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The Kyoto Protocol and Beyond: Pareto Improvements to Policies that Mitigate Climate Change

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ABSTRACT

Article 17 of the Kyoto Protocol allowed emissions trading; Article 12 defined a Clean Development Mechanism (CDM). In a simple theoretical model we adapt standard gains from trade results to demonstrate that, relative to any status quo with specified worldwide aggregate emissions: first, emissions trading with a suitable international distribution of permit rights generally allows each nation more consumption while aggregate emissions remain constant; second, the CDM generally adds to these efficiency gains by reducing further the total cost of achieving any target worldwide emissions level. The provisions of the 2015 Paris Agreement that grant credit for carbon removals allow even further potential gains. Contrary to some claims, the Kyoto Protocol is not "defunct"; instead, retaining its key provisions of emissions trade and the CDM while including credit for carbon removals could make emissions reductions much more affordable. Yet an essential part of the institutional background required to make international trade in emissions permits function well has been destroyed by the Paris Agreement, since it lacks mandatory limits of the kind that the Kyoto Protocol imposed.
`[176 words]`

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THE KYOTO PROTOCOL AND BEYOND

1 Introduction

1.1 Motivation

The abstract of Nordhaus's (2015) presidential address to the American Economic Association begins as follows:

> Notwithstanding great progress in scientific and economic understanding of climate change, it has proven difficult to forge international agreements because of free-riding, as seen in the defunct Kyoto Protocol.

A similar sentiment had been expressed earlier by Newell, Pizer, and Raimi (2014). Moreover, the recently negotiated Paris Agreement abandons the mandatory emissions limits specified by the Kyoto Protocol, and its prolongation in the Doha Amendment, which had the backing of international law. They have been replaced them by the essentially voluntary and unenforceable Intended Nationally Determined Contributions (INDCs).

That said, we contend that some of the key provisions of the Kyoto Protocol should be revived. Indeed, in our simple theoretical model, our main conclusion will be that the emissions trade specified in Article 17 can be arranged in such a way that every nation will enjoy no less consumption than in any status quo with the same worldwide total level of emissions; moreover, it will have more consumption unless the status quo allocation of the total level of emissions is already efficient. This accords with Weyant's (1993, p. 36) admittedly dated estimate that international emissions trade "can reduce the costs of control by one-third or more, by equalizing the marginal cost of control across all nations."

1.2 Economic Efficiency and the Kyoto Protocol

The key Article 17 is clearly inspired by the economic principle of free trade for emissions permits. Nevertheless, its theoretical rationale has remained somewhat obscure. After all, unrestricted emissions trade should minimize the total worldwide cost of achieving any fixed level of total worldwide emissions. Yet the earlier paper by Chichilnisky and Heal (1994) (henceforth C&H) showed that only in a special case would a constrained optimal international allocation of abatement activities imply such an overall cost minimum.[1] These results depend, however, on the important constraint that each nation's consumption has to match its own economic output after allowing for abatement costs. This constraint not only has the intended effect of excluding free international transfers; it also removes any opportunity to trade national output in exchange for the right to increased emissions, or to sell unwanted emissions permits in exchange for additional national consumption.

The present paper relaxes this key constraint by postulating a competitive emissions market. Indeed, consider any status quo international allocation of national consumption and carbon emissions, and fix the total emissions in this status quo — possibly an explicit target, or a "global carbon budget". Now distribute just enough emissions licences to firms or nations so that each can afford their status quo allocation. Then allow firms and/or nations to buy and sell these licences in a competitive market. This free trade in permits will lead to an allocation that not only minimizes total abatement costs worldwide; it is also a Pareto gain in the sense that, except in the special case when the status quo already minimizes total abatement costs, it raises every country's consumption level. The argument, moreover, is far simpler than that outlined in Hammond (2001).

1.3 Further Gains from Clean Development and Carbon Removals

The Clean Development Mechanism of the Kyoto Protocol allows those nations listed in its Annex I, the developed nations which accepted limitations on their emissions, to gain credit for certified emissions reductions that result from officially approved projects located in countries that are not listed in Annex I. The argument laid out in Section 4.3 can be extended to this case, and used to demonstrate how the CDM also allows Pareto gains. Further gains are likely to emerge from any efficient new technology, such as carbon removals technology considered in Section 4.5.

1.4 Outline of Paper

After this introduction, Section 2 sets out the basic model. Following C&H, it has one private good and emissions. We assume that emissions feature as an input to the production process, allowing more output to be produced until a ceiling level of emissions is reached. We show how this formulation relates to the alternative in C&H that is based on abatement costs.

