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Pricing Pollution

Abstract

I examine a policy-making game among countries that must choose both a policy instrument (e.g., a tax or a quota) and its intensity (i.e., the tax rate or the quota level) to price pollution. When countries price pollution non-cooperatively, they not only set the intensity inefficiently, they are also likely to adopt Pigouvian fees, despite quotas being better from a welfare perspective. Adopting a Pigouvian fee to address a multi-country externality generates a risk externality, and non-cooperatively chosen quotas can generate higher social welfare than maximum social welfare Pigouvian fees can deliver.

JEL-Codes: C720, D810, F500, H210, Q380, Q580.

Keywords: environmental policy, global pollution, international relations.

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1 Introduction

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

While the following analysis applies to most global public goods, let me focus on an example of addressing a global pollution problem to fix ideas. A century of economic research suggests that putting a price on pollution is the best way to address a pollution problem (Pigou, 1920; Dales, 1968; Montgomery, 1972; Weitzman, 1974; Nordhaus, 2006; Stern, 2007; Pindyck, 2019).[1]

What is the best way to price pollution? Following the footsteps of Pigou, Dales, and Montgomery, Weitzman (1974) lays the intellectual foundation for considering alternative ways of pricing pollution under incomplete information. A sensible policy raises pollution abatement by taking into account both the benefit and the cost of abatement. Weitzman shows that a Pigouvian fee is less efficient than a cap-and-trade scheme when the slope of the marginal abatement cost function is small relative to the slope of the marginal abatement benefit function. Conversely, a cap-and-trade scheme is less efficient when the slope of the marginal abatement benefit function is small relative to the slope of the marginal abatement cost function.[2] The literature building upon Weitzman (1974) examines the best way to price global pollution when the policy instrument applies globally. In the case of mitigating climate change, many economists suggest that adopting a pollution tax is more efficient than adopting a cap-and-trade system. Nordhaus (2006), Sterner and Coria (2012), Goulder and Schein (2013), and Stavins (2020) summarize the enormous contributions regarding the pros and cons of adopting different policy instruments for pricing pollution.

Recently, when Economic Experts Panel members of the Chicago Booth School of Business were asked whether they agree that carbon taxes represent a better way to implement climate policy than cap-and-trade schemes, about 80% of the confidence-weighted votes agreed with the claim and voted for a carbon tax, while the remaining respondents were uncertain.[3] However, the question for the Economic Experts Panel members does not allow considerations of national boundaries. In responding to the question, it is unclear if the experts have the United States or the World in mind. In fact, the potential inefficiency from countries choosing policy instruments non-cooperatively has been absent in the literature. Because of that, the analysis of this paper examines the welfare implications of national sovereignty in choosing a pollution pricing instrument.

To motivate the ramifications of national sovereignty, consider an example of two sovereign countries, N and S. Each country receives a benefit of $B_i = aQ - \frac{b}{2}Q^2$ from the total abatement $Q \equiv q_N + q_S$, where q_N and q_S are private abatements of N and S. Abatement costs firms operating in each country: $C_i = [1 + \theta_i]\, q_i + \frac{c}{2}q_i^2$, where the shock θ_i

[1] A list of economists supporting carbon pricing is reported at `https://www.eaere.org/statement/`.

[2] I use a pollution (carbon) tax or Pigouvian fee as synonyms for the price instrument and a quota or a cap-and-trade scheme for the quantity instrument.

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

is drawn independently from $\{-1, 1\}$ for each country with the probability $Pr(\theta_i = 1) = \frac{1}{2}$. Let firms choose abatement after observing θ_i and facing a policy instrument a regulator commits to before the realization of θ_i and $a = \frac{8}{3}$, $b = 1$, and $c = \frac{6}{5}$ so that the slope of the marginal cost function [c] is higher than the slope of the marginal benefit function [b]. Solving the example, one notices that the social welfare from the non-cooperatively chosen equilibrium quotas is $\frac{65}{64}\frac{55}{18}$, which is greater than the maximum social welfare from adopting Pigouvian fees, $\frac{55}{18}$. In this example, the welfare countries obtain when they choose Pigouvian fees cooperatively is strictly lower than the welfare countries obtain when they choose pollution quotas non-cooperatively. This example suggests that something is missing from conventional thinking. The question is what.

The main substantive contribution of this paper is to show the general insight that *adopting a Pigouvian fee to address an externality, in a multi-decision-maker setting with incomplete information, generates its own negative externality.* In supplying a global public good (e.g., mitigating climate change), a multi-decision-maker setting arises because of an international institutional rule of respecting a country's national sovereignty in choosing a pollution pricing instrument. When the inefficiency from adopting Pigouvian fees is high, non-cooperatively chosen quotas can generate higher social welfare than the maximum possible social welfare from adopting Pigouvian fees.[4]

I refer to the inefficiency arising from a Pigouvian fee's negative externality as the *PvQ inefficiency*. The simplest way to illustrate the origin of the PvQ inefficiency is by generalizing Weitzman's workhorse model to a policy-making game involving multiple countries. Allowing for multiple countries with the political power to choose their own policies captures the role of national sovereignty and the geographical limits of policies enacted in a country. Thus, a country benefits from the global supply of a public good and incurs a private cost of contributing to the global supply. When setting policies, a country's regulator does not foresee the technological opportunities or challenges firms face to comply with the regulation. What is the best way of addressing 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 policy inefficiency – a risk externality, which arises as a result of a country choosing a policy instrument that imposes a negative externality on other countries. Thus, environmental policy can be inefficient due to the *intensity inefficiency* (i.e., the inefficiency arising when a country imposes a lower tax level or a higher pollution quota than what is socially optimal) or the *PvQ inefficiency*, or both.

To establish the PvQ inefficiency in a general setting, the first result I discuss examines the PvQ inefficiency when countries commit to any comparable policy intensities, including the socially optimal or the equilibrium policy intensities. To understand the incentives behind the inefficiency, suppose a country prefers the price instrument. A country prefers the price instrument to let firms operating in its jurisdiction benefit from the flexibility to respond to shocks and deliver a higher abatement level when they face a low abatement cost, or a lower abatement level when

[4]Note that the inefficiency does not arise from practical limitations of adopting a tax, such as countries with a weak fiscal capacity failing to enforce a tax and avoid evasion (Acemoglu, 2005; Besley and Persson, 2009, 2011), the difficulty of imposing a tax and changing it over time (Slemord and Bakija, 2017), the ease of allowing exceptions and loopholes, the ease of being undermined through subsidies to complementary inputs, etc. Since the analysis in this paper focuses on efficiency only, considerations of distribution and practical issues similar to the ones mentioned above are outside the scope of this paper. For a more complete coverage of other issues in addition to efficiency, see Sterner and Coria (2012), Goulder and Schein (2013), and Stavins (2020).

they face a high abatement cost. However, this flexibility introduces variability in the country's abatement level. This variability, in turn, generates a cross-country risk externality since other countries would pay a positive risk premium to avoid this variability. When choosing the price instrument, a country considers only its own benefit from cost reductions and ignores the externality it imposes on other countries. A country's risk externality increases with the number of countries exposed to it, and when the global risk premium is too high, adopting a quota instead becomes socially optimal.

