Prices vs. Quantities with Multiple Countries*

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Abstract

What is the best policy for mitigating climate change and managing other multilateral public goods? To answer this question, this paper examines a policy-making game among several countries in the face of cost uncertainty. Governments choose both the intensity of a policy (i.e., price level or quantity level) and the type of policy: price or quantity (e.g., carbon tax or emissions quota). When cost shocks are country-specific, this paper shows that countries tend to choose the price instrument despite the quantity instrument being superior from a welfare perspective. In particular, the paper shows that the social welfare from non-cooperatively chosen quantities (e.g., emissions quotas) may dwarf the social welfare from first-best price levels (e.g., carbon taxes). Strikingly, when cost shocks are world-wide, global carbon taxes are inefficient unless the ratio of the slope of the marginal abatement cost function to the slope of the marginal benefit function exceeds $80,000$.

JEL Codes: C7, D8, F5, H21, Q28, Q58.

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1 Introduction

Global public goods improve humanity's welfare and sustain the planet's long-term health. They enable nations to address problems such as climate change, infectious diseases, and the proliferation of weapons of mass destruction. Despite their indispensability, these goods are undersupplied (Barrett, 2007). A relevant question is: what is the best way to manage such goods and minimize overall inefficiencies? The answer to this question not only shapes humanity's welfare in our time, it also has substantial ramifications for the welfare of future generations.

To fix ideas, focus on climate change. The best climate policy based on conventional wisdom rests on Weitzman's rule (Weitzman, 1974). The rule is: "[if] the curvature of the benefit function [b] is small relative to the curvature of the cost function [c], then price-type regulation is more efficient, and the converse holds true" (Nordhaus, 2006, p. 33). Nordhaus adds, "the structure of the costs and damages in climate change gives a strong presumption to price-type approaches." Similarly, Mankiw (2009, p. 18) argues that "cap-and-trade systems are also relatively inefficient," unlike carbon taxes. In 2018, when Economic Experts Panel members of the Chicago Booth School of Business were asked whether carbon taxes represented a better climate policy compared to cap-and-trade schemes, their response was given with an overwhelming majority. About 80% of the respondents agreed with the claim whereas the rest were uncertain. Not even a single voice disagreed with the claim.[1]

With the consensus view in mind, consider an example from Weitzman's workhorse model to allow for political boundaries. Next, introduce two sovereign countries, say N and S. Each country benefits $B = \frac{3}{2}Q - \frac{b}{2}Q^2$ from the total abatement $Q \equiv q_N + q_S$, where q_N and q_S are the private abatements of N and S.[2] Abatement costs each country $C_i = [1 + \theta_i] q_i + \frac{c}{2}q_i^2$, where θ_i takes the value 1 or -1, independently, with equal probability. Let $b = 1$ and $c = \frac{6}{5}$. What is the best way of supplying abatement in this environment?

The answer from conventional wisdom is unequivocal – a carbon tax is better, since $c > b$. Yet, solving the example results in a social welfare of $\frac{25}{117}$ from the first-best carbon taxes and of $\frac{90}{117}$ from the first-best carbon quotas. Remarkably, the social welfare resulting from the non-cooperatively chosen equilibrium quotas is $\frac{255}{512}$, which is more than twice of the social welfare from the first-best carbon taxes. This example suggests that something is missing from conventional thinking. The question is what.

[1] http://www.igmchicago.org/surveys/climate-change-policies

[2] Following the standard convention, goods are assumed to be good. The paper uses abatement q_i, not pollution e_i. Even though policies cap pollution, and not abatement, using abatement makes the presentation better and retains the insights, since $q_i \equiv K - e_i$ for some constant K.

The basic idea advanced in this paper is that a country using a carbon tax imposes a risk externality on other countries, thereby causing inefficiency. Henceforth, I refer to the inefficiency due to this risk externality as the *PvQ inefficiency.* It arises from a policy's *type*: carbon tax vs. quota. With at least two countries and $c > b$, the risk externality becomes significant and the social welfare from a non-cooperatively chosen quota dwarfs the social welfare from the first-best carbon tax.

The remainder of this paper investigates the factors driving the result in the example by examining the origin and significance of the PvQ inefficiency. To this end, the paper analyzes the question regarding the best policy by extending Weitzman's workhorse model to a game of policy-making involving several countries supplying a public good. A country benefits from the global supply and incurs a private cost of contributing to the global supply. While setting policies, a country's regulator cannot foresee the technological realities faced by firms, operating within the regulator's jurisdiction, when complying with the regulation. Thus, this paper examines the best way of managing a multilateral externality when countries choose both the type and intensity of a policy in a strategic setting and in the face of technological uncertainty. The analysis of the game formalizes the presence of a novel source of inefficiency — risk externality. This inefficiency arises as a result of a country choosing a policy type that imposes a negative externality on other countries. On top of explaining the outcome in the example above, this inefficiency generates a rich set of results and rationalizes empirical observations hard to reconcile with conventional thinking.

The PvQ inefficiency is distinct from the well-understood *intensity inefficiency* (i.e., the inefficiency arising when a country imposes a lower carbon-tax level or a higher pollution quota than the first-best). To establish this distinction formally, the first result examines the PvQ inefficiency when countries commit to the first-best levels of prices or quantities. More precisely, let a planner fix the policy intensity of each country to the first-best level. However, let a country choose its own policy type knowing that it will have to implement the first-best intensity in either case. Despite the fact that the price or quantity level is fixed at the first-best level, Proposition 1 shows that the policy type chosen by countries is inefficient.

Establishing that the PvQ inefficiency arises without a suboptimal policy intensity is necessary in order to isolate it from other sources of distortion. Yet, the appropriate notion of inefficiency calls for comparing countries' choice in equilibrium with the planner's choice. Hence, Proposition 2 establishes the PvQ inefficiency by analyzing the outcome from the set of policies countries choose in equilibrium relative to a Pareto-efficient outcome a social planner would have chosen.

To understand the economics behind the PvQ inefficiency, suppose a country prefers the price instrument, since firms operating in its jurisdiction will have the flexibility of delivering a lower abatement if they happen to have a high abatement cost in the future. However, this regulatory flexibility introduces variability in the country's abatement. This variability, in turn, generates a cross-country risk externality. This is due to the fact that all other countries face variability in the total abatement independently of the policy type they choose. When choosing the price instrument, a country only considers its own private benefit from cost-reductions and ignores the risk externality it imposes on other countries. Hence, the country's choice of policy type becomes inefficient. In a situation with several countries, the risk externality increases and forcing countries to adopt a quota becomes socially optimal.

The presence of the PvQ inefficiency implies that the supply of a multilateral public good suffers from an extra source of policy distortion, on top of the inefficiency arising from suboptimal policy intensity. The PvQ inefficiency and the intensity inefficiency are distinct, and each source of inefficiency can arise independently. Thus, Proposition 3 establishes the signature of the PvQ inefficiency by comparing the distortion due to the PvQ inefficiency with the distortion due to the intensity inefficiency. Unexpectedly, there exists a condition under which quotas, whose amounts are chosen non-cooperatively, result in higher collective welfare compared to the first-best carbon taxes, whose amounts are chosen to maximize social welfare.

These results prevail in various contexts. If the cost shock is global, both the planner's choice and countries' equilibrium policy choices exhibit asymmetry. This result is in direct contrast with the symmetric choices under independent shocks. On top of explaining why identical countries may choose different policies, a global cost shock provides sharp results. It rationalizes why a union of sovereign states, such as the US and the EU, often chooses the quantity instrument instead of the price instrument. Moreover, for global carbon taxes to be socially optimal for n countries facing a global cost shock, the slope of the marginal abatement cost function has to exceed the slope of the marginal benefit function by an order of $2n^2$.

