RESOURCES
for the FUTURE

The International Diffusion of Climate Policy: Theory and Evidence

Geoffroy G. Dolphin and Michael G. Pollitt

Working Paper 21-23
August 2021

About the Authors

Geoffroy Dolphin is a postdoctoral fellow at Resources for the Future.

Michael Pollitt is a professor of business economics at the University of Cambridge Judge Business School.

Acknowledgements

The authors gratefully acknowledge the support of the UK Economic and Social Research Council. The authors are grateful to Frikk Nesje and Dallas Burtraw as well as seminar participants at Resources for the Future and to the Energy Policy Research Group (Cambridge) Energy & Environment seminar series for helpful comments on this and earlier versions of this paper.

About RFF

Resources for the Future (RFF) is an independent, nonprofit research institution in Washington, DC. Its mission is to improve environmental, energy, and natural resource decisions through impartial economic research and policy engagement. RFF is committed to being the most widely trusted source of research insights and policy solutions leading to a healthy environment and a thriving economy.

Sharing Our Work

THE INTERNATIONAL DIFFUSION OF CLIMATE POLICY: THEORY AND EVIDENCE

G.G. Dolphin*[a] and M.G. Pollitt[b]

[a]*Resources for the Future, 1616 P St NW, Washington, DC, USA,*
and Energy Policy Research Group, University of Cambridge, Trumpington St, Cambridge CB2 1AG, UK
[b]*Judge Business School and Energy Policy Research Group, University of Cambridge, Trumpington St, Cambridge CB2 1AG, UK*

This version: August 2021

Abstract

Globally coordinated climate action has resulted in suboptimal GHG emission reductions and unilateral, second-best, climate policies have so far provided the bulk of these reductions. Using an open economy general equilibrium framework, we propose that the adoption of climate policy is partly determined by a process of policy diffusion whereby actions of foreign jurisdictions affect domestic conditions and policy decisions. We focus on diffusion mechanisms related to (i) access to improved foreign abatement technology and (ii) policy adoption by foreign jurisdictions. We apply our framework to the adoption of feed-in tariffs (FiT), renewable portfolio standards (RPS) and carbon pricing mechanisms. Overall, results highlight differences among policies. The evidence suggests that improved access to climate change mitigation technologies leads to earlier adoption of RPS and carbon taxes but not FiT or an emissions trading system (ETS). It also suggests that countries with common *legacy* institutions influence each other's adoption decisions in the case of FiT.

Keywords: climate policy, policy diffusion, technology access

JEL Classification: Q54, Q58

1 Introduction

Under the architecture of the United Nations Framework Convention on Climate Change (UNFCCC), and of the Paris Agreement in particular, the global climate change mitigation regime is only as strong as the sum of its parts —that is, emissions reductions

---

*Corresponding author (gd396@cam.ac.uk). The authors gratefully acknowledge the support of the UK Economic and Social Research Council. The authors are grateful to Frikk Nesje and Dallas Burtraw as well as seminar participants at Resources for the Future and to the Energy Policy Research Group (Cambridge) Energy & Environment seminar series for helpful comments on this and earlier versions of this paper.

commitments formulated by the Parties to the Convention and the policies enacted to achieve them.[1] Thus, to understand the dynamics of the global regime, we need to understand the determinants of unilateral climate policy adoption.

Over the last three decades an increasing number of jurisdictions have adopted policies to help them achieve greenhouse gas (GHG) emissions reduction. Typically, studies seeking to explain adoption focus on internal political and economic conditions (e.g., Congleton (1992); Hahn (1990)). These studies, we believe, overlook an important explanation for the developments observed over the last 30 years: *policy diffusion*. Indeed, under the architecture of the Paris Agreement, mechanisms of policy diffusion may play an outsized role in the strengthening of national—and hence global—climate change mitigation policy regimes.

Under the provisions of the agreement, parties are expected to submit upward revised emissions reduction commitments every five years (Paris Agreement, art. 3, 4). That time window, it is hoped, will allow parties to observe the stringency of each other's commitment as well as learn from each other's (newly) adopted policies and technologies. This, in turn, could reduce perceived or actual cost of regulating emissions and induce more stringent domestic commitments.[2] An indication that such a dynamic might already be at play is provided by successive updates of the Climate Action Tracker thermometer (CAT (Climate Action Tracker), 2021), which represents the projected median global temperature rise (by 2100) implied by countries' intended nationally determined contributions (INDCs): every updated assessment of countries INDCs since 2015 resulted in a lower projected temperature increase. Whether an ambitious global climate policy regime can emerge from successive rounds of strengthening of unilateral national policies

---

[1] Since greenhouse gases (GHGs) are *global* pollutants, any environmentally effective solution requires a reduction in world emissions. However, no world government capable of enforcing worldwide reductions in GHG emissions exists. Instead, a multitude of sovereign states interact within the Westphalian system of international relations and its founding principles (self-determination, legal equality of states and no third-party interference in internal affairs) make cooperation the only available option to efficiently address global public good problems like climate change (Barrett, 2003). It is precisely these principles—and their implications—that shaped the United Nations Framework Convention on Climate Change (UNFCCC), formally established in 1992.

[2] Provisions of the agreement offer the flexibility to Parties to put forward emissions reduction strategies based on a variety of abatement policies and technologies in the hope that it will foster their demonstration and diffusion across sectors and jurisdictions (Paris Agreement, art. 6-1, 6-8, 7-6, 7-7, 10).

depends crucially on the strength of policy diffusion mechanisms.

To identify salient mechanisms, we take stock of the main determinants of domestic climate policies over the last 30 years: (i) free riding and the international competitiveness of domestic GHG-intensive sectors; (ii) the cost and availability of GHG-abatement technologies and (iii) the uncertainty surrounding the political and economic implications of said policies. Each of these concerns has contributed to keeping global, and most national, climate change mitigation ambitions low. Yet in recent years, the cost of some GHG-abating technologies has plummeted, especially in the power sector (IRENA (International Renewable Energy Agency), 2020), as some jurisdictions embarked on their development and deployment. In addition, the adoption of (more stringent) climate change mitigation policies by an increasing number of jurisdictions may have dampened both free riding and international competitiveness concerns, as well as provided additional information on (successful) policy designs.

Following Simmons and Elkins (2004), we hypothesize that the processes of policy diffusion are related to two main mechanisms. : First, an alteration of the net payoffs of domestic climate policy induced by (a) policy adoption in foreign jurisdictions which alters the magnitude of free riding and the international competitiveness cost of more stringent domestic environmental policy;[3] and (ii) abatement technology development by foreign jurisdictions which reduces the domestic cost of emissions reduction (see, e.g., Heal (1993)); and second, an update on the expected (political) cost of policy adoption, derived from policy adoption in foreign jurisdictions.

Importantly, we note that the hypothesised mechanisms of diffusion are not necessarily clear a priori and are explicitly accommodated in a static general equilibrium model based on Copeland and Taylor (2003). First, it accounts for free riding and leakage effects (Copeland and Taylor, 2005) that might result from changes in domestic environmental regulation and are due to differences in relative input factor endowments, changes in

---

[3] For example, the international competitiveness disadvantage created by more stringent carbon pricing policy is alleviated when all members of a closed trading club implement it. Such a club could be closed *de facto*, a group of countries that trade mostly among themselves, or *de jure*, a group of countries that implement external CO_2 adjustment tariffs (see, e.g., Nordhaus (2015)).

relative international prices, and so forth (see, e.g., Antweiler et al. (2001)).[4] Second, it highlights the role played by access to abatement technology, which is the motivation behind discussions about its institutionalized transfer among groups of jurisdictions (e.g., UNFCCC, art. 4.5) and provides the rationale for a substantial body of work that seeks to shed light on channels of (abatement) technology diffusion.[5] Third, it captures the informational signal that policy adoption contains. Governments often lack sufficient understanding of the consequences of a particular policy innovation (Simmons and Elkins, 2004), in which case *inaction* may simply reflect a lack of accurate information. Climate policy adoption by one jurisdiction may carry a signal about the low cost of the said policy, prompting other jurisdictions to "mimick" their neighbour.

Using this framework as a guide for our empirical investigation, we test these hypotheses with respect to the adoption of four policies targeting the power sector: carbon tax, emissions trading, feed-in tariffs, and renewable portfolio standards. The motivation for our empirical focus is threefold. First, the power sector was faced early on with binding regulations mandating either GHG emissions reduction or the use of alternatives to fossil fuel-based power generation technologies.[6] Second, the four instruments analyzed here constitute the main tools used so far to achieve these objectives. Third, a standard hypothesis of the environmental economics literature is that environmental quality is a normal good, and hence the stringency of environmental regulation can be expected to rise as the national income grows. However, as in the case of SO_2 and NO_x emission regulation (Lovely and Popp, 2011), adoption of the policies discussed here does not seem to be related (only) to levels of GDP per capita. Figure 1 shows the level of GDP per

---

[4] Antweiler et al. (2001) formulate two main hypotheses: the *pollution haven hypothesis*, which states that since environmental regulation raises the cost of manufacturing goods, pollution-intensive economic activity will relocate to jurisdictions with lower environmental standards, and the *factor endowment hypothesis*, which claims that standard forces such as factor endowments and technology determine the pattern of trade, not just environmental policy (Copeland and Taylor, 2003). Several empirical studies have provided evidence in support of the second hypothesis and, de facto, cast serious doubt on the first (Tobey, 1990; Grossman and Krueger, 1993; Jaffe et al., 1995).

[5] The focus of this paper is on the role played by bilateral relationships and, in that respect, differs from approaches adopted, for example, by Vega and Mandel (2018). Their approach "accounts for the impact of each country not only on its direct connections, but also on the global diffusion process" (462).

[6] Adoption of policies aiming at reducing emissions in other sectors of the economy (e.g., transport) has recently gained momentum. However, these are relatively few and too recent to lend themselves to a meaningful empirical investigation.

capita against the year of policy adoption. If national income were the only determinant of policy adoption, one would expect countries to adopt regulation at similar levels of GDP per capita through time. Yet the panels in the figure indicate that other factors might be at play, which suggests that an increase in national income, though important, is not the only way to get countries to adopt more stringent climate policy. The literature on policy diffusion offers a useful route to explain these recent climate policy adoption events.

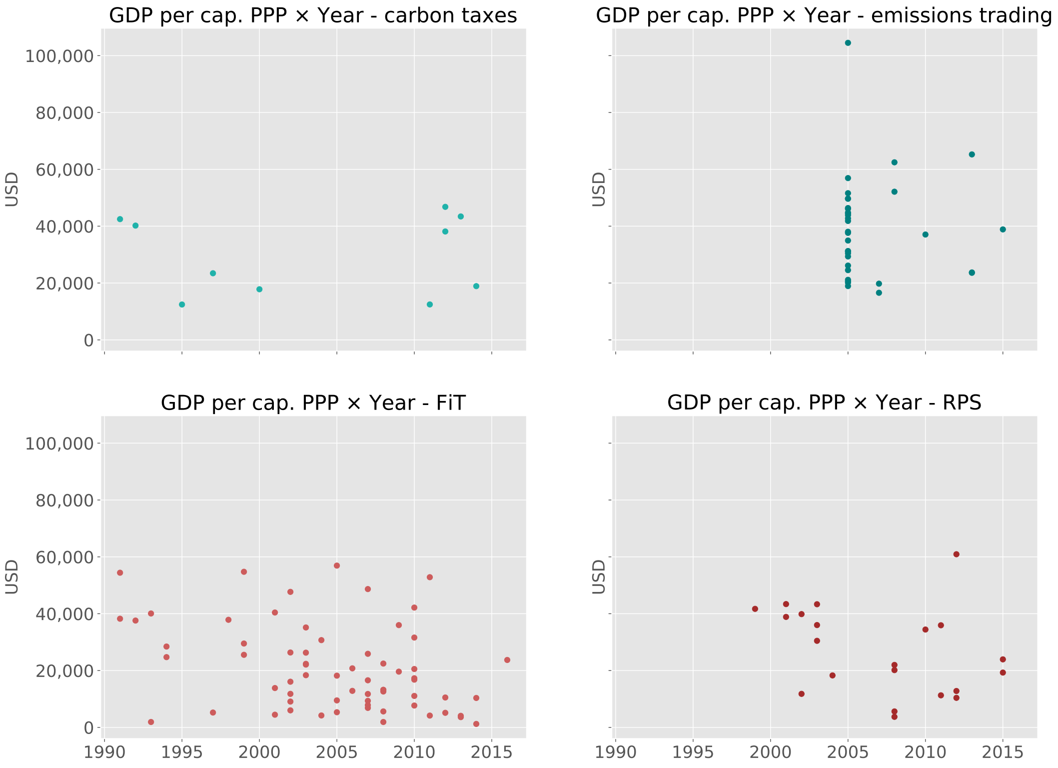

Figure 1. Adoption of climate policies in national jurisdictions, 1990–2016

The remaining of this paper is organized as follows: Section 2 introduces a formal framework to support our empirical discussion, and Section 3 builds on it to introduce our hypotheses. Section 4 presents the data, and Section 5 presents the modelling strategy and results. Finally, Section 7 concludes.

2 Theoretical Framework

We cast our discussion within a stylized multicountry general equilibrium model of international trade with transboundary pollution, adapted from Copeland and Taylor (2003).[7] We distinguish between primary factors of production and consumption goods (Dixit and Norman, 1980). Primary factors are nontradable while goods are tradable. Labour is mobile across sectors but not across countries.

We assume that n is large and that all countries have the same *relative* size so that each country cannot, individually, influence its terms of trade (Grossman and Helpman, 1991).[8] The model is static, productive factors are in inelastic supply and environmental quality is a global public good.[9] Finally, factor endowments vary across countries and determine trade patterns.

2.1 Technology

We assume strictly concave, constant returns to scale technology (CRS) and linearly homogenous production functions for both goods x and y. That is, the set of technologically feasible (r, t), T, is convex. The production of good x generates pollution, e, as a by-product, while the production of good y does not.[10] The production function of the clean good y is:

$$y = F(K_y, L_y). \tag{1}$$

In industry X, abatement activity is considered to be costly to firms; that is, firms

---

[7] This is a two factors $\mathbf{r} = (r_1 = K, r_2 = L)$ – two goods $\mathbf{t} = (t_1 = x, t_2 = y)$ model. The two main adjustments are (i) an explicit recognition of the role played by (improvements in) abatement technology in the determination of domestic climate policy, and (ii) a reinterpretation of the regulatory threshold as depending on expectations about the economic and political cost of policy intervention. Jurisdictions are indexed by $i = 1, 2, \ldots, n$.

[8] While assuming away the impact of domestic environmental policy on world prices excludes the possibility for policy makers to manipulate their terms of trade by their choice of climate policy, it allows us to keep the argument focused on the mechanisms of interest. Strategic setting of environmental policy for the purpose of manipulation of the terms of trade is not considered here.

[9] The mechanisms under consideration in this paper are dynamic in nature (e.g. accumulation of knowledge or abatement technology over time). However, so long as the policy decision is influenced by the accumulated stock rather than flow variables, and that there are no intertemporal strategic interactions, a static model is sufficient to capture the essence of the the problem at hand.

[10] This is without loss of generality and it can easily be extended to a context with $m > 2$ goods exhibiting different emissions intensities. See Levinson and Taylor (2008) for a partial equilibrium example and Copeland and Taylor (1994) for a general equilibrium discussion.

produce potential output $B(K_x, L_x)$ and can choose to redirect a fraction $\phi \in [0,1]$ of inputs to the abatement process, which will, in turn, reduce the net output of good x. In other words, the net production of x is the difference between potential production and production foregone due to the use of resources in abatement activity, $(\phi K_x, \phi L_x)$. As a result, emissions intensity in that sector is a choice variable. The joint production of x and e is given by

$$\begin{aligned} x &= B(K_x, L_x) - B(\phi K_x, \phi L_x) \\ &= (1-\phi)B(K_x, L_x) \qquad (2) \\ e &= \chi(\phi)\Omega B(K_x, L_x), \qquad (3) \end{aligned}$$

where the second line of equation (2) follows from the CRS assumption. $\chi(\phi)$ is the abatement function, with more abatement efforts leading to less emissions—that is, $\frac{d\chi}{d\phi} < 0$, and $\chi(0) = 1; \chi(1) = 0$.[11]

In the absence of abatement $(\phi = 0, \chi(\phi) = 1)$, each unit of good x produces Ω units of pollution; conversely, if all resources are devoted to abatement $(\phi = 1,\ \chi(\phi) = 0)$, no production takes place and thus no pollution is produced. $0 < \Omega \leq 1$ is therefore the unabated level of pollution attached to each unit of the dirty good and can be interpreted as a technological parameter for the abatement activity.[12] A decrease in Ω then denotes an improvement in the abatement technology (Brock and Taylor, 2010) and, for given levels of potential production and abatement effort, a decrease in emissions.

