# ECONOMIC SIZE AND THE SCOPE OF CONTROL OVER GREENHOUSE GAS EMISSIONS

Peter Kennedy
Department of Economics
University of Victoria

18 March 2016

**ABSTRACT**

I examine the implications of variance and skewness in the distribution of GDP for the properties of the non-cooperative equilibrium in greenhouse gas emissions. The key consequence of these features of the GDP distribution is that some countries have much greater *scope of control* over global emissions than others. This has a number of interesting implications. First, global emissions are decreasing in the variance of the GDP distribution but emissions for an individual country of any given GDP are increasing in that variance. Second, the scope-of-control effect on technology choices underlies a technique effect that can produce an environmental Kuznets curve across countries. Third, very large countries may *under-emit* relative to the first-best solution as a best response to the high-emissions-technology choices made by smaller countries. Fourth, the prospects for cooperative action – as determined by the potential gains from trade available from emissions trading – are increasing in the skewness of the GDP distribution because of the large induced asymmetry in marginal abatement costs across countries in the non-cooperative equilibrium.

## 1. INTRODUCTION

One of the most striking features of the climate change problem is the skewness in the distribution of emissions. The three largest emitters – China, the US and the EU – accounted for around 57% of global emissions in 2010. [1] In comparison, the median emitter accounted for just 0.023% of the global total. This skewness in the distribution of emissions is in turn explained primarily by skewness in the distribution of GDP. The three largest economies – the EU, the US and China – accounted for 60% of global GDP in 2010 while the median economy accounted for just 0.026%.

These features of the global economy mean that the vast majority of countries are effectively powerless to affect unilaterally the global emissions that cause their climates to change. The median emitter could reduce its emissions to zero and still see no meaningful reduction in the climate change it faces. The same is true for most emitters outside the top three. In contrast, significant reductions by China, the US or the EU would have a substantial affect on future climate change. This dramatic asymmetry in the scope of control over global emissions has important implications for the strategic interaction among countries in the non-cooperative equilibrium. Relative to a setting in which all countries are the same, the smallest emitters have a much weaker incentive to reduce emissions, while the largest emitters have a much stronger incentive to do so. Thus, global emissions depend not only on aggregate GDP but on how that GDP is distributed across countries.

The purpose of this paper is to explore the implications of this scope-of-control asymmetry in the context of a model that is simple enough to allow the derivation of closed-form solutions but nonetheless flexible enough to allow unrestricted variation across countries in terms of GDP, vulnerability to climate change, and marginal abatement costs.

I focus on three issues of interest. First, I examine how the properties of the GDP distribution affect global emissions in the non-cooperative equilibrium (NCE), and the distribution of those emissions across countries. I show that aggregate emissions are declining in the variance of the GDP distribution, and that emissions for a country of any given size are increasing in that variance, in a manner that also depends on the skewness of the distribution. I also show that scope-of-control asymmetry across countries can generate an environmental

[1] The source of all data cited in this paper is the World Bank's *World Development Indicators 2013*. GDP is calculated in current US dollars. All data is for 2010, the most recent year for which comprehensive and reliable cross-country data is available at the time of writing.

Kuznets curve (EKC) in the cross-country relationship between GDP and emissions. I then explore how variation across countries with respect to climate-change vulnerability and country-specific abatement-cost factors can affect these equilibrium relationships.

Second, I examine how the properties of the GDP distribution affect the relationship between the first-best solution (FBS) and the NCE. I show that the extent to which a country emits too much in the NCE (relative to the FBS) depends critically on its position in the GDP distribution, and that the largest economies potentially *under-emit* in the NCE. I then show that variation across countries with respect to vulnerability can weaken (or strengthen) these GDP-related results if vulnerability is negatively (or positively) correlated with economic size.

Third, I explore the implications of asymmetric scope of control for the prospects for *cooperative* action among countries, as determined by the potential gains from trade available from emissions trading. I examine the relationship between country characteristics and the direction of transfers under emissions trading, and show that the smallest, least vulnerable economies are most likely to gain from trading when initial allowances are based on NCE emissions. I then show that aggregate gains from trade are increasing in the skewness of the GDP distribution.

In the literature on climate change to date, the properties of the GDP distribution, and its implications for strategic interaction among countries, has received surprisingly little attention. Other aspects of cross-country heterogeneity have been widely explored. For example, Copeland and Taylor (1995) provide a seminal analysis of the role of differences in income *per capita* – and the implications for trade – in transboundary pollution flows. In a related vein, the EKC hypothesis that relates income *per capita* to pollution [Grossman, and Krueger (1995)], was extended to transboundary pollutants early in its development [Holtz-Eakin and Selden (1995)]. However, EKC models to date have not explored the implications of heterogeneity with respect to absolute economic size in a setting with strategic interaction among countries.

In contrast, asymmetry across countries with respect to abatement cost and vulnerability to damage has been studied extensively in the literature on non-cooperative abatement and cooperative treaty formation. Barrett (2003) provides a comprehensive synthesis of this work. More recent work has also examined the implications of heterogeneity with respect to abatement cost and vulnerability for the abatement-adaptation mix in a strategic setting. [Barrett (2008), Ebert and Welsch (2012), and Buob and Stephan (2013)]. This type of heterogeneity is in turn often related back to asymmetry with respect to income *per capita*.

While differences in income *per capita* are clearly germane to many aspects of the climate-change problem, these differences alone do not explain much of the variation across countries with respect to *absolute* emissions (see Section 2 below), and absolute emissions are the ultimate source of damage. In this particular respect, economic size is much more important than income *per capita*. In view of the extreme asymmetry manifest in the GDP distribution, it therefore makes sense to focus on heterogeneity with respect to economic size as a shaping force of the strategic interaction across countries in practice.

To my knowledge, the only existing papers that consider the implications of economic size for scope of control over emissions are Kennedy (2014) and Farnham and Kennedy (2014). The first of these papers examines cooperative agreements among heterogeneous countries; the second examines the implications of heterogeneity for the welfare impacts of adaptation. In this paper I take the basic model used in those papers and explore in more detail how the properties of the distribution of GDP determine some key aspects of the climate change game between countries.

The rest of my paper is organized as follows. Section 2 presents data that highlights key properties of the distribution of emissions and the distribution of GDP that motivate the focus of the paper. Section 3 presents the theoretical model, and Section 4 derives the FBS. Section 5 then characterizes the NCE, and derives results on the role of variance and skewness in the GDP distribution, and the impact of GDP-heterogeneity on the relationship between the NCE and the FBS. Section 6 examines the role of variance and skewness on the prospects for cooperative action supported by emissions trading. Section 7 provides some concluding remarks. An Appendix contains derivations and proofs not included in the main text.

