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Abstract:
Linkage of cap-and-trade systems is typically advocated by economists on a general analogy with the beneficial linking of free-trade areas and on the specific grounds that linkage will ensure cost effectiveness among the linked jurisdictions. An appropriate and widely accepted specification for the damages of carbon dioxide (CO_2) emissions within a relatively short (say 5-10 year) period is that marginal damages for each jurisdiction are constant (although they can differ among jurisdictions). With this defensible assumption, the analysis is significantly clarified and yields simple closedform expressions for all CO_2 permit prices. Some implications for linked and unlinked voluntary CO_2 cap-and-trade systems are derived and discussed.

Keywords: linkage, cap and trade, pollution, climate change

JEL classification: Q50, Q51, Q52, Q54, Q58

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Sammendrag

Sammenkobling av kvotehandelssystemer for klimagasser blir ofte anbefalt av økonomer. Det kan gi opphav til effektivitetsgevinster på samme måte som sammenkobling av frihandelsområder ved at slik sammenkobling sikrer kostnadseffektivitet i utslippsreduksjoner mellom de tilknyttede jurisdiksjonene. Innenfor en relativt kort tidsperiode (5-10 år) er det rimelig og allment akseptert at man kan anta at marginale skader av CO2-utslipp for hver jurisdiksjon er konstante (selv om de kan være forskjellige mellom jurisdiksjoner). Med en slik antakelse blir analysen av sammenkobling av kvotehandelssystemer betydelig forenklet og vi utleder enkle uttrykk for kvoteprisene. Dette paperet

1 Introduction

Abatement of carbon dioxide (CO_2) emissions is today's premier global public good.[1] It is difficult enough to resolve a local public goods problem within a jurisdiction having effective governance with an ability to levy payments. But when the problem is international in scope, and where there is no overarching top-down international governance structure, it can render a global public goods problem virtually unsolvable.

The key issue here is the notorious free-rider problem. Everyone wants to free ride off the contributions of others. A jurisdiction bears the full costs of its abatement, but it only reaps a fraction of the global benefits. The result is a non-cooperative selfish equilibrium where everyone abates far less than would be socially desirable in a cooperative solution. The key issue is that it takes a strong government to enforce a socially desirable cooperative solution. In the global arena there is no such strong international government with powers to assign CO_2 emissions targets and enforce penalties for non-compliance.

Reduced to its core essence, the COP21 Paris Agreement of 2015 is strictly a bottom-up voluntary agreement based on a periodically repeated 'pledge and review' process. Just before a performance period, at the end of the previous performance period, each country volunteers a 'nationally determined contribution' (NDC) for its own CO_2 emissions. After the performance period (five years in COP21), actual emissions are reported but there are no penalties for a country not complying with its own volunteered NDC. In this sense the COP21 Paris Agreement is doubly voluntary: The self-announced pledges are strictly voluntary in the first place, and compliance with the previous self-announced pledges in the performance period is also strictly voluntary. The Agreement talks about developed countries aiding developing countries with financial support for 'sustainability' based on climate mitigation and adaptation, but the cash flows have thus far been meager.

Not surprisingly, there has been broad take-up of such a strictly voluntary agreement. Before the U.S. dropped out, the COP21 Paris Agreement nominally covered countries accounting for some 97 of world CO_2 emissions. There is widespread acknowledgement that the highly under-ambitious NDCs actually named are not nearly enough to keep global warming on a track below the stated goal of no more than a worldwide average temperature increase of 2°C.

On the positive side, the COP21 Paris Agreement has highlighted the importance to the international community of dealing with climate change. And it encourages credibly transparent standards of reporting, monitoring, and verification by each participating coun-

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[1] For expositional simplicity we pretend that carbon dioxide (CO_2) is the only greenhouse gas (GHG). CO_2 is by a wide margin the most important GHG, but it is not the only GHG.

try, which is a necessary first step for any accord. COP21 also contains an agreement for countries to pledge, review, and re-pledge new intended NDCs periodically (every five years), hopefully inspiring ever-greater levels of NDC ambition over time.