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[1] The analysis was largely anticipated in Chichilnisky (1993). For a later presentation, see Sheeran (2006).

Next, Section 3 analyses what our assumptions imply for the emissions demands of both individual firms (or other emitting units) and nations as a whole.

Section 4 contains our main results on Pareto gains from emission trade, both for national markets and integrated international markets, as well as gains from the clean development mechanism and from the use of "carbon removals technology" that can absorb and capture carbon dioxide.

The final Section 5 offers suggestions for extensions in future work, as well as a concluding summary.

2 A Model with One Private Good and Emissions

2.1 Nations and Emissions

Consider a world with a finite set of nations K indexed by k. We extend C&H's framework by considering within each nation $k \in K$ a finite set J_k of firms, or "emitting units", whose carbon emissions will be monitored. Let $J := \cup_{k \in K} J_k$ be the set of all such firms.

We assume that there is a single private good — a Hicksian composite commodity, in effect, as an aggregate of many private goods whose relative prices are assumed to be unaffected by environmental policy. For each $j \in J$, let $e_j \in \mathbb{R}_+$ denote the quantity of carbon emissions that are detected as coming from firm j.[2] These emissions are effectively an input to the process of producing firm j's output $y_j \in \mathbb{R}_+$ of the composite commodity.

In the following, we denote total emissions in each nation $k \in K$ by

$$E^k := \sum_{j \in J_k} e_j \tag{1}$$

and global total emissions by

$$E := \sum_{j \in J} e_j \tag{2}$$

2.2 National Welfare

Following the C&H model, we assume that each nation $k \in K$ evaluates outcomes using its own utility function. Here we assume it takes the form $u^k(c^k, E)$ which is increasing in national consumption c^k but decreasing in total emissions E. Because our discussion is limited

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[2] In this section we restrict attention to non-negative emissions. An important extension to allow negative emissions is set out in Section 4.5.

to finding Pareto improvements, without any stronger concept of world welfare, different nations' utility functions can be treated as ordinal and non-comparable between nations. Indeed, because most of our analysis considers a fixed level of total emissions E, in order to find a Pareto improvement, we look only for changes that increase each nation's consumption when E is fixed.

2.3 Production Functions

For each firm j, we postulate a production function with diminishing returns to the firm's own emissions, and with negative marginal returns once emissions surpass a threshold value e_j^*. Specifically, for each firm $j \in J$ we assume the existence of a continuous production function $\mathbb{R}_+ \ni e_j \mapsto y_j = \eta_j(e_j) \in \mathbb{R}_+$. Using primes to denote differentiation, we assume that each function η_j satisfies

1. there is a *saturating level* $e_j^* > 0$ of emissions having the property that $\eta_j(e_j) = \eta_j(e_j^*)$ for all $e_j \geq e_j^*$ and $\eta_j(e_j) < \eta_j(e_j^*)$ for all $e_j \in [0, e_j^*)$;
2. $\eta_j'(e_j) > 0$ and $\eta_j''(e_j) < 0$ for all $e_j \in (0, e_j^*)$;
3. there is a *critical price* $p_j^C > 0$ which is the (finite) limit of $\eta_j'(e_j)$ as $e_j \to 0$ from above.

2.4 Reference Levels and Abatement Costs

To facilitate comparison with C&H's results, we note that each production function in Section 2.3 has an equivalent formulation involving abatement costs. Indeed, for each firm j, let e_j^R denote some reference level of emissions, and $y_j^R := \eta_j(e_j^R)$ the corresponding reference level of output. Then, for any alternative level e_j of firm j's emissions, we can define its abatement level $a_j := e_j^R - e_j$ as the net reduction in emissions. Of course, abatement can be negative, whereas emissions cannot — at least in the absence of the kind of carbon removals technology that we consider in Section 4.5.

Then, given these reference levels, the production function in Section 2.3 implies that each firm's cost of abatement, expressed as lost output, is given by the function

$$(-\infty, e_j^R] \ni a_j \mapsto \gamma_j(a_j) := y_j^R - \eta_j(e_j^R - a_j) \in [0, y_j^R] \tag{3}$$

Then $\gamma_j'(a_j) = \eta_j'(e_j^R - a_j)$ and $\gamma_j''(a_j) = -\eta_j''(e_j^R - a_j)$, so our assumptions in Section 2.3 also imply that $\gamma_j'(a_j) > 0$ and $\gamma_j''(a_j) > 0$ for all $a_j \geq e_j^R - e_j^*$.