## 2. THE DISTRIBUTION OF EMISSIONS AND OUTPUT

This section presents some data to highlight the variance and skewness in the distribution of emissions and the distribution of GDP. Figure 1 plots the logarithm (base 10) of percentage emissions shares against the logarithm of percentage GDP shares for 153 economies in 2010. The 27 countries of the EU (in 2010) are treated as comprising a single economy in view of their coordinated climate change policies. The graph is presented in logarithmic terms because the skewness of both distributions is so extreme that only a few data points would otherwise be distinguishable from a mass of points clustered near the origin. In reading the graph, recall that $\log_{10}(100) = 2$ and that $\log_{10}(0.01) = -2$.

The figure conveys three key messages. First, a handful of big economies account for the bulk of emissions. The biggest three emitters – China, the US and the EU – together account for 57% of the global total. The top ten emitters as a group account for 79% of the total, and the next ten account for another 11%. The bottom 50% of emitters together account for just 0.53% of global emissions. The emissions share of the median emitter is 0.023%.

Second, the distribution of GDP is also highly skewed. The biggest three economies – the EU, the US and China – together account for 60% of global output. The top ten economies as a group account for 83% of the total, and the next ten account for another 8%. The bottom 50% of economies together account for just 0.71% of global GDP. The GDP share of the median economy is 0.026%.

Third, there is a strong positive correlation between emissions shares and GDP shares. Other country-specific factors are also clearly at play since GDP variation does not account for all of the variation in emissions, and some of these factors (such as abatement costs and vulnerability to damage) are likely related to income *per capita*. However, variation in income *per capita* alone cannot explain much of the variation in emissions shares, as evident from Figure 2. The figure plots the logarithm of percentage emissions shares against the logarithm of GDP *per capita*. It is clear from Figures 1 and 2 together that absolute economic size is the more important explanatory variable.

Overall, the data indicate that the key properties of the emissions distribution are driven overwhelmingly by the properties of the GDP distribution. The variance and skewness of this distribution in turn creates a dramatic asymmetry between large and small economies in terms of their scope of control over global emissions. It is this asymmetry that motivates the modeling approach here.

## 3. THE MODEL

Let $y_i > 0$ denote the economic output of country *i* (as measured by its GDP). Aggregate output is $Y = \sum_i^n y_i$ , where *n* is the number of countries. Emissions from country *i* are denoted $e_i$.

These emissions are a function of $y_i$ and the production-technologies used in country *i*. Those technologies collectively imply an emissions-intensity for country *i* as a whole, denoted $(1-x_i)\in[0,1]$. Hence,

(1) $$e_i = (1-x_i)y_i$$

The cost of producing output $y_i$ in country *i* is

(2) $$c(y_i, x_i, \gamma_i) = \left(\frac{x_i^2}{\gamma_i}\right)y_i$$

where $\gamma_i > 0$ is the idiosyncratic "cost parameter" for country *i*, reflecting such factors as *per capita* GDP, economic composition, fossil fuel deposits and other geographic characteristics (all of which may in turn be inter-related). Note that production cost is increasing and strictly convex in the cleanliness of the technologies used but linear in output. I later consider the possibility that $\gamma_i$ and $y_i$ are correlated.

Global emissions are denoted

(3) $$E = \sum_{i=1}^{n} e_i$$

and the associated damage to country *i* is

(4) $$d(y_i, \delta_i, E) = \delta_i y_i E^2$$

where $\delta_i > 0$ is the idiosyncratic "damage parameter" for country *i*, as determined by the same sort of country-specific factors that determine $\gamma_i$, as described above. I later consider the possibility that $\delta_i$ and $y_i$ are correlated.

The damage function in (4) has two noteworthy properties. First, damage is strictly convex in global emissions. This is a standard assumption in the literature and is best viewed as an imperfect but convenient way of capturing certain stock-pollutant aspects of the climate change problem that would otherwise have to be dealt with in a fully specified dynamic model. Its key implication is that emissions are strategic substitutes in the non-cooperative game among countries.

Second, climate-related damage to any particular country is linear in its GDP. This reflects the fact that damage rises with the scale of economic activity affected by adverse climate-related events. For example, crop losses from a prolonged drought of any given severity are more-or-less proportional to the size of the crop affected. Similarly, extreme weather events that disrupt power grids and transportation links have larger absolute impacts when they affect a larger scale of industrial activity. Note that this does not imply that larger economies necessarily suffer more damage overall; idiosyncratic factors underlying the size of $\delta_i$ are also clearly important.

It will prove useful to define two summary variables based on $\{\delta_i\}$ and $\{\gamma_i\}$ that play a key role in the analysis that follows. Let $w_i = y_i / Y$ denote the global GDP-share for country $i$. Then the weighted-average values for the cost and damage parameters across countries are

(5) $$\bar{\gamma} = \sum_{i=1}^{n} w_i \gamma_i$$

and

(6) $$\bar{\delta} = \sum_{i=1}^{n} w_i \delta_i$$

respectively. Note that if all countries are identical with respect to their cost and damage parameters (that is, if $\gamma_i = \gamma \ \ \forall i$ and $\delta_i = \delta \ \ \forall i$ ) then $\bar{\gamma} = \gamma$ and $\bar{\delta} = \delta$. This artificial special case will sometimes prove useful to highlight the specific importance of heterogeneity with respect to GDP.

**4. THE FIRST-BEST SOLUTION**

The FBS minimizes total global cost, defined as the sum of production cost and damage, aggregated across all countries:

(7) $$\min_{\{x\}} \sum_{i=1}^{n} \left( \frac{x_i^2 y_i}{\gamma_i} + \delta_i y_i \left[ \sum_{j=1}^{n} (1 - x_j) y_j \right]^2 \right)$$

The solution to this problem potentially requires some countries to adopt zero-emission technologies. In the Appendix I show that the set of countries whose technologies generate strictly positive emissions in the FBS is $P = \{ i \mid \gamma_i < \gamma^+ \}$ where

(8) $$\gamma^+ = \bar{\gamma}_P + \frac{1}{\bar{\delta} Y Y_P}$$

and where $Y_P = \sum_{i\in P} y_i$ and $\bar{\gamma}_P = \sum_{i\in P} \gamma_i y_i / Y_P$. Note that (8) is not a closed-form solution; the actual set of countries with positive emissions depends on the specific distribution of $\{y_i\}$ and $\{\gamma_i\}$. However, (8) tells us that countries are partitioned into two groups on the basis of $\gamma_i$: low-$\gamma$ countries have positive emissions, while high-$\gamma$ emissions have zero emissions. (Recall that a high value of $\gamma_i$ implies a low cost). Note that at least one country must have positive emissions in the FBS: $\gamma^+ \to \infty$ as $Y_P \to 0$.