What is the underlying 'model' of human behavior that might allow the COP21 Paris Agreement to be seen as a step toward a resolution of the climate-change externality? There appears to be an implicit assumption here that CO_2 polluters will significantly drive down their emissions voluntarily based largely on altruism and 'blame and shame' from others, without any top-down setting of emissions targets or enforcement of penalties for non-compliance. If only everyone followed the full golden rule, this line of reasoning might begin with, the global-warming problem could be solved. The COP21 Paris Agreement might then be seen as a first tentative step toward demonstrating the spirit of golden-rule-like behavior, which might hopefully inspire further steps toward even more golden-rule-like behavior by inspiring ever-more-ambitious NDC targets in a virtuous circle.

There seems to be little question but that some jurisdictions throughout the world have gone beyond the most narrow definition of pure self-interest in proposing relatively more ambitious emissions targets, even if this level of ambition still falls well short of full golden-rule behavior. Altruism may thus help somewhat, and is to be encouraged, but most economists would express at least partial skepticism about this golden-rule model because it is typically difficult to resolve free-rider problems by altruism alone. In this paper we go to the opposite extreme of altruistic behavior by examining the consequences of a model of pure self interest.

A jurisdictional cap-and-trade system assigns allowances of CO_2 caps to emitters within a jurisdiction and then allows (or even encourages) internal free trade in permits. Total emissions of CO_2 must equal the sum of all allocated caps. Regulators of a cap-and-trade system can thus control the total amount of CO_2 emissions within their jurisdiction by controlling the sum of all allocated caps. As economists have long emphasized, a cap-and-trade system is cost effective because it minimizes total abatement costs for each chosen level of total CO_2 emissions via ensuring that every emitter in the jurisdiction sets its marginal cost of abatement equal to the equilibrium price of permits.

Economists have typically advocated *linkage* of different cap-and-trade jurisdictions by rough analogy with the beneficial linking of free-trade areas and on the more specific basis that this will ensure cost effectiveness among the linked jurisdictions.[2] An unlinked cap-and-trade system guarantees cost effectiveness only within its own jurisdiction. A linked cap-and-trade system goes further by also ensuring cost effectiveness among the linked ju-

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[2] See, for example, the extremely comprehensive article of Mehling, Metcalf, and Stavins (2018), and the numerous further references they cite.

risdictions taken as a whole.

The argument for linkage based on cost effectiveness might make sense when there is an overall top-down governance structure that can force Pareto-improving side payments among the linked participants. But absent such a powerful overall governance structure, this cost-effectiveness argument in a strictly voluntary cap-and-trade system loses its force. Cap-and-trade jurisdictions that have linked their cap-and-trade systems will issue their own voluntary caps on the basis of a host of domestic political-economy considerations including, prominently, self interest. Narrow self interest, which is being modeled in this paper as if it were the sole motivation, will cause linked jurisdictions to pay relatively little attention to what is for them a strictly hypothetical argument about minimization of overall compliance costs. Be that as it may, there is a widespread feeling among most economists that linking cap-and-trade jurisdictions is a good idea.

The generally favorable attitude toward linkage has found its way into the COP21 Paris Agreement.[3] Paragraph 6.2 outlines a framework for recognizing traded obligations (called 'international transfer of mitigation outcomes') so that double counting is avoided because a party to the agreement is allowed to include traded reductions undertaken by another party to count toward the first party's NDC. Paragraph 6.3 states that: 'The use of internationally transferred mitigation outcomes to achieve nationally determined contributions under this Agreement shall be voluntary and authorized by participating parties'. The inclusion of articles 6.2 and 6.3 opens the door to linking cap-and-trade systems (or, indeed, any market-based mechanisms).

