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Carbon dating: When is it beneficial to link ETSs?

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Abstract

We propose a theory of the economic advantage (EA) of regulating carbon emissions by linking two emissions trading systems versus operating them under autarky. Linking implies that permits issued in one system can be traded internationally for use in the other. We show how the nature of uncertainty, market sizes, and sunk costs of linking determine EA. Even when sunk costs are small so EA>0, autarky can be preferable to one partner, depending on jurisdiction characteristics. Moreover, one partner's permit price volatility under linking may increase without making linking the less preferred option. An empirical application calibrates jurisdiction characteristics to demonstrate the economic significance of our results which can make linking partner match crucial for the effectiveness and success of the Paris Agreement.

JEL: Q58, H23.

Keywords: Emission Trading, Climate Change Policy, Market-based Regulation, Linking.

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1 Introduction

Markets for emission permits have long been an important climate policy tool in driving emission reduction efforts in a cost-effective and flexible way. The Paris Agreement (2015), adopted by 195 countries during the 21st Conference of Parties (COP21), has been interpreted as encouraging the use of these markets (Stavins (2016)). World Bank (2015) identifies one region consisting of 31 nations, eight individual nations and 23 sub-national jurisdictions which currently regulate carbon emissions using emissions trading systems (ETSs), and 13 additional ETSs are at various stages of development. The increasing number of planned and proposed systems suggests that a bottom-up policy architecture in which these systems interact will be a significant element of the global climate change policy framework in the future (European Commission (2015), *The Economist* (2015), and *The Financial Times* (2015)).

In fact, some systems have already linked, meaning one recognizes the other's permits for compliance and vice versa. There is an active link between the ETSs of Quebec and California, the so-called Western Climate Initiative (WCI), which four US states (New York, Vermont, Oregon and Washington) and two Canadian provinces (Ontario and Manitoba) have expressed interest in joining. The Regional Greenhouse Gas Initiative (RGGI) in the northeastern United States is effectively a system of jurisdictions with linked ETSs. Recently, the EU and Switzerland have concluded negotiations to link the European Union Emission Trading System (EU ETS) to the Swiss system, although the link is not yet active. Egypt, Vietnam, and Mexico announced plans to launch domestic ETSs that could link to other carbon markets.

In this paper we use a simple theoretical framework to quantify the economic advantage of linking over autarky, hereafter EA, and study how it depends on the combination of shocks affecting each jurisdiction and the jurisdictions' sizes; we refer to this combination as *pair characteristics*. A jurisdiction in this context is the set of entities that are under the control of a regulator who can design policies independently of regulators in other jurisdictions. We focus on bilateral links between jurisdictions and say that the ETSs are linked if the regulators in both jurisdictions agreed ex ante that the permits issued in one can be surrendered against compliance requirements in the other. Throughout we assume competitive permit trading.

We find that aggregate EA is increasing in jurisdictions' sizes and shock variances, but decreasing in the correlation of shocks and the exogenous sunk costs of linking. The latter includes the costs of negotiating the linking agreement, harmonizing the rules of the previously independent systems, setting up a platform for inter-jurisdictional transactions and other administrative costs. Some of these costs have already been recognized in the Paris Agreement (2015).

A novel contribution of our paper is to analyze how aggregate EA is distributed between the linking jurisdictions as a function of pair characteristics and the level of sunk costs. Specifically, we identify the conditions under which one jurisdiction is worse off even when aggregate EA is positive. Put differently, some linking partner matches, what we call carbon dates, generate greater value than others and for some carbon dates one partner can be worse off than staying single. When looking for a carbon date, our model helps answer the question: who is a good match?

Our framework also allows us to evaluate the permit price volatility under autarky and linking. We find that price volatility may increase or decrease relative to autarky depending on pair characteristics, and note that linking may be beneficial for a jurisdiction even if its price volatility increases under linking.

To put our analytical results into context, we calibrate pair characteristics to historical emissions data of ten key jurisdictions and evaluate aggregate and jurisdiction-specific EAs. The jurisdictions we consider include individual nations, a supranational region, as well as sub- and supranational sectors, reflecting the recent discussions among climate policy negotiators at COP21. This empirical exercise demonstrates that there is substantial, economically meaningful, and policy relevant variation among possible links between jurisdictions and confirms that the 'linking partner match' is not a trivial exercise.

Our theoretical model is an adaptation of the static model in Weitzman (1974) to two jurisdictions and to the case where pollution is uniformly mixed. It is similar in spirit to the multi-firm case considered in Yohe (1976) and the multinational production location decision studied in De Meza and Van der Ploeg (1987). However, in Yohe (1976) shocks are identically distributed and the comparative advantage of a uniform tax over a quantity standard is computed as a function of industry size. Here we are interested in the difference between the net benefits associated with two quantity instruments operated under linking and autarky, and place no restrictions on the distribution of the shocks. In De Meza and Van der Ploeg (1987) the sizes of plants are irrelevant, shocks are plant-specific and the objective of the multinational is to maximize profit by relocating production across plants in different counties. Cost and production levels at individual plants matter only to the extent that they contribute towards this objective. Accordingly, our focus on jurisdiction-specific EA is an important conceptual difference from this study.

Similarly, Yates (2002) develops a general framework for analyzing the aggregate economic advantage of trading permits across divisions within the same jurisdiction. These divisions can be interpreted as time, firms, regions with varying geographic and institutional characteristics, etc. In his framework *a single regulator* decides whether to allow trading across divisions. Yates finds that in the case of uniformly mixed pollutants, decentralized trading across divisions is optimal and should be adopted by the regulator.[1]

Yates (2002) anticipates our finding that when sunk costs are small, inter-jurisdiction trading is preferable from a social perspective. However, that linking will be adopted is not a forgone conclusion when regulators in each jurisdiction (often but not exclusively sovereign countries), must agree to trading. To show this we unpack the comparative advantage formula in Yates (2002) by decomposing aggregate economic advantage into three readily interpretable quantities, namely volatility, dependence, and pair size effects. This allows us to discipline how the three effects jointly operate in theory, and to evaluate their economic significance using real world data.

As described by Flachsland, Marschinski, and Edenhofer (2009) and Jaffe, Ranson, and Stavins (2009), linked jurisdictions will tend to experience reduced price volatility because domestic shocks are spread over a larger market. We clarify the conditions under which the conventional view does not apply. A similar effect has recently been observed by Caselli et al. (2015) in the international trade context as well. Openness to international trade can lower GDP volatility when country-specific shocks are the most important source of volatility. Hence, there is scope for diversification through trade. However, declines in GDP volatility due to international trade is by no means guaranteed.

Finally, Flachsland et al. (2009) and Jotzo and Betz (2009) comment on the relevance of

[1] Interpreting divisions as time periods, Yates and Cronshaw (2001), Williams (2002) and Fell, MacKenzie, and Pizer (2012) show that banking and borrowing provisions can be an optimal regulatory response to cost shocks.

increased liquidity and argue that the largest economic benefit comes from linking large ETSs. Our pair size effect captures and qualifies this result. It is an increasing function of each jurisdiction's size. Crucially, the increase in EA consequent to an increase in the size of a given jurisdiction makes it and its partner better off, but not equally so because the latter captures a greater share of the increase in value.

The policy literature on linking also mentions a host of other benefits and costs which are hard to quantify in our simple economic analysis. For example, linking provides opportunities to improve the administration and governance of linked permit markets. Insofar as linking leads to the alignment of the administration and design of markets, it streamlines the compliance process and can lead to reduced administrative costs for businesses operating in those jurisdictions. Moreover, the benefits of linking can have ramifications that go beyond the geographical jurisdiction of the linking partners. Indeed, linking can lead to a leveling of the international playing field and to an improved support of global cooperation for tackling climate change. At the same time, the process of linking can require significant and costly efforts that may discourage it despite the potential benefits. These include the alignment of technical requirements (e.g. monitoring, reporting and verification (MRV), and tracking systems) and of design features (e.g. level of ambition, mode of allocation, inter-temporal flexibility, price management rules) all of which have to be negotiated. Papers focusing on various aspects of these issues include Flachsland et al. (2009), Ranson and Stavins (2016), Burtraw et al. (2013), and Bodansky et al. (2015).

Others have explored the strategic implications of linking. Helm (2003), Rehdanz and Tol (2005), Carbone, Helm, and Rutherford (2009), and Holtsmark and Midttomme (2015) investigate the incentives to alter domestic emission caps when national permit markets are linked. Pizer and Yates (2015) investigate the implications of a delink clause on market outcomes under linking and propose the inclusion of flexible delinking provisions. Finally, a series of recent papers examines the club as a model for international climate policy (Nordhaus (2015), Victor (2015), Green, Sterner, and Wagner (2014) and Keohane, Petsonk, and Hanafi (2015)).