Under what conditions do *all* countries have positive emissions? Setting $Y_P = Y$ and $\bar{\gamma}_P = \bar{\gamma}$ in $\gamma^+$, it follows that all countries have positive emissions in the FBS if and only if

$$(9) \qquad \gamma_i < \bar{\gamma} + \frac{1}{\bar{\delta} Y^2} \quad \forall i$$

I henceforth restrict attention to a setting where (9) holds.

Now consider the characteristics of the FBS in that setting. The solution to (7) prescribes a technology for country *i* given by (see the Appendix):

$$(10) \qquad x_i^{**} = \gamma_i \left( \frac{\bar{\delta} Y^2}{1 + \bar{\gamma} \bar{\delta} Y^2} \right)$$

Note that $x_i^{**}$ is proportional to $\gamma_i$: lower-cost countries use cleaner technologies in the FBS. Note too that $x_i^{**}$ is independent of both $y_i$ and $\delta_i$ – except in so far as theses variables affect aggregate variables – because the damage done by the emissions from any given country is *global* in scope.

Given the technologies prescribed by (10), emissions for country *i* are

$$(11) \qquad e_i^{**} = y_i \left( 1 - \gamma_i \frac{\bar{\delta} Y^2}{1 + \bar{\gamma} \bar{\delta} Y^2} \right)$$

and global emissions are

$$(12) \qquad E^{**} = \frac{Y}{1 + \bar{\gamma} \bar{\delta} Y^2}$$

Taking the ratio of (11) and (12) yields the share of global emissions for country *i* in the FBS. After some manipulation this reduces to

$$(13) \qquad \frac{e_i^{**}}{E^{**}} = w_i [1 - (\gamma_i - \bar{\gamma}) \bar{\delta} Y^2] \quad \forall i$$

This tells us that if all countries have the same cost parameter then the emissions share for country *i* is simply equal to its share of global output (since the term in the inner-brackets reduces to zero in that case). However, if countries differ on the basis of their cost parameters, and country *i* has a cost-parameter greater than the weighted-average across countries, then its share of global emissions is *less* than its share of global GDP. The converse is true for a low-$\gamma$ country. This reflects the fact that a low-$\gamma$ country has a higher marginal cost of using cleaner technologies, and is therefore allowed to emit more than its GDP-based share of emissions in the FBS. The converse is true for a high-$\gamma$ country.

## 5. THE NON-COOPERATIVE EQUILIBRIUM

In the NCE, the policy-maker in country *i* chooses a technology that minimizes the sum of domestic production cost and domestic damage:

(14) $$\min_{x_i} \frac{x_i^2 y_i}{\gamma_i} + \delta_i y_i [(1 - x_i) y_i + E_{-i}]^2$$

where $E_{-i}$ denotes aggregate emissions from all countries other than country *i*. Solving (14) yields a technology choice for country *i* as a function of global emissions:

(15) $$x_i(E) = \gamma_i \delta_i y_i E$$

Using (1) and setting $E = e_i + E_{-i}$, (15) can be expressed as a best-response function in terms of domestic emissions:

(16) $$e_i(E_{-i}) = \frac{y_i - \gamma_i \delta_i y_i^2 E_{-i}}{1 + \gamma_i \delta_i y_i^2}$$

This tells us that emissions for country *i* are declining in $E_{-i}$: emissions are strategic substitutes. This property of the best-response function (standard in most models of climate change), stems directly from the strict convexity of the damage function with respect to aggregate emissions.[2]

From (15), it is straightforward to solve for equilibrium global emissions (see the Appendix for the details):

(17) $$E^* = \frac{Y}{1 + \phi Y^2}$$

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[2] Interesting exceptions include Golombek and Hoel (2004) who argue that technology spillovers across countries could mean that emissions are strategic complements, and Ebert and Welsch (2011) who show that adaptation – as a substitute for abatement – can also cause emissions to be strategic complements.

where

(18) $$\phi = \sum_{j=1}^{n} \gamma_j \delta_j w_j^2$$

Substituting (17) into (15) yields the equilibrium technology choice for country *i*,

(19) $$x_i^* = \gamma_i \delta_i y_i \left( \frac{Y}{1+\phi Y^2} \right)$$

and substituting (19) into (1) yields equilibrium emissions for country *i*:

(20) $$e_i^* = y_i - \left( \frac{Y}{1+\phi Y^2} \right) \gamma_i \delta_i y_i^2$$

*5.1 The Scope-of-Control Effect*

Expression (19) tells us that the cleanliness of technologies used by country *i* in the NCE is increasing in $y_i$, $\delta_i$ and $\gamma_i$. The roles of $\delta_i$ and $\gamma_i$ are clear: greater domestic damage and lower abatement costs both motivate a lower level of emissions for any given level of GDP.

The role of $y_i$ is more nuanced, and relates specifically to a scope-of-control effect. In gross terms, economic size plays three roles in its impact on technology choices here. First, emissions cause greater absolute damage for a high-GDP country. Second, the aggregate cost of production, using any given technology, is also rising in $y_i$. These two forces are mutually offsetting in this model. In particular, $y_i$ can be taken outside the maximand in (14), leaving only its role in the emissions function as a determinant of the technology choice:

(21) $$y_i \left( \frac{x_i^2}{\gamma_i} + \delta_i [(1-x_i)\boldsymbol{y_i} + E_{-i}]^2 \right)$$

That remaining role of $y_i$ arises because higher-GDP countries generate more emissions for any given set of technologies used. Critically, this means that higher-GDP countries have greater control over global emissions – and hence, over the environmental damage they suffer – than do smaller-GDP countries. This in turn means that higher-GDP countries have more incentive to adopt cleaner technologies. In contrast, it is clear from (21) that most of the damage suffered by a small economy is determined by $E_{-i}$, and this is beyond its control. Thus, small economies have little incentive to adopt cleaner technologies in the non-cooperative equilibrium.

This asymmetric scope of control across countries – and its impact an incentives to adopt cleaner technologies – has a number of interesting implications for the properties of the NCE. The first of these is the role of variance in the GDP distribution.

*5.2 The Role of Variance in the GDP Distribution*

Consider the special case where $\delta_i = \delta \quad \forall i$ and $\gamma_i = \gamma \quad \forall i$ . In that case, $\phi$ reduces to

(22) $$\phi_0 = \gamma\delta\sum_{j=1}^{n} w_j^2 = \gamma\delta\left(\frac{1}{n} + n\sigma^2\right)$$

where $\sigma^2$ is the variance of $\{w_i\}$ and $1/n$ is its mean. Making this substitution in (17) yields equilibrium global emissions for this special case:

(23) $$E^* = \frac{nY}{n + \gamma\delta(1 + n^2\sigma^2)Y^2}$$

The following proposition highlights the role of $\sigma^2$ here.