As shown in Section 3.3, this parameter plays a central role in the determination of a jurisdiction's equilibrium emissions (i.e., climate policy). As a result, mechanisms leading to improvements in domestic abatement technology, which constitute one of the focal points of our discussion, are particularly important.

To keep the discussion as focused as possible on this parameter, we note that, given equation (3), constraining the number of pollution units that the sector is allowed to

---

[11] As noted by Copeland and Taylor (2003), adopting this specification is equivalent to assuming an explicit pollution abatement function. (See Appendix A.1.)

[12] Restricting Ω to values below or equal to 1 ensures that emission intensity is below or equal to 1 and avoids unnecessary complexities in the firm's profit maximization problem. In Copeland and Taylor (2003), Ω is constant and, by choice of units, set equal to 1.

release in the environment constrains its net production in the same way limited availability of an input would. Therefore, following Copeland and Taylor (2003, 2004) we treat pollution as an input into the production process of good x and reformulate equation (2) accordingly. Under the assumption that $\chi(\phi) = (1-\phi)^{\alpha}$, we can rewrite equation (2) as

$$x = \left(\frac{e}{\Omega}\right)^{\alpha} B(K_x, L_x)^{1-\alpha} \tag{4}$$

which expresses the net production of x as a function of *effective emissions*, e/Ω (i.e., emissions per emissions required for a unit of potential output), and potential output.

Proof. See Appendix A.2. ☐

Equation (4) allows us to make three observations with important implications for domestic climate policy. First, it highlights once again the importance of the quality of the abatement technology: as emissions per unit of potential output (Ω) decrease, net output increases. This is because improvements in abatement technology free up resources that were previously devoted to abatement, making them available for actual production (see the discussion in Appendix A.2). In other words, for a given e, as the abatement technology improves, the production of the dirty good expands. Second, an improvement in abatement technology decreases the emissions intensity of the economy.[13] The third observation is summarized in the following lemma.

Lemma 1. *The effect on the net output of good x of a change in pollution emissions decreases in Ω; that is,* $\left|\frac{\partial x}{\partial e}\Big|_{\Omega^{Low}}\right| > \left|\frac{\partial x}{\partial e}\Big|_{\Omega^{High}}\right|$.

Proof. The cost of tightening pollution policy in sector X is driven by the diversion of resources from actual production to abatement activities. From equation (4) it is easy to

---

[13] This observation uses a standard implication of Cobb-Douglas production functions: the share of payments in total value added to a factor of production is equal to the associated output elasticity parameter; that is,

$$\frac{\delta \frac{e}{\Omega}}{px} = \alpha \Leftrightarrow i \equiv \frac{e}{x} = \frac{\alpha \Omega p}{\delta} \tag{5}$$

where δ is the price of emissions (see Section 2.2) and p is the relative price of good x. Furthermore, equation (5) indicates that emissions intensity also depends on emissions price (δ). (Appendix A.4 discusses that relationship further.)

see how net output changes as a result of a change in allowed emissions:

$$\frac{\partial x}{\partial e} = \alpha \frac{e^{\alpha-1}}{\Omega^{\alpha}} B(K_x, L_x)^{1-\alpha} > 0, \tag{6}$$

which increases as Ω decreases. □

Although this lemma might seem counterintuitive, it reflects the increased opportunity cost of reducing emissions when the economy is very efficient at abating—that is, when the productivity of each unit of pollution (x/e) is high.

2.2 Production Decision and Pollution Demand

Equipped with these technological priors, we now look at the production decision of firms.[14] This decision determines the relative size of the dirty sector and, ultimately, determines the pollution demand schedule, which will affect optimal climate policy.

Good y is the numeraire (with price p_y normalized to 1), and the relative price of good x in terms of good y is denoted p. The optimal output vector $\mathbf{t} = (x, y)$ will depend on primary input endowments, $\mathbf{r} = (K, L)$; output prices, $\mathbf{p} = (p, 1)$; and for the pollution-emitting sector, emissions e. Thus, the firms' problem is

$$\max_{\mathbf{t}} \{\mathbf{p}.\mathbf{t} \mid (t, r, e/\Omega) feasible\}. \tag{7}$$

Since input factors (K, L) are supplied inelastically, the firms' decision determines the relative allocation of inputs into each sector. In the dirty good sector, the firms face the additional decision of how much of these resources to devote to abatement. The solution to this problem defines the optimum (technologically feasible) vector of output,

$$\hat{\mathbf{t}} \equiv t(\mathbf{p}, \mathbf{r}, e/\Omega). \tag{8}$$

Consequently, the (maximum) revenue function can be defined as

$$g\left(p, K, L, \frac{e}{\Omega}\right) = \mathbf{p}.t(\mathbf{p}, \mathbf{r}, e/\Omega). \tag{9}$$

The revenue function is convex in $\mathbf{p}$, $\bigtriangledown_{pp} g(\mathbf{p}, \mathbf{r}, e/\Omega) > 0$, but concave in $\mathbf{r}$,

---

[14] The detailed production decision problem of firms in sectors x and y is presented in Appendix A.3.

$\bigtriangledown_{rr} g(\mathbf{p}, \mathbf{r}, e/\Omega) < 0$.[15] In addition, we have the following lemma.

Lemma 2. *The revenue function is increasing and concave in e*

$$\partial g(\mathbf{p}, \mathbf{r}, e/\Omega)/\partial e > 0; \partial g(\mathbf{p}, \mathbf{r}, e/\Omega)/\partial^2 e < 0, \tag{a}$$

but decreasing and convex in Ω

$$\partial g(\mathbf{p}, \mathbf{r}, e/\Omega)/\partial \Omega < 0; \partial g(\mathbf{p}, \mathbf{r}, e/\Omega)/\partial^2 \Omega < 0. \tag{b}$$

That is, as the abatement technology deteriorates, revenue falls at a decreasing rate.

Proof. (a) The fact that the revenue function is increasing in e follows from Lemma 1, and the concavity of the revenue function in e can be justified following the same argument as for $\boldsymbol{r}$ (see Dixit and Norman 1980, 31). (b) With relative price $\boldsymbol{p}$ and total resources $\boldsymbol{r}$ held constant, a deterioration of the abatement technology will (i) induce a reallocation of resources from the dirty to the clean sector, as clean good production is now relatively more profitable (see equation (A.6) in Appendix A.3); and (ii) reduce net output in the dirty sector (see equation 4). Similarly, convexity results from the convexity in Ω of the production in the dirty sector.

□

If we further assume that profit-maximizing firms maximize national income, this revenue function can be interpreted as the *national income function*, $G(p, K, L, \frac{e}{\Omega})$.[16] Hence we write

$$I \equiv G\left(p, K, L, \frac{e}{\Omega}\right) = \max_{x,y} \left\{\mathbf{p} \cdot \mathbf{t} : \mathbf{t} \in T(K, L, \frac{e}{\Omega})\right\}, \tag{10}$$

where I denotes the national income. The national income function preserves all the properties of the revenue function.

At this stage, it is useful to note the relationship between the national income function and the price of emissions. For given prices and factor endowments, the value of

---

[15] For an informal justification of this statement, see Dixit and Norman (1980), 31.

[16] The assumption that profit-maximizing firms in perfectly competitive environments maximize national income is a standard result in microeconomic theory that has been used extensively in the international trade literature. It holds as long as the negative environmental externality considered does not cause adverse production externalities. See Copeland and Taylor (1994, 1995).

a pollution permit, denoted δ, is the marginal effect on national income of additional pollution:

$$\delta \equiv \frac{\partial G(\mathbf{p}, \mathbf{r}, e/\Omega)}{\partial e} \tag{11}$$

Lemma 3. *A marginal increase in domestic environmental policy stringency leads to a loss of domestic income, I, of δ.*

Proof. This follows straightforwardly from equation (11) and results from the diversion of some domestic resources to abatement activity in the dirty good sector, which in turn reduces the net (optimal) supply by domestic producers.[17] ☐

In addition, note that equation 11 gives the demand schedule of firms for pollution. Given that $G(.)$ is concave in e (Lemma 2), the demand schedule is decreasing. Hence, we also have the following lemma.

Lemma 4. *For a given net output of the dirty good sector, an improvement in the abatement technology reduces pollution demand; that is, $\frac{\partial G(\mathbf{p}, \mathbf{r}, e/\Omega)}{\partial e \partial \Omega} > 0$.*

Proof. First, note from equation (5) that the demand for pollution can be expressed as the emissions intensity times the production of good x; that is $e = i(p, \delta, \Omega) \times x(p, \delta, K, L)$. Now, using equation (5) again, it is easy to note that an improvement in abatement technology (i.e., a decrease in Ω) leads to a decrease in emissions intensity – a *technique* effect. Hence, for a given level of production in the X sector, an improvement in abatement technology decreases demand for pollution. ☐

2.3 Consumers

Let us assume the existence of N identical consumers in each country. Consumers derive utility from the consumption of both goods x and y and incur disutility —damage (D)—from global pollution E. The utility function is strongly separable with respect to

---

[17] Moreover, given the concavity in $\boldsymbol{p}$ of the national income function, the marginal value (in terms of national income) of a domestic unit of pollution increases with the price of the dirty good, which, under certain conditions, would further reduce incentives for unilateral action. Yet, Copeland and Taylor (2005) showed that, in addition to the standard positive incentive to free-ride, a small economy's reaction to other jurisdictions' emissions reductions would depend on the substitution and income effects induced by a change in the relative price of the dirty good.

consumption goods and environmental quality. Each consumer of jurisdiction i has the following utility:

$$U^i \equiv U^i(x, y, E) = u^i(x, y) - D(E), \tag{12}$$

where $E = \sum_j e_j + e_i$ and e_j denotes the emissions of jurisdiction j.[18] $u^i_x(x, y)$, $u^i_y(x, y) \geq 0$, $u^i_{xx}(x, y), u^i_{yy}(x, y) < 0$ and $D'(E) > 0, D''(E) > 0$. Note, in addition, that $u^i(x, y)$ is homothetic.[19] Consumers maximize utility given goods prices, which determine the revenue function specified by equation (9), and (global) pollution levels. Using duality, we can write consumer i's indirect utility function, which gives the maximum utility attainable for given prices and income (I), as

$$V^i \equiv V(\mathbf{p}, I, E) = v(\mathbf{p}, I) - D(E) \tag{14}$$

Consumers earn their revenue from their ownership of factors of production, capital, and labour, which are remunerated at the equilibrium market rate. In a perfectly competitive economy, the total value of payments to all factors of production is equal to the maximum value of production. It will thus depend on the composition of the economic production, the price at which said production is sold, and environmental policy. Eventually, using the homotheticity assumption, function $v(.)$ can be written as a function of real income – $I/\omega(\mathbf{p})$, where $\omega(\mathbf{p})$ is a price index:

$$V^i(\mathbf{p}, I, E) = v(\mathbf{p}, I) - D(E) = v(1, I/\omega(\mathbf{p})) - D(E)$$

$$V^i(R, E) \equiv v(R) - D(E). \tag{15}$$

This means that the consumers' indirect utility boils down to the indirect utility

---

[18] Note that equation (12) assumes that the consumer does not derive any utility from global environmental quality. One could take this form of altruism into account by attributing a strictly positive weight to the damage that domestic emissions impose on other jurisdictions. For example,

$$U^i \equiv U^i(x, y, E) = u^i(x, y) - [\alpha D_1(E)] + \beta D_2(E)], \tag{13}$$

where $\beta = 1 - \alpha < 1$ and D_1 and D_2 denote domestic and foreign (or world) environmental damage, respectively. Care for the global environment will reduce equilibrium emissions level.

[19] With homotheticity, the analysis is simplified in two ways. First, the indirect utility function can be written as an increasing function of real income. Second, it ensures that relative consumption patterns do not change with income which, in turn, makes trade patterns dependent on factor endowments and relative costs only (Copeland and Taylor, 2003).

derived from real income, R, net of the damage from global emissions, E.

2.4 Equilibrium Pollution Supply

Climate policies have been developed at the global level over the last three decades in a largely uncoordinated and noncooperative fashion.[20] We therefore consider a noncooperative Nash equilibrium where pollution policy is endogenous and decided by a self-interested government, which maximizes the utility of a representative consumer given world prices and rest-of-the-world (ROW) emissions.[21] Government policy is cast in terms of pollution targets, e_i. The problem of the government is as follows:

$$\max_{e_i} \quad V^i(R, E) \tag{16}$$

$$s.t.: \qquad R = [G(p, K, L, \frac{e_i}{\Omega})]/\omega(\mathbf{p}) \tag{17}$$

$$E = E_{-i} + e_i, \tag{18}$$

where E_{-i} is the total aggregate emissions of all jurisdictions bar the emissions of jurisdiction i. The optimality condition of this maximization problem is:

$$\underbrace{V_R R_E}_{(1)} + \underbrace{V_R R_p p_e}_{(2)} + \underbrace{V_E}_{(3)} = 0 \tag{19}$$

Proof. To obtain equation (19), we acknowledge all the direct and indirect dependencies of V^i on domestic emissions e_i. First, domestic emissions affect the indirect utility via their impact on the national (real) income (see equation 15). They can affect the national income in two ways: (i) directly, by constraining the production of the dirty good, $\frac{e_i}{\Omega}$ (see Lemma 3); or (ii) indirectly, by altering the relative price of the dirty good on world markets, $p(e)$. Second, domestic emissions affect the indirect utility via their impact on

---

[20] Perhaps with the exception of the Kyoto Protocol and the European Union. However, as has been argued in previous literature, the emissions reduction objective agreed to by parties to the protocol might not be far off their non-cooperative policy (Barrett, 1994).

[21] Unlike Lovely and Popp (2011), we do not consider the policymaking entity to be politically motivated—that is, it does not attach any weight to contributions of politically organized groups.

total world emissions E. To show this more clearly, we write

$$V^i(\underbrace{G(p(e), K, L, \frac{e_i}{\Omega})/\omega(\mathbf{p})}_{R}, \underbrace{E_{-i} + e_i}_{E}), \tag{20}$$

of which we take the total derivative with respect to e_i. (Given the presence of indirect dependencies of V on e_i and composed functions, we must resort to the chain rule.) This derivative is then written as

$$\frac{dV}{de_i} = \frac{\partial V}{\partial R}\frac{\partial R}{\partial p}\frac{dp}{de_i} + \frac{\partial V}{\partial R}\frac{\partial R}{\partial e_i} + \frac{\partial V}{\partial E}\frac{dE}{de_i}. \tag{21}$$

Note that $\frac{dE}{de_i} = \frac{d[E_{-i}+e_i]}{de_i} = \frac{dE_{-i}}{de_i} + 1$. Hence if the domestic economy takes other jurisdictions' emissions as given, which is our baseline assumption, then $\frac{dE_{-i}}{de_i} = 0$ and $\frac{dE}{de_i} = 1$.[22] Importantly, from the point of view of the domestic economy, this term captures free-riding and leakage issues. Indeed, if an economy's decision to reduce domestic emissions leads to less absolute reduction in world emissions, $dE/de_i < 1$, then domestic incentives to reduce emissions will decrease.

Next, defining $V_R \equiv \frac{\partial V}{\partial R}$, $R_p \equiv \frac{\partial R}{\partial p}$, $p_e \equiv \frac{\partial p}{\partial e}$ and $V_E \equiv \frac{\partial V}{\partial E}$ yields the left-hand side of equation (19). Finally, note that V is a concave function because of the structure imposed on $u(.)$ earlier. Hence, setting equation (21) to 0 defines a maximum.

□

That is, the government's decision reflects the tradeoff between the direct effect of emissions change on the nation's real income (1), the effect of the induced change in the price of the dirty good on real income (2), and the effect of emissions change on the consumer's utility (3). However, if world prices are exogenous to domestic policy changes—that is, $p_e \equiv \frac{dp}{de_i} = 0$—(2) is equal to zero and there is no domestic real income effect of a change in domestic emissions via changes in world prices. Hence,

$$R_E = \underbrace{-V_E/V_R}_{\equiv MD(R,E)} \tag{22}$$

with $V_E < 0$ and $V_R > 0$. Equation (22) equates the marginal benefit of increased

---

[22] We relax that assumption in Section 3.2.

emissions (i.e., the resulting increase in real income) to the domestic marginal damage of pollution and defines the optimal level of emissions e^*. Given that domestic consumers account for domestic benefits of emissions abatement only, this outcome is suboptimal from a global planner's perspective.

