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**AGGREGATE EMISSION INTENSITY TARGETS:
APPLICATIONS TO THE PARIS AGREEMENT**

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Aggregate Emission Intensity Targets:

Applications to the Paris Agreement

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Abstract

We develop the concept of *aggregate* emission targets, which are goals for national emissions but do not dictate the forms of regulation used to achieve the goals. We compare aggregate emission intensity, quantity, and price targets adopted at the national level but implemented cost effectively at the firm level. We obtain simple ranking conditions that depend on the slope ratio of marginal emission damage and marginal abatement cost curves, and threshold parameters determined by the variance and covariance of GDP and business-as-usual emission. We apply the ranking conditions to the top 12 CO₂ emitters with specific GHG targets in the Paris Agreement, and obtain a robust result that intensity targets dominate quantity targets for most of these nations.

JEL: Q58

Keywords: aggregate intensity target, quantity target, price target, climate change, INDC, Paris Agreement

1 Introduction

Intensity emission targets have attracted increasing attention in international climate negotiations. By putting a cap on a nation's carbon emission per unit of GDP instead of on its total net emission, intensity targets have been touted as being growth friendly and are seen as a way to attract participation in international climate agreements by countries concerned with economic growth and development (Frankel (1999), Lutter (2000), Philibert and Pershing (2001), Kolstad (2005), Pizer (2005), Herzog, Baumert and Pershing (2006)). In the Paris Agreement, a number of developing countries proposed intensity targets in their Intended Nationally Determined Contributions (INDCs), including the People's Republic of China (PRC), India, Malaysia, Chile, Mexico, Uruguay, and Tunisia. Interests in intensity targets are not limited to developing nations. Singapore proposed an intensity target (36% reduction), and the United States under the Bush administration announced intensity targets back in 2002, partly due to concerns about economic growth. In this paper, we evaluate whether the world's major carbon emitters should adopt intensity targets vis-a-vis quantity (as well as price) targets for carbon emission.

If the future growth rate of a nation's GDP is known for sure, then an intensity target can be made to achieve the same level of emission as a quantity target that puts an absolute cap on the nation's total net emission: the government can simply set the intensity target at a level that equals the quantity target divided by future GDP. Arguments in support of intensity targets can only be made in a model with uncertainties. In fact, a potentially desirable feature of intensity targets is that they can help reduce uncertainties in abatement costs compared with quantity targets (Sue Wing, Ellerman and Song (2009) and Jotzo and Pezzey (2007)). Since the target is relaxed (or tightened) when GDP and thus the business-as-usual (BAU) emission are higher (or lower), the required abatement levels do not swing as much as under quantity targets. However, as uncertainties in abatement levels are reduced by intensity targets, the associated net emission becomes more uncertain. *A priori*, it is not clear whether uncertainties in abatement costs are more important than those in emission damages, especially for global pollutants where the damages are imposed on all nations. Further, as cautioned by Newell and Pizer (2008), intensity targets are pro-

cyclical and might be undesirable from a macroeconomic perspective.¹ So far empirical evidence is mixed regarding the desirability of intensity targets relative to quantity and price targets on pure economic grounds. Pizer (2005) argues that the main advantage of intensity targets lies in their *framing* emission targets in political discourses not as a “cap,” which has the connotation of “capping economic growth.”

In this paper, we address the fundamental questions about the desirability of intensity targets from the social welfare perspective: how do intensity targets perform relative to quantity and price targets, and which of the three targets should a nation adopt in reducing its greenhouse gas (GHG) emissions? In a static framework with convex abatement cost and emission damage functions, we investigate which of the targets minimizes the total expected cost for a given level of expected emission. We obtain simple and intuitive ranking conditions that rely on a parsimonious set of parameters, and empirically apply these conditions to the top CO₂ emitting nations to find out which targets they should respectively adopt.

There is a large and growing literature on intensity *instruments*, that is, caps imposed on emission intensities of individual firms, similar to firm level emission taxes and standards (see, for example, Ebert (1998), Fischer (2003), Quirion (2005), Fischer and Fox (2007), Jotzo and Pezzey (2007), Newell and Pizer (2008), Webster, Wing and Jakobovits (2010), Fischer and Springborn (2011), Holland (2012), Branger and Quirion (2014), and Caparros, Just and Zilberman (2015)).² Intensity instruments are a special form of performance standards and have been adopted to regulate firm emission, such as in the lead phase-out program of the United States during the 1980s and in cases of state level renewable portfolio standards that require utilities to have certain percentages of total electricity generated from renewable sources (Lyon (2016)). Most of the literature on intensity instruments builds on the seminal work of Weitzman (1974) and studies the effects of uncertainty and information asymmetry about abatement costs on instrument rankings. Intensity instruments can partly address information asymmetries about abatement costs because the *ex post* emission cap depends on the realization of the firm’s output, which is assumed to be correlated with its

¹Heutel (2012) shows in a business cycle model facing productivity shocks that optimal environmental regulations (in the form of a quantity cap or an emission tax) *should* be pro-cyclical: more emissions should be allowed during economic expansion and less during contraction.

²Peterson (2008) provides a good review of the literature up to 2008.

abatement cost. Newell and Pizer (2008) shows that the *ex post* emission cap can be indexed to any observable variable that is correlated with the firm's private signals about its abatement cost. The ranking conditions are extended to include the ability of the firms to respond to regulation in the extensive margin, by increasing their outputs (or whatever index the instrument uses) as in Helfand (1991), Fischer and Springborn (2011), and Holland (2012), or by adopting clean technologies as in Caparros et al. (2015). Although increased outputs under the intensity instrument can lead to higher economic growth, the associated environmental impacts might be undesirable, especially when the intensity instruments are implemented with grandfathered tradable permits (Kling and Zhao (2000)).

Findings from the intensity instruments literature have been used to draw conclusions about intensity targets vis-a-vis tax and quantity targets at the national level. Newell and Pizer (2008) apply their model to national climate data and find that indexing emission caps to economic output is desirable for some but not all countries. Ellerman and Wing (2003) applies Weitzman (1974) and an earlier version of Newell and Pizer (2008) to discuss national intensity targets in the context of international climate negotiations. Jotzo and Pezzey (2007) also adopts the Weitzman framework to study optimal indexation for a number of nations. The implicit assumption is that when a nation adopts a certain type of target, the target will be implemented by the same type of instrument. National tax targets will be implemented by firm level emission taxes, national quantity targets by firm level emission caps, and national intensity targets by intensity instruments where each firm's emission cap is indexed to its output. Overall, the findings from the literature are mixed, with complicated ranking conditions that depend not only on the relative slopes of the marginal abatement cost and marginal emission damage functions as in Weitzman (1974) but also on correlation structures of the cost functions with observables such as GDP. Quirion (2005) finds that intensity targets are mostly dominated by quantity or price targets, and Marschinski and Edenhofer (2010) argues that intensity targets might not even reduce abatement cost uncertainties as much as quantity targets.

We depart from the intensity instrument literature and study *aggregate* intensity, quantity and tax targets where the targets are adopted at an aggregate level (national, regional or sectorial), but

are implemented cost effectively through firm level taxes or cap and trade.³ That is, we do not let the form of the aggregate target pre-determine the form of the implementation mechanism. In the case of aggregate intensity targets implemented by cap and trade, since the indexing of emission to output is only at the aggregate level, each firm's permit allocation is detached from its output. Aggregate intensity targets will, therefore, not raise a firm's incentives to increase their outputs in order to obtain higher emission caps such as under intensity instruments. This hybrid system might be more politically appealing than intensity instruments. Aggregate intensity targets have been adopted by PRC which is in the process of setting up a "regular" carbon market to implement its national intensity targets.

Setting aggregate intensity, quantity, and tax targets requires information about the aggregate (that is, national, regional, or sectorial) abatement cost function, instead of the individual firm's cost functions. As such, although there may still be uncertainties about aggregate abatement costs, there is no information asymmetry between the regulator and the regulated: the government does not have less information about the aggregate abatement costs than any individual firm. This observation allows us to depart from the framework of Weitzman (1974) and the intensity instrument literature: in our baseline model, there is no uncertainty about the abatement cost function itself. Instead, similar to Sue Wing et al. (2009),⁴ the only uncertainties in our model are about GDP and its emission intensity. These uncertainties then translate into uncertainties in BAU emission, and in turn to those in required abatement or net emission or both, and finally to uncertainties in abatement costs and/or environmental damages. More importantly, the Weitzman ranking conditions become much more complicated once intensity targets are considered. If firms are regulated through intensity instruments, they have incentives to raise outputs to be allowed to emit more (Kling and Zhao (2000)), with the strength of the response dependent on the correlation

³Cost effective implementation of aggregate intensity targets requires us to make projections about future GDP and thus future allowable total emission. If implemented by a cap and trade scheme, annual adjustment mechanisms can be built in to allow for GDP shocks, such as during the permit reconciliation periods or through permit reserves and buy-back mechanisms. These adjustment mechanisms are often used to defend price collars such as in California's carbon cap and trade program (Grull and Taschini (2011)). As an example of tax targets being implemented by cap and trade, the Canadian province of Alberta has recently adopted a permit trading scheme where the permit price is pre-set at 30 CAD per ton of carbon, defended by permit auctions and buy-backs (Leach, Adams, Cairns, Coady and Lambert (2015)).

⁴Sue Wing et al. (2009) focuses on abatement cost uncertainty and uses the resulting uncertainty levels under different instruments as the criterion for ranking intensity and quantity targets.

between marginal production and abatement costs.⁵ The rankings between intensity instruments and price or quantity instruments depend not only on the slopes of the marginal abatement cost (MAC) and marginal damage (MD) curves, but also on the correlation between abatement costs and outputs. It is difficult to reliably estimate the abatement cost functions, and even more difficult to estimate their correlation with outputs. By studying aggregate targets, we remove the information asymmetry between the regulator and the polluting firms, thereby removing the firms' incentives to respond by adjusting their outputs. Consequently, our ranking conditions are able to achieve a dichotomy between the ratio of the slopes of the MAC and MD curves, and threshold parameters that depend only on the variance and covariance matrix of GDP and BAU emission. The latter can be reliably estimated using historical data, and we only need to know the range of possible values of the former, instead of its point estimate, to rank aggregate targets.

Nations rarely set their emission targets at socially optimal levels. Instead of comparing the three targets at their respective optimal levels, as is done by many papers in the intensity instrument literature, we anchor the three targets so that *ex ante* they lead to the same level of expected emission.⁶ Moreover, we show that the target rankings at the emission equivalent levels are preserved when comparing the targets at their respective optimal levels, but not vice versa. Our ranking conditions are, therefore, more general than those based on each target's respective optimal level, and hold under both criteria of cost effectiveness and efficiency.

For readers who are familiar with the intensity instrument literature, below we highlight the major contributions of our paper relative to this literature. (i) Our paper does not treat aggregate (price, quantity and intensity) targets as regulatory instruments facing firms. Instead, the targets are imposed only on a nation or sector but are implemented cost effectively through "regular" taxes or cap and trade schemes. This setup is likely to be a better match for the real world settings in the Paris Agreement. (ii) When comparing the aggregate targets, we anchor them so that they lead to the same expected net emission. Emission equivalent comparisons are more general than comparisons at their respective optimal levels. In contrast, the intensity instrument

⁵In contrast, the expected emissions are the same under tax and quantity instruments.

⁶Webster et al. (2010) and Kolstad (2005) adopt a similar approach. Although Branger and Quirion (2014) compare quantity and intensity instruments at emission equivalent levels, do not do so for price instruments.

literature focuses on comparing instruments at their optimal levels. (iii) Our ranking conditions are relatively easy to empirically estimate due to the dichotomy between the slope ratio of the MD and MAC curves and the variance-covariance matrix of the GDP and total emission. In contrast, in the intensity instrument literature, the threshold parameters themselves also depend on the MAC function, making these parameters difficult to estimate. (iv) We rank the Paris Agreement targets for the world’s top CO₂ emitting nations and provide a rich set of robustness checks of the rankings. Specifically, using annual data of GDP and CO₂ emission, we estimate their variance-covariance matrix and, thus, the threshold parameters in the ranking conditions for each of these nations. We are able to obtain dominance relations between aggregate intensity and quantity targets without knowing the point estimates of the slope ratio of the MAC and MD curves. The dominance relations are robust to sampling errors, to structural breaks of economic growth, as well as to the time paths of achieving the INDC targets. To our knowledge, this is the first paper to provide both point estimates and confidence intervals of the ranking conditions.

The paper is organized as follows. We set up the basic model in Section 2, and develop ranking conditions of the aggregate quantity, intensity, and price targets in Sections 3 and 4. In Section 5, we apply our ranking conditions to the top 12 CO₂ emitters in the world that have committed to quantifiable emission reduction targets in their INDCs in the 2015 Paris Agreement. We conclude the paper in Section 6.

2 Model Setup

Consider a nation, region, or sector that produces aggregate output y with emission intensity s , resulting in a business-as-usual (BAU) emission of $e^b = ys$. The only sources of uncertainty in our model arise from y and s : the government does not know the future (e.g., in the target year) values of y or s , but it does know that they are distributed on $[y_l, y_h]$ and $[s_l, s_h]$ with joint distribution function $F(\cdot, \cdot)$. To reduce emissions, the government chooses among three aggregate emissions targets: a quantity target \underline{e} , representing the maximum level of emissions allowed for the economy so that *ex post* realized net emission $e \leq \underline{e}$; an intensity target \underline{s} , which is the maximum level of emission intensity of the economy so that *ex post* the realized intensity $s \equiv e/y \leq \underline{s}$; and

a price target $\underline{\tau}$, which represents an emission tax or target permit price level. We adopt the convention that underlined variables represent policy targets. We use price target and tax target interchangeably. To reduce clutter, when confusion does not arise, we call the aggregate intensity, quantity, and price targets simply intensity, quantity, and price targets. Theoretically, a target represents a policy goal that a nation is trying to but may not necessarily achieve. In deriving our theoretical results (Sections 2 - 4) we assume that the targets are always achieved. Doing so is without loss of generality since we can always let the targets represent the achieved goals. In the empirical part (Section 5), we do allow the targets to be under- or over-achieved.