**PROPOSITION 1**. If $\delta_i = \delta \quad \forall i$ and $\gamma_i = \gamma \quad \forall i$ then global emissions are decreasing in $\sigma^2$ .

This result stems directly from the scope-of-control effect. A single large economy is able to control – through its technology choices – a greater fraction of the global emissions that damage its climate than a collection of smaller economies with the same aggregate output can do (when acting non-cooperatively). A mean-preserving spread of the distribution pushes more countries into the upper tail of the distribution, where there are greater returns from cleaner technology adoption. It also pushes more countries into the lower tail of the distribution but these countries are small contributors to global emissions anyway, due to their small GDPs. Thus, an increase in variance leads to a decline in aggregate emissions.

Proposition 1 tells us that if aggregate GDP was distributed evenly over all countries then equilibrium emissions would be higher than under a distribution with a mix of large and small economies. It also tells us something about how emissions might evolve over time as global output grows. In particular, consider a setting where all economies are growing at the same rate. In that case, $\sigma^2$ remains unchanged as $Y$ grows. If $\delta$ and $\gamma$ are also time-invariant then global emissions reach a turning point when global output reaches

(24) $$\hat{Y} = \left( \frac{n}{\gamma\delta(1+n^2\sigma^2)} \right)^{\frac{1}{2}}$$

This turning-point level for global output is decreasing in $\sigma^2$.

**PROPOSITION 2**. If $\delta_i = \delta \;\; \forall i$ and $\gamma_i = \gamma \;\; \forall i$ then emissions from any individual country with given GDP are increasing in $\sigma^2$.

*Proof*. Substitute $\phi = \phi_0$ from (22) in (20) and differentiate with respect to $\sigma^2$.

This result reflects the fact that emissions are strategic substitutes. A reduction in aggregate emissions due to an increase in the variance of GDP causes a country of any given economic size – fixed in the GDP distribution – to *raise* its own emissions. This means that the behaviour of any given country depends critically on the specific distribution of global GDP.

It is important to stress that Propositions 1 and 2 are based on the special case where countries are identical with respect to their damage and cost parameters. If instead these parameters differ across countries – as seems likely in practice – then whether or not these results continue to hold depends on the extent to which damage parameters and cost parameters are correlated with GDP. In particular, if $\delta_i$ and $\gamma_i$ are both negatively correlated with $y_i$, then a mean-preserving spread that pushes more countries into the upper tail of the GDP distribution may not necessarily cause global emissions to fall: the impact of reduced values for $\delta_i$ and $\gamma_i$ could in principle offset the scope-of-control effect. Conversely, if $\delta_i$ and $\gamma_i$ are both positively correlated with $y_i$ then the forces behind Propositions 1 and 2 are strengthened.

Whether or not strong correlations of this type exist in practice is ultimately an empirical question, but it is useful to consider some of the potential channels through which these correlations might arise. First, large economies are better placed to exploit any economies of scale that might exist in adaptation measures, thereby reducing the net damage they incur. To the extent that large economies also tend to occupy large and diverse geographic areas, these economies may also have more flexibility to adjust to climate change than smaller economies. These linkages suggest that $\delta_i$ and $y_i$ could be negatively correlated. At the same time, large economies are best-positioned to exploit any economies of scale in the development and adoption of cleaner technologies, and countries with large and diverse land bases may have the best opportunities to pursue alternatives to fossil fuels in energy provision. These linkages suggest that $\gamma_i$ and $y_i$ could be positively correlated. Thus, the overall implications for whether Propositions 1 and 2 are strengthened or weakened by these potential correlations are mixed, and there seems no reason to believe that the role of variance in the distribution would be diminished in any systematic way.[3]

*5.3 Implications for an Environmental Kuznets Curve*

The special case where $\delta_i = \delta \;\; \forall i$ and $\gamma_i = \gamma \;\; \forall i$ also usefully highlights the role of the scope-of-control effect in the relationship between output and emissions across countries. In that special case, the coefficients on the income variables in (20) are the same for all countries, and so equilibrium emissions exhibit an environmental Kuznets curve (EKC): an inverted U-shaped relationship between output and emissions.

In general, an EKC reflects the opposing forces of *scale* and *technique* effects as output rises. The scale effect is driven by simple arithmetic: emissions rise as output rises for any given technology. The technique effect captures the subtler proposition that countries adopt increasingly cleaner technologies as output grows. The EKC hypothesis posits that on balance, these two effects produce an inverted U-shaped relationship between output and emissions.

The literature to date has proposed two main theories behind a technique effect: a preference-based explanation in which demand for environmental quality rises as income *per capita* grows; and a cost-based explanation that assumes increasing returns to abatement.[4] The technique effect in my model has a different source altogether, and it is specific to transboundary pollutants. It derives from the fact that higher-GDP countries have greater control over global emissions than do smaller-GDP countries, and hence have more incentive to adopt cleaner technologies.

[3] Many factors that affect damage and abatement cost may be more closely related to GDP *per capita* than to economic size *per se*. However, big countries are not necessarily rich, and small countries are not necessarily poor, so these factors are unlikely to have significant implications for Propositions 1 and 2.

[4] See Copeland and Taylor (1994) for an example of former, and Andreoni, and Levinson (2001) for an example of the latter.

The existing empirical evidence for an EKC is mixed, and appears to be especially weak in the context of greenhouse gas emissions.[5] There are many things that could account for that weakness – including the possibility that technique effects are in fact a fiction – but it may be very difficult to observe an over-arching relationship between emissions and output in the data even if one actually exists, due to uncontrolled variation across countries with respect to other key determinants. In the context of my model, heterogeneity with respect to $\delta_i$ and $\gamma_i$ could easily obscure the cross-section relationship between emissions and income predicted by (20) above. An EKC may even be difficult to observe in time series data for a single country if $\delta_i$ and $\gamma_i$ are not stable over time. With respect to $\delta_i$ in particular, information about the climate-related consequences of emissions continues to evolve, and this means that historical data may be a poor predictor of current and future relationships between emissions and output. Thus, while an obvious EKC may not show up in the data, the technique effects that motivate theoretical EKC relationships may nonetheless be very important in practice.

*5.4 The NCE in Relation to the FBS*

Recall from Section 4 above that neither $y_i$ nor $\delta_i$ are relevant for the emissions level of country *i* in the FBS (except in so far as they affect aggregate values) because damage from emissions from any given country is global. In contrast, $y_i$ and $\delta_i$ are both highly relevant to the emissions level of country *i* in the NCE because that country is concerned only about damage to itself. In this respect, the scope-of-control effect has important implications for how the NCE and the FBS differ across countries. That relationship is described in the following proposition.