Conversely, given the cost functions (3), the production function of each firm $j \in J$ can be recovered by defining

$$\eta_j(e_j) := y_j^R - \gamma_j(e_j^R - e_j) \tag{4}$$

So the two formulations are entirely equivalent, though the production function is somewhat simpler as its definition does not depend on any reference levels. That is why we prefer to use production functions rather than abatement costs throughout the rest of the paper.

3 Emission Demands

3.1 Emission Demand Functions

For each firm or plant $j \in J$, consider the mapping

$$(0, e_j^*] \ni e_j \mapsto \eta_j'(e_j) \in [0, p_j^C)$$

from emissions levels not exceeding the ceiling e_j^* to the corresponding marginal product. Because of our assumptions in Section 2.3, this is a strictly decreasing bijection between two half open intervals. It therefore has a strictly decreasing inverse

$$[0, p_j^C) \ni p \mapsto \eta_j'^{-1}(p) \in (0, e_j^*]$$

Faced with any emissions price $p \geq 0$, each firm $j \in J$ has a profit-maximizing emissions demand quantity $e_j = q_j(p)$ that maximizes $\eta_j(e_j) - p\, e_j$ with respect to e_j subject to the non-negativity constraint $e_j \geq 0$. Provided that $p < p_j^C$, this quantity demanded is determined by the first-order condition $\eta_j'(q_j(p)) = p$. Allowing also for the case when $p \geq p_j^C$, this demand quantity therefore satisfies

$$q_j(p) = \begin{cases} \eta_j'^{-1}(p) & \text{if } 0 \leq p < p_j^C; \\ 0 & \text{if } p \geq p_j^C \end{cases} \tag{5}$$

Because of the assumption that $\eta_j'(e_j) \to p_j^C$ as $e_j \to 0$, each firm's has a continuous emissions demand function

$$\mathbb{R}_+ \ni p \mapsto q_j(p) \in [0, e_j^*].$$

Also, when p is restricted to the interval $[0, p_j^C)$, we can take the differential of the first-order condition $\eta_j'(q_j(p)) = p$ to obtain

$$\eta_j''(q_j(p))dq_j = dp \quad \text{and so} \quad q_j'(p) = 1/\eta_j''(q_j(p)) < 0.$$

3.2 The Aggregate Emission Demand Function

The aggregate emissions demand function is the mapping

$$\mathbb{R}_+ \ni p \mapsto Q(p) := \sum_{j \in J} q_j(p) \in [0, E^*]$$

where $E^* := \sum_{j \in J} e_j^*$ is the aggregate emissions quantity when all firms reach their saturation level.

For each emissions price $p \geq 0$ we partition the set J into the two sets

$$J^+(p) := \{j \in J \mid p \geq p_j^C\} \quad \text{and} \quad J^-(p) := \{j \in J \mid p < p_j^C\}$$

of firms, according to whether $p \geq p_j^C$ or $p < p_j^C$. For firms in $j \in J^+(p)$ the emissions price p is high enough to drive their emissions demand $q_j(p)$ down to 0; for firms in $j \in J^-(p)$, on the other hand, the emissions price p is low enough for them to have a positive emissions demand $q_j(p)$.

These definitions evidently imply that

$$Q(p) = \sum_{j \in J} q_j(p) = \sum_{j \in J^-(p)} q_j(p)$$

Let $P^C := \{p_j^C \mid j \in J\}$ denote the (finite) set of *critical prices*. Provided that $p \notin P^C$, there is a neighbourhood N of p such that $N \cap P^C = \emptyset$. For all $\tilde{p} \in N$, the set $J^-(\tilde{p})$ equals $J^-(p)$; moreover, for all $j \in J^-(p)$ the mapping $N \ni \tilde{p} \mapsto q_j(\tilde{p})$ is differentiable. These facts imply that $\tilde{p} \mapsto Q(\tilde{p})$ is differentiable at p, with derivative there given by

$$Q'(p) = \sum_{j \in J^-(p)} q_j'(p) = \sum_{j \in J^-(p)} [1/\eta_j''(q_j(p))] < 0 \tag{6}$$

Over its whole domain $\mathbb{R}_+$, therefore, the aggregate emissions demand function $p \mapsto Q(p)$ is continuous and piecewise differentiable; there can be kinks at critical prices $p \in P^C$. Because one or more negative terms drop out of the sum (6) at any critical price, there will a flattening effect on the negative slope $Q'(p)$ as p increases from just below the kink to just above it.

Similar properties obviously hold for the aggregate national emissions demand

$$Q^k(p) = \sum_{j \in J_k} q_j(p)$$

of each nation $k \in K$.

