Voluntary Prices vs. Voluntary Quantities*

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Abstract

We extend the standard 'Prices vs. Quantities' framework to cover two independent and identical jurisdictions, A and B. Both jurisdictions set a price or quantity to maximize their own expected welfare conditional on the instrument type and amount chosen by the other jurisdiction. With iid uncertainty, a dominant strategy of both jurisdictions is to choose a price instrument when the slope of marginal benefit is less than the slope of marginal cost and a quantity instrument when the condition is reversed. With n countries, if the slope of marginal benefit is equal to the slope of marginal cost, the welfare cost at the equilibrium in which countries coordinate on prices is *higher*, by a factor of n, than the welfare cost at the equilibrium in which countries coordinate on quantity. By extending the standard 'Prices vs. Quantities' criterion from the basic choice framework to a strategic setting, we allow the choice of policy type and amount to take into account the free-riding by other jurisdictions and discover the welfare benefit of coordination on quantities.

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1 Introduction

Choosing the best instrument for controlling negative externality from pollution has been a long-standing central issue in environmental economics. Pigou (1920) introduced and subsequently popularized the central concept of placing a price-charge on pollution (since called a 'Pigouvian tax') as an efficient way to correct a pollution externality. This Pigouvian-tax approach dominated economic thinking about the pollution externality problem for about the next half-century.

Dales (1968) introduced the idea of creating property rights in the form of tradeable pollution permits (aka 'allowances') as an efficient alternative to a Pigouvian tax. Montgomery (1972) rigorously proved the formal equivalence between a price on pollution and a dual quantity representing the total allotment of tradeable permits. Henceforth, it became widely accepted that there is a fundamental isomorphism between a Pigouvian tax on pollution and the total quantity of caps allotted in a cap-and-trade system, with all permits trading at the same competitive-equilibrium market price as the Pigouvian tax. For every Pigouvian tax, there exists a quantity of tradeable permits allotted whose competitive-equilibrium market price equals the Pigouvian tax. And for every total quantity of tradeable permits, there exists a competitive-equilibrium market price that would yield the same result if imposed as a Pigouvian tax. So far all the analysis has taken place in a deterministic context with full certainty.

Weitzman (1974) shows that there is no longer an isomorphism between price and quantity instruments when there is uncertainty in cost and benefit functions. When uncertainty is introduced, setting a fixed price stabilizes marginal cost while leaving the total quantity of pollution variable, whereas setting a fixed total quantity of tradeable permits stabilizes total quantity while leaving price (or marginal cost) variable. The question then becomes: which instrument is better under which circumstances?

Weitzman (1974) derives a relatively simple formula for the 'comparative advantage of prices over quantities', denoted in the paper as Δ. The sign of Δ depends on the relative slopes of the marginal abatement-cost curve and the marginal abatement-benefit curve. When the marginal benefit curve is flatter than the marginal cost curve, the sign of Δ is positive (prices are favored over quantities). Conversely,when the marginal benefit curve is steeper than the marginal cost curve, the sign of Δ is negative (quantities are preferred over prices).

This led to the development of a sizable literature on the optimal choice of price vs. quantity policy instruments under uncertainty.[1] Adar and Griffin (1976), Fishelson (1976), and Roberts and Spence (1976) analyzed seemingly alternative (but ultimately similar) forms of uncertainty. Weitzman (1978), Yohe (1978), Kaplow and Shavell (2002), and Kelly (2005) extended the basic model to cover various aspects of nonlinear marginal benefits and nonlinear marginal costs. Yohe (1978) and Stavins (1995) analyzed a situation where uncertain marginal costs are correlated with uncertain marginal benefits. Chao and Wilson (1993), and Zhao (2003) incorporated investment behavior into the basic framework of instrument choice under uncertainty. In these extensions, the results generally preserve the earlier insight that, all else held equal, flatter marginal benefits or steeper marginal costs tend to favor prices while steeper marginal benefits or flatter marginal costs tend to favor quantities.[2]

Extensions to cover stock externalities in a dynamic multi-period context were made by Hoel and Karp (2002), Pizer (2002), Newell and Pizer (2003), and Fell, MacKenzie and Pizer (2012), among others. The extensions to dynamic stock externality kept much of the 'flavor' of the original Δ story, which was phrased in terms of emission flows throughout a regulatory period (followed by a new regulatory period with new decision-relevant parameters). In particular, for the case of climate change from accumulated stocks of atmospheric carbon dioxide (CO_2), this stock-based literature concludes that Pigouvian taxes are strongly favored over cap-and-trade throughout the relevant regulatory period. This is because the flow of CO_2 emissions throughout a realistic regulatory period is only a tiny fraction of the total stock of atmospheric CO_2 (which actually does the damage), and therefore the corresponding marginal flow benefits of CO_2 abatement within, say, a five to ten year regulatory period are very flat, implying that prices have a strong comparative advantage over quantities.