The paper is organized as follows. Section 2 introduces the model and defines jurisdiction-specific and aggregate EA. The analytical results and the empirical application can be found in Sections 3 and 4. Section 5 discusses the implications of relaxing the key model assumptions. Section 6 concludes. An appendix contains the derivations and proofs.

2 Theoretical model and equilibrium

Our analysis relies on a simple static model that specializes Weitzman (1974) and Yohe (1976) to the case of quantity-based policies designed to regulate uniformly mixed pollution in two countries with independent regulatory authorities.[2] The total benefits from emissions in country i are a function of the level of emissions $q_i \geq 0$ and are subject to country-specific shocks θ_i

$$B_i(q_i, \theta_i) \quad = \quad b_0 + (b_1 + \theta_i)q_i - \frac{b_2}{2\psi_i}q_i^2 \quad \text{where} \quad i = 1, 2.$$

The coefficients $b_0, b_1, b_2 \geq 0$ are identical across countries. We characterize and discuss the shocks in detail below. The parameter $\psi_i > 0$ controls the level of emissions in country i. To see this, consider the cost-minimizing response to an arbitrary positive permit price p in the absence of shocks, i.e. $b_1 - \frac{b_2}{\psi_i}q_i = p$. Then $\psi_1 > \psi_2$ implies that $q_1 > q_2$. We refer to this as country 1 being greater in size. Note that $\psi_1 > \psi_2$ does not imply that country 1 is larger along other economic dimensions.[3]

There is an alternative and observationally equilvalent interpreration of the coefficient ψ_i as a measure of country-specific abatement technology. In this interpretation, assuming all else is equal, $\psi_1 > \psi_2$ corresponds to country 1 having access to lower-cost abatement opportunities at the margin. We discuss the implications of allowing for diffferences in technology as well as size in Section 5.

Carbon dioxide is a uniformly mixed stock pollutant and total climate change damages in

[2]Jurisdiction is more appropriate since ETSs can be set up and linked, at sectoral, subnational, national or regional levels. We use country for brevity in Sections 2 and 3.

[3]On average, Canadian emissions are greater than Brazilian emissions, which would imply $\psi_{CAN} > \psi_{BRA}$. This is true despite the fact that Brazil's real GDP and population are, respectively, twice and five times larger than Canada's.

each country are a function of aggregate quantity emitted, $q_1 + q_2$. Accordingly, we have

$$D_i(q_1 + q_2) = d_0 + d_1(q_1 + q_2) + \frac{d_2}{2}(q_1 + q_2)^2,$$

where $d_0, d_1, d_2 \geq 0$. We assume that the effect of exogenous and fixed emissions from the rest of the world are subsumed in these parameters. Note that the level of aggregate damages corresponds to the sum $D_1(q_1 + q_2) + D_2(q_1 + q_2)$.

The rest of this section illustrates the source of the economic advantage of linking, first informally in a deterministic setting with arbitrary quotas, and then in a stochastic setting where quotas are such that expected permit prices under autarky are equal across countries. Then to proceed formally we state our assumptions regarding the shocks θ_i. Finally, we discuss how the regulators set the quotas under linking and autarky which allows us to charactherize the equilibiria subject to these quotas.

Suppose that the countries are identical in every respect except that country 1 is larger ($\psi_1 > \psi_2$). For illustration purposes, Figure 1 assumes the two countries impose the same quota on emissions despite the difference in size ($\hat{q}_1 = \hat{q}_2$). This implies a higher autarky price in country 1 and an inefficiency in the way emission reductions are allocated across countries due to the price wedge $\hat{w}$. Under linking, the price difference is eliminated as permits flow from country 2 to 1 until both countries face the same price $\hat{p}_L$. In a sense, linking increases the cap in the high-price country and reduces it by the same amount in the low-price country leaving the aggregate cap unchanged. Both countries gain from the reallocation of emission reductions. The marginal benefit curves MB_i, quotas $\hat{q}_i$, the price wedge $\hat{w}$ and the linking equilibrium price $\hat{p}_L$ are illustrated in Figure 1.

Next, suppose the countries set their quotas so that each country's autarky price is equal to $\hat{p}_L$. Denoting these quotas $\tilde{q}_1$ and $\tilde{q}_2$ in Figure 1, we note that there is no longer any incentive to trade. Now assume that a positive shock occurs in country 1 and shifts its marginal benefit curve up to MB_1'. This opens up another wedge $\tilde{w}$ between the autarky prices and creates potential gains from trade. If the two ETSs are linked, the post-shock price difference that we would have observed under autarky is immediately eliminated and the linking equilibrium price $\tilde{p}_L$ efficiently reallocates emission reductions across countries to realize the potential gains from trade. But how are the total benefits and their distribution between the two countries determined? The shaded triangles in

Figure 1 shed light on this question. They suggest that the magnitude of the shock and ψ_i play a key role. We develop this idea analytically in the next section.

< Figure 1 here >

We now specify the nature of the shocks in more detail. Specifically, we assume that country-specific shocks are limited to the intercepts of the marginal benefit schedules. These shocks capture the net effect of factors that may influence emissions and their associated benefits such as business cycle and technology shocks, country-specific events, changes in the prices of factors of production, weather fluctuations, etc. For example, a favorable aggregate total factor productivity shock would increase the benefits of emissions and in our model would correspond to $\theta_i > 0$.[4]

The shock distributions and their variance-covariance matrix, are at the heart of our analysis. We impose minimal restrictions: shocks are mean-zero, constant variance, and possibly correlated random variables.[5] That is, for $i = 1, 2$ we define

$$\begin{aligned} \mathbb{E}(\theta_i) &= 0, \\ V(\theta_i) &= \sigma_i^2, \\ \mathrm{Corr}(\theta_1, \theta_2) &= \rho \in [-1, 1]. \end{aligned} \tag{1}$$

Also, we assume that $b_1 + \theta_i > 0$ for every possible realization of the shock. This assumption ensures that without regulation, the marginal benefit of emissions is always positive and the emission control problem under investigation is non-trivial.

We refer to the combination of shock characteristics and country sizes in a given pair as *pair characteristics* and denote it as $\{(\psi_1, \sigma_1), (\psi_2, \sigma_2), \rho\}$. Finally, we introduce the sunk cost of linking $\epsilon \geq 0$. We assume that aggregate sunk costs are exogenous, proportional to the size of the linked systems, and shared according to country size. That is, given pair characteristics, the total linking cost is $(\psi_1 + \psi_2)\epsilon$ where country 1 incurs $\psi_1\epsilon$.

In what follows we analyze the case where the regulator in each country sets its quota so as to maximize its net benefits under autarky taking the other country's quota choice as

[4]Below, we interpret these shocks as being related to the cyclical components of emissions obtained using the Hodrick-Prescott filter.

[5]We assume mean-zero shocks for convenience. Our results hold for $\mathbb{E}(\theta_i) \neq \mathbb{E}(\theta_j) \neq 0$.

given. The resulting non-cooperative equilibrium quota pair, characterized in Appendix A, is denoted as $(\bar{q}_1, \bar{q}_2)$.[6] We assume that the quotas remain the same *under both autarky and linking* so that aggregate outcomes under the two regimes are comparable.

Given these quotas, the regulator in each country faces a simple choice between two options: operating an ETS under autarky, where the competitive equilibrium is denoted by the pairs (p_{Ai}, q_{Ai}) for $i = 1, 2$, or linking the system with the other country's ETS, in which case the competitive equilibrium is given by the triple (p_L, q_{L1}, q_{L2}). The regulators make this choice by comparing the level of expected net benefits under autarky to expected net benefits under linking. Linking takes place only when both regulators agree ex ante to link.

Throughout the paper we restrict our attention to interior equilibria and discuss the implications of relaxing this assumption in Section 5. The *autarky equilibrium* (AE) in country i is given by

$$(p_{Ai}, q_{Ai}) = (b_1 - \frac{b_2}{\psi_i}\bar{q}_i + \theta_i, \bar{q}_i). \tag{2}$$

In words, the autarky equilibrium quantity is fixed at the level of the quota, the equilibrium price is positive, increasing in the country's own shock but is independent of the other country's shock.