While linkage may give some jurisdictions incentives to choose more ambitious caps, it could also give other jurisdictions incentives to choose less ambitious caps. It is a seeming paradox that cap-and-trade among the parties to the Paris Agreement might lead to even higher emissions. If linkage of cap-and-trade systems does little more than replace one non-cooperative equilibrium with another, it will still be a far cry from the more cooperative outcome that might accompany a genuine international governance structure.

The insight that linking voluntary cap-and-trade systems may lead to higher levels of pollution emissions is not new.[4] The most complete rigorous analysis of this possibility is the pioneering work of Helm (2003), who models both unlinked and linked cap-and-trade systems as a non-cooperative Nash equilibrium among self-interested countries. His fairly general treatment of environmental pollution finds that overall effects on total emissions are ambiguous and he derives moderately complicated conditions for when pollution is increased

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[3] See Paris Agreement (2015).

[4] Early preliminary intimations of this tendency are expressed in Bohm (1992), Eyckmans and Proost (1996), and Krishna and Tan (1999). This issue is also discussed later in Green, Sterner, and Wagner (2014) and in Mehling, Metcalf, and Stavins (2018).

or decreased by linkage.

An appropriate and widely accepted specification for the damages of CO_2 emissions within a relatively short (5-10 year) period is that marginal damages are constant for each jurisdiction (although they can differ among jurisdictions). With this defensible assumption, the analysis is significantly clarified and yields simple closed-form expressions for all (linked and unlinked) CO_2 permit prices. Some sharp insights are then available. How a linked jurisdiction sets its voluntary caps relative to actual emissions (and whether the jurisdiction buys or sells CO_2 permits) is fully characterized by a simple linear proportionality condition that depends only on the difference between the jurisdiction's marginal damages and the average marginal damages of the entire linked system. Some implications for linked and unlinked voluntary CO_2 cap-and-trade systems are derived and discussed.

2 The Model

The emphasis in the model of this paper is on clarity of exposition and the appealing simplicity of clean crisp analytical results. Hopefully the model embodies enough of 'reality' to give some useful insights on an important issue.

Let there be a total of n ($\geq$2) cap-and-trade jurisdictions. Throughout this paper we economize on notation by not redundantly pointing out that index i always runs from $i = 1, 2, ..., n$ or that index j always runs from $j = 1, 2, ..., n$. Henceforth it is understood that i (or j) refer to one of the n jurisdictions under consideration.

For each i, the marginal damage of emissions within a pledge-and-review cycle is given as d_i. The marginal damages curve is thus assumed here to be flat in emissions flows. This assumption, which is standard in the climate-change literature, is appropriate for CO_2 emissions because it is the stock of accumulated CO_2 that does the damage and the relatively small flow of CO_2 emissions within, say, a 5-10 year period has an effectively linear impact on the overall stock of atmospheric CO_2. Let e_i represent the emissions flow of jurisdiction i. Let $D_i(E)$ denote the total damage to jurisdiction i of total emissions $E \equiv \sum e_i$ and let $D_i'(E)$ represent the marginal damage to jurisdiction i of total emissions E. Then we are assuming here that

$$D_i'(E) = d_i, \tag{1}$$

and the $\{d_i\}$ coefficients thus provide an unambiguous ordering of the marginal damages of emissions among the n cap-and-trade jurisdictions. [5] The constancy of marginal damages

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[5] Note that, other things being equal, jurisdictions with higher (lower) populations will tend to have larger (smaller) marginal damages of total emissions.

for each jurisdiction, which is a natural assumption for CO_2, allows for a simplification of results, which seemingly has not been taken full advantage of in this literature.

On the abatement cost side, let $C_i(e_i)$ denote the cost to jurisdiction i of emissions e_i, where $C_i'(e_i) < 0$ and $C_i''(e_i) > 0$. Note, importantly, that the marginal cost of *abatement* for jurisdiction i is *minus* $C_i'(e_i)$.