In addition to the stock dimension, free-riding at an international level lies at the heart of the CO_2 problem. This problem manifests itself in weak mitigation efforts among countries, which do not capture the full benefits of their abatement. At worst, mitigation efforts in

[1] Given the number of published papers on 'Prices vs. Quantities', we have only included a subset that we subjectively judge to be most relevant to this paper.

[2] Note that combinations of instruments, such as a fixed price with a floor and ceiling on quantities, must supersede in expected welfare both a pure price and a pure quantity, because both of these pure instruments are special cases of such combinations of instruments. This insight traces back to Roberts and Spence (1976).

other countries may decrease due to carbon leakage and the migration of fossil-fuel intensive production across national jurisdictions. The Paris Climate Agreement, concluded in 2015, attempts to take a bottom-up approach to the international free-rider problem using Intended Nationally Determined Contributions (INDCs), chosen voluntarily and non-cooperatively by each country. As the name indicates, INDCs are both intended and voluntary promises that are meant to be enforced by "blame and shame" mechanism. However, it is not clear if the "social" forces of "blame and shame" that aim at steering individuals towards "socially" accepted behaviors can similarly steer countries and "enforce" the INDCs. To be credible, these promises must be equilibrium choices, i.e., consistent with maximization of a national welfare.

To study the role of the international free-rider problem, we extend the standard 'Prices vs. Quantities' criterion into a game-theoretic equilibrium framework. We focus on two independent 'identical twin' jurisdictions A and B, which each set a price or quantity independently to maximize their expected welfare conditional on the instrument type and value chosen by the other jurisdiction. Let b be the common slope of both marginal benefit functions and c be the common slope of both marginal cost functions. With iid uncertainty, we find that it is a dominant strategy for both jurisdictions to choose a price instrument when $b < c$ and a quantity instrument when $b > c$. For n countries, if $b = c$, then the welfare cost at the equilibrium in which countries coordinate on prices is n times *higher* than the welfare cost at the equilibrium in which countries coordinate on quantity.

Thus, the result here extends the standard 'Prices vs. Quantities' criterion from the basic choice framework to a setting with multiple countries using the dominant strategy equilibrium framework. In doing so, we not only formalize the voluntary promises of the INDCs, but also identify the conditions under which for voluntary prices and voluntary quantities regulation can fulfill the INDCs. In addition, we demonstrate the collective benefits of coordinating on quantities despite each country being indifferent between price and quantity when $b = c$.

2 A Model of Regulatory Game

Suppose that there are two identical countries A and B. Following standard convention, goods are good, and instead of focusing on pollution, we focus on abatement. A country $i \in \{A, B\}$ benefits from the total global abatement of $q_A + q_B$ and incurs a private abatement cost. A country's abatement is chosen by firms located in the country. From the viewpoint of a regulator in country i, the net social benefit of abatement is described by

$$W^i = B\left(q_A + q_B, \eta_i\right) - C\left(q_i, \theta_i\right). \tag{1}$$

To facilitate comparability to the literature that follows Weitzman (1974), we assume:

$$B\left(q_A + q_B, \eta_i\right) \equiv \left[\beta + \eta_i\right]\left[q_A + q_B\right] - \frac{b}{2}\left[q_A + q_B\right]^2, \text{ and}$$

$$C\left(q_i, \theta_i\right) \equiv \left[\gamma + \theta_i\right] q_i + \frac{c}{2} q_i^2.$$

In this setting, each regulator chooses the type of regulatory policy instrument $\mathbb{P}_i \in \{\bar{p}_i, \bar{q}_i\}$, where abatement is regulated through price $\bar{p}_i$ or quantity $\bar{q}_i$ under informational constraint.