In order to characterize the *linking equilibrium* (LE) we define $n \in [-\bar{q}_2, \bar{q}_1]$ as the number of permits exported from country 1 to country 2 with the understanding that when $n < 0$, country 1 imports permits. In an LE,[7]

$$(p_L, q_{L1}, q_{L2}) = \left(K + \frac{\psi_1\theta_1 + \psi_2\theta_2}{\psi_1 + \psi_2}, \bar{q}_1 - n, \bar{q}_2 + n \right), \tag{3}$$

where the constant K and n are

$$K = b_1 - \frac{b_2\,(b_1 - d_1)}{b_2 + d_2\,(\psi_1 + \psi_2)} \quad \text{and} \quad n = \frac{1}{b_2}\frac{\psi_1\psi_2}{(\psi_1 + \psi_2)}\,(\theta_2 - \theta_1)\,.$$

[6] Appendix A also characterizes the cooperative solution to the quota-setting problem and shows that the analytical results about the aggregate benefits of linking remain unaltered. In fact, any other quota pair that generates the same expected price under autarky would not alter our results.

[7] The full characterization of the autarky and linking equilibria, including the corner solutions, is available upon request.

In particular, the country with the higher shock will import permits because the regulated entities there place a greater value on permits. As illustrated earlier, linking increases the effective cap in the high-shock country and reduces it by the same amount in the low-shock country leaving the aggregate cap unchanged.[8]

Economic advantage under linking versus autarky

We are finally in a position to address the question raised in the title of the paper. To that end we define the country-specific EA (δ_i) as the difference between the net benefits under linking minus the net benefits under autarky given exogenous, country-specific sunk costs of linking, $\psi_i \epsilon \geq 0$. We define aggregate EA (Δ) as the sum of country-specific advantages.[9]

Under autarky, permit costs and initial owners' rents cancel out. However, they differ in value under linking. In fact, when country 1 exports its permits, it reduces its emissions below $\bar{q}_1$ and sells unused permits at $p_L > p_{A1}$. Country 2, instead, imports permits and increases its emissions beyond its cap. Linking allows country 2's private benefits of emissions to increase, yet at a lower overall permit cost because $p_L < p_{A2}$.

Making use of the interior equilibrium assumption, we obtain:

$$\begin{aligned}
\delta_1 &= B_1(\bar{q}_1 - n, \theta_1) - B_1(\bar{q}_1, \theta_1) + p_L n - \psi_1 \epsilon, \\
\delta_2 &= B_2(\bar{q}_2 + n, \theta_2) - B_2(\bar{q}_2, \theta_2) - p_L n - \psi_2 \epsilon, \qquad (4) \\
\Delta &= [B_1(\bar{q}_1 - n, \theta_1) + B_2(\bar{q}_2 + n, \theta_2)] - [B_1(\bar{q}_1, \theta_1) + B_2(\bar{q}_2, \theta_2)] - (\psi_1 + \psi_2)\,\epsilon.
\end{aligned}$$

δ_i and Δ are random variables evaluated at equilibrium prices and allocations. Below we will refer to the expected country-specific and expected aggregate EA by simply using the terms 'individual' / 'country-specific' and 'aggregate' EA, respectively.

[8] This is the market-based analog of the outcome approximated using regulator-imposed trading ratios in Holland and Yates (2015) and Muller and Mendelsohn (2009).

[9] Formally, country-specific EA can be written as the difference between private benefits net of permit costs, minus emission damages, plus initial permit holders' rents, under linking and under autarky, where the former must also account for the sunk costs of linking. This corresponds to $\delta_i = [B_i(q_{Li}, \theta_i) - p_L q_{Li} - D_i(q_{Li} + q_{Lj}) + p_L \bar{q}_i - \psi_i \epsilon] - [B_i(q_{Ai}, \theta_i) - p_{Ai} q_{Ai} - D_i(q_{Ai} + q_{Aj}) + p_{Ai} \bar{q}_i]$.

3 Analytical results

This section defines the three components that constitute $E[\Delta]$, relates them to existing literature, and highlights the analytical contributions of the current paper. In Proposition 1, we show how $E[\Delta]$ is split between the countries and characterize the cases where one country may be worse off under linking even when aggregate economic advantage is positive, i.e. $E[\Delta] > 0$. We then study the permit price variability under linking and autarky. In Proposition 2 we spell out the condition under which a country with $E[\delta_i] > 0$ faces an increase in price volatility relative to autarky. All proofs are provided in Appendix B.

Definition. Given pair characteristics $\{(\psi_1, \sigma_1), (\psi_2, \sigma_2), \rho\}$ where $\psi_i > 0$, $\sigma_i \geq 0$ and $\rho \in [-1, 1]$ for $i = 1, 2$, define pair size effect (PSE), volatility effect (VE) and dependence effect (DE) as

$$\begin{aligned} PSE(\psi_1, \psi_2) &= \frac{\psi_1 \psi_2}{2b_2 (\psi_1 + \psi_2)}, \\ VE(\sigma_1, \sigma_2) &= \sigma_1^2 + \sigma_2^2, \\ DE(\sigma_1, \sigma_2, \rho) &= -2\sigma_1 \sigma_2 \rho. \end{aligned}$$

We start with a few remarks about these effects. First, PSE is increasing in each of its arguments so that larger linked systems feature a greater PSE. However, for a given total size of the linked countries, $\psi_1 + \psi_2 = \tilde{\psi}$, PSE is maximized when $\psi_1 = \psi_2 = \tilde{\psi}/2$. Conversely, in a link where country sizes differ, the smaller country determines the magnitude of PSE. Second, VE is positive except in the trivial case when shock variances are zero in both countries. Third, DE is decreasing in ρ, may be positive or negative depending on the sign of ρ but it can never be larger than VE in absolute value, i.e. $|DE| \leq VE$. The interplay of these effects and $\mathbb{E}[\Delta]$ are described in the following lemma.

Lemma. *Let $\epsilon \geq 0$, then $\mathbb{E}[\Delta] = PSE\,(VE + DE) - (\psi_1 + \psi_2)\,\epsilon$.*

In words, aggregate EA is the sum of volatility and dependence effects scaled by the pair size effect net of sunk costs. Taking a step back, $\mathbb{E}[\Delta]$ is increasing in the participating countries' sizes and shock variances but decreasing in the correlation of shocks and the sunk costs.[10] In a recent theoretical study of the optimal scope of price and quantity policies, Caillaud and Demange (2015) observe a similar result but limit their analysis to the analog of our aggregate EA.

Two special cases under the assumption of zero sunk costs help intuition. When the variances of shocks are equal and they are perfectly positively correlated ($\sigma_1 = \sigma_2 > 0$, $\rho = 1$), $\mathbb{E}[\Delta] = 0$ because $VE + DE = 0$ regardless of PSE. That is, linking cannot generate any additional value over autarky because a price wedge never emerges. In effect, for all possible realizations of the shock pair, the implied autarky prices are always equal. This eliminates any incentive to trade permits internationally so there is no economic advantage of linking over autarky. At the opposite extreme is the case with perfect negative correlation ($\sigma_1 = \sigma_2 > 0$, $\rho = -1$) and the economic advantage of linking is at its maximum. That is, a country prefers the demand in its partner's market to be perfectly inversely related to its own because this always generates the largest price wedge. More generally, for $PSE(VE + DE) > 0$, we need two conditions to be satisfied i) $\sigma_i > 0$ in at least one country and ii) $\rho < 1$ or $\sigma_i \neq \sigma_j$. Below, we assume that $PSE(VE + DE) > 0$.

The effect of PSE on $E[\Delta]$ notwithstanding, versions of the lemma were noted in other contexts. For example, in a more general framework, Yates (2002) shows that decentralization, the analog of linking here, is always preferred for uniformly mixed pollutants and provides an isomorphic comparative advantage formula. As discussed in the introduction, the production location decision of multinationals (De Meza and Van der Ploeg (1987)) and the optimality of banking and borrowing of tradable pollution permits (Yates and Cronshaw (2001) and Fell et al. (2012)) can also be viewed in this light. The focus of these studies is the aggregate EA from the point of view of a single regulator. In contrast, Proposition 1 shows how this aggregate value is distributed across countries that are under the control of independent regulators.

Proposition 1. *Let $\epsilon \geq 0$. Then for $i = 1, 2$ and $i \neq j$*

$$\mathbb{E}\left[\delta_i\right] = \frac{\psi_j}{\psi_i + \psi_j}\mathbb{E}\left[\Delta\right] + \left(\psi_j - \psi_i\right)\epsilon.$$

[10] The observation that variability can be beneficial has a long history in economics, e.g. Waugh (1944), Oi (1961), and Markowitz (1952).

An immediate implication of the proposition is that when $\psi_i = \psi_j$, $E[\Delta]$ is equally shared between the countries. Moreover, when linking costs are zero $\epsilon = 0$, linking cannot make the countries worse off. When linking costs are not negligible, $\epsilon > 0$, it is possible to find pair characteristics such that $\mathbb{E}[\delta_i] = \mathbb{E}[\delta_j] \lesseqgtr 0$. Put differently, with $\epsilon > 0$ links between some country pairs will be beneficial, while for others it will not. However, countries in a given pair will not disagree on whether the link is worthwhile or not.

