

in the footnote to the table.) Those composite indexes are also correlated with the League of Conservations Voters scores, but not with the share of the population living in non-attainment counties or the pollution costs. Unadjusted pollution abatement costs are negatively correlated with all of the other indexes, but as we argued earlier those mostly reflect the type of manufacturing in each state. Once we adjust for states' industrial compositions at the level of 3 or 4-digit NAICS codes, those correlations are less negative, but are never strongly positive. Column (9) shows that some indexes, like the Forbes ranking, vary across states within a narrow range, while others vary considerably from state to state.

Table 3.2 shows the correlations among four similar measures across 24 countries. The table includes energy use; pollution abatement costs; the World Economic Forum Global Competitiveness Executive Opinion Survey which asks CEOs to assign a score between 1 and 7 to environmental policy stringency; and the Environmental Performance Index which ranks countries using 20 indicators of environmental health (for example: child mortality and access to drinking water) and ecosystem vitality (for example: change in forest cover, trend in carbon intensity, and wastewater treatment). The disparity between indices across countries is even larger than across US states. The highest correlation is only 0.52, between the WEF survey and countries' energy intensities, where high energy intensity counts as lax policy. Abatement costs, unadjusted for industrial compositions, appear uncorrelated with anything. And column (5) shows that across countries the relative swings in abatement costs are more than 15 times as large as the relative swings in the Environmental Performance Index.

One interpretation of the low correlations in Tables 3.1 and 3.2 is that whatever information the indexes do contain is not consistent across measures, and that even if one of them captures a comprehensive measure of stringency, the others must therefore be failing to capture that measure. A more positive interpretation (List and Co,

2000) is that regulatory stringency is multidimensional, and that each index captures different aspects of that stringency. There is no particular reason, for example, to expect that in Table 3.1 the “24/7 Wall Street" ranking of a state’s environmental policy would be correlated with the share of its population in non-attainment counties. And there is no reason to expect that in Table 3.2 business executives’ ranking of a country’s environmental policy would be correlated with its abatement costs, which may have more to do with industrial composition. Whether Tables 3.1 and 3.2 undermine the credibility of any one index or reinforce the idea that regulatory stringency is multidimensional, the low correlations do caution us against putting too much faith in research results that rely on only one measure of stringency.

3.4 A New Emissions-based Approach

In this final section we propose assembling a new measure that could be used to assess environmental regulatory stringency. The idea rests on the same microeconomic principle behind the shadow-price approach discussed previously, that profit-maximizing firms will use each factor of production until its marginal revenue product is equal to its price. Emitting pollution is a factor of production like any other. Without regulation, the price of emissions is low, and firms will emit pollution until the marginal product they get from emitting extra pollution falls to close to zero. As environmental regulations raise the cost of emissions, firms will emit less pollution. Hence, one could compare emissions of various industries across countries or states, and use emissions per dollar of value added – emissions intensity – as a measure of regulatory stringency. By averaging emissions per dollar of value added across industries, an emissions-based measure of stringency could be constructed. Where emissions intensity in a country is higher, it could be concluded that the cost of polluting is lower because regulations are less stringent. Where emissions intensity is lower, regulations must be more stringent.

The idea behind using emissions intensity as a measure of regulatory stringency originates with the production function approach outlined in van Soest et al. (2005). That approach would ideally employ plant-level data on all factors of production in addition to emissions – labour, capital, materials, etc. But such plant-level data are confidential and difficult to access, and our approach would depend solely on aggregate industry-level emissions data, which more and more countries are beginning to develop and make publicly available. We combine the intuition behind the van Soest approach – that regulated firms will emit less – with the cost-based approach taken by Levinson and Keller (2002).

Let e_j be emissions per dollar of value added in jurisdiction j, averaged across all industries:

$$e_j = \frac{E_j}{V_j} \tag{3.1}$$

where E_j and V_j denote total emissions and value added in jurisdiction j, summed across all industries. Let e_i be the emissions per dollar of value added in industry i, averaged across all jurisdictions:

$$e_i = \frac{E_i}{V_i} \tag{3.2}$$

where E_i and $V_i$denote total emissions and value added in industry i, summed across all jurisdictions. Then denote $\widehat{e_j}$ as the predicted emissions per dollar of value added in jurisdiction j, assuming each of its industries uses the average emissions intensity for all jurisdictions.

$$\widehat{e_j} = \frac{1}{V_j} \sum_i V_{ij} e_i \tag{3.3}$$

This is a prediction of j's emissions intensity based solely on its industrial composition (the V_{ij}'s) and the average emissions intensities of those industries in other jurisdictions. If a country has a lot of high-emitting industries, we would expect it to have a high value of $\widehat{e_j}$. If its mix of industries is relatively clean, we would expect a low $\widehat{e_j}$.