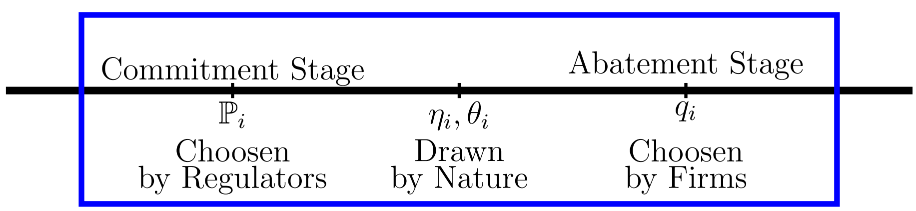

Figure 1: Timing of the Game.

After countries simultaneously commit to $\mathbb{P}_i$, nature reveals the independent values of θ_i and η_i for firms in each country. The shocks are iid, with $\mathbb{E}\left[\theta_i\right] = \mathbb{E}\left[\eta_i\right] = 0$ and variances of σ_θ^2 and σ_η^2. Then, a representative firm in country i chooses abatement q_i given the realization of the shocks and the policy instrument the regulator has chosen. Finally, payoffs are realized for both countries.

3 Analysis

We use backward induction to solve for the equilibrium under the four potential regulatory regimes. In the final stage, firms comply with regulation given the realization of shocks and the regulatory policy $\mathbb{P}_i$ chosen by the regulator in country i. For a country, the ex-post welfare is maximized when q_i is chosen to maximize W^i in (1) given realized η_i and θ_i and the abatement in the other country q_{-i}. The ex-post optimal abatement q_i^* is given by

$$q_A^* = \frac{\beta - \gamma}{b + c} - \frac{b}{b + c} q_B + \frac{\eta_A - \theta_A}{b + c}, \text{ and} \tag{2}$$

$$q_B^* = \frac{\beta - \gamma}{b + c} - \frac{b}{b + c} q_A + \frac{\eta_B - \theta_B}{b + c}. \tag{3}$$

Note that the reaction functions (2) and (3) capture the weak and strong forms of the international free-rider problem. A country only accounts for its own benefit, so the intercepts of the reaction functions are lower than that of a global planner. Moreover, the reaction functions have negative slopes because of the strong form of the international free-rider problem. When a country commits to more abatement, the other country reduces its abatement. As b increases, so do reductions in abatement due to the crowding-out.

The regulators cannot implement their ideal choice (2) and (3) due to an informational gap. Instead, each regulator must set a minimum quantitative quota $\bar{q}_i$ or charge a price per unit of abatement $\bar{p}_i$ to incentivize firms to incorporate the extra information about the shocks. Given the regulator's choice of policy, a firm's optimal reaction function under the regulatory constraint, is given by

$$q_i\left(\bar{q}_i, \theta_i\right) \equiv \arg\min_{q_i} \left[\gamma + \theta_i\right] q_i + \frac{c}{2} q_i^2 \text{ such that } q_i \geq \bar{q}_i \tag{4}$$

when abatement is regulated through quantity or

$$q_i(\bar{p}_i, \theta_i) \equiv \arg\max_{q_i} \left\{\bar{p}_i q_i - \left[\gamma + \theta_i\right] q_i - \frac{c}{2} q_i^2\right\} \tag{5}$$

when abatement is regulated through price. While firms must comply with the quantitative restriction, their compliance balances the marginal benefit of compliance $\bar{p}_i$ and its marginal cost, $\gamma + \theta_i + cq_i$ under the price regulation. The marginal compliance cost depends on the realization of θ_i, observed by firms prior to compliance.

When the regulator chooses the form of regulation, it knows that firms will react optimally to their extra information given the regulatory constraint. Thus, if the regulator in country A commits to a quantitative quota $\bar{q}_A$ and the regulator in country B commits to a quantitative quota $\bar{q}_B$, countries face an ex-post welfare loss DWL^i due to the discrepancy between $\bar{q}_i$ and q_i^*. The welfare loss is given by

$$DWL^A(\bar{q}_A, \bar{q}_B) = \frac{b+c}{2}\left[\bar{q}_A - \frac{\beta - \gamma - b\bar{q}_B + \eta_A - \theta_A}{b+c}\right]^2, \text{ and} \tag{6}$$

$$DWL^B(\bar{q}_A, \bar{q}_B) = \frac{b+c}{2}\left[\bar{q}_B - \frac{\beta - \gamma - b\bar{q}_A + \eta_B - \theta_B}{b+c}\right]^2. \tag{7}$$