If a supranational union such as the European Union (EU) interacts with independent countries in choosing policies, it internalizes the risk externality of the price instrument only within its member states. Thus, the externality persists since countries outside the union fail to internalize the externality inflicted on the union's members, and vice versa. In turn, this result implies, ceteris paribus, that a union of countries is more likely to adopt the quantity instrument than the price instrument, whereas the converse holds true for independent countries. This prediction rationalizes an empirical observation that is hard to square with conventional wisdom. The quantity instrument is chosen in a union such as the United States (US) to regulate SO_2 and in a union such as the EU to regulate CO_2 (Schmalensee and Stavins, 2013; Stavins, 2018), whereas the price instrument is chosen in individual countries (World Bank and Ecofys, 2018).

In addition, this rationalizes the fact that countries choose the quantity instrument when belonging to a union and choose the price instrument when not belonging to a union.[3]

The analysis so far has focused on flow-type public goods. Whereas this case covers many important public goods, the benefits from some public goods, such as mitigating climate change, depend on the stock as well. For stock-dependent public goods, foresight becomes a crucial determinant of the efficient policy type. If policy-maker decisions in all countries are environmentally myopic, the initial stock does not play any role in the choice between the price and quantity instruments. This result is in direct contrast with the widely held belief that a stock favors using the price instrument over using the quantity instrument. On the contrary, if policy-maker decisions involve perfect foresight and consider the stock's benefits in the future, the qualitative results remain intact, even though parametric space changes in favor of the quantity instrument. Combined, these generalizations establish that the PvQ inefficiency arises in wider settings than in the case examined in the basic model.

The remainder of this paper proceeds as follows: the next section describes contributions to the literature, while the following section presents the elements of the model. The basic results section examines the origin and significance of the PvQ inefficiency. Afterward, the model is generalized in order to consider various features and to generate testable predictions. The final section concludes the paper.

2 Contributions to the Literature

The choice between price and quantity is one of the long-standing issues in different fields of economic research. To raise its profit, a firm in an oligopoly chooses to compete with its rivals either in quantity or in price (Cournot, 1838; Bertrand, 1883; Tirole, 1988; Singh and Vives, 1998). To raise revenue, while minimizing distortions in international trade, a revenue-constrained policy-maker chooses between a tariff and a quota (Bhagwati, 1968; Dasgupta and Stiglitz, 1977). Similarly, to overcome the glass ceiling problem in publicly listed corporations and in political parties, policy-makers in the EU and other countries choose between a price incentive and a quota (Chattopadhyay and Duflo, 2004; Bagues and Esteve-Volart, 2010; Ahern and Dittmar, 2012; Matsa and Miller, 2013; Casas-Arce and Saiz, 2015; Besley et al., 2017; Bertrand et al., 2019). Finally, to reduce emissions and maintain the supply of a domestic public good, countries choose between fees and quotas (Pigou, 1920; Dales, 1968; Montgomery, 1972; Weitzman, 1974).

[3] These countries include Denmark, Germany, Italy, Netherlands, Norway, Sweden, and the United Kingdom. Even though Norway is not a member of the EU, it still adheres to EU regulations.

The results in this paper contribute to different strands of the literature, which are based on Pigou (1920), Dales (1968), Montgomery (1972), and Weitzman (1974). This literature has considered alternative forms of uncertainty (Adar and Griffin, 1976; Roberts and Spence, 1976), various aspects of nonlinearities (Weitzman, 1978; Yohe, 1978; Kelly 2005), a correlation between uncertain marginal costs and benefits (Yohe, 1978; Stavins, 1996), and stock externalities (Hoel and Karp, 2002; Newell and Pizer, 2003; Goulder and Schein, 2013, among many others).

The approach in Mideksa and Weitzman (2019) comes closest to the framework presented here. Although they study the same question in a strategic framework with multiple countries and although their study establishes the single result that the policy type chosen by countries in equilibrium is governed by Weitzman's rule, they do not pay any attention to the issues in focus here. Thus, unlike the rest of the literature, including Mideksa and Weitzman (2019), this paper identifies the PvQ inefficiency arising due to sovereign nations choosing their own policies, it establishes the significance of this inefficiency, and it generalizes the results to wider settings. These settings include the cost shocks being global or regional, a supranational union interacting with independent countries, and the benefits from a public good being stock-dependent. In addition, the analysis also generates new testable predictions.

The contributions of this paper complement to the literature on distortions of market-based policies with incomplete coverage, such as the carbon leakage literature (Markusen, 1975; Hoel, 1994; Harstad, 2012) and the green paradox literature (Sinn, 2008; van der Ploeg and Withagen, 2012; Jensen et al., 2015). In relation to these streams of literature, the current contribution highlights an inefficiency arising even when a policy's coverage is complete. Similarly, the contributions also advance the literature explaining inefficient policies by using the limits of agency (Meltzer and Richards, 1981; Alesina and Rodrik, 1994; Besley, 2006; Callander and Raiha, 2017), the power of organized interest (Buchanan and Tullock, 1975; Grossman and Helpman, 1994; Rodrik, 1995; Aidt and Dutta, 2004), the problem of commitment (Acemoglu, 2003), political ease for future removal (Austen-Smith et al., 2019), and distributional concerns (Goulder, 1995; Mackenzie and Ohundorf, 2012). Instead of relying on political frictions, the current contribution identifies an inefficiency arising due to countries' boundaries of political power. Thus, it is complements the rich body of knowledge using political frictions to explain the prevalence of inefficient policy instruments.

3 Basic Model

Suppose $N \equiv \{1, 2, ..., n\}$ is the set of countries indexed by $i = 1, 2, ..., n$. A country benefits from the total abatement of $Q \equiv \sum_{j \in N} q_j$ and incurs a private cost $C_i(q_i, \theta_i)$ from abatement of q_i made by firms operating in its own jurisdiction. The reduced-form shock to cost, θ_i, is drawn independently from a distribution with bounded support, zero mean, and positive variance. From the viewpoint of country i's regulator, the net benefit from abatement is

$$W^i \equiv B(Q) - C_i(q_i, \theta_i). \tag{1}$$

To squarely focus on new insights, while maintaining comparability with the vast post-Weitzman (1974) literature, I follow Weitzman (1974) and assume:

$$B(Q) \equiv B'Q - B''Q^2/2, \text{ and} \tag{2}$$

$$C_i(q_i, \theta_i) \equiv [C' + \theta_i] q_i + C'' q_i^2/2, \tag{3}$$

with B', B'', C', and C'' being positive parameters.[4] An interested reader is referred to Weitzman (1974), which establishes (2) and (3) as a second-order approximation of a general $B(Q)$ and $C_i(q_i, \theta_i)$ functions or to Dasgupta and Stiglitz (1977) for elaborate justifications of the workhorse model's features. The current paper extends this workhorse model to allow multiple countries having the decision power on a policy's type and intensity within their own countries. The extension captures the role of national borders and the effect such boundaries of political power impose on the geographical limits and the applicability of policies enacted in a given country.

The game of policy-making among n countries unfolds as described in Figure 1. First, each country's decision maker chooses the type of policy $t_i \in \{p, q\}$, where abatement is regulated through the price instrument p_i or the quantity instrument q_i.

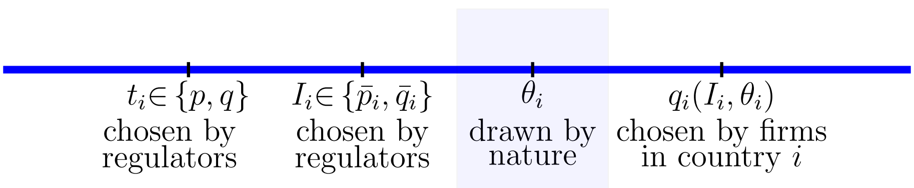

Figure 1: Timing of the Game.

Second, after having observed the chosen profile of types $\mathbf{t} \equiv (t_1, ..., t_n)$, countries

[4] Since the results are robust to independent shocks affecting the benefit function, such shocks are excluded in the rest of the discussion.

simultaneously choose the intensity $I_i \in \{\bar{p}_i, \bar{q}_i\}$, where $\bar{p}_i \in \mathbb{R}_+, \bar{q}_i \in \mathbb{R}_+$. Thus, choices in both stages are made under informational constraints. To put it more precisely, decision-makers in each country act without knowing the random variables' realization beforehand (except knowing the distribution, $\mathbb{E}[\theta_i] = 0$ and variance σ_i^2). Once regulators have committed the type and the intensity of the policy instrument, the independent values of shocks in each country are revealed. These realized values determine how much it costs a firm to comply with a regulatory constraint. Following Weitzman (1974), I assume that the cost shocks are non verifiable, thus non-contractible.