3.3 Feasible Allocations with and without International Transfers

A *feasible allocation with international transfers* will be a combination of an *international consumption profile* $\mathbf{c}^K = \langle c^k \rangle_{k \in K} \in \mathbb{R}^K_+$ and an *inter-firm emissions profile* $\mathbf{e}^J = \langle e_j \rangle_{j \in J} \in \mathbb{R}^J_+$ that together satisfy the *international feasibility constraint*

$$C := \sum_{k \in K} c^k \leq Y := \sum_{j \in J} \eta_j(e_j) \tag{7}$$

A *feasible allocation without international transfers* will be a combination $(\mathbf{c}^K, \mathbf{e}^J)$ of two such profiles that, for each nation $k \in K$, together satisfy the *national feasibility constraint*

$$c^k \leq Y^k := \sum_{j \in J^K} \eta_j(e_j) \tag{8}$$

When there are international transfers, we define the *net transfer* to each nation K$\in K$ as

$$t^k := c^k - Y^k \tag{9}$$

Let $\mathbf{t}^K := \langle c^k \rangle_{k \in K} \in \mathbb{R}^K$ denote the international profile of net transfers. Obviously, the international feasibility constraint (7) is satisfied if and only if $\sum_{k \in K} t^k \leq 0$.

4 Gains from Emissions Trading

4.1 A Status Quo Allocation

As usual when discussing the gains from trade, we postulate a status quo feasible allocation described by the triple $(\bar{\mathbf{c}}^{\mathbf{K}}, \bar{\mathbf{e}}^{\mathbf{J}}, \bar{\mathbf{t}}^{\mathbf{K}})$ that consists of profiles:

1. $\bar{\mathbf{c}}^{\mathbf{K}} = \langle \bar{c}^k \rangle_{k \in K}$ of national consumption levels;
2. $\bar{\mathbf{e}}^{\mathbf{J}} = \langle \bar{e}_j \rangle_{j \in J}$ of monitored emissions by different plants;
3. $\bar{\mathbf{t}}^{\mathbf{K}} = \langle \bar{t}^k \rangle_{k \in K}$ of net transfers to each nation — often assumed to be zero.

Note that this status quo should *not* be interpreted as the historical *status quo ante* allocation that existed *before* a specific reform; rather it is the *counter-factual* future allocation that would have occurred in *in the absence of* that reform.

In this paper, the status quo will be a feasible allocation without emissions trade, but where some other policy instruments or voluntary agreements do succeed in limiting global aggregate emissions to some target level or carbon budget $\bar{E} := \sum_{j \in J} \bar{e}_j$ satisfying $\bar{E} < E^* :=$

$\sum_{j\in J} e_j^*$. If this assumption were violated, we would be back in a world where each nation was failing to observe even voluntary controls on its emissions.

In the case when no international transfers are possible, one will have $\bar{t}^k = 0$ and so $\bar{c}^k = \sum_{j\in J_k} \phi_j(e_j)$ for all $k \in K$.

4.2 Gains from Separated National Emissions Trading

Within any nation $k \in K$, let $\bar{E}^k := \sum_{j\in J^K} \bar{e}_j$ denote total national emissions in the *status quo*. Assume that $\bar{E}^k > 0$. Also, let $\hat{p}^k := \max_{j\in J^K} p_j^C$ denote the highest critical price for all the firms in nation k.

Now suppose that one or more nations $k \in K$ institutes internal emissions trade of a fixed supply of its own permits equal to its status quo total emissions $\bar{E}^k$. The equilibrium price p^k that equates demand for permits to this fixed supply must solve the equation $Q^k(p) = \bar{E}^k$. Because the function $p \mapsto Q^k(p)$ is strictly decreasing and continuous for all $p \in [0, \hat{p}^k]$, it induces a bijection

$$[0, \hat{p}^k] \ni p \mapsto Q^k(p) \in [0, \sum_{j\in J^K} e_j^*]$$

So country k's market clearing permit price will be $p^k := (Q^k)^{-1}(\bar{E}^k)$.

Following the discussion in Section 3.1, at this equilibrium price, the emission demand $e_j = q_j(p^k)$ of each firm $j \in J_k$ is given by (5). It therefore maximizes w.r.t. e_j the profit $\eta_j(e_j) - p^k e_j$ that firm j earns after subtracting the market value of the emission permits it needs to buy.