If the cost shock is global (e.g., the great recession in 2008), both the Pareto optimal and the equilibrium policy instruments exhibit asymmetry. This result contrasts with the symmetric choice of policy instruments under independent shocks. With a global shock, a country's optimal policy instrument becomes strictly strategic and depends on the policy instruments adopted by other countries. With independent shocks, a country's optimal policy instrument is strategically independent of the policy instruments of other countries. In addition to explaining why identical countries may choose different policies, a global cost shock provides an efficiency-based explanation as to why a union of sovereign states often chooses the quantity instrument instead of the price instrument. For global carbon taxes to be Pareto 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 $2n^2$. With more than 200 countries, adopting global carbon taxes is inefficient unless $c/b > 80,000$.

How significant can the PvQ inefficiency be? 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. Since the PvQ inefficiency and the intensity inefficiency are distinct and can arise independently, the next result I discuss establishes the importance of the PvQ inefficiency by comparing its distortion with the distortion due to the intensity inefficiency, for a general correlation structure of shocks. Strikingly, there exists a condition under which non-cooperatively chosen quotas result in higher collective welfare than taxes chosen to maximize social welfare.

Moreover, probing the PvQ inefficiency in various contexts suggests new *falsifiable* predictions, some of which are consistent with a number of empirical observations that have been hard to reconcile with the common policy prescription mentioned earlier. For example, if a supranational union such as the 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 members of the union, 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. This prediction is consistent with an observation that the quantity instrument is often chosen in a federation such as the 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 often chosen in individual countries (World Bank and Ecofys, 2018).[5] Similarly, when the cost shock is global (e.g., the great recession in 2008), countries tend to choose asymmetric policy instruments, *all else being equal*.

The remainder of this paper proceeds as follows. The next section describes contributions to the literature, followed by a section presenting the elements of the

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

model. After presenting the framework, the following section examines the origin and significance of the PvQ inefficiency. The final section concludes the paper after discussing empirical predictions based on the theory.

2 Contributions to the Literature

The choice between price and quantity is a long-standing issue 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 policymaker chooses between a tariff and a quota (Bhagwati, 1968; Dasgupta and Stiglitz, 1977). To crack the glass ceiling problem for women, policymakers choose between a price incentive and a quota (Chattopadhyay and Duflo, 2004; Besley et al., 2017; Bertrand et al., 2019).

The contributions of this paper advance the literature explaining inefficient policies stemming from the limits of agency (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), and political ease for repealing (Austen-Smith et al., 2019). Instead of relying on political frictions, the current contribution identifies an inefficiency arising due to countries' boundaries of political power. In doing so, it complements the rich body of knowledge using political frictions to explain the prevalence of inefficient policy instruments.

Besides, the contributions of this paper complement 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). The current contribution highlights an inefficiency arising even when the coverage of a policy is complete.

The results in this paper also contribute to the literature focusing on reducing emissions and maintaining the supply of a domestic public good (Pigou, 1920; Dales, 1968; Montgomery, 1972; 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), coalition formation and international agreements (Endres and Finus, 2002; Eichner and Pethig, 2015; Kornek and Marschinski, 2018), multiple pollutants and countries (Ambec and Coria, 2013; Ambec and Coria, 2018; Mideksa and Weitzman, 2019), stock externalities (Hoel and Karp, 2002; Newell and Pizer, 2003; Goulder and Schein, 2013; Karp and Traeger, 2018), and many more contributions not cited here due to space constraints.

The current paper, unlike the rest of the literature, discovers a negative externality arising from sovereign nations non-cooperatively choosing their own Pigouvian fees. It also identifies the conditions in which this inefficiency can be significant, and generalizes the results to different settings (e.g., the cost shocks being global or regional, a supranational union interacting with independent countries, and the benefits from a public good being stock-dependent). Furthermore, the analysis also generates new and falsifiable empirical predictions.

3 Basic Model

Suppose $N \equiv \{1, 2, ..., n\}$ is the set of countries indexed by $i = 1, 2, ..., n$.[6] 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 jurisdiction. The reduced-form shock to cost, θ_i, is drawn from a distribution with bounded support having a zero mean, $\mathbb{E}[\theta_i] = 0$, and a positive variance σ_i^2. From the viewpoint of country i's regulator, the net benefit from abatement is

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

where $B''(.) < 0 < B'(.)$ for all $Q \geq 0$, $\frac{\partial}{\partial q_i} C_i(q_i; \theta_i) \equiv C_i'(q_i; \theta_i) > 0$, and $\frac{\partial^2}{\partial q_i^2} C_i(q_i; \theta_i) \equiv C_i''(q_i; \theta_i) > 0$ for all $q_i \geq 0$ and $i \in N$.[7]

Remark 1. Note that (1) allows for heterogeneity in size among countries. Thus, country i's business as usual emissions is higher than country j's if $C_i'(0; 0) > C_j'(0; 0)$ even when $C_i''(q_i; 0) = C_j''(q_i; 0) = C''(q_i; 0)\, \forall i, j \in N$.

First, a decision-maker in each country chooses the type of policy $T_i \in \{\tau, TP\}$, where abatement is priced through the price (tax) instrument τ or through the quantity (tradable permit) instrument TP. Let $\mathbf{T} \equiv (T_1, ..., T_n)$ be the vector of the type of policy instruments countries choose. Without loss of generality, unless otherwise stated, suppose the set M contains m countries with the price instrument $T_i = \tau$, and the set $R \equiv N - M$ contains the remaining $n - m$ countries with the quantity instrument $T_i = TP$ at the first stage.