Let p be an exogenously imposed tax-price on emissions (it does not matter what is the source of the tax-price p, so long as it is perceived as exogenous). Let e_i here represent the emissions quantity reaction of jurisdiction i to the tax-price p. The functional relationship between e_i and p is given by the condition that marginal abatement cost equals price, or

$$p = -C_i'(e_i). \tag{2}$$

Let the function $e_i(p)$ represent the *inverse* of the marginal cost of abatement function $-C_i'(e_i)$ in (2). We can then write and conceptualize, whenever appropriate to the context, that

$$e_i = e_i(p), \tag{3}$$

where $e_i'(p) < 0$ because $C_i''(e_i) > 0$.

The two simple specifications (1) (which is very specific to CO_2), and (3) (which is entirely general for any cost functions $\{C_i(e_i)\}$ with $C_i''(e_i) > 0$) constitute the analytical framework for the study of unlinked and linked voluntary cap-and-trade systems investigated in this paper.[6]

3 Unlinked Voluntary Cap-and-Trade Systems

Independent unlinked jurisdiction i seeks to minimize over e_i the expression $D_i(E) + C_i(e_i)$. Let the solution be denoted $\widehat{e}_i$. Then $\widehat{e}_i$ satisfies the first-order condition $D_i'(\sum \widehat{e}_j) = -C_i'(\widehat{e}_i)$. Substituting from (1) and (3), this first-order condition translates into

$$\widehat{e}_i = e_i(d_i), \tag{4}$$

with the corresponding autarchic-internal cap-and-trade emissions price being

$$\widehat{p}_i = d_i. \tag{5}$$

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[6] We can only hope in this paper that, as is often the case in economic theory, an analytically-tractable flow model, standing in for a more complicated stock-flow situation, is capable of offering some useful insights. We have in mind here a pledge-and-review cycle of maybe five to ten years or so, which may be short enough to justify the model specification here.

Thus, it turns out, in the unlinked voluntary case of this model there is no strategic interaction among the n jurisdictions.

The total emissions of all jurisdictions, denoted $\widehat{E}$, is then

$$\widehat{E} \equiv \sum \widehat{e}_i = \sum e_i(d_i). \tag{6}$$

The free-riding voluntary autarchic emissions levels $\{\widehat{e}_i\}$ do not, by a wide margin, represent socially optimal emission levels. The socially optimal level of e_i, denoted e_i^*, satisfies the Lindahl-Samuelson public-goods condition $\sum d_j = -C_i'(e_i^*)$ for all i, whose inverse is $e_i^* = e_i(\sum d_j)$ and which clearly represents a lower level of emissions than $\widehat{e}_i$ given by equation (4).

The total socially optimal emissions level of all jurisdictions is then

$$E^* \equiv \sum e_i^* = \sum_i e_i(\sum_j d_j), \tag{7}$$

which is clearly lower than the free-riding total emissions $\widehat{E}$ given by equation (6). The corresponding uniform shadow price of socially optimal emissions (that also ensures cost effectiveness) is $p^* = \sum d_i$, which is clearly higher than the average unlinked voluntary cap-and-trade price $\sum \widehat{p}_i/n = \sum d_i/n$. However, as an extension of the argument about cost effectiveness given in the Introduction, socially optimal levels of CO_2 emissions or the socially optimal shadow emissions price of CO_2 are largely irrelevant for strictly voluntary cap-and-trade systems with no overarching top-down governance structure that can determine the initial allocation of CO_2 caps and penalize non-compliance. Absent such a powerful overall governance structure, the socially optimal solution in a strictly voluntary cap-and-trade system loses much of its rationale.

4 Linked Voluntary Cap-and-Trade Systems

Suppose that the n jurisdictions have been persuaded to link their cap-and-trade systems. We now investigate the steady-state Nash-equilibrium outcome of such linkage. This case presents far more of an analytical challenge than the case of unlinked cap-and-trade systems due to the strategic interaction among linked jurisdictions.