At the final stage, a representative firm in each country chooses the abatement level conditional on the type and the intensity of the regulatory instrument in place and on the realization of the shocks. Unless it is stated otherwise, the proceeding analysis focuses on the pure-strategy subgame-perfect equilibrium, henceforth equilibrium.

4 Basic Results

To identify the equilibrium strategies, I first consider equilibrium strategies beginning with the final subgame and then work backward. In the last stage, firms choose abatement. Since firms operate in a regulatory space in which they are exposed to technology shocks and a given regulation (i.e., either a quota $\bar{q}_i$ or a price per unit of abatement $\bar{p}_i$), a firm's abatement is contingent on technology shock and regulation. The regulation and technology shocks are in turn limited by the boundaries of decision power that sovereign countries exercise.

A firm optimally chooses abatement given a realized shock and a regulatory constraint in place. A representative firm's optimal reaction function is

$$q_i(\bar{q}_i, \theta_i) \equiv \arg\min_{q_i \geq \bar{q}_i} C_i(q_i, \theta_i) \tag{4}$$

when abatement is regulated through quantity or

$$q_i(\bar{p}_i, \theta_i) \equiv \arg\max_{q_i} \{\bar{p}_i q_i - C_i(q_i, \theta_i)\} \tag{5}$$

when abatement is regulated through price.

When a firm is exposed to a quantity-based regulation $\bar{q}_i$, its abatement minimizes the cost of compliance. Being fixed ex ante, the quantity instrument prohibits a country's abatement from responding to firms' ex post marginal cost. However, when a firm is exposed to a price-based regulation $\bar{p}_i$, its abatement balances marginal cost, $\frac{\partial}{\partial q_i} C_i(q_i, \theta_i)$, with the marginal benefit $\bar{p}_i$. Since firms know the realized value of cost shocks θ_i before choosing abatement, the price instrument allows firms to incorporate the extra information about shocks, thereby letting a country's abatement respond to firms' ex post marginal costs.

4.1 The Origin of The PvQ Inefficiency

A social planner chooses the most efficient policy. When it chooses policies, the social planner takes the boundaries of sovereignty across countries as given. At the initial stage of the policy-making game, a social planner chooses the first-best policy type for each country to maximize the collective welfare. The maximization anticipates correctly that all countries implement the policy's first-best intensity and that firms react optimally in accordance with (4) or (5). After the first-best policy types are chosen for all countries, the planner chooses a policy's first-best intensity to maximize the collective welfare taking into account firms' optimal reactions to the relevant policy.

In a non-cooperative world of several nations, a country's decision maker chooses a policy type to maximize the country's welfare. The maximization anticipates correctly that all countries choose a policy intensity and that firms react optimally in accordance with (4) or (5). After all countries choose a policy type, a country's decision maker chooses a policy's intensity to maximize the country's welfare while anticipating firms' reactions to the relevant policy correctly. This choice of policy intensity focusing on a country's interest results in the well-known inefficiency in which a policy intensity ignores the broader benefits of the public good even the absence of political market failures. To abstract from intensity inefficiency for a moment, suppose the level of price or quantity a country implements is fixed at the first-best level. Do countries still choose the right policy type? To answer this question, suppose the set M contains m countries with the price instrument, and the set $R \equiv N - M$ contains the remaining $n - m$ countries with the quantity instrument at the first stage.

Proposition 1. *Suppose a price's or a quantity's intensity is fixed at the first-best value. All countries using the price instrument is socially optimal,* $m^{**} = n$, *if* $C'' > nB''$*; and* $m^{**} = 0$ *when the condition is reversed. Each country's choice at the same profile of prices and quantities implies* $m^{*} = n$ *only if* $C'' > B''$, *and* $m^{*} = 0$ *when* $B'' > C''$. *All countries inefficiently choose the price instrument when* $1 < \frac{C''}{B''} < n$.[5]

Proof: Based on (4) and (5), define $\bar{Q} \equiv \sum_{j \in R} q_j(\bar{q}_j, \theta_j)$, $\hat{Q} \equiv \sum_{j \in M} q_j(\bar{p}_i, \theta_i) + \sum_{j \in M} \theta_i / C''$, where $q_i(\bar{p}_i, \theta_i) = [\bar{p}_i - C'] / C'' - \theta_i / C''$. The first-best intensities of $\bar{q}_j$ and $\bar{p}_i$ that maximize the social welfare $\mathbb{E}W$ are $\bar{q}_j^{**} = [B'n - C'] / [B''n^2 + C'']$ and $\bar{p}_i^{**} = n [C''B' + nC'B''] / [B''n^2 + C'']$. Reinserting these optimal values into $\mathbb{E}W$

[5]In the rest of the text, the superscripts $**$ and $*$ are used to designate the socially optimal and the individually optimal choices, respectively.

implies

$$\mathbb{E}W = \frac{n}{2}\frac{[nB' - C']^2}{n^2B'' + C''} + \frac{C'' - nB''}{2C''^2}\sum_{i=1}^{m}\sigma_i^2. \tag{6}$$

At the first stage, the policy's type is chosen to maximize (6). Thus, if $C'' > nB''$, the collective welfare $\mathbb{E}W$ increases in m and the planner chooses the price instrument for all countries. However, when $C'' < nB''$, the planner's expected welfare decreases in m and assigning the quantity instrument for all countries becomes socially optimal.

The welfare difference for country i from committing to the quantity instrument instead of to the price instrument when *all* countries commit to the first-best amount of prices $\bar{p}_i^{**}$ and quantities $\bar{q}_i^{**}$ is

$$\mathbb{E}W^i\left(q_i(\bar{q}_i^{**}, \theta_i), \phi_{-i}\right) - \mathbb{E}W^i\left(q_i(\bar{p}_i^{**}, \theta_i), \phi_{-i}\right) = \frac{B'' - C''}{2C''^2}\sigma_i^2, \tag{7}$$

where ϕ_{-i} is the vector of $q_j(I_j^{**}, \theta_j)$ with $I_j^{**} \in \{\bar{q}_j^{**}, \bar{p}_j^{**}\}$ for all $j \in N - \{i\}$.[6] Thus, country i obtains higher welfare from committing to the price instrument if $C'' > B''$ and from committing to the quantity instrument if $B'' > C''$ as claimed. *Q.E.D.*

Proposition 1 established the PvQ inefficiency at the strategy profile of the first-best intensities of prices and quantities. The inefficiency arises when countries are left free to choose a policy's type whereas the intensity of a price or a quantity each country chooses is fixed at the first-best level. This formulation isolates the inefficiency that arises solely due to a policy's type. Thus, regardless of the policy type countries choose, every country will implement the first-best intensity.

To appreciate the significance of this result, think about the Kyoto Protocol (KP) and the Paris Climate Agreement (PCA). Both the KP and the PCA have focused on cutting emissions. Thus, in the ideal scenario, these agreements deliver the first-best policy intensity in each country. Proposition 1 suggests that even the ideal KP or PCA leaves the PvQ inefficiency on the loose.

In a world with several countries, each country chooses both a policy's type and intensity to advance its own interest. The next question is: what happens to the PvQ inefficiency if both the policy type and intensity are aimed at advancing individual welfare. The following result establishes that the inefficiency persists on the equilibrium path when both the type and intensity of a policy are aimed at advancing individual welfare (i.e., instead of being fixed at the first-best level).

[6] A notation with the subscript $-i$ has the conventional meaning, that is, the strategies of all players who are not player i is written as s_{-i}.