Second, after having observed the chosen profile of types $\mathbf{T}$, countries simultaneously choose the intensity $I_i \in \{t_i, \kappa_i\}$, where a tax level $t_i \in \mathbb{R}_+$ whenever pollution is priced using the price instrument and similarly a tradable quota level $\kappa_i \in \mathbb{R}_+$ whenever pollution is priced using the quantity instrument. Let $\mathbf{I} \equiv (I_1, ..., I_n)$.[8]

Policy choices in both stages are made under informational constraints. More precisely, decision-makers in each country act without knowing the realization of the random variables beforehand, except knowing the distribution. This assumption captures the notion that a regulator, when committing to a policy, does not have the same information as individuals regarding the available abatement options for each firm. Going forward, I maintain the assumption in Weitzman (1974) that the cost shocks are non-verifiable, and thus non-contractible.[9]

Once policymakers have committed to the type $\mathbf{T}$ and the intensity $\mathbf{I}$ of policy instruments, the values of shocks in each country are realized. The realized values

[6] There is a similar approach that starts with one region and splits it up into smaller regions. Weitzman (1974) used this approach in a single policymaker environment. However, the micro-foundation for splitting up a region into smaller regions imposes restrictive assumptions regarding the abatement technology and the shocks. I follow the conventional approach of using a country as a unit of analysis as in Alesina, Angeloni, and Etro (2005), Barrett (2007), and Harstad (2012).

[7] A notation with the subscript $-i$ is used with the conventional meaning – a vector with the subscript $-i$ denotes the same vector with its i^{th} component removed.

[8] The sequential choice of $\mathbf{T}$ and $\mathbf{I}$ is for clarity of exposition, and the results persist if the choice is made simultaneously.

[9] For example, in 2005 when the EU was setting up abatement goals for 2020, it could not know and contract on the fact that the great recession would occur in 2008 and reduce abatement costs.

determine how much it costs firms to comply with a regulatory constraint. At the final stage, firms in each country choose the abatement level q_i, where $\mathbf{q} \equiv (q_1, ..., q_n)$, conditional on the regulatory instrument in place and on the realization of the shocks.

Since the intensity of a given policy instrument can take any non-negative value, identifying a more efficient policy instrument requires comparing equivalent policy intensities. The basis for comparison can be equivalence in expected abatement or expected marginal abatement cost.

Comparability. *A price instrument with intensity $\hat{t}_i$ is comparable to a quantity instrument with intensity $\hat{\kappa}_i$ in pricing pollution if and only if*

$$\mathbb{E}_{\theta_i}\left[q_i(\hat{t}_i;\theta_i)\right] = q_i(\hat{\kappa}_i;\theta_i) \text{ and } \hat{t}_i = \frac{\partial}{\partial q_i}\mathbb{E}_{\theta_i}\left[C_i\left(q_i(\hat{\kappa}_i;\theta_i);\theta_i\right)\right]. \quad (2)$$

I focus on the pure-strategy (subgame-perfect) equilibrium. A pure-strategy equilibrium is a configuration $(\mathbf{T}^*, \mathbf{I}^*, \mathbf{q}^*)$, where a country's policy instrument $T_i^* \in \{\tau, TP\}$, its intensity $I_i^* : T_i \to \mathbb{R}_+$, and abatement $q_i^* : T_i \times I_i \to R_+$ such that $(\mathbf{T}, \mathbf{I})$ is the strategy of policymakers and $\mathbf{q}$ is the strategy of firms, abatement is the best response to the type and intensity of a policy instrument, and the type and intensity of a policy instrument are the best responses to abatement.[10]

Remark 2. The model can also shed light on the incentive problem facing multiple principals (e.g., regional branches of a corporation) when contributing to a collective good (e.g., a product brand building) and incentivizing agents (e.g., regional marketing companies) to supply the right amount of a public good (e.g., advertising effort).

4 An Inefficiency Result

Let me start with a general result of inefficiency. For any comparable policy intensities, countries tend to choose the price instrument even if it is Pareto inefficient.

Proposition 1. *For any comparable policy intensities $\{\hat{t}_i, \hat{\kappa}_i\}$, a country chooses $T_i = \tau$ inefficiently when*

$$\frac{\sigma^2_{\sum_{M\cup\{i\}} q_j(\hat{t}_j;\theta_j)} - \sigma^2_{\sum_M q_j(\hat{t}_j;\theta_j)}}{\sigma^2_{q_i(\hat{t}_i;\theta_i)}} \leq \frac{C_i''\left(\mathbb{E}q_i\left(\hat{t}_i;\theta_i\right)\right)}{\left|B''\left(\hat{Q}\right)\right|} \leq \frac{n\sigma^2_{\sum_{M\cup\{i\}} q_j(\hat{t}_j;\theta_j)} - n\sigma^2_{\sum_M q_j(\hat{t}_j;\theta_j)}}{\sigma^2_{q_i(\hat{t}_i;\theta_i)}},$$

where $\hat{Q} = \sum_N q_j(\hat{\kappa}_j;\theta_j)$ and $\sigma^2_X = \mathbb{E}[X - \mathbb{E}[X]]^2$.

Proof: *see Appendix.*

Thus, for any comparable policy instruments, countries tend to inefficiently choose the price instrument. This is because the price instrument's cost-savings are captured privately and its risk premium is borne globally.

[10] The superscripts $**$ and $*$ are used to designate the socially optimal and the individually optimal choices, respectively, in the remainder of the text.

To obtain sharper results regarding the nature and significance of the inefficiency, while maintaining comparability with and continuity to the vast literature based on Weitzman (1974), I continue with $Q \equiv \sum_{j\in N} q_j$ to follow Weitzman (1974, p. 483) and assume:

$$W^i = B'Q - B''Q^2/2 - [C' + \theta_i]\, q_i - C''q_i^2/2, \qquad \text{(W-A)} \qquad (3)$$

with B', B'', C', and C'' being positive parameters. An interested reader is referred to Weitzman (1974), who establishes (3) as a second-order approximation of a general $B(Q) - C_i(q_i;\theta_i)$ function, or to Dasgupta and Stiglitz (1977) for elaborate justifications.

5 Equilibrium Analysis

To identify the equilibrium strategies, I first consider equilibrium strategies beginning with the final subgame, where firms choose abatement, and then work backward. Since firms operate in a regulatory space in which they are exposed to technology shocks, a firm's abatement is contingent on technology shocks and regulation. An optimal reaction function for firms is

$$q_i(\kappa_i;\theta_i) \equiv \arg\min_{\kappa_i} C_i\,(q_i;\theta_i) \qquad (4)$$

when abatement is regulated using the quantity instrument or

$$q_i(t_i;\theta_i) \equiv \arg\min_{q_i} \{C_i\,(q_i;\theta_i) - t_i q_i\} \qquad (5)$$

when abatement is regulated using the price instrument. When a firm is exposed to a quota κ_i, its abatement minimizes the cost of compliance. Being fixed ex ante, a quota prohibits a country's abatement from responding to firms' ex post marginal cost. However, when a firm is exposed to a tax t_i, its abatement balances marginal cost, $\frac{\partial}{\partial q_i} C_i\,(q_i;\theta_i)$, with the marginal benefit t_i. Since firms know the realized value of cost shocks θ_i before choosing abatement levels, a tax allows firms to incorporate the extra information about shocks, thereby letting a country's abatement respond to firms' ex post marginal costs.