Note that even though we presume that all jurisdictions play individually and non-cooperatively against all other jurisdictions, some aspects of the rules of the game must be agreed upon beforehand. In particular, property rights, which are traded on the permit market, must be enforced. A jurisdiction must reveal its post-cap-and-trade permits to ensure consistency with its actual post-cap-and-trade emissions. (This is the meaning of Paragraph 6.2 of the COP21 Paris Agreement, previously referred to.)

Let the *actual* post-cap-and-trade emissions of jurisdiction i be denoted e_i^a. For any given exogenously-imposed CO$_2$ permit (or allowance) price P, the actual-emissions reaction of jurisdiction i is obtained by the condition $-C_i'(e_i(P)) = P$. This condition yields the same inverse-function formula as (3), rewritten here for emphasis as

$$e_i^a = e_i(P), \tag{8}$$

where $e_i'(P) < 0$.

Let $E^a \equiv \sum e_i^a$ represent *total actual* post-cap-and-trade emissions. We now seek to find the equilibrium permit price for the linked cap-and-trade system as a function of total actual emissions, denoted $P(E^a)$. Looking at actual emissions and adding up expression (8) over all i, we obtain $E^a(P) = \sum e_i(P)$, which, when inverted, yields the basic equation for the equilibrium permit price as a function of total actual emissions, namely $P(E^a)$.

Next, let e_i^c represent the emissions permits or caps issued voluntarily by jurisdiction i. The superscript 'c' stands for *cap* (and also for *control* variable). Define $E^c \equiv \sum e_i^c$ to be the total voluntary emissions caps or permits, and note that in equilibrium $E^c = E^a$. Let $\widetilde{e}_i^c$ represent the Nash-equilibrium self-interested number of voluntary emissions permits issued by jurisdiction i, contingent on Nash-equilibrium self-interested voluntary emissions permits $\widetilde{e}_j^c$ for all other jurisdictions $j \neq i$. Then $\widetilde{e}_i^c$ must *maximize* over all possible voluntary emissions caps e_i^c the expression

$$\left\{ P(e_i^c + \sum_{j \neq i} \widetilde{e}_j^c) \times (e_i^c - e_i^a) \right\} - \left(D_i(e_i^c + \sum_{j \neq i} \widetilde{e}_j^c) + C_i(e_i^a) \right), \tag{9}$$

where we understand e_i^a in expression (9) as being some implicit function of e_i^c.

The second term of (9), in round brackets, represents the loss of welfare to jurisdiction i from emissions damages and costs.

Let us examine more closely the important expression within the curly brackets of (9). If $e_i^a > e_i^c$, then jurisdiction i is obliged to *buy* from other jurisdictions $(e_i^a - e_i^c)$ emissions permits, costing it a cash *loss* of $P \times (e_i^a - e_i^c)$, which renders the expression in the curly brackets of (9) negative, reflecting cash outflows out of jurisdiction i. If $e_i^a < e_i^c$, then jurisdiction i can *sell* to other jurisdictions $(e_i^c - e_i^a)$ emissions permits, earning it a cash *revenue* of $P \times (e_i^c - e_i^a)$, which renders the expression in the curly brackets of (9) positive, reflecting cash inflows into jurisdiction i. To summarize here, the expression in the curly brackets of (9) exactly equals the *net* cash flow into jurisdiction i from inter-jurisdictional tradable permits.