Proposition 2. *In equilibrium, each country chooses the price instrument only if* $C'' > B''$. *When* $1 < \frac{C''}{B''} < n$, *there exists a PvQ inefficiency (i.e.,* $m^* = n$ *and* $m^{**} = 0$*).*

Proof: To find the equilibrium, continue assuming m countries, members of the set M, have committed to the price instrument at the first stage. Assume also that members of the set $\tilde{R} \equiv N - M - i$ (i.e., $n - m - 1$ countries) have committed to the quantity instrument at the first stage. At the second stage, firms operating in country $j \in \tilde{R}$ choose abatement $q_j(\bar{q}_j, \theta_j) = \bar{q}_j$, and let $\bar{Q} \equiv \sum_{j \in \tilde{R}} q_j(\bar{q}_j, \theta_j)$. For $j \in M$, firms choose abatement $q_j(\bar{p}_j, \theta_j) = [\bar{p}_j - C'] / C'' - \theta_j / C''$, and let $Q_M \equiv \sum_{j \in M} q_j(\bar{p}_j, \theta_j)$. The regulator in country i, at the first stage, chooses $\bar{q}_i$ to maximize $\mathbb{E}W^i\left(q_i(\bar{q}_i, \theta_i), \hat{\phi}_{-i}\right)$ whereas $\bar{p}_i$ to maximize $\mathbb{E}W^i\left(q_i(\bar{p}_i, \theta_i), \hat{\phi}_{-i}\right)$, where $\hat{\phi}_{-i}$ is the vector of $q_j(I_j^*, \theta_j)$ with $I_j^* \in \{\bar{q}_j^*, \bar{p}_j^*\}$ for all $j \in N - \{i\}$. Once the optimal $\bar{q}_i^*$ and $\bar{p}_i^*$ are reinserted, one arrives at the value functions $\mathbb{E}W^i\left(q_i(\bar{q}_i^*, \theta_i), \hat{\phi}_{-i}\right)$ and $\mathbb{E}W^i\left(q_i(\bar{p}_i^*, \theta_i), \hat{\phi}_{-i}\right)$. Country i's welfare difference from committing to the quantity instrument instead of to the price instrument is

$$\mathbb{E}W^i\left(q_i(\bar{q}_i^*, \theta_i), \hat{\phi}_{-i}\right) - \mathbb{E}W^i\left(q_i(\bar{p}_i^*, \theta_i), \hat{\phi}_{-i}\right) = \frac{B'' - C''}{2C''^2}\sigma_i^2. \tag{8}$$

Thus, on the equilibrium profile of abatement, country i obtains higher welfare from committing to the price instrument if $C'' > B''$ and from committing to the quantity instrument if $B'' > C''$ as claimed. *Q.E.D.*

In equilibrium, (8) implies that a country's choice of a policy type follows a particular rule: committing to the price instrument is optimal only if the marginal cost function's slope greater than the private marginal benefit function's slope, and committing to the quantity instrument is optimal when the condition is reversed. However, (6) implies that the policy type that maximizes collective welfare follows a different rule: committing to the price instrument is socially optimal only if the marginal cost function's slope is greater than the marginal social benefit function's slope. Hence, the supply of a multilateral public good suffers from the PvQ inefficiency whenever the marginal social benefit function's slope is greater than the marginal cost function's slope, which in turn is greater than the marginal private benefit function's slope.

4.2 The Significance of The PvQ Inefficiency

After establishing that a distortion arises from countries' choice of a policy type, the natural question is about the importance – how significant can type's inefficiency be?

Given the model's setup, welfare is maximized when both sources of distortions are absent. The two sources of inefficiency add to the effect of the other since each can arise independently. Countries might have the right type of policy even though the amounts are set inefficiently. Alternatively, countries might have the wrong type of policy while the intensity is set at the first-best level or vice versa.

The independence of the two sources of policy distortions allows a simple way of illustrating the significance of the PvQ inefficiency. Thus, one can simply compare the welfare from the two sources of inefficiency. That is, compare the welfare from each country having the wrong type of policy despite the policy's intensity is set at the first-best level with the welfare from each country having the right policy type despite the policy's intensity is set at an inefficient level. Thus, the next proposition identifies the condition under which the collective welfare from the first-best amounts of carbon taxes is lower than the collective welfare from non-cooperatively determined amounts of emissions quotas.

Proposition 3. *Suppose the shocks θ_i are identically and independently distributed with zero mean and σ^2 variance. The social welfare from the non-cooperatively chosen quantities is higher than the social welfare from the first-best prices if $\mu(n) > \frac{1}{\sigma^2}$, where $\mu(n) \equiv \frac{nB''-C''}{n^2B''+C''}\left[\frac{nB''+C''}{[1-n]C''}\frac{n^2B''+C''}{B'C''+nC'B''}\right]^2$.*

Proof: The welfare from non-cooperatively determined quantities is given by $\sum_i^N \mathbb{E}W^i\left(q_i(\bar{q}_i^*,\theta_i), q_{-i}(\bar{q}_{-i}^*,\theta_{-i})\right)$. Inserting the solution from (4) into the expression for $\sum_i^N \mathbb{E}W^i\left(q_i(\bar{q}_i,\theta_i), q_{-i}(\bar{q}_{-i}^*,\theta_{-i})\right)$, one arrives at:

$$\sum_{i=1}^{n} \mathbb{E}W^i\left(q_i(\bar{q}_i^*,\theta_i), q_{-i}(\bar{q}_{-i}^*,\theta_{-i})\right) = n\left[nB'-C'\right]\left[\frac{B'-C'}{nB''+C''}\right] - \frac{n\left[n^2B''+C''\right]}{2}\left[\frac{B'-C'}{nB''+C''}\right]^2. \quad (9)$$

Comparing the value $\sum_{i=1}^{n} \mathbb{E}W^i\left(q_i(\bar{q}_i^*,\theta_i), q_{-i}(\bar{q}_{-i}^*,\theta_{-i})\right)$ in (9) with the value $\mathbb{E}W$ in (6), one arrives at the expression stated in the Proposition after undertaking some steps of simplification. *Q.E.D.*

The result that the non-cooperatively determined amounts of quotas can dominate the first-best intensities of prices can appear counter-intuitive upon the first encounter, particularly for a well-trained economist. However, the explanation is straight forward. All else held the same, a country's optimal policy type balances the trade-off between the flexibility to take advantage from cost-reducing shocks and the risk that the policy is too loose or too tight ex post. A fixed quantity is inflexible and does not allow a country to benefit from cost-reducing shocks, yet it avoids ex ante abatement risk.

The price instrument, nonetheless, allows a country to benefit from socially useful cost-reducing shocks, yet it imposes a risk of being too loose or too tight ex post. Thus, it is rational for a country to choose the price instrument only if the benefit from private cost savings exceeds the private cost of having a variable abatement. For a planner, however, it is rational to choose the price instrument only if the cost saving for each unit of abatement is greater than the social cost of having a too loose or too tight policy ex post.

The misalignment between the private and social costs highlights the risk externality arising from using the price instrument. When a country uses the price instrument, it benefits from the cost savings but fails to consider the risk externality its choice imposes on other countries in making the global abatement volatile. The externality has an important ramification for a policy's type efficiency – when it is large, the set of non-cooperatively determined quotas generates higher welfare than the set of first-best intensities of carbon taxes.

Armed with Proposition 3's insight, it is easier to explain the outcome of the example in the introduction section. When there is only one country, type's inefficiency does not arise. However, since there are more than 200 sovereign countries, examining the consequences of having many countries is necessary. With many countries, a country's optimal rule for choosing a policy's type departs from the rule that would have maximized collective welfare. This is because a country adopting a carbon tax imposes a negative risk externality on other countries. When there are many countries and when these countries' first-best carbon taxes generate negative risk externality, countries are better-off with a non-cooperatively determined and inefficiently low quotas. For these reasons, conventional wisdom gives a misleading answer by eschewing the fact that more than 200 sovereign countries choose their own policies.

5 Generalizations

The following sections generalize the main result to capture more realistic settings, which are missing from the basic model. To this end, the model is extended to allow for a global cost shock, a supranational union decision-maker such as the EU, or distinct technological shocks for countries inside and outside a supranational union's boundaries, and the dynamic feature of public goods.[7]

[7] While all these features can be analyzed together within a single model, I discuss each case separately for ease of exposition. Such a model can be obtained from the author upon request.