5.1 The Origin of Environmental Policy Inefficiencies

In choosing efficient policies, the social planner takes the boundaries of sovereignty across countries as fixed. At the stage of choosing policy intensities, the planner chooses the best policy intensities $\{t_i^{**}, \kappa_i^{**}\}_{i=1}^n$ for all countries that maximize the collective welfare, $\mathbb{E}[\sum_N W^i]$ taking into account firms' optimal reactions to the policy intensities, (4) and (5).

In a non-cooperative world of multiple nations, a country's decision-maker chooses a policy intensity t_i^* or κ_i^* in order to maximize the country's welfare $\mathbb{E}[W^i]$. This maximization anticipates that all countries choose a policy intensity and that firms react optimally in accordance with (4) or (5). After all countries adopt their own policy instruments, a country's decision-maker chooses a policy's intensity in order to maximize the country's welfare given firms' reactions to the chosen policy.

The socially optimal intensity of price is $t_i^{**} = \frac{nC''B'+n^2C'B''}{n^2B''+C''}$ whereas the equilibrium intensity of price is $t_i^* = \frac{C''B'-nB''(B'-C')}{nB''+C''}$, $\forall i \in M$. And, the socially optimal intensity of quantity is $\kappa_i^{**} = \frac{nB'-C'}{n^2B''+C''}$ whereas the equilibrium intensity of quantity is $\kappa_i^* = \frac{B'-C'}{nB''+C''}$, $\forall i \in R$. There exists inefficiency in a policy intensity, $t_i^* < t_i^{**}$ and $\kappa_i^* < \kappa_i^{**}$, whenever $n > 1$. The following Lemma establishes the welfare consequence of the intensity inefficiency from adopting the price instrument.

Lemma 1. *The magnitude of the price instrument's intensity inefficiency $IE_\tau(n)$ is given by*

$$IE_\tau(n) = \frac{n}{2}\left[n^2B'' + C''\right]\left[\frac{nB' - C'}{n^2B'' + C''} - \frac{B' - C'}{nB'' + C''}\right]^2. \tag{6}$$

Proof: *see Appendix.*

The reason why individually optimal policy intensities are less than the socially optimal levels is that decision-makers only consider their own country's interest and not the broader benefits of the policy for all countries.

5.1.1 The PvQ Inefficiency

At the initial stage, all policymakers choose the best way of pricing pollution. Before proceeding further, it is worth noting that the equilibrium (or the socially optimal) policy intensities are comparable.

Remark 3. For each country, both the best policy intensities $\{t_i^{**}, \kappa_i^{**}\}_{i=1}^n$ and the equilibrium policy intensities $\{t_i^*, \kappa_i^*\}_{i=1}^n$ are comparable.

The fact that the socially optimal policy intensities $\{t_i^{**}, \kappa_i^{**}\}_{i=1}^n$ are comparable has an interesting implication. If the level of price or quantity a country implements is fixed at the socially optimal level, does it price pollution efficiently? While this thought experiment is unrealistic, it is worth knowing whether countries will price pollution efficiently.[11] Together with Proposition 1, Remark 3 implies that inefficiency arises from adopting the price instrument even when countries adopt the socially optimal policy intensities. To appreciate the significance of this result, consider the Kyoto Protocol (KP) and the Paris Climate Agreement (PCA), which have focused on getting the domestic policy intensities to be socially optimal (Battaglini and Harstad, 2016 and 2019). In an ideal scenario, these agreements deliver socially optimal policy intensities, letting the PvQ inefficiency on the loose.

What is the magnitude of the PvQ inefficiency? A social planner chooses the socially optimal policy instrument for each country to maximize the collective welfare while correctly anticipating that all countries implement the socially optimal policy intensity and that firms react optimally in accordance with (4) or (5). The welfare loss from

[11] The thought experiment is the following: suppose a truly multinational and technocratic group of economists, say in the World Bank or the IMF, have calculated the socially optimal carbon tax or carbon quota for each country, leaving the choice between the two instruments for countries. Could there be any remaining inefficiency if countries were to pick the carbon tax or quota calculated for them by the impartial technocrats?

countries adopting the price instrument despite adopting the quantity instrument is socially optimal is given by the PvQ inefficiency.

Proposition 2. *The magnitude of the PvQ inefficiency $PvQ(m)$, when m countries adopt the price instrument, is given by*

$$PvQ(m) = \frac{nB'' \left[\sum_M \sigma_i^2 + 2\sum_{i=1}^{m-1}\sum_{j=i+1}^{m}\rho_{ij}\sigma_i\sigma_j\right] - C''\sum_M \sigma_i^2}{2\left[C''\right]^2}, \tag{7}$$

where ρ_{ij} is the Pearson correlation coefficient for θ_i and θ_j for $i \neq j$.

Proof: *see Appendix.*

The two policy instruments are equally efficient and $PvQ(m) = 0$ when policymakers know everything individual firms know. However, economic research since Hayek (1945) has questioned the realism of this assumption. The result cited earlier from the Chicago Booth School of Business's survey of economic experts who supported a carbon tax over a quota suggests that these economists believe that the assumption that policymakers have identical information as firms is inaccurate.

With differential information, the price instrument is more efficient if the preference for risk is neutral – a positive cost-saving is obtained with zero risk premium. Risk neutrality is a valid assumption when the marginal environmental damage from an extra unit of pollution at low levels of pollution is exactly equal to the marginal environmental damage from an extra unit of pollution at high levels of pollution, which is not the case for most environmental problems. As Pindyck (2007, p. 47) writes, "environmental cost and benefit functions tend to be highly nonlinear." In fact, for most pollution problems, the preference for risk is negative and the risks of crossing environmental thresholds are significant. With differential information, risk aversion, and multiple countries, the risk externality arises. With risk externality, a country's commitment to the price instrument is inefficient when the $PvQ(m) \neq 0$.

The PvQ inefficiency in (7) depends upon the degree of correlation of shocks across countries, which can be independent and country-specific or global or perfectly correlated. In reality, the shocks can exist between the two extremes. To obtain sharp predictions, let us explore the two extreme cases in greater detail.