There is also no disagreement between countries when $\psi_i \neq \psi_j$ and $\epsilon = 0$. In this case, the larger country receives a smaller share of $E[\Delta]$. To see this let $\psi_i > \psi_j$ and observe that in Proposition 1 the share of $E[\Delta]$ due to country i is $\psi_j/(\psi_i + \psi_j)$. Despite the fact that country i receives a smaller share, it prefers linking to autarky because $0 < E[\delta_i] < E[\delta_j]$. A more interesting case arises when $\epsilon > 0$ which is explored in the following corollary.

Corollary. *Assume $\psi_1 = 1$ and $\psi_2 \in (0, 1)$ without loss of generality. Then $\mathbb{E}[\delta_1] < 0 < \mathbb{E}[\delta_2]$* and *$\mathbb{E}[\Delta] > 0$ when $\hat{\epsilon}$ satisfies*

$$\frac{\psi_2}{(1+\psi_2)} PSE(VE + DE) < \hat{\epsilon} < \frac{1}{(1+\psi_2)} PSE(VE + DE).$$

Negotiating and implementing a linking agreement may be complicated and costly, and no link will make economic sense if these upfront costs, ϵ, are too high. The corollary clarifies the condition under which the linking agreement will not be established even if $\mathbb{E}[\Delta] > 0$. This is because under the assumed cost sharing rule the regulator in country 1 faces too high costs and will not consent.

Next we consider the cases where both countries are better off under linking and show that this does not necessarily imply that the price volatility declines in both countries after linking.

Proposition 2. *Assume $\epsilon \geq 0$ is sufficiently small so $\mathbb{E}[\delta_i] \geq 0$ for $i = 1, 2$. Moreover, assume $0 \leq \sigma_1 < \sigma_2$ and $\psi_1 = 1$ without loss of generality. Then $V[p_{A2}] > V[p_L]$ for all allowed pair characteristics and $V[p_{A1}] < V[p_L]$ when*

$$\psi_2 > \frac{2(\sigma_1^2 - \sigma_1\sigma_2\rho)}{(\sigma_2^2 - \sigma_1^2)}.$$

In a mutually beneficial link, the permit price volatility always declines in the more volatile country relative to autarky but it may increase in the less volatile country. Put differently, a decline in price volatility is not a necessary condition for linking to be preferred. This is trivially true when $\sigma_1 = 0$ and $\epsilon = 0$, because the right hand side of the inequality is 0. Intuitively, under autarky the marginal benefit in country 1 is constant whereas the marginal benefit in country 2 depends on the shock realization. Consequently, ex post autarky permit price levels will almost surely differ. It is this difference in prices that makes linking mutually beneficial. This is despite the fact that under linking, country 1 agrees to 'import' some volatility from country 2; yet, it is well compensated for doing so. When $\sigma_1 > 0$, one must also account for the linking partners' relative sizes and the correlation of shocks. As our empirical application in the next section shows, it is not difficult to satisfy this condition in the real world. Hence, contrary to most people's intuition, higher price volatility relative to that under autarky does not necessarily leave a country worse off.

4 Empirical application

This section demonstrates the economic and policy relevance of our analytical results. We revert to using the term 'jurisdiction', and focus on potential bilateral links that may be formed amongst the hypothetical ETSs of ten real-world jurisdictions. Our goal is to illustrate the variation that exists in the empirical counterparts of PSE, VE and DE as well as the aggregate and jurisdiction-specific EA.

To align our empirical exercise with the theoretical model above, we assume that the hypothetical ETS in a given jurisdiction covers all carbon emissions, and that jurisdiction-specific quotas are set so that expected permit prices under autarky are equal. We also assume that the sunk costs of linking are zero and maintain our assumption that the jurisdictions in a bilateral link have identical technology. While this assumption lacks realism, it reduces substantially the data required to calibrate the model. Moreover, in the next section we argue that it is a conservative assumption in the sense that relaxing it would strengthen our results.

Our sample includes several *countries*, i.e. China, USA, Japan, South Korea, Mexico, and Egypt; a *supranational* region consisting of the countries which are members of the European Union plus Iceland, Norway, and Liechtenstein; a *subnational* but crucial sector, namely the power sector in the USA; and two *supranational* sectors whose emissions are sizable, rapidly growing, and currently unregulated, i.e. International Aviation (IAB) and Marine Bunkers (IMB).[11] Arguably, the 44 possible linking arrangements between these jurisdictions are broadly representative of possible future links that may be considered.[12]

We obtain annual country level carbon dioxide emissions data covering 1950-2012 from the World Resources Institute.[13] We complement this dataset with IAB and IMB emissions data covering 1971-2012 from the Organization for Economic Co-operation and Development, and data for the USPWR emissions covering 1950-2011 from the Energy Information Administration. We denote an observation from jurisdiction i and year t entry by e_{it}.

To calibrate ψ_i, σ_i and ρ, we start by noting that in our model the natural logarithm of laissez-faire emissions are given by

$$ln\left(q_i^{LF}\right) = ln\left(\frac{b_2}{\psi_i}\right) + ln\left(b_1 + \theta_i\right).$$

We associate each component of $ln\left(q_i^{LF}\right)$ with the trend and cyclical components of emissions obtained using the HP filter introduced by Hodrick and Prescott (1997) with the penalty parameter $\lambda = 6.25$ for annual data. This is in the spirit of Doda (2014) and consistent with our interpretation of variation in the marginal benefits of emissions as being driven by business cycle and/or technology shocks, country-specific events, changes in the prices of factors of production, weather fluctuations, etc.

Formally, the HP filter decomposes the observed series $\{ln(e_{it})\}$ into two time series $\{e_{it}^t, e_{it}^c\}$ where $ln(e_{it}) = e_{it}^t + e_{it}^c$ in each year t. Since our model is static, we assume in each jurisdiction i the final observation of the trend component is related to the size of the jurisdiction through

$$ln\left(\frac{b_2}{\psi_i}\right) = e_{i,2012}^t.$$

[11]We refer to individual jurisdictions as CHN, USA, JPN, KOR, MEX, EGY, EUR, USPWR, IAB and IMB, respectively.

[12]We note that the link between USA and USPWR is excluded.

[13]For China, we exclude observations from 1950-1975 because this period features uncharacteristic fluctuations associated with the Great Leap Forward and Cultural Revolution.

Given our assumption that technology is identical across jurisdictions, the only source of variation in ψ_i is the differences in $e^t_{i,2012}$. We normalize $\psi_{CHN} = 100$ and set $b_2 = 0.5$. We note that these amount to choosing the units in which EA is measured. Consequently, the quantitative results below can be compared across pairs and jurisdictions. However, the value of a particular link and how it is shared between jurisdictions, remains sensitive to technology differences and, given those differences, to the calibration of ψ_i. In the context of our highly stylized model, and without reliable estimates of how b_2 may vary across jurisdictions, we consider our calibration of ψ_i as a reasonable first pass.

The calibrated values of ψ_i are provided in Table 1.[14] We highlight that these imply that the largest pairing, that between CHN and USA, has a PSE of 35.5 and the smallest PSE is between the pair MEX and EGY, e.g. 1.59.

< Table 1 here >

Next, we assume that the cyclical components e^c_{it} provide information about the distribution of the underlying jurisdiction-specific shocks θ_i. Then given our model, e^c_{it} is related to a draw from the distribution of θ_i so that

$$ln(b_1 + \theta_i) = e^c_{it}$$

We note that e^c_{it} obtained using the HP filter is a stationary time series and compute the standard deviation of θ_i consistent with the model using

$$\sigma_i = \sigma\left(\exp\left(e^c_{it}\right)\right).$$

The calibrated σ_i are provided in Table 2.

< Table 2 here >

Finally, we turn to the calibration of the correlation coefficient ρ. Taking as given the relationship between θ_i and e^c_{it} implied by our model and discussed above, we calibrate ρ_{ij} using

$$\rho_{ij} = Corr\left(\exp\left(e^c_{it}\right), \exp\left(e^c_{jt}\right)\right).$$

The results are given in Table 3, where ρ_{ij} statistically different from zero at 10% level

[14]Since USPWR data is missing for 2012, we use $e_{USPWR,2011}$ to compute ψ_{USPWR}.

are indicated with an asterisk. We observe that ρ_{ij} can be positive, approximately zero, or negative. In the former case, the demand for permits will tend to move together in the two jurisdictions, attenuating the EA of linking through a negative DE. In the latter case, DE will be positive and augment the EA of linking. Emissions in jurisdictions whose economies are tightly interconnected through trade and financial flows will likely move together, especially if jurisdictions' emissions are procyclical. If the economic links between jurisdictions are weak and/or they are geographically distant, one would expect a low level of correlation. Finally, if a jurisdiction's business cycles are negatively correlated with others, also observing negative correlations in emissions fluctuations would not be surprising. These conjectures are consistent with empirical studies such as Calderon, Chong, and Stein (2007) which provides evidence on international business cycle synchronization and trade intensity, and Doda (2014) which analyzes the business cycle properties of emissions. Finally, Burtraw et al. (2013) suggest that demand for permits may be negatively correlated over space due to exogenous weather shocks.