5.1 A Global Shock and The PvQ Inefficiency

Arguably, we are living in a time when countries are going through deep digital, financial, and commercial integration. It is possible that knowledge and abatement technologies invented in one place flow quickly to other places. Technologies invented in one place for reducing the cost of generating pollution-free energy can make their way to other parts of the planet in a few months. In this setting, assuming independent technological shocks might not capture this important aspect of reality. To examine the consequences of deep technological interdependence, this section replaces the assumption of independent shocks with a global shock, that is, $\theta_i = \theta$ and $\sigma_i^2 = \hat{\sigma}^2,\ \forall i \in N$. In addition, let us continue assuming that the set M contains m countries with the price instrument and the set $R \equiv N - M$ contains the remaining $n - m$ countries with the quantity instrument at the first stage.

A global technology shock has numerous consequences. When countries face identical cost shocks, the risk associated with prices is compounded, unlike the case of country-specific and independent shocks. This feature exacerbates the price instrument's negative externality and generates richer implications.

First, with a global cost shock, an ideal social planner's choice and an individual country's choice in equilibrium exhibit asymmetry — only some countries choose the price instrument despite all countries being identical in every respect. For comparison, in all cases examined so far, both the non-cooperative and the socially optimal choices exhibit symmetry – the price instrument is chosen by *all* countries only if $C'' > B''$ and by the social planner for *all* countries only if $C'' > nB''$. Second, the condition for a country's choice of a policy type departs from the standard condition in which all countries adopt the price instrument unless $B'' > C''$. With global cost shocks, the equilibrium number of countries adopting the quantity instrument is positive, despite $C'' > B''$. Third, the condition for a social planner's choice of a policy type also changes. That is, a social planner assigns the price instrument to no country despite $C'' > B''$ if $C'' < 4nB''$. Through these effects, a global shock makes the PvQ inefficiency even more powerful than it is under independent shocks.

Proposition 4. *Suppose the cost shock is identical in all countries. Then m^{**} is the nearest integer to $\frac{C''}{2nB''}$ whereas m^* is the nearest integer to $max\{\frac{C''-B''}{2B''}, 0\}$. The PvQ inefficiency persists when the cost shock is global. The social welfare from the non-cooperatively chosen quantities is higher than the social welfare from the first-best prices if $\frac{\left[C''-n^2B''\right]\left[C''+n^2B''\right]}{\left[[1-n]C''\frac{B'C''+nC'B''}{nB''+C''}\right]^2} > \frac{1}{\hat{\sigma}^2}$.*

Proof: To prove this case, define $\bar{Q} \equiv \sum_{j\in R} \bar{q}_j$, $\hat{Q} \equiv \sum_{j\in M} q_j(\bar{p}_j, \theta) + m\theta/C''$, where $q_i(\bar{p}_i, \theta) = \left[\bar{p}_i - C'\right]/C'' - \theta/C''$. The social welfare from committing to a policy's type is

$$\begin{aligned} \mathbb{E}W &= [B'n - C']\left[\bar{Q} + \hat{Q}\right] - \frac{nB''}{2}\left[\bar{Q} + \hat{Q}\right]^2 - \frac{C''}{2}\sum_{j\in R}\bar{q}_j^2 \\ &\quad -\sum_{i\in M}\frac{C''}{2}\left[\frac{\bar{p}_i - C'}{C''}\right]^2 + \frac{m\left[C'' - nmB''\right]}{2C''^2}\hat{\sigma}^2 \end{aligned} \tag{10}$$

The values of $\bar{q}_j$ and $\bar{p}_i$ that maximize $\mathbb{E}W$ in (10) are given by $\bar{q}_j^{**} = [B'n - C'] / [B''n^2 + C'']$ and $\bar{p}_i^{**} = n\left[C''B' + nC'B''\right] / \left[B''n^2 + C''\right]$. Reinserting these optimal values into $\mathbb{E}W$ implies

$$\mathbb{E}W = \frac{n}{2}\frac{\left[nB' - C'\right]^2}{n^2B'' + C''} + \frac{m\left[C'' - nmB''\right]}{2C''^2}\hat{\sigma}^2.$$

At the first stage, the optimal policy's type is chosen to maximize $\mathbb{E}W$. The $\mathbb{E}W$ is concave in m. The first-order condition with respect to m is

$$m^{**} = \frac{1}{2n}\frac{C''}{B''}. \tag{11}$$

Note that (11) has a stark implication. In reality, the value of n is about 200 sovereign countries. Thus, for global carbon taxes to become socially optimal, the value of C'' has to exceed the value of B'' by the order of $2n^2$, which is 80,000. The magnitude can be compared to the case of independent shocks, where the value of C'' has to exceed the value of B'' by the order of n, which is 200.

Since $\mathbb{E}W$ increases in the number of countries using the price instrument m when $m < m^{**}$, the planner chooses the price instrument until $m = m^{**}$ or the nearest integer to m^{**}. This choice implies

$$\mathbb{E}W = \frac{n}{2}\frac{\left[nB' - C'\right]^2}{n^2B'' + C''} + \frac{\hat{\sigma}^2}{8nB''}.$$

Similarly, country i's welfare difference from committing to the quantity instrument $\bar{q}_i^*$ instead of committing to the price instrument $\bar{p}_i^*$ when *all* countries commit to the equilibrium amount of prices and quantities is

$$\mathbb{E}W^i\left(q_i(\bar{q}_i^*, \theta), \hat{\phi}_{-i}\right) - \mathbb{E}W^i\left(q_i(\bar{p}_i^*, \theta), \hat{\phi}_{-i}\right) = \frac{\left[2m+1\right]B'' - C''}{2C''^2}\hat{\sigma}^2, \tag{12}$$

where $\hat{\phi}_{-i}$ is the vector of $q_j(I_j^*, \theta_j)$ with $I_j^* \in \{\bar{q}_j^*, \bar{p}_j^*\}$ for all $j \in N - \{i\}$.

If no country has committed to the price instrument and $m = 0$, (12) implies that a country benefits from committing to the price instrument only if $B'' < C''$. This rule for a country's optimal strategy is identical to the rule when the cost shocks are independent. However, when the number of countries that have committed to the price instrument is positive m, (12) implies that a country benefits from committing to the price instrument only if $B'' < \frac{C''}{2m+1}$. In equilibrium, a country is indifferent between committing to the price instrument or to the quantity instrument; thus the equilibrium m^* becomes the nearest integer to

$$m^* = \max\left\{0, \frac{C'' - B''}{2B''}\right\}. \qquad (13)$$

If $\frac{C''}{B''} = 2n + 1$, then $m^* = n$ and $m^{**} \leq 2$; whereas if $\frac{C''}{B''} = 2n^2$ for $n > 1$, then $m^* = m^{**} = n$. *Q.E.D.*

Note that conventional wisdom calls for global carbon taxes when $\frac{C''}{B''} > 1$. In the framework adopted in this paper, this particular rule inefficient. This is best illustrated in figure (2) and figure (3). The figures present the equilibrium number and the socially optimal number of countries committing to the price instrument, m^* and m^{**}, conditional on the the cost shocks being country specific and iid or global.

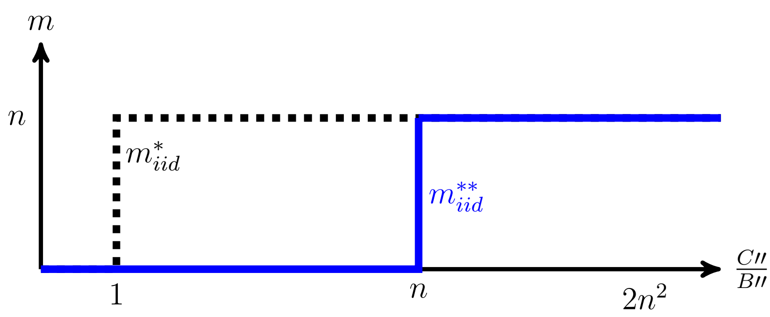

Figure 2: The equilibrium number and the socially optimal number of countries committing to the price instrument, m^*_{iid} and m^{**}_{iid}, when the cost shocks are iid.