Another way to think about this is as follows. The actual emissions intensity of a jurisdiction is equivalent to a weighted average of the actual emissions per dollar of value added of each industry in that jurisdiction (e_{ij}) where the weights are the industries' shares of total output in that jurisdiction ($\frac{V_{ij}}{V_j}$), though we won't need or want disaggregated jurisdiction-industry emissions data because we can just use the aggregate equivalent $\frac{E_j}{V_j}$. The predicted emissions intensity of a jurisdiction is a weighted average of the national average emissions per dollar of value added in each industry (e_i), where the weights are the same ($\frac{V_{ij}}{V_j}$).

A measure of the stringency of regulations, R_j, is just the ratio of predicted emissions intensity to actual emissions intensity:

$$R_j = \frac{\widehat{e_j}}{e_j} \tag{3.4}$$

Countries that impose higher pollution abatement costs on their industries will have smaller-than-predicted emissions, and higher levels of R_j, no matter what their industrial compositions. The index R_j could be constructed for particular pollutants or particular media. Or it could be summed across various pollutants and media to construct a general measure of regulatory stringency. Critically, this measure could in theory also be constructed on an annual basis to observe changes over time.

In addition to data on value added by industry and jurisdiction, constructing the index in equation (3.4) requires two key variables. The first is E_j, the total amount of pollution emitted in each jurisdiction. This does not need to be industry-specific, though it does need to be limited to the industries that comprise the index. (That is to say, it should not include transportation or household pollution if those are not part of equation (3.4)). The second variable is E_i, the total amount of pollution emitted by each industry. This does not need to be jurisdiction-specific.

In the United States, two such emissions inventories have been created. The first was assembled by the World Bank using US EPA emissions data in 1987, and was called the Industrial Pollution Projection System (IPPS) (Hettige et al., 1995). The IPPS listed emissions intensities for various air and water pollutants and for each four-digit Standard Industrial Classification (SIC) code. Unfortunately, that emissions inventory was not repeated in subsequent years, and so although a version of equation (3.4) could be constructed for 1987, it would not be feasible to construct a panel. Also, the IPPS is not differentiated by state, so aggregate state emissions would have to be estimated from other sources.

A second US source has more promise. In recent years the US EPA has begun compiling its own emissions inventory, called the Trade and Environmental Assessment Model (TEAM). So far the TEAM is available for 1997, 2002, and 2007, and is organized by four-digit North American Industry Classification System (NAICS) codes. This has the advantage that it has been repeated three times, and so a panel can be constructed, and it is available state-by-state, facilitating calculation of both E_j and E_i.

There are two possible sources for emissions data in Europe. The first is the European Pollution Emissions Register (EPER) for 2001 and 2004. Although the database covers both air and water emissions for over 9 000 facilities, the facilities are not classified into detailed industries. For example, the manufacturing sector includes only 14 activities. This level of aggregation is problematic because each activity is comprised of a variety of industries and products, some of which might be highly pollution-intensive even if the activity appears clean on average.

An alternative possible source of annual EU emissions data, starting in 2007, is the European Pollution Release and Transfer Registry (E-PRTR). The E-PRTR classifies the economic activity of facilities at the four-digit level of the NACE classification, including 67 manufacturing activities. Despite progress in the level of detail of the classification, the data still have important shortcomings, specifically with regards to coverage of facilities since the thresholds for reporting are high for some industries and pollutants.

While the international data necessary to calculate (3.4) may not yet be suitable, assembling such data should be a high regulatory priority for reasons unrelated to measuring stringency. The US EPA began compiling the TEAM data in order to analyse the environmental consequences of trade agreements. Emissions inventories like TEAM are key environmental management tools, helping regulators assess the most important sources of pollution. They are also a key product of the regulatory process, as more and more pollution regulations require monitoring the resulting data can be aggregated to create emissions inventories. So it is likely that in the future emissions inventories will improve, in the United States, Europe and elsewhere.

Constructing a stringency measure based on emissions ratios as in equation (3.4) would go a long way towards overcoming three of the four conceptual obstacles outlined in the first section. Such a measure would be theoretically motivated by pollution-abatement costs. It would be divisible by pollutant, and therefore could be used either as a summary measure for all the multidimensional aspects of environmental policy in a country, or disaggregated for particular pollutants or media. It would be a panel, and so examinations of changes in economic outcomes in response to changes in this measure would help ameliorate simultaneity issues. It also inherently controls for industrial composition. But it would only be informative about environmental costs faced by existing sources of pollution. That obstacle may be unavoidable for any empirical cost-based measure of regulatory stringency.

