Enforcing International Environmental Cooperation: Technological Standards Can Help[*]

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Abstract

Market-based environmental policies, such as emissions trading or pollution taxes, are less costly than command-and-control regulation. Yet technological standards have been used in international environmental agreements, and they figure prominently among proposals to mitigate global warming. Why? I show that technological standards can be combined with market-based instruments to create collective enforcement power. They allow countries to internationally enforce the domestic installation of pollution-control equipment, which is useful for three reasons. First, if a country can avoid costly installation without punishment, defection is more profitable. Second, if other countries nevertheless install, their ability to punish the defector by suspending cooperation decreases. With technological standards, this "double dividend" is not attainable. Finally, without technological standards, countries must credibly commit to a collectively time-inconsistent international agreement. Technological standards are most useful when cooperation is difficult to enforce and requires costly and lengthy domestic adjustments. Global warming fulfills all three conditions.

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1 Introduction

Planetary environmental deterioration, and global warming in particular, have drawn much attention to the strategic design of international environmental agreements (Barrett 2003). In this article, I evaluate the merits of two different policy instruments that countries can use in international environmental cooperation:

1. *Economy-wide market-based instruments* assign a price or quota on pollution or overconsumption without requiring any specific domestic measures.
2. *Technological standards* mandate the installation of specific pollution-control or resource-saving equipment in certain sectors of economic activity.

The defining feature of the first category is *flexibility* while the second category is characterized by *rigidity*.

The conventional wisdom emphasizes the virtues of flexibility. Environmental economists are virtually unanimous on the superior cost-effectiveness of flexible economy-wide market-based instruments, such as emissions trading or Pigouvian taxes, over intrusive command-and-control regulation (Fischer and Newell 2008; Keohane, Revesz, and Stavins 1998; Kverndokk, Rosendahl, and Rutherford 2004; Oates 1999; Stern 2006; Weitzman 2007). The price mechanism allows economic actors to capitalize on their private information, which results in a decentralized allocation of mitigation efforts that minimizes the societal cost while maximizing the incentive to develop new technologies for pollution control (Stavins 2005).

Against this unfavorable background, it is interesting that technological standards have historically been used in many international environmental agreements and are now being proposed as a means to effective international climate policy after the Kyoto Protocol expires in 2012. Although efficient instruments have been available to reduce transboundary pollution and conserve resources, countries have frequently agreed on technological standards. Most importantly, the idea of a "sectoral agreement" based on technological benchmarks to mitigate global warming has recently gained currency (Barrett 2008; Sawa 2008). Indeed, technological standards are already an important part of the energy and climate package that the European Union adopted in December 2008.

The existing literature provides several explanations for technological standards. Mitchell (1994) and Ausubel and Victor (1992) argue that in some cases, such as the international marine pollution regime, technological standards are easier to monitor than efficient instruments. Sawa (2008) writes that they can be enforced through trade sanctions without violating the rules of the World Trade Organization. Barrett (2006) shows that they can help countries coordinate efforts to develop breakthrough technologies. What is common to these three explanations is that they emphasize the need to enforce international environmental cooperation (Barrett 2008). However, it is noteworthy that at least one of the following conditions must hold. First, the monitoring rationale only applies if it is easier to identify technological standards than efficient instruments such as pollution taxes. Second, the legal argument depends on features of international trade law that are outside the model. Finally, technological standards only facilitate the development of breakthrough technologies under unconventional production technologies, such as strong increasing returns to scale.

I offer a complementary rationale for technological standards that applies even if none of the three conditions holds. To advance the argument, I embed a standard general-equilibrium economy in a repeated cooperation game. Economic activity generates negative externalities, such as carbon dioxide emissions. To maximize global welfare, countries should impose a "pollution tax" that represents a larger class of efficient instruments. Before the game begins, entrepreneurs in each country can develop and install new pollution-control equipment, but cost minimization requires local knowledge that is not available to the government. Countries can choose an international environmental agreement that permits "flexible installation" to capitalize on innovation or flexibility, or they can impose a rigid technological standard.

The key result is that a technological standard increases the maximal pollution tax that countries can enforce. If countries use flexible installation to capitalize on private information, they cannot enforce the installation of pollution-control equipment. After all, they do not even know what equipment should be installed in any given company. And even if they did, international law does not authorize punishment because flexible installation is voluntary. As a result, a country that does not intend to comply obtains a double dividend: it avoids the cost of installation *and* enjoys the benefits of free riding for some time. But if countries choose a technological standard, they can immediately punish a country for failing to install the equipment, so a country avoids the cost of installation *or* enjoys the benefits of free riding for one time period. Technological standards reduce the payoff to the most profitable defection and increase the cost of the resulting punishment.

Additionally, technological standards help countries solve a paradoxical political problem of collective time-inconsistency. If countries do not use technological standards, they must choose a lower pollution tax than is otherwise enforceable, for reasons given in the previous paragraph. They therefore have a common incentive to impose a higher pollution tax by rewriting the agreement immediately after the pollution-control equipment is installed. But if this is the anticipated reaction, cooperation is not enforceable in the installation phase. Without technological standards, countries must in commit to a "third-best" pollution tax that they would rather renegotiate as soon as possible.[1] To my knowledge, this paradoxical effect has not been previously recognized by students of international cooperation.

The analysis has important empirical and policy implications. Empirically, the results imply that countries will use technological standards to solve international environmental problems that require a a lengthy structural transition carrying high adjustment costs. This outcome is quite paradoxical because it is exactly under these conditions that the deadweight loss from technological standards is maximized. From a policy perspective, the analysis provides support for the use of technological standards in international environmental cooperation and yields a political-economic rationale for combining technological standards with economy-wide market-based instruments, such as a pollution tax or emissions trading. Notably, global warming is a prime example of conditions under which the theory should apply (Unruh 2000).

Although I have cast the argument in terms of international environmental cooperation for parsimony and clarity, I believe the theoretical analysis can shed light on a wide range of international cooperation problems that involve negative externalities and require new technology. The most important assumption is that cost minimization requires private information diffused through the economy. This assumption applies to a wide range of international collective-action problems beyond the global environment, such as optimal trade or regulatory reform (Dewatripont and Roland 1992; Nsouli, Rached, and Funke 2005; Sandler 2004). The analysis should therefore be of interest to a broad audience of political economists and provide a solid foundation for future theoretical and empirical work.

I proceed as follows. In Section 2, I examine the empirical record and review the literature. In Section 3, I present the general-equilibrium model. In Section 4, I introduce the repeated cooperation game. In Section 5, I introduce the equilibrium concept. In Section 6, I present the key result. In

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[1] For "renegotiation-proofness" in game theory, see Barrett (1994) and Farrell and Maskin (1989). For the concept of the "second best" in economics, see Krishna and Panagariya (2000).