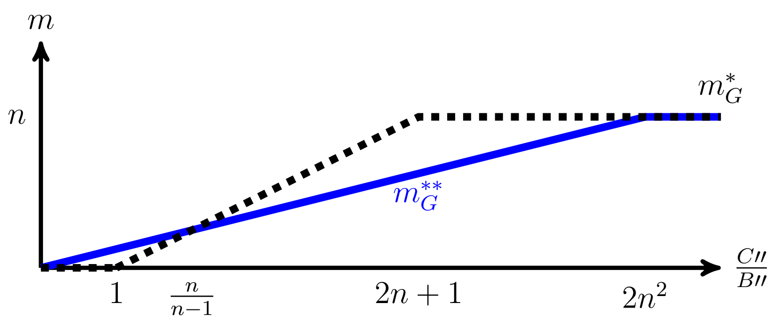

Figure 3: The equilibrium number and the socially optimal number of countries committing to the price instrument, m^*_{iid} and m^{**}_{iid}, when the cost shocks are global.

For $n \in \mathbb{N}$ and $n > 1$, the fraction $\frac{n}{n-1}$ is weakly less than 2 and it approaches the value 1 as the value of n increases. With 200 countries, $\frac{n}{n-1} \approx 1.01$. Thus, the dashed line representing the number of countries committing to the price instrument in equilibrium is above the solid line representing the socially optimal number of countries committing to the price instrument for $n \geq 2$. This suggests that the number of countries committing to the price instrument is suboptimally high and the PvQ inefficiency prevails whether the cost shocks are *iid* and country specific or global. In fact, for the price instrument to be socially optimal, the fraction $\frac{C''}{B''}$ has to exceed the number n with iid cost shocks and the number $2n^2$ with global cost shock.

5.2 A Supranational Union and The PvQ Inefficiency

Overlapping institutions and supranational unions play significant roles in the conduct of national policies. Certainly, the nation-state has monopolized the power over the conduct of national policies for a very long time. Recently, however, some supranational unions have been delegated to manage important policy domains on behalf of member countries. Particularly since the 1990s, different supranational unions have been granted decision power on sovereign countries' policy domains such as facilitating international trade and protecting the global climate. Moreover, such institutions execute their policies while leaving the political boundaries among member states on other policy domains intact (Alesina et al., 2003).

In Europe, since the beginning of the 1970s, environmental policy has been executed at the EU level through the Single European Act, the Maastricht Treaty, the formation of the EU, and ultimately the establishment of the European Emissions Trading Scheme (Knill and Leifferink, 2013). As Alesina et al. (2005: 602) note, the EU's "goal has been provision of public goods and common policies for the member states." Thus, environmental policies enacted at the EU level are designed to enhance the member countries' collective interest. When policies enacted at the EU level are enforced in all member states, a natural question becomes – how does the extension of political power's boundaries affect environmental policies' efficiency?

To answer this question, the basic model is extended to allow a supranational institution to interact with the remaining sovereign countries in choosing the type and intensity of environmental policy. Let Ω be the set of $|\Omega|$ member countries of a supranational union, where $|Y|$ is the cardinality of a set Y. Let also $\Omega \equiv \Omega_M \cup \Omega_R$ such that the set Ω_M contains $|\Omega_M|$ member countries that the union assigns the price instrument and the set Ω_R of the remaining $|\Omega| - |\Omega_M|$ countries for which the union assigns the quantity instrument at the first stage. Similarly, suppose the set $\hat{M}$ of $\hat{m}$ countries outside the union, $N - \Omega$, which have committed to the price instrument and the remaining set $\hat{R} \equiv N - \hat{M} - \Omega$ of $n - \hat{m} - |\Omega|$ countries, which have committed to the quantity instrument at the first stage. Since any of these subsets can be empty, the partition is without loss of generality.

At the stage of choosing a policy's intensity, Ω's most preferred levels of prices and quantities maximize the expected collective welfare of the member states taken together, $W_\Omega \equiv \sum_{i\in\Omega} W^i$ where W^i is given by (1) and maximization is subject to firms' rationality constraints of (4) or (5) in all countries. In such a setting, members of Ω consider the price instrument's risk externality on other members. Thus, Ω adopts the price instrument in a narrower range of parameters than in the condition that arises in the absence of the supranational union.

Proposition 5. *If the price's or quantity's amount is determined to maximize supranational union Ω's welfare, then the union benefits from committing to the price instrument only if $C'' > |\Omega|B''$. If $nB'' > C'' > |\Omega|B''$, then the equilibrium number of countries choosing the price instrument is $\hat{m}^* + |\Omega|^* = n$, whereas the socially optimal number is $\hat{m}^{**} = |\Omega|^{**} = 0$, implying that the equilibrium policy type is inefficient, both inside and outside the supranational union.*

Proof: To identify the equilibrium strategy, note that, when the union Ω determines a policy's intensity for each member country, it will correctly anticipate firms' individual rationality constraints. So, firms operating in countries committing to the quantity instrument choose abatement $q_j(\bar{q}_j, \theta_j) = \bar{q}_j$, where $j \in \hat{R} \cup \Omega_R$; and, firms operating in a country committing to the price instrument choose abatement $q_j(\bar{p}_j, \theta_j) = [\bar{p}_j - C']/C'' - \theta_j/C''$, where $j \in \hat{M} \cup \Omega_M$. Let $Q_{\hat{R}} \equiv \sum_{j\in\hat{R}} q_j(\bar{q}_j, \theta_j)$, $Q_{\Omega_R} \equiv \sum_{j\in\Omega_R} \bar{q}_j$, $Q_{\hat{M}} \equiv \sum_{j\in\hat{M}} q_j(\bar{p}_j, \theta_j) + \sum_{i\in\hat{M}} \theta_i/C''$, and $Q_{\Omega_M} \equiv \sum_{i\in\Omega_M} q_i(\bar{p}_i, \theta_i) + \sum_{i\in\Omega_M} \theta_i/C''$ so that

$$\kappa \equiv Q_{\hat{R}} + Q_{\hat{M}} + Q_{\Omega_M} + Q_{\Omega_R} = \frac{[n + |\Omega|^2 - |\Omega|]\, B' - nC'}{[n + |\Omega|^2 - |\Omega|]\, B'' + C''}. \tag{14}$$

The interim indirect utility becomes

$$\begin{aligned}
\mathbb{E}W_\Omega \;=\; & |\Omega|\left[B' + |\Omega|\frac{C'B''}{C''}\right]\kappa - |\Omega|\frac{B''}{2}\kappa^2 - C'|\Omega|\frac{|\Omega|B' - C'}{C''} \\
& -\frac{C''}{2}\sum_{i\in\Omega_R}\left[\left[\frac{|\Omega|B' - C'}{C''} - \frac{|\Omega|B''}{C''}\kappa\right]^2 + \left[\frac{|\Omega|B' - C'}{C''} - \frac{|\Omega|B''}{C''}\kappa\right]^2\right] \\
& -|\Omega|B''\left[\sum_{\hat{M}}\sigma_i^2/[2C''^2]\right] + \frac{C'' - |\Omega|B''}{2\,[C'']^2}\sum_{j\in\Omega_M}\sigma_i^2.
\end{aligned}$$

Inserting the value (14) into $\mathbb{E}W_\Omega$ implies that the sign of $C'' - |\Omega|B''$ determines the effect on the union's indirect utility of the optimal policy type. The indirect utility is decreasing in the number $|\Omega_M|$ if $C'' < |\Omega|B''$; and, if $|\Omega|B'' < C''$, then the union chooses the price instrument. And, $|\Omega|B'' < C''$ implies $B'' < C''$ since $|\Omega| \geq 1$. Thus, when $|\Omega|B'' < C''$, countries inside and outside the union choose the price instrument, which is socially inefficient whenever $C'' < nB''$. *Q.E.D.*

A union's reaction to risk externality explains at least two observations consistently. First, it explains why the quantity instrument is chosen in unions with supreme states: the US to regulate SO_2 and the EU to regulate CO_2 (Schmalensee and Stavins, 2013; Stavins, 2018); yet, the price instrument is chosen in relatively more unitary countries: Argentina, Chile, Colombia, Singapore, and South Africa (World Bank and Ecofys, 2018). Second, it explains why countries choose the quantity instrument when being a member of a union and the price instrument when not. Countries such as Denmark, Germany, Italy, Netherlands, Norway, Sweden, and the United Kingdom in the 1990s had chosen a carbon tax to reduce CO_2 (Barde et a1., 2001). However, as a member of the EU, these same countries have chosen the quantity instrument as of 2005 and participate in the EU emissions trading scheme as a primary way to supply abatement.