The welfare cost that each country faces depends on its own regulation, but also on the regulatory outcome in the other jurisdiction. The value of $\bar{q}_A$ that minimizes the expected welfare cost $\mathbb{E}[DWL^A(\bar{q}_A, \bar{q}_B)]$ is

$$\bar{q}_A = \frac{\beta - \gamma}{b+c} - \frac{b}{b+c}\bar{q}_B, \tag{8}$$

and the value of $\bar{q}_B$ that minimizes the expected welfare cost $\mathbb{E}[DWL^B(\bar{q}_A, \bar{q}_B)]$ is

$$\bar{q}_B = \frac{\beta - \gamma}{b+c} - \frac{b}{b+c}\bar{q}_A. \tag{9}$$

The best reaction functions (8) and (9) exhibit the regulatory free-rider problem wherein a regulator reduces its quantitative quota when the other regulator raises its quantitative quota of abatement. Figure 2 plots the two regulators' quantitative best reaction functions. As shown in the figure, there is a unique fixed point on the best response functions from which neither regulator has an incentive to unilaterally deviate. The unique fixed point $(\bar{q}_A, \bar{q}_B)$ at which the best response functions intersect is:

$$\bar{q}_A = \frac{\beta - \gamma}{2b+c} \text{ and } \bar{q}_B = \frac{\beta - \gamma}{2b+c}. \tag{10}$$

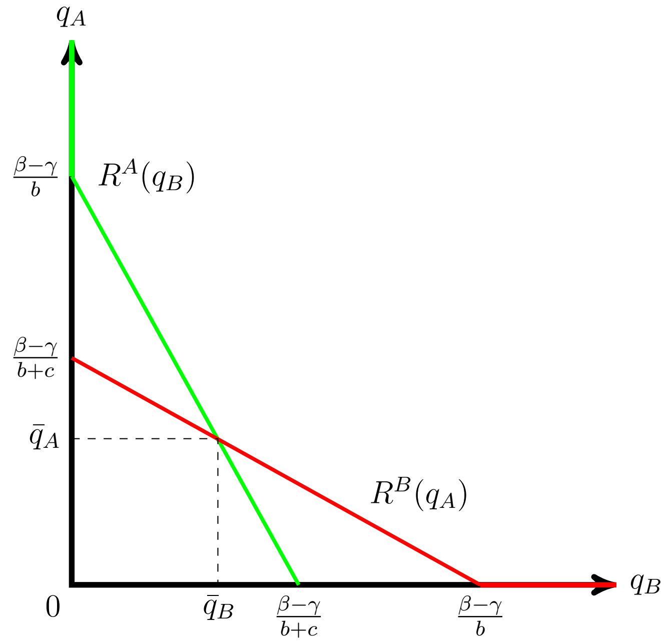

Figure 2: Best Response Abatement Functions.

Since these reaction functions are entirely non-cooperative, they correspond to the INDCs enshrined in the Paris Climate Agreement. The minimized expected welfare loss at the equilibrium value of the INDCs profile $(\bar{q}_A, \bar{q}_B)$ is

$$\mathbb{E}[DWL^i(\bar{q}_A, \bar{q}_B)] = \frac{\sigma_\eta^2 + \sigma_\theta^2}{2[b+c]}, \text{ for } i \in \{A, B\}\,. \tag{11}$$

Equation (11) suggests that, all else held equal, the higher the variability of the shocks or the lower the sum of the slopes of marginal benefit and cost of abatement, the greater the expected welfare cost of committing to a given quantitative regulation.

For ease of presentation, we work with normalized the payoffs, first multiplying the value of $\mathbb{E}[DWL^i(.,.)]$ with $2[b+c]$, subtracting σ_η^2, and finally dividing by σ_θ^2. Thus, the normalized welfare cost when both countries adopt quantity regulation is

$$[2[b+c]\mathbb{E}[DWL^i(\bar{q}_A, \bar{q}_B)] - \sigma_\eta^2]/\sigma_\theta^2 = 1, \text{ for } i \in \{A, B\}\,. \tag{12}$$

A regulatory deviation by country A to price $\bar{p}_A$, given that the regulator in country B commits to a quantitative quota $\bar{q}_B$, results in an ex-post welfare loss due to the discrepancies between $q_A(\bar{p}_A)$ and q_A^*, and $\bar{q}_B$ and q_B^*.