3.5 Concluding Thoughts

We have tried to point out that obstacles to evaluating environmental regulatory stringency are not ordinary difficulties of data collection but involve deeper conceptual issues: multidimensionality, simultaneity, industrial composition, and capital vintage. While these obstacles do not mean that measuring stringency is impossible, any proposed measurement should be evaluated with them in mind.

Approaches to measuring stringency can be divided into five broad categories, with different strengths and weaknesses. Surveys of businesses' abatement expenditures have the advantage of varying over time, and across industries and states in ways that comport with intuition. But the surveys are not limited to costs stemming from environmental regulations, and they only measure existing industries' costs, which may differ from potential new entrants' costs if regulations are vintage-differentiated. Moreover, the surveys ask respondents to distinguish costs they incur for environmental reasons from costs incurred for other goals, a task businesses may find increasingly difficult. Direct assessments of regulations are particularly sensitive to multidimensionality and simultaneity, and so researchers typically narrow their questions to focus on particular case studies and look for natural experiments where regulatory changes have been imposed on jurisdictions by external considerations. Composite rankings compress the multidimensional problem down to one number, but they are inherently ad hoc and make assessing cardinal magnitudes difficult. Indexes based on pollution or energy use are sometimes used as measures of stringency and other times used as measures of laxity, reflecting their inherent simultaneity. Finally, measures based on public-sector environmental efforts include enforcement, an important element of stringency, but provide an ambiguous proxy for stringency since some types of public expenditure can decrease private-sector costs.

What would the ideal measure of environmental regulatory stringency look like? It would be relatively easy to calculate based on data governments already collect or data governments should collect towards other policy objectives. It would be available annually so as to facilitate panel data models that address some sources of simultaneity. It would be cardinal, enabling assessment of magnitudes. It would be available for various pollutants and media or combinable as one overarching measure of multidimensional stringency. It would be theoretically related to the costs facilities incur when they abate pollution, but it would not be mechanically determined by industrial composition.

Of the measures we have discussed, most fall far short of these goals. The regulations themselves are too complex and dissimilar across countries to create consistent measures of stringency, except in narrow case studies that are not generalizable. It is hard to imagine surveys of business executives or government officials meeting those standards. Composite indexes, though numerous, are rarely conducted consistently as panels, are not theoretically grounded in costs, and are typically impossible to disaggregate by pollutant or media. Public-sector efforts as measured by expenditures or enforcement are conducted differently in every state and country and fail to capture key aspects of stringency. Pollution abatement cost surveys shift the burden to private-sector managers by asking them to answer difficult conceptual questions they may be incapable of answering. Given the difficulties in capturing environmental stringency in a single easily computable cardinal measure for multiple pollutants over multiple years, the ideal measure might depend on its intended purpose.

Finally, we have proposed a new emissions-based measure that could be used to assess environmental standard stringency. The idea hinges on the intuition that regulated firms will emit less. The new method would calculate each jurisdiction's predicted emissions based on its industrial composition and the average emissions intensity of each if its industries. Where actual emissions exceed predicted emissions, we would conclude that environmental regulation is less stringent than average, and vice versa. This new index could be computed for a particular pollutant or media, or it could be aggregated to serve as a general measure of environmental regulatory stringency. Only two sets of data would be necessary to construct this measure: (1) value added by industry and jurisdiction, which is already available, and (2) emissions by industry and jurisdiction, which is beginning to be available and which we believe countries should be collecting anyway towards other worthwhile policy goals. While those data are currently not available across countries, they do exist for US states in 1997, 2002, and 2007 in the form of the EPA's TEAM emissions inventory. Soon we are planning to construct the index in equation (3.4) for the US as a test of its usefulness, and to encourage other countries to assemble comparable emissions inventories.

As we noted at the top, important policy debates center on measures of jurisdictions' environmental stringency: pollution havens, environmental dumping, harmonization, leakage, etc. So while we understand the importance of measuring environmental regulatory stringency, we hope that this discussion provides a sense of realism about the obstacles facing the task, an understanding of where existing methods may fall short, and some perspective when evaluating research results based on the types of measures used so far.

3.6 TABLES

3.7 APPENDIX. TAXONOMY OF MEASURES OF ENVIRONMENTAL REGULATORY STRINGENCY

The following table splits research in this field into five categories based on the methods used to measure stringency: (1) private-sector pollution abatement expenditures; (2) direct assessments of the regulations themselves; (3) composite indexes meant to compress the multidimensional problem down to one number; (4) measures based on ambient pollution, emissions, or energy use; and (5) pollution control efforts by governments. Under each heading we have described examples of the approach taken, and representative research using that approach.