Moreover, Weitzman's theory has a precise testable prediction. If a researcher observes countries' policy type and the values of B'' and C'', then the theory's prediction can be tested empirically using an empirical model of policy type's indicator variable on the value of $B'' - C''$. Yet, if the value of B'' or C'' is not observable to a researcher, the testability ceases to exist. With risk externality, that is not the case. All else being the same, a union of sovereign nations is more likely to adopt the quantity instrument instead of the price instrument than a unitary country does.[8]

5.3 A Regional Shock and The PvQ Inefficiency

The post-World War II European Coal and Steel Community has been transformed into the European Common Market since 1957 by the Treaty of Rome. With the formation of the European Single Market, the European Monetary System, and finally the formal establishment of the EU, the member countries have been deeply integrated. Thus, assuming a common technology shock within the union can be a more realistic feature. In addition, the degree of integration within the European Union is very different from the integration between North and South America or from the integration in the Asian region. Finally, the reason why such a union does not fall apart once it

[8]The discussion so far has abstracted from the details of the EU's complex decision-making process, which is far from being similar to a benevolent planner's decision-making process. Depending on the voting rule in place, the actual decision-making process can involve bargaining and coalition formation to enact an EU-wide policy. However, the above analysis is equivalent to an outcome under a unanimity voting rule with side payments. In general, the voting rule becomes a key determinant of a policy's type. When the rule requires only few countries to choose the price instrument for the price instrument to be adopted at the EU level, then the price instrument is adopted. On the other hand, when a majority is required (i.e., the Treaty of Lisbon requires 55-72% votes for approval in many policy domains), then the result is qualitatively similar to that reported in the Proposition.

is formed can be due to symmetric co-movements of economy-wide shocks (Mundell, 1961; Kenen, 1969; Alesina and Barro, 2002; Alesian, Barro, and Tenreyro, 2003).

To capture a regional shock's consequences on environmental policy's efficiency, assume that the cost shocks are identical within the supranational union's members whereas the shocks are independent in the countries that are weakly integrated with each other. That is, $\theta_i = \theta$ and $\sigma_i^2 = \hat{\sigma}^2$, $\forall i \in \Omega$, and θ_i are independently distributed $\forall i \in N - \Omega$. Moreover, let $\Omega \equiv \Omega_M \cup \Omega_R$, where the set Ω_M contains $|\Omega_M|$ member countries for which the union assigns the price instrument and the set Ω_R contains the remaining $|\Omega| - |\Omega_M|$ countries for which the union assigns the quantity instrument at the first stage. Similarly, let the set $\hat{M}$ of $\hat{m}$ countries outside the union, $N - \Omega$, have committed to the price instrument and the remaining set $\hat{R} \equiv N - \hat{M} - \Omega$ of $n - \hat{m} - |\Omega|$ countries be those that have committed to the quantity instrument at the first stage.

Proposition 6. *Suppose countries in a supranational union face a common shock while the rest face independent shocks. In countries with a common shock, the socially optimal number of countries using the price instrument is the nearest integer to* $|\Omega_M|^{**} = \frac{1}{2n}\frac{C''}{B''}$ *whereas the equilibrium number is the nearest integer to* $|\Omega_M|^* = n|\Omega_M|^{**}$*. The PvQ inefficiency persists when the cost shocks are regional.*

Proof. Since $\theta_i = \theta$ and $\sigma_i^2 = \hat{\sigma}^2$ $\forall i \in \Omega$, the planner's choice is different from the one described in the proof of Proposition 2. Thus, at the second stage, firms operating in a country that has committed to the quantity instrument choose abatement of $q_j(\bar{q}_j, \theta_j) = \bar{q}_j$, where $j \in \hat{R} \cup \Omega_R$. Similarly, firms operating in a country that has committed to the price instrument choose abatement of $q_j(\bar{p}_j, \theta_j) = [\bar{p}_j - C'] / C'' - \theta_j / C''$, where $j \in \hat{M} \cup \Omega_M$. Let $Q_{\hat{R}} \equiv \sum_{j \in \hat{R}} q_j(\bar{q}_j, \theta_j)$, $Q_{\Omega_R} \equiv \sum_{j \in \Omega_R} \bar{q}_j$, $Q_{\hat{M}} \equiv \sum_{j \in \hat{M}} q_j(\bar{p}_j, \theta_j) + \sum_{i \in \hat{M}} \theta_i / C''$, and $Q_{\Omega_M} \equiv \sum_{i \in \Omega_M} q_i(\bar{p}_i, \theta_i) + |\Omega_M| \theta / C''$. The expected social welfare from committing to a policy type is

$$\begin{aligned}
\mathbb{E}W \; = \; & [nB' - C'] \left[\sum_{j \in \hat{R} \cup \Omega_R} \bar{q}_j + \sum_{j \in \hat{M} \cup \Omega_M} \frac{\bar{p}_j - C'}{C''} \right] - \sum_{j \in \hat{R} \cup \Omega_R} \frac{C''}{2} \bar{q}_j^2 - \sum_{i \in \hat{M} \cup \Omega_M} C' \left[\frac{\bar{p}_i - C'}{C''} \right] \\
& - \frac{nB''}{2} \left[\sum_{j \in \hat{R} \cup \Omega_R} \bar{q}_j + \sum_{j \in \hat{M} \cup \Omega_M} \frac{\bar{p}_j - C'}{C''} \right]^2 - \sum_{i \in \hat{M} \cup \Omega_M} \frac{C''}{2} \left[\frac{\bar{p}_i - C'}{C''} \right]^2 \\
& + \frac{[C'' - nB''] \sum_{j \in \hat{M}} \sigma_i^2 + |\Omega_M| \left[C'' - n|\Omega_M| B'' \right]}{2 \left[C'' \right]^2} \hat{\sigma}^2. \qquad (15)
\end{aligned}$$

At the first stage, the types of policies are chosen to maximize $\mathbb{E}W$ in (15). For all countries with an independent shock, a symmetric policy instrument is applied, that is, the price instrument is applied only if $C'' > nB''$. For countries with a perfectly correlated shock, the first-order condition with respect to m is $|\Omega_M|^{**} = \frac{1}{2n}\frac{C''}{B''}$. Since $\mathbb{E}W$ is concave in $|\Omega_M|$, the first-order condition is sufficient. For a country outside the union, (8) continues to hold. The remaining step is to show the union's choice. The expected social welfare of the supranational union from committing to the types of policies are

$$\begin{aligned}\mathbb{E}W_\Omega &= [|\Omega|\,B' - C']\left[\sum_{j\in\hat{R}\cup\Omega_R}\bar{q}_j + \sum_{j\in\hat{M}\cup\Omega_M}\frac{\bar{p}_j - C'}{C''}\right] - \sum_{j\in\Omega_R}\frac{C''}{2}\bar{q}_j^2 \\ &\quad -\frac{|\Omega|\,B''}{2}\left[\sum_{j\in\hat{R}\cup\Omega_R}\bar{q}_j + \sum_{j\in\hat{M}\cup\Omega_M}\frac{\bar{p}_j - C'}{C''}\right]^2 - \sum_{i\in\Omega_M}\frac{C''}{2}\left[\frac{\bar{p}_i - C'}{C''}\right]^2 \\ &\quad -\frac{|\Omega|\,B''\sum_{j\in\hat{M}}\sigma_i^2 - |\Omega_M|\,[C'' - |\Omega_M|^2 B'']\hat{\sigma}^2}{2\,[C'']^2}.\end{aligned}$$

The optimal number of member countries of the supranational union adopting the price instrument is $|\Omega_M|^* = \frac{C''}{2B''}$. As $\mathbb{E}W_\Omega$ is strictly concave in $|\Omega_M| > 0$, the first-order condition is sufficient. *Q.E.D.*

The results regarding the nature of cost shocks in the previous propositions have testable predictions. All else being the same, when cost shocks are global, the number of independent countries adopting the quantity instrument in equilibrium is positive even when $C'' > B''$. If the cost shocks are regional, then the union assigns the price instrument to *none* of its member countries despite $C'' > B''$ when $C'' < 4B''$.