Section 7, I examine the empirical implications of the analysis. In Section 8, I discuss the result. In Section 9, I examine the paradox of the third best. In Section 10, I consider the special case of global warming. In Section 11, I offer a summary and consider extensions to other issues in international politics.

2 Motivation

The microeconomic theory of environmental regulation is unambiguous as to the superior allocative efficiency of economy-wide market-based instruments over command-and-control technological standards (Aidt 1998; Barrett 2003; Oates 1999; Stern 2006; Weitzman 1974). Modern information economics highlights the informational advantages that individuals and companies have about their own activities as a central virtue of the market as an allocation structure (Hayek 1945; Kruger, Oates, and Pizer 2007; Mookherjee 2006; Stavins 2005). If the purpose is to reduce pollution, why should individuals and companies be denied the right to choose how that reduction is achieved? The complexity of any modern economy implies that the government has less information about the best way to reduce pollution in any given location than engineers who are thoroughly familiar with the relevant production systems. Given this information asymmetry, the best way to internalize the cost of pollution is to simply use a price signal as an incentive to producers and consumers.

Technological standards are also a barrier to technical change (Fischer and Newell 2008; Kverndokk, Rosendahl, and Rutherford 2004; Weyant and Olavson 1999). If companies are forced to choose a specific technology, why should they invest resources to develop new technologies? These innovations are only usable if they accord with the technological standard, so the incentive to innovate is diminished. For example, if the country subsidizes or mandates wind power and nuclear energy, the profitability of solar power decreases. And if solar power is actually a better technology than wind power and nuclear energy, this is not good news.

In international environmental affairs, political-economic considerations give yet another argument against technological standards. Even if we accept the idea that politicians sometimes engage in special-interest politics to increase the probability of political survival (Aidt 1998; Keohane, Revesz, and Stavins 1998; Maloney and McCormick 1982), it is not clear why *international* policies must be inefficient. Politicians stay in office as long as their domestic constituents support them, so it seems that all countries have a common interest in maximizing the efficiency of international environmental cooperation and only exploit domestic opportunities to transfer rents.

In light of these arguments, it seems that technological standards should only be used in those rare instances in which efficient instruments are not available for some reason. For example, the use of conservation areas in biodiversity conservation might turn out to be efficient if it is not possible to protect threatened species otherwise. But in most cases, countries should have a common incentive to minimize the cost of environmental protection.

Against this unfavorable backdrop, it is interesting that technological standards have historically been used in many international environmental agreements despite high costs. Already the North Pacific Fur Seal Treaty of 1911 was based on a ban on hunting seals on the sea (Barrett 2003). While this ban was indeed effective, it was also inefficient because the cost of catching a given number of seals was higher on the sea than on the land. The marine pollution regime, consisting of the 1973 International Convention for the Prevention of Pollution from Ships and a modifying 1978 Protocol, prescribed a specific technological standard (Mitchell 1994). This technological standard did reduce pollution from ships but is suppressed incentives to develop alternative less costly technologies. Article II of the 1988 Protocol on Nitrogen Oxides to the 1978 Convention on Long-Range Transboundary Air Pollution requires that the parties "[a]pply national emissions standards to major new stationary sources and/or source categories, and to substantially modified stationary sources in major source categories, based on the best available technologies which are economically feasible." Such emissions standards appear unnecessary because the protocol also specifies targets for each country. The 2001 Stockholm Convention on Persistent Organic Pollutants provides a list of chemicals to be eliminated or restricted, with a limited number of exempted uses. This regulation dampens the incentive to develop new uses, whereas a simple fee could have been used to avoid this dynamic distortion.

A particularly important recent example is the energy and climate package that the European Union enacted in December 2008. It specifies *inter alia* a legally binding target for renewable energy sources to cover one fifth of the total energy mix.[2] While this overall target seems broad, it is actually quite constraining compared to the economically most efficient approach that only specifies an economy-wide cap on greenhouse emissions and other pollutants. The energy industry must produce one fifth of its output using specific technologies suitable for renewable energy production, which precludes

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[2] "EU Leaders Reach New Climate Deal." *BBC News* December 12, 2008.

many other techniques to reduce emissions, such as nuclear power. The legislation also promotes technological benchmarking. Sawa (2008, 12) writes that "in the EU ... sectoral approaches are being considered in the form of benchmarking, as an effective method for allocating allowances among the actors in the [emissions trading scheme]." Please note that this allocation bias creates incentives to choose benchmarked technologies even if they are actually not optimal.

The interest in technological standards as an instrument of climate policy appears to be shared by many countries outside Europe. In May 2008, the Japanese government submitted a proposal for a sectoral approach to international climate policy after the Kyoto Protocol expires in 2012.[3] In addition to calling for bottom-up strategies and assessment of sectoral potentials for reductions in greenhouse gas emissions, it emphasizes the importance of technological benchmarks. According to Meckling and Chung (2009), the United States has also promoted a sectoral approach that builds on technological standards in the negotiations. In December 2008, twenty major emitters attended a Summit on Sectoral Cooperation in Warsaw to establish an official Warsaw Dialogue on this approach.

Given the importance of technological standards in international environmental agreements, it is important for international political economists to understand what advantages they might have. The extant literature provides three main rationales that I now discuss. These rationales are valid, but I discuss some limitations and contrast them with my argument. However, I omit a discussion of *technology subsidies* that could be efficient because the development of clean technology produces positive externalities (Fischer and Newell 2008; Weyant and Olavson 1999). I also do not discuss the possibility that countries use technological standards as a bargaining tactic in international negotiations.

First, one idea that has gained currency among scholars is the possibility that technological standards could permit enforcement through trade sanctions without violating international trade law (Barrett 2008; Sawa 2008). Under international trade law, countries cannot impose tariffs on pollution-intensive imports from countries that do not regulate pollution simply because there is a perception of "unfair" competitive advantage, but specific

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[3] "Information, Views and Proposals on Paragraph 1 of Bali Action Plan." Submission by the Government of Japan for the Second Session of the *Ad Hoc* Working Group on Long-Term Cooperative Action under the United Nations Framework Convention on Climate Change in May 2008. [http://unfccc.int/files/meetings/ad_hoc_working_groups/lca/application/pdf/submissionjapan.pdf].

technological standards are admissible in certain circumstances.[4] However, the legal complexity of the issue implies that the validity of this argument is unclear. The World Trade Organization has only resolved a handful of trade-environment disputes, so the set of precedents is not particularly large (Neumayer 2001; Young 2005).

A related argument concerns competitiveness and the possibility of "carbon leakage" as pollution-intensive industries shift to countries that do not regulate pollution (Biermann and Brohm 2005; Esty 2001). A technological standard could expand the set of countries that are ready to participate in international environmental cooperation. Some countries might be unwilling to accept binding commitments, but they could nevertheless consider limited participation. This would alleviate competitiveness concerns in countries that are ready to accept binding commitments. This explanation is plausible for political-economic reasons, but it remains unclear why countries cannot use efficient instruments to achieve the desired distribution of gains.