5.1.2 Consequences of a Global Shock

Arguably, we are living in a time when countries are going through extensive digital, financial, and commercial integration. Knowledge about abatement technologies invented in one place can flow quickly to other place, while a technology of generating pollution-free energy can make its way to other parts of the planet in a few months. 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 $\sigma_i^2 = \hat{\sigma}^2,\ \forall i \in N$.

With a global shock, the welfare loss from adopting the price instrument becomes $PvQ(m) = \frac{m[nmB'' - C'']}{2C''^2}\hat{\sigma}^2$, and the Pareto optimal number of countries adopting the price instrument is the nearest integer to

$$m^{**} = \frac{1}{2n}\frac{C''}{B''}. \tag{8}$$

Note that (8) has a stark implication. In reality, the value of n is about 200 sovereign countries. Thus, for global 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.

Lemma 2. *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 $max\{0, \frac{C''-B''}{2B''}\}$.*

Proof. Country i's welfare difference from committing to the quantity instrument κ_i^* instead of committing to the price instrument t_i^* when *all* countries commit to the equilibrium amount of prices and quantities is

$$\mathbb{E}W^i\left(q_i(\kappa_i^*;\theta), q_{-i}(I_{-i}^*;\boldsymbol{\theta}_{-i})\right) - \mathbb{E}W^i\left(q_i(t_i^*;\theta), q_{-i}(I_{-i}^*,\boldsymbol{\theta}_{-i})\right) = \frac{[2m+1]\,B'' - C''}{2C''^2}\hat{\sigma}^2. \tag{9}$$

If a country expects that no other country will adopt the price instrument in equilibrium, (9) implies that a country benefits from committing to the price instrument only if $B'' < C''$. However, if a country expects that other countries will adopt the price instrument in equilibrium, (9) 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 the quantity instrument; thus the equilibrium m^* becomes the nearest integer to

$$m^* = \max\left\{0, \frac{C''-B''}{2B''}\right\}. \tag{10}$$

In this particular case, a country having $B'' = \frac{C''}{2m+1}$ is indifferent between adopting the price and the quantity instrument; hence, it has a mixed strategy whereas the remaining countries have a pure strategy of choosing either the price or the quantity instrument. If $\frac{C''}{B''} = 2n+1$, then $m^* = n$ and $m^{**} \leq 2$; whereas if $\frac{C''}{B''} \geq 2n^2$ for $n > 1$, then $m^* = m^{**} = n$. *Q.E.D.*

A global technology shock has numerous implications. First, with a global cost shock, a 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. Second, with a global cost shock, the equilibrium number of countries adopting the quantity instrument is positive, despite $C'' > B''$. Third, a social planner assigns the price instrument to no country despite $C'' > B''$ if $C'' < 4nB''$.

5.1.3 Consequences of Independent Shocks

If the cost shocks are country-specific and independent, $\rho_{ij} = 0$, the magnitude of the PvQ inefficiency takes a simple form, $PvQ(m) = \frac{nB''-C''}{2C''^2}\sum_{i=1}^{m}\sigma_i^2$. When $C'' > nB''$, the policy distortion decreases in m and all countries choosing the price instrument is Pareto inefficient.

Lemma 3. *At the equilibrium levels of policy intensities, there exists a PvQ inefficiency if* $1 < \frac{C''}{B''} < n$.

Proof. To find the equilibrium, continue assuming m countries have committed to the price instrument at the first stage. Also assume that members of the set $\tilde{R} \equiv N - M - i$ of $n - m - 1$ countries have committed to the quantity instrument at the first stage. Country i's welfare gain from committing to the price instrument instead of the quantity instrument is

$$\mathbb{E}W^i \left(q_i(t_i^*; \theta_i), q_{-i}(I_{-i}^*; \boldsymbol{\theta}_{-i})\right) - \mathbb{E}W^i \left(q_i(\kappa_i^*; \theta_i), q_{-i}(I_{-i}^*, \boldsymbol{\theta}_{-i})\right) = \frac{C'' - B''}{2C''^2}\sigma_i^2. \tag{11}$$

In sum, on the equilibrium profile of abatement, country i obtains higher welfare from committing to the price instrument if $C'' > B''$, but a country's choice of the price instrument is inefficient whenever $1 < \frac{C''}{B''} < n$. *Q.E.D.*

5.2 The Significance of the PvQ Inefficiency

As noted earlier, there are two potential sources of policy distortion when countries non-cooperatively choose both their policy instrument and policy intensity. Countries may adopt socially optimal policy instruments but inefficient intensities or inefficient policy instruments but socially optimal intensities. Or a country may have both a policy instrument and a policy intensity inefficient. To evaluate the significance of the PvQ inefficiency, one can compare the welfare losses from these two sources of inefficiency and ask – under which conditions does the collective welfare from non-cooperatively determined emissions quotas exceed the maximum welfare that can be obtained from taxes?

Proposition 3. *The social welfare from the non-cooperatively chosen quantities is higher than the social welfare from the socially optimal prices (i) when the cost shocks are identically and independently distributed across all countries if* $\mu_{iid}(n) > \frac{1}{\sigma^2}$, *(ii) when the cost shock is identical across all countries if* $\frac{n^2B''-C''}{nB''-C''}\mu_{iid} > \frac{1}{\hat{\sigma}^2}$, *where*

$$\mu_{iid}(n) \equiv \frac{[nB'' - C'']}{[n^2B'' + C''][C'']^2} \left[\frac{nB' - C'}{n^2B'' + C''} - \frac{B' - C'}{nB'' + C''}\right]^{-2}.$$

Proof: *see Appendix.*

To interpret the result, note that σ^2 measures the degree of information differential between regulators setting policies and individual firms deciding the amount of emissions to reduce. When σ^2 (or $\hat{\sigma}^2$) $\to 0$, regulators not only know as much as individuals regarding the available abatement options but can also correctly anticipate shocks such as the great recession before they occur. However, if the information differential between regulators and individual firms is large and σ^2 (or $\hat{\sigma}^2$) $\to \infty$, the sufficient condition for the result is easily satisfied.

The result that the welfare from non-cooperatively determined quotas can exceed the maximum welfare from adopting Pigouvian fees may appear counter-intuitive at first glance. However, the economics is straightforward. All else being equal, a country's optimal policy instrument balances the trade-off between the flexibility to take advantage of cost-reducing shocks and the risk that abatement will be too low or too high ex post. A fixed quantity is inflexible and does not allow a country to benefit from cost-reducing shocks, yet it avoids the risk premium from variable abatement. The price instrument, in contrast, allows a country to benefit from socially useful cost-reducing shocks, yet it imposes the risk that abatement will be too low or too high 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 risk premium. However, Pareto optimality calls for adopting the price instrument only if the social cost saving for each unit of abatement is greater than the social risk premium from 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 the risk externality to other countries can be too high.