3 Determinants of equilibrium climate policy

3.1 National Income

In this setup, global environmental quality is a normal good. Formally, we make the following proposition:

Proposition 1. *As real income rises, equilibrium emissions decrease.*

Proof. Note that an increase in real income lowers the marginal utility of income (V_R); that is, $\mathrm{V}_{RR} < 0$. This, in turn, raises the marginal damage of emissions for a given level of emissions ($MD_R > 0$). As a result, equation (22) defines a lower emissions equilibrium. □

3.2 Free Riding, International Market Power and Carbon Leakage

The effect of climate policy strengthening in an open economy (i.e., a tighter emissions cap) is twofold. First, it may have an impact on national income. Second, if the economy is large relative to the size of the world market, increased emissions reduction might lead to significant free riding by noncommitted economies as well as 'carbon leakage' if its action induces a rise in the relative price of the dirty good (Copeland and Taylor, 2005), both of which reduce the environmental effectiveness of the domestic policy tightening.

To understand these effects, it is helpful to analyze the situation of a small and large emitter separately. For a small open economy with no international market power, $p_e \equiv \frac{dp}{de_i} = 0$, and the income effect of domestic environmental policy tightening boils down to (1) in equation 19. It is therefore strictly negative. In addition, the emissions (as a share of the world total) of such an economy are likely to be small and hence any policy tightening is unlikely to induce any significant free riding ($\frac{dE_{-i}}{de_i} \approx 0$).

For a country with some international market power, $p_e \equiv \frac{dp}{de_i} < 0$ and the total income effect will now be given by (1) + (2) in equation (19), where the impact of a change in the world price of the dirty good on real income, R_p, depends on the country's net position with regard to exports of the dirty good. It is positive (negative) if the country is a net exporter (importer) of the dirty good (Copeland and Taylor, 2005). As a result, while the total income effect of policy tightening is unequivocally negative for a large net importer of the dirty good, its sign is ambiguous for a large net exporter.[23]

A large economy (or a sufficiently large group of economies) would also account for the fact that its own (unilateral) emissions reduction might: (i) induce free riding on the part of other economies; or (ii) lead to a change in the world price of the dirty good and induce carbon leakage.[24] To see these latter effects formally, consider again $\frac{dE_{-i}}{de_i}$ and note that it can be decomposed as follows:

$$\frac{dE_{-i}}{de_i} = \underbrace{\frac{\partial E_{-i}}{\partial e_i}}_{(A)} + \underbrace{\underbrace{\frac{\partial E_{-i}}{\partial p}}_{(B.1)} \underbrace{\frac{dp}{de_i}}_{(B.2)}}_{(B)}, \tag{23}$$

where (A) captures the pure free-riding effect and (B) captures the leakage effect, which depends on the sensitivity of ROW emissions to the relative price of the dirty good in international markets (B.1) and a country's international market power (B.2). The free riding effect is negative—that is, domestic emission reductions induce non-committed foreign jurisdictions to increase theirs. The leakage effect is negative, since $dp/de_i \leq 0$

---

[23] Although it is possible that some net dirty good exporters have considered this effect, the record of climate policy development does not suggest that it has been strong enough to offset the direct negative income impact (1) as well as the impact of free riding and carbon leakage, and induce significant emissions reduction. Hence we rule out this possibility in our empirical investigation.

[24] Copeland and Taylor (2005) show that leakage is not inevitable. (see previous note). It is also worth noting that the literature on carbon leakage identifies two leakage mechanisms (see, e.g., Fowlie and Reguant (2018)): (i) a trade channel, whereby the production of the dirty good is relocated to jurisdictions with less stringent environmental regulation; and (ii) an input price channel, whereby stringent environmental regulation in a large country leads to a substantial reduction in demand for a polluting input, putting downward pressure on its price in the international market and thereby incentivizing its use in noncommitted countries. The present framework accounts for the first of these mechanisms only. In practice, however, there is little ex-post evidence that carbon pricing and the climate policies implemented so far have induced significant carbon leakage (see, e.g., Ward et al. (2015)).

and $\partial E_{-i}/\partial p > 0$. As a result, $\frac{dE_{-i}}{de_i} < 0$.

The free-riding problem occurs even if countries do not engage in international trade and is only a function of the share of unconstrained world emissions. Carbon leakage, on the contrary, also depends on a country's market power, which determines the magnitude of impact of domestic regulatory changes on the relative price of the dirty good in international markets. If a country has no market power ($dp/de_i = 0$), then $dE_{-i}/de_i = \partial E_{-i}/\partial e_i$; if it has some market power, then the extent of the leakage effect depends on the country's market power and the responsiveness of RoW emissions to domestic policy tightening (B.1).

The free-riding and leakage effects are both positively related to the number of non-committed countries or, more precisely, the share of unconstrained emissions; that is, dE_{-i}/de_i increases (in absolute terms) if the latter increases. This effect induces higher equilibrium emissions or, equivalently, lower climate policy ambition. Equivalently,

Proposition 2. *Reduced free riding (or reduced carbon leakage) tightens the domestic abatement equilibrium.*

Proof. More stringent foreign climate policy (a decrease in the share of unconstrained RoW emissions) lowers the value (in absolute terms) of A and B.1 in equation (23). Hence, denoting foreign climate policy stringency by η, we can write $\left|\frac{\partial E_{-i}}{\partial e_i}|_{\eta^{high}}\right| < \left|\frac{\partial E_{-i}}{\partial e_i}|_{\eta^{low}}\right|$; that is, more stringent foreign climate policy strengthens the incentive for domestic policy strengthening. □

Much of the discussion around strengthening climate policy in relatively richer and larger economies has therefore focused on ways to avoid free riding and carbon leakage, providing the motivation for calls to increase the number of economies committing to emissions reduction and, more specifically, increase the share of world GHG emissions covered by such commitments.

3.3 Technological Spillovers

As section 2.4 suggested, and as highlighted by integrated assessment modelling exercises (e.g., Kriegler et al. (2014)), abatement technology, Ω, is a key determinant of the economy's (equilibrium) level of emissions. In particular, under certain conditions, an improvement in domestic abatement technology reduces equilibrium emissions. To see this, recall from the proof of Lemma 4 that an improvement in abatement technology induces a *technique* effect, and observe from Appendix A.3 that it also induces a *composition* effect. For a given price of emissions, the former lowers total emissions in the dirty sector ($\frac{\partial G(\mathbf{p},\mathbf{r},e/\Omega)}{\partial e \partial \Omega} > 0$; see Lemma 4) whereas the latter raises them. Hence, the effect on equilibrium emissions will depend on the relative intensity of both effects. We thus make the following proposition:

Proposition 3. *Assuming that the composition effect is smaller than the technique effect, an improvement in abatement technology reduces equilibrium emissions as defined by equation 22.*

Proof. Formally, the technique and composition effects are apparent in $e = i(p, \delta, \Omega) \times x(p, \delta, K, L)$. Assuming that the decrease in emissions intensity—that is, the technique effect (Lemma 4) more than outweighs the rise in dirty good production arising from the diversion of resources from the clean to the dirty sector (composition effect), an improvement in domestic abatement technology shifts the pollution demand schedule to the left and reduces total (equilibrium) emissions. $\square$

3.4 Updated Information

The third channel through which domestic policy decisions can be altered is via an update of the informational set from which governments draw. Governments introducing a major policy innovation often lack information to understand the magnitude of its implementation cost and have little foreign experience to draw on in order to judge its effectiveness (Simmons and Elkins, 2004).[25] This can delay implementation of more stringent envi-

---

[25] In terms of climate policy this can represent the cost associated with the reallocation of resources from one industrial sector to another or the political cost of sustaining abatement policies (Mideksa,

ronmental policy. Early policy experience reveals information about the actual cost of implementation as well as institutional design features that can reduce them.[26] Therefore, the accumulation of information on past (foreign) policy experience would induce a reduction in the expected political and societal cost of policy adoption and lead to increased domestic policy stringency.

To show this in a more formal way, we start by noting that the government's first decision (prior to choosing the emissions level) is whether or not to regulate, and it will choose the option that maximizes the representative consumer's utility. In the presence of regulation, pollution is chosen according to equation (22) and utility rises monotonically with income. In the no regulation case, the consumer faces ever-increasing pollution, which, assuming decreasing marginal utility of consumption and constant marginal disutility of pollution, implies that utility initially rises and ultimately declines with income (see Appendix A.5). If the regulation is expected to require a fixed amount of primary inputs $(\bar{K}, \bar{L})$, regulatory activity will not occur until a threshold level of income, $\bar{I}$, above which the consumers' utility under regulation surpasses their utility under no regulation, is reached. Equivalently, a decrease in the expected regulatory cost reduces the income threshold at which policy activity is triggered. We define the expected regulatory cost as $\mathbb{E}(\bar{K}, \bar{L}) \equiv \Phi$ and formalize what we have discussed in the following proposition:

Proposition 4. *A decrease in the expected fixed cost of regulation lowers the policy activity income threshold; that is,* $\partial \bar{I} / \partial \Phi > 0$.

Proof. See Appendix A.5. □

4 Empirical Analysis and Data

The above theoretical framework described in Section 1 relates policy adoption to three sets of factors: (i) national income, free riding and carbon leakage; (ii) access to foreign abatement technology; and (iii) information on policy adoption by foreign jurisdictions.

2016).

[26] For instance, at the international level, one can think of the EU-ETS as playing such role; at the subnational level, California's ETS might be thought of as playing a similar role with respect to other US states.

We apply this framework to the adoption of four climate policy instruments targeting the power sector—namely, emissions trading, carbon tax, feed-in-tariffs (FiT) for wind and solar, and renewable portfolio standards (RPS). We collected data on the adoption of these policies and construct variables capturing the factors under investigation. Our sample includes up to 126 countries with yearly observations from 1990 to 2016.[27]

4.1 Policies

As of 2016, the last year of our sample, feed-in tariffs had been introduced in 76 countries, 21 countries had enforced renewable portfolio standards, 11 had implemented carbon taxes, and 34 had been operating an emissions trading system (REN21, 2020; Dolphin, 2020; World Bank, 2020).[28]

We measure adoption as a binary variable indicating whether a country had adopted the policy by year t.[29] Information on (the year of) adoption of these policies is not readily available. Adoption data on carbon pricing mechanisms was collected as part of an earlier effort (Dolphin et al., 2020). Information on the adoption of feed-in tariffs and renewable portfolio standards was collected from REN21 (2020) and supplemented with information from the International Energy Agency policies database (IEA, 2020). Figure 2 shows, for each type of policy, the cumulative number of countries having adopted the policy by year t as a percentage of the total number of countries in our sample (126), over the period 1990-2016.

Typically, policy adoption over time follows a S-shaped trajectory: a relatively long period of time with few early adopters is followed by a period exhibiting a higher rate of

---

[27] As in Simmons and Elkins (2004), our data is both left- and right-censored. Left-censoring means that observations for some countries are missing in the first half of the 1990s due to the unavailability of some data for these countries in that period. However, all countries are observed for at least one period prior to policy adoption. Right-censoring means that many countries did not adopt the policy by the end of the sample period.

[28] Note that these figures are specific to the power sector and include both existing and terminated schemes. A number of countries (e.g., some of those participating in the EU ETS) introduced carbon taxes in other sectors of their economy. In addition, some countries (e.g., Sweden) terminated their carbon tax in the power sector when this sector was included in an emissions trading system.

[29] Our focus is on policy adoption, not policy reversals or repeals. This implies that there are only two "policy states" possible and the "policy event"—that is, introduction of *a* climate change mitigation policy—occurs only once. In addition, note that the collected information reflects policy development at the country level and ignores subnational developments.

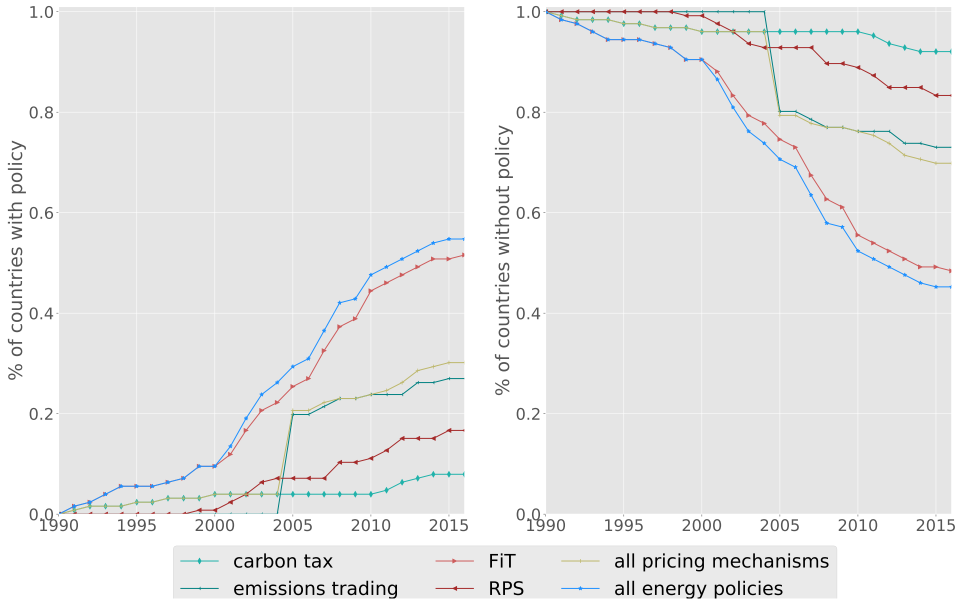

Figure 2. Climate policy adoption in the power sector

adoption, which is, in turn, itself followed by a period with a low adoption rate. In the present case, while the adoption of feed-in tariffs and, to an extent, renewable portfolio standards exhibit such a pattern, the adoption of carbon pricing policies does not. Figure 2 shows this clear contrast and suggests that these policies are in different stages of their international diffusion.

This contrast, together with the differing natures of these policies at hand, is worth noting. While one might be considered that all policies contribute to GHG emissions reductions, only carbon pricing mechanisms directly target the GHG externality. FiT and RPS target R&D market failures and are perhaps primarily technology policies. In addition, except for a few countries that introduced carbon taxes in the first half of the 1990s, policies that provided technology support—and, incidentally, did not create an explicit price signal on CO_2 emissions—were clearly favored by policymakers. The introduction of carbon pricing mechanisms is a much more recent phenomenon.

4.2 Hypotheses and Covariates

Some of the factors discussed in this paper, such as access to the international technological frontier in abatement technologies or information from policy adoption in foreign jurisdictions, are underpinned by specific diffusion channels and hence are "spatial" in nature. We construct variables that capture them by combining proxies for the technological frontier or policy adoption in foreign countries (x) with relevant spatial weight matrices (Γ). These "diffusion regressors" (Simmons and Elkins, 2004) are defined as follows:

$$\Lambda_{i,t}(\Gamma_{i,t}, x_t) \equiv \sum_{j \in \Theta_{i,t}} \gamma_{i,j,t} \times x_{j,t}$$

where i denotes the country and t the year; $\Theta_{i,t}$ is the set of all partner jurisdictions of jurisdiction i in year t; $\gamma_{i,j,t}$ is the partner-specific bilateral weight in year t; and $x_{j,t}$ is the partner-specific value of variable x in that same year. The elements of Γ vary according to the nature of the "distance"/channel between spatial units. We next present the empirical proxies associated with each of these mechanisms.

4.2.1 National Income, Free Riding and Leakage Risk

Our first hypothesis relates to the negative relationship between national income and equilibrium emissions.

Hypothesis 1. *An increase in real income raises the marginal damage of emissions and lowers equilibrium emissions level.*

Proof. Follows immediately from Proposition 1. ☐

We use GDP per capita (PPP, thousand constant 2011 USD), which captures the standard income effect and, assuming that environmental quality is a normal good, should have a positive influence of policy adoption.

Our next hypothesis relates to our argument that the effect of free riding on policy adoption is independent from trade relationships and that it is a function of policy stringency across the rest of the world.

Hypothesis 2 (a). *The introduction of (more stringent) climate change mitigation policies by the rest of the world reduces free riding and strengthens the domestic abatement equilibrium.*

Proof. Follows immediately from Proposition 2. □

We capture the risk of free riding by a measure of the mean policy at the global level: the share of global power sector emissions covered by the policy under study. The risk of free riding decreases as the global mean policy rises.[30]

Finally, we consider the trade-related carbon leakage, which, unlike free riding, is related to a country's trading relationships.