Second, Mitchell (1994) notes that monitoring is an important reason why the marine pollution regime was based on technological standards. It is difficult to monitor the use of flexible instruments because ships can simply release pollution on the sea. Instead, by choosing a technological standard the presence of which can be easily verified in the port, countries could monitor compliance (Ausubel and Victor 1992). But the explanation is only applicable to situations in which technological standards are easier to monitor than other instruments. In the case of global warming, it could be difficult to verify compliance with technological standards in all Chinese factories, whereas reliable data on greenhouse gas emissions is not difficult to collect.

Finally, a technological standard could help countries coordinate efforts to develop clean energy technology in the presence of increasing returns. Barrett (2006) shows that while technological standards are often as difficult to enforce as are emissions targets, a technological standard could facilitate equilibrium selection under economies of scale.[5] A weakness of this explanation is that it does not consider the possibility of committing to efficient subsidies or other superior incentive schemes for technology development.

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[4] See Charnovitz (2001) for the relationship between international trade and environmental regulation.

[5] For circumstances in which pollution taxes can induce inefficiency under nonconvexities production technologies, see Hoel (1998).

3 The Economy

Consider n identical countries with closed economies (Aidt 1998). All countries i are populated by a unit continuum of identical citizens with a labor endowment L. Unlimited amounts of raw material can be extracted from the ground at a strictly positive exogenous cost z measured in units of labor.

Each country produces goods $k = 0, 1$, where good 0 is the numeraire. Production in the numeraire sector uses labor as the only input, so under profit maximization and mobile labor, wages and the price of the numeraire good can be normalized at $w^i = q^i = 1$. In sector 0, the quantity of labor used is denoted by L_0^i.

Sector 1 is a "polluting industry" in which companies use labor and raw material. The common consumer and producer price of good 1 in any country i is denoted by p^i. Labor demand is denoted by L_1^i and raw material demand by R^i. The production function has constant returns to scale and decreasing returns to any individual input. Profit maximization thus implies that consumer prices are uniquely determined by the marginal productivities of labor and raw material.

Each unit of raw material R^i used in country i generates harmful emissions E^i linearly according to $E^i = \alpha^i R^i$, where the pollution intensity $\alpha^i \in [0, 1]$ is determined by previous investment in pollution-control equipment. Emissions cause social damage $g(\sum_{j\neq i} E^j)$ to *other* countries, where g is twice differentiable, increasing, and strictly convex. Intuitively, the marginal damage caused by each additional unit of pollution is growing. As an important simplification, emissions do not cause any domestic damage, so without international cooperation, no country controls pollution.

Citizens purchase the two goods and suffers damage from international emissions $\sum_{j\neq i} E^j$. The utility representation is quasi-linear and additively separable:

$$U^i = c_0^i + u(c_1^i) - g(\sum_{j\neq i} E^j), \tag{1}$$

where u is twice differentiable, increasing, and strictly concave. Here, c_k^i denotes consumption of good k and τ^i the tax rate on pollution. Consumer income comprises the wage $L_0^i + L_1^i$ and tax revenue $\tau^i E^i$. In the present context, it is innocuous to exclude other taxes because they are never optimal for pollution control (Aidt 1998; Limão 2005).

Given the quasi-linear utility representation, the budget constraint

$$c_0^i = L + \tau^i E^i - p^i d^i(p^i) \tag{2}$$

yields the indirect utility of the representative consumer:

$$V^i = L + \tau^i E^i + u(d^i(p^i)) - p^i d^i(p^i) - g(\sum_{j \neq i} E^j), \tag{3}$$

where d^i is the demand for good 1. This demand is assumed to be strictly positive for both goods, so set L large enough. With zero profits under perfect competition,

$$p^i d^i(p^i) = zR^i + \tau^i E^i + L_1^i, \tag{4}$$

so indirect utility simplifies to

$$V^i = L - L_1^i - zR^i + u(d^i(p^i)) - g(\sum_{j \neq i} E^j). \tag{5}$$

4 International Cooperation

Let each country $i = 1, ..., N$ be a player in an infinitely repeated game with a pollution tax $\tau^i \in [0, \infty)$ as the single choice variable (Fearon 1998; Keohane 1984; McGillivray and Smith 2000). The pollution tax is representative of a larger class of efficient economic instruments, such as emissions trading or charge fees (Stavins 2005). The payoff to country i is the indirect utility of the representative citizen over time,

$$\sum_{t=0}^{\infty} \delta^t \cdot V^i(\tau_t), \tag{6}$$

where $\delta \in (0, 1)$ is the common discount factor and $\tau_t = (\tau_t^1, ..., \tau_t^n)$ is the vector taxes across economies at time t. The game is stationary, so I drop the indicator t and use the subscript to label vectors.

To gain intuition, consider the one-stage Nash equilibrium τ_{NE} and the collective optimum τ_C. In the one-stage Nash equilibrium τ_{NE}, no country i sets a pollution tax: $\tau_{NE}^i = 0$ for all i. The collectively optimal policy strikes a balance between the domestic abatement cost and the international benefits of pollution abatement. Formally, the following first-order condition can be shown to characterize the collective optimum:

$$\begin{aligned} \tau_C^i : \frac{\partial \sum_{i=1}^N V^i(\tau_C)}{\partial \tau^i} &= 0 \Leftrightarrow \qquad (7) \\ \frac{\partial u}{\partial d^i} \frac{\partial d^i}{\partial p^i} \frac{\partial p^i}{\partial z} - \frac{\partial L_1^i}{\partial z} - z \frac{\partial R^i}{\partial z} &= (N-1) \cdot \frac{\partial g((N-1) \cdot E^i)}{\partial E^i} \frac{\partial R^i}{\partial z}. \end{aligned}$$

On the second line, the left side represents the marginal domestic cost of taxation, as consumers increase the share of the numeraire and firms choose a domestically inefficient combination of factor inputs (L_1^i, R^i). The right side represents the marginal international cost of pollution. The tax τ^i is strictly positive and identical across countries i. Notably, it does not depend on the pollution intensity of the production α^i because only emissions and not the usage of raw material *per se* is taxed.

The repeated game is parametrized by a vector $\mathbf{s} = (\mathbf{s}^1, ..., \mathbf{s}^n)$, where $\mathbf{s}^i = 1$ if country i has developed and installed pollution-control equipment, and $\mathbf{s}^i = 0$ otherwise. Assume

$$\alpha^i = \begin{cases} \beta & | \ \mathbf{s}^i = 0 \\ \gamma & | \ \mathbf{s}^i = 1 \end{cases}, \tag{8}$$

where $\gamma < \beta$ so that installation reduces the pollution intensity of raw-material usage. The pollution-control equipment is developed and installed at a pre-game stage to capture the notion that the influence of new technology is felt with delay (Stern 2006).