The regulatory reaction functions minimize the expected welfare cost of regulation. The value of $\bar{p}_A$ that minimizes the expected welfare cost $\mathbb{E}[DWL^A(\bar{p}_A, \bar{q}_B)]$ and the value of $\bar{q}_B$ that minimizes the expected welfare cost $\mathbb{E}[DWL^B(\bar{p}_A, \bar{q}_B)]$ are:

$$\bar{p}_A = \frac{c\beta + b\gamma}{b+c} - \frac{bc}{b+c}\bar{q}_B, \text{ and} \tag{13}$$

$$\bar{q}_B = \frac{c\beta + [b-c]\gamma}{c[b+c]} - \frac{b}{c[b+c]}\bar{p}_A. \tag{14}$$

Like reaction functions (8) and (9), these reaction functions are downward sloping due to the international free-rider problem.[3] The unique fixed point $(\bar{p}_A, \bar{q}_B)$ at which the best response reaction functions (13) and (14) intersect is:

$$\bar{p}_A = \frac{c\beta + 2b\gamma}{2b+c} \text{ and } \bar{q}_B = \frac{\beta - \gamma}{2b+c}. \tag{15}$$

Given $(\bar{p}_A, \bar{q}_B)$ in (15), the normalized value of the minimized expected welfare loss is given by

$$[2[b+c]\mathbb{E}[DWL^A(\bar{p}_A, \bar{q}_B)] - \sigma_\eta^2]/\sigma_\theta^2 = \left[\frac{b}{c}\right]^2, \text{ and} \tag{16}$$

$$[2[b+c]\mathbb{E}[DWL^B(\bar{p}_A, \bar{q}_B)] - \sigma_\eta^2]/\sigma_\theta^2 = 1 + \left[\frac{b}{c}\right]^2. \tag{17}$$

With (11), (16), and (17), we have all the necessary pieces to establish the condition under which committing to one regulatory form would be more beneficial than committing to another. The difference in expected welfare from price regulation versus quantity regulation given the other country uses quantity regulation is given by

$$\Delta^A(\bar{q}_B) = \frac{b-c}{2c^2}\sigma_\theta^2. \tag{18}$$

[3] Counterintuitively, it may appear that when regulation across countries takes different forms, the free-rider response in (13) depends on the slope of the marginal compliance cost c in addition to the slope of marginal benefit, b. This contrasts with the case in which regulation is identical in type, (e.g. (8) and (9)). However, this observation is deceptive since the reaction function (14) is undefined if $c = 0$.

The following lemma summarizes the substantive implication of $\Delta^A(\bar{q}_B)$ formula.

Lemma 1. *If the regulator in country B commits to quantity regulation, then the regulator in country A is strictly better off by committing to price regulation if $c > b$ and quantity regulation if $b > c$.*

Lemma 1 suggests that as long as $|b - c| \neq 0$, the payoff from adopting one regulatory form dominates the payoff from adopting another, provided that the other country uses quantity regulation.

What happens if county B, instead, commits to price regulation? If the regulator in country A commits to a price $\bar{p}_A$ and the regulator in country B commits to a price $\bar{p}_B$, firms choose abatement such that

$$\max_{q_i} \bar{p}_i q_i - \left[[\gamma + \theta_i] q_i + \frac{c}{2} q_i^2 \right].$$

The optimal abatement in each country is:

$$q_A(\bar{p}_A) = \frac{\bar{p}_A - \gamma - \theta_A}{c}, \text{ and} \tag{19}$$

$$q_B(\bar{p}_B) = \frac{\bar{p}_B - \gamma - \theta_B}{c}. \tag{20}$$

The ex-post welfare loss occurs due to the discrepancies between $q_A(\bar{t}_A)$ in (19) and q_A^* in (2) and $q_B(\bar{p}_B)$ in (20) and q_B^* in (3). The prices that minimize the expected welfare cost of regulation in each country are:

$$\bar{p}_A = \frac{c\beta + b\gamma}{b + c} - \frac{b}{b + c}\bar{p}_B, \text{ and} \tag{21}$$

$$\bar{p}_B = \frac{c\beta + b\gamma}{b + c} - \frac{b}{b + c}\bar{p}_A. \tag{22}$$