Let $D(e)$ be the nation's damage function of net emission e and $C(a)$ be the cost function of abatement a , with both $D(\cdot)$ and $C(\cdot)$ being increasing and convex, and $D'(0), C'(0) \geq 0$. For simplicity, we assume that the emission targets are always binding for all realizations of y and s :

$$\underline{e} \leq y_l s_l; \quad \underline{s} \leq s_l; \quad \underline{\tau} \leq C'(y_l s_l). \quad (1)$$

The first condition implies that the quantity target \underline{e} is still binding even if the *ex post* BAU emission is at its lowest possible level $y_l s_l$. The second condition means that the intensity target \underline{s} is binding even if the *ex post* intensity is at its lowest level s_l . Finally, the third condition ensures that with probability one not all emission is abated, that is, the *ex post* net emission is always positive.

We assume that the three kinds of targets only affect the emissions and emission intensities, but do not affect output y . The relevant welfare effects thus include only the abatement costs and emission damages. Under an exogenously set quantity target \underline{e} , abatement needs to be undertaken so that the *ex post* net emission always equals \underline{e} , regardless of the realizations of y and s . The required abatement, $a = ys - \underline{e}$, is positive and random. The expected total social cost, including both the expected abatement cost and the expected emission damage, is

$$TC_Q(\underline{e}) = D(\underline{e}) + E_{y,s}C(ys - \underline{e}), \quad (2)$$

where subscript Q denotes the quantity target, and $E_{y,s}$ is expectation with respect to y and s . Under an exogenously set intensity target \underline{s} , the *ex post* net emission has to be $y\underline{s}$, implying that the required abatement is $ys - y\underline{s}$. Thus, the expected total cost is

$$TC_I(\underline{s}) = E_y D(y\underline{s}) + E_{y,s} C(ys - y\underline{s}), \quad (3)$$

where subscript I represents the intensity target. Under tax target τ , the aggregate abatement has to be such that the marginal abatement cost equals the target tax level:

$$C'(a) = \tau, \tag{4}$$

leading to a fixed level of (aggregate) abatement $a(\tau)$, and a stochastic net emission $e(\tau, ys) = ys - a(\tau)$. The expected total cost is

$$TC_P(\tau) = E_{y,s}D(e(\tau; ys)) + C(a(\tau)), \tag{5}$$

where subscript P represents the price/tax target.

Instead of comparing the three targets at their respective optimal levels, we anchor them so that they lead to the same expected net emission. Specifically, the target levels are chosen to satisfy

$$\underline{e} = E_y(y)\underline{s} = E_{y,s}e(\tau; ys). \tag{6}$$

In the traditional framework of Weitzman (1974), the distinction between comparisons at emission equivalent levels versus at the respective optimal levels is unimportant because both the optimal quantity and the price tools lead to the same expected abatement (and thus net emission). However, as we will show later, the optimal intensity target leads to a different level of expected net emission from that under the optimal price and quantity targets. Comparing the targets at their respective optimal levels necessarily means comparing them at different net emission levels. We also show that rankings of the three targets at emission equivalent levels extend to rankings at the respective optimal levels, but not vice versa.

To obtain analytical rankings of the three targets, we follow Weitzman (1974) and the literature on intensity instruments, and assume quadratic cost and damage functions:

$$D(e) = d_0 + d_1e + d_2e^2, \quad \text{and} \quad C(a) = c_0 + c_1a + c_2a^2, \tag{7}$$

with constant parameters $d_1, d_2, c_1, c_2 \geq 0$. Note that because there is no information asymmetry about abatement costs, c_1 is assumed to be non-random.

3 Target Comparisons

In this section, we will welfare order the three aggregate targets anchored at an exogenously given level of expected net emission. From (6), for any quantity target \underline{e} , the emission equivalent intensity target is $\underline{s} = \underline{e}/E_y(y)$. Using the quadratic functional form of (7) in (4) and (6), we know that the emission equivalent price target is

$$\underline{\tau} = c_1 + 2c_2(E(y\mathbf{s}) - \underline{e}), \quad (8)$$

leading to the *ex post* net emission of

$$e(\underline{\tau}; y\mathbf{s}) = y\mathbf{s} - E(y\mathbf{s}) + \underline{e}. \quad (9)$$

Using the total cost functions in (2), (3), and (5), we know

Proposition 1 (i) *The aggregate intensity target dominates the aggregate quantity target if and only if $d_2/c_2 \leq \Omega$, where*

$$\Omega = \frac{2\text{Cov}(y\mathbf{s}, y)}{\text{Var}(y)\underline{s}} - 1. \quad (10)$$

(ii) *The aggregate price target dominates the aggregate quantity target if and only if $d_2/c_2 \leq 1$.*

(iii) *The aggregate intensity target dominates the aggregate price target if and only if $c_2/d_2 \leq \Phi$, where*

$$\Phi = 1 + \frac{2\underline{s}(\text{Cov}(y\mathbf{s}, y) - \text{Var}(y)\underline{s})}{\text{Var}(y\mathbf{s}) - 2\text{Cov}(y\mathbf{s}, y)\underline{s} + \text{Var}(y)\underline{s}^2} = 1 + \frac{2\underline{s}(\text{Cov}(y\mathbf{s}, y) - \text{Var}(y)\underline{s})}{\text{Var}(y\mathbf{s} - y\underline{s})}. \quad (11)$$

The proof is given in Appendix A. A major advantage of these ranking conditions is that they achieve a dichotomy between the slope ratio of the MD and MAC curves, and parameters Ω and Φ that depend only on the variance-covariance matrix of GDP y and BAU emission $y\mathbf{s}$. The dichotomy makes it much easier to empirically apply the ranking conditions, as we will show in Section 5.

Proposition 1 also shows that the ranking conditions have the flavor of Weitzman (1974) and those in the intensity instrument literature: the ranking depends on the relative slope of the MD and MAC curves. However, the underlying reason for the welfare rankings is different from that in Weitzman (1974), as we graphically illustrate in Appendix B. In our model, since the expected net emission (as well as the expected abatement) is the same across the three targets, any welfare

difference among them can arise only from how each target distributes uncertainties in the BAU emission ys to net emission and abatement. Under the quantity target, the entire uncertainties in ys are borne by abatement (which equals $ys - \underline{e}$) because the net emission is fixed at the target level \underline{e} . The price target does exactly the opposite by fixing the abatement and distributing all uncertainties to net emission. Thus, if the cost function is more convex than the damage function (that is, $c_2 > d_2$), then the price target dominates the quantity target because the former distributes all uncertainties to the less convex damage function. The intensity target lies somewhere in-between: the net emission's share of the uncertainty is given by $y\underline{s}$ while the abatement's share is given by $ys - y\underline{s}$. Compared with the quantity target, the intensity target moves $y\underline{s}$ amount of uncertainties from abatement to net emission,⁷ and doing so is desirable if the abatement cost function is more convex than the emission damage function, that is, if d_2/c_2 is low. Compared with the price target, the intensity target moves some of the uncertainties (proportional to $ys - y\underline{s}$) from net emission to abatement, and doing so is desirable when the abatement cost function is less convex than the emission damage function, that is, when c_2/d_2 is low.

Proposition 1 shows that the ranking of the three aggregate targets depends on the comparison between the slope ratio d_2/c_2 and the two threshold parameters Ω and Φ . The relative magnitude of these two parameters determines the layout of the “dominance regions.” Let

$$\bar{s} \equiv \text{Cov}(ys, y)/\text{Var}(y), \quad (12)$$

which implies that $\text{Cov}(ys, y) = \bar{s}\text{Var}(y) = \text{Cov}(y\bar{s}, y)$. That is, \bar{s} represents a “certainty equivalent” level of emission intensity so that emission $y\bar{s}$ maintains the same covariance with GDP y as BAU emission ys with y . When y and s are independent, $\bar{s} = E(s)$. From (10) and (11), we know $\Omega \geq 1$ and $\Phi \geq 1$ if and only if $\underline{s} \leq \bar{s}$. Then

Corollary 1 *(i) If $\underline{s} < \bar{s}$, then $\Omega > 1 > 1/\Phi$. The most preferred aggregate target is quantity when $d_2/c_2 \geq \Omega$, intensity when $1/\Phi \leq d_2/c_2 < \Omega$, and price when $d_2/c_2 < 1/\Phi$.*

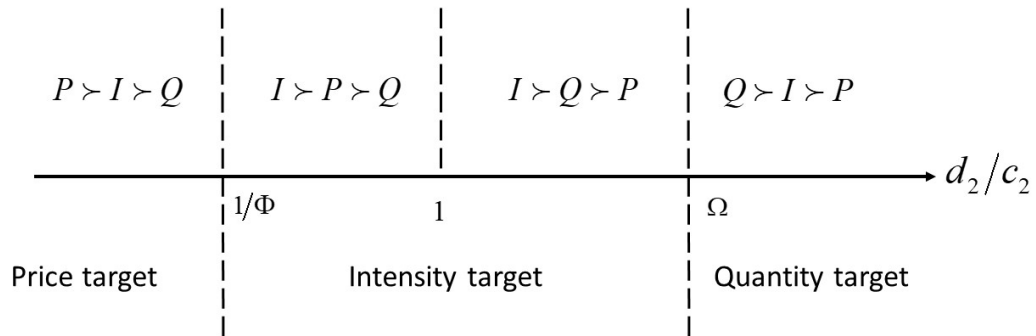
⁷Strictly speaking, the variance of net emission increases from zero under the quantity target to $\text{Var}(y)\underline{s}^2$ under the intensity target. The variance of abatement decreases from $\text{Var}(ys)$ to $\text{Var}(ys - y\underline{s})$. The decrease in the variance of abatement is best seen when y and s are independent. In this case, $\text{Var}(ys) = \text{Var}(y)\text{Var}(s) + \text{Var}(y)(E(s))^2 + \text{Var}(s)(Ey)^2$ while $\text{Var}(y(s - \underline{s})) = \text{Var}(y)\text{Var}(s - \underline{s}) + \text{Var}(y)(E(s - \underline{s}))^2 + \text{Var}(s - \underline{s})(Ey)^2$. Thus, $\text{Var}(ys) - \text{Var}(y(s - \underline{s})) = \text{Var}(y)((E(s))^2 - (E(s - \underline{s}))^2)$. Since $s > \underline{s}$ for all values of s , $Es > E(s - \underline{s}) > 0$, implying $(Es)^2 > (E(s - \underline{s}))^2$.

(ii) If $\underline{s} \geq \bar{s}$, then $\Omega \leq 1 \leq 1/\Phi$. The quantity target is preferred when $d_2/c_2 > 1$ and the price target is preferred when $d_2/c_2 \leq 1$. The intensity target is always dominated by either the price or the quantity target, or both.

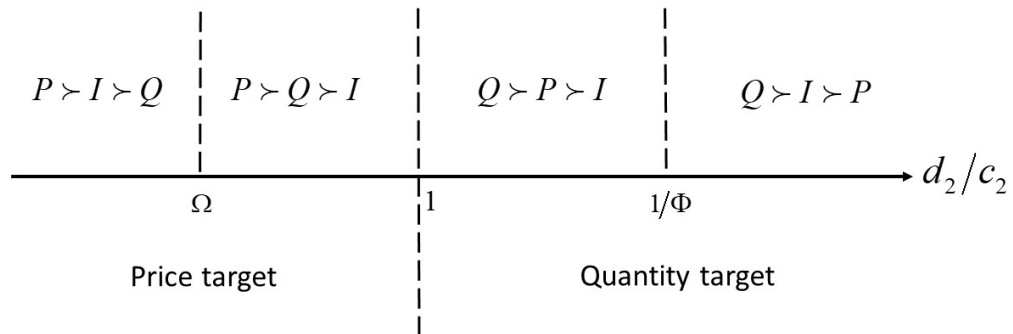
Figure 1 shows the pairwise and overall dominance relations among the three targets for various values of the slope ratio. Panels (a) and (b) correspond to (i) and (ii) of Corollary 1 respectively. The section above the horizontal axis shows the pairwise dominance relations (represented by \succ) of price (P), quantity (Q), and intensity (I) targets, and the section below the axis indicates the most preferred or the dominant target. Thus, intensity targets have the chance of being the most preferred choice only when the target is stringent enough so that $\underline{s} < \bar{s}$. The empirical analysis in Section 5 shows that this is also the most empirically relevant case for top CO₂ emitters of the world. Even when the target is lax so that $\underline{s} > \bar{s}$, if the only feasible targets are quantity and intensity targets, the latter dominates the former when the slope ratio d_2/c_2 is lower than Ω .

Corollary 1 shows that the intensity target can dominate both price and quantity targets only when the targets are sufficiently stringent so that $\underline{s} < \bar{s}$. It also shows that the values of Ω and $1/\Phi$ play important roles in affecting the desirability of each of the three targets. Figure 2 shows Ω and $1/\Phi$ as functions of \underline{s} . We know from (10) that Ω is decreasing in \underline{s} , with $\Omega > 1$ when $\underline{s} < \bar{s}$ and $\Omega < 1$ when $\underline{s} > \bar{s}$. Thus, *as target \underline{s} decreases, thereby becoming more stringent, it is more likely that the intensity target dominates the quantity target.* In fact, given any slope ratio d_2/c_2 , there exists a threshold stringency level $\tilde{s} = \frac{2\text{Cov}(ys,y)/\text{Var}(y)}{1+d_2/c_2}$ so that the intensity target dominates the quantity target if and only if $\underline{s} \leq \tilde{s}$. In Appendix C, we show that $\Phi = 1$ when $\underline{s} = 0$, is increasing for $\underline{s} \in (0, \hat{s}_1)$ and decreasing for $\underline{s} \in (\hat{s}_1, \hat{s}_2)$, where $\hat{s}_1 < \hat{s}_2$ are laid out as in Figure 2. Thus, starting at \bar{s} , as the target becomes more stringent (that is, moving to the left), the region $[1/\Phi, \Omega]$, in which the intensity target is the most preferred, becomes larger. When the target becomes more stringent than \hat{s}_1 , further tightening of the target raises $1/\Phi$, making it less likely that the intensity target dominates the price target. That is, when the target \underline{s} is moderate (that is, close to \bar{s}), further tightening of the target tends to favor the intensity target. However, for sufficiently tight target (so that $\underline{s} < \hat{s}_1$), further tightening of the target tends to favor the price target.