**PROPOSITION 3**. In relation to the FBS solution,

(a) aggregate emissions in the NCE are too high if $n > 1$;

(b) emissions for country *i* in the NCE are too *low* if $w_i > \tilde{w}_i$, where

$$\tilde{w}_i = \frac{\bar{\delta}}{\delta_i}\left(\frac{1+\phi Y^2}{1+\bar{\gamma}\bar{\delta}Y^2}\right) \tag{25}$$

and too high otherwise.

[5] Studies focusing on global pollutants include Holtz-Eakin and Selden (1995), Cole *et. al.* (1997), Schmalensee *et. al.* (1998), Fonkych and Lempert (2005), and Aldy (2005). Lieb (2004) argues that on balance, the evidence for an EKC is weaker for global pollutants. See Wagner and Müller-Fürstenberger (2008) for a critical overview.

*Proof*. See the Appendix.

Part (a) of Proposition 3 is a standard result; it reflects the transboundary externality that is fundamental to the climate change problem. Part (b) of the proposition is novel. It tells us that equilibrium emissions for some economies could be *too low* relative to the FBS.

To understand this result, consider first the special case where $\delta_i = \delta \ \ \forall i$ and $\gamma_i = \gamma \ \ \forall i$. In that case, (25) reduces to

(26) $$\tilde{w}_0 = \frac{1 + \phi_0 Y^2}{1 + \gamma\delta Y^2}$$

where $\phi_0$ is given by (22) and repeated below for ease of reference:

(27) $$\phi_0 = \gamma\delta \sum_{j=1}^{n} w_j^2 = \gamma\delta\left(\frac{1}{n} + n\sigma^2\right)$$

Note that $\phi_0 < \gamma\delta$ (since $w_j < 1 \ \ \forall j$), so $\tilde{w}_0 < 1$. Thus, there can exist a large country for whom $w_i > \tilde{w}_0$. This country under-emits relative to the FBS. This possibility reflects the fact that a very large country within the GDP distribution has control over such a large share of global emissions – through its choice of technologies – that it can partly compensate for under-abatement by smaller countries by over-abating itself. Note that it does so purely out of self-interest.

It is clear from (26) that $\tilde{w}_0$ is increasing in $\sigma^2$. Thus, an under-emitting country is most likely to exist when $\sigma^2$ is small. On the other hand, if $\sigma^2 = 0$ then $w_j = 1/n \ \ \forall j$ and $\tilde{w}_0 > 1/n$, so no country can be large enough to under-emit. This apparent inconsistency with respect to the role of $\sigma^2$ arises because skewness also plays a key role here, but skewness cannot exist in a distribution without variance.

To understand this point, consider the following thought experiment. Imagine an artificial setting with a single large country whose global GDP share is equal to one, and $n-1$ identical small countries whose GDPs are all zero. This distribution has the largest possible variance of any distribution with $n$ elements and a mean of $1/n$. In this setting, the single large country emits the FBS level of emissions because there is no effective externality when only one country has a positive GDP. Now imagine drawing all of the small identical countries towards the mean, and reducing the GDP share of the large country so as to keep that mean unchanged. The variance of the distribution falls as a consequence but now there *does* exist an externality across countries, and the single large country now has an incentive to under-emit relative to the FBS. As convergence towards the mean continues, the single large country eventually becomes too small to be able to influence global emissions in a meaningful way, and so it becomes an over-emitter, along with each of the smaller countries. Thus, variance and skewness act jointly on the relationship between the NCE and the FBS.

Now return to the more general case where countries differ with respect to GDP *and* with respect to their damage parameters. It is clear from (25) that, *ceteris paribus*, a high-$\delta$ country is more likely to under-emit than a low-$\delta$ country. This reflects the fact that a country will exercise any scope of control it has over global emissions only if those emissions actually matter to it. Thus, a large but low-damage economy may over-emit, while a smaller but higher-damage economy may under-emit.

Note that differences across countries with respect to $\gamma$ play no role in (25), except in so far as these parameters affect aggregate values. This is because there is no difference between the private domestic cost and the global social cost of using cleaner technologies. It is only in the *benefits* of cleaner technology use – as determined by $w_i$ and $\delta_i$ – that the divergence between private and social values arises, because abatement is a global public good.

## 6. GAINS FROM TRADE AND THE POTENTIAL FOR COOPERATIVE ACTION

The literature on international environmental agreements highlights the key role that emissions trading can play in supporting a global treaty to reduce emissions. In the standard model (see Barrett (2001), for example), an aggregate cap is set for treaty members, and allowances are allocated across members, typically under a rule that relates allowances to NCE emission levels.[6] Allowances can then be traded among treaty members. Countries who purchase additional allowances transfer wealth to the countries who sell those allowances, and these transfers thereby allow the cooperative gains to be shared among treaty members. This sharing of gains can entice would-be free-riders to enter the treaty.

The potential to support cooperation in this way depends critically on the gains that can be realized from emissions trading. Those gains from trade in turn depend on the extent to which

[6] Treaty allowances in practice could be based on many factors but most theoretical analyses focus on “pragmatic” allowance rules [Altamirano-Cabrera and Finus (2006)] that relate allowances to existing emissions.

marginal abatement costs differ across countries in the NCE. In a setting with identical countries, there is no trading at all. In contrast, in a setting with widely heterogeneous marginal abatement costs, the gains from trade can be substantial

Imagine a setting in which a treaty initially caps aggregate emissions at the NCE level, and each country is assigned allowances equal to its existing NCE emissions. In the absence of income growth, every country would be willing to join such a treaty. Let *p* denote the trading price for allowances. Then the choice problem for country *i* is

$$(28) \qquad \min_{x_i} \frac{x_i^2 y_i}{\gamma_i} + \delta_i y_i (E^*)^2 - p(e_i^* - (1-x_i) y_i)$$

The solution to this problem is

$$(29) \qquad x_i(p) = \frac{p\gamma_i}{2}$$

and the corresponding emissions level for country *i* is

$$(30) \qquad e_i(p) = \left(1 - \frac{p\gamma_i}{2}\right) y_i$$

Aggregate emissions are

$$(31) \qquad E(p) = \left(1 - \frac{p\bar{\gamma}}{2}\right) Y$$

Setting $E(p) = E^*$ and solving for *p* then yields the equilibrium price of allowances:

$$(32) \qquad \hat{p} = \frac{2}{\bar{\gamma}} \left( \frac{\phi Y^2}{1 + \phi Y^2} \right)$$

At this price, emissions for country *i* are

$$(33) \qquad \hat{e}_i = \left(1 - \frac{\gamma_i}{\bar{\gamma}} \frac{\phi Y^2}{(1 + \phi Y^2)}\right) y_i$$

Note that emissions for country *i* are now independent of its own damage parameter. This reflects the fact that the level of aggregate emissions – and hence, damage to any country – is now fixed under the treaty. Moreover, the relationship between emissions and GDP is now linear, just as it is in the FBS; recall (11). Aggregate emissions are of course still too high relative to the FBS but that level of aggregate emissions is now achieved at least-cost globally. The associated cost savings constitute the gains from trade under the treaty. To calculate these gains from trade and their distribution across countries, let us first consider the pattern of trade.