Intercepts and slopes of the reaction functions (21) and (22) are consistent with those of a public good. The unique fixed point $(\bar{p}_A, \bar{p}_B)$ at which the best response reaction functions (21) and (22) intersect is

$$\bar{p}_A = \bar{p}_B = \frac{c\beta + 2b\gamma}{2b + c}, \tag{23}$$

and the minimized expected welfare loss is

$$[2[b+c]\mathbb{E}[DWL^i(\bar{p}_A,\bar{p}_B)] - \sigma_\eta^2]/\sigma_\theta^2 = 2\left[\frac{b}{c}\right]^2, \text{ for } i \in \{A,B\}\,. \tag{24}$$

If country A instead deviates to regulation using a quantity $\bar{q}_A$, given that the regulator in country B commits to a price $\bar{p}_B$, there is an ex-post welfare loss due to the discrepancy between $\bar{q}_A$ and q_A^*, and $q_B(\bar{p}_B)$ and q_B^*. The value $\bar{q}_A$ that minimizes the expected welfare cost $\mathbb{E}[DWL^A(\bar{q}_A,\bar{p}_B)]$ is

$$\bar{q}_A = \frac{c\beta + [b-c]\gamma}{c[b+c]} - \frac{b}{c[b+c]}\bar{p}_B, \tag{25}$$

whereas the value of $\bar{p}_B$ that minimizes the expected welfare cost $\mathbb{E}[DWL^B(\bar{q}_A,\bar{p}_B)]$ is

$$\bar{p}_B = \frac{c\beta + b\gamma}{b+c} - \frac{bc}{b+c}\bar{q}_A. \tag{26}$$

The unique point $(\bar{q}_A,\bar{p}_B)$ at which the reaction functions (25) and (26) intersect is

$$\bar{q}_A = \frac{\beta-\gamma}{2b+c} \text{ and } \bar{p}_B = \frac{c\beta + 2b\gamma}{2b+c}, \tag{27}$$

and the resulting minimized expected welfare loss is

$$[2[b+c]\mathbb{E}[DWL^A(\bar{q}_A,\bar{p}_B)] - \sigma_\eta^2]/\sigma_\theta^2 = 1 + \left[\frac{b}{c}\right]^2, \tag{28}$$

$$[2[b+c]\mathbb{E}[DWL^B(\bar{q}_A,\bar{p}_B)] - \sigma_\eta^2]/\sigma_\theta^2 = \left[\frac{b}{c}\right]^2. \tag{29}$$

Thus, the difference in expected welfare loss from price regulation versus quantity regulation given the other country uses price is

$$\Delta^A(\bar{p}_B) = \frac{b-c}{2c^2}\sigma_\theta^2. \tag{30}$$

Lemma 2. *If the regulator in country B commits to price regulation, then the regulator in country A is strictly better off by committing to price regulation if $c > b$ and quantity regulation if $b > c$.*

Unexpectedly, the expressions in (30) and (18) are identical, suggesting that a country's welfare from committing to a given instrument rests entirely on the parameters b and c. Specifically, it depends on the difference between the parameter representing international free-riding and the parameter representing the slope of the marginal compliance cost. Because the two countries are identical, the results in Lemma 1 and Lemma 2 also apply to country B. Lemmas 1 and 2, together with the symmetry between the two countries, imply the main result of this paper:

Proposition. *If $b = c$, then there are multiple Pareto ranked pure strategy equilibria. For each country, choosing quantity regulations is a Pareto dominant Nash-Equilibrium. If $b < c$, then using price is a dominant strategy equilibrium. Similarly, if $b > c$, then using quantity is a dominant strategy equilibrium.*

The logic can be easily understood with the help of the payoff matrix in Table 1. Comparing the payoffs in Table 1, one finds that a dominant strategy for both jurisdictions is to choose a price instrument when $b < c$ and to choose a quantity instrument when $b > c$.

		Country B	
		$\bar{p}_B$	$\bar{q}_B$
Country A	$\bar{p}_A$	$2\left[\frac{b}{c}\right]^2, 2\left[\frac{b}{c}\right]^2$	$\left[\frac{b}{c}\right]^2, \left[\frac{b}{c}\right]^2 + 1$
	$\bar{q}_A$	$\left[\frac{b}{c}\right]^2 + 1, \left[\frac{b}{c}\right]^2$	$1, 1$

Table 1: The Expected Welfare Cost of Committing to a Price or Quantity.