$<$ Table 3 here $>$

Using Tables 1-3 we calculate $\{(\psi_1, \sigma_1), (\psi_1, \sigma_1), \rho_{ij}\}$ for all pairs in our sample. In turn, this allows us to compute $\mathbb{E}[\Delta]$ and $\mathbb{E}[\delta_i]$ as well as their components PSE, VE and DE. Before presenting our results, we address a few questions that may arise regarding our calibration strategy. First, we assume that the pair characteristics are not affected by the recent introduction of climate change policies. Some emitters in some of the jurisdictions in our sample are regulated under these policies. We argue that any possible effects would be limited because these policies have not been particularly stringent, affect only a portion of the jurisdiction's emissions, and do so only in the last few years of our sample.

Second, we use the HP filter to decompose the observed emissions series into its trend and cyclical components. Not surprisingly, the calibrated pair characteristics are altered somewhat when we alternatively use the band pass filter recommended by Baxter and King (1999), the random walk band pass filter recommended by Christiano and Fitzgerald (2003) or the simpler log quadratic/cubic detrending procedures. However, their effect on the results we discuss below are minimal so we restrict our attention to the HP filter.[15]

Third, we take the calibrated ρ_{ij} reported in Table 3 at face value in our computations,

[15] The results obtained using alternative filters are available upon request.

rather than setting insignificant correlations to zero. This does not alter the results in a meaningful way.

Fourth and finally, we do not view the results of this empirical exercise as precise estimates of the aggregate or jurisdiction-specific EA of linking. We merely illustrate the variation that exists so as to provide some guidance for detailed empirical assessments of potential future links between ETSs in the real world.

We start with an overview of the results for all 44 pairs in Figure 2. The two panels of the figure show how $\mathbb{E}[\Delta]$ varies with its components, namely PSE and $VE+DE$. For clarity of exposition, the axes in each panel use log scales. The main message from both panels is one of substantial heterogeneity across pairs. Focusing first on the top panel we note that the pairs that generate the greatest aggregate EA involve the largest jurisdictions in the sample. However, the relationship is not monotonic, even among the largest jurisdictions. For example, the link between CHN and USPWR features a greater $\mathbb{E}[\Delta]$ despite having a smaller PSE than the link between CHN and EUR. For jurisdiction pairs whose PSE is more moderate, this observation is all the more valid. Consider for example the link between EUR and IAB, which has the median PSE in our sample and observe that pairs with similar PSE can generate much larger or smaller aggregate EA, e.g. the JPN link with KOR and the IAB link with USA, respectively. Similarly, the link between the two smallest jurisdictions in the sample EGY and MEX, generates more value than the link between EUR and USA.

$<$ Figure 2 here $>$

Turning to the bottom panel of the figure, it becomes clear why this last link has a small $\mathbb{E}[\Delta]$: it has the smallest VE and the smallest $DE < 0$. USA and EUR are systems in advanced economies which exhibit low variability in their emissions. Moreover, they are well integrated through deep trade and financial links so their economic activity and emissions are highly positively correlated, implying a negative DE. At the other extreme, we observe a cluster of links which involve EGY, due to the fact that EGY is the most volatile jurisdiction in the sample which also happens to be negatively correlated with all the other jurisdictions in the sample. In between the extremes, there is much variability in $\mathbb{E}[\Delta]$ for a given level of $VE+DE$. In short, each of VE, DE and PSE can be crucial for $\mathbb{E}[\Delta]$.

Next we view the results from the perspective of a given jurisdiction. Figure 3 highlights the case of the three largest ETSs in the sample, namely CHN, USA, and EUR. In all panels, the left graph exhibits $\mathbb{E}[\Delta]$ and $\mathbb{E}[\delta_i]$, the middle graph VE and DE, and the right graph PSE when jurisdiction i links with another jurisdiction in the sample. A crucial feature of these graphs is that linking partners for jurisdiction i are ordered so that the link with the left-most partner is its most preferred, i.e. has the largest $\mathbb{E}[\delta_i]$.

$<$ Figure 3 here $>$

CHN is by far the largest ETS in the sample so its share of $\mathbb{E}[\Delta]$ is always less than half. Under the assumption that all CHN emissions are covered, its most preferred partner is determined by whether ETS regulation in the United States covers the whole economy, i.e. USA, or only its power sector, i.e. USPWR. If the American ETS only covers the latter, CHN is better off in a link with EUR. This is the case despite the fact that the link between CHN and USPWR has i) a larger VE, ii) a less negative DE and iii) features a greater $\mathbb{E}[\Delta]$. It is just not big enough! Assuming links with CHN are not feasible, a similar reasoning applies in the case of the bilateral links between USA, EUR, and JPN.

In Figure 3, PSE largely determines the ranking of partners. A systematic exception is the ordering of the links with EGY and IAB for these big jurisdictions. Despite being less than half as large as the aviation sector, EGY is a preferred partner because its demand for permits is expected to be volatile and negatively correlated with CHN, USA, and EUR.[16]

Finally, we consider the permit price volatility under autarky and linking. In a majority of cases, linking would imply lower volatility for both partners. However, for 9 out of the 44 possible pairs, price volatility under linking is higher than under autarky for one of the partners. This is illustrated in Figure 4 using as an example the pairs in which EUR is one of the partners. The pairs are ranked according to PSE and the horizontal line indicates the autarky price volatility in EUR. The bars plot a given partner's price volatility under autarky and the price volatility under linking predicted by our model.

$<$ Figure 4 here $>$

[16] Illustrations of the results for the remaining jurisdictions in the sample, i.e. those involving sectors and smaller countries, are available from the authors upon request.

In the sample, EUR is the third largest jurisdiction and is characterized by the lowest permit price volatility under autarky. Linking with larger partners can raise or lower its permit price volatility, e.g. CHN versus USPWR; so can linking with smaller partners, e.g. JPN versus MEX. Note also that a link with a very volatile partner does not imply that price volatility increases, e.g. EGY or KOR. If the variable of interest is price volatility before and after a link, the message of the figure is clear: one must take the condition in Proposition 2 seriously. At the same time, we remind the reader that under our maintained assumption $\epsilon = 0$, all of these links are mutually beneficial.

To summarize, there are good, better, and much better bilateral links among the jurisdictions in our sample. This is true in aggregate and for individual jurisdictions and regardless of whether price volatility decreases or not. However, it is not readily obvious which potential partner is better. Not all carbon dates are created equal and one must be careful in selecting a partner.

That said, care must be taken with the interpretation of these results. In particular, we do not view them as a precise guide for policymakers in jurisdictions contemplating a link, but rather as a first pass analysis of the economic cost savings that feature in the policymakers' calculus. The decision to create a link will be based on a variety of considerations beyond cost-effectiveness. While our results shed new light on how the bottom-up international architecture of tradable permit programs could evolve given the cost savings, we abstract from non-economic benefits as well as the considerable political and regulatory challenges that could arise in the context of linking.

5 Sensitivity to key assumptions

In this section we discuss the sensitivity of our results to key assumptions we make, namely those regarding technologies, cost sharing rule, cap setting framework, and interior solution.

Technology differences The asymmetry in our model is dictated by jurisdiction size. Jurisdictions' abatement technologies are assumed to be identical. Relaxing this assumption is straightforward. To this end, replace the size parameter ψ_i with $\gamma_i = \gamma(\beta_i, \psi_i) = \psi_i \cdot \beta_i$ where β_i is an independent determinant of abatement costs at the margin. The new parameter γ_i jointly captures the combination of abatement technology and size of jurisdiction i and allows us to explicitly model the differences in abatement opportunities.

Analytically, this change of variable has no consequence for our results. In particular, a higher β_i for a given size is observationally equivalent to an appropriately chosen ψ_i for a given abatement technology. When looking for a partner, jurisdictions seek one that has a large γ_i and in our simple framework it is irrelevant whether a large γ_i is due to a large ψ_i or a large β_i.