Hypothesis 2 (b). *The introduction of (more stringent) climate change mitigation policies by trading partners reduces the risk of carbon leakage and strengthens the domestic abatement equilibrium.*

Proof. Follows immediately from Proposition 2. □

Our proxy for the leakage *risk* is a weighted average of the policy stringency in import partner countries. Policy stringency is captured by an indicator recording the presence (absence) of policy, multiplied by the CO_2 intensity (CO_2/MWh) of the power sector.[31] The logic behind this proxy is that jurisdictions will be more sensitive to policies implemented by their larger (relative to total imports) and dirtier import partners. Leakage *risk* per se is inversely related to the policy stringency of import partners. Hence, a higher value denotes a lower leakage risk. Figure 3 present this metric for selected jurisdictions.

4.2.2 Abatement Technology Stock

Section 3.3 shows how the abatement equilibrium depends on the quality of the abatement technology. Therefore, how this technology is developed and accumulated by a jurisdic-

---

[30] Simmons and Elkins (2004) use the average of countries with the policy in the sample (mean global policy). They interpret this variable as the "global norm" and suggest that the probability of adoption increases as it increases; that is, as the global norm veers toward adoption of the policy, this puts increased pressure on countries that have yet to adopt it. We estimated models with such a variable in earlier versions of this work.

[31] Another way to measure leakage risk is to assess the policy stringency of countries with which a country competes in the same foreign markets (see Simmons and Elkins (2004)). In addition, potentially more accurate measures of policy stringency could be constructed based, for instance, on the observed level of carbon prices, feed-in rate, or renewable energy target. While a comprehensive dataset of carbon prices is available from Dolphin et al. (2020), this is not the case for feed-in rates or target renewables shares in electricity production. Botta and Kozluk (2014) collected such data for the development of an environmental policy stringency index, but those data are limited to OECD (and a few non-OECD) economies.

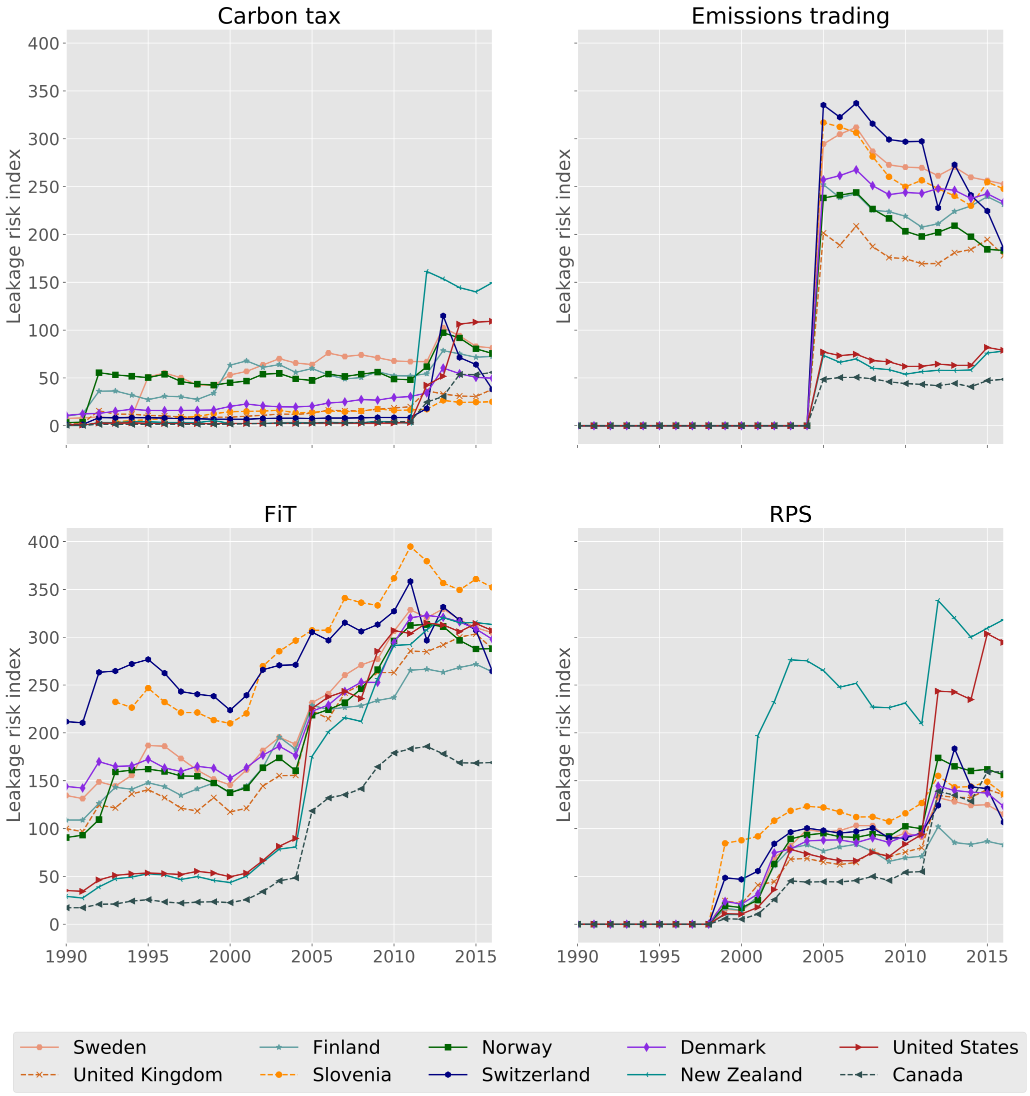

Figure 3. Leakage risk

tion plays a significant role in the evolution of its CO_2 emissions and policy activity. One possibility for such accumulation is the spillover of foreign technological development (i.e. foreign jurisdictions' abatement technology stock) on domestic abatement technology (Bloom et al., 2013; Dechezlepretre and Glachant, 2011). This accumulation of technology in foreign partners might enhance home productivity or prompt countries inside the technological frontier to imitate the products of frontier countries. For example, Lanjouw and Mody (1996) show that imported equipment was a major source of environmental technology for some countries, especially in East Asia. We denote these jurisdiction-specific spillovers as ψ, formally accounting for them by assuming an explicit dependence of domestic abatement technology: $\Omega(\psi)$, with $\psi > 0$ and $\frac{\partial\Omega(.)}{\partial\psi} < 0$. This leads to our third hypothesis.

Hypothesis 3. *Access to improved foreign abatement technology strengthens the domestic abatement equilibrium.*

Proof. Follows immediately from Proposition 3. □

The literature has mainly focused on bilateral transfers of technology across jurisdictions and has noted three main market channels: (i) international trade in intermediate goods (e.g., export and import of equipment);[32]; (ii) foreign direct investments (e.g., multinational corporations can bring home country clean production techniques to host countries); and (iii) licensing. We focus on the first channel and suggest that the strength of the technology spillover effect is linked to bilateral trade relationships (Grossman and Helpman, 1991). Thus the domestically available foreign abatement technology, $\Omega(\psi)$, depends on (i) foreign abatement technology stock and (ii) its transfer through international trade.[33]

Our primary focus is on technology *accessed* through imports, as in Lovely and Popp (2011).[34] Imports of intermediate goods embody foreign technology that is extracted by the recipient country and contributes to the domestic stock of abatement technology. To reflect this, we construct ψ as the import-share-weighted average of the technology stock of trade partners, as in Coe and Helpman (1995). Our main variable capturing the abatement technology stock available in a foreign partner is the discounted cumulative count since 1980 of patents for *climate change mitigation technologies related to energy*

---

[32] The standard technology diffusion channel associated with trade is that of diffusion through its embodiment in internationally traded goods. However, Grossman and Helpman (1991) have also argued that knowledge varies according to the number of contacts between domestic and foreign agents, which in turn are directly proportional to trade flows.

[33] This assumes that technology diffusion is not only a trade-related phenomenon but also local in nature. However it might be argued that what matters is a global technological pool (Fracasso and Vittucci Marzetti, 2015). We test a variable reflecting a global, trade-unrelated, diffusion process in Section 6. This latter variable is conceptually similar to that constructed by Lovely and Popp (2011).

[34] Export flows can also affect domestic technology (Falvey et al., 2004). Section 6 investigates and discusses that possibility.

generation, transmission, or distribution.[35] This approach builds on earlier literature suggesting the use of patent data as a proxy for the output of the innovation process (Griliches, 1990; Dechezlepretre et al., 2013). The patents used to construct the stock are those applied for at the European Patent Office. We sorted the patents by *priority date*, which is closest to the actual inventive activity, and assigned each individual patent is to the inventor's country of residence. Figure 4 shows the import-share-weighted foreign knowledge stock for selected OECD and non-OECD countries.

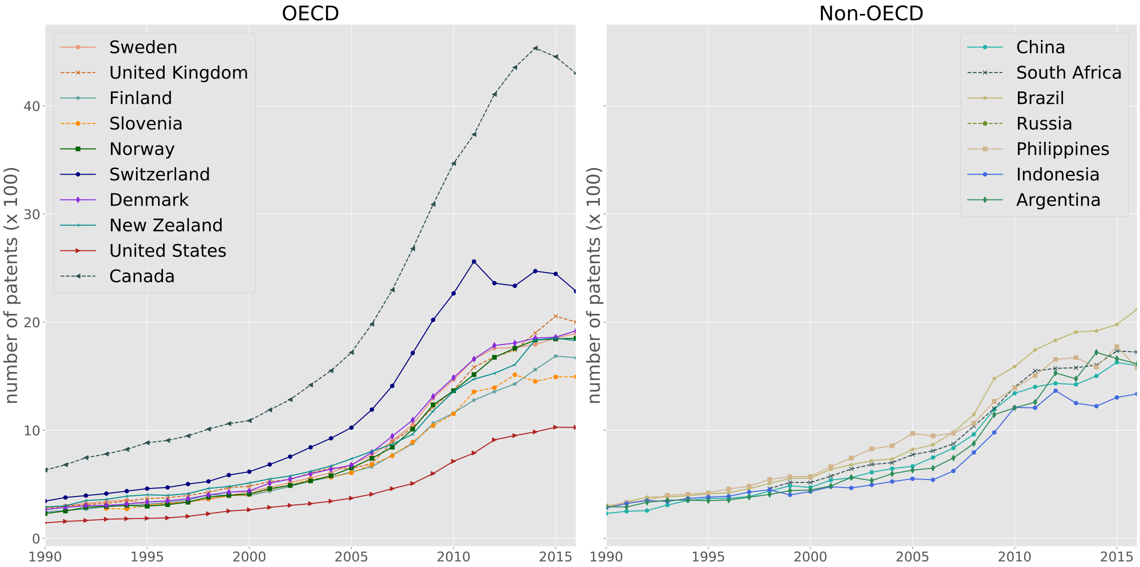

Figure 4. Foreign knowledge stock (import-weighted)

It is possible, however, that since the weights used add up to one, they do not adequately capture the effect of the *level* of imports (Coe and Helpman, 1995). Yet one might expect that two countries facing the same composition of imports are affected differently by a foreign partner's knowledge stock depending on how much it imports relative to its GDP. Hence we include in our empirical investigation the interaction between the potentially available foreign knowledge stock and the level of a country's openness to international trade, as measured by the share of imports in GDP (Coe and Helpman,

---

[35] Alternative knowledge stocks, based for instance on narrower patent categories can be constructed (see, e.g., https://stats.oecd.org/Index.aspx?DataSetCode=PAT_DEV). In Section 6, we also discuss results based on stocks constructed with data on installed wind and solar generation capacity. The stocks are calculated using a simplified version of the perpetual inventory method (OECD (Organisation for Economic Co-operation and Development), 2009). Assumptions are made to calculate initial values of net stocks. The discount rate used for the patents stock is 10 percent, which follows earlier literature (Lovely and Popp, 2011; Hall et al., 2005); that for installed renewable capacity is 4 percent.

1995; Lovely and Popp, 2011).

4.2.3 Information

In Section 3.4, we showed that the expected regulatory cost affects the equilibrium. The literature on policy diffusion typically assumes that countries can learn from successful policy implementation in other countries (rational Bayesian updating) or through specific communication networks; that is, as foreign policy experience (α_i) is accumulated and/or abatement technology is deployed (σ_i), the expected fixed regulatory cost decreases. Thus, we write $\Phi(\alpha_i, \sigma_i)$, with $\frac{\partial \Phi(\alpha_i,\sigma_i)}{\partial \alpha_i} < 0, \frac{\partial \Phi(\alpha_i,\sigma_i)}{\partial \sigma_i} < 0$, and present the following hypothesis.

Hypothesis 4. *Policy implementation by jurisdictions with common cultural traits or a shared communications network strengthens the domestic abatement equilibrium.*

Proof. Follows immediately from Proposition 4. □

We analyze the diffusion of this information through communication networks and across countries with common cultural traits (e.g. a shared religion or language) or institutional heritage (e.g., colonial). Information can be transmitted through private and official bilateral contacts (Simmons and Elkins, 2004). Total bilateral trade is our proxy for the intensity of private contacts, while membership in a preferential trading area (PTA) captures the intensity of official contacts. Figure 5 shows that even countries that did not implement carbon pricing or other climate change mitigation policies domestically are exposed to it (e.g., Canada and the United States). Transmission across countries with common cultural traits or institutional heritage is tested using dyadic weight matrices capturing shared religion, common official language, and common colonizer. These and the PTA dyadic matrix are taken from Head et al. (2010).

4.2.4 Control Mechanisms

In discussing the diffusion of policies across jurisdictions, it is important to control for domestic political and economic conditions that could influence a jurisdiction's adoption

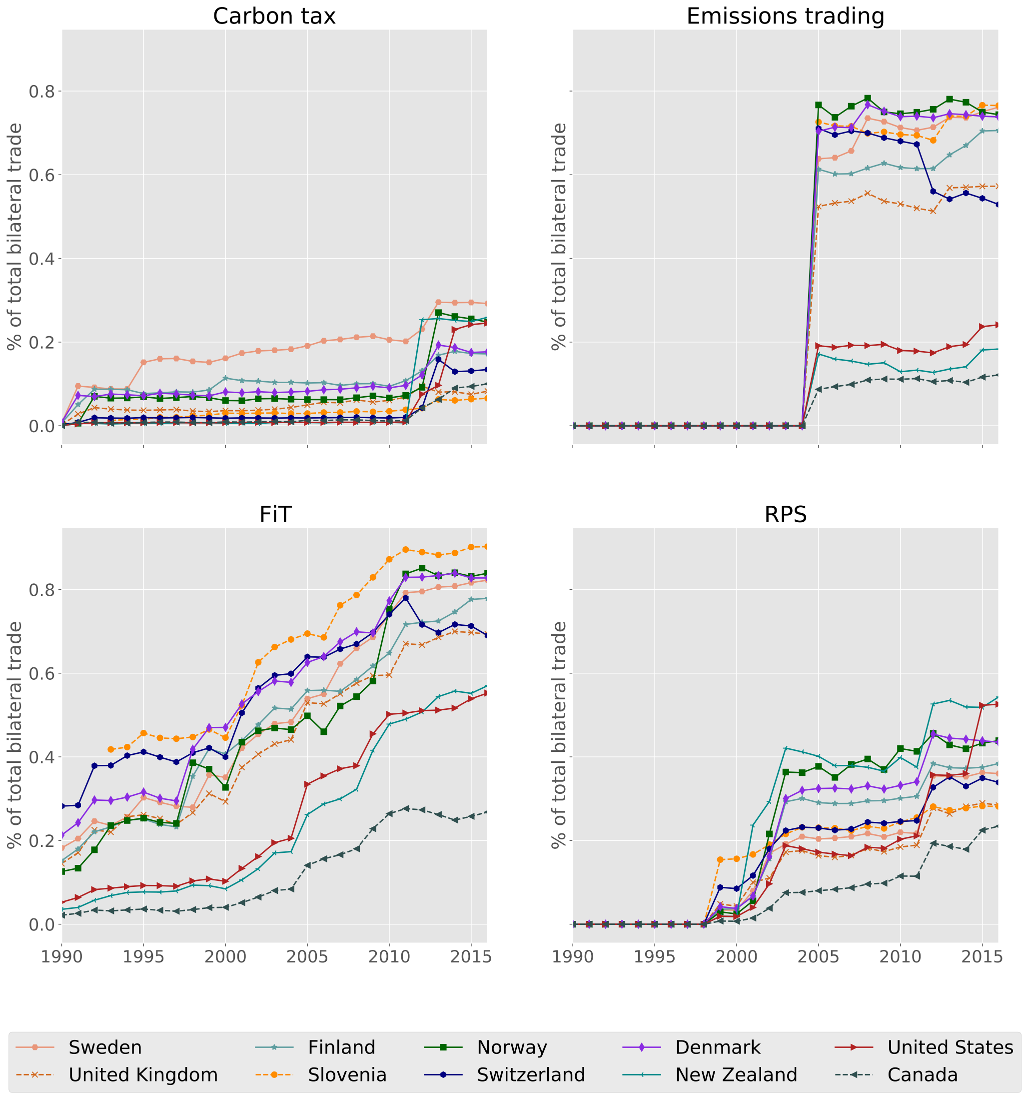

Figure 5. Private communications

of policies (Volden et al., 2008). This is because the observed adoption outcome(s) could also reflect the fact that similar jurisdictions respond similarly, yet independently, to the same issue. To control for these, an indicator of democracy and the share of electricity generated from fossil fuel sources are included in the estimated models. This last variable accounts for the fact that the impact on national income of a more stringent climate policy in the power sector will be larger if it is heavily reliant on CO_2-emitting technologies.