The two threshold parameters Ω and $1/\Phi$ depend on the correlation between GDP y and



(a) $\underline{s} < \bar{s}$



(b) $\underline{s} > \bar{s}$

Figure 1: Ranking of Price, Quantity, and Intensity Targets

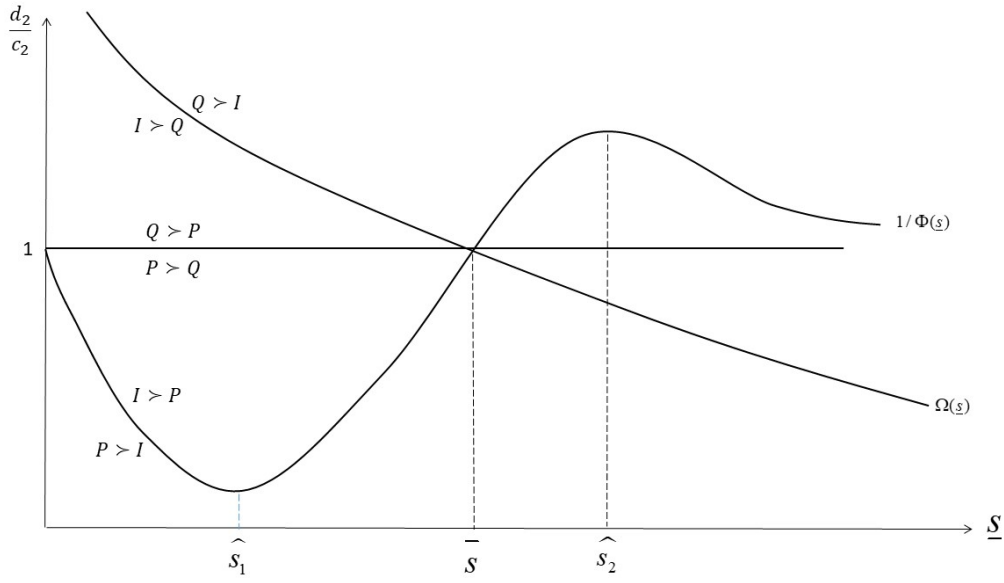


Figure 2: Dependence of Ranking Conditions on Target Stringency

intensity s . When they are independent, which might be a good approximation of certain real world cases,⁸ the threshold parameters and the ranking conditions become much simpler. Specifically,

Proposition 2 *When GDP y and intensity s are independent, Ω simplifies to*

$$\Omega' = \frac{2E(s)}{\underline{s}} - 1 > 1, \quad (13)$$

and Φ simplifies to

$$\Phi' = 1 + \frac{2 \left(\frac{E(s)}{\underline{s}} - 1 \right)}{\left(\frac{E(s)}{\underline{s}} - 1 \right)^2 + \left(\frac{E(s)}{\underline{s}} \right)^2 \left(1 + \frac{\text{Var}(y)}{\text{Var}(s)} \right)} > 1. \quad (14)$$

In this case, the ranking between intensity and quantity targets depends only on the relative stringency of the target, $E(s)/\underline{s}$, and is independent of the variances of GDP and BAU emission. In contrast, Φ' is increasing in the relative variability of GDP $\text{Var}(y)/(E(y))^2$. Thus, as the GDP

⁸Pizer (2005) shows that the correlation between y and s for several industrialized nations is rather low. The correlation could be even lower when the focus of study is a specific sector. The sector's aggregate output could face shocks from downstream sectors and exogenous demands, while its emission intensity faces uncertainties from energy prices or production technologies. For example, outputs from the iron and steel industry in PRC are mainly affected by demand shocks in infrastructure development and construction, while uncertainties in its carbon intensity arise mostly from fuel use efficiency due to adoption of new technologies.

becomes more uncertain, it is more likely that the intensity target dominates the price target. Further, Φ' is decreasing in the relative variability of intensity $\text{Var}(s)/(E(s))^2$: as the intensity becomes more uncertain, it is less likely that the intensity target dominates the price target. Intensity targets are pro-cyclical and are particularly suited to deal with uncertainties in outputs. Thus, higher levels of uncertainties in GDP tend to favor the intensity target over the price target. In contrast, by fixing the target intensity, the intensity target is less effective in alleviating uncertainties in intensities. Finally, since $\underline{s} < E(s) = \bar{s}$, in Figure 1, only Panel (a) arises, and in Figure 2, only the portion to the left of \bar{s} becomes relevant.

If GDP y and intensity s are correlated, as their covariance $\text{Cov}(y, s)$ increases, so does $\text{Cov}(ys, y)$. From (10) and (11), we know both Ω and Φ are increasing in $\text{Cov}(ys, y)$ holding $\text{Var}(y)$ and $\text{Var}(ys)$ fixed. Thus

Corollary 2 *All else equal, a higher positive correlation between GDP y and intensity s (and thus between GDP y and BAU emission ys) favors the intensity over the quantity and price targets.*

In the part to the left of \bar{s} in Figure 2, as the correlation between y and s rises, the interval $[1/\Phi, \Omega]$ becomes larger, expanding the region of slope ratios d_2/c_2 in which the intensity target is most preferred. Recall that under intensity targets, the net emission is $y\underline{s}$ and abatement equals $ys - y\underline{s}$. A higher correlation between ys and y reduces the uncertainty in abatement but leaves unchanged the uncertainty in net emission, thereby reducing the expected total costs associated with intensity targets. The correlation is higher if GDP growth is driven by the expansion of energy intensive sectors such as heavy industries, and lower if economic growth is driven by the adoption of new and cleaner technologies or expansion of cleaner industries such as the service sector. If the path of a pollutant follows the environmental Kuznets curve, then the correlation between GDP and emission decreases over time. Although there is strong evidence to support the existence of environmental Kuznets curves for a number of pollutants, the evidence is mixed for CO2 emission (Galeotti, Lanza and Pauli (2006)).

4 Extensions of the Basic Model

We next study how the ranking conditions that we obtained earlier can be extended to more general settings.

4.1 Comparing targets at their respective optimal levels

So far we have compared the three targets so that they are expected emission equivalent, that is, we have compared the policies based on certain notions of cost effectiveness. Most papers in the intensity instrument literature follow the tradition of Weitzman (1974) and compare the instruments at their respective optimal levels. The next Proposition shows that our results readily extend to comparisons of the targets at their respective optimal levels, \underline{e}^* , \underline{s}^* , and $\underline{\tau}^*$, where the star notation represents a target level that is chosen to minimize the expected total costs:

$$\alpha^* = \arg \min_{\alpha} TC(\alpha), \quad \alpha \in \{\underline{e}, \underline{s}, \underline{\tau}\},$$

where $TC(\cdot)$ represents the total expected cost found in (2), (3), and (5) (but with the subscript removed to reduce clutter).

Proposition 3 *Let $\alpha, \beta \in \{\underline{e}, \underline{s}, \underline{\tau}\}$.*

(i) If $TC(\alpha) \leq TC(\beta)$ for all expected emission equivalent levels of α and β , then $TC(\alpha^) \leq TC(\beta^*)$.*

(ii) Let $\alpha^e(\beta)$ be the level of α that is expected emission equivalent to target β . If $TC(\alpha^e(\beta)) \leq TC(\beta^)$, then $TC(\alpha^*) \leq TC(\beta^*)$.*

Proposition 3(i) states that, among the aggregate quantity, intensity and price targets, if one target dominates another emission equivalent target at all stringency levels, then the former at its own optimal level also dominates the latter at the latter's own optimal level. Proposition 3(ii) relaxes the sufficient condition. If one target dominates the other cost effectively as the latter's expected emission level, then the former dominates the latter in terms of social welfare. Thus, the ranking conditions in Propositions 1 are broader than and imply the ranking conditions of respectively optimal targets, which provide ranking based on social optimality. In Section 5, we

show empirically that Proposition 3(i) is likely to hold between quantity and intensity targets for most top CO₂ emitters.

A related question is whether the three targets at their respective optimal levels lead to the same expected net emission. We show below that this is true for the optimal quantity and price targets but not true for the optimal intensity target.

Proposition 4 *The expected net emission is the same under the optimally chosen quantity and price targets, but is different from that under the optimally chosen intensity target: $E_{y,s}(e(\underline{e}^*)) = E_{y,s}(e(\underline{\tau}^*)) \neq E_{y,s}(e(\underline{s}^*))$.*

The fact that both optimal quantity and price targets lead to the same expected emission is akin to Weitzman (1974). However, the optimally chosen intensity target leads to different expected emission. This is consistent with the findings of Jotzo and Pezzey (2007), and is why when comparing intensity and other targets at their respective optimal levels, the ranking conditions are often extremely complicated. In contrast, we obtain relatively simple and yet sufficient ranking conditions by comparing targets at emission equivalent levels.

What if one is not restricted to choosing among the three targets? Given the quadratic damage and abatement cost functions in (7), we can show that the first best emission target is an affine function of the *ex post* BAU emission ys , with the slope given by $c_2/(c_2 + d_2)$. The three aggregate targets, as functions of ys , all have slopes different from that of the first best: the quantity target has a slope of zero, the price target has a slope of one, and the intensity target has a random slope of \underline{s}/s . Presumably a linear combination of the price and quantity targets can achieve the first best slope of $c_2/(c_2 + d_2)$, but practical application of these combinations has been limited.

4.2 Transboundary pollution

For transboundary pollutants, a nation's emission affects not only the home country but also other countries. There is, thus, a wedge between the effects of its emission on the nation's own welfare and the effects on the global welfare. In the case of greenhouse gases, which are global pollutants, the emission damages are borne by all nations. Suppose that there are n nations with the same emission damage function $D(\cdot)$, so that the global damage is given by $nD(\cdot)$. If the nation's objective is

to maximize global welfare, that is, to minimize the global cost $E_{y,s}[C(ys - e) + nD(e)]$, then the ranking conditions are similar to those in Proposition 1 but involve comparison between the slope ratio nd_2/c_2 (rather than d_2/c_2) with $1/\Phi$ and Ω . Specifically,

Proposition 5 *If a nation chooses between the three emission equivalent aggregate targets to maximize global welfare, then*

- (i) *The aggregate intensity target dominates the aggregate quantity target if and only if $\frac{nd_2}{c_2} \leq \Omega$;*
- (ii) *The aggregate price target dominates the aggregate quantity target if and only if $nd_2/c_2 \leq 1$;*
- (iii) *The aggregate intensity target dominates the aggregate price target if and only if $\frac{c_2}{nd_2} \leq \Phi$.*

The proof follows that of Proposition 1 but with the damage function $D(\cdot)$ replaced by $nD(\cdot)$. Increasing the number of nations n is equivalent to multiplying the slope of the MD curve by n , effectively raising the MAD/MC slope ratio by n . Such a change favors the quantity target. When the number of nations is large, it is possible that it is in a nation's own best interest (that is, accounting for $D(\cdot)$ rather than $nD(\cdot)$) to choose a price or an intensity target, while it is in the world's best interest (that is, accounting for $nD(\cdot)$ rather than $D(\cdot)$) to choose a quantity target. Specifically, *if the choice is between quantity and intensity targets, then accounting for global externalities favors the quantity target.*

4.3 Uncertain abatement cost function with asymmetric information

If a nation chooses a price target, then it is conceivable that the target is implemented through an emission tax. In this case, individual firms will respond to the tax based on their own abatement cost functions, for which they have information advantages over the government. To study the implications of the information asymmetry on the ranking conditions, we follow Weitzman (1974) and re-introduce intercept uncertainties in the marginal abatement cost function.⁹ Specifically, an individual firm's abatement cost function becomes (cf. (7))

$$\tilde{C}(a) = c_0 + (c_1 + \theta)a + c_2a^2, \tag{15}$$

⁹Although we focus on abatement cost uncertainties, we can verify that intercept uncertainties in the emission damage function do not affect the ranking conditions (similar to the case of Weitzman (1974)).

where θ is a random variable with $E(\theta) = 0$ and $\text{Var}(\theta) = \sigma_\theta^2$, and is independent of the random shocks to output y and intensity s .

Using (15) and repeating the same procedure used in deriving the expected total cost functions under the three targets, we can show that the total costs under the quantity and intensity targets, $TC_Q(\underline{e})$ and $TC_I(\underline{s})$, are unaffected by the presence of uncertainty θ and remain the same as in (2) and (3). Thus, the ranking condition between the two targets in Proposition 1(i) remains valid under cost uncertainty. We can also show that the total expected cost under the price target becomes

$$\tilde{TC}_P(\underline{\tau}) = TC_P(\underline{\tau}) + \frac{\sigma_\theta^2}{2c_2} \left(\frac{d_2}{c_2} - 1 \right), \quad (16)$$

where $TC_P(\underline{\tau})$, given in (5), is the total cost without cost uncertainties. The last term in (16) is precisely the difference between the total costs under the price and quantity tools in Weitzman (1974). Thus, *the ranking condition between the price and quantity targets in Proposition 1(ii) is unchanged: the price target welfare dominates the quantity target if and only if $c_2 \geq d_2$* . Uncertainties in BAU emission ys and in abatement cost θ work together to magnify the advantages of one target over the other (with the coefficient $\text{Var}(ys)$ in (26) being replaced by $(\text{Var}(ys) + \sigma_\theta^2/2)$).