Empirically, our key result that there is substantial, economically meaningful, and policy relevant *variation* in the EA of alternative pairs is reinforced. To see this, observe that in the top panel of Figure 2 China, due to its size, is systematically a partner in the linking arrangements that generate the largest EA. It is also the jurisdiction with the greatest low-cost abatement opportunities, i.e. a large β_i which is absent from the model by construction. Allowing it will amplify the technology-adjusted size of China meaning that our results constitute a lower bound for the *variation* that we highlight in Section 4.

Cost sharing rules The corollary to Proposition 1 shows that even when the aggregate EA of linking is positive, autarky can be preferable to one partner when its linking costs are sufficiently large to offset the benefits. Therefore, the economic viability of linking depends on how jurisdictions share costs and, ultimately, the net benefits. Given the breadth of situations for which cost sharing rules are relevant, one could consider alternative mechanisms motivated by different criteria. We believe that the exogenous linking costs being shared according to jurisdiction size is a natural starting point and note that Proposition 1 is sufficiently general to allow the implementation of other rules. That said, we abstract from side payments and strategic manipulation of cost sharing rules to ensure the formation of all pairs with $\mathbb{E}[\Delta] > 0$. This promising line of research is beyond the scope of the current paper.

Cooperative and non-cooperative cap setting We consider sovereign regulators who can design and implement policies independently. This is an important conceptual difference from the studies cited in the introduction. We also assume that linking takes place only when both regulators agree ex ante to link and that the quotas are independent of the linking decision. Against this backdrop, it is natural to start from a non-cooperative solution to the quota-setting problem which is the benchmark case we discuss above. In

Appendix A we set up and solve a joint optimization problem where the two regulators maximize the expected total net benefits when setting the quotas and show that our analytical results are the same under both regimes. While our results are robust along this dimension, our paper is silent on the potential interaction between the levels of quotas and the linking decision itself. Our work on this topic is ongoing.

Interior equilibrium Throughout the paper we restrict our attention to interior equilibria. In essence, this is a restriction imposed on the shocks such that countries' caps are binding and permit prices are non-zero. In Appendix C we use a simple example to provide a detailed exposition of what interior equilibrium means in our context and the conditions under which the equilibrium would not be interior. This assumption allows substantial simplification in obtaining analytical results because damages under autarky and linking are equal, and cancel out, when computing jurisdiction-specific EA. Moreover, restricting our attention to interior equilibria allows us to uniquely determine the linking price p_L without arbitrarily specifying who is making the price, i.e. bargaining power between the permit buyer and the permit seller. Finally, replacing the interior equilibrium assumption with one about bargaining power, we can proceed numerically to obtain very similar results because corner solutions are typically rare.

6 Conclusions

We use a simple model to evaluate the economic advantage of regulating carbon emissions by linking the ETSs of two jurisdictions versus operating them under autarky. The paper's main innovation is in quantifying and analyzing the sensitivity of aggregate and jurisdiction-specific economic advantage to the characteristics of the jurisdictions. We decompose the economic advantage of linking into pair size, volatility, and dependence effects. We identify conditions on the parameters describing the nature of the uncertainty in the model and exogenous sunk costs under which one, but not the other jurisdiction, prefers autarky even when the aggregate economic advantage of linking is positive. We show that permit price volatility does not necessarily decline under linking as many would expect, and identify a condition under which it increases for one partner in mutually beneficial links. In an empirical application, we calibrate pair characteristics to the observed emissions in ten key jurisdictions including China, USA, Europe, and international aviation and shipping. We document substantial variation in economic advantage and its components when the hypothetical ETSs in these jurisdictions are linked to demonstrate that the 'linking partner match' exercise can be crucial.

The analytical and quantitative results above speak directly to a topical policy debate, namely the use of markets in responding to the climate change externality. Indeed, the Paris Agreement, which was adopted by 195 countries during the 21st Conference of Parties, contains trading provisions which support the use of 'internationally transferred mitigation outcomes'. The ultimate aim of these provisions is to improve the cost effectiveness of global emissions reduction efforts. As the signatories to the Agreement ramp up their 'Nationally Determined Contributions', the so-called NDCs, and the low-cost mitigation opportunities become more scarce, enhancing the cost effectiveness of such efforts via linking is likely to become increasingly prominent in national and international policy fora.

Our study is only a first-pass analysis of the issues that arise in the context of linking ETSs and leaves several important questions for future research. First, our static analysis takes as given the quotas under both linking and autarky. A dynamic analysis of linking and quota setting incentives of regulators is clearly called for. Second, we assume linking costs are shared according to size. Although this is a natural starting assumption, the likelihood of the success of a linking arrangement could be increased via means of lump sum side payments or changes in the cost sharing rules. Conversely, unilateral imposition of distortionary taxes to capture a greater share of the value generated in a linking arrangement will reduce the chances of the link being formed in the first place. Third, we only consider the linking of ETSs which have identical design features. This assumption can be relaxed by allowing differences in the stringency of enforcement, eligibility of offset credits, cost-containment provisions, and common definition of emissions. Finally, emissions trading is but one of the policy instruments for regulating emissions and there is no reason why linkages between permit markets and markets for other instruments such as energy efficiency certificates, renewable obligations, etc. cannot be envisioned.

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Tables

Table 1: Calibrated values of size parameter ψ_i

	CHN	**USA**	**EUR**	**USPWR**	**JPN**	**IMB**	**KOR**	**IAB**	**MEX**	**EGY**
ψ_i	100	55.038	38.699	23.223	12.966	6.708	6.645	5.089	4.904	2.356

Table 2: Calibrated values of shock standard deviation σ_i

	CHN	**USA**	**EUR**	**USPWR**	**JPN**	**IMB**	**KOR**	**IAB**	**MEX**	**EGY**
σ_i	0.028	0.019	0.017	0.021	0.033	0.033	0.034	0.028	0.026	0.050

Table 3: Calibrated values of shock correlation ρ_{ij}

	CHN	**EGY**	**EUR**	**IAB**	**IMB**	**JPN**	**KOR**	**MEX**	**USA**	**USPWR**
CHN	1.000									
EGY	-0.395*	1.000								
EUR	0.460*	-0.101	1.000							
IAB	0.496*	-0.279*	0.507*	1.000						
IMB	0.194	-0.148	0.534*	0.359*	1.000					
JPN	0.394*	-0.123	0.461*	0.315*	0.385	1.000				
KOR	0.247	-0.397*	0.277*	0.041	0.221	0.360*	1.000			
MEX	-0.244	-0.174	0.086	0.185	0.255	0.269*	-0.138	1.000		
USA	0.525*	-0.186	0.652*	0.637*	0.523	0.347*	0.419*	0.080	1.000	
USPWR	0.220	-0.146	0.581*	0.551*	0.525	0.297*	0.302*	0.110	na	1. 000