Consider any alternative allocation $\tilde{\mathbf{e}}^{J_k} = \langle \tilde{e}_j \rangle_{j\in J_k}$ of emissions to the firms in nation k whose aggregate $\sum_{j\in J_k} \tilde{e}_j$ equals the total emissions $\bar{E}^k = \sum_{j\in J_k} \bar{e}_j$ in the status quo. Then compared with k's national output $\tilde{Y}^k = \sum_{j\in J_k} \eta_j(\tilde{e}_j)$ in this alternative allocation, profit maximization by each firm $j \in J_k$ in equilibrium implies that the equilibrium national output $Y^k = \sum_{j\in J_k} \eta_j(e_j)$ will satisfy

$$Y^k = \sum_{j\in J_k} [\eta_j(e_j) - p^k e_j] + \sum_{j\in J_k} p^k e_j \geq \sum_{j\in J_k} [\eta_j(\tilde{e}_j) - p^k \tilde{e}_j] + p^k \bar{E}^k = \sum_{j\in J_k} \eta_j(\tilde{e}_j) = \tilde{Y}^k \quad (10)$$

Hence in equilibrium the aggregate level of national output is maximized.

A particular alternative allocation, of course, is the status quo $\bar{\mathbf{e}}^{J_k}$ itself. Hence equilibrium national output also satisfies

$$Y^k = \sum_{j\in J_k} [\eta_j(e_j) - p^k e_j] + \sum_{j\in J_k} p^k e_j \geq \sum_{j\in J_k} [\eta_j(\bar{e}_j) - p^k \bar{e}_j] + p^k \bar{E}^k = \sum_{j\in J_k} \eta_j(\bar{e}_j) = \tilde{Y}^k \quad (11)$$

Moreover, there is strict inequality except in the special case when $\eta_j(e_j) - p^k e_j = \eta_j(\bar{e}_j) - p^k \bar{e}_j$ for all $j \in J_k$, which holds if and only if the emission demand of each firm $j \in J$ is already maximizing profit in the status quo. This proves:

Theorem 1 *Consider any separate national emissions market operating in just one country, with aggregate national emissions fixed at their status quo level. In that national market, the competitive equilibrium allocation of emissions maximizes national output. In particular, the competitive equilibrium level of national output is no lower than in the status quo, and is higher except in the special case when each firm's profit is already maximized in the status quo.*

If any set $S \subseteq K$ of countries all introduce separate national markets for carbon emissions, the same result holds — that is, each nation $k \in S$ will benefit individually, except in the special case when the profits of each firm $j \in J_k$ are already maximized in the status quo.

4.3 Gains from Integrated International Emissions Trading

A market in one nation can sell its entire aggregate emissions allowance to emitting units and keep the sales revenue to meet its own domestic purposes. It can also offer rebates to existing firms that have to buy permits. In our simple model, none of these affect aggregate national output.

Once we move to an integrated market involving several nations, however, one needs a well specified rule for sharing the sales revenue. Moreover, provided this rule is carefully selected, it is general possible to arrange that all participating nations simultaneously enjoy higher output than in the status quo.

Let K now denote the set of nations that participate in one integrated carbon market, and let $\bar{E}$ be the status quo level of total emissions for this set. For each nation $k \in K$, let $\bar{Y}_k$ and $\bar{C}_k$ denote respectively the status quo output and consumption. One has

$$\bar{C}_k = \bar{Y}_k + \bar{t}_k \tag{12}$$

where $\bar{t}_k$ is nation k's *net transfer*. Obviously $\sum_{k \in K} \bar{t}_k = 0$, implying that

$$\sum_{k \in K} \bar{C}_k = \sum_{k \in K} (\bar{Y}_k + \bar{t}_k) = \sum_{k \in K} \bar{Y}_k \tag{13}$$

In the special case when there are no international transfers in the status quo, one will also have $\bar{t}_k = 0$ for all $k \in K$.

Following an analysis like that in Section 4.2, in an integrated market for emissions permits there will be an equilibrium at a price p^K satisfying $Q(p^K) = \bar{E}$, where $p \mapsto Q(p)$ is the continuous and strictly decreasing aggregate demand function discussed in Section 3.2. The equilibrium allocations of emissions and firm outputs will then be

$$\mathbf{e}^J(p^K) = \langle q_j(p^K) \rangle_{j \in J} \quad \text{and} \quad \mathbf{y}^J(p^K) = \langle \phi_j(q_j(p^K)) \rangle_{j \in J} \tag{14}$$

It follows that the aggregate emissions and output in each nation $k \in K$ are respectively

$$E^k(p^K) = \textstyle\sum_{j \in J_k} q_j(p^K) \quad \text{and} \quad Y^k(p^K) = \textstyle\sum_{j \in J_k} \phi_j(q_j(p^K)) \tag{15}$$