At a pre-game stage, each country i chooses between three options:

1. To do nothing, so that the pollution-control equipment is never developed, $\mathbf{s}^i = 0$.
2. To develop a rigid technological standard, so that "compulsory installation" follows, $\mathbf{s}^i = 1$.
3. To fund entrepreneurs who develop and distribute new pollution-control equipment, so that "flexible installation" follows, $\mathbf{s}^i = 1$.

The total cost of compulsory installation is a permanent loss of $(1 - \delta) \cdot x$ labor units. The total cost of flexible installation is a permanent loss of $(1 - \delta) \cdot y$ labor units. To capture the benefits of innovation and flexibility, let $y < x$.

Why must country i subsidize the development of pollution-control equipment to induce flexible installation? First, this convenient assumption avoids entry considerations under imperfect competition. If individual citizens could profitably develop and install pollution-control equipment, a complex model with monopolistic or oligopolistic competition would be necessary. With efficient subsidies, the simple general-equilibrium model introduced above can be used. Second, this assumption captures the stylized fact that innovation generates substantial positive externalities (Fischer and Newell 2008; Weyant and Olavson 1999). The development of new pollution-control equipment is essentially a public good, so public funding is warranted because it corrects a market failure (Barrett 2009).

Compulsory and flexible installation have identical effects on pollution intensity, but a mandatory technological standard is also a legal act by the government that can be enforced as part of an international agreement. This distinction could be motivated either on legal grounds or simply because flexible installation is *de facto* unobservable to foreign countries. What matters is that flexible installation is not "contractible" (Bolton and Dewatripont 2005; Tirole 1999). Formally, before the repeated game begins, nature sends a noiseless public signal that reveals if country i has imposed a technological standard or not. But if country i did not impose a technological standard, no other country $j \neq i$ learns whether it induced flexible installation or not.

The payoff to country i can now be written as

$$\sum_{t=0}^{\infty} \delta^t V^i(\tau_t \mid \mathbf{s}) - \theta^i, \tag{9}$$

where $\theta^i \in \{x, y, 0\}$ hinges on whether pollution-control equipment is installed and the flexible or compulsory nature of this installation.

5 Equilibrium

I consider symmetric subgame-perfect equilibria of the game. This focus is warranted with identical countries, for symmetric play maximizes utility as long as the cost of installation is low enough relative to the marginal cost of pollution.[6] Throughout, I assume the collective optimum defined by (7) is not enforceable with or without pollution-control equipment. If the collective optimum is attainable, the question of enforcement is moot.

I compare three different international agreements that each characterize symmetric behavior on the equilibrium path:

1. In the *no-installation equilibrium*, each country i chooses not to install pollution-control equipment but imposes a stationary pollution tax.
2. In the *compulsory-installation equilibrium*, each country i imposes a technological standard and imposes a stationary pollution tax.
3. In the *flexible-installation equilibrium*, each country i undergoes flexible installation without a technological standard and imposes a stationary pollution tax.

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[6] The analysis of asymmetric equilibria is easy but tedious and uninformative.

The assumption that the pollution tax is stationary is not necessary for the results, but it simplifies notation.

Equilibrium behavior is enforced through a simple grim-trigger strategy, whereby each country i permanently reverts to a zero tax $\tau^i = 0$ following any deviation (Fearon 1998; McGillivray and Smith 2000; Rosendorff 2005). While this strategy is perhaps not fully plausible because governments cannot credibly commit to permanently suspending international cooperation, it is simple and permits a sharp analytical focus on the key issue.[7] In all three equilibria, failure to impose the equilibrium tax at time t results in a punishment at time $t+1$. But only installation through a technological standard is contractible, so a permanent reversion to a zero pollution tax at time $t = 0$ is only admissible in the compulsory-installation equilibrium. Enforcing installation is unnecessary in the no-installation equilibrium, while failure to implement flexible installation at the pre-game stage cannot trigger a punishment because other countries cannot identify the deviation.

6 The Result

To solve the model, I find the maximal enforceable tax rate τ_*^i for the three equilibria. I concentrate on finding the equilibrium that maximizes the common payoff (9). There are two enforcement constraints. First, in the repeated game, no country i should benefit from a deviation to the individually rational tax $\tau^i = 0$ at any time. Second, in the pre-game stage, they must ensure that pollution-control equipment is installed or not installed as expected.

In the repeated game, the benefit of defection by imposing the zero tax $\tau^i = 0$ on the polluting industry is enhanced production and consumption efficiency,

$$V^i(0, \tau_*^{-i} \mid \mathbf{s}_*) - V^i(\tau_*^i, \tau_*^{-i} \mid \mathbf{s}_*). \tag{10}$$

This benefit is increasing and strictly convex in the equilibrium tax τ_*^i by (5). The punishment for defection is

$$\frac{\delta}{1-\delta}\left(V^i(\tau_* \mid \mathbf{s}_*) - V^i(0 \mid \mathbf{s}_*)\right). \tag{11}$$

As long as the tax rate is below the collective optimum, this cost is increasing and strictly concave in the level of cooperation by (5). To ensure compliance in the repeated game, (11) must weakly exceed (10).

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[7] The extension to alternative enforcement strategies is trivial but cumbersome.

In a no-installation equilibrium, the maximal enforceable tax rate τ_*^i is found by fixing $\mathbf{s}_* = 0$ and setting (11) equal to (10). No country i has an incentive to deviate by imposing a technological standard because the payoff from this defection is negative.

A compulsory-installation equilibrium can be made part of an international agreement, so other countries immediately revert to the one-stage Nash equilibrium if a government fails to impose the technological standard. The benefit from defection at the pre-game stage is simply x, as it is never optimal to invest if a permanent reversion to the one-stage Nash equilibrium is expected and pollution is therefore not taxed. The cost of defection is

$$\frac{1}{1-\delta}\left(V^i(\tau_* \mid \mathbf{s}_*) - V^i(0 \mid 0, \mathbf{s}_*^{-i})\right). \tag{12}$$

What is the maximal enforceable tax rate τ_*^i? The severity of the punishment for defection in the pre-game stage clearly *increases* with the tax rate τ_*^i by (12) because the value of lost cooperation grows, so the only constraint that is binding in equilibrium is that (11) equals (10). A compulsory-installation equilibrium thus exists if and only if (12) does not exceed x for the implicitly defined tax rate.

Note that the one-stage Nash equilibrium resulting from punishment is not identical to that obtaining if no country invests. Industries in other economies have installed pollution-control equipment with the expectation that cooperation results. Even though there is no tax on pollution, this equipment reduces the pollution-intensity of production, while the factor inputs and the level of production are not changed. Country i benefits from cheating others into installing the equipment because it enjoys reduced transboundary pollution without any investment or cooperation at all.