Table 1. Summary statistics

Statistic	N	Min.	Median	Max.	St. Dev.
Tax	3,182	0	0	1	0.200
ETS	3,182	0	0	1	0.316
FiT	3,182	0	0	1	0.433
RPS	3,182	0	0	1	0.248
Communication - private - Tax	3,182	0.000	0.011	0.310	0.049
Communication - private - ETS	3,182	0	0	1	0.238
Communication - private - FiT	3,182	0.008	0.343	0.913	0.253
Communication - private - RPS	3,182	0	0.1	1	0.158
Cultural sim. - language - Tax	3,182	0	0	2	0.367
Cultural sim. - religion - Tax	3,182	0	0.6	3	0.764
Cultural sim. - colon. - Tax	3,182	0	0	2	0.347
Communication - PTA - Tax	3,182	0	0	5	1.254
Cultural sim. - language - ETS	3,182	0	0	8	1.461
Cultural sim. - religion - ETS	3,182	0	0	15	4.302
Cultural sim. - colon. - ETS	3,182	0	0	4	0.859
Communication - PTA - ETS	3,182	0	0	24	3.711
Cultural sim. - language - FiT	3,182	0	1	19	3.434
Cultural sim. - religion - FiT	3,182	0.000	2.586	23.443	5.859
Cultural sim. - colon. - FiT	3,182	0	0	15	3.190
Communication - PTA - FiT	3,182	0	0	23	4.739
Cultural sim. - language - RPS	3,182	0	0	6	1.295
Cultural sim. - religion - RPS	3,182	0	0.2	8	1.977
Cultural sim. - colon. - RPS	3,182	0	0	2	0.441
Communication - PTA - RPS	3,182	0	0	7	1.286
Knowledge stock - local (imports)	3,182	0.222	5.192	45.340	6.474
Technology stock - local (imports)	3,182	0.713	1,726.457	55,790.460	6,615.558
Knowledge stock × imports	3,182	0.005	196.017	4,760.844	412.362
Technology stock × imports	3,182	0.459	65,288.310	5,226,810.000	386,361.700
Leakage - Tax	3,182	0.000	6.332	190.192	25.114
Leakage - ETS	3,182	0	0	381	88.161
Leakage - FiT	3,182	0.000	166.123	796.961	129.748
Leakage - RPS	3,182	0	52.5	662	83.149
Free riding - Tax	3,182	0	0.0	0	0.041
Free riding - ETS	3,182	0	0	0	0.050
Free riding - FiT	3,182	0.054	0.175	0.649	0.219
Free riding - RPS	3,182	0	0.1	1	0.186
% elec. from fossil fuels*	3,182	0.000	0.629	4.031	0.353
% elec. ff. × CO_2 intensity*	3,182	0.000	213.241	6,272.304	343.205
Import shares	3,182	0.016	37.225	221.010	26.892
GDP per capita (PPP, 2017 constant USD)*	3,182	469.136	11,928.720	115,415.400	19,236.520
Electoral democracy index*	3,182	0.017	0.591	0.924	0.272

Variables marked with * are scaled in the regressions so that a one-unit change represents a 10% deviation from the mean. This aids with interpretation and follows Lovely and Popp (2011)

5 Model Estimation

The approach taken in this paper follows the literature on policy and technology adoption, which typically investigates such questions using survival, or time-to-event, analysis.[36] Most modern approaches to survival analysis focus on the estimation of the hazard function, which determines the probability of occurrence of the event of interest in any period and based on which the probability of survival, the *survival function*, can be defined. In this approach, all units enter the sample in a somewhat arbitrarily determined year from which jurisdictions are at risk of adopting the policy and leave as soon as a failure (i.e., policy adoption) occurs.

The relationship between covariates and the probability of adoption can be specified in a number of ways. We adopt a popular specification of the hazard function that factors the hazard into a baseline hazard (which does not vary by country) and a factor whose value depends on country-specific, time-varying, covariates; that is, it implies a proportional relationship between the covariates and the baseline hazard function. A canonical presentation of the proportional hazard function to be estimated is:

$$h(t, \mathbf{X_t}, \boldsymbol{\beta}) = h_0(t) \exp\left(\mathbf{X_t'}\boldsymbol{\beta}\right), \tag{24}$$

where t denotes the year, $\boldsymbol{\beta}$ is the set of parameters to be estimated, and $\boldsymbol{X_t}$ is the set of country-specific covariates.

Estimating the hazard function requires specifying the baseline hazard. We do not have theoretical priors guiding the choice of the baseline hazard function and hence report the results under three different assumptions for its functional form: Cox, exponential, and Weibull. As noted by Lovely and Popp (2011), the exponential distribution assumes that the baseline hazard is constant over time, whereas the other two distributions assume a dependence on time. We report the estimation results of each of these models for each of the four policies. We use robust standard errors in all the models to control for the possibility that observations within a country are not independent (clustering) (Murillo

---

[36] See Simmons and Elkins (2004) and Lovely and Popp (2011) for analyses of policy adoption. See also references in Lovely and Popp (2011) for studies on technology adoption.

and Martinez-Gallardo, 2007).

Our sample starts in 1990, the year during which the first country-level carbon pricing mechanism (Finland) and the second feed-in tariff scheme (Germany) were introduced, and ends in 2016, the last year for which patent data are available. More generally, the early 1990s correspond to a period of increased international climate policy activity (the UNFCCC was signed in 1992), which is likely to have prompted domestic action. In addition, as in Lovely and Popp (2011) and Murillo and Martinez-Gallardo (2007), a country drops out of the sample after adoption, effectively leaving us with a different total number of observations for each policy analyzed. Among these observations, several of our units of observation are right-censored, as the policy had not been adopted by the end of our observation period.

5.1 Results

Estimations of our main models (Table 2) are based on the full sample of countries. Our comments are based primarily on the results of the Cox and Weibull models. Only the exponential model is able to robustly estimate coefficients of variables with a trend, and which exhibit little cross-country variation, relative to variation over time. In other cases, the variable is collinear with the baseline hazard trend. Since this is the case for some of our variables (e.g., the average global policy and, to an extent, the local knowledge stock), we report results of this model as well.

Hypothesis 1: National income. The estimated coefficients suggest that higher income per capita raises the probability of adoption of RPS, ETS, and carbon taxes but lowers that of FiT. The effects are small, however, and only precisely estimated in the case of an ETS. In that case, a 10 percent increase in income per capita would raise the likelihood of adoption by 5 percent.[37] Yet this result is likely driven primarily by EU-ETS countries.

The context of adoption of these policies, which we described in the introduction, helps

---

[37] Based on the estimated coefficient in the Cox model: $\exp(0.051) = 1.052$.

in understanding these results. As Figure 1 showed, for countries that have adopted these policies, the GDP per capita *at the time of adoption* varies significantly. More specifically, in the case of FiT, the GDP per capita of countries adopting feed-in tariffs seems to decrease over time. This suggests that national income per capita might not be the main determinant of policy adoption, at least in the case of FiT. This is in contrast to the result reported by Lovely and Popp (2011) for coal plant regulations but is in line with the analysis by Alizada (2018), who looks specifically at adoption of FiT and RPS.

It is worth noting, however, that there is a key difference between carbon pricing mechanisms and the other two policies: the former seem to have been thus far introduced in high income countries (as per 2019 World Bank categories) whereas the latter have been adopted in countries with relatively lower income. The implementation of carbon pricing mechanisms is complicated by the fact that they make the cost of emissions explicit to emitters, so their enactment is more difficult from a political economy standpoint.

Hypothesis 2: Free riding and leakage. We argued in Section 3 that reduced free riding and risk of carbon leakage could raise the probability of policy adoption. Reduced risk of free riding due to policy adoption by other countries does not appear to play a significant role in policy adoption so far. Our model estimates do not identify any discernible effect, and one that consistent across policies. These inconclusive results are in line with those of Simmons and Elkins (2004) on the diffusion of liberal economic policies.

The evidence regarding the role of leakage risk is mixed. Estimates are consistent with our theoretical prediction in the case of ETS. An increase in the import-weighted stringency of climate policy (i.e., a reduction in the leakage risk), is positively related to the probability of adoption. All else equal, a 1 percentage point increase in the share of imports covered by an emissions trading system would raise domestic adoption probability by 1 percent. Estimates show a negligible effect for other policies. For FiT and RPS, this may be unsurprising, as the former is a direct subsidy to the deployment of renewable generation capacity and the latter imposes only an indirect cost to industrial consumers of electricity.

Hypothesis 3: Knowledge stock. We next turn to the role of the knowledge stock. Results from the Cox and Weibull models suggest that, overall, the *local*, import-weighted, knowledge stock raises the probability of adoption of both RPS and carbon taxes. In particular, a 100-unit increase in the import-weighted patent stock raises the probability of adoption by 30 percent in the case of RPS or 34 percent in the case of carbon taxes. For both policies, the effect is consistent across all three estimated models. The estimated effect for FiT and ETS is inconsistent across models, and an order of magnitude smaller (1–2 percent) in the case of FiT. The former might be explained by the fact that by 2005, when the EU introduced its emission trading system, the stock of patents relating to GHG-free technologies in the power sector had not grown significantly, and that a limited number of countries introduced ETS independently from the EU ETS between then and the end of our sample (2016). Moreover, these trading systems were introduced in both innovating and non-innovating countries, with respect to GHG-abating technologies. For the former, this would suggest that the adoption of ETS preceded rather than followed technological innovation. For the latter, it suggests that other factors played a more determinant role in policy adoption. One possible explanation is that feed-in tariffs were introduced precisely to support the deployment of renewable energy technologies, at least in innovating countries. The technological stock might have influenced adoption of FiT in noninnovating countries. (Section 6.1.1 investigates effects specific to noninnovating countries.) Interestingly, the results also indicate that, compared with the base level of technology, an increase in the import share of a country reduces the probability of adoption. This effect is small, however: a 1 percentage point increase reduces the likelihood of adoption by 0.6 percent.

Hypothesis 4: Information. Information drawn from culturally similar peers does not seem to be a strong driver of policy adoption. Two measures of cultural similarity, common language and common religion, relate negatively to the probability of policy adoption across all four policies. We take this to suggest that these policies have been introduced in a culturally diverse group of countries. One notable exception to this narrative is for FiT, which seem to have diffused more rapidly within groups of countries with common *legacy* institutions, as captured by the policies of countries with which they share a common colonizer. Adoption by one more country with whom a jurisdiction shares such legacy raises the probability of adoption by about 4–14 percent.

We find no robust evidence that structured communication networks play a consistent role in the adoption of climate policy. Results suggest that official channels of communication (as proxied by PTA membership) have a positive impact on adoption of FiT, RPS, and ETS and a negative impact on the adoption of carbon taxes. However, only in the case of ETS is the associated coefficient estimated with reasonable confidence. This result is very likely driven by the countries participating in the EU ETS, which are economically and institutionally integrated.

Finally, our estimation results suggest a strong and statistically robust positive impact of the strength of the electoral democracy on the probability of adoption of all policies analyzed here. In other words, countries in which electoral democracy is sustained tend to have introduced the policies earlier. We also note that the share of electricity from fossil fuels is positively related to adoption—a 10% increase in that share raises the probability of adoption by 3–10%—but this effect is imprecisely estimated.

Table 2. Estimation results

	Cox				Weibull							
	Cox prop. hazards				*parametric prop. hazards*							
	FiT	RPS	ETS	Tax	FiT	RPS	ETS	Tax	FiT	RPS	ETS	Tax
Free riding									0.174	0.670	21.647	2.654
									(1.488)	(2.522)	(17.350)	(10.404)
Leakage	−0.001	−0.000	0.008***	−0.007	−0.002	−0.001	0.018***	−0.006	−0.000	−0.000	0.009*	−0.007
	(0.002)	(0.007)	(0.005)	(0.027)	(0.002)	(0.007)	(0.005)	(0.029)	(0.002)	(0.006)	(0.005)	(0.029)
Cultural sim. - colon.	0.133**	−0.620	0.143	0.936	0.042	−0.835	0.017	0.747	0.100**	−0.560	0.250	0.810
	(0.054)	(0.881)	(0.279)	(1.131)	(0.047)	(0.852)	(0.277)	(1.115)	(0.046)	(0.816)	(0.279)	(1.122)
Cultural sim. - com. lang	−0.124**	−0.254	−0.246**	−0.826	−0.171***	−0.325*	−0.363**	−0.532	−0.128**	−0.195	−0.251*	−0.580
	(0.055)	(0.189)	(0.140)	(0.960)	(0.055)	(0.190)	(0.151)	(0.868)	(0.052)	(0.192)	(0.140)	(0.876)
Cultural sim - religion	−0.044	−0.254*	0.002	−1.887***	−0.069*	−0.215	0.037	−1.314**	−0.032	−0.196	0.009	−1.374**
	(0.037)	(0.153)	(0.051)	(0.728)	(0.036)	(0.150)	(0.053)	(0.560)	(0.036)	(0.151)	(0.051)	(0.570)
Communication - official	0.028	0.041	0.059***	−0.246	0.023	0.206	0.153***	−0.093	0.009	0.069	0.020	−0.124
	(0.029)	(0.185)	(0.055)	(0.383)	(0.020)	(0.129)	(0.037)	(0.272)	(0.024)	(0.136)	(0.025)	(0.281)
Communication - private	1.798	−2.833	1.663	10.730	−0.706	−10.446**	2.260	5.510	1.672	0.345	2.167	5.847
	(1.249)	(3.785)	(2.234)	(14.285)	(1.165)	(4.214)	(2.311)	(15.015)	(1.189)	(3.130)	(2.284)	(16.082)
Local knowledge stock (KS)	0.016	0.260***	−0.040	0.313***	−0.086**	0.214***	−0.302***	0.201**	−0.002	0.224***	0.018	0.218**
	(0.047)	(0.084)	(0.091)	(0.122)	(0.043)	(0.078)	(0.103)	(0.100)	(0.043)	(0.076)	(0.071)	(0.103)
Local KS × import share	−0.000	−0.006***	0.000	−0.005**	−0.000	−0.008***	0.001	−0.004*	−0.000	−0.005***	−0.000	−0.004*
	(0.001)	(0.002)	(0.001)	(0.003)	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.002)
% elec. from fossil fuel	0.026	0.037	0.043**	0.058	0.041*	0.018	0.074**	0.074	0.032	0.041	0.054	0.072
	(0.023)	(0.049)	(0.037)	(0.053)	(0.023)	(0.050)	(0.037)	(0.076)	(0.021)	(0.041)	(0.034)	(0.071)
GDP per capita	−0.011	0.020	0.051***	0.028	−0.005	0.042*	0.097***	0.010	−0.009	0.018	0.041**	0.013
	(0.014)	(0.025)	(0.022)	(0.047)	(0.014)	(0.025)	(0.024)	(0.050)	(0.014)	(0.024)	(0.020)	(0.051)
Electoral dem. index	0.200***	0.186***	0.260**	0.478***	0.250***	0.215***	0.448***	0.505**	0.201***	0.167***	0.274***	0.503***
	(0.038)	(0.064)	(0.103)	(0.161)	(0.040)	(0.065)	(0.144)	(0.197)	(0.038)	(0.062)	(0.103)	(0.193)
Constant					3.171***	3.144***	3.488***	7.052***	6.795***	8.102***	12.413***	10.330***
					(0.105)	(0.114)	(0.074)	(1.488)	(0.333)	(0.514)	(1.857)	(1.305)
log(shape)					1.583***	2.064***	2.933***	0.553*				
					(0.099)	(0.149)	(0.129)	(0.289)				
Observations	2,453	2,994	2,857	3,059	2,453	2,994	2,857	3,059	2,453	2,994	2,857	3,059
R^2	0.022	0.010	0.034	0.010								
Max. possible R^2	0.212	0.064	0.107	0.030								
Log-likelihood	−265.833	−84.285	−112.684	−32.060	−371.945	−130.126	−82.421	−77.509	−440.150	−167.554	−166.067	−78.975
Wald test (df = 11)	60.080***	30.740***	279.550***	34.560***								
LR test (df = 11)	53.742***	31.022***	98.888***	30.141***								
Score (Logrank) test (df = 11)	51.958***	22.141**	100.037***	23.617**								
Note:	$^{***}p < 0.01,^{**} p < 0.05,^{*} p < 0.1$											

6 Discussion and Robustness Checks

To check the robustness of our main results, we estimate a number of additional models. First, we test whether our main diffusion mechanisms are present for (i) noninnovating countries; and (ii) for policy aggregates (i.e., when carbon pricing policies and FiT + RPS are considered as part of the same group of policies). Second, we investigate the role of potential alternative diffusion mechanisms.