The presence of the cost uncertainty changes the ranking condition between the price and intensity targets. As shown in Figure 1, when the equivalent targets are sufficiently stringent so that $\underline{s} < \bar{s}$ (Panel (a)), the price target dominates the quantity target if and only if $d_2/c_2 < 1/\Phi < 1$. We can show that adding the cost uncertainty raises the threshold value $1/\Phi$, enlarging the region in which the price target dominates the quantity target. The reason is that when the slope ratio d_2/c_2 equals the threshold $1/\Phi$, $d_2/c_2 < 1$. Then, the last term in (16) is negative, which reduces the total cost under the price target and thus favors the price target. In contrast, when the targets are lax so that $\underline{s} > \bar{s}$ (Panel (b)), the intensity target dominates the price target if and only if $d_2/c_2 > 1/\Phi > 1$. Then, adding the cost uncertainty will reduce threshold $1/\Phi$, thereby favoring the intensity target. The reason is that when the slope ratio is at the threshold value, that is, when $d_2/c_2 = 1/\Phi$, $d_2/c_2 > 1$. Then, the last term in (16) is positive, raising the total cost under the price target. In summary, *uncertainties and information asymmetry in the abatement cost function favor the price target when $\underline{s} < \bar{s}$ but favor the intensity target when $\underline{s} > \bar{s}$* .

5 Application to INDCs

We next apply the ranking conditions in Proposition 1 to evaluate the INDCs proposed in the 2015 Paris Agreement by the top 15 GHG emitters. It is notoriously difficult to obtain reliable data to estimate the MAC and MD functions, limiting the empirical applicability of the Weitzman conditions. Our ranking conditions in Proposition 1 have two advantages that greatly improve their empirical applicability. First, the conditions achieve a dichotomy between the slope ratio d_2/c_2 and the threshold parameters Ω and $1/\Phi$. Second, the two threshold parameters only depend on the variance-covariance matrix of GDP and BAU emission, which can indeed be reliably estimated. We will estimate the two thresholds $1/\Phi$ and Ω for each of the top GHG emitters and identify “regions of target dominance” by answering the following question: “what value does the slope ratio d_2/c_2 have to be for a particular target to dominate another target?” It turns out that for most nations, the estimated region of dominance, especially that between intensity and quantity targets, is disjoint from the range of plausible values of the slope ratio. Consequently we are able to obtain clear-cut dominance relations without explicitly estimating the slope ratio. This is arguably the biggest advantage of comparing aggregate targets instead of comparing the instruments facing the firms. In the latter case, the ranking conditions involve not only the slope ratio but also threshold parameters that depend on certain aspects of the abatement cost function which are difficult to estimate due to data limitations.

5.1 Empirical Model Specification

There is a large literature forecasting future GDP and energy consumption or carbon emission for individual nations, regions, and the world, with the main focus being on whether one Granger-causes the other (see Ozturk (2010) for a survey). Our task is simpler: we only need to estimate the correlation structure of GDP and BAU carbon emission for future target years (e.g., year 2030). As such, we are not concerned with estimating the levels or causality between the two variables. When the ranking conditions do require estimates of future values of GDP,¹⁰ we tap into the literature

¹⁰When quantity targets are proposed in INDCs, we need to divide these emission targets by future GDP values to obtain the equivalent intensity target \underline{g} , as required by the ranking conditions in Proposition 1.

and obtain such forecasts from existing studies.

There is also a large literature on whether real GDP (or per capita real GDP) is unit root or trend stationary, with mixed evidence. For instance, Nelson and Plosser (1982)'s challenge of the treatment of $\log(\text{GDP})$ as being trend stationary has itself been challenged by a number of studies, with these challenges being challenged further more (see, for example, Murray and Nelson (2000) and Hegwood and Papell (2007)). Overall, there is support for trend stationarity of GDP or $\log(\text{GDP})$ if structural breaks are included to account for major shocks to the economy (Perron (1989) and Zivot and Andrews (2002)).

The threshold parameters $1/\Phi$ and Ω are not sensitive to whether or not the GDP and BAU emission are stationary. To see this, let $\mathbf{z}_t = (y_t, y_t s_t)'$ be the vector of GDP and BAU emission (or their log values) in period t . Suppose that \mathbf{z}_t follows process

$$\mathbf{z}_t = \boldsymbol{\alpha}_0 + \boldsymbol{\alpha}_1 t + \mathbf{w}_t. \quad (17)$$

If \mathbf{z}_t is trend stationary, then the variance-covariance matrix of \mathbf{w}_t is time-invariant and can be estimated from the OLS residuals of (17). Suppose instead that \mathbf{z}_t follows a unit root process, so that

$$\mathbf{w}_t = \mathbf{w}_{t-1} + \boldsymbol{\epsilon}_t,$$

where the variance-covariance matrix of $\boldsymbol{\epsilon}_t$, denoted as $\text{Var}(\boldsymbol{\epsilon})$, is time invariant. Then the variance-covariance matrix of \mathbf{w}_t depends on t . Specifically, based on data up to year t_0 , the variance of \mathbf{w}_T in year $T > t_0$ is given by $\text{Var}(\mathbf{w}_T) = (T - t_0)\text{Var}(\boldsymbol{\epsilon})$. However, from (10) and (11), both Ω and Φ depend on the *ratios* of the variance and/or covariance of GDP and BAU emission, and are independent of T since $T - t_0$ cancels out in the numerators and denominators. Thus, the presence or absence of unit root in (17), which is a critical issue for forecasting, is tangential for the purpose of estimating the two threshold parameters $1/\Phi$ and Ω .

We assume trend stationarity for both GDP and BAU emission after testing and accounting for structural breaks. We further conduct robustness checks for different break points if structural breaks are detected. Specifically, for each country or region, we estimate the following empirical

model using annual GDP and CO₂ emission data:

$$\ln(x_t) = \beta_0 + \beta_1 t + u_t, \quad (18)$$

where x_t is GDP y_t or CO₂ emission $y_t s_t$ in year t , for $t = 1, \dots, T$, and u_t are *iid*.¹¹ The log specification is used to predict future values of GDP and CO₂ emissions. To estimate the variance-covariance matrix of y_t and $y_t s_t$, we have to “de-log” the variables. Because $E(x_t) = \exp(\beta_0 + \beta_1 t)E(\exp(u_t))$, the fitted values of x_t are obtained as

$$\hat{x}_t = \exp(\hat{\beta}_0 + \hat{\beta}_1 t) \sum_t \exp(\hat{u}_t)/T,$$

where $\sum_t \exp(\hat{u}_t)/T$ is the estimator for $E(\exp(u_t))$ (Cameron and Trivedi (2009), p103). The prediction error for x_t is $x_t - \hat{x}_t$. The prediction errors for GDP and CO₂ emission are then used to calculate the sample variance-covariance matrix, which forms the estimator for the variance-covariance matrix of GDP and BAU emissions. Note that we do not take the structural approach by estimating the GDP and CO₂ equations jointly, such as estimating (18) using the seemingly unrelated time series equation (SUTSE) approach. By not estimating the causal relationship between GDP and CO₂ emissions, we take the reduced form approach and obtain more robust variance-covariance estimates.

5.2 Data

The list of top GHG emitters is based on 2014 emission data, and only nations with explicit commitments in their INDCs are included. Among the world’s top 15 GHG emitters, we exclude Indonesia and Iran, which committed to reduction targets relative to BAU emission in 2030 for which we do not have reliable estimates. We also exclude Saudi Arabia, which only committed to a set of actions instead of quantifiable reduction targets.

The INDC targets of the remaining 12 top emitters are obtained from the CAIT Climate Data Explorer (World Resources Institute (2016)) and are summarized in Table 1. Most nations proposed quantity targets, with PRC and India proposing intensity targets. Although Republic of Korea and Mexico proposed reductions relative to their BAU emission in 2030, the former included a specific

¹¹We also fitted the data using linear specifications. For most countries and for both GDP and CO₂ emission, the log specification fits the data better than the linear specification based on log-likelihood ratio tests.

Table 1: INDC Targets

Nation	Base Year	Target Year	Target Type	Target Reduction*
PRC	2005	2030	Intensity	60-65%
United States	2005	2025	Quantity	26-28%
European Union	1990	2030	Quantity	40%
India	2005	2030	Intensity	33-35%
Russian Federation	1990	2030	Quantity	25-30%
Japan	2005	2030	Quantity	25.4%
Republic of Korea**		2030	BAU-Q	37%
Canada	2005	2030	Quantity	30%
Brazil	2005	2025	Quantity	37%
Mexico**		2030	BAU-I	25%
Australia	2005	2030	Quantity	26-28%
South Africa***		2025-2030	Quantity	398-614 Mt CO ₂ e

* Target REduction represents the percentage reduction in emission level or intensity relative to the base year. It is not the same as the targetted emission intensity.

** Even though Republic of Korea committed to a reduction target relative to BAU emission, it did specify that the BAU emission will be 850.6 Mt CO₂eq. Mexico committed to a BAU reduction target, but also noted that the target is equivalent to a 40% reduction in GHG intensity of GDP from 2013 to 2030. We use Mexico's 2012 intensity level (for which we have data) as an approximation for its 2013 level.

*** South Africa's target is specified as a range of net GHG emission.

BAU emission level while the latter specified a BAU intensity. In this regard, Republic of Korea proposed a quantity target while Mexico proposed an intensity target. Not a single nation proposed a price target.

Annual GDP (in 2005 dollars) and CO₂ emission data (excluding land use change and forestry) from 1960 to 2012 are obtained from WRI's CAIT database.¹² For nations with quantity targets, we need to calculate the equivalent intensity target, which requires us to use its forecasted GDP for the target year. We obtain such forecasts from USDA ERS International Macroeconomic Data Set (USDA ERS (2016)).¹³

¹²This is available at www.wri.org/resources/data-sets/cait-historical-emissions-data-countries-us-states-unfccc.

¹³Because the historical GDP data from WRI CAIT are in 2005 dollars while the USDA ERS projected GDP data are in 2010 dollars, we converted the latter to 2005 dollars.

5.3 Estimation Results

The estimation results for the GDP and CO₂ equations for each country are presented in Appendix D. The point estimates of the threshold parameters $1/\Phi$ and Ω and their bootstrapped 95% confidence intervals are presented in Table 2. The underlying point estimates of the variance-covariance matrix of GDP and CO₂ emissions are presented in Table 4 of Appendix D. The estimates depend on the target emission levels, which are to be achieved in the future. The time paths of achieving the targets are not specified by the nations. Our strategy is to first estimate the threshold parameters using the INDC emission targets (reported in Table 2), and then re-estimate the parameters assuming that the targets are either under- or over-achieved (reported in Section 5.4). The former estimates help compare the targets for future years when the targets are achieved, while the latter estimates do so for the transition years when the nations progress toward their targets and the post-target years when the nations move beyond their targets. When a nation's target is an interval, we use its midpoint in calculating the two threshold parameters. For instance, in the case of PRC we assume an intensity reduction target of 62.5%.

Based on the estimates in Table 2, Figure 3 illustrates the regions of dominance in terms of the slope ratio d_2/c_2 . Specifically, the quantity target dominates (the other two targets) when the slope ratio falls within the red colored regions (the right end of the bars), while the intensity target dominates (the other two targets) in the light blue regions (middle sections of the bars) and the price target dominates (the other two targets) in the yellow regions (left end of the bars). The figure also illustrates the 95% confidence intervals for the boundaries of these dominance regions. It is worth noting that, other than for South Africa, the confidence interval of $1/\Phi$ and that of Ω do not overlap for any nation. This implies that there is a region of the values of d_2/c_2 (between the two confidence intervals) in which we can conclude with confidence that a nation's preferred target is the intensity target. South Africa is a special case because its mean target emission level of 2030 is in fact higher than its current emission; however, we can show that the two confidence intervals separate out when its INDC target drops below its current emission level.

Although the literature does not contain reliable estimates of the two slopes for the 12 nations, the most common argument is that d_2 is much lower than c_2 . For example, Hoel and Karp (2001)

Table 2: Estimates and Comparisons of INDCs and Preferred Targets

Nation	$\widehat{1/\Phi}$	C.I. of $1/\Phi$	$\widehat{\Omega}$	C.I. of Ω	Target in INDC	Preferred Target*
PRC	0.901	[0.838, 0.964]	9.901	[4.465, 15.253]	Intensity	Intensity
United States	0.730	[0.657, 0.804]	4.902	[3.552, 6.255]	Quantity	Intensity
European Union	0.629	[0.588, 0.669]	3.155	[2.520, 3.783]	Quantity	Intensity
India	-0.922	[-1.641, -0.201]	-0.272	[-0.627, 0.0837]	Intensity	Quantity
Russian Federation	0.389	[0.318, 0.460]	2.950	[2.412, 3.491]	Quantity	Intensity
Japan	0.530	[0.407, 0.653]	2.151	[1.674, 2.628]	Quantity	Intensity
Republic of Korea	0.411	[0.357, 0.465]	3.484	[2.805, 4.163]	BAU-Q	Intensity
Canada	0.682	[0.646, 0.717]	6.897	[5.780, 7.995]	Quantity	Intensity
Brazil	0.695	[0.649, 0.741]	7.016	[5.987, 8.0457]	Quantity	Intensity
Mexico	0.499	[0.459, 0.538]	4.464	[4.001, 4.938]	BAU-I	Intensity
Australia	0.868	[0.827, 0.909]	13.661	[8.892, 18.415]	Quantity	Intensity
South Africa	0.852	[0.515, 1.189]	1.314	[0.637, 1.991]	Quantity	Not Sure**

* Preferred Target refers to the target that should be chosen if the choice is between quantity and intensity targets, under the assumption that the slope ratio d_2/c_2 is less than one.