With a large number of countries, a country's optimal rule for choosing a policy instrument departs from the rule that would maximize collective welfare – a country adopting a Pigouvian tax imposes a negative risk externality on other countries. When the socially optimal Pigouvian taxes of these countries generate negative risk externality, countries are better off with non-cooperatively determined and inefficiently low quotas. For this reason, an analysis ignoring the fact that more than 200 sovereign countries can have a non-zero value for risk and insurance provides a misleading answer. Of course, welfare can be further improved if countries adopt socially optimal quotas.

What do these results mean for pricing a pollution problem? Perhaps, focusing on the pollutant CO_2, what is the best policy instrument for pricing carbon?[12] According to the results, the answer depends upon the values of C'' and B'' for climate mitigation and the number of countries. Without a significant mitigation effort, it is impossible to have a direct estimate of the value of C''. This is because the climate mitigation project is unique: it is a massive project that shapes the world economy and involves multiple generations and technological revolutions. Nevertheless, with more and more abatement over time, it is reasonable to expect that the knowledge regarding the value of C'' improves over time. However, the case of learning the value of B'' is even more difficult. This is because climate change is mainly a planetary consequence of increased atmospheric concentrations of CO_2, which have increased from 280 parts per million in the late 1700s to 413.52 parts per million in May 2019. The current concentrations are at a level unseen in modern times, at least over the past 800,000 years, and remain in the atmosphere for many years.

While Nordhaus (2008) and others have taken a defensible approach of learning from the existing data, this approach can be challenged on several grounds. First, this approach suffers from extrapolation bias. Specifically, to what extent does the existing data capture the correct shape of the damage function from climate change?[13] Second, assuming the

[12] Recently, Kotlikoff et al. (2020) use a dynamic macro-finance perspective to arrive at a somewhat suggestive evidence pointing that cost of carbon-risk can be as large or larger than the cost of damage from carbon. Note that Kotlikoff et al. (2020) use carbon tax as a synonym to a carbon price and, unlike the current contribution, their result does not arise from non-cooperative decision making.

[13] While revising this paragraph in March 2020, most countries are on lockdown to control the spread of the COVID-19 virus. This lockdown has been hitting the GDP of the world economy hard. If one were to extrapolate the cost and benefit functions of controlling the COVID-19 virus from similar viruses in the past, it would be apparent that this extrapolation is wildly inaccurate due to extrapolation bias.

value $B'' \approx 0$ is equivalent to assuming the marginal environmental damage from an extra unit of pollution at low levels of pollution is exactly equal to the marginal environmental damage from an extra unit of pollution at high levels of pollution, which is not the case for climate change, at least according to the IPCC reports. Third, Weitzman (2010) has shown that the shape of the damage function is sensitive to small changes in the underlying assumptions.

Due to the sheer complexity of the problem, the approach taken in this paper is somewhat simpler. Instead of taking a stand on the values of C'' and B'', it is relatively easier to generate a set of testable predictions from the theory and point experts in empirical research to independently falsify the predictions rigorously based on data that can be observed.[14] I pursue this approach in the next section to examine the set of testable predictions that emerge from risk externality.

6 Testable Predictions

This section discusses the empirical implications of risk-externality in the context of a supranational union, a global technological shock, and a stock aspect of a public good. In this section, I focus on an intuitive discussion of the new testable predictions.[15]

A Supranational Union. Supranational unions and institutions play significant roles in the conduct of national policies. The nation-state has held a monopoly on the conduct of national policies for a very long time. However, since the 1990s, different supranational institutions have been granted decision power on the policy domains of sovereign countries, such as facilitating international trade and protecting the global climate. Such institutions execute their policies while leaving the political boundaries among member states on other policy domains intact (Alesina et al., 2003).

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

At the stage of choosing a policy's intensity, a union Ω's most preferred levels of prices and quantities maximize the expected collective welfare of the member states taken together, $\mathbb{E}W_\Omega \equiv \sum_{i\in\Omega} \mathbb{E}W^i$ where $\mathbb{E}W^i$ is given by (3) and maximization is subject to

[14] Note that if a researcher observes countries' policy instrument and the values of B'' and C'', she can test the prediction of the theory easily. The concept of risk externality provides three more empirical predictions that can be tested even when the value of B'' or C'' are unobservable to a researcher.

[15] Extensions of the basic model behind the testable predictions are reported in the previous versions of the manuscript and can be available from the author upon request.

firms' rationality constraints of (4) or (5) in all countries.[16] In such a setting, members of the union consider the price instrument's risk externality on other members. Thus, the union adopts the price instrument in a narrower range of parameters than in the condition arising in the absence of the supranational union.

Testable Prediction: *All else being equal, a union of sovereign jurisdictions such as the EU or a federation of states is more likely to choose carbon markets instead of a carbon tax compared to a unitary jurisdiction.*

Testing predictions requires a careful empirical examination, and this is beyond the scope of this paper. However, it seems that a union's reaction to risk externality provides an efficiency-based explanation for some of the observed behavior that unions of states are *more likely* to choose the quantity instrument while countries with a unitary government are *more likely* to choose the price instrument. Numerous suggestive examples can be found in the realm of climate change. The United States, a federation of 50 states, chose the quantity instrument to regulate SO_2. Similarly, the EU, a supranational union, uses a quantity instrument to regulate CO_2 (Schmalensee and Stavins, 2013; Stavins, 2018). This behavior is particularly stark among countries that acceded to the EU relatively recently. In the 1990s, Denmark, Germany, Netherlands, Italy, Sweden, and the UK all used carbon taxes to reduce CO_2 (Barde et a1., 2001). After joining the EU, these same countries chose the quantity instrument once the Maastricht Treaty went into effect, and they now participate in the EU emissions trading scheme. Meanwhile, countries with unitary governments tend to choose a tax to regulate greenhouse gases, as Argentina, Chile, Colombia, Singapore, and South Africa all do (World Bank and Ecofys, 2018).[17] However, this is not conclusive empirical evidence and, certainly, it is possible to find a counterexample. Whereas a risk externality implies the testable prediction that, all else being equal, a union of sovereign nations is more likely to adopt the quantity instrument than a unitary country, the conditional prediction rests on *all else being equal.*

In addition to the case of a union of countries, the analysis lends itself also for a testable empirical prediction in relation to the degree of correlation of technological shocks. The theory has a sharp prediction regarding which equilibrium strategies countries choose when the shocks are independent and the equilibrium strategies chosen when the shocks are globally correlated.