6.1 Robustness of Diffusion Channels

6.1.1 Noninnovating Countries

We mentioned in Section 5.1 that the dynamics of policy adoption for large innovators may differ from those of noninnovating countries. One reason for this is that early adopters of a given policy are often also innovators in the technologies most immediately targeted by it, and policy adoption might have preceded technological development. To shed light on this theoretical possibility, we investigate whether excluding innovating countries from the sample changes the estimation results with respect to the effect of knowledge stock on policy adoption. In particular, we estimate models excluding the innovators belonging to the highest decile of countries' cumulative discounted domestic patent stock in 2016, which includes, in order, the United States, Germany, Japan, France, Korea, Denmark, UK, Italy, Switzerland, and the Netherlands. The results are shown in Table 3.

The effect of the local knowledge stock on the adoption of climate policies in the pool of noninnovating countries is in line with that uncovered by models estimated on the full sample of countries. It is negatively related to the probability of adoption of FiT and ETS but positively related to the adoption of RPS (and tax, but the estimate is less precise in this case). This is consistent with the fact that FiTs have been introduced, early on in the sample, as technology policies aiming to accelerate the development and deployment of renewable electricity generation technologies, whereas RPS were introduced much later, once a more advanced technological base had been developed. Turning to cultural similarity, results are consistent with those obtained when estimating the models using the

Table 3. Noninnovating countries

	Cox prop. hazards			
	FiT	RPS	ETS	Tax
Leakage	−0.003	−0.002	0.015***	−0.012
	(0.002)	(0.007)	(0.003)	(0.040)
Cultural sim. - colon.	0.013	−1.028	0.118	1.159**
	(0.050)	(0.863)	(0.226)	(1.084)
Cultural sim. - com. lang	−0.182**	−0.120	−0.271***	−17.645***
	(0.064)	(0.192)	(0.146)	(9,350.155)
Cultural sim - religion	−0.072	−0.119	0.018	−1.105
	(0.039)	(0.142)	(0.045)	(0.712)
Communication - official	0.064***	0.185*	0.094***	−0.043
	(0.024)	(0.160)	(0.042)	(0.331)
Communication - private	−1.439	−7.644	0.612	−1.333
	(1.269)	(4.055)	(1.475)	(20.777)
Local knowledge stock (KS)	−0.128**	0.159**	−0.162***	0.177
	(0.049)	(0.075)	(0.078)	(0.107)
Local KS × import share	−0.000	−0.007***	0.000	−0.004*
	(0.001)	(0.002)	(0.001)	(0.003)
% elec. from fossil fuel	0.054**	0.033	0.057**	0.017
	(0.024)	(0.053)	(0.034)	(0.093)
GDP per capita	−0.001	0.058**	0.076***	0.027
	(0.016)	(0.029)	(0.017)	(0.058)
Electoral dem. index	0.261***	0.181**	0.367***	0.430***
	(0.042)	(0.064)	(0.103)	(0.167)
Observations	2,341	2,796	2,684	2,848
R^2	0.052	0.015	0.066	0.007
Max. possible R^2	0.275	0.082	0.128	0.034
Log-likelihood	−313.447	−98.840	−92.926	−39.104
Wald test (df = 11)	147.080***	33.600***	939.850***	1,273.870***
LR test (df = 11)	125.516***	42.710***	183.086***	20.987**
Score (Logrank) test (df = 11)	122.230***	33.207***	501.620***	17.133
Note:	$^{***}p < 0.01, ^{**}p < 0.05, ^{*}p < 0.1$			

full sample. There is one notable difference with results previously obtained with regard to the role of communication channels: a larger estimated (positive) effect on domestic adoption of policy adoption by countries with which a jurisdiction has a PTA (official communication channel).

6.1.2 Policy Aggregates

When seeking to abate power sector emissions, jurisdictions may decide to resort to some, but not all, of the policy instruments analyzed here. In particular, it is possible that they may use *either* of a carbon tax or emissions trading, and *either* of feed-in tariffs or renewable portfolio standards. In other words, these policies may substitute for one another. Therefore, we estimate the models in Table 1 for two aggregated groups of policies: carbon pricing (tax and emissions trading) and technology policies (FiT and RPS).[38]

---

[38] The construction of outcome and diffusion variables follows the same approach as for disaggregated policies: policy indicator variables take the value of 1 when either carbon tax or emissions trading (FiT or RPS) is implemented.

Table 4. Policy aggregates

	Cox		Weibull			
	Cox prop. hazards		*parametric prop. hazards*			
	FiT or RPS	Any pricing	FiT or RPS	Any pricing	FiT or RPS	Any pricing
Free riding					0.319	4.649
					(1.342)	(5.724)
Leakage	0.000	0.007^{*}	0.000	0.010^{*}	0.000	0.009^{*}
	(0.002)	(0.005)	(0.002)	(0.005)	(0.002)	(0.005)
Cultural sim. - colon.	0.119^{**}	0.247	0.019	0.135	0.080^{*}	0.231
	(0.054)	(0.226)	(0.044)	(0.216)	(0.044)	(0.219)
Cultural sim. - com. lang	-0.148^{***}	-0.347^{***}	-0.190^{***}	-0.445^{***}	-0.143^{***}	-0.364^{***}
	(0.050)	(0.129)	(0.048)	(0.122)	(0.047)	(0.124)
Cultural sim - religion	−0.037	−0.035	-0.064^{*}	−0.027	−0.030	−0.028
	(0.034)	(0.048)	(0.033)	(0.046)	(0.033)	(0.047)
Communication - official	0.029	0.033	0.037^{**}	0.062^{**}	0.018	0.027
	(0.024)	(0.047)	(0.017)	(0.025)	(0.019)	(0.023)
Communication - private	1.055	1.341	-2.228^{**}	−0.338	1.240	1.243
	(1.231)	(2.381)	(1.065)	(2.201)	(1.145)	(2.304)
Local knowledge stock (KS)	0.053	0.060	−0.058	−0.059	0.030	0.050
	(0.044)	(0.069)	(0.043)	(0.063)	(0.039)	(0.066)
Local KS × import share	−0.001	−0.001	−0.000	0.000	−0.000	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
% elec. from fossil fuel	0.036	0.031	0.057^{***}	0.042	0.040^{**}	0.043
	(0.023)	(0.027)	(0.021)	(0.033)	(0.020)	(0.027)
GDP per capita	−0.009	0.056^{***}	0.004	0.064^{***}	−0.008	0.053^{***}
	(0.013)	(0.019)	(0.013)	(0.019)	(0.013)	(0.019)
Electoral dem. index	0.217^{***}	0.351^{***}	0.286^{***}	0.452^{***}	0.216^{***}	0.381^{***}
	(0.038)	(0.087)	(0.041)	(0.099)	(0.038)	(0.092)
Constant			3.041^{***}	4.021^{***}	6.933^{***}	10.403^{***}
			(0.099)	(0.216)	(0.348)	(0.792)
log(shape)			1.673^{***}	1.754^{***}		
			(0.096)	(0.139)		
Observations	2,388	2,789	2,388	2,789	2,388	2,789
R^2	0.028	0.038				
Max. possible R^2	0.228	0.120				
Log-likelihood	−275.689	−124.280	−376.718	−168.798	−454.474	−209.958
Wald test (df = 11)	82.450^{***}	185.950^{***}				
LR test (df = 11)	67.071^{***}	108.573^{***}				
Score (Logrank) test (df = 11)	66.053^{***}	105.099^{***}				

Note: $^{***}p < 0.01,^{**} p < 0.05,^{*} p < 0.1$

6.2 Alternative Diffusion Channels

6.2.1 Global, Local or Domestic Knowledge

Because it is weighted by the bilateral share of imports, the knowledge stock proxy used in our main models assumes that the foreign knowledge pool from which countries derive spillovers is *local* in nature. Yet this is far from certain (Fracasso and Vittucci Marzetti, 2015), and countries could derive knowledge from a global knowledge stock. This is the assumption in Lovely and Popp (2011). We test whether a global rather than local knowledge stock affects policy adoption by constructing country-specific global knowledge stocks. The country-specific global stock subtracts the domestic stock of patents from the global stock. Results are indicative of some positive effect of the global knowledge stock across all policies except carbon taxes. This effect is in the range of 1 percent (ETS) to 7 percent (RPS) for every 100-unit increase in the global knowledge stock. It is, however, imprecisely estimated. Finally, the identified effects do not seem to be driven by the domestic knowledge stock.

6.2.2 Knowledge Stock versus Technology Deployment

An open question is whether it is technology development or deployment that triggers policy adoption. While patents measure the inventive activity and denote the potential availability of a technology, installed capacity more closely reflects its commercial availability. Unlike patents, installed capacity has the advantage of measuring directly the deployment (and availability) of two electricity generation technologies that have allowed the power sector to significantly reduce CO_2 emissions, especially over the last decade. Increased cumulative installed capacity also has implications for technology learning.[39] Technology deployment is captured by the total global wind and solar electricity generation net installed capacity. There is no discernible and consistent effect of global technology deployment on policy adoption.

6.2.3 Technology Access within Integrated Markets

The first relates to technology access within a set of integrated markets such as that of the European Union. The EU's single market provides a high degree of economic integration between member countries and significantly reduces the cost of cross-border trade. This might influence the ease with which countries are able to access abatement technology developed within it. To test the effect of the EU's single market, we use the discounted sum count of patents across partners belonging to the same market. To this end, we construct dyadic matrix recording affiliation to the same market (the EU) for each pair of countries in the sample in any given year between 1990 and 2016. The impact of the EU specific knowledge stock is negligible in the case of all policies except ETS. In that case, a 100-unit increase in the discounted patent stock raises the probability of adoption by about 6.5 percent.

---

[39] Additional installed capacity increases the stock of technology from which other jurisdictions can learn and contributes to the reduction of the (unit) cost of the technology through learning-by-doing (Arrow, 1962). In the case of solar photovoltaics, for example, IRENA (International Renewable Energy Agency) (2012) finds that costs decline by 22 percent for every doubling of capacity. Both of these effects improve access to abatement technology.

6.2.4 Disembodied Knowledge

The main channel of technology diffusion discussed so far is that of technology access through imports. However, the literature notes that export flows can also affect domestic technology (Falvey et al., 2004). Exports emphasize learning-by-doing and the "pure idea exchange and knowledge spillovers gained from formal and informal contacts" (Funk, 2001), which can encourage more efficient employment of resources or stimulate new indigenous technologies.[40] The impact of disembodied knowledge (i.e. pure exchange of ideas) on policy adoption is imprecisely estimated. It is negligible in the case of FiT, positive (negative) but imprecisely estimated in the case of RPS (ETS). It is, however, positive and relatively large in the case of carbon taxes: a 100-unit increase in the export-weighted discounted patent stock raises the probability of adoption by 34 percent. Yet this needs to be interpreted with caution, given the low number of adopters of carbon taxes in the sample.

6.2.5 Peer Pressure

Fankhauser et al. (2016) suggest that peer pressure or suasion can play a role in the international diffusion of policy (stringency). Frankel and Rose (2005) note that one may observe the international ratcheting of environmental standards: when a "significant" jurisdiction introduces more stringent environmental standards, others might follow suit. The legal literature on environmental policy refers to this as the "California effect" (see, e.g., Vogel (1995); Perkins and Neumayer (2012)). There is evidence, if only anecdotal, that several jurisdictions (e.g. Norway, the European Union) are making relatively stringent emissions reduction commitments at home and are actively encouraging other jurisdictions to take steps toward climate change mitigation.

Several channels of suasion exist. We choose to analyze the effect of former colonial relationships, which lasted until after 1945. We construct, for each country, a count of pol-

---

[40] There is also the theoretical possibility that competition in international markets might drive domestic exporters to acquire and adapt foreign technologies. Evidence of a "trading-up" effect, i.e., the fact that greater exports to jurisdictions with more stringent (environmental) regulations leads to a strengthening of domestic regulations, has been provided by Perkins and Neumayer (2012) for the automotive industry.

icy adoption by their respective former colonial powers using a dyadic matrix of bilateral colonial relationships.[41] Those colonial powers may still have significant economic and institutional ties with their former colonies, which might provide them with some leverage on policy choices of the latter. This effect is tested for FiT, RPS, and ETS, but not for carbon taxes as there is too little variation in the variable to provide robust estimates in this case. Estimated coefficients suggest a positive relationship between policy adoption by a former colonial power and the probability of adoption by its former colonies; with the effect strongest in the case of RPS. However, the estimated effect cannot be robustly differentiated from zero.

---

[41] Another possibility to exert pressure on partners, especially developing and emerging economies, is through official development assistance (ODA). To gauge whether bilateral development assistance is used to prompt recipient jurisdictions to introduce climate change mitigation legislation, we constructed a proxy for partner jurisdictions' policy stringency where the bilateral weights are the bilateral shares of ODA between recipient and donor countries. However, models for the group of countries that are net recipients of ODA were not robustly estimated and are therefore not reported.