**PROPOSITION 4**. Under an emissions trading program in which the initial allowance for each country is set equal to its NCE emissions, country *i* is a buyer (seller) of allowances if $w_i\delta_i > (<) \phi / \bar{\gamma}$ .

*Proof*. See the Appendix.

This tells us that large, high-damage economies are buyers of allowances. These countries therefore transfer wealth to small, low-damage countries via emissions trading. Why? Large, high-damage countries were using the cleanest technologies in the NCE, precisely because they are large (via the scope-of-control effect), and high-damage (which makes their scope of control worth exercising). In contrast, small, low-damage countries were using relatively dirty technologies in the NCE and so face relatively low marginal abatement costs relative to the price that can be earned by selling allowances.

*Skewness in the GDP Distribution and the Aggregate Gains from Trade*

The potential for a treaty to support cooperative action to *reduce* global emissions below the NCE level depends critically on the aggregate gains from trade that exist at the NCE. [Barrett (2001)]. The gains from trade (GFT) for country *i* is the difference between its domestic cost in the no-trade NCE and its domestic cost after trade, inclusive of net permit purchases. Making this calculation (see the Appendix) yields

$$(34) \qquad GFT_i = y_i \gamma_i (YE^*)^2 \left( w_i \delta_i - \frac{\phi}{\bar{\gamma}} \right)^2$$

Note that $GFT_i > 0$ for any country that trades allowances (whether as a buyer or seller).

Summing across countries then yields aggregate gains from trade under the treaty:

$$(35) \qquad \sum_{j=1}^{n} GFT_j = Y^3 (E^*)^2 \left( \sum_{j=1}^{n} \gamma_i \delta_i^2 w_i^3 - \frac{\phi^2}{\bar{\gamma}} \right)$$

To focus on the specific importance of the GDP distribution here, consider again the special case where $\gamma_i = \gamma \ \ \forall i$ and $\delta_i = \delta \ \forall i$ . Imposing these conditions, and making the substitution for $E^*$ from (23), yields an expression for aggregate gains from trade in terms of the *skewness* of $\{w_i\}$, denoted $\theta$ (see the Appendix):

(36) $$\sum_{j=i}^{n} GFT_j = (1 - n^2\sigma^2 + n\sigma\theta)\left(\frac{Y^5\gamma\delta^2 n^2\sigma^2}{[n + \gamma\delta Y^2(1 + n^2\sigma^2)]^2}\right)$$

The following result then follows directly from (36).

**PROPOSITION 5**. Under an emissions trading program in which the initial allowance for each country is set equal to its NCE emissions, aggregate gains from trade are increasing in the skewness of the distribution of global GDP shares.

Why? A high (and positive) skewness means that a small number of large economies account for a large fraction of GDP. These countries have substantial scope of control over emissions and consequently choose relatively clean technologies. In contrast, small economies have little scope of control, and so choose relatively dirty technologies, *ceteris paribus*. Thus, high skewness creates a high degree of heterogeneity across countries with respect to marginal abatement costs in the NCE. This heterogeneity in turn underlies the gains from trade that arise from emissions trading which allows marginal abatement costs to become equalized across countries.

When countries also differ according to their damage parameters, the effect of skewness in the GDP distribution cannot be identified so cleanly. As noted earlier, $\delta_i$ affects the extent to which a country exercises its scope of control, so a negative correlation between $\delta_i$ and GDP weakens the effect of skewness on gains from trade, while a positive correlation strengthens it. It should be noted however, that differences across countries with respect to vulnerability to damage would have to be *very* large in order to have much offsetting effect on the role of skewness in the GDP distribution, given the magnitude of that skewness in practice.

It should be stressed that the actual structure of a cooperative treaty to reduce emissions – in terms of its membership and aggregate abatement achieved – depends on the entire GDP distribution, and not just on variance and skewness alone. For example, if there exists a country that happens to have a damage parameter and GDP share such that it is neither a buyer nor seller of allowances then that country will not join a treaty that requires it to reduce emissions since it gains nothing from trade. Proposition 5 tells us that aggregate gains from trade are increasing in the skewness of the GDP distribution, but the position of *every* country in that distribution is relevant to what a treaty could actually achieve. Thus, even in the context of the simple model I have presented here, an investigation of cooperative action requires numerical analysis based on data for GDP and for damage and cost parameters. While an empirical study of that type is beyond the scope of this paper, the theoretical model I have presented could provide a useful starting point.

## 7. CONCLUSION

This paper has examined the implications of variance and skewness in the distribution of GDP for the properties of the NCE in greenhouse gas emissions. The key consequence of these features of the GDP distribution is that some countries have much greater scope of control over global emissions than others. Large economies have a greater incentive to adopt cleaner technologies than do small economies because those large economies can have a significant impact on the emissions that affect their climates. In contrast, small economies have essentially no control over their own climate destinies, and therefore have little incentive to adopt costly abatement technologies.

This asymmetry in scope of control across countries has a number of interesting implications for the NCE. First, global emissions are decreasing in the variance of the GDP distribution but emissions for an individual country of any given GDP are increasing in that variance. Second, the scope-of-control effect on technology choices underlies a technique effect that can produce an EKC across countries if damage and abatement cost parameters do not differ too widely across those countries. Third, very large countries may *under-emit* relative to the FBS as a best response to the high-emissions-technology choices made by small countries. Fourth, the prospects for cooperative action – as determined by the potential gains from trade available from emissions trading – are increasing in the skewness of the GDP distribution because of the induced asymmetry in marginal abatement costs across countries in the NCE.

It should be noted that the model I have presented here is in many respects quite limited. In particular, the linear and quadratic relationships I have assumed likely do not reflect the true complexity of the GDP-emissions relationship in practice. However, the model does allow for unrestricted heterogeneity across countries with respect to GDP, abatement costs and vulnerability to damage. Moreover, it can be solved analytically and is therefore amenable to calibration. In this respect, it may prove more widely useful in the investigation of climate-change issues beyond those I have explored here.