** For South Africa, although the point estimate of Ω is greater than one, the 95% confidence interval contains values less than one. Thus it is possible that $d_2/c_2 > \Omega$ and the preferred target is the quantity target, and possible that the reverse is true so that the intensity target is preferred.

and Newell and Pizer (2003) argue that the slope of the MD function tends to be small for stock pollutants, because the flow is much smaller than the stock level.¹⁴ Newell and Pizer (2008), Jotzo and Pezzey (2007), and Branger and Quirion (2014) assume that $c_2 \gg d_2$, although they do not provide estimates of the explicit magnitudes of the difference. Ackerman and Bueno (2011) compares the estimated marginal abatement costs for a number of nations from different models and shows that the slope of MAC differs across nations and models and tends to be increasing as the abatement level rises. Bonen, Semmlery and Klasen (2014) reviews the damage functions from CO2 emission in three major integrated assessment models. However, none of these studies provides point estimates or confidence intervals of d_2 or c_2 for the 12 nations in our study.

We follow the literature and assume that $d_2/c_2 < 1$ for the 12 nations, but in fact, it is possible that $nd_2/c_2 < 1$ even when the global benefit multiplier n is included in the calculation. Then, from Figure 3, if the choice is between quantity and intensity targets, all of the 12 nations but India and South Africa should choose intensity targets. The left endpoints of the confidence intervals for Ω all exceed one. The case for intensity targets over quantity targets is particularly strong for PRC, Canada, Brazil, Mexico and Australia, for which the left endpoints of Ω 's confidence interval exceed 4. The case is weaker for Japan, for which the left endpoint is about 1.67. India is special in that the intensity target is dominated by both the quantity and price targets. The confidence intervals of $1/\Phi$ and Ω overlap for South Africa, so that it is difficult to pin down the optimal target unless its slope ratio d_2/c_2 falls outside the two confidence intervals. For instance, if $d_2/c_2 < 0.6$, that is, if the MD slope is at least 40% lower than the slope of the MAC, then South Africa should choose the intensity target over the quantity target.

These observations contrast sharply with the proposed targets in INDCs in the Paris Agreement: PRC and, to a certain extent, Mexico are the only nations that proposed the “correct” type of target, that is, the intensity target. India proposed an intensity target but it is dominated by a quantity target. South Africa proposed a quantity target, and it might be dominated by the equivalent intensity target if the slope of its MD curve is at least 40% lower than that of its MAC curve. Although all other nations proposed quantity targets, they are dominated by the equivalent

¹⁴However, Parsons and Taschini (2013) shows that when there are permanent shocks to abatement costs, quantity caps can be preferred to price control, even for stock pollutants.

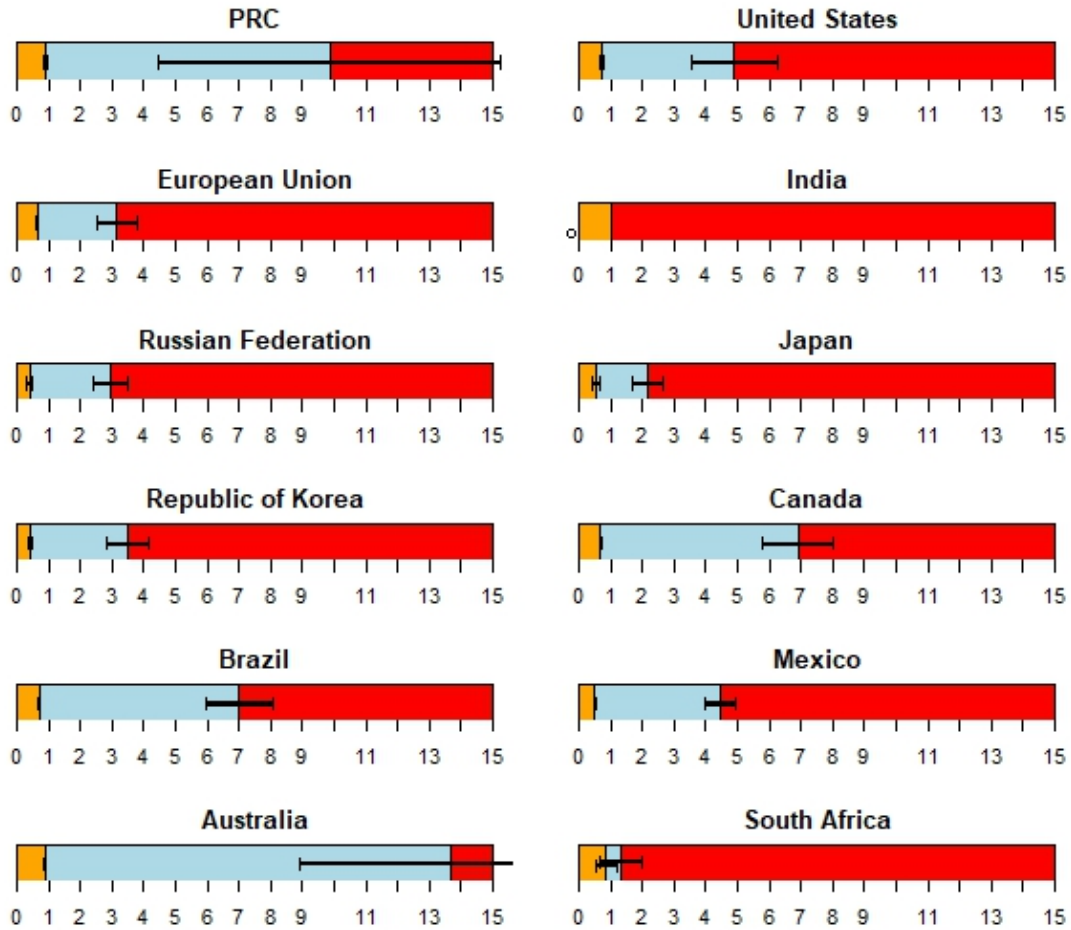


Figure 3: Intervals of d_2/c_2 Values for Dominant Targets

intensity targets. The last two columns of Table 2 contain the proposed targets in INDCs and the preferred targets if choosing between quantity and intensity targets.

Table 2 and Figure 3 also indicate that for most nations, the price target is the optimal target if d_2 is lower than a third of c_2 . The lowest value of the left endpoints of the confidence intervals of $1/\Phi$ is 0.318 for Russian Federation, followed by 0.357 for Republic of Korea. However, if $d_2/c_2 > 0.5$, that is, if the slope of the MD curve is at least half of that of the MAC, then the intensity targets dominate price targets for Russian Federation, Republic of Korea and Mexico. Overall, the ranking between price and intensity targets is less clear-cut than that between quantity and intensity targets if we only go so far as accepting that $d_2/c_2 < 1$.

5.4 Robustness

Our results demonstrate the dominance of aggregate intensity over quantity targets for most of the top emitters. We next conduct a series of robustness checks to investigate the sensitivity of our conclusions to the key parameters of our model. We first recalculate the estimates $\widehat{1/\Phi}$ and $\hat{\Omega}$ for different values of \underline{s} , mainly to evaluate whether our rankings of the targets will change as the targets are under- or over-achieved. The rankings for under-achieved targets are relevant for the years leading up to the target years, as the nations gradually reduce their emissions to the targeted levels. The rankings for over-achieved targets are relevant for the time period after the target years, if the nations continue to cut down their CO₂ emissions. For each nation, we re-estimate the rankings for a set of emission reductions $\gamma(s_0 - \underline{s})$, where s_0 is carbon intensity level in base year, \underline{s} is the equivalent target intensity level in its INDC, and $\gamma \in \{0.05, 0.10, 0.25, 0.5, 0.75, 1, 1.25, 1.5\}$. That is, we evaluate how the range of ranking conditions delineated by $1/\Phi$ and Ω will change as a nation's INDC target reduction is reduced to 5% or raised to 150% of its proposed target.

Figure 4 shows how thresholds $\widehat{1/\Phi}$ and $\hat{\Omega}$ vary as a function of γ for four nations. The graphs for other nations show similar patterns and are presented in Appendix E. As shown in (10), Ω increases as the committed abatements are enhanced (that is, as γ increases). However, even when the emission reduction commitments in the INDCs are reduced by 50%, $\hat{\Omega}$ is still over 2 for most nations, indicating that intensity targets still dominate quantity targets. This conclusion is likely

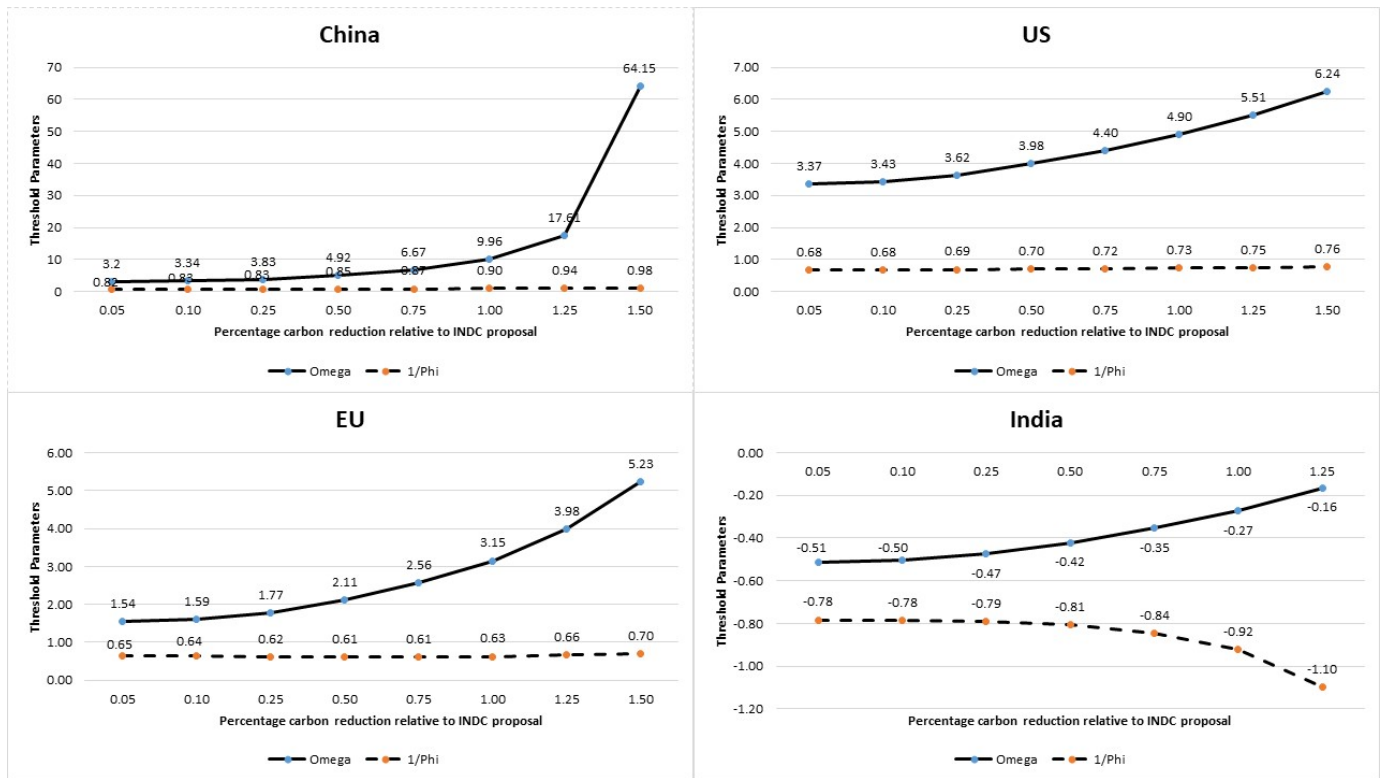


Figure 4: Threshold Values for Under- and Over-Achieved Targets

to hold even when the INDC target is relaxed to 5% of each nation’s committed level. On the other hand, as the INDC targets are relaxed, $\widehat{1/\Phi}$ decreases but by a tiny amount for all nations. Thus, it is unlikely that under- or over-achieving the INDC targets will change the ranking between intensity and price targets.

We next study how the estimates of the two threshold parameters vary as different subsamples of the GDP and CO₂ data are used to control for possible structural breaks. In our baseline estimation, we already controlled for obvious structural changes for PRC and Russian Federation: the data for PRC (1978-2012) are after the start of its reform, and the data for Russian Federation (1989-2012) are after the collapse of the Soviet Union. We used the full sample (1960-2012) for all other nations in the baseline estimation. Table 3 shows how the estimated threshold parameters $\widehat{1/\Phi}$ and $\widehat{\Omega}$ would change when only data after structural breaks are used for these nations. For each nation and for both GDP and CO₂, the Chow test for the structural breaks (assuming stationary u_t in (18)) is significant at less than 1% significance level. For some nations there is possibly more

than one break. The United States experienced two breaks that coincide with the two Oil Crises (the 1973-1975 crisis and the 1979 crisis). For European Union, we include two possible breaks, one around 1970 (based on statistical testing) and one around 1973 (the first Oil Crisis). Japan is tested for two breaks, one around the first Oil Crisis and the second at the start of the “lost decade” (that is, year 1988). The breaks for the other nations mostly occur around one of the two Oil Crises, and the specific break year is detected through Chow tests.

Table 3 indicates the robustness of the conclusion that intensity targets dominate quantity targets for most nations. If we maintain the assumption that $d_2/c_2 < 1$, the dominance of intensity over quantity targets is robust for United States, European Union, Republic of Korea, Canada, Mexico and Australia. For these nations, the threshold $\widehat{1/\Phi}$ remains less than one, implying that the ranking between price and intensity targets might not change either. The finding that in India the absolute target dominates the intensity target is also robust. However, for Japan (for one structural break, in year 1974) and Brazil, the new point estimates for Ω are less than one and those for threshold $\widehat{1/\Phi}$ are greater than one. Thus, for these two nations, it is possible that controlling for structural breaks might reverse the ranking relation between intensity and quantity targets, and between intensity and price targets. For South Africa, controlling for structural breaks might cause the intensity target to be dominated by either price or quantity targets. But as we noted earlier, its target emission is higher than historical emission. Overall, our conclusion that intensity targets dominate quantity targets is robust for most of the major emitters.