Figures

Figure 1: Graphical illustration of country-specific linking benefits

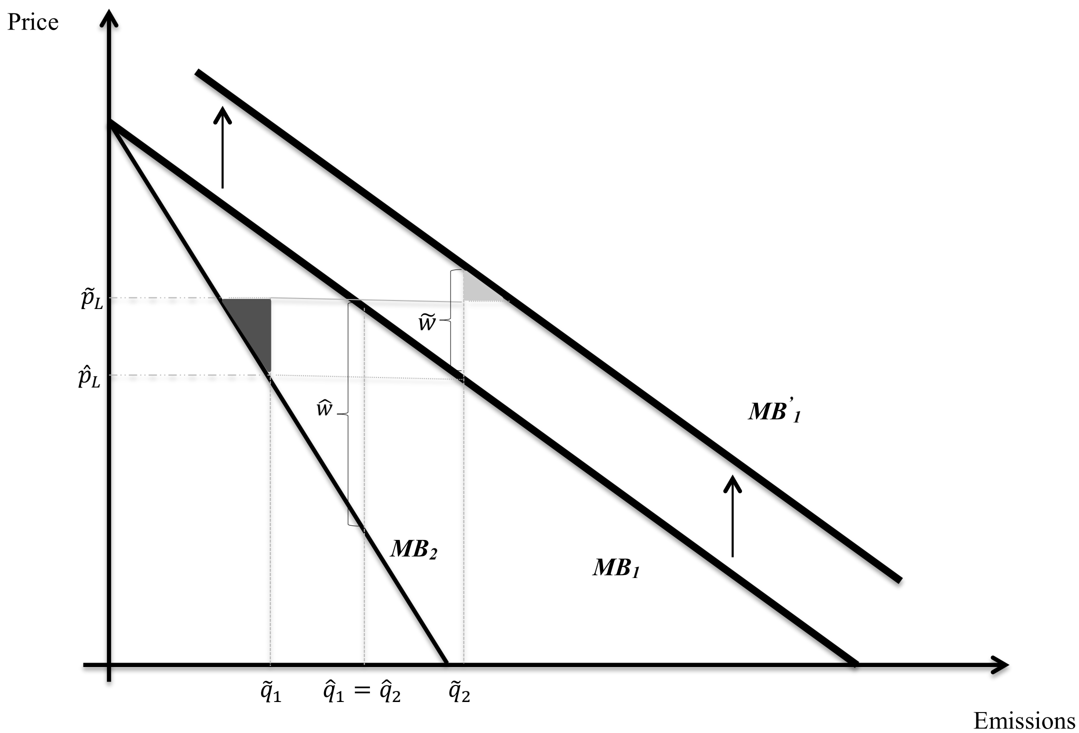
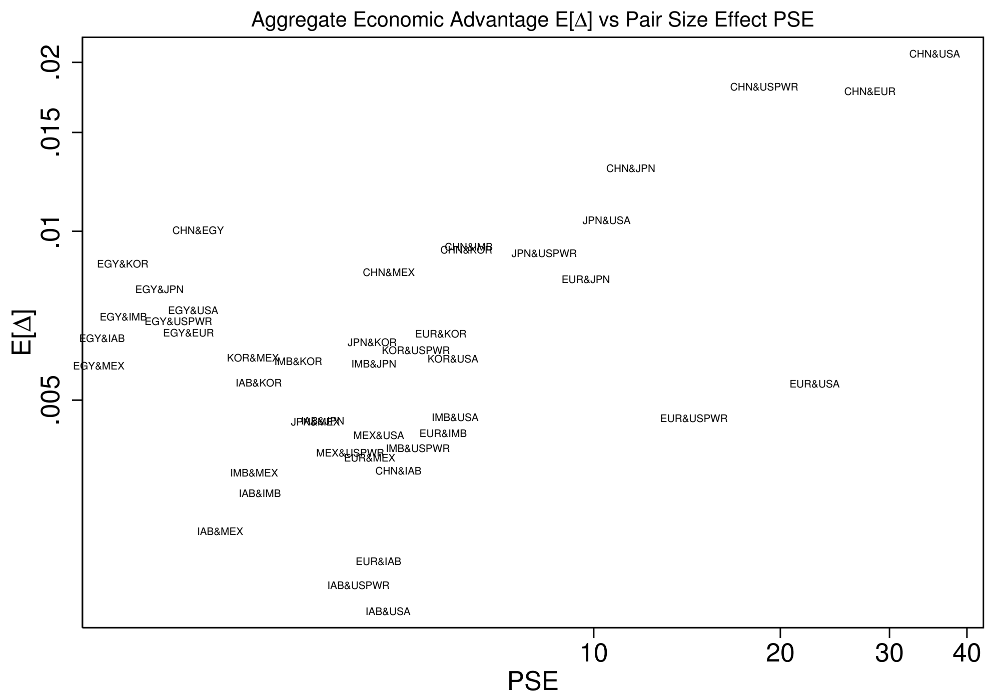


Figure 2: Overview of the results



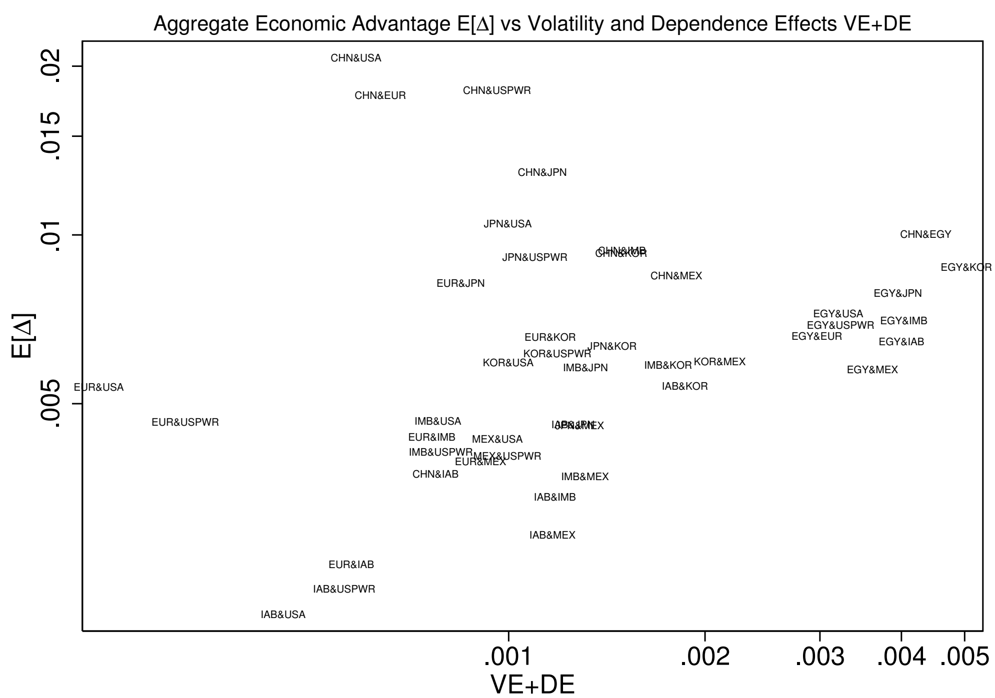


Figure 3: Large jurisdictions and their partners

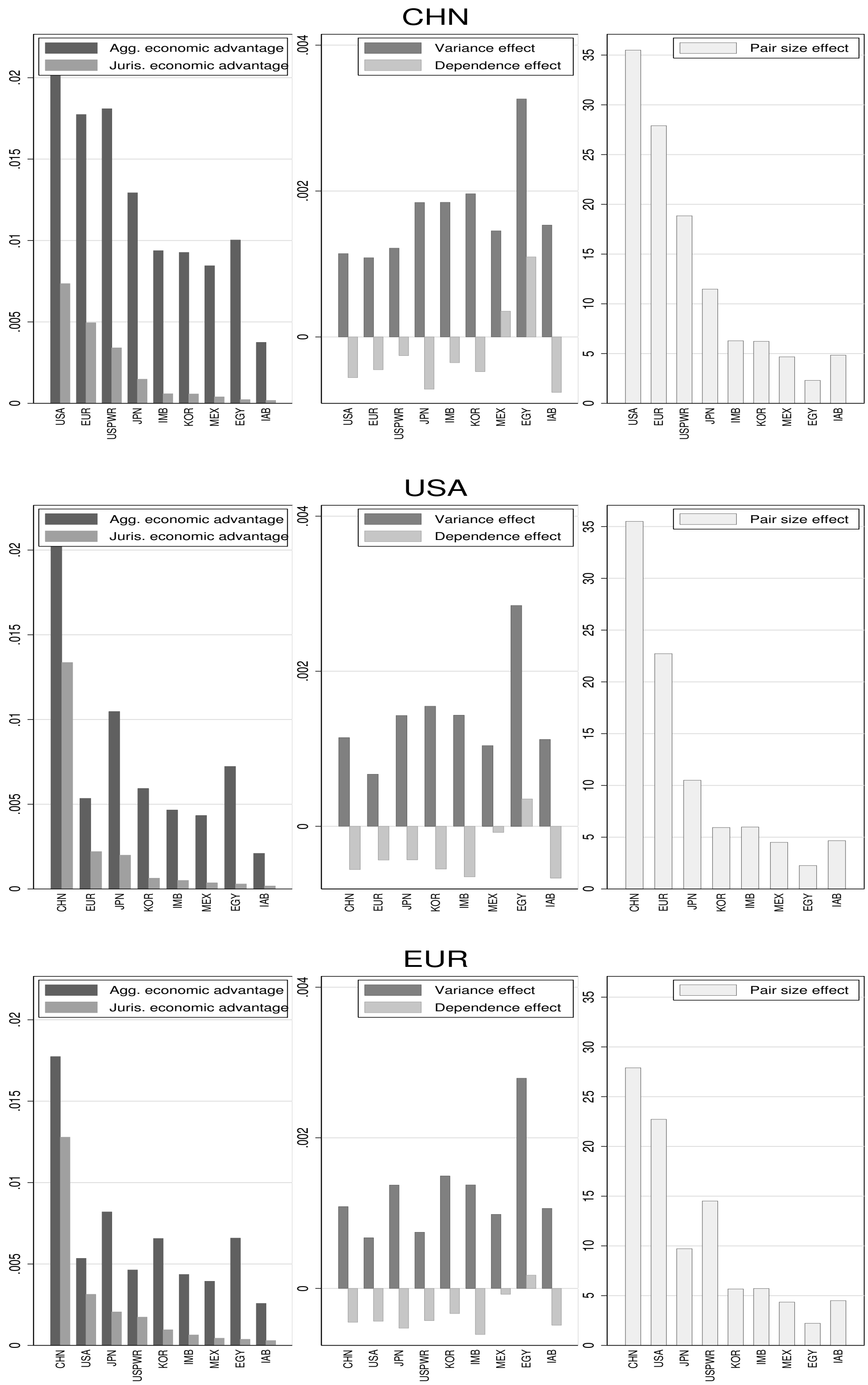
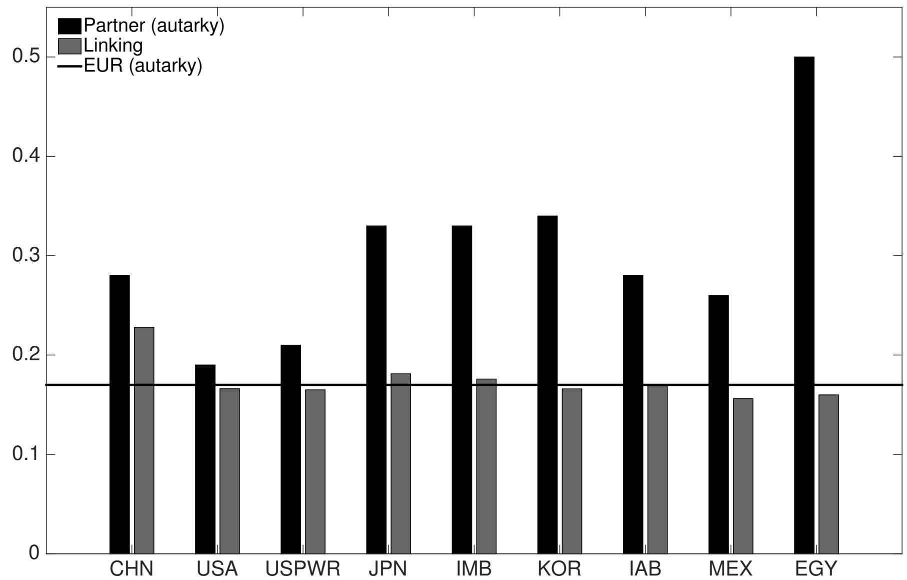