Testable Prediction: *All else being equal, if technology shocks are country-specific and independent, then countries are more likely to choose symmetric policy instruments; whereas if technology shocks are globally correlated, countries are more likely to choose asymmetric policy instruments.*

[16] This assumption abstracts from the details of the EU's complex decision-making process, which is far from a benevolent planner's decision-making process. Depending on the voting rule in place, the actual decision-making process may involve bargaining and coalition formation to enact an EU-wide policy. However, the above conclusion 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 a 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.

[17] According to Forbes, the UK is considering to revert to imposing carbon tax after Brexit. https://www.forbes.com/sites/davekeating/2019/09/09/uk-to-impose-carbon-tax-after-no-deal-brexit/#2447f3b43ab5

A Stock Dimension. For ease of presentation, the analysis so far has avoided the distinction between the flow and stock aspects of public goods. Whereas the benefit from many public goods is derived entirely from the flow of supply, the benefits of mitigating climate change are derived from reducing the atmospheric stock of greenhouse gases, particularly CO_2. Abatement today reduces environmental damage not only today but also for many years to come. Is the PvQ inefficiency relevant if benefits depend on a stock and if the contribution to the stock today is very small relative to the existing stock?

For stock-dependent public goods affecting the welfare of many countries, the risk externality extends to the future, creating an intertemporal risk trade-off. Even for a single regulator, adopting the price instrument delivers a cost-saving today but imposes a risk premium both today and in the future. In this case, foresight becomes a crucial determinant of the efficient policy type. If policymakers in all countries are environmentally myopic and ignore the future consequences of current policies, 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 adopting the price instrument over adopting the quantity instrument.

On the contrary, if policymakers exhibit foresight and consider the stock's benefits in the future, the qualitative results remain intact, but the parametric space changes in favor of the quantity instrument. The price instrument's cost-saving needs to be higher than the discounted sum of the risk premium today and in the future, unlike the myopic case in which the cost-saving has to exceed only the current risk premium. Thus, the relationship between the PvQ inefficiency and stock-based public goods also offers a testable prediction even when the values of B'' and C'' are unobserved.

Testable Prediction: *All else being equal, a country's likelihood of choosing a quota (instead of choosing a tax) is higher if the benefit from a public good is derived from stock instead of from flow.*

Note that Karp and Traeger (2018) use the assumptions in the DICE model and show that uncertain future technological change can bring about a positive correlation between marginal benefits and marginal costs and that such a positive correlation tends to favor the quantity instrument, as shown by Stavins (1996).[18] The prediction from risk externality regarding the effect of stock remains even when one shuts off the mechanism in Karp and Traeger (2018) and allows zero correlation of cost shocks over time. To sum up, the notion of risk externality offers at least three testable predictions.

7 Conclusion

What is the welfare implication of national sovereignty in choosing a pollution pricing instrument? To answer this question, the analysis has focused on a framework in which countries choose both the type and intensity of a policy in a strategic setting while facing technological uncertainty. Countries' choice of policy instruments can favor the price instrument, which in turn can give rise to the PvQ inefficiency. Focusing on efficiency, this paper has examined the *conceptual* origin and significance of the PvQ inefficiency,

[18] Whereas most of the previous analyses based on the parameters of the DICE model favor a Pigouvian fee, the robustness of DICE's parameters to extrapolation bias remains to be seen in the future.

which in turn has generated both a policy message and testable predictions for rigorous scrutiny in future empirical research.

The PvQ inefficiency has a clear implication for climate policy. International climate negotiations, notably the Kyoto Protocol being an agreement on quantities instead of prices, are consistent with the outcome of the analysis reported here. However, climate negotiations have focused on addressing the intensity inefficiency by encouraging countries to meet emissions targets without specifying how the emissions should be reduced. That is important. Besides, the notion of risk externality advanced in this paper implies that climate negotiations should not ignore the choice of a climate policy instrument.

As a positive contribution, the PvQ inefficiency provides empirical predictions that are consistent with the observation that countries are more likely to 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 the 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). The PvQ inefficiency's prediction is consistent with this outcome: belonging to a union, countries collectively choose quota to avoid imposing the negative externality of taxes on the members. While the consistency of predictions with some observed behavior can be encouraging, it is not a substitute for a serious empirical evaluation. A rigorous empirical test of these predictions is essential and left for future research.

As a substantive contribution, this study 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, but it has also resulted in insights complementary to those in the literature. The PvQ inefficiency is of interest for several reasons. First, it arises despite countries adopting a market-based rather than a command-and-control policy instrument. Second, it persists even in the absence of 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 of carbon leakage and the green paradox. The PvQ inefficiency 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.

To sum up, economic analysis suggests that pricing pollution is the most efficient way of addressing a pollution problem. The analysis reported in this paper suggests that a political institution (e.g., national sovereignty) can interact with policy instruments in a non-obvious manner.[19] However, several institutional rules govern and shape the international political economy. Thus, there is a need for more conceptual and empirical research on the consequences of the existing political institutions for identifying ways of

[19] This observation is not new. Krugman (1991, pp. 2-3) writes: "... the tendency of international economists to turn a blind eye to the fact that countries both occupy and exist in space – a tendency so deeply entrenched that we rarely even realize we are doing it – has, I would submit, had some serious costs. These lie not so much in lack of realism – all economic analysis is more or less unrealistic – as in the exclusion of important issues and, above all, of important sources of evidence."

addressing various environmental problems.