## APPENDIX

**Derivation of Expressions (8) – (12)**

Differentiate (7) with respect to $x_i$, set equal to zero, and solve for $x_i$ to yield

(A1) $$x_i^+ = \gamma_i E \sum_{i=1}^{n} \delta_i y_i = \gamma_i E Y \bar{\delta}$$

where the "+" superscript indicates that this solution is valid only if it generates positive emissions ( $x_i < 1$ ). If $\gamma_i \geq 1/(EY\bar{\delta})$ then the first-best technology for country *i* is $x_i^{**} = 1$ (with no associated emissions). Let $P = \{i \mid x_i^+ < 1\}$ denote the set of countries with positive emissions in the FBS. Then $e_i = (1 - x_i^+) y_i$ for $i \in P$ and $e_i = 0$ for $i \notin P$. Thus, aggregate emissions are

(A2) $$E = \sum_{i \in P} (1 - \gamma_i E Y \bar{\delta}) y_i = Y_P - \sum_{i \in P} EY\bar{\delta}\gamma_i y_i = Y_P - EY\bar{\delta}Y_P \bar{\gamma}_P$$

where $Y_P = \sum_{i \in P} y_i$ and $\bar{\gamma}_P = \sum_{i \in P} \gamma_i y_i / Y_P$. Collecting terms in (A2) and solving for *E* yields

(A3) $$E^{**} = \frac{Y_P}{1 + \bar{\delta}\bar{\gamma}_P Y Y_P}$$

Substituting $E^{**}$ for *E* in (A1) yields

(A4) $$x_i^+ = \gamma_i \left( \frac{\bar{\delta} Y Y_P}{1 + \bar{\delta}\bar{\gamma}_P Y Y_P} \right)$$

Thus, $x_i^+ < 1$ if and only if

(A5) $$\gamma_i < \bar{\gamma}_P + \frac{1}{\bar{\delta} Y Y_P}$$

This is condition (8) in the text. If this conditions holds for all *i*, then $\bar{\gamma}_P = \bar{\gamma}$ and $Y_P = Y$ . Thus, $x_i^{**} < 1 \;\; \forall i$ if and only if

(A6) $$\gamma_i < \bar{\gamma} + \frac{1}{\bar{\delta} Y^2} \quad \forall i$$

This is condition (9) in the text. Setting $Y_P = Y$ and $\bar{\gamma}_P = \bar{\gamma}$ in (A4) then yields expression (10) in the text. Similarly, setting $Y_P = Y$ and $\bar{\gamma}_P = \bar{\gamma}$ in (A3) yields expression (12) in the text. Finally, setting $x_i = x_i^*$ in (1) yields expression (11) in the text.

**Derivation of Expression (17)**

Using (15) and (1), emissions for country *i* are

(A7) $$e_i(E) = [1 - x_i(E)]y_i = y_i - \gamma_i \delta_i y_i^2 E$$

Summing across $i$ and dividing both sides by $Y^2$ yields

(A8) $$\frac{E}{Y^2} = \frac{1}{Y} - E\sum_{i=1}^{n} \gamma_i \delta_i w_i^2$$

Solving for *E* yields expression (17) in the text.

**Proof of Proposition 3**

(a) Using (12) and (17), take the ratio of $E^*$ and $E^{**}$ to yield

(A9) $$\frac{E^*}{E^{**}} = \frac{1 + \bar{\gamma}\bar{\delta}Y^2}{1 + \phi Y^2}$$

Recall that $\phi = \sum_{j=1}^{n} \gamma_j \delta_j w_j^2$ and that $\bar{\gamma}\bar{\delta} = \sum_{j=1}^{n} \gamma_j w_j \sum_{j=1}^{n} \delta_j w_j$ . Thus, $\phi < \bar{\gamma}\bar{\delta}$ if $n > 1$.

(b) Using (10) and (19), take the ratio of $x_i^*$ and $x_i^{**}$ to yield

(A10) $$\frac{x_i^*}{x_i^{**}} = \frac{w_i \delta_i (1 + \bar{\gamma}\bar{\delta}Y^2)}{(1 + \phi Y^2)\bar{\delta}}$$

This ratio is greater than one if and only if $w_i > \tilde{w}_i$, as defined in expression (25) in the text.

**Proof of Proposition 4**

From (20) and (33), we have

(A11) $\hat{e}_i - e_i^* = y_i \gamma_i \left( \delta_i y_i - \frac{\phi Y}{\bar{\gamma}} \right) \left( \frac{Y}{1+\phi Y^2} \right)$

This is positive (negative) if and only if $\delta_i y_i > (<) \phi Y / \bar{\gamma}$. Dividing both sides by $Y$ yields the inequality in Proposition 4.

**Derivation of Expression (34)**

Domestic cost for country *i* in the NCE is

(A12) $C_i^* = \frac{(x_i^*)^2 y_i}{\gamma_i} + d_i^*$

where $x_i^*$ is given by (19) and $d_i^*$ is the domestic damage it incurs in the NCE, given by

(A13) $d_i^* = \delta_i y_i (E^*)^2$

In comparison, domestic cost for country *i* in the trading equilibrium is

(A14) $\hat{C}_i = \frac{\hat{x}_i^2 y_i}{\gamma_i} + d_i^* + \hat{p}(\hat{e}_i - e_i^*)$

where $\hat{x}_i$ is given by (29) with *p* evaluated at $\hat{p}$ from (32). Damage is unchanged because aggregate emissions are unchanged. The gains from trade for country i are

(A15) $GFT_i = C_i^* - \hat{C}_i$

Making the substitutions from (A12), (A13) and (A11) yields expression (34) in the text.

**Derivation of (36)**

Setting $\gamma_i = \gamma \;\; \forall i$ and $\delta_i = \delta \;\forall i$ and making the substitution for $E^*$ from (23) yields

(A16) $\sum_{j=i}^{n} GFT_j = Y^3 (Z^*)^2 \gamma \delta^2 \left( \sum_{j=1}^{n} w_i^3 - \left( \frac{1}{n} + n\sigma^2 \right)^2 \right)$

In general, the skewness of $\{w_i\}$ is

(A17) $\theta = \frac{\mathbf{E}[w^3] - 3\mu\sigma^2 - \mu^3}{\sigma^3}$

where $\mathbf{E}[w^3] = \sum_{j=1}^{n} w_j^3 / n$ and $\mu$ is the mean of $\{w_i\}$. Since, $\sum_{j=1}^{n} w_j = 1$, it follows that $\mu = 1/n$. Thus,

(A18) $\sum_{j=1}^{n} w_j^3 = n\theta\sigma^3 + 3\sigma^2 - \frac{1}{n^2}$

Making this substitution in (A17) yields expression (36) in the text.