The Nash-equilibrium linked cap-and-trade actual emissions of jurisdiction i is denoted $\widetilde{e}_i^a$. The Nash-equilibrium emissions permits (or caps) voluntarily issued by jurisdiction i is denoted $\widetilde{e}_i^c$. Taking derivatives with respect to e_i^c and making use of (1), the first-order condition for $\widetilde{e}_i^c$ to maximize over all e_i^c expression (9) in a self-interested Nash equilibrium is

$$\left[\frac{\partial}{\partial e_i^c}\left\{P(e_i^c+\sum_{j\neq i}\widetilde{e}_j^c)\times(e_i^c-e_i^a)\right\}\right]_{e_i^c=\widetilde{e}_i^c;\, e_i^a=\widetilde{e}_i^a}-\left(d_i+C_i'(\widetilde{e}_i^a)\frac{\partial e_i^a}{\partial e_i^c}\right)=0. \tag{10}$$

Let $\widetilde{E}$ $(=\sum \widetilde{e}_i^c=\sum \widetilde{e}_i^a)$ be total Nash-equilibrium emissions in the linked cap-and-trade system. Then the expression in the first term of the left hand side of equation (10) can be evaluated in a Nash equilibrium as

$$\left[\frac{\partial}{\partial e_i^c}\left\{P(e_i^c+\sum_{j\neq i}\widetilde{e}_j^c)\times(e_i^c-e_i^a)\right\}\right]_{e_i^c=\widetilde{e}_i^c;\, e_i^a=\widetilde{e}_i^a}=P(\widetilde{E})\times\left(1-\frac{\partial e_i^a}{\partial e_i^c}\right)+P'(\widetilde{E})\times(\widetilde{e}_i^c-\widetilde{e}_i^a). \tag{11}$$

Next, substitute (11) into equation (10). After rearranging terms, we then derive

$$d_i+\left[P(\widetilde{E})+C_i'(\widetilde{e}_i^a)\right]\frac{\partial e_i^a}{\partial e_i^c}-P(\widetilde{E})-P'(\widetilde{E})\times(\widetilde{e}_i^c-\widetilde{e}_i^a)=0. \tag{12}$$

The term within the square brackets on the left hand side of (12) is zero because price equals marginal abatement cost in a cap-and-trade system. The first-order condition (12) then becomes

$$d_i-P(\widetilde{E})-P'(\widetilde{E})\times(\widetilde{e}_i^c-\widetilde{e}_i^a)=0. \tag{13}$$

Add up over all i the expression (13), yielding the equation

$$\sum d_i-nP(\widetilde{E})-P'(\widetilde{E})\times\sum(\widetilde{e}_i^c-\widetilde{e}_i^a)=0. \tag{14}$$

In equilibrium,

$$\sum \widetilde{e}_i^a=\sum \widetilde{e}_i^c, \tag{15}$$

so that the last term of the left hand side of equation (14) vanishes, turning equation (14) into

$$\sum d_i-nP(\widetilde{E})=0. \tag{16}$$

Define $\overline{d}$ to be the *average* marginal damage across all n jurisdictions

$$\overline{d}\equiv\frac{\sum d_i}{n}, \tag{17}$$

and let $\widetilde{P} \equiv P(\widetilde{E})$ be the equilibrium price of permits in the linked cap-and-trade system. Then we have from (16) and (17) the fundamental result that

$$\widetilde{P} = \overline{d}. \tag{18}$$

It should be appreciated that equation (18) has been derived under extremely general assumptions about the abatement cost functions. The only substantive assumption, which accounts for the utter simplicity of expression (18), is the eminently defensible specification that marginal damages are constant for CO_2 emissions within a relatively short (5-10 year) period.

5 Linked vs. Unlinked Voluntary Cap-and-Trade

We have already derived for the unlinked voluntary cap-and-trade system that the self-volunteered autarchic price of permit within jurisdiction i is $\widehat{p}_i = d_i$. Define $\widehat{P}$ to be the *average* unlinked voluntary permit price over all jurisdictions

$$\widehat{P} \equiv \frac{\sum \widehat{p}_i}{n}. \tag{19}$$

Then, making use of (5), (17), and (19), equation (18) can be rewritten as

$$\widetilde{P} = \widehat{P}. \tag{20}$$

which means that the linked voluntary permit price is the *average* of the unlinked voluntary permit prices.