Table 5. Alternative channels: FiT and RPS

	Cox prop. hazards											
	SM	DK	Glob.	Tech. dep.	Colonizer	Dom.	SM	DK	Glob.	Tech. dep.	Colonizer	Dom.
Leakage	−0.001	−0.001	0.001	−0.001	−0.001	0.001	−0.001	−0.000	−0.007	−0.000	−0.001	−0.007
	(0.002)	(0.002)	(0.004)	(0.002)	(0.002)	(0.004)	(0.008)	(0.007)	(0.009)	(0.007)	(0.007)	(0.009)
Cultural sim. - colon.	0.137^{**}	0.133^{**}	0.209^{***}	0.125^{**}	0.133^{**}	0.209^{***}	−0.605	−0.597	−0.700	−0.998	−0.953	−0.700
	(0.055)	(0.054)	(0.076)	(0.055)	(0.054)	(0.076)	(0.886)	(0.873)	(0.940)	(0.937)	(0.981)	(0.940)
Cultural sim. - language	-0.119^{**}	-0.125^{**}	-0.162^{***}	-0.118^{**}	-0.125^{**}	-0.162^{***}	−0.291	−0.275	−0.025	−0.115	-0.311^{*}	−0.025
	(0.055)	(0.056)	(0.064)	(0.056)	(0.056)	(0.064)	(0.191)	(0.190)	(0.217)	(0.199)	(0.204)	(0.217)
Cultural sim. - relig.	−0.043	−0.044	−0.037	−0.046	−0.043	−0.037	-0.258^{*}	−0.245	−0.134	−0.214	-0.256^{*}	−0.134
	(0.037)	(0.037)	(0.042)	(0.038)	(0.039)	(0.042)	(0.157)	(0.152)	(0.155)	(0.166)	(0.155)	(0.155)
Communication - official	0.028	0.029	0.017	0.028	0.028	0.017	0.049	0.039	−0.012	0.035	0.075	−0.012
	(0.029)	(0.029)	(0.031)	(0.028)	(0.029)	(0.031)	(0.184)	(0.185)	(0.189)	(0.184)	(0.190)	(0.189)
Communication - private	1.541	1.767	0.958	1.703	1.793	0.958	−2.887	−2.819	−4.627	−4.467	−2.508	−4.627
	(1.298)	(1.296)	(1.831)	(1.249)	(1.252)	(1.831)	(3.726)	(3.818)	(4.667)	(3.868)	(3.754)	(4.667)
Local knowledge stock (KS)	0.019	0.019	−0.055	0.015	0.016	−0.055	0.241^{***}	0.209^{**}	0.265^{***}	0.247^{***}	0.271^{***}	0.265^{***}
	(0.047)	(0.055)	(0.061)	(0.047)	(0.047)	(0.061)	(0.085)	(0.102)	(0.097)	(0.084)	(0.086)	(0.097)
Local KS × import share	−0.000	−0.000	−0.001	−0.000	−0.000	−0.001	-0.006^{***}	-0.006^{***}	-0.008^{***}	-0.007^{***}	-0.006^{***}	-0.008^{***}
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Knowledge stock EU	0.005						−0.007					
	(0.006)						(0.008)					
Disembodied knowledge		−0.003						0.040				
		(0.031)						(0.049)				
Global foreign KS			0.016						0.054			
			(0.029)						(0.049)			
Global renewables cap.				0.071						0.339		
				(0.123)						(0.282)		
Peer pressure - colonizer					0.011						0.712	
					(0.156)						(0.862)	
Domestic KS						−0.016						−0.054
						(0.029)						(0.049)
% elec. from fossil fuel	0.024	0.027	0.039	0.028	0.026	0.039	0.045	0.038	0.087^{*}	0.055	0.032	0.087^{*}
	(0.024)	(0.024)	(0.028)	(0.023)	(0.024)	(0.028)	(0.049)	(0.049)	(0.057)	(0.048)	(0.049)	(0.057)
GDP per capita	−0.014	−0.012	−0.019	−0.008	−0.012	−0.019	0.025	0.023	0.039^{*}	0.045^{*}	0.016	0.039^{*}
	(0.015)	(0.014)	(0.017)	(0.015)	(0.014)	(0.017)	(0.025)	(0.025)	(0.029)	(0.026)	(0.025)	(0.029)
Electoral dem. index	0.196^{***}	0.201^{***}	0.216^{***}	0.202^{***}	0.201^{***}	0.216^{***}	0.209^{***}	0.188^{***}	0.167^{**}	0.210^{***}	0.190^{***}	0.167^{**}
	(0.038)	(0.038)	(0.049)	(0.038)	(0.038)	(0.049)	(0.070)	(0.065)	(0.069)	(0.066)	(0.064)	(0.069)
Observations	2,453	2,453	1,509	2,453	2,453	1,509	2,994	2,994	1,991	2,994	2,994	1,991
R^2	0.022	0.022	0.030	0.022	0.022	0.030	0.011	0.011	0.013	0.012	0.011	0.013
Max. possible R^2	0.212	0.212	0.256	0.212	0.212	0.256	0.064	0.064	0.079	0.064	0.064	0.079
Log-likelihood	−265.502	−265.829	−200.291	−265.518	−265.831	−200.291	−83.871	−83.972	−68.798	−81.992	−83.968	−68.798
Wald test (df = 12)	60.140^{***}	60.010^{***}	41.030^{***}	60.050^{***}	61.020^{***}	41.030^{***}	37.470^{***}	37.860^{***}	19.250^{*}	36.160^{***}	32.650^{***}	19.250^{*}
LR test (df = 12)	54.405^{***}	53.750^{***}	45.892^{***}	54.373^{***}	53.746^{***}	45.892^{***}	31.850^{***}	31.648^{***}	26.748^{***}	35.607^{***}	31.656^{***}	26.748^{***}
Score (Logrank) test (df = 12)	54.327^{***}	52.075^{***}	39.161^{***}	52.358^{***}	51.973^{***}	39.161^{***}	23.216^{**}	22.892^{**}	15.161	24.631^{**}	22.518^{**}	15.161
Note:	$^{***}p < 0.01, ^{**}p < 0.05, ^{*}p < 0.1$											

Table 6. Alternative channels: ETS and Tax

	Cox prop. hazards									
	SM	DK	Glob.	Tech. Dep.	Dom.	SM	DK	Glob.	Tech. Dep.	Dom.
Leakage	0.003	0.008^{**}	0.007^{**}	0.008^{***}	0.007^{**}	−0.009	−0.013	−0.023	−0.009	−0.023
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.026)	(0.028)	(0.032)	(0.028)	(0.032)
Cultural sim. - colon.	0.126	0.118	0.090	0.135	0.090	0.850	0.993	0.988	0.982	0.988
	(0.281)	(0.281)	(0.292)	(0.282)	(0.292)	(1.018)	(1.183)	(1.107)	(1.141)	(1.107)
Cultural sim. - language	-0.201^{**}	-0.239^{**}	−0.127	-0.241^{**}	−0.127	−0.925	−1.043	−0.895	−0.967	−0.895
	(0.150)	(0.141)	(0.153)	(0.141)	(0.153)	(0.934)	(0.988)	(0.956)	(1.012)	(0.956)
Cultural sim. - relig.	0.008	0.001	0.011	0.004	0.011	-1.941^{***}	-1.774^{***}	-1.929^{***}	-2.036^{***}	-1.929^{***}
	(0.051)	(0.051)	(0.053)	(0.051)	(0.053)	(0.737)	(0.741)	(0.749)	(0.791)	(0.749)
Communication - official	0.076^{***}	0.060^{***}	0.063^{***}	0.061^{***}	0.063^{***}	−0.230	−0.273	−0.267	−0.243	−0.267
	(0.066)	(0.055)	(0.061)	(0.055)	(0.061)	(0.384)	(0.389)	(0.389)	(0.385)	(0.389)
Communication - private	2.706	1.858	2.538	1.548	2.538	11.317	13.830	20.227	12.063	20.227
	(2.399)	(2.253)	(2.377)	(2.266)	(2.377)	(13.844)	(14.282)	(16.363)	(14.731)	(16.363)
Local knowledge stock (KS)	−0.036	0.009	−0.104	−0.046	−0.104	0.256^{**}	0.171	0.304^{**}	0.321^{***}	0.304^{**}
	(0.090)	(0.117)	(0.122)	(0.095)	(0.122)	(0.125)	(0.188)	(0.121)	(0.125)	(0.121)
Local KS × import share	−0.000	0.000	−0.000	0.000	−0.000	-0.004^{*}	-0.004^{**}	-0.004^{**}	-0.005^{**}	-0.004^{**}
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Patent stock EU	0.060^{***}					−0.009				
	(0.020)					(0.010)				
Disembodied KS		-0.060^{*}					0.096			
		(0.092)					(0.100)			
Global foreign KS			0.014					-0.038^{*}		
			(0.035)					(0.032)		
Global renewables cap.				0.010					−0.037	
				(0.039)					(0.053)	
Domestic KS					−0.014					0.038^{*}
					(0.035)					(0.032)
% elec. from fossil fuel	−0.023	0.045^{**}	0.036^{*}	0.044^{**}	0.036^{*}	0.049	0.055	0.068	0.060	0.068
	(0.041)	(0.037)	(0.038)	(0.037)	(0.038)	(0.054)	(0.054)	(0.055)	(0.055)	(0.055)
GDP per capita	0.058^{***}	0.049^{***}	0.045^{***}	0.052^{***}	0.045^{***}	0.036	0.023	0.003	0.021	0.003
	(0.025)	(0.022)	(0.026)	(0.022)	(0.026)	(0.047)	(0.052)	(0.058)	(0.049)	(0.058)
Electoral dem. index	0.212^{**}	0.264^{***}	0.209	0.267^{**}	0.209	0.533^{***}	0.517^{*}	0.421^{**}	0.480^{***}	0.421^{**}
	(0.107)	(0.104)	(0.118)	(0.107)	(0.118)	(0.183)	(0.203)	(0.183)	(0.165)	(0.183)
Observations	2,857	2,857	1,844	2,857	1,844	3,059	3,059	2,045	3,059	2,045
R^2	0.039	0.034	0.038	0.034	0.038	0.010	0.010	0.012	0.010	0.012
Max. possible R^2	0.107	0.107	0.144	0.107	0.144	0.030	0.030	0.041	0.030	0.041
Log-likelihood	−105.763	−112.460	−107.110	−112.644	−107.110	−31.575	−31.550	−30.649	−31.868	−30.649
Wald test (df = 12)	209.700^{***}	305.300^{***}	177.050^{***}	282.090^{***}	177.050^{***}	40.400^{***}	29.060^{***}	32.130^{***}	32.730^{***}	32.130^{***}
LR test (df = 12)	112.730^{***}	99.335^{***}	71.752^{***}	98.968^{***}	71.752^{***}	31.111^{***}	31.160^{***}	24.993^{**}	30.523^{***}	24.993^{**}
Score (Logrank) test (df = 12)	135.459^{***}	100.203^{***}	64.260^{***}	100.053^{***}	64.260^{***}	24.694^{**}	25.359^{**}	23.461^{**}	23.723^{**}	23.461^{**}

Note: $^{***}p < 0.01, ^{**}p < 0.05, ^{*}p < 0.1$

7 Conclusions

Under the architecture of the Paris Agreement, the stringency of the global climate policy regime, and whether it is consistent with the temperature warming objective enshrined in the agreement, is determined by the stringency of the policy regime of individual countries. The first step towards more stringent policy regimes is to adopt GHG emissions-reducing policies, and one way to strengthen the global regime is through their widespread international adoption of these policies. This places the emphasis squarely back on unilateral climate policy actions and their domestic determinants. Such determinants are, in turn, affected by developments in the international technological and policy environment. This sequence of dependence is at the core of the policy diffusion process that we have discussed in this paper.

Our analysis focused on three sets of determinants of domestic policy adoption: (i) national income, free riding, and leakage risk; (ii) GHG abatement technology and (iii) expected policy implementation cost. We highlighted how each might be affected by changes in the international policy or technological environment. Specifically, we hypothesized that (i) increased per capita income (Hypothesis 1) (ii) reduced free-riding and leakage risk from increased policy adoption by foreign partners (Hypothesis 2(a) and 2(b)), (iii) access to improved foreign abatement technology (Hypothesis 3), (iv) learning from policy adoption by foreign jurisdictions (Hypothesis 4) could all independently lead to more stringent domestic policy. Our analysis offered some insights with regard to each of these hypotheses. First, higher income per capita raises the probability of adoption of RPS, ETS, and carbon taxes but lowers that of FiT. However, the estimated effects are small, which suggests that other factors play a role in policy adoption. Second, a reduction in the leakage risk increases the probability of adoption of carbon pricing mechanisms, but not of nonprice policies. Given that the risk of induced leakage is greatest for carbon pricing policies, this is perhaps unsurprising. However, an interesting corollary is that carbon pricing mechanisms face better odds of adoption if implemented by all members of a group of trade-integrated countries. Third, the accumulation of knowledge on abatement technologies raises the probability of adoption of all policies analyzed here, except

ETS. The effect is strongest and most robustly estimated for RPS and carbon taxes. This is in line with the observed development of climate policy over the period of our sample. Indeed, feed-in tariff policies have been introduced primarily in support of the development of specific technologies whereas RPS and carbon pricing mechanisms were introduced once a more mature and less costly technological base had been developed. Finally, there is little empirical evidence in support of our fourth hypothesis, suggesting that the policies analyzed in this paper were adopted by an institutionally and culturally diverse set of countries.

Overall, this suggests that factors other than countries' income per capita have been driving climate policy adoption thus far, at least in the power sector. This implies that rising income per capita (and willingness to pay for global environmental quality) may not be the only way to induce policy adoption by currently lower-income countries. In fact, while improving aggregate economic conditions would likely improve the prospects of policy adoption, other channels might prove more effective. Importantly, however, these channels hinge on the external effects of unilateral climate change mitigation policy or technology developments. In particular, in contrast to some of the results in the *top-down* environmental coalition formation literature, our results suggest that persuading key countries to adopt tighter climate change mitigation policy frameworks or develop emissions abatement technologies might result in simultaneous or sequential policy strengthening by other jurisdictions. For example, the implications, in terms of policy diffusion and strengthening, of China adopting a more stringent policy regime may well be much more significant than those of a similar action by a smaller country, such as Vietnam. In 2018, China represented on average 20 percent of total imports among East Asia and Pacific countries. Given this, and the relatively high CO_2 intensity of its power sector (627g/kWh in 2016), a more stringent domestic policy targeting that sector could substantially raise the odds of adoption of more stringent climate policies in these countries. On the other hand, further technological innovations by countries like the United States and Germany, which are well integrated in the international trading system, hold the highest potential for international technological spillovers.

Our discussion also emphasizes the importance of bilateral relationships for the implementation of domestic environmental policies, providing a new perspective on the emergence of bottom-up climate coalitions and the role that international institutional architecture may play in it. Relatedly, it suggests that we might have to revisit our assessment of the multilateral approach to climate change mitigation. Indeed, although we must be disappointed when international environmental agreements set lenient targets, it is possible that their very existence and architecture will foster the bilateral exchange of policy ideas or abatement technologies, which, in turn, would increase the "unilateral" ambition of jurisdictions. In that respect, we believe that the European experience holds particularly strong insights for future climate policy developments. Indeed, integration, be it through trade or broader institutional arrangements, seems to foster policy diffusion by enhancing access to technological advances within the integrated group and strengthening the policy signal.

We started our investigation by asking whether a process of policy diffusion could help bring the noncooperative GHG emissions outcome enshrined in the Paris Agreement in closer alignment with its temperature warming objective. Enough time has elapsed since 1990 to shed some light on this question. We believe that the results presented in this study provide some support for the existence of policy diffusion mechanisms. In that sense, unilateral adoption of climate policies and/or development of abatement technologies by some jurisdictions may diffuse beyond their domestic border and induce enhanced GHG emissions reductions by other jurisdictions.

References

Alizada, K. (2018). Rethinking the diffusion of renewable energy policies: A global assessment of feed-in tariffs and renewable portfolio standards. *Energy Research and Social Sciences*, 44:346–361.

Antweiler, W., Copeland, B., and Taylor, M. (2001). Is free trade good for the environment? *American Economic Review*, 91(4):877–908.

Arrow, K. (1962). The economic implications of learning by doing. *Review of Economic Studies*, 29:154–174.

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers*, 46:878–894.

Barrett, S. (2003). *Environment and statecraft: The strategy of environmental treaty-making*. Oxford University Press, Oxford, UK.

Bloom, N., Schankerman, M., and Van Reenen, J. (2013). Identifying technological spillovers and product market rivalry. *Econometrica*, 81(4):1347–1393.

Botta, E. and Kozluk, T. (2014). Measuring environmental policy stringency in OECD countries: A composite index approach. *OECD Economics Department Working Papers*, Paris.

Brock, W. and Taylor, M. (2010). The Green Solow model. *Journal of Economic Growth*, 15:127–153.

CAT (Climate Action Tracker) (2021). The CAT thermometer. https://climateactiontracker.org/global/cat-thermometer/.

Coe, D. and Helpman, E. (1995). International R&D spillovers. *European Economic Review*, 39:859–887.

Congleton, R. (1992). Political institutions and pollution control. *Review of Economics and Statistics*, 74(3):412–421.

Copeland, B. and Taylor, M. (1994). North-south trade and the global environment. *Quarterly Journal of Economics*, 109:755–787.

Copeland, B. and Taylor, M. (1995). Trade and transboundary pollution. *American Economic Review*, 85(4):716–737.

Copeland, B. and Taylor, M. (2003). *Trade and the environment: Theory and evidence.* Princeton University Press, Princeton, NJ.

Copeland, B. and Taylor, M. (2004). Trade, growth and the environment. *Journal of Economic Literature*, 42:7–71.

Copeland, B. and Taylor, M. (2005). Free trade and global warming: A trade theory view of the Kyoto protocol. *Journal of Environmental Economics and Management*, 49:205–234.

Dechezlepretre, A. and Glachant, M. (2011). Invention and transfer of climate change mitigation technologies: A global analysis. *Review of Environmental Economics and Policy*, 5(1):109–130.

Dechezlepretre, A., Glachant, M., and Meniere, Y. (2013). What drives the international transfer of climate change mitigation technologies? Empirical evidence from patent data. *Environmental and Resource Economics*, 54:161–178.

Dixit, A. and Norman, V. (1980). *Theory of international trade.* Cambridge Economic Handbooks. Cambridge University Press, Cambridge, UK.

Dolphin, G. (2020). World carbon pricing database. https://github.com/gd1989/WorldCarbonPricingDatabase.