These categories overlap. Some of the composite indexes use measures drawn from other categories such as public expenditures or emissions. Some researchers use measures that fall into multiple categories, either in combination or in separate estimations, so some papers appear multiple times in the table. Because the literature is so extensive we have limited the selection in Table 1 to samples of each approach that are either relatively new or provide noteworthy examples of older work. In our choice of papers, we have not focused on the particular application – pollution havens, trade, labor demand, etc. – but rather on the measurement of stringency.

The listing in this table is not chronological. Instead, it is based on how often the approaches have been used by researchers, and our opinion of how successful they have been at overcoming the obstacles described above. In our assessment, the most promising is in fact the newest: measures that use industries' reported expenditures on pollution abatement.

Table 3.1: Correlations among Measures of US State Policy

	Non-attainment counties (1)	24/7 Wall Street (2)	Greenopia (3)	Forbes (4)	League of Conservation Voters (5)	PACE / value added (6)	PACE adjusted 3-digit (7)	PACE adjusted 4-digit (8)	Coeff. of variation (9)
Non-attainment counties	1								0.92
24/7 Wall Street	0.21	1							0.57
Greenopia	0.11	0.56	1						0.57
Forbes	0.27	0.51	0.81	1					0.26
League of Conservation Voters	0.31	0.24	0.60	0.68	1				0.5
PACE / value added	−0.22	−0.22	−0.56	−0.57	−0.50	1			0.58
PACE by 3-digit NAICS	−0.25	0.11	−0.35	−0.37	−0.44	0.68	1		0.4
PACE by 4-digit NAICS	−0.04	0.24	−0.08	−0.05	−0.04	0.10	0.61	1	0.55

Sources: (1) Share of state population living in non-attainment counties based on EPA non-attainment designation and county-level US Census data from 2010; (2) 24/7 Wall Street 2010 ranking of US states based on the environmental problems in each state and how effectively these problems are addressed; (3) Greenopia 2011 State Sustainability Index based on air quality, water quality, recycling rate, number of LEED buildings, green business density, per capita water consumption, per capita energy consumption, per capita emissions, per capita waste generation, and several renewable energy statistics; (4) Forbes 2007 America's Greenest States ranking based on six equally weighted categories: carbon footprint, air quality, water quality, hazardous waste management, policy initiatives and energy consumption; (5) LCV 2010 Congressional delegation environment scorecard based on the voting record of all members on Congress on the most important environmental legislation considered that year; (6) U.S. Bureau of Economic Analysis 2005 PACE data divided by value added (U.S. Census Bureau, 2008); (7) 2005 PACE data adjusted for statesâĂŹ industrial compositions at the level of 3-digit NAICS codes; (8) 2005 PACE data adjusted for states' industrial compositions at the level of 4-digit NAICS codes.

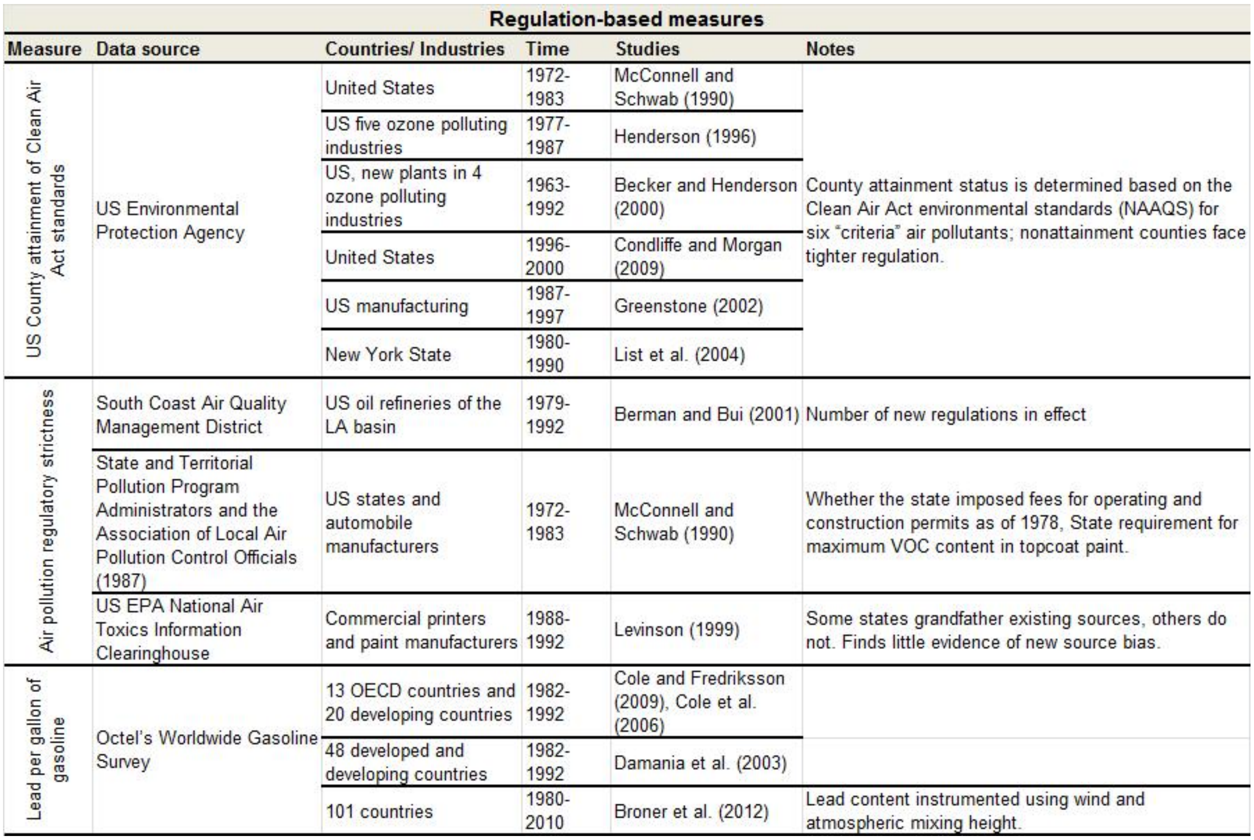
Table 3.2: Correlations among Measures of Countries' Policies