We have repeatedly relied on the simplifying, but justified, assumption that, within a relatively short period (say 5-10 years), marginal damages are constant for each jurisdiction. Using this simplifying assumption again, how a linked jurisdiction sets its voluntary caps relative to actual emissions (and whether the jurisdiction buys or sells CO_2 permits) is fully characterized by a simple condition depending on the relationship between the jurisdiction's marginal damages and the average marginal damages of the entire linked system.

From (18), $\widetilde{P}(E) \equiv \widetilde{P} = \overline{d}$, and then equation (13) can be rewritten as

$$\widetilde{e}_i^c - \widetilde{e}_i^a = k \times (\overline{d} - d_i), \tag{21}$$

where

$$k \equiv \frac{-1}{P'(\widetilde{E})} > 0 \tag{22}$$

is viewed by all jurisdictions i as the same positive constant of proportionality.

Equation (21) is revealing. The only instrument under direct control of jurisdiction i is its voluntary cap e_i^c. Controlling the setting of its own voluntary cap e_i^c is the only way for jurisdiction i to influence total emissions $\widetilde{E}$. In Nash equilibrium, $e_i^c = \widetilde{e}_i^c$. It is then natural to ask: When does jurisdiction i set its control cap $e_i^c (= \widetilde{e}_i^c)$ relatively low and when does jurisdiction i set its control cap $e_i^c (= \widetilde{e}_i^c)$ relatively high? The natural benchmark for the voluntary setting of cap $e_i^c (= \widetilde{e}_i^c)$ is a comparison with the actual post-cap-and-trade emissions of i – namely $\widetilde{e}_i^a$. For all jurisdictions i, the actual equilibrium emissions $\widetilde{e}_i^a$ are a natural standard for comparison with equilibrium cap $\widetilde{e}_i^c$ because $\sum \widetilde{e}_i^c = \sum \widetilde{e}_i^a$ and because $\{\widetilde{e}_i^a\}$ represents actual emissions normed to the *same* common price $\widetilde{P}$. Equation (21) tells us exactly what is the sought-after difference $(\widetilde{e}_i^c - \widetilde{e}_i^a)$.

From equation (21), we have the quantitative result that $\widetilde{e}_i^c - \widetilde{e}_i^a$ is directly proportional to $\overline{d} - d_i$ with the same constant of proportionality $k > 0$ for all i. This implies two qualitative results:

$$d_i > \overline{d} \iff \widetilde{e}_i^c < \widetilde{e}_i^a, \tag{23}$$

and

$$d_i < \overline{d} \iff \widetilde{e}_i^c > \widetilde{e}_i^a. \tag{24}$$

The interpretation of condition (23) should be relatively clear. When the marginal damage d_i to jurisdiction i is greater than the average marginal damages of the entire linked system $\overline{d}$, then jurisdiction i wants its voluntary cap $e_i^c = \widetilde{e}_i^c$ to be relatively lower, in order to cut back total emissions even though, in this case, jurisdiction i ends up spending cash to buy $(\widetilde{e}_i^a - \widetilde{e}_i^c) > 0$ emissions permits to counter-balance the relatively low setting of its voluntary cap.

The interpretation of condition (24) should likewise be relatively clear (but in the opposite direction of (23)). When the marginal damage d_i to jurisdiction i is less than the average marginal damages of the entire linked system $\overline{d}$, then jurisdiction i wants its voluntary cap $e_i^c = \widetilde{e}_i^c$ to be relatively higher, in order to allow total emissions to be higher, a direction toward which jurisdiction i is relatively tolerant because d_i is relatively low. In this case, jurisdiction i ends up with more cash by selling $(\widetilde{e}_i^c - \widetilde{e}_i^a) > 0$ emissions permits to counter-balance the relatively high setting of its voluntary cap, which is part of its motivation to issue relatively higher emissions permits.