Dolphin, G., Pollitt, M., and Newbery, D. (2020). The political economy of carbon pricing: A panel analysis. *Oxford Economic Papers*, 72(2).

Falvey, R., Foster, N., and Greenaway, D. (2004). Imports, exports, knowledge spillovers and growth. *Economics Letters*, 85:209–213.

Fankhauser, S., Gennaioli, C., and Collins, M. (2016). Do international factors influence the passage of climate change legislation? *Climate Policy*, 16(3):318–331.

Fowlie, M. and Reguant, M. (2018). Challenges in the measurement of leakage risk. *AEA Papers and Proceedings*, 108:124–129.

Fracasso, A. and Vittucci Marzetti, G. (2015). International trade and R&D spillovers. *Journal of International Economics*, 96:138–149.

Frankel, J. and Rose, A. (2005). Is trade good or bad for the environment? Sorting out the causality. *Review of Economics and Statistics*, 87(1):85–91.

Funk, M. (2001). Trade and international R&D spillovers among OECD countries. *Southern Economic Journal*, 67:725–736.

Griliches, Z. (1990). Patent statistics as economic indicators: A survey. *Journal of Economic Literature*, 28(4):1661–1707.

Grossman, G. and Helpman, E. (1991). Trade, knowledge spillovers, and growth. *European Economic Review*, 35:517–526.

Grossman, G. and Krueger, A. (1993). *Environmental impacts of a North American Free Trade Agreement.* MIT Press, Cambridge, MA.

Hahn, R. (1990). The political economy of environmental regulation: Towards a unifying framework. *Public Choice*, 65:21–47.

Hall, B., Jaffe, A., and Trajtenberg, M. (2005). Market value and patent citations. *RAND Journal of Economics*, 36(1):16–38.

Head, K., Mayer, T., and Ries, J. (2010). The erosion of colonial trade linkages after independence. *Journal of International Economics*, 81(1):1–14.

Heal, G. (1993). *Trade, innovation, environment*, chapter Formation of international environmental agreements, pages 301–322. Springer Netherlands, Dordrecht.

IEA (2020). Policies database.

IRENA (International Renewable Energy Agency) (2012). Renewable energy technologies: Cost analysis series. *IRENA Working Paper.*

IRENA (International Renewable Energy Agency) (2020). Renewable power generation costs in 2019. Technical report, IRENA, Abu Dhabi.

Jaffe, A., Peterson, S., Portney, P., and Stavins, R. (1995). Environmental regulation and the competitiveness of U.S. manufacturing: What does the evidence tell us? *Journal of Economic Literature*, 33(1):132–163.

Kriegler, E., Weyant, J., Blanford, G., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S., Tavoni, M., and van Vuuren, D. (2014). The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, 123:353–367.

Lanjouw, J. and Mody, A. (1996). Innovation and the international diffusion of environmentally responsive technology. *Research Policy*, 25:549–571.

Levinson, A. and Taylor, M. (2008). Unmasking the pollution haven effect. *International Economic Review*, 49(1):223–254.

Lovely, M. and Popp, D. (2011). Trade, technology, and the environment: Does access to technology promote environmental regulation? *Journal of Environmental Economics and Management*, 61:16–35.

Mideksa, T. (2016). Leadership and climate policy. *Unpublished*, Available at: https://sites.google.com/site/torbenmideksa/home.

Murillo, M. and Martinez-Gallardo, C. (2007). Political competition and policy adoption: Market reforms in Latin American public utilities. *American Journal of Political Science*, 51(1):120–139.

Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, 105(4):1339–1370.

OECD (Organisation for Economic Co-operation and Development) (2009). Measuring capital OECD manual. Technical report, OECD, Paris.

Perkins, R. and Neumayer, E. (2012). Does the “California effect” operate across borders? Trading- and investing-up in automobile emission standards. *Journal of European Public Policy*, 19(2):217–237.

REN21 (2020). Renewables 2020 global status report. Technical Report ISBN 978-3-948393-00-7, REN21, Paris: REN21 Secretariat.

Simmons, B. and Elkins, Z. (2004). The globalization of liberalization: Policy diffusion in the international political economy. *American Political Science Review*, 98(1):171–189.

Tobey, J. (1990). The effects of domestic environmental policies on patterns of world trade: An empirical test. *Kyklos*, 43(2):191–209.

Vega, S. H. and Mandel, A. (2018). Technology diffusion and climate policy: A network approach and its application to wind energy. *Ecological Economics*, 145:461–471.

Vogel, D. (1995). *Trading up: Consumer and environmental regulation in a global economy.* Harvard University Press, Cambridge, MA.

Volden, C., Ting, M. M., and Carpenter, D. P. (2008). A formal model of learning and policy diffusion. *American Political Science Review*, 102(3):319–332.

Ward, J., Sammon, P., Dundas, G., Peszko, G., Kennedy, P., Wienges, S., and Prytz, N. (2015). Carbon Leakage: Theory, evidence and policy design. Technical report, Partnership for Market Readiness, World Bank, Washington, DC.

World Bank (2020). *State and trends of carbon pricing*. Washington, DC.

A Theoretical Appendix

A.1 Abatement Function

Define the abatement technology as $A(e^P, v^A)$, where e^P is the potential amount of pollution produced and v^A is the (absolute) amount of resources allocated to abatement. $A(.)$ is a CRS activity. Then, $e = e^P - A(e^P, v^A) \Leftrightarrow e = e^P(1 - A(1, v^A/e^P))$. Now, recall that without abatement activity, $e^P = x = \Omega B(.)$ and $v^A/B(.) = \phi$. Hence, $e = \Omega B(.)(1 - A(1, \phi))$ where we have defined $(1 - A(1, \phi))$, as $\chi(\phi)$.

A.2 Pollution as Input

We start by rearranging equation (3) to obtain an explicit analytical expression of abatement effort, $\phi = \chi^{-1}[e/(\Omega B(K_x, L_x))]$. Substituting this expression in equation (2) we can then write

$$x = \left(1 - \chi^{-1}\left[\frac{e}{\Omega B(K_x, L_x)}\right]\right) B(K_x, L_x). \tag{A.1}$$

This clearly shows that net production of the dirty good depends on (i) potential production, which in turn depends on the amount of resources the economy allocates to the dirty sector; (ii) the number of emission units available to the sector. Importantly, the effect of both factors on net production depends on their effect on abatement effort.

Hence, we next show that $\partial\chi^{-1}(.)/\partial e < 0$ and $\partial\chi^{-1}(.)/\partial B(.) > 0$, which implies that an increase in available emissions units lowers abatement effort and raises net production. Indeed, define $C \equiv e/B(K_x, L_x)$. By the inverse function theorem, we know that $\chi^{-1}(.)$ satisfies $\partial\chi^{-1}(.)/\partial C < 0$. By the definition of C, we have $\partial C/\partial e > 0$ and $\partial C/\partial B(.) < 0$. Hence we must have $\partial\chi^{-1}(.)/\partial e < 0, \partial\chi^{-1}(.)/\partial B(.) > 0$.[42]

Finally, equation (A.1) is simplified if we define the abatement function as $\chi(\phi) =$

---

[42] This leads to two interesting observations: first, an increase in emissions allowance raises net output of good x; second, an increase in potential output $B(.)$ affects net output via a production channel and an abatement channel. The first one straightforwardly tends to raise production, and higher potential production leads to higher actual production. The second tends to lower actual production and is more indirect: $\chi(\phi)$ gives the abatement efforts as a function of the ratio of unabated to total potential emissions. Hence, when potential production (and emissions) increases, that ratio decreases, for a given level of actual emissions. This requires an increase in abatement efforts, which, in turn, depresses net output. Whether one or the other effect dominates is eventually an empirical question, but it seems plausible to assume that the former outweighs the latter.

$(1-\phi)^{1/\alpha}$. This expression satisfies the properties imposed earlier on the abatement technology and implies that there are diminishing returns to abatement effort. We then have $\phi = 1 - \left(\frac{e}{\Omega B(K_x, L_x)}\right)$ and we can rewrite (A.1) as

$$x = \left(\frac{e}{\Omega}\right)^{\alpha} B(K_x, L_x)^{1-\alpha}. \tag{A.2}$$

A.3 Firms' Profit Maximization

The firms in the Y sector does not pollute and the profit function is thus

$$\pi^y = pF(K_y, L_y) - wL_y - rK_y. \tag{A.3}$$

In the X (dirty) sector,

$$\begin{aligned} \pi^x &= pX(K_x, L_x) - wL_x - rK_x - \delta e \\ &= \underbrace{p(1-\alpha\Omega)}_{\text{net producer price}} \; X(K_x, L_x) - wL_x - rK_x. \end{aligned} \tag{A.4}$$

We derive the second equality by substituting e for its value, given by equation (5), and rearranging the terms. Next, recalling that

$$\frac{\delta \frac{e}{\Omega}}{px} = \alpha \tag{A.5}$$

and that $0 < \alpha < 1$ and $0 < \Omega \leq 1$, it is easy to see that $\alpha\Omega$ represents the share of pollution payments in total value added. We note two observations. First, assuming constant α, a decrease in the share of pollution payments can be interpreted as reflecting a decrease in Ω—that is, an improvement in abatement technology. Second, as Ω decreases, the net revenue (i.e., revenue net of pollution permit payment) increases.

This together with the relative price of the good determines the allocation of resources between sectors. Indeed, recalling our perfect competition assumption, Euler's theorem, and the fact that labor and capital are inelastically supplied, we have

$$F_K = p(1-\alpha\Omega)X_K = r \ ; \ F_L = p(1-\alpha\Omega)X_L = w,$$

where X_K, X_L and F_K, F_L denote the marginal productivity of factors in sectors X and Y, respectively; that is, factors of production are remunerated at the value of their marginal product, which, since both sectors trade inputs in the same markets, is equalized across sectors. Rearranging the above yields,

$$\frac{F_K}{X_K} = \frac{F_L}{X_L} = p(1 - \alpha\Omega) \equiv S. \tag{A.6}$$

This is the equilibrium resource allocation condition.

Based on that condition, we note that when Ω decreases (i.e., abatement technology improves), "payments to pollution" per unit of dirty good produced decrease, making the dirty good sector relatively more attractive and inducing a reallocation of the economy's resources from the clean to the dirty good sector. In other words, an improvement in the abatement technology induces a change in the *composition* of the economy.

Finally, equation (A.6) provides an interesting result: the effect of a change in relative price on resource allocation varies with the abatement technology Ω; that is, define Ω^{high} and Ω^{low}, denoting *poor* and *good* abatement technology, respectively. Then

$$\left.\frac{\partial S}{\partial p}\right|_{\Omega^{high}} < \left.\frac{\partial S}{\partial p}.\right|_{\Omega^{low}} \tag{A.7}$$

When a jurisdiction has good abatement technology, a change in the relative price of the dirty good will induce a larger reallocation of resources from the clean to the dirty sector.

A.4 Prices, Emissions Intensity, and Abatement Efforts

It now becomes possible to derive an expression of ϕ in terms of prices. Using equation (5) to note that total emissions are equal to $e = ix$, we can rewrite the production function (A.2) as

$$x = \left(\frac{ix}{\Omega}\right)^{\alpha} B(K_x, L_x)^{1-\alpha}.$$

Yet, we also know that $x = (1 - \phi)B(K_x, L_x)$. Hence,

$$i = (1 - \phi)^{(1-\alpha)/\alpha}\Omega, \tag{A.8}$$

which suggests that the emissions intensity of the economy decreases in two cases: when more resources are devoted to abatement and when the abatement technology improves. Now, substituting i for its expression in equation (5) yields

$$\frac{\alpha\Omega p}{\delta} = (1-\phi)^{(1-\alpha)/\alpha}\Omega$$

and we can therefore write

$$\phi = 1 - \left(\frac{\alpha p}{\delta}\right)^{\alpha/(1-\alpha)}. \tag{A.9}$$

As it turns out, abatement effort is independent from Ω, the abatement technology quality. However, an improvement in abatement technology might affect equilibrium abatement effort through its effect on equilibrium emissions price.

In a general equilibrium context, the total effect of a (positive) technological change in abatement comes in two ways. First, for a given (equilibrium) price of emissions, pollution payments per unit of dirty good decrease, inducing a shift of inputs from the clean to the dirty sector and hence stimulating production in the latter; this is the *composition* effect identified in Section A.2, which tends to raise pollution demand. Second, the technological improvement also induces a reduction in the emissions intensity of the dirty sector—a *technique* effect, which tends to reduce pollution demand.

If the technique effect is stronger than the composition effect, then an improvement in abatement technology will lead to a decrease in pollution demand. The ensuing downward adjustment in equilibrium emissions price δ will induce a decrease in abatement effort.

A.5 Regulatory Threshold

The present discussion is based on Copeland and Taylor (2003). We adopt a constant relative risk aversion utility function for the consumption component of utility and a constant marginal disutility of emissions. Therefore, the indirect utility function becomes

$$V(p, I, E) = \frac{[I/\omega(\mathbf{p})]^{1-\eta}}{1-\eta} - \lambda E, \text{ with } \eta \neq 1,$$

where $E = E_{-i} + e_i$. For simplicity, it is assumed that the economy produces only one (dirty) good so that income is

$$I = p\left(\frac{e_i}{\Omega}\right)^{\alpha} B(K,L)^{1-\alpha}.$$

To find equilibrium emissions, we derive the inverse pollution demand

$$\alpha p\left(\frac{e_i}{\Omega}\right)^{\alpha-1} \Omega^{-1} B(K,L)^{1-\alpha} \Leftrightarrow \alpha\, \underbrace{p\left(\frac{e_i}{\Omega}\right)^{\alpha} B(K,L)^{1-\alpha}}_{=I} \left(\frac{E_i}{\Omega}\right)^{-1} \Omega^{-1} \Leftrightarrow \frac{\alpha}{e_i} I \tag{A.10}$$

and the pollution supply

$$-\frac{V_{E_i}}{V_R} \Leftrightarrow -\frac{-\lambda}{\left[\frac{(I/\beta(p))^{-\eta}}{\beta(p)}\right]}. \Leftrightarrow -\frac{\lambda\beta(p)}{R^{-\eta}} \tag{A.11}$$

Equating (A.10) and (A.11) and solving for e_i yields

$$e_i = \frac{\alpha}{\lambda} R^{1-\eta}. \tag{A.12}$$

Substituting (A.12) in the utility function leads to

$$V^R(p, I, E) = \left[\frac{1}{1-\eta} - \alpha\right] R^{1-\eta} - \lambda E_{-i}. \tag{A.13}$$

At this stage, we can note that if the economy incurs a fixed cost of regulation, income will be reduced. Indeed, suppose that regulation is expected to require $(\bar{K}, \bar{L})$ of resources (i.e., $\mathbb{E}(\bar{K}, \bar{L}) \equiv \Phi$); then the expected resources available for production are $(K - \bar{K}, L - \bar{L})$, the potential production becomes $B^R \equiv B(K - \bar{K}, L - \bar{L})$, and income is

$$I^R = p\left(\frac{e_i}{\Omega}\right)^{\alpha} (B^R)^{1-\alpha}.$$

If the expected cost of regulation decreases, then income increases following an increase in potential output. As a result, utility under regulation is now higher at any level of initial endowment in (K, L) of the economy. Formally, we have $\partial V^R / \partial \Phi < 0$.

In the no-regulation case, no abatement takes place, so real income is equal to (potential) output and emissions are directly proportional to it. Utility is then defined as

$$V^{NR}(p, I, E) = \frac{R^{1-\eta}}{(1-\eta)} - \lambda R - \lambda E_{-i}. \tag{A.14}$$

It can be shown that (A.14) first rises and then declines with real income. V^{NR} increases over $[0, \sqrt[\eta]{1/\lambda}[$ and decreases over $]\sqrt[\eta]{1/\lambda}, +\infty$. Indeed, $\frac{\partial V^{NR}}{\partial R} = R^{-\eta} - \lambda$ is positive over $[0, \sqrt[\eta]{1/\lambda}[$, equals 0 in $R = \sqrt[\eta]{1/\lambda}$, and is negative over $]\sqrt[\eta]{1/\lambda}, +\infty$. Since V^R is monotonically increasing over the interval $[0, +\infty$, there exists a unique level of income such that $V^R = V^{NR}$ and beyond which $V^R > V^{NR}$; that is, we can write $\bar{I} \equiv V^R = V^{NR}$. Given $\partial V^R / \partial \Phi < 0$, we have $\partial \bar{I} / \partial \Phi > 0$.