	Environmental Performance (1)	Abatement costs (2)	WEF Survey (3)	Energy Intensity (4)	Coefficient of Variation (5)
Env. Performance	1				0.11
Abatement Costs	0.26	1			1.72
WEF Survey	0.36	−0.04	1		0.14
Energy Intensity	0.44	0.38	0.52	1	0.47

Sources: (1) 2010 Environmental Performance Index which ranks countries based on changes in their environmental performance and is produced by the Yale Center for Environmental Law, CIESIN of Columbia University, the World Economic Forum and the Joint Research Center of the European Commission; (2) Pollution abatement costs from the US Bureau of Economic Analysis (2005), Eurostat Environmental Expenditure Database (2005), and Statcan (2006); (3) 2011 World Economic Forum Global Competitiveness Executive Opinion Survey ranking of environmental regulatory stringency by CEOs; (4) Energy use from the World Bank World Development Indicators divided by GDP from the IMF World Economic Outlook for 2010.

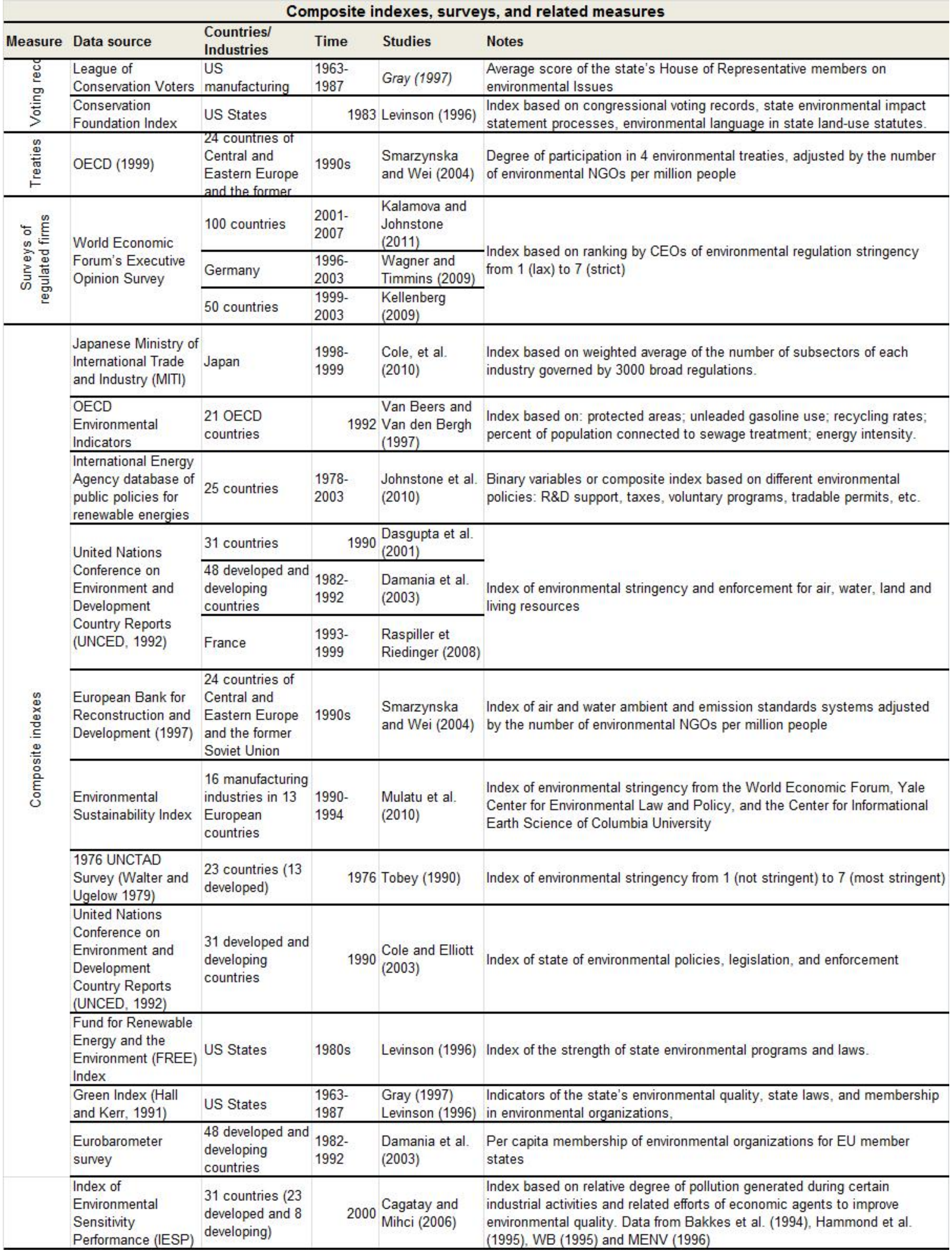
Private-sector costs

Measure	Data source	Countries/Industries	Time	Studies	Notes
Private-sector pollution abatement costs	US Bureau of Economic Analysis (BEA) Pollution Abatements Costs and Expenditures (PACE) US BEA PACE	US states, automobile manufacturers	1972-1983	McConnell and Schwab (1990)	Pollution abatement operating costs per dollar of shipments or as a proportion of new capital expenditures by industry in the state.
		US manufacturing	1982	Levinson (1996)	Pollution abatement operating costs by industry and US state. Coefficient on the state dummy in a plant-level regression of PACE on plant characteristics.
			1977-1994	Keller and Levinson (2001)	Pollution abatement costs adjusted by state industrial composition.
			1977-1994	Millimet and Roy (2012)	
		US pulp and paper, oil refineries and steel mills	1990-2000	Shadbegian and Gray (2005)	Pollution abatement operating costs divided by the plant's capacity
		US pulp and paper, plastics, petroleum and steel	1979 - 1991	Morgenstern et al. (2001)	Estimated total burden of environmental regulation using a cost model allowing for interaction between environmental expenditures (pollution abatement operating costs and capital expenditures) and non-environmental expenditures
		United States	1973-1985	Jorgenson and Wilcoxen (1990)	Dynamic CGE model projects growth of US economy with and without environmental regulation