Suppose that permits corresponding to the status quo total emissions level $\bar{E}$ are all sold at the equilibrium price p^K. Then the corresponding total permit sales revenue is $R := p^K \, \bar{E}$. We assume that this revenue is divided up between the nations $k \in K$ so that each nation receives an amount

$$r^k := p^K \, \bar{E}^k \geq 0 \tag{16}$$

equal to the market value of what its emissions would have been in the *status quo* $\bar{E}_k$. Obviously, this rule implies that

$$\textstyle\sum_{k \in K} r^k = \sum_{k \in K} p^K \, \bar{E}^k = p^K \sum_{k \in K} \bar{E}^k = p^K \, \bar{E} = R \tag{17}$$

Suppose too that the status quo transfer $\bar{t}_k$ to each nation k is frozen. Then, after it buys the emission permits that its firms use, the aggregate consumption of each nation $k \in K$ is

$$\begin{aligned} C^k &= Y^k - p^K \, E^k + r^k + \bar{t}^k = Y^k - p^K \, E^k + p^K \, \bar{E}^k + \bar{C}^k - \bar{Y}^k \\ &= \bar{C}^k + (Y^k - p^K \, E^k) - (\bar{Y}^k - p^K \bar{E}^k) \end{aligned} \tag{18}$$

because of (16) and (12). That is, the net increase in consumption equals the net increase in output minus the value of the net increase in used emissions permits.

Now, following the discussion of the national market case, the emission demand $e_j = q_j(p^K)$ of each firm $j \in J_k$ at the equilibrium price p^K maximizes w.r.t. e_j the profit $\eta_j(e_j) - p^K e_j$ net of its spending on emission permits.

Consider any alternative allocation $\tilde{\mathbf{e}}^J = \langle \tilde{e}_j \rangle_{j \in J}$ of emissions to the firms in all the nations $k \in K$ whose aggregate $\sum_{j \in J} \tilde{e}_j$ equals the total emissions $\bar{E} = \sum_{j \in J} \bar{e}_j$ in the status quo. Then compared with aggregate output $\tilde{Y} = \sum_{j \in J} \eta_j(\tilde{e}_j)$ in this alternative allocation, the equilibrium aggregate output $Y = \sum_{j \in J} \eta_j(e_j)$ will satisfy

$$Y = \textstyle\sum_{j \in J} [\eta_j(e_j) - p^K e_j] + \sum_{j \in J} p^K e_j \geq \sum_{j \in J} [\eta_j(\tilde{e}_j) - p^K \tilde{e}_j] + p^K \bar{E} = \sum_{j \in J} \eta_j(\tilde{e}_j) = \tilde{Y} \tag{19}$$

Hence in equilibrium aggregate output, which equals aggregate consumption, is maximized.

Furthermore, the aggregate profit of each nation $k \in K$ satisfies

$$Y^k - p^K E^k = \sum_{j \in J_k} [\eta_j(e_j) - p^K e_j] \geq \sum_{j \in J_k} [\eta_j(\bar{e}_j) - p^K \bar{e}_j] = \bar{Y}^k - p^K \bar{E}^k \tag{20}$$

When combined with (18), this implies that $C^k \geq \bar{C}^k$ with equality if and only if every firm $j \in J_k$ would already be maximizing its profit at its emissions level $\bar{e}_j$ in the status quo. Hence:

Theorem 2 *In any integrated international system of emissions markets, suppose that any international transfers are frozen at their status quo levels, before each nation receives as a rebate the market value of the permits that it would need to buy in order to maintain its status quo emissions. Then the competitive equilibrium level of each nation's consumption is no lower than in the status quo, and is higher except in the special case when each firm's profit is already maximized in the status quo.*

Note that a particular status quo could be an allocation that results from segmented national markets. Theorem 2 can be applied to show that linking up these segmented markets and forming one overall international emissions market allows a Pareto improvement — except, as ever, when the status quo global allocation of permits is already efficient. The same is true if the status quo is any of the allocations described in Chichilnisky (1993), Chichilnisky and Heal (1995) or Sheeran (2006), where each nation's consumption is constrained to equal its own output.

4.4 Clean Development

To extend our model so that the effects of a clean development mechanism can be analysed, we partition the set of nations K into two subsets:

- A set M of full *member nations* that accept limitations on their emissions, and are allowed to receive carbon credits under the clean development mechanism;
- A complementary set N of *non-member* nations that remain exempt from emissions limitations, and can host projects under the rules of the clean development mechanism.