6 Conclusions

In this paper, we welfare rank aggregate intensity vis-a-vis price and quantity targets when they are imposed on a nation but not directly on firms. In the context of the Paris Agreement, these targets only represent the nations’ commitments but are not chosen as their regulatory instruments. In fact, none of the INDCs has specified how a nation will achieve its proposed target. In this regard, our model more closely represents the real world. The greatest advantage of our model relative to the literature, which treats aggregate targets as regulatory instruments, is that the ranking conditions for the three aggregate targets are parsimonious in parameters, with a dichotomy between the

Table 3: Robustness Check: Effects of Structural Breaks

Nations	Base Model			Control for Structural Breaks						Robust?
	Years	$\hat{\Omega}$	$\widehat{1/\Phi}$	Years	$\hat{\Omega}$	$\widehat{1/\Phi}$	Years	$\hat{\Omega}$	$\widehat{1/\Phi}$	
United States	1960-2012	4.90	0.73	1973-2012	3.32	0.62	1980-2012	3.65	0.51	Yes
European Union	1960-2012	3.15	0.63	1970-2012	2.46	0.85	1973-2012	1.75	0.89	Yes
India	1960-2012	-0.27	-0.92	1980-2012	-0.031	4.95	—			Yes
Japan	1960-2012	2.15	0.53	1974-2012	0.21	5.58	1988-2012	3.22	0.64	Mixed
Republic of Korea	1960-2012	3.48	0.41	1980-2012	2.38	0.43	—			Yes
Canada	1960-2012	6.90	0.68	1974-2012	5.31	0.77	—			Yes
Brazil	1960-2012	6.99	0.70	1981-2012	0.71	1.01	—			No
Mexico	1960-2012	4.46	0.50	1983-2012	1.14	0.85	—			Yes
Australia	1960-2012	13.66	0.87	1985-2012	7.86	0.88	—			Yes
South Africa	1960-2012	1.31	0.85	1978-2012	-0.12	31.93	—			No

ratio of the slopes of the marginal emission damage and marginal abatement cost curves, and two threshold parameters that depends only on the variance-covariance matrix of the GDP and business-as-usual emission. Given that the latter can be reliably estimated from historical GDP and emission data for most nations, it is possible to rank the three aggregate targets without knowing the point estimates of the slope ratio, which are difficult to obtain due to data limitations.

Instead of comparing the three targets at their respective optimal levels, we anchor them so that they lead to the same expected net emission. The ranking of emission equivalent targets still holds when comparing the targets at their respective optimal levels, but not vice versa. We further show that intensity targets are more likely to dominate the other two because the GDP and BAU emission are more positively correlated, and are more likely to dominate the quantity target as the targets become more stringent.

We apply the ranking conditions to the top 12 CO₂ emitters that have submitted explicit emission reduction commitments in their INDCs to the Paris Agreement. Using their historical GDP and CO₂ emission data, we estimate the variance-covariance matrix of GDP and BAU carbon emission and the threshold ranking parameters. We also conduct robustness checks against sampling errors, percentage of the targets achieved, and structural changes. The confidence intervals of the threshold parameters are far removed from the plausible ranges of the slope ratio, which enables us to reliably rank the targets for these nations. We find that for all nations but India and South Africa, the intensity targets dominate the quantity targets if we accept that the MD curve is less steep than the MAC curve. The case for intensity targets is particularly strong and robust for PRC, Canada, Mexico and Australia. India is the only nation for which the intensity target is dominated by both the quantity and price targets. If the slope of the MD curve is less than a third of the slope of the MAC curve, then the price target dominates both intensity and quantity targets for all nations. Overall, our findings provide strong support for aggregate intensity targets if the choice is only between intensity and quantity targets. In this case, among the top 12 polluters, only PRC and to a certain extent Mexico proposed the “correct” type of targets.

To obtain sharp results, we assumed that the abatement cost and emission damage functions are independent of economy wide shocks in GDP and emission intensity. It is conceivable that both functions are correlated with both variables, and the correlation might go in opposite directions. For

instance, a rich nation might have access to new abatement technologies that reduce its abatement costs, indicating a negative correlation between MAC and GDP. On the other hand, a low income nation might be based mostly on fossil fuel energies with plenty of low-hanging fruits for reducing its emission, indicating a positive correlation between MAC and GDP. The correlation can also be of different signs at different levels of GDP. Without estimating the correlation coefficient, we can conjecture the likely implications of such correlation on the ranking conditions. Suppose that MAC and GDP are positively correlated but that MD and GDP are independent. Then a variation in GDP will imply more uncertainty in MAC, and this will likely favor the tax target than the intensity and quantity target, and the intensity over the quantity target (since the price target distributes all uncertainties in BAU emission to net emission, while the quantity target distributes all uncertainties to abatement). We can make similar conjectures for the effects of other correlation patterns, but leave future work to explicitly model the correlation structures and their implications for ranking the aggregate targets.

We also assumed that the aggregate targets are always binding (cf. (1)). Allowing the targets to be binding for a subset of the realizations of GDP and intensity will introduce a layer of non-linearity that will likely complicate the analysis. A major difficulty arises from the possibility that expected emission equivalence will imply different probabilities of the targets being binding under different targets. Under the intensity target, these probabilities are determined by uncertainties in intensity only. However, under the price and quantity targets, the probabilities are determined by uncertainties in BAU emission, which is a product of GDP and intensity. Unless GDP and intensity are sufficiently negatively correlated, uncertainties in BAU emission will likely exceed those in intensity only, thereby raising the probability that the price and quantity targets are non-binding. Again, explicit models are needed to fully evaluate the implications of non-binding targets.

Our model can be extended in several directions. One of the arguments in support of intensity targets is that they are more amenable to economic growth. Although our model is static, it would be interesting and important to compare the three aggregate targets in a growth model to evaluate their long-run effects. The dynamic effects become more important and interesting if we allow the emission targets to affect the output directly. Another direction in which our model can be extended is to study optimal target forms. As recognized by Newell and Pizer (2003), intensity

targets are a special kind of indexing where the target emission level is indexed to outputs (or GDP). Both Newell and Pizer (2003) and Jotzo and Pezzey (2007) find that, for individual firms, the optimal indexation typically involves setting emission as an affine function or even a nonlinear function of GDP. We showed in Section 4.1 that the optimal *ex post* emission is an affine function of BAU emission given quadratic abatement cost and emission damage functions. A natural next step is to study how to practically implement such an affine function through possible combinations of quantity, price, and/or intensity targets.

A Proofs

Proof of Proposition 1. (a) We first prove part (i) of the Proposition. Using the quadratic forms in (7), it is straightforward to verify that

$$E_y D(y\underline{s}) = D(E(y)\underline{s}) + d_2[E((y\underline{s})^2) - (E(y\underline{s}))^2] = D(E(y)\underline{s}) + d_2 \text{Var}(y\underline{s}) \quad (19)$$

$$E_{y,s} C(y s - \underline{e}) = C(E(y s - \underline{e})) + c_2[E((y s - \underline{e})^2) - (E(y s - \underline{e}))^2] \quad (20)$$

$$E_{y,s} C(y s - y\underline{s}) = C(E(y s - y\underline{s})) + c_2[E((y s - y\underline{s})^2) - (E(y s - y\underline{s}))^2] \quad (21)$$

Substituting these to $TC_Q(\cdot)$ in (2) and $TC_I(\cdot)$ in (3), and noting that $\underline{e} = E_y(y)\underline{s}$ from (6), we know

$$D(\underline{e}) - E_y D(y\underline{s}) = -d_2 \text{Var}(y\underline{s})$$

$$E_{y,s} C(y s - \underline{e}) - E_{y,s} C(y s - y\underline{s}) = c_2[2\underline{s}(E(y s)E(y) - E(y^2 s)) - \text{Var}(y\underline{s})]$$

Using these two equations, we get

$$TC_Q(\underline{e}) - TC_I(\underline{s}) = -d_2 \text{Var}(y\underline{s}) + c_2[2\text{Cov}(y s, y)\underline{s} - \text{Var}(y\underline{s})], \quad (22)$$

which implies that the welfare gain of the intensity target over the equivalent quantity target is

$$-(TC_I(\underline{s}) - TC_Q(\underline{e})) = \text{Var}(y\underline{s})(c_2 \Omega - d_2) \quad (23)$$

(b) To prove part (ii) of the Proposition, note from (20) that

$$TC_Q(\underline{e}) = D(\underline{e}) + C(E(y s - \underline{e})) + c_2 \text{Var}(y s). \quad (24)$$

From (9), we obtain the abatement level under tax as $E(y s) - \underline{e}$. Using a similar approach to

deriving (20), we get the expected total cost under the price target as

$$TC_P(\underline{\tau}) = D(\underline{e}) + d_2 + \text{Var}(ys)C(E(ys - \underline{e})). \quad (25)$$

Taking the difference between (24) and (25), we know that the welfare advantage of the price target over the equivalent quantity target is given by

$$-(TC_P(\underline{\tau}) - TC_Q(\underline{e})) = \text{Var}(ys)(c_2 - d_2). \quad (26)$$

(c) To prove part (iii) of the Proposition, note that, by subtracting (22) from (26) and simplifying, we obtain the welfare gain of the price target over the equivalent intensity target as

$$\begin{aligned} -(TC_P(\underline{\tau}) - TC_I(\underline{s})) &= (\text{Var}(ys) - 2\text{Cov}(ys, y)\underline{s} + \text{Var}(y)\underline{s}^2)(c_2 - d_2\Phi) \\ &= \text{Var}(ys - y\underline{s})(c_2 - d_2\Phi) \end{aligned} \quad (27)$$

■

Proof of Proposition 2. If y and s are independent, then $\text{Cov}(ys, y) = \text{Var}(y)E(s)$. By substituting this into (10), we obtain the equality in (13). Since the intensity target is always binding with $\underline{s} \leq s_l$ (cf. (1)), we know $E(s) > \underline{s}$, implying the inequality in (13). Since y and s are independent, we also know (cf. Footnote 7)

$$\text{Var}(ys - y\underline{s}) = \text{Var}(s)E(y^2) + \text{Var}(y)(E(s) - \underline{s})^2.$$

By substituting this equation and $\text{Cov}(ys, y) = \text{Var}(y)E(s)$ into (11), we obtain

$$\Phi' = 1 + \frac{2\underline{s}(E(s) - \underline{s})}{(E(s) - \underline{s})^2 + \text{Var}(s)E(y^2)/\text{Var}(y)}.$$

By substituting in $E(y^2) = \text{Var}(y) + (E(y))^2$ and dividing the numerator and denominator by \underline{s}^2 , we obtain (14). ■

Proof of Proposition 3. Since α dominates β when they are emission equivalent, $TC(\alpha^e(\beta)) \leq TC(\beta)$ for all β , including when $\beta = \beta^*$. However, since α^* is the optimal level of α , we know $TC(\alpha^*) \leq TC(\alpha^e(\beta^*))$. Combining the two inequalities, we know $TC(\alpha^*) \leq TC(\beta^*)$. ■

Proof of Proposition 4. By taking derivatives of the total costs with respect to \underline{e} in (24) and (25), we get

$$E_{y,s}(e(\underline{e}^*)) = E_{y,s}(e(\underline{\tau}^*)) = \frac{c_1 - d_1}{2(c_2 + d_2)} + \frac{c_2}{c_2 + d_2}E(ys). \quad (28)$$

Under the intensity target, $TC(\underline{s}) = E_y D(y\underline{s}) + E_{y,s} C(y\underline{s} - y\underline{s})$, with $E_y D(\cdot)$ given in (19) and $E_{y,s} C(\cdot)$ given in (21). Taking derivative of $TC(\underline{s})$ with respect to \underline{s} , solving for the optimal \underline{s} , and multiplying with $E(y)$, we get

$$E_{y,s}(e(\underline{s}^*)) = \frac{c_1 - d_1}{2(c_2 + d_2)} \frac{(E(y))^2}{(E(y))^2 + \text{Var}(y)} + \frac{c_2}{c_2 + d_2} \frac{E(y^2 s) E(y)}{E(y^2)}. \quad (29)$$

By substituting $E(y^2 s) = \text{Cov}(y, ys) + E(y)E(ys)$ and $E(y^2) = \text{Var}(y) + (E(y))^2$ to (29), we know that the difference between the two emission levels is

$$E_{y,s}(e(\underline{e}^*) - e(\underline{s}^*)) \propto \frac{c_1 - d_1}{2E(ys)c_2} + \left(1 - \frac{\rho_{y,ys}}{CV_y/CV_{ys}}\right), \quad (30)$$

where $CV_y = \sqrt{\text{Var}(y)}/E(y)$ and $CV_{ys} = \sqrt{\text{Var}(ys)}/E(ys)$ are the coefficients of variation of y and ys . Further, when y and s are independent, $E(y^2 s) = E(y^2)E(s)$. Then (29) simplifies to

$$E_{y,s}(e(\underline{s}^*)) = \frac{c_1 - d_1}{2(c_2 + d_2)} \frac{(E(y))^2}{(E(y))^2 + \text{Var}(y)} + \frac{c_2}{c_2 + d_2} E(ys). \quad (31)$$

Thus $E(e(\underline{s}^*)) \leq E(e(\underline{e}^*))$ if and only if $c_1 \geq d_1$. ■

B Distinction from Weitzman (1974)

Our model is different from that of Weitzman (1974) in two main aspects. First, as shown in Kling and Zhao (2000) and Newell and Pizer (2008), a firm has incentives to increase its output when facing emission intensity regulation in the Weitzman framework, since doing so effectively relaxes the cap on the firm's emissions (or raises the number of emission permits it receives). In contrast, such incentives do not arise in our model since the firm faces cost-effective regulation such as a traditional pollution tax, even when a nation adopts an (aggregate) intensity target. As a result, our ranking conditions in Proposition 1 do not depend on factors that determine firms' output and emission responses to the intensity instrument, such as the correlation between abatement costs and output in Newell and Pizer (2008). Second, even when restricted to the price and quantity targets, the mechanisms underlying the ranking conditions in our model are still different from those in Weitzman (1974). We focus on the second distinction in this section.