In the flexible-installation equilibrium, the compliance problem is subtle. It is clear that no country i benefits from imposing a technological standard because there is flexible installation in equilibrium. We can also safely ignore the possibility that country i does not promise a reward, so that no company undergoes flexible installation, but then does not defect. To see why, note that in that case pollution-control equipment is worthless in the repeated game, so the no-installation equilibrium Pareto-dominates the flexible-installation equilibrium.

All that remains is to see if country i benefits from doing nothing and then defecting. If it defects in the repeated game, the deviation must be at time $t = 0$ because the equilibrium strategy is stationary. Since flexible installation is not contractible, country i also saves the cost of unnecessary flexible installation y by simply choosing not to reward flexible installation. Thus, the aggregate benefits from the most profitable collusive defection are given by

$$y + V^i(0, \tau_*^{-i} \mid 0, \mathbf{s}_*^{-i}) - V^i(\tau_*^i, \tau_*^{-i} \mid \mathbf{s}_*). \tag{13}$$

The first benefit is that the citizens need not install. The second benefit is that other countries cooperate for one period while the defector free rides. They cannot punish a country for failing to implement flexible installation because the very idea is that measures to reduce pollution intensity are voluntary. The cost of defection is therefore simply δ times (12):

$$\frac{\delta}{1-\delta}\left(V^i(\tau_* \mid \mathbf{s}_*) - V^i(0 \mid 0, \mathbf{s}_*^{-i})\right). \tag{14}$$

Upon flexible installation, (14) must weakly exceed (13). Note in particular that punishment is delayed by one period, so it is *always* less costly than under flexible installation.

The analysis above can now be used to select the best possible equilibrium. If it is the no-installation equilibrium, the question of technological standards is moot. But suppose the cost of pollution-control equipment is not prohibitive so that the no-installation equilibrium is not a good choice. Should countries choose compulsory or flexible installation? The cost difference $x - y > 0$ favors flexible installation. However, I have shown that the benefits of defection increase while the costs decrease under flexible installation.

Proposition 1. *The maximal enforceable tax rate in a compulsory-installation equilibrium is higher than in a flexible-installation equilibrium.*

If countries write an international agreement that prescribes the second-best symmetric vector of taxes $(\tau_* \mid \mathbf{s}_* = 1)$, all countries are exactly *indifferent* between defection and compliance in every period of the repeated game. But if they also inform the domestic companies that they will not comply, and avoid immediate punishment because flexible installation is voluntary, the benefit from defection must be strictly higher. The second best is not enforceable, so countries must choose a costly technological standard or a lower pollution tax.

The result reveals a fundamental tradeoff between technological standards and flexible installation. While the expected cost of flexible installation is unambiguously lower than the cost of compulsory installation, flexible installation must induce a lower tax rate for reasons of enforceability. Upon imposing technological standards, countries can enforce compulsory installation by immediately suspending cooperation if a country fails to set the contractible standard on industries. If the cost of is low enough, technological standards enable the use of efficient instruments.

Since flexible installation induces a third-best tax rate, it is accompanied by a collective time-inconsistency problem. In the repeated game, the countries have a common interest in replacing the current tax rate with the maximal enforceable tax rate. As a result, they prefer immediate renegotiation of the international agreement. But if they expect renegotiation, the third-best tax rate is replaced by the second-best tax rate in the repeated game, so no country has an incentive to encourage flexible installation, and the equilibrium unravels. In addition to building additional collective enforcement power, countries must commit to an inferior international agreement that is collectively time-inconsistent.

7 Empirical Implications

The model has a number of empirical implications that lay a foundation for systematic hypothesis testing. I first consider so small changes in three familiar exogenous parameters that the decision to install is not changed. The following proposition shows that standard comparative statics follow:

Proposition 2. *The equilibrium tax rate* τ_* *is decreasing in the price elasticity of consumption* $\mid \frac{\partial d^i(\cdot)}{\partial p^i} \frac{p^i}{d^i(p^i)} \mid$ *but increasing in the marginal damage of pollution* $\frac{\partial g}{\partial E^i}$ *and in the number of countries* n.

First, as price elasticity increases, the deadweight loss from taxation increases, so the benefits of defection in the repeated game increases. Second, as the marginal damage of pollution increases, the value of future cooperation increases, so the cost of defection increases. Finally, as the number of countries increases, defection results in loss of cooperation by a higher number of other countries, so the cost of defection increases. Importantly, all three effects derive from the imperative of enforcement while economic efficiency is irrelevant.

Consider now changes in the cost of flexible and compulsory installation. These are the most important comparative statics because they are unique to the model.

Proposition 3. *Small changes in the cost of compulsory installation have no effect on equilibrium behavior. If the cost of compulsory installation decreases so much that technological standards now replace flexible or no installation, the equilibrium tax rate increases.*

Small changes in the cost of installation cannot remove the collective incentive to impose a technological standard. Additionally, small changes in the cost of compulsory installation have no effect in the repeated game, so they do not change the second-best tax τ_*. To see why, recall that installation and cooperation are fully separable. But if the cost of installation decreases enough, the benefit of reducing pollution at a lower cost outweighs the cost of installation. The tax rate increases for two reasons. First, the lower cost of mitigating pollution reduces the incentive to defect, thus creating collective enforcement power. Second, the value of future cooperation increases as the compliance cost decreases, so the cost of defection increases.

Consider next the more complex case of flexible installation. Now changes in installation affect the enforcement constraints at the production and consumption stage:

Proposition 4. *Under flexible installation, a small decrease (increase) in the cost of flexible installation causes an increase (decrease) in the tax rate. If the cost of flexible installation decreases so much that that flexible installation now replaces compulsory or no installation, the equilibrium tax rate decreases relative to compulsory installation while the effect is ambiguous relative to no installation.*

Avoiding the cost of installation is part of the benefits from defection upon flexible installation, so a decrease in these costs releases enforcement power that countries can use to impose a more stringent tax on pollution. Countries cannot even enforce the second-best tax when they choose flexible installation, so the benefits could indeed be significant.

In contrast, the effect of a cost reduction on the equilibrium tax rate is ambiguous. If countries previously chose compulsory installation, the equilibrium tax rate must decrease because the optimal defection avoids the installation cost under flexible installation. But if the previous choice was no installation, there are two countervailing effects. On the one hand, the cost of compliance and the value of cooperation increase. On the other hand, the value of the optimal defection could increase. It is not clear which effect is dominant.

Consider finally changes in the effectiveness of pollution-control equipment:

Proposition 5. *A change in the pollution intensity of production with pollution-control equipment has the following effects:*

1. *Under no installation, if there is a large enough reduction, countries choose flexible or compulsory installation in the new equilibrium. If it is compulsory installation, the equilibrium tax rate increases. If it is flexible installation, the change in the equilibrium tax rate is ambiguous.*
2. *Under either installation, a small increase (decrease) causes a decrease (increase) in the equilibrium tax rate.*

The first part tells us that as the efficacy of pollution-control equipment increases, countries more likely install it. If they choose compulsory installation, this allows them to enforce of a higher tax. If they choose flexible installation, this could necessitate a lower tax because the returns to defection grow when installation is required. The second part tells us that a decrease in pollution intensity allows higher equilibrium tax rates because international cooperation causes fewer consumption and production distortions.