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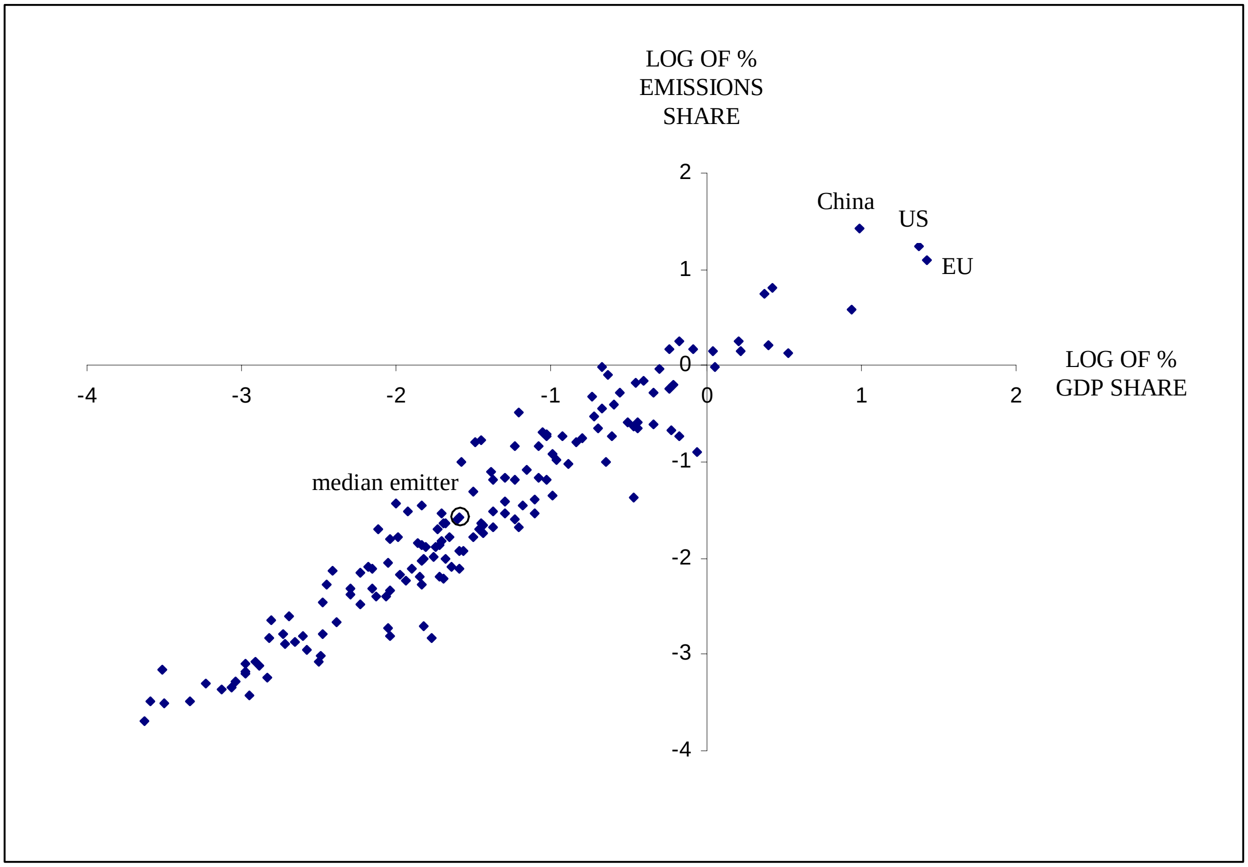


FIGURE 1: THE DISTRIBUTION OF $CO_2$ EMISSIONS AND GDP (2010)

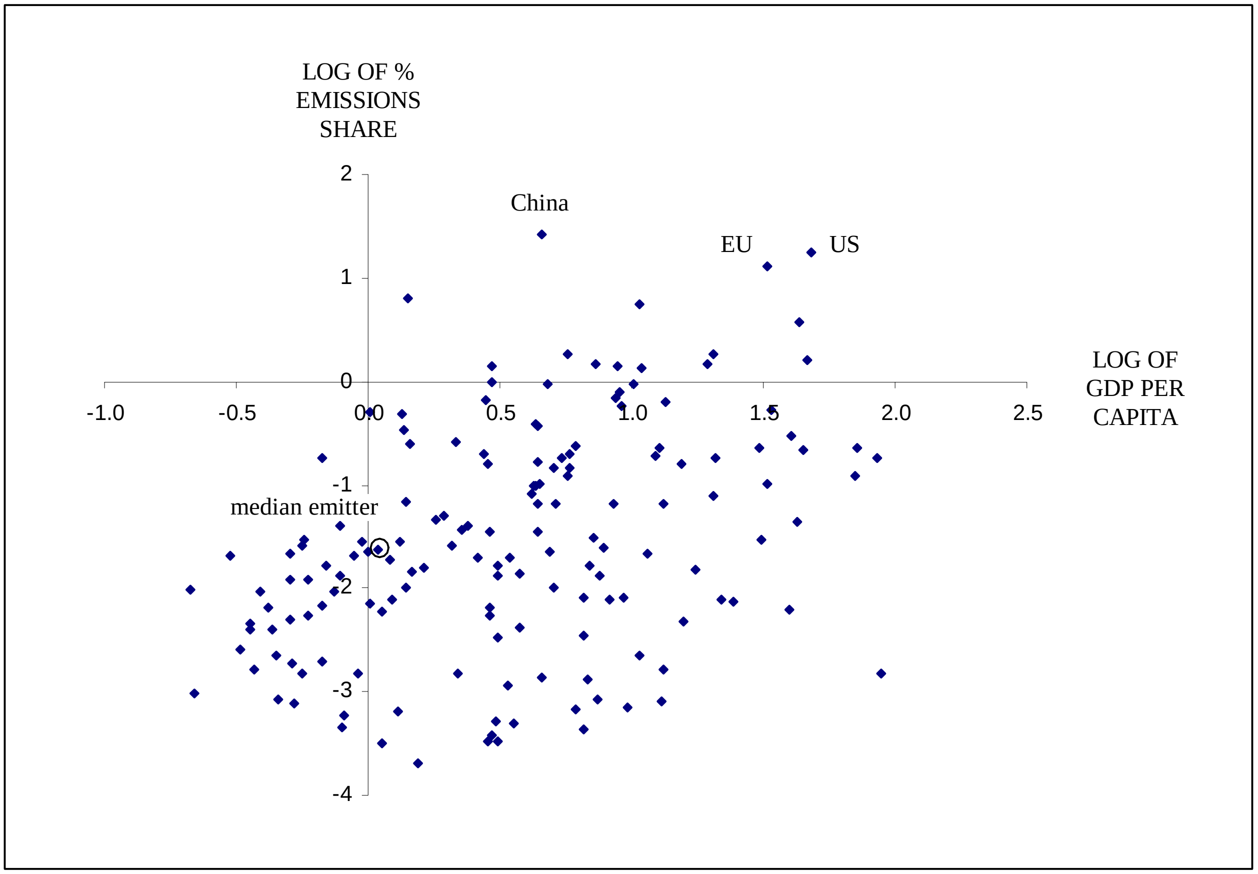


FIGURE 2: THE DISTRIBUTION OF $CO_2$ EMISSIONS AND GDP PER CAPITA (2010)