In Weitzman (1974), the abatement cost function is uncertain, as given in (15), and the uncertain parameter θ is observed only by the regulated firms. Figure 5(a) shows the welfare losses from the price and quantity tools relative to the *ex post* optimum. The price and quantity tools are set at

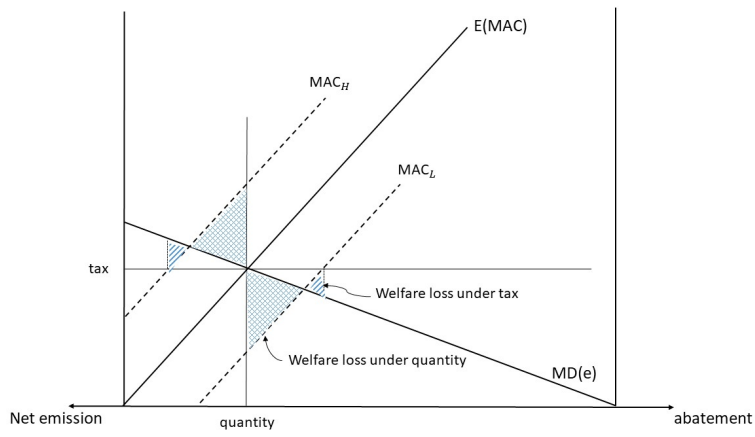
levels so that the expected MAC equals MD. The meshed areas represent the welfare losses under the quantity tool and the parallel shaded areas represent those under tax, when the MAC is higher or lower than the expected level. Since the MAC curve has a higher slope than the MD curve, tax dominates the quantity tool.

Figures 5(b) and 5(c) show the welfare losses associated with aggregate quantity and price targets in our model, when the MAC is deterministic but the BAU emission ys is stochastic. The horizontal axis has two directions: increasing abatement to the right and increasing net emission to the left. There are two “origins”, the distance between which measures the level of BAU emission. In both figures, the quantity and tax levels are set so that $MAC = MD$ at the expected BAU emission level $E(ys)$.

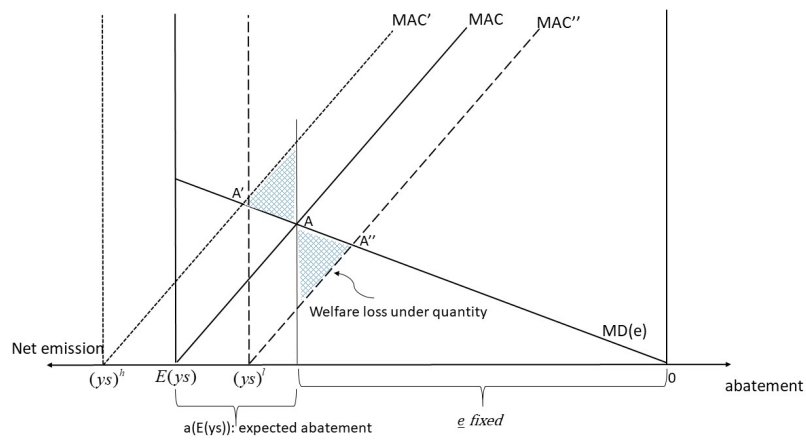
Panel (b) depicts the welfare losses under the aggregate quantity target. Given that the net emission is fixed by the target, as the *ex post* BAU emission varies from its expected level, the distance between the two origins (“0” to the right, and “ $E(ys)$ ”, “ $(ys)^h$ ” or “ $(ys)^l$ ” to the left) changes correspondingly, resulting in parallel shifts of the MAC curve (from MAC to MAC’ or MAC”). Consider the case when the *ex post* BAU emission is at $(ys)^h$, which is higher than expected. In this case, the left origin moves to the left from $E(ys)$ to $(ys)^h$, “carrying” with it the MAC curve, which is now labelled MAC’. The *ex post* optimum is at point A' , while the aggregate quantity target fixes the net emission corresponding to point A . The meshed triangle between A' and A thus measures the welfare loss relative to the *ex post* optimum. By comparing Panels (a) and (b), we observe similarity between the welfare losses under the aggregate quantity target in Panel (b) to those under the quantity tool in Panel (a). However, the underlying mechanisms are different: in Panel (a), the MAC curve shifts up and down in response to the *ex post* realizations of the intercept parameter θ , while in Panel (b), the MAC curve shifts left and right to move together with the left origin, in response to the *ex post* realizations of the BAU emission ys .

Panel (c) shows the welfare losses under the aggregate price target in our model. Since the abatement level is fixed by the price target, the left origin is fixed at “0” while the right origin moves corresponding to the realizations of BAU emission ys . The resulting parallel shaded areas of welfare losses are similar to those in Panel (a), but is again driven by different mechanisms.

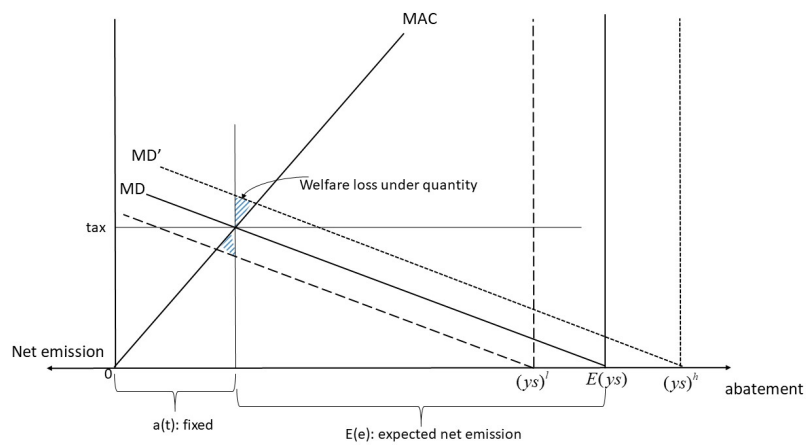
The welfare losses under the aggregate quantity target in Panel (b) are higher than those under



(a) Expected welfare loss in Weitzman model



(b) Expected welfare loss under aggregate quantity target



(c) Expected welfare loss under aggregate price target

Figure 5: Welfare Losses in Weitzman (1974) vs. in Our Model

the price target in Panel (c). Geometrically, even though the MAC and MD curves move by the same horizontal distance (which equals the distance between the *ex post* realized ys and the expected BAU emission $E(ys)$), the different slopes of the two curves mean that the vertical shifts of the two curves are different, leading to the welfare loss triangles of different sizes.

C Shape of $\Phi(\underline{s})$ and $1/\Phi(\underline{s})$

From (11), it is easy to see that $\Phi = 1$ when $\underline{s} = 0$. By taking derivative of Φ with respect to \underline{s} , we obtain

$$\frac{d\Phi}{d\underline{s}} \propto \text{Cov}(ys, y)\text{Var}(y)\underline{s}^2 - 2\text{Var}(ys)\text{Var}(y)\underline{s} + \text{Cov}(ys, y)\text{Var}(ys). \quad (32)$$

Since the right hand side is quadratic in \underline{s} , we know there are at most two roots in equation $d\Phi/d\underline{s} = 0$, \hat{s}_1 and \hat{s}_2 , with $\hat{s}_2 \geq \hat{s}_1 \geq 0$, given by

$$\hat{s}_1 = \frac{\text{Var}(ys)}{\text{Cov}(ys, y)} \left(1 - \sqrt{1 - \rho_{ys,y}^2}\right), \quad \hat{s}_2 = \frac{\text{Var}(ys)}{\text{Cov}(ys, y)} \left(1 + \sqrt{1 - \rho_{ys,y}^2}\right)$$

where $\rho_{ys,y} = \text{Cov}(ys, y)/\sqrt{\text{Var}(ys)}\sqrt{\text{Var}(y)}$ is the correlation coefficient of GDP y and BAU emission ys . Further,

$$\frac{d\Phi}{d\underline{s}} \begin{cases} < 0 & \text{if } \hat{s}_1 < \underline{s} < \hat{s}_2 \\ \geq 0 & \text{if } \underline{s} \leq \hat{s}_1 \text{ or } \underline{s} \geq \hat{s}_2 \end{cases} \quad (33)$$

It is straightforward to show that $\bar{s} \leq \hat{s}_2$ since $\rho_{ys,y} \leq 1$ (and $\bar{s} = \hat{s}_2$ if y and s are independent). By taking the inverse of $\Phi(\underline{s})$, we obtain the shape of $1/\Phi(\underline{s})$ in Figure 2.

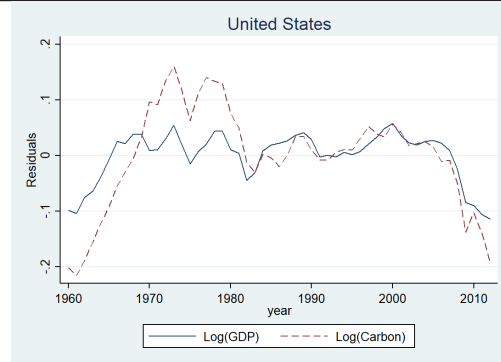
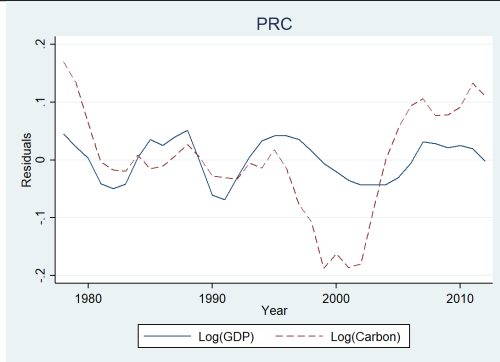
D Estimation Results of the GDP and Carbon Equations

The tables that follow show the estimation results and standard errors (in brackets) of the Log(GDP) and Log(Carbon) equations, and the figures graph the residuals of the two equations, for the 12 nations. Almost all of the variables are significant at 1% level (represented by ***), and one is significant at 5% level, (represented by **). As expected, the residuals demonstrate positive correlations between GDP and CO₂ emission for all countries.

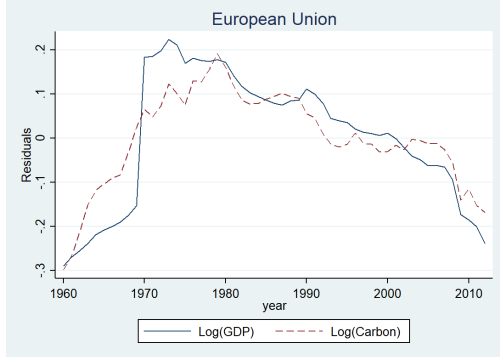
The models are estimated using annual GDP and CO₂ data from 1960 to 2012, except that

PRC's data range is 1978 – 2012 (that is, after the start of its economic reform), and Russian Federation's data range is 1989 – 2012 (that is, after the collapse of the Soviet Union).

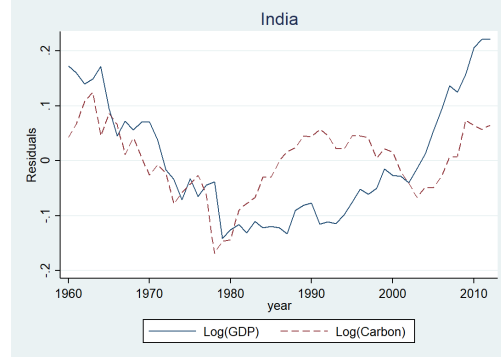
PRC			United States		
	Log(GDP)	Log(Carbon)		Log(GDP)	Log(Carbon)
year	0.095*** (0.001)	0.056*** (0.002)	year	0.031*** (0.000)	0.011*** (0.001)
_cons	-176.072*** (1.184)	-104.259*** (3.088)	_cons	-45.949*** (0.808)	-13.407*** (1.647)
<i>N</i>	35	35	<i>N</i>	53	53
r2	0.999	0.976	r2	0.991	0.775



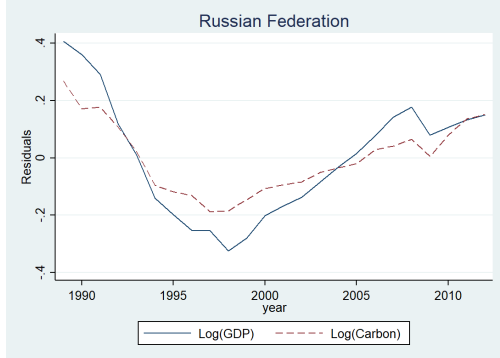
European Union		
	Log(GDP)	Log(Carbon)
year	0.033*** (0.001)	0.003*** (0.001)
_cons	-50.616*** (2.728)	1.379 (1.948)
N	53	53
r2	0.921	0.197



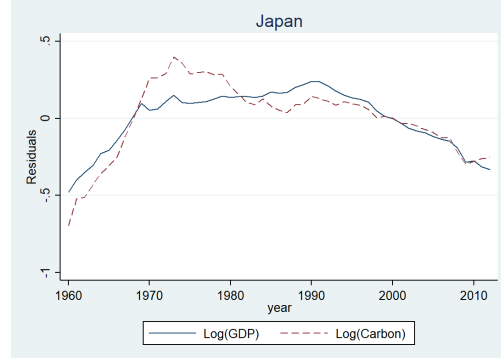
India		
	Log(GDP)	Log(Carbon)
year	0.049*** (0.001)	0.054*** (0.001)
_cons	-85.122*** (1.951)	-101.717*** (1.131)
N	53	53
r2	0.980	0.994



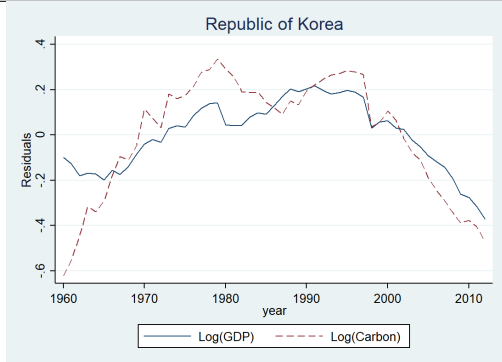
Russian Federation		
	Log(GDP)	Log(Carbon)
year	0.016** (0.006)	-0.011*** (0.004)
_cons	-19.364 (12.416)	28.915*** (7.559)
N	24	24
r2	0.241	0.269