An interesting result shows up when $b = c$. When this is the case, there are multiple pure strategy equilibria Nash Equilibria. This is because a regulator is indifferent between price and quantity given the strategy of the other regulator. However, since the payoffs associated with the different equilibria can be Pareto ranked, the equilibrium in which each country chooses quantities is compelling because it is Pareto dominant. With two countries, the welfare cost at the equilibrium in which countries coordinate on prices is two fold higher than the welfare cost at the equilibrium in which countries coordinate on quantity. This is because the equilibrium in which countries coordinate on prices is produces too much volatility in abatement. The relative variability would be the same with one regulator (Weitzman, 1974). In fact extending the number of countries to a finite n so that $Q \equiv \sum_{j=1}^{n} q_j$ and (1) becomes $W^i = [\beta + \eta_i]Q - \frac{b}{2}Q^2 - [\gamma + \theta_i]q_i - \frac{c}{2}q_i^2$ gives the following general theorem, whose proof is in the appendix.

Theorem: *For a finite n number of countries, if $b = c$, then the welfare cost at the equilibrium in which countries coordinate on prices is n times higher than the welfare cost at the equilibrium in which countries coordinate on quantity.*

To emphasize the significance of our results, we remind the reader that this result is based on a dominant strategy equilibrium concept, which imposes the weakest possible condition of rationality, and calls upon rational decision makers to exclude strategies with payoffs that are strictly dominated by others. Since every dominant strategy is a Nash equilibrium, the result is also a Nash Equilibrium, and holds even when we weaken the assumptions of rational expectations or the Nash-conjecture. Moreover, the equilibria in (10), (15), (23), and (27) are non-cooperative, and thus they correspond to the INDCs enshrined in the Paris Climate Agreement. Our model not only formalizes the voluntary contributions but also identifies the conditions under which the optimal 'Price vs. Quantity' rule can be implemented under the Paris agreement.

4 Concluding Discussion

The model presented in this paper makes a number of simplifying assumptions. We assume a completely symmetric 'identical twin' jurisdictions with the same linear marginal cost and marginal benefit functions, differing only by iid marginal cost shocks and iid marginal benefit shocks.[4] Nonetheless, this simplification allows us to extend the standard 'Prices vs. Quantities' framework to cover two independent 'identical twin' jurisdictions, which each set a price or quantity to maximize their own expected welfare conditional on the instrument choice and value chosen by the other jurisdiction.

[4]Hoel and Karp (2002), after discussing about the consequences of departing from iid assumption, settle for the iid shocks. Karp and Zhang (2005) consider correlated abatement cost in the context of climate change and conclude that "for a range of parameter values commonly used in global warming studies, taxes dominate quotas ... regardless of the extent of cost correlation." In our case, allowing perfect correlation of shocks does not affect the conclusion when $b > c$. Using Prices continue to be a dominant strategy if $c > f(b)$ instead of $c > b$.

While we only present the symmetric case, our results are robust to considerations of alternative sequences of moves by regulators, multiple heterogeneous countries, coalitional decision making by groups of countries, and asymmetric policy environments. Because of the dominance property, the equilibrium outcome of the regulatory game is robust to alternative sequences of commitments. This allows us to describe equilibrium outcomes in cases where regulators in different countries commit after others and that information is publicly known.

Similarly, the assumption of the two identical countries might appear limiting. After all, with multiple and heterogeneous countries, deviation needs to be conditioned on any price-quantity commitment configurations by the other $n-1$ countries. Although, for ease of presentation, we have presented a model of two identical countries, our results generalize to any finite number of heterogeneous countries having own b_i and c_i.[5] Asymmetric policy environments in which some countries choose quantity and others choose price (e.g., Chile and South Africa) are also captured by the model, which generalizes to an asymmetric policy environment.

Taken together, the key result demonstrates the relative advantage of price over quantity for a given country, independent of the type of policy instrument other countries choose; and it is the same criterion as the original 'Prices vs. Quantities' formula. Despite the simplifications, our results suggest that the original criterion may still have wider applicability for determining instrument choice in a non-cooperative strategic environment.

5 Appendix: Proof

The minimized expected welfare loss from a quantity regulation, given a subset $\hat{M}$ of with $\left|\hat{M}\right| = m < n$ countries adopt price regulation, is

$$[2\,[b+c]\,\mathbb{E}DWL^i(\bar{q}_i, \sum_{j=1}^{n} q_j - \bar{q}_i) - \sigma_\eta^2]/\sigma_\theta^2 = 1 + m\left[\frac{b}{c}\right]^2. \tag{31}$$

[5] In showing the result is robust in any finite n number of heterogeneous countries, care needs to be taken in verifying that a country has no incentive to deviate from the equilibrium, in which deviation needs to be conditioned on any price-quantity commitment configurations by all the possible subsets of the $n-1$ countries. In the process, one would observe that the results generalize also to a setting in which a coalition of group of countries like the European Union is a player.