How do total emissions compare between linked and unlinked voluntary cap-and-trade systems? Going back to equation (3), we can derive a simple condition for comparing total emissions, which, unfortunately, is not so simple to understand completely. A linked voluntary cap-and-trade system emits *less* in total than an unlinked cap-and-trade system if

$$\sum e_i(d_i) > \sum e_i\left(\overline{d}\right), \tag{25}$$

and conversely a linked voluntary cap-and-trade system emits *more* in total than an unlinked cap-and-trade system if

$$\sum e_i(d_i) < \sum e_i\left(\overline{d}\right). \tag{26}$$

Each of the n terms of (25) and (26) can be signed. If $d_i > \overline{d}$, then $e_i(d_i) < e_i(\overline{d})$ (with interpretation $\widehat{e}_i < \widetilde{e}_i^a$). Conversely, if $d_i < \overline{d}$, then $e_i(d_i) > e_i(\overline{d})$ (with interpretation $\widehat{e}_i > \widetilde{e}_i^a$). This signing of $e_i(\cdot)$ terms might be interpreted as hinting that the right and left hand sides of (25) and (26) might not differ greatly from each other since roughly half of the jurisdictions have the inequality in $e_i(\cdot)$ going one way and roughly the other half have the inequality in $e_i(\cdot)$ going the other way. However, this is merely crude heuristic hand-waving, not a formal argument.

Conditions (25) and (26) are not easy to analyze rigorously and could go either way, depending here on the distribution of the $\{d_i\}$ and the functions $\{e_i(\cdot)\}$. The literature is not decisive on this issue. Plausible arguments have been made on both sides.[7]

It is also difficult to characterize in general whether a jurisdiction has higher welfare from joining a linked cap-and-trade system or from remaining autarchic. It might have been presumed on basic principles of trade theory that joining a linked cap-and-trade system (offering a quasi-constant permit price of emissions) delivers higher welfare to a jurisdiction than remaining at the fixed autarchic level of emissions. However, this presumption does not hold in general for the situation here, where jurisdictions are gaming the system by strategically setting their own tradable emissions caps. [8]

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[7] For example, Holtsmark and Sommervoll (2012) plausibly argue that total emissions are likely to be *higher* under linked voluntary cap-and-trade than under unlinked voluntary cap-and-trade. On the other hand, Carbone, Helm, and Rutherford (2009) plausibly argue that total emissions are likely to be *lower* under linked voluntary cap-and-trade than under unlinked voluntary cap-and-trade. Both of these two examples involve static games (as does this paper). In a dynamic model with both fossil fuels and renewables, Holtsmark and Midtømme (2016) argue that linking leads to lower emissions. At this stage we think it is an open question how linkage of cap-and-trade systems influences emissions.

[8] Section III of Godal and Holtsmark (2011) contains just such a counterexample where joining a linked cap-and-trade system yields lower welfare to a jurisdiction than remaining at the fixed autarchic level of emissions. In this paper we restrict ourselves to comparing linked and unlinked voluntary cap-and-trade systems without inquiring deeply into the individual motivations for participating in a linked system.

6 Concluding Remarks

An appropriate and widely accepted specification for the marginal damages of CO_2 emissions within a relatively short (5-10 years, say) period is that they are constant for each jurisdiction. This critical, but defensible, assumption greatly clarifies the analysis and yields simple closed-form expressions for all (linked and unlinked) CO_2 emissions prices. The current paper has derived and discussed some implications of this simplicity for linked and unlinked voluntary CO_2 cap-and-trade systems. How a linked jurisdiction sets its voluntary caps relative to actual emissions (and whether the jurisdiction buys or sells CO_2 permits) is fully characterized by a simple linear proportionality condition that depends only on the difference between the jurisdiction's marginal damages and the average marginal damages of the entire linked system. Whether linkage increases or decreases overall emissions depends on a condition that is easy to express but difficult to evaluate rigorously, and the answer could go either way.

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