	US BEA PACE, and interviews with plant-level accountants and corporate-level managers	55 US steel mills	1979-1988	Joshi et al. (2001)	Visible costs identified as "environmental" v. estimated hidden environmental costs embedded in other accounts
	US Bureau of Economic Analysis (BEA) Pollution Abatements Costs and Expenditures (PACE) US BEA PACE	Manufacturing sectors in Canada, West Germany, Japan, US	1973-1982	US CBO (1985)	Pollution abatement capital expenditures
	US BEA PACE; Statistical agencies in Germany and Netherlands	US, Netherlands and German manufacturing	1977-1992	Mulatu et al. (2004)	
	Statistics Division, Taiwan Ministry of Economic Affairs	Taiwan manufacturing	1987-1997	Tsai (2002)	
	US BEA PACE; German statistical agency; Japan Ministry of International Trade and Industry; Netherlands statistical agency	US, German, Netherlands and Japanese manufacturing	1975-2002	Aiken et al. (2009)	Pollution abatement capital expenditures as a ratio of total capital expenditures
	Dept. of Environment, Food and Rural Affairs (DEFRA)	United Kingdom	1999-2003	Cole and Elliott (2007)	Pollution abatement capital expenditure and operating costs
	German Statistical Yearbook	German industries	1975-1991	Conrad and Wastl (1995)	
	Eurostat Environmental Expenditures and Taxes database	19 countries from the EU and Central and Eastern Europe	1996-1999	Jug and Mirza (2005)	Capital expenditures and operating costs in environmental protection activities
	Statistics Canada, unpublished report	Quebec, Canada manufacturing sector	1985-1988	Dufour et al. (1998)	Pollution abatement expenditures divided by total cost in industry.
	Japan's Research Institute of the Economy Trade and Industry	Japan	1989-2003	Cole Elliott and Obuko (2010)	Waste disposal costs per unit of output
Estimated costs via shadow prices	US Federal Energy Regulatory Commission	14 coal-burning power plants in Wisconsin	1990-1992	Coggins and Swinton (1996)	Shadow price of SO2 emissions: $293. Actual auction futures price in 1992: $170-$400.
	IEA Energy Balances and the OECD International Sectoral Database	9 European countries	1978-1996	van Soest et al. (2005)	High variability within countries. Pattern across industries not consistent across countries.