The minimized expected welfare loss from a price regulation, given a subset $\hat{M}$ of with $\left|\hat{M}\right| = m < n$ countries adopt price regulation, is

$$[2\,[b_i + c_i]\,\mathbb{E}DWL^i(\bar{p}_i, \sum_{j=1}^{n} q_j - \bar{q}_i) - \sigma_\eta^2]/\sigma_\theta^2 = \left[\frac{b}{c}\right]^2 + m\left[\frac{b}{c}\right]^2.$$

Thus, if $b = c$, then the normalized welfare cost when all countries commit to quantity takes the value of 1 whereas the normalized welfare cost when all countries commit to price takes the value of n. Thus, setting $m = 0$ vs. $m = n - 1$ gives the claimed result. QED

References

[1] Adar, Zvi, and James M. Griffin (1976). "Uncertainty and the Choice of Pollution Control Instruments." *Journal of Environmental Economics and Management*, 3: 178-188.

[2] Chao, Hung-Po, and Robert Wilson (1993). "Option Value of Emission Allowances." *Journal of Regulatory Economics*, 5: 233-249.

[3] Dales, John H. (1968). *Pollution, Property, and Prices: An Essay on Policy-making and Economics.* Toronto: University of Toronto Press.

[4] Fell, Harrison, Ian A. MacKenzie, and William A. Pizer (2012). "Prices versus Quantities versus Bankable Quantities." *Resource and Energy Economics*, 34(4): 607-623.

[5] Feng, Hongli, and Jinhua Zhao (2006). "Alternative Intertemporal Trading Regimes with Stochastic Abatement Costs." *Resource and Energy Economics*, 28(1): 24-40.

[6] Fishelson, Gideon (1976). "Emission Control Policies under Uncertainty." *Journal of Environmental Economics and Management*, 3: 189–197.

[7] Goulder, Lawrence H., and Andrew R. Schein (2013). "Carbon Taxes vs. Cap and Trade: A Critical Review." *Climate Change Economics,* 4(3): 1-28.

[8] Hoel, Michael, and Larry Karp (2002). "Taxes versus Quotas for a Stock Pollutant." *Resource and Energy Economics*, 24(4): 367-384.

[9] Kaplow, Louis, and Steven Shavell (2002). "On the Superiority of Corrective Taxes to Quantity Regulation." *American Law and Economics Review*, 4(1): 1-17.

[10] Karp, Larry, and Jiangfeng Zhang (2005). "Regulation of Stock Externalities with Correlated Abatement Costs." *Environmental and Resource Economics*, 32 (2): 273-300.

[11] Kelly, David L. (2005). "Price and Quantity Regulation in General Equilibrium." *Journal of Economic Theory*, 125: 36-60.

[12] Montgomery, W. David (1972). "Markets in Licenses and Efficient Pollution Control Programs." *Journal of Economic Theory*, 5(3): 395-418.

[13] Newell, Richard, and William Pizer (2003). "Regulating Stock Externalities under Uncertainty." *Journal of Environmental Economics and Management*, 45: 416-432.

[14] Pigou, Arthur C. (1920). *The Economics of Welfare*. London: Macmillan.

[15] Pizer, William A. (2002). "Combining Price and Quantity Controls to Mitigate Global Climate Change." *Journal of Public Economics*, 85: 409-434.

[16] Roberts, Mark J., and A Michael Spence (1976). "Effluent Charges and Licenses under Uncertainty." *Journal of Public Economics*, 5: 193-208.Rubin, Jonathan D. (1995). "A Model of Intertemporal Emission Trading, Banking, and Borrowing." *Journal of Environmental Economics and Management*, 31: 269-286.

[17] Weitzman, Martin L. (1974). "Prices *vs.* Quantities." *Review of Economic Studies*, 41(4): 477-491.

[18] Weitzman, Martin L. (1978). "Optimal Rewards for Economic Regulation." *American Economic Review*, 68: 683-691.

[19] Yohe, Gary W. (1978). "Towards a General Comparison of Price Controls and Quantity Controls under Uncertainty." *Review of Economic Studies*, 45: 229-238.