8 Discussion

The efficiency-feasibility tradeoff stems from the impossibility of writing a treaty that mandates the installation of pollution-control equipment without sacrificing flexibility. Individual companies hold private information about local conditions, and they do not have an incentive to tell the governments what their true costs are. If the government uses the price signal to maximize efficiency, it cannot credibly claim to other governments that the pollution-control equipment will be installed, as flexible installation is neither verifiable nor subject to sanctions under international law.

To capture the double dividend of defection, the government might have to guide industry expectations so as to purposefully discourage flexible installation. In many circumstances, the government might simply inform the industry about the intention not to comply, especially if the companies are organized as an interest group (Aidt 1998; Maggi and Rodriguez-Clare 1998; Olson 1965). But explicit steering is not a necessary condition for enforceability problems. If the companies understand that the forthcoming pollution tax is so high that defection is profitable to the government, they can induce the government to defect by simply refusing to install pollution-control equipment. Since pollution control generally *reduces* profits to existing companies, it is not difficult to conceive of conditions under which the industry has a preference against international environmental cooperation. And even if the industry has no coordination capacity, compliance under flexible installation requires a self-fulfilling prophecy in a rational expectations equilibrium.

The possibility of collusion between the government and the companies has interesting implications for the effect of the domestic regime type on enforceability of international environmental cooperation. A useful distinction can be made between coordinated and liberal market economies because the role of the state in managing the economy is bigger in the former case (Hall and Soskice 2001; Molina and Rhodes 2002; Shonfield 1965; Thelen 2004). This presumably facilitates collusion between the government and the industry, so it could be that coordinated market economies readily choose technological standards, not only because the government prefers to directly manage economic activity, but also because these countries have greater commitment problems under flexible installation. Of course, the effect of any other factors that give special interests access to the government is qualitatively similar.

Another important factor is transparency (Svolik 2006). In international environmental cooperation, I have used the difficulty of verification as one justification for the assumption that countries cannot punish failure to implement flexible installation. This is plausible as long as production technology is complex enough, but domestic transparency could nevertheless complicate collusion. If investors note that *aggregate* investment in clean technology is significantly lower than expected, this sends an informative signal to other countries. Even though it is entirely possible that any given plant in Ohio need not undergo major adjustments, it is highly implausible that the entire United States could avoid substantial investments. Transparent investment decisions and effective dissemination of information through the financial markets could allow partial enforcement of flexible installation. This could be difficult under international law, but if other countries understand that non-compliance is forthcoming, they could informally agree to reduce cooperation or otherwise punish the defector (Dai 2002; Lipson 1991).

My argument is thus compatible with theories that focus on monitoring difficulties (Mitchell 1994). The conventional formulation has emphasized monitoring complications that efficient policy instruments cause, while my theory assumes that such complications are not present. Instead, the present argument builds on the notion that flexibility in installation – a *consequence* of imposing a price on pollution – complicates verification. Yet the effect is qualitatively similar, as countries must choose technological standards to avoid the problem. The key difference is that where my theory applies, countries should use a policy mix that is not available if efficient instruments are too difficult to monitor. This empirically falsifiable hypothesis is useful for comparison.

The result also sheds light on the possibility that technological standards facilitate the use of trade sanctions (Barrett 2008; Sawa 2008). In the model, I have used a simple grim-trigger enforcement strategy and ignored the possibility of sanctions through issue linkage (Lohmann 1997). The central result does not depend on this specific enforcement strategy because the benefits and costs of defection are present even if sanctions are used. However, one reason why installation of pollution-control equipment limits enforcement is the effect on pollution levels in the one-stage Nash equilibrium. If companies install, the pollution intensity of production decreases even without any taxation, so the cost of punishment to the defector decreases. This effect does not apply to sanctions, however, so my argument actually *strengthens* the case for sanctions through issue linkage. Again, a useful falsifiable hypothesis follows because countries should be most willing to consider sanctions if international environmental cooperation requires installation of pollution-control equipment.[8]

The combination of technological standards and a pollution tax is another notable feature of the analysis. The extant literature on technological standards highlights their advantages in enforcement, but there are few results on the optimal policy mix under imperfect enforcement. In my model, the choice of technological standards *increases* the optimal pollution tax, so the efficiency-feasibility tradeoff turns out to be much more complicated than previously thought. Economic theory emphasizes the advantages of economy-wide market-based instruments while enforcement concerns recommend technological standards, but the present analysis shows that technological standards are often a precondition for efficient instruments. This complementarity relationship could explain why international environmental agreements often contain this specific policy mix.

For tractability, I have omitted an analysis of nonstationary tax rates. However, the enforcement problem I have identified provides a potential rationale for a gradual increase in pollution taxation. If states agree on gradually increasing the pollution tax, they can reduce the incentive to de-

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[8] In general, the use of trade sanctions is rare and highly contentious in international environmental affairs (Biermann 2001; Charnovitz 2001; Eckersley 2004).

viate under flexible installation while avoiding some of the deadweight loss. But this does not qualify the central result, because nonstationary tax rates are always inefficient in a repeated game.

An important simplification is that the installation of pollution-control equipment does not restrict competition. This is reasonable because each country prefers not to induce production and consumption distortions, but it could fail if the real cost of installation is so high that positive profits are necessary. In this case, the true cost of pollution-control equipment increases with equilibrium prices. Does this strengthen or weaken the case for technological standards? On the one hand, technological standards increase the cost of installation, so they induce larger distortions as well. On the other hand, it is probably easier for a government to verify the true cost of installation if there is a technological standard, so the compensation strategy I have outlined might be easier to implement with a technological standard. In this case, imperfect competition *strengthens* the case for technological standards.

Another noteworthy simplification is that the only difference between compulsory and flexible installation is cost. An alternative approach is to allow variation in pollution intensity, so that the less pollution-intensive technology has an advantage. Even in this case, the result on enforceability holds, although it is possible that technological standards appear in less favorable light if they fail to reduce the cost of cooperation.

The analysis builds on several convenient assumptions that are not essential. In the model, negative externalities are strictly international and the economies are closed. These are important simplifying assumptions, but they are not essential for the central result. The possibility of international trade in particular could reveal unforeseen effects, and possibly shed light on the relationship between technological standards and trade sanctions, but the fact that unverifiable installation cannot be enforced appears robust. Another assumption that might seem problematic is the irreversibility of installation (Watson 1999). However, the central result holds even if each country can at any time partially recover the cost of installation or switch off the pollution-control equipment. This possibility facilitates enforcement because the value of the one-stage Nash equilibrium to the defector decreases, but flexible installation is nevertheless more difficult to enforce than compulsory installation. Finally, I have assumed that flexible installation is unobservable to reduce notation, but all results hold if other countries i obtain an informative signal about flexible installation with some probability $\rho \in (0, 1)$, as long as this probability is not too high.