Regulation-based measures

Measure	Data source	Countries/ Industries	Time	Studies	Notes
US County attainment of Clean Air Act standards	US Environmental Protection Agency	United States	1972-1983	McConnell and Schwab (1990)	County attainment status is determined based on the Clean Air Act environmental standards (NAAQS) for six "criteria" air pollutants; nonattainment counties face tighter regulation.
		US five ozone polluting industries	1977-1987	Henderson (1996)	
		US, new plants in 4 ozone polluting industries	1963-1992	Becker and Henderson (2000)	
		United States	1996-2000	Condliffe and Morgan (2009)	
		US manufacturing	1987-1997	Greenstone (2002)	
		New York State	1980-1990	List et al. (2004)	
Air pollution regulatory strictness	South Coast Air Quality Management District	US oil refineries of the LA basin	1979-1992	Berman and Bui (2001)	Number of new regulations in effect
	State and Territorial Pollution Program Administrators and the Association of Local Air Pollution Control Officials (1987)	US states and automobile manufacturers	1972-1983	McConnell and Schwab (1990)	Whether the state imposed fees for operating and construction permits as of 1978, State requirement for maximum VOC content in topcoat paint.
	US EPA National Air Toxics Information Clearinghouse	Commercial printers and paint manufacturers	1988-1992	Levinson (1999)	Some states grandfather existing sources, others do not. Finds little evidence of new source bias.
Lead per gallon of gasoline	Octel's Worldwide Gasoline Survey	13 OECD countries and 20 developing countries	1982-1992	Cole and Fredriksson (2009), Cole et al. (2006)	
		48 developed and developing countries	1982-1992	Damania et al. (2003)	
		101 countries	1980-2010	Broner et al. (2012)	Lead content instrumented using wind and atmospheric mixing height.



Composite indexes, surveys, and related measures					
Measure	**Data source**	**Countries/ Industries**	**Time**	**Studies**	**Notes**
Voting reco	League of Conservation Voters	US manufacturing	1963-1987	*Gray (1997)*	Average score of the state's House of Representative members on environmental Issues
	Conservation Foundation Index	US States	1983	Levinson (1996)	Index based on congressional voting records, state environmental impact statement processes, environmental language in state land-use statutes.
Treaties	OECD (1999)	24 countries of Central and Eastern Europe and the former	1990s	Smarzynska and Wei (2004)	Degree of participation in 4 environmental treaties, adjusted by the number of environmental NGOs per million people
Surveys of regulated firms	World Economic Forum's Executive Opinion Survey	100 countries	2001-2007	Kalamova and Johnstone (2011)	Index based on ranking by CEOs of environmental regulation stringency from 1 (lax) to 7 (strict)
		Germany	1996-2003	Wagner and Timmins (2009)	
		50 countries	1999-2003	Kellenberg (2009)	
Composite indexes	Japanese Ministry of International Trade and Industry (MITI)	Japan	1998-1999	Cole, et al. (2010)	Index based on weighted average of the number of subsectors of each industry governed by 3000 broad regulations.
	OECD Environmental Indicators	21 OECD countries	1992	Van Beers and Van den Bergh (1997)	Index based on: protected areas; unleaded gasoline use; recycling rates; percent of population connected to sewage treatment; energy intensity.
	International Energy Agency database of public policies for renewable energies	25 countries	1978-2003	Johnstone et al. (2010)	Binary variables or composite index based on different environmental policies: R&D support, taxes, voluntary programs, tradable permits, etc.
	United Nations Conference on Environment and Development Country Reports (UNCED, 1992)	31 countries	1990	Dasgupta et al. (2001)	Index of environmental stringency and enforcement for air, water, land and living resources
		48 developed and developing countries	1982-1992	Damania et al. (2003)	
		France	1993-1999	Raspiller et Riedinger (2008)	
	European Bank for Reconstruction and Development (1997)	24 countries of Central and Eastern Europe and the former Soviet Union	1990s	Smarzynska and Wei (2004)	Index of air and water ambient and emission standards systems adjusted by the number of environmental NGOs per million people
	Environmental Sustainability Index	16 manufacturing industries in 13 European countries	1990-1994	Mulatu et al. (2010)	Index of environmental stringency from the World Economic Forum, Yale Center for Environmental Law and Policy, and the Center for Informational Earth Science of Columbia University
	1976 UNCTAD Survey (Walter and Ugelow 1979)	23 countries (13 developed)	1976	Tobey (1990)	Index of environmental stringency from 1 (not stringent) to 7 (most stringent)
	United Nations Conference on Environment and Development Country Reports (UNCED, 1992)	31 developed and developing countries	1990	Cole and Elliott (2003)	Index of state of environmental policies, legislation, and enforcement
	Fund for Renewable Energy and the Environment (FREE) Index	US States	1980s	Levinson (1996)	Index of the strength of state environmental programs and laws.
	Green Index (Hall and Kerr, 1991)	US States	1963-1987	Gray (1997) Levinson (1996)	Indicators of the state's environmental quality, state laws, and membership in environmental organizations,
	Eurobarometer survey	48 developed and developing countries	1982-1992	Damania et al. (2003)	Per capita membership of environmental organizations for EU member states
	Index of Environmental Sensitivity Performance (IESP)	31 countries (23 developed and 8 developing)	2000	Cagatay and Mihci (2006)	Index based on relative degree of pollution generated during certain industrial activities and related efforts of economic agents to improve environmental quality. Data from Bakkes et al. (1994), Hammond et al. (1995), WB (1995) and MENV (1996)