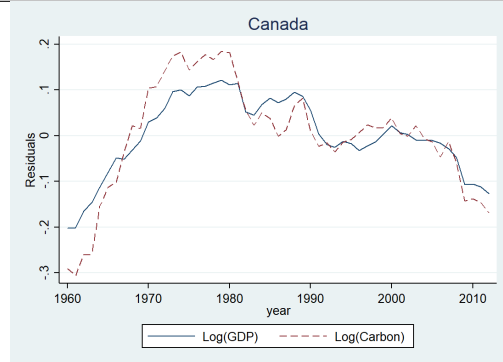
Japan		
	Log(GDP)	Log(Carbon)
year	0.035*** (0.002)	0.024*** (0.002)
_cons	-54.942*** (3.410)	-40.513*** (4.375)
N	53	53
r2	0.891	0.696



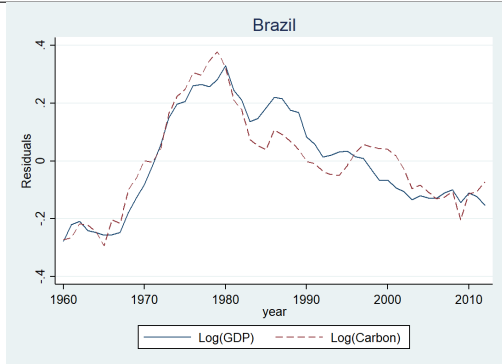
Republic of Korea		
	Log(GDP)	Log(Carbon)
year	0.077*** (0.001)	0.072*** (0.002)
_cons	-140.851*** (2.764)	-138.115*** (4.701)
<i>N</i>	53	53
<i>r</i> ²	0.984	0.948



Canada		
	Log(GDP)	Log(Carbon)
year	0.032*** (0.001)	0.018*** (0.001)
_cons	-49.439*** (1.524)	-29.537*** (2.201)
<i>N</i>	53	53
<i>r</i> ²	0.971	0.836



Brazil		
	Log(GDP)	Log(Carbon)
year	0.040*** (0.002)	0.041*** (0.002)
_cons	-66.337*** (3.129)	-76.339*** (3.009)
<i>N</i>	53	53
<i>r</i> ²	0.927	0.935



Mexico		
	Log(GDP)	Log(Carbon)
year	0.038*** (0.001)	0.041*** (0.002)
_cons	-62.231*** (2.458)	-76.764*** (3.463)
<i>N</i>	53	53
<i>r</i> ²	0.948	0.917

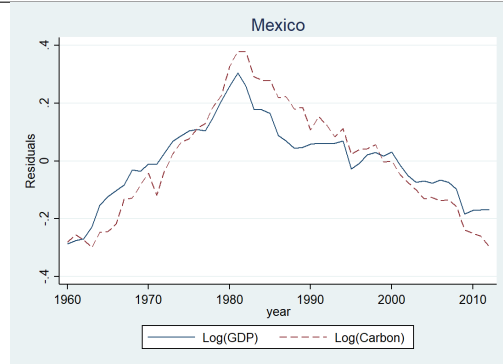
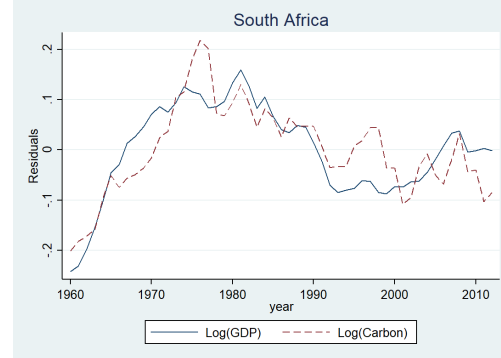
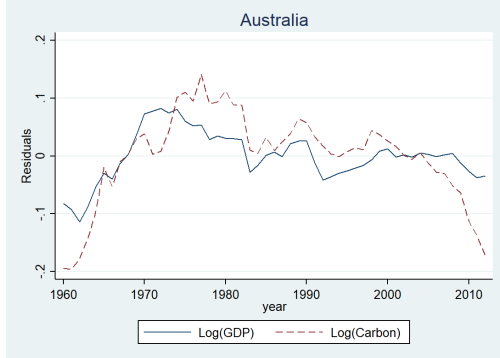


Table 4: Point Estimates of the GDP-CO₂ Variance-Covariance Matrices

Nation	Var(y)	Var(ys)	Cov(ys, y)
PRC	$2.22e + 9$	$1.95e + 5$	$1.19e + 7$
United States	$2.11e + 11$	$1.58e + 5$	$1.37e + 8$
European Union	$1.61e + 12$	$1.60e + 5$	$4.04e + 8$
India	$5.31e + 9$	$1.80e + 3$	$1.94e + 6$
Russian Federation	$1.92e + 10$	$5.15e + 4$	$3.04e + 7$
Japan	$4.08e + 11$	$3.43e + 4$	$1.00e + 8$
Republic of Korea	$1.66e + 10$	$1.16e + 4$	$1.37e + 7$
Canada	$3.20e + 9$	$1.88e + 3$	$2.19e + 6$
Brazil	$7.79e + 9$	$9.33e + 2$	$2.37e + 6$
Mexico	$5.32e + 9$	$3.03e + 3$	$3.90e + 6$
Australia	$1.54e + 8$	$3.61e + 2$	$1.76e + 5$
South Africa	$1.51e + 8$	$3.47e + 2$	$1.50e + 5$

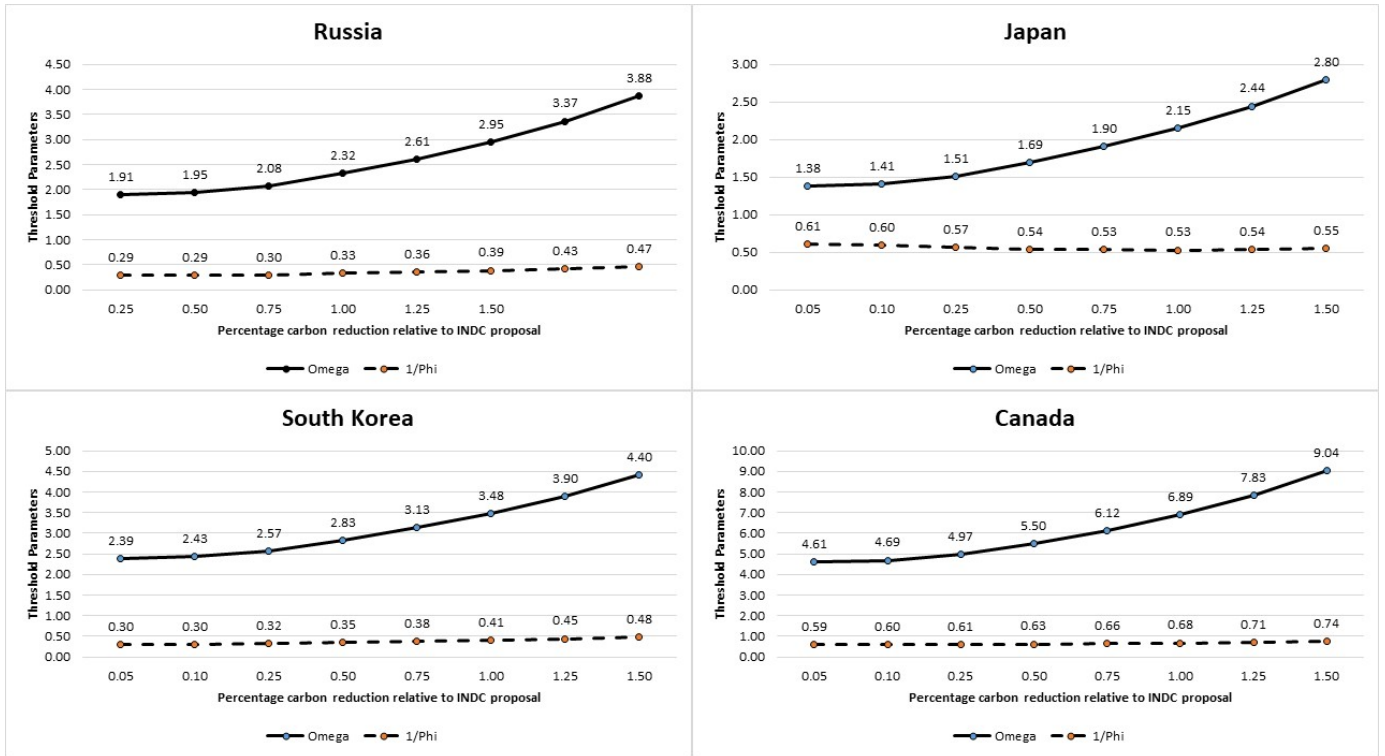
Australia			South Africa		
	Log(GDP)	Log(Carbon)		Log(GDP)	Log(Carbon)
year	0.034*** (0.000)	0.028*** (0.001)	year	0.027*** (0.001)	0.024*** (0.001)
_cons	-54.403*** (0.786)	-50.632*** (1.430)	_cons	-41.351*** (1.665)	-42.263*** (1.635)
N	53	53	N	53	53
r2	0.993	0.968	r2	0.953	0.943



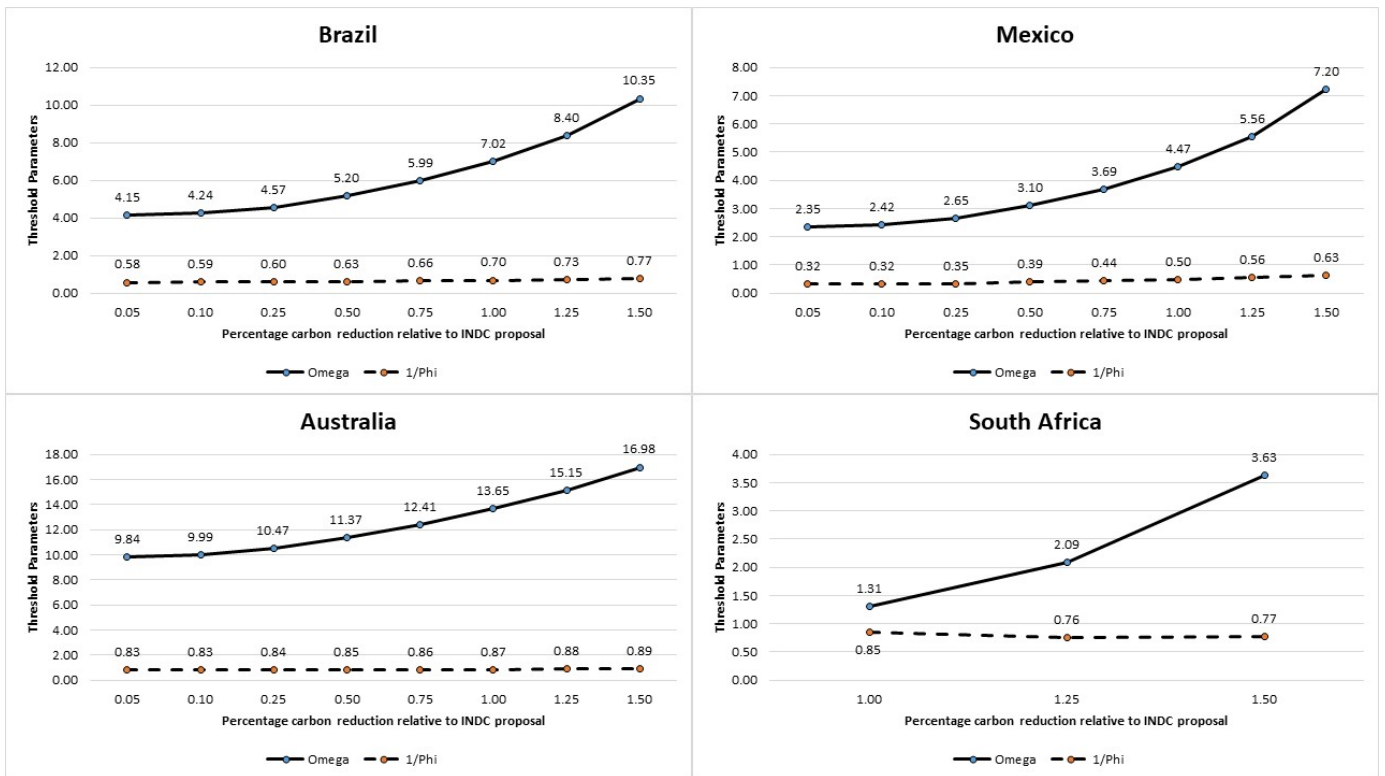
The following table contains the estimated values of the variances of GDP and carbon emissions, as well as their covariance, for each of the 12 nations.

E Details of Robustness Check

Figure 6 supplements Figure 4 and shows, for each of the remaining eight nations, how the estimated threshold parameters $\widehat{1/\Phi}$ and $\widehat{\Omega}$ would change as the committed reductions in GO_2 emission are varied relative to the INDC commitment. The pattern of the dependence is similar to those in Figure 4: as the targets are strengthened (by up to 50%), $\widehat{\Omega}$ tends to increase, making it more likely that the intensity target dominates the quantity target, while $\widehat{1/\Phi}$ slightly increases for all but Japan and South Africa, for which the change is non-monotonic. If the INDC emission reduction targets are not completely achieved, then $\widehat{\Omega}$ decreases but is still higher than 1 even when only 25% of the INDC targets are achieved. These results demonstrate the robustness of our conclusion that the intensity targets dominate the quantity targets for most nations.



(a)



(b)

Figure 6: Threshold Values for Under- and Over-Achieved Targets

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