In this setting, member nations $k \in M$ can be treated much like those in the previous set K. Non-member nations $k \in N$ could be treated as having a status quo allocation in which each firm $j \in J^N := \cup_{k \in N} J_k$ is at its emissions ceiling e_j^*, maximizing output without any regard to the social cost of carbon emissions. Instead, however, we simply assume that there is a status quo allocation in which each firm j in a non-member nation — i.e., each $j \in J^N := \cup_{k \in N} J_k$ — has emissions $\bar{e}_j$.

The clean development mechanism can then be modelled as allowing any nation $k \in M$ to adopt any firm $h \in J^N$, and reduce firm h's emissions to some amount e_h that is below the status quo level $\bar{e}_h$, in exchange for being able to increase its own national emissions from $\bar{E}^k$ to $\bar{E}^k + \bar{e}_h - e_h$. Under this arrangement, firm h's reduced emissions are balanced by increased emissions by the nations $k \in M$, so total world emissions are unchanged. Then a similar argument to those used to establish the gains from internationally integrated carbon markets shows that, ignoring an exceptional case, world output goes up while total emissions remain the same; moreover, this extra world output can be distributed to generate an actual Pareto improvement.

4.5 Carbon Removal Technology

Carbon removal occurs whenever carbon dioxide is captured either from exhaust fumes, or in the case of direct air carbon capture (DACC), from the ambient air. Recent technological developments have been making carbon removal not only feasible, but increasingly cost effective, especially when the captured carbon is put to industrial use.[3] The Paris Agreement allows credit for carbon removals to be set against debits for carbon emissions, partly as a response to this claim:

> Scenarios that are *more likely than not* to limit temperature increase to 2°C are becoming increasingly challenging, and most of these include a temporary overshoot of this concentration goal requiring net negative CO2 emissions after 2050 and thus large-scale application of carbon dioxide removal (CDR) technologies.[4]

Since that statement, Gasser (2015) for one has made a similar point more forcefully. And at the insistence of a group of small island states whose very existence is threatened by the

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[3] Graciela Chichilnisky is co-founder and CEO of Global Thermostat LLC. She is also the co-inventor and co-patentee of Carbon Negative Technology™, as described by Eisenberger, Cohen, Chichilnisky *et al.* (2009), Chichilnisky (2011), Chichilnisky and Eisenberger (2011), as well as Choi *et al*. (2011). Global Thermostat is among the 11 “finalists” announced by the Virgin Earth Challenge, a competition with a $25 million prize that Sir Richard Branson launched in 2007 as an incentive for developing “scalable and sustainable ways of removing greenhouse gases from the atmosphere in an environmentally sustainable and economically viable way” — see `http://www.virginearth.com`. Peter Hammond has no financial interest in Global Thermostat.

[4] See page 191 of IPCC (2014).

rise in sea levels to be expected as a result of global warming, the Paris Agreement has set an aspiration of limiting the global average temperature increase to 1.5°C.

The theoretical discussion of this paper is easily adapted to accommodate carbon removal technology. One considers an additional set H_k of firms located in each nation $k \in K$ for each of which:

1. Carbon dioxide emissions e_h are negative.

2. There is a minimum amount $\underline{e}_h < 0$ of negative emissions, equivalent to a maximum amount $-\underline{e}_h > 0$ of carbon removal.

3. There is a production function $[\underline{e}_h, 0] \ni e_h \mapsto y_h = \phi_h(e_h) \in \mathbb{R}$ satisfying $\phi_h(0) = 0$ and $\phi_h''(e_h) < 0$ for all $e_h \in [\underline{e}_h, 0]$. That is, the marginal cost $-\phi_h'(e_h)$ of absorbing carbon dioxide is always strictly increasing.

Here the output $y_h = \phi_h(e_h)$ allows for any possible sales revenue that comes from selling captured carbon dioxide as an input to other industries. With this reformulation, the profit of each firm $h \in H_k$ can still be written as

$$\pi_h(e_h) = \phi_h(e_h) - p\, e_h \tag{21}$$

Compared with Section 2.3, the only differences that carbon removals technology creates are that $-p\, e_h > 0$ represents the credit received for the negative emissions $-e_h$ of carbon, whereas $\phi_h(e_h)$ is the net profit from using those e_h units of captured carbon in an industrial process.