5.4 Stock Effects and The PvQ Inefficiency

Whereas the benefit from many public goods is derived entirely from the flow of supply, in some cases, the benefits are derived from the stock. A natural example of stock-based benefits is climate change mitigation. This is because climate change is mainly a planetary consequence of increased atmospheric concentrations of greenhouse gases, in particular CO_2. CO_2 emissions increased from 280 parts per million in the late 1700s to 413.52 parts per million on 3 May 2019.[9] The current concentrations are at a level unseen, at least over the past 800,000 years.

The CO_2 emissions remain in the atmosphere for many years, and abatement today reduces environmental damages not only today but also for many years to come. What is the relevance of the PvQ inefficiency for public goods whose benefits depend on a stock and a period's contribution to the stock is very small relative to the existing

[9] Accessed on January 14, 2019 from `https://www.co2.earth/` and `https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases`.

stock? In fact, in voting for the claim that "carbon taxes are a better way to implement climate policy than cap-and-trade," one of the members of the Economic Experts Panel of IGM at the Chicago Booth, Markus Brunnermeier, comments –"[tax is] preferable since marginal abatement cost curve is uncertain, but steeper than marginal damage curve. Latter is flat since CO2 is a stock."[10]

To capture the stock factor in a multilateral setting, suppose there is a very large initial stock S_{t-1} before the regulatory game is played. Thus, by comparing the outcome when the stock of the public good is high or low, the consequence of stock on the PvQ inefficiency can be understood. In addition, to capture the persistence benefits from a stock into the future, assume that part of the total current total stock $S_t = gS_{t-1} + Q_t$ continues to provide benefits in the future with partial depreciation $S_{t+1} = g^2 S_{t-1} + gQ_t$ after a period, where $1 - g \in [0, 1]$ is the fraction of the stock that depreciates from one period to the next.

To illustrate the key insight in the simplest setting, let a regulator cares about only one more period. Depending on the definition of a period, this can be an innocuous simplification. If one considers the period for which a regulator is appointed for the US's Environmental Protection Agency or for an environment ministry in democratic countries of the industrialized world, the assumption is a reasonable first approximation (Weitzman, 2018, p.6). With this extension, the expression in (1) becomes

$$W^i \equiv B(S_t) + \beta B(S_{t+1}) - C_i(q_{i,t}, \theta_{i,t}),$$

where $\beta \in [0, 1]$ is a discount factor, $S_t = gS_{t-1} + Q_t$, $S_{t+1} = g^2 S_{t-1} + gQ_t$, and $Q_t = \sum_{j \in N} q_{j,t}$.

Proposition 7. *Suppose a public good involves stock. The first-best policy type is the price instrument only if* $C'' > n[1+\beta g^2]B''$. *On the equilibrium path, each country benefits from committing to the price instrument only if* $C'' > [1 + \beta g^2]B''$. *The PvQ inefficiency is present when* $[1 + \beta g^2]B'' < C'' < n[1 + \beta g^2]B''$.

This Proposition's proof is similar to the ones for Propositions 1 and 2, and it is omitted. This Proposition highlights a number of substantive insights. First, for an individual country or a social planner, the size of the initial stock does not affect the PvQ inefficiency or play any role in the choice between the price instrument vs. the quantity instrument. To see this, suppose regulators in all countries are myopic and fix $\beta = 0$ while assuming a very high amount of S_{t-1}. If $\beta \to 0$, then a country's (or an ideal social planner's) rule for choosing a carbon tax vs. a quota on the equilibrium path is identical to the rule stated in Proposition 2. This outcome is intuitive since

[10]Source: `http://www.igmchicago.org/surveys/climate-change-policies`

the initial stock does not affect the trade-off between the flexibility to save costs ex ante and the cost of abatement risk. Second, the PvQ inefficiency continues to present when the benefit from a public good is affected by a large initial stock or when the benefit persists into the future. Thus, in multilateral and dynamic settings in which the benefit from a public good comes from stock, the PvQ inefficiency and the risk externality from carbon taxes continue to persist.

In addition, the relationship between the PvQ inefficiency and stock-based public goods also offers a testable prediction even when the values of B'' and C'' is unobserved. All else being the same, a country's likelihood of choosing the quantity instrument (instead of choosing the price instrument) is higher if the benefit from a public good is derived from stock instead of from flow. That is, for a flow public good, a country's equilibrium strategy is the price instrument if $C'' > B''$. Whereas for a stock public good, a country's equilibrium strategy is the price instrument only if $C'' > B'' + \beta g^2 B''$.

6 Concluding Discussion

This paper has extended Weitzman's workhorse model to allow for a large number of countries individually contributing to a multilateral public good while boundaries of power for sovereign countries are binding. Countries choose both the type and intensity of a policy in strategic settings while facing technological uncertainty. This paper has examined the origin and significance of the PvQ inefficiency and has generated both a policy message and testable predictions.

The PvQ inefficiency has a clear implication for climate policy. International climate negotiations, in relation to the Kyoto Protocol or the Paris Climate Agreement, have focused on emissions cuts, seeking to address the intensity inefficiency. The notion of risk externality advanced in this paper implies that carbon tax is not equivalent to tradable emissions quotas. To avoid significant welfare losses, climate negotiations and policy-making also have to take the PvQ inefficiency into account.

As a positive contribution, the PvQ inefficiency explains an empirical puzzle having plagued conventional wisdom – the observation that countries choose carbon taxes independently but choose quantities when belonging to a union. Different countries such as Denmark, Germany, Italy, Netherlands, Norway, Sweden, and the United Kingdom independently chose the price instrument in the 1990s to regulate abatement of CO_2. However, as members of the EU, these countries chose the quantity instrument as of 2005 and have participated in the EU emissions trading scheme to regulate emissions (Schmalensee and Stavins, 2013; Stavins, 2018). This outcome is at odds with the suggestion from Economic Experts Panel members of IGM at the Chicago Booth School of Business to use carbon taxes to address climate change. The PvQ inefficiency rationalizes this fact as follows. Consistent with conventional wisdom, a country can find it individually rational to use a carbon tax to address climate change. However, using a carbon tax induces a negative externality on the union's remaining members by generating a cost of too tight or too loose regulation ex post. Belonging to a union, a country internalizes the negative externality and chooses a quota to avoid the negative externality of the carbon tax on the member states.

As a substantive contribution, this research responds to Acemoglu (2003, p. 649), who invites "future research on the causes of inefficient policies and the factors preventing the application of the political Coase theorem." Not only has the analysis isolated and identified the cause of the PvQ inefficiency, it has also resulted in insights complementary to different insights in the literature. The PvQ inefficiency can be of interest for the following reasons. First, it arises despite countries adopting a market-based rather than a command-and-control policy instrument, which has been a source of significant distortion in the supply of public goods (Schmalensee and Stavins, 2017). Second, it persists even in the absence of electoral or political frictions, such as a lack of credible commitments, agency problems, or the influence of organized interest groups, which have also been considered the primary political sources of policy distortions in the literature. Third, it arises despite market-based policy instruments having complete geographical coverage and lacking the inter-temporal perverse incentive causing problems such as carbon leakage and the green paradox. The PvQ inefficiency, as emphasized in this paper, arises due to the interaction between an externality spanning multiple countries and due to uncertainty regarding technological possibilities affecting the abatement costs of sovereign countries.

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