Emissions and energy use					
Measure	**Data source**	**Countries/ Industries**	**Time**	**Studies**	**Notes**
Emissions	United Nations Environment Program	15 developed countries and 7 developing	1985-1990	Xing and Kolstad (2002)	Economy-wide emissions of sulfur dioxide
Ambient pollution	US EPA	US counties	1977 and 1982	MConnell and Schwab (1990)	Actual ozone reading for counties failing to attain national AQ standards.
Emissions reductions	World Development Indicators and OECD (1996)	24 countries of Central and Eastern Europe and the former Soviet Union	1990s	Smarzynska and Wei (2004)	Actual reductions in emissions of carbon dioxide, lead and water pollutants scaled by GDP growth
	Monthly Report Steam Electric Plant Air and Water Quality Control Data; State Implementation Plans for the Clean Air Act	US electric utilities	1973-1979	Gollop and Roberts (1993)	Firm-specific based on stringency, enforcement, and estimated unconstrained emissions.
Energy use	World Bank World Development Indicators.	31 developed and developing economies	1980-1995	Cole and Elliott (2003)	Change in energy intensity (energy/GDP) and level of energy intensity in 1980
	Energy Balances of OECD Countries; International Energy Agency	24 OECD countries	1990-1996	Harris et al. (2003)	Six indexes based on final energy consumption or primary energy supply, normalized by GDP or population
	IEA Energy Balances and the OECD International Sectoral Database	Food and beverages and primary metals industries in Europe.	1978-1996	van Soest et al. (2005)	Difference between a polluting input's shadow price and purchase price.

Public expenditures and enforcement					
Measure	**Data source**	**Countries/ Industries**	**Time**	**Studies**	**Notes**
Public sector expenditures	OECD (1995)	48 developed and developing countries	1982-1992	Damania et al. (2003)	Public environmental R&D expenditure as a proportion of GDP
	Council of State Governments (1991)	US manufacturing	1963-1987	Gray (1997)	Public spending per capita on each state's programs for environment and natural resources in 1988
	OECD (1999) - and comparison with national EU sources: Eurostat for France and Netherlands, UK Department of the Environment (1992) for the United Kingdom	United States, United Kingdom, France, Netherlands	1985-1997	Pearce and Palmer (2001)	Pollution abatement expenditure per capita by public and private sectors
State monitors and inspections	National Governor's Association (1982)	United States	1982	*Levinson (1996)*	Number of employees at state environmental agencies divided by the number of existing manufacturing plants
	US Environmental Protection Agency	US manufacturing plants	1963-1987	*Gray (1997)*	Number of air inspections at manufacturing plants normalized by the number of manufacturing plants for each US state
		US manufacturing plants near 4 US cities	2000-2002	*Shadbegian and Gray (2012)*	

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