9 Towards a Theory of the Third Best

An important finding is the collective time-inconsistency problem that accompanies flexible installation. Flexible installation is not contractible, so a defecting country obtains a double dividend. This implies that the maximal enforceable *ex post* tax rate cannot be enforced *ex ante*. Consequently, all countries have a common preference for renegotiating the agreement to improve environmental quality. But if a country believes the agreement will be immediately renegotiated, *ex ante* defection will again be profitable under flexible installation. Technological standards remedy this problem because they ensure that the maximal enforceable tax rate is identical before and after installation as long as technological standards are enforceable and profitable in the first place.

This result is an important special case of the "renegotiation problem." In international cooperation theory, renegotiation is usually a problem because it constrains the use of punishment strategies "off the equilibrium path" (Barrett 1994; Carrubba 2005, 2009). Briefly, the idea is that countries cannot credibly threaten to inflict substantial damage on the defector if the collateral damage on the *punishers* is also substantial. For example, to drown the world in pollution is hardly a credible threat to enforce international environmental cooperation. The paradox of a third-best tax rate is different, however, because it implies that equilibrium behavior is renegotiable. It is not that countries must credibly commit to imaginary or counterfactual threats that are rarely if ever carried out. Instead, a profitable opportunity to renegotiate inevitably appears even if no country deviates, so the maximal enforceable tax rate in the game is lower than the maximal enforceable tax rate in the subgame after installation. This previously unrecognized problem appears difficult because it is difficult to conceive of a credible collective commitment to behavior that nobody will prefer in the future.

Contract theory offers useful insights into this problem (Bolton and Dewatripont 2005; Hart and Moore 1988; Tirole 1999). A common assumption in the literature is that contracts should not be renegotiable. But contract theorists usually build on the restrictive assumption that contractible behavior *per se* is automatically enforced, while my analysis requires that even contractible behavior must be endogenously enforced. The analysis here shows that the problem of endogenous enforcement, so important in international politics, gives rise to collective time-inconsistencies that resemble those identified in the contracting literature under a set of entirely different assumptions regarding property rights.

How general is the phenomenon? Consider any situation in which social agents commit to cooperation but imperfectly verifiable costly adjustments are a precondition for success. If the most profitable defection comprises non-cooperation, it also comprises failure to adjust because adjustment is only profitable conditional on cooperation. The benefits of defection are strictly higher *ex ante*, so the agent must *strictly* prefer cooperation to defection in the cooperation phase. But this implies that some enforcement power is unused, so either enforcement power is in abundant supply or the maximal enforceable level of cooperation is vulnerable to defection *ex ante*.

Third parties have an important role in effecting this paradox. To see why, consider the context of international environmental cooperation and suppose private information was indeed necessary to minimize the cost of installation, but this private information was held by each government. Then the government could avoid the paradox of the third best by simply announcing an installation plan and implementing it in a transparent fashion. But if private information is held by the companies, a government must extract this information from them even though they have incentives to exaggerate the cost to maximize compensation, and then ensure that foreign governments can monitor these installations even though they are fully decentralized. While this commitment could be credible in some circumstances, it requires elaborate institutional designs that could increase the cost of international cooperation.

10 Application to Global Warming

As a specific application, I briefly consider the design of an international agreement to mitigate long-term global warming after the Kyoto Protocol expires in 2012 (Aldy and Stavins 2007). This is a truly global problem that exhibits unusually salient incentives to defect, has a long time horizon, and could give rise to path dependencies. It is therefore a prime example of the conditions under which the theory should apply.

First, reductions of greenhouse gas emissions are the quintessential public good. As Barrett (2008, 240) writes: "[c]limate change may or may not be the most important problem the world has ever faced, but it is certainly the greatest challenge for collective action." Most individual countries contribute only a little to global warming, especially in comparison with such giants as China and the United States, so the reward for free riding is large. The sustainable energy transition required to achieve significant reductions in the atmospheric concentrations of carbon dioxide and other greenhouse gases, let alone the global reductions of 50 per cent envisioned by the European

Union to prevent global warming above two degrees Celsius, necessitate costly adjustments in the vast majority of countries (IPCC 2007).

Second, these adjustments can only be achieved over a timespan of decades. To increase the generation of clean energy and improve energy efficiency, countries must undergo at least one investment cycle.[9] It is simply too costly to immediately overhaul the energy and transportation sectors. An important implication of the long time frame is that the required up-front costs only produce tangible periods with a significant lag.

Third, the sustainable energy transition that is required exhibits path dependence.[10] As Unruh (2000) and Unruh and Carrillo-Hermosilla (2006) show, the energy sector changes slowly. This complicates efforts to decarbonize the economy both in industrialized and developing countries, but it also implies that were such a decarbonization effort to succeed, it would be highly resistant to a reversal. A country that uses renewable energy for most of its final energy consumption and has successfully converted the societal infrastructure to one based on public transportation and energy conservation, might be able to attain low greenhouse gas emissions for years even if it were to refrain from further policy adjustments.

These three features of the strategic problem provide insight into the potential benefits of technological standards. If countries are to achieve significant emissions reductions in the long term, they must ensure that defectors are punished promptly. The payoff to avoiding a costly and lengthy energy transition is high, and the payoff in the form of significant emissions reductions could materialize only in the future. Additionally, other countries lose their ability to punish a defector in the future if they do undergo this energy transition, as their ability to rapidly revert to the one-stage Nash equilibrium with high greenhouse gas emissions is severely constrained. Technological standards therefore warrant serious consideration in the international negotiations for a long-term agreement to mitigate global warming.

11 Conclusion

The tradeoff between cost effectiveness and political feasibility is central to the design of international environmental agreements. I have shown that to enforce compliance with a treaty that purports to solve a global collective-action problem, countries sometimes gain from imposing technological stan-

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[9] For the economics of climate change, see Stern (2006). For a critical review, see Weitzman (2007).

[10] For the concept of path dependence, see Arthur (1989); Pierson (2000).

dards despite strong economic arguments to the contrary. This claim follows from an examination of the incentives to defect under various international environmental agreements. My key analytical result is that these incentives are stronger if countries do not impose a technological standard. This problem gives rise to a phenomenon that I call the paradox of the third best, whereby countries must credibly commit to a pollution tax that they will prefer to renegotiate in the future. The analysis informs policy by characterizing the conditions under which technological standards can improve enforceability. This appears to be true in the crucial case of global warming.