Note that we do not impose the assumptions that $y_h = \phi_h(e_h)$ can never be positive, or that $\phi_h'(e_h) > 0$ implying that losses rise as removals increase. Indeed, the recent developments we mention in footnote 3 show the promise of making carbon removals technology profitable, when it is combined with selling the captured CO_2 gas to other industries, and given the current atmospheric concentration of CO_2. This is true even when the price at which credit is received for capturing CO_2 drops to zero. Of course, as an empirical fact this implies that there can be firms $h \in H := \cup_{k \in K} H_k$ using carbon removals technology such that $\phi_h(e_h) > 0$ and $\phi_h'(e_h) < 0$ for all negative values of e_h that are close enough to 0.

Also, now the *critical price* p_h^C is the limit of $\phi_h'(e_h)$ as $e_h \to 0$ from below rather than above. Then the profit-maximizing choice of e_h is negative if and only if the price of carbon emissions satisfies $p > p_h^C$. Note that this critical price could be negative when $\phi_h'(e_h) < 0$ for all negative emissions with e_h close to 0. A negative price, of course, would mean that a charge has to be paid for the right to capture CO_2 from the atmosphere. If $p_h^C < 0$, then carbon removals technology would be profitable for small amounts of captured carbon even if a negative emissions price below $-p_h^C$ had to be paid for the right to capture that carbon.

With these assumptions, all the previous arguments of Sections 4.2, 4.3, and 4.4 retain their validity, subject only to modifying the signs of e_h and possibly y_h for all $h \in H$.

5 Concluding Remarks

5.1 Taxes or Cap and Trade

Obviously, the cap and trade system with a market for emissions permits that we consider here is equivalent to a system with a uniform tax based on emissions, and an appropriate division of the tax revenue.

5.2 Beyond Flawed Compensation Tests

There is a traditional literature on gains from trade that considers potential gains from trade, and uses the compensation tests due to Kaldor and Hicks. By using the approach set out in Hammond (1993) and in Hammond and Sempere (1995) for gains from trade results in a more traditional setting, the flawed compensation tests can be avoided.

5.3 Extensions

The paper considers only a model with a single time period and a single good. An important extension would have many goods, to allow for the effect of emissions controls on relative prices in the general economy. A related extension could allow for emissions at different times to be treated as different goods. In these settings there are important lessons one can draw from results such as those in Diamond and Mirrlees (1971), Dixit and Norman (1986), Hammond and Sempere (1995), and Hammond (2000).

5.4 Achieving Emission Reductions

The paper has discussed some particular Pareto improvements to policies that mitigate climate change. None of these policies, however, actually reduce total emissions, since these are held fixed at a status quo level. All the policies considered here, including even the introduction of carbon removals technology, merely improve the distribution of abatement activities so as to increase aggregate output, while also ensuring that each nation enjoys higher consumption — disregarding, of course, the exceptional case where the *status quo* is already efficient.

That said, the total abatement costs of reaching any target level of aggregate emissions reductions will be reduced. Indeed, carbon removals are becoming profitable even when the price received as payment for capturing carbon is zero. Then the reduced abatements costs could be highly significant if carbon removals were deployed on a suitably massive scale. Is it too much to hope that most of those reduced costs will be foregone in order to exploit the fact that a more rapid decline in aggregate emissions will have become more affordable? Indeed, can we even look forward to eventual reductions in the atmospheric concentration of CO_2?

5.5 The Kyoto Protocol after the Paris Agreement: Where Next?

The Kyoto Protocol specified, for the richer countries listed in its Annex I, politically expedient mandatory limits over the period 2008–12 for the emissions of greenhouse gases. At the end of 2012, the Doha Amendment extended and even lowered these limits, though the amendment has not been ratified by enough nations to acquire legal force. Many commentators have expressed the view that, by removing these mandatory limits and replacing them by the essentially voluntary and unenforceable Intended Nationally Determined Contributions (INDCs), the world has taken a dangerous step backwards in its struggle to control emissions of greenhouse gas emissions.

This paper offers another reason for concern. We have argued that, at least in principle, the world is likely to be able to find reduced emissions much more affordable if the potential aggregate cost reductions arising from the gains from trading emissions permits internationally can be more fully realised. Yet such trade becomes much harder to arrange in the absence of an international institutional framework for controlling the supply of such permits, as well as for monitoring the emissions that they allow. Now, the Paris Agreement may help to build up some of the international institutional infrastructure which will eventually be needed to support emissions trade between nations. Yet for the time being it is hard to see how such international trade can occur at all now that the Paris Agreement has removed the fundamental basis for such trade that the mandatory limits of the Kyoto Protocol had provided. Also lost is the main source of revenue for the Clean Development Mechanism and its successor, the Green Climate Fund.

Following the suggestive title of Chichilnisky and Sheeran (2009), it seems that there are many good features of Kyoto that really do need to be saved — or rather, after Paris, revived.

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