Appendix: Proofs

Proof of Proposition 1. The expected welfare from adopting the price instrument is

$$\begin{aligned}\mathbb{E}W^i\left(q_i\left(\hat{t}_i;\theta_i\right),q_{-i}\left(I_{-i};\theta_{-i}\right)\right) &\approx B\left(\hat{Q}\right)+\frac{1}{2}B''\left(\hat{Q}\right)\sigma^2_{\sum_{M\cup\{i\}}q_j\left(\hat{t}_j;\theta_j\right)}\\ &-C_i\left(\mathbb{E}q_i\left(\hat{t}_i;\theta_i\right)\right)-\frac{1}{2}C_i''\left(\mathbb{E}q_i\left(\hat{t}_i;\theta_i\right)\right)\sigma^2_{q_i\left(\hat{t}_i;\theta_i\right)}.\end{aligned}$$

Similarly, the expected welfare from adopting the quantity instrument is

$$\begin{aligned}\mathbb{E}W^i\left(q_i\left(\hat{\kappa}_i;\theta_i\right),q_{-i}\left(I_{-i};\theta_{-i}\right)\right) &\approx B\left(\hat{Q}\right)+\frac{1}{2}B''\left(\hat{Q}\right)\sigma^2_{\sum_{M}q_j\left(\hat{t}_j;\theta_j\right)}\\ &-C_i\left(\mathbb{E}q_i\left(\hat{\kappa}_i;\theta_i\right)\right).\end{aligned}$$

For any country i, adopting the price instrument is welfare improving only if

$$B''\left(\hat{Q}\right)\sigma^2_{\sum_{M\cup\{i\}}q_j\left(\hat{t}_j;\theta_j\right)}-B''\left(\hat{Q}\right)\sigma^2_{\sum_{M}q_j\left(\hat{t}_j;\theta_j\right)}\geq C_i''\left(\mathbb{E}q_i\left(\hat{t}_i;\theta_i\right)\right)\sigma^2_{q_i\left(\hat{t}_i;\theta_i\right)};$$

however, adopting the quantity instrument is Pareto optimal if

$$nB''\left(\hat{Q}\right)\sigma^2_{\sum_{M\cup\{i\}}q_j\left(\hat{t}_j;\theta_j\right)}-nB''\left(\hat{Q}\right)\sigma^2_{\sum_{M}q_j\left(\hat{t}_j;\theta_j\right)}\leq C_i''\left(\mathbb{E}q_i\left(\hat{t}_i;\theta_i\right)\right)\sigma^2_{q_i\left(\hat{t}_i;\theta_i\right)}.$$

Country i adopts the price instrument inefficiently only if

$$\frac{\sigma^2_{\sum_{M\cup\{i\}}q_j\left(\hat{t}_j;\theta_j\right)}-\sigma^2_{\sum_{M}q_j\left(\hat{t}_j;\theta_j\right)}}{\sigma^2_{q_i\left(\hat{t}_i;\theta_i\right)}}\leq\frac{C_i''\left(\mathbb{E}q_i\left(\hat{t}_i;\theta_i\right)\right)}{\left|B''\left(\hat{Q}\right)\right|}\leq\frac{n\sigma^2_{\sum_{M\cup\{i\}}q_j\left(\hat{t}_j;\theta_j\right)}-n\sigma^2_{\sum_{M}q_j\left(\hat{t}_j;\theta_j\right)}}{\sigma^2_{q_i\left(\hat{t}_i;\theta_i\right)}}.$$

Q.E.D.

Proof of Lemma 1. From (5), it follows that the best response abatement levels to the price intensity t_i is $q_i(t_i;\theta_i)=\frac{t_i-C'-\theta_i}{C''}$. Using (3) to arrive at $\sum_N \mathbb{E}W^i$, reinserting the best response abatement into $\sum_N \mathbb{E}W^i$, and maximizing $\sum_N \mathbb{E}W^i$ with respect to $\{t_i\}$, one arrives at $t_i^{**}=\frac{nC''B'+n^2C'B''}{n^2B''+C''}$. Again, using the best responses in (3) and maximizing the $\mathbb{E}W^i$, one arrives at the t_i that maximizes country i's welfare: $t_i^*=\frac{C''B'-nB''(B'-C')}{nB''+C''}$. Solving for the abatement that t_i^* and t_i^{**} induce and reinserting the induced abatement back into (3), and solving for $\sum_N \mathbb{E}W^i\left(q_i\left(t_i^{**},\theta_i\right),q_{-i}\left(t_{-i}^{**},\theta_{-i}\right)\right)-\sum_N \mathbb{E}W^i\left(q_i\left(t_i^{*},\theta_i\right),q_{-i}\left(t_{-i}^{*},\theta_{-i}\right)\right)$, one arrives at (6). *Q.E.D.*

Proof of Proposition 2. Using (5), the best response abatement level to the price instrument becomes $q_i(t_i;\theta_i)=\frac{t_i-C'-\theta_i}{C''}$. Using (3) to arrive at $\sum_N \mathbb{E}W^i$, inserting

$\{q_i(t_i;\theta_i)\}_{i\in M}$ in $\sum_N \mathbb{E}W^i$ and solving $\max_{\{t_i\}_{i\in M},\{\kappa_i\}_{i\in R}} \sum_N \mathbb{E}W^i$, one arrives at $t_i^{**} = \frac{nC''B'+n^2C'B''}{n^2B''+C''}$ and $\kappa_i^{**} = \frac{nB'-C'}{n^2B''+C''}$. $\sum_M \left[\mathbb{E}W^i\left(q_i\left(\kappa_i^{**},\theta_i\right), q_{-i}\left(\kappa_{-i}^{**},\theta_{-i}\right)\right) - \mathbb{E}W^i\left(q_i\left(t_i^{**},\theta_i\right), q_{-i}\left(t_{-i}^{**},\theta_{-i}\right)\right)\right]$ gives (7). Note that Remark 4 implies the PvQ inefficiency is also given by the difference between $\sum_M \left[\mathbb{E}W^i\left(q_i\left(\kappa_i^{*},\theta_i\right), q_{-i}\left(\kappa_{-i}^{*},\theta_{-i}\right)\right)\right]$ and $\sum_M \left[\mathbb{E}W^i\left(q_i\left(t_i^{*},\theta_i\right), q_{-i}\left(t_{-i}^{*},\theta_{-i}\right)\right)\right]$. *Q.E.D.*

Proof of Proposition 3. The welfare from non-cooperatively determined quantities is given by $\sum_N \mathbb{E}W^i\left(q_i(\kappa_i^*;\theta_i), q_{-i}(I_{-i}^*;\theta_{-i})\right)$, whereas the welfare from socially optimal prices is $\sum_N \mathbb{E}W^i\left(q_i(t_i^{**};\theta_i), q_{-i}(t_{-i}^{**};\theta_{-i})\right)$. Comparing the value $\sum_{i=1}^n \mathbb{E}W^i\left(q_i(\kappa_i^*;\theta_i), q_{-i}(I_{-i}^*;\boldsymbol{\theta}_{-i})\right)$ with the value $\sum_N \mathbb{E}W^i\left(q_i(t_i^{**};\theta_i), q_{-i}(t_{-i}^{**};\theta_{-i})\right)$, under the assumptions of iid shocks or a global shock, one arrives at the expression stated in the Proposition. *Q.E.D.*

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