Importantly, the analysis lays a solid foundation for future research on international cooperation and political economy. The simple model provides a flexible platform for various extensions, and the central assumptions are not specific to international environmental affairs. The theoretical results shed light on a new causal mechanism that political economists have not recognized, while the empirical implications permit systematic hypothesis testing. To demonstrate the added value of the analysis in other fields of international politics, I conclude by discussing an extension to international trade liberalization and regulatory reform.

To maximize the benefits from international economic exchange, countries can agree to remove distortionary or protectionist trade policies and regulations that constitute non-tariff barriers to trade (Kono 2006). Before they can reap the gains, however, they must undergo a costly adjustment, as relative prices change and transitional unemployment reduces economic growth (Nsouli, Rached, and Funke 2005). Ideally, countries could agree on a liberalization target to be met after an adjustment period. If the domestic companies, including state enterprises, find this commitment credible, they capitalize on their private information to minimize the cost of adjustment. As in international environmental affairs, it is often better that the government does not engage in micromanagement of the economy.

The present analysis reveals a potential enforceability problem. If the government can collude with the domestic companies, it can inform them that it is not committed to maintaining liberal economic policies. The domestic companies avoid the cost of adjustment, and if other countries liberalize, exporters will have new profitable opportunities to increase profits (Milner 1988). Consequently, countries might have to agree on specific reforms, such as privatization or rapid dismantling of regulatory policies and institutions. This increases the cost of reform but allows countries to enforce more ambitious liberalization targets.

The enforceability problem could give rise to a renegotiation problem as well if the reform is reciprocal. If multiple countries agree on reciprocal liberalization without a detailed adjustment program, they could have a collective incentive to renegotiate the liberalization target *ex post*. If they agree on a detailed adjustment program as well, they avoid this renegotiation problem. But if reform is not reciprocal, so that one country reforms in exchange for foreign aid or access to the World Trade Organization, this renegotiation problem disappears, as the unwilling reformer is perfectly satisfied with the fact that the absence of a detailed adjustment programs reduces the maximal enforceable reform.

Appendix

Proof of Proposition 1

Suppose the two equilibria exist. As shown in the main text, optimal defection in the repeated game occurs at time $t = 0$. In the repeated game, each country i is indifferent between defection and cooperation under compulsory installation at all times t. But under flexible installation, the most profitable defection implies that the payoff to defection increases by y, while the punishment remains unchanged because it continues to be imposed at time $t = 1$. Thus, any tax rate $\tau^i \geq \tau^i_*$ prompts defection under flexible installation. ■

Proof of Proposition 2

Verify that a small increase in $\mid \frac{\partial d^i(\cdot)}{\partial p^i} \frac{p^i}{d^i(p^i)} \mid$, where the first fraction is strictly negative and the second fraction is strictly positive, occurs if and only if $\frac{\partial d^i(\cdot)}{\partial p^i}$ grows because $d^i(x) = \int_0^x \frac{\partial d^i(p^i)}{\partial p^i} dp^i$. Consider first compulsory installation. Since the increase in $\mid \frac{\partial d^i(\cdot)}{\partial p^i} \frac{p^i}{d^i(p^i)} \mid$ is small, it does not affect the installation of pollution-control equipment. In equilibrium, each country i is exactly indifferent between defection and cooperation. When $\frac{\partial d^i(\cdot)}{\partial p^i}$ increases by a small amount, an examination of (5) shows that the payoff from defection (10) increases while the cost of defection (11) decreases. But then any tax rate $\tau \geq \tau_*$ is not enforceable and τ_* must thus decrease. Consider next flexible installation. Since the increase in $\mid \frac{\partial d^i(\cdot)}{\partial p^i} \frac{p^i}{d^i(p^i)} \mid$ is small, it does not affect the installation of pollution-control equipment. In equilibrium, each country i is exactly indifferent between defection and cooperation. When $\frac{\partial d^i(\cdot)}{\partial p^i}$ increases by a small amount, the payoff from defection (13) increases while the cost of defection (14) decreases. Since the decision to install is unaffected, it must be that any tax rate $\tau \geq \tau_*$ is not enforceable and τ_* must thus decrease.

Consider now a small global increase in $\frac{\partial g(\cdot)}{\partial E^i}$. Consider first compulsory installation and observe that the decision to install is unchanged. Note that for a given τ_*, an increase in $\frac{\partial g(\cdot)}{\partial E^i}$ leaves the payoff from defection (10) unaffected while the cost of defection (11) increases. Since countries cannot achieve optimal play, increasing the tax rate by $\epsilon \to 0$ increases the payoff to all countries i. Consider next flexible installation and observe that the decision to install is unaffected. Proceeding as in the first part of this proof, note that (13) is unaffected while (14) increases. Thus, proceed as above to show that τ_* increases.

Consider finally a small increase in n. Observe that when $\frac{n+1}{n}$ is sufficiently small, the decision to install is unaffected for compulsory and flexible installation. Proceed as above to see that the payoff from defection is unaffected while the cost of defection increases for compulsory and flexible installation, which implies that τ_* can be increased.

Proof of Proposition 3

Fix (x_*, τ_*). Examining (10) and (11), small changes in x_* do not affect the enforcement constraint. Moreover, small changes in x_* do not affect the installation decision.

Fix (θ_*, τ_*), where $\theta_* \neq x_*$. Small changes in x do not affect the installation decision. Now suppose the decrease in x is large enough so that compulsory installation becomes profitable. If countries did not install previously, $\gamma < \beta$ implies that for a given τ_*, (10) decreases while (11) increases because the cost of cooperation decreases. If countries used flexible installation previously, the payoff from the optimal defection at time $t = 0$ decreases by y, so τ_* can be increased. ■

Proof of Proposition 4

Fix (y_*, τ_*). A small decrease in y does not affect the installation decision but, since the payoff from defection (13) equals the cost of defection (14), tax rate τ_* can be increased by some strictly positive amount.

Fix (θ_*, τ_*), where $\theta_* \neq y_*$. Small changes in y do not affect the decision to invest. Now suppose the decrease in y is large enough so that flexible installation becomes profitable. If the previous choice was compulsory installation, the payoff from the optimal defection at time $t = 0$ increases by y, so τ_* can be increased. If the previous choice was no installation, consider the following examples. To see that τ_* can sometimes be increased, let $y \to 0$ and proceed as in the proof of Proposition 3. To see that τ_* must sometimes be decreased, fix some positive y and note that both (13) and (14) can increase. ■

Proof of Proposition 5

To prove the first part, note that as γ decreases, the domestic cost of a given tax rate τ_* decreases. Thus, for sufficiently low γ, it becomes strictly profitable to install. Examine (10) and (11) and proceed as in the proof of Proposition 3.

To prove the second part, note that a small reduction in γ does not affect the decision to install. For compulsory installation, note that for a given τ_*, (10) decreases while (11) increases. For flexible installation, note that for a given τ_*, (13) decreases while (14) increases. $\blacksquare$

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