Figure 4: Permit price volatility under linking and autarky



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Appendix

A Alternative solutions to the quota-setting problem

Non-cooperative quotas

Given the set-up presented in Section 2, we solve the control problem of two risk-neutral regulators in a second best world where non-cooperative emission caps must be fixed ex ante. This is without loss of generality. All propositions in Section 3 hold under a cooperative framework and risk-aversion as well. We present the cooperative equilibrium solution below for comparison. First best emissions are not presented here but are available upon request from the authors.

We maximize the aggregate net benefits of one country given the other country's emission quota. Formally, we solve the following system

$$\begin{aligned} &\max_{q_1 \geq 0} \quad \mathbb{E}\left[B_1(q_1, \theta_1) - D_1(q_1 + q_2)\right] \qquad \text{given} \qquad q_2 = \bar{q}_2, \\ &\max_{q_2 \geq 0} \quad \mathbb{E}\left[B_2(q_2, \theta_2) - D_2(q_1 + q_2)\right] \qquad \text{given} \qquad q_1 = \bar{q}_1. \end{aligned} \tag{A.5}$$

The solution to the problem in (A.5) is denoted by a pair of emissions quotas $\{\bar{q}_1, \bar{q}_2\}$ which is obtained by setting the *country's* expected marginal benefits equal to *its* marginal damages:

$$\begin{aligned} \bar{q}_i &= \frac{\psi_i \left(b_1 - d_1\right)}{d_2 \left(\psi_1 + \psi_2\right) + b_2}, \\ \bar{Q} &= \frac{\left(\psi_1 + \psi_2\right)\left(b_1 - d_1\right)}{d_2 \left(\psi_1 + \psi_2\right) + b_2}. \end{aligned} \tag{A.6}$$

The non-cooperative linking equilibrium is defined in the text in Equation (3).

Cooperative quotas

Formally, the cooperative program is

$$\max_{\{q_1 \geq 0, q_2 \geq 0\}} \quad \mathbb{E}\left[B_1(q_1, \theta_1) - D_1(q_1 + q_2) + B_2(q_2, \theta_2) - D_2(q_1 + q_2)\right]. \tag{A.7}$$

The solution to the problem in (A.7) is denoted by a pair of emissions quotas $\{\bar{q}_1^c, \bar{q}_2^c\}$ which is obtained by setting expected marginal benefits equal to *aggregate* marginal damages:

$$\begin{aligned}\bar{q}_i^c &= \frac{\psi_i\left(b_1 - \mathbf{2}d_1\right)}{\mathbf{2}d_2\left(\psi_1+\psi_2\right)+b_2}, \\ \bar{Q}^c &= \frac{\left(\psi_1+\psi_2\right)\left(b_1 - \mathbf{2}d_1\right)}{\mathbf{2}d_2\left(\psi_1+\psi_2\right)+b_2}.\end{aligned} \tag{A.8}$$

We have emphasized the difference with respect to $\bar{q}_i$ in bold. It is straightforward to show that quotas selected cooperatively are more stringent than quotas selected non-cooperatively. As such, the resulting cooperative linking equilibrium features a higher permit price p_L^c given by

$$(p_L^c, q_{L1}^c, q_{L2}^c) = \left(K^c + \frac{\psi_1\theta_1+\psi_2\theta_2}{\psi_1+\psi_2}, \bar{q}_1^c - n^c, \bar{q}_2^c + n^c\right) \tag{A.9}$$

where $K^c = b_1 - \frac{b_2(b_1-2d_1)}{b_2+2d_2(\psi_1+\psi_2)} = b_1 - \frac{b_2}{\psi_i}\bar{q}_i^c$. Notwithstanding, the amount of permits traded $n^c = n$ as in Equation (3). Namely, it is the same under both regimes and the analytical results about the EA and the country-specific benefits remain unaltered.

B Proof of Lemma and Propositions

Proof of Lemma

We first evaluate the aggregate economic advantage of linking over autarky. Substituting $n = \frac{1}{b_2}\frac{\psi_1\psi_2}{(\psi_1+\psi_2)}(\theta_2-\theta_1)$ in the third line of Equation (4), we obtain

$$\begin{aligned}\Delta &= -n(b_1+\theta_1) - \frac{b_2}{2\psi_1}(-2\bar{q}_1 n + n^2) - \psi_1\epsilon + n(b_1+\theta_2) - \frac{b_2}{2\psi_2}(2\bar{q}_2 n + n^2) - \psi_2\epsilon \\ &= n(\theta_2-\theta_1) + n\Big(\frac{b_2\bar{q}_1}{\psi_1} - \frac{b_2\bar{q}_2}{\psi_2}\Big) - \frac{b_2}{2}\Big(\frac{n^2}{\psi_1} + \frac{n^2}{\psi_2}\Big) - \Big(\psi_1+\psi_2\Big)\epsilon \\ &= n\Big[\theta_2 - \theta_1 - n\frac{b_2}{2}\frac{\psi_1+\psi_2}{\psi_1\psi_2}\Big] - \Big(\psi_1+\psi_2\Big)\epsilon \\ &= \frac{1}{2b_2}\frac{\psi_1\psi_2}{\psi_1+\psi_2}\left(\theta_2-\theta_1\right)^2 - \Big(\psi_1+\psi_2\Big)\epsilon.\end{aligned}$$

Using (2), we derive the expression for the expected aggregate EA which completed the proof of the Lemma:

$$\begin{aligned}\mathbb{E}\left[\Delta\right] &= \frac{1}{2b_2}\frac{\psi_1\psi_2}{\psi_1+\psi_2}\mathbb{E}(\theta_2-\theta_1)^2 - (\psi_1+\psi_2)\epsilon \\ &= \frac{1}{2b_2}\frac{\psi_1\psi_2}{\psi_1+\psi_2}(\sigma_1^2+\sigma_2^2-2\sigma_1\sigma_2\rho) - (\psi_1+\psi_2)\epsilon.\end{aligned}$$

Proof of Proposition 1

We now evaluate the country-specific economic advantage of linking over autarky. Substituting $n = \frac{1}{b_2}\frac{\psi_1\psi_2}{(\psi_1+\psi_2)}(\theta_2-\theta_1)$ in the first line of Equation (4), we obtain

$$\begin{aligned}
\delta_1 &= -n(b_1+\theta_1) - \frac{b_2}{2\psi_1}(-2\bar{q}_1 n + n^2) + p_L n - \psi_1\epsilon \\
&= n\Big[\frac{\psi_1\theta_1+\psi_2\theta_2}{\psi_1+\psi_2} - \theta_1 - \frac{b_2}{2\psi_1}n\Big] - \psi_1\epsilon \\
&= n\frac{\psi_2}{2(\psi_1+\psi_2)}(\theta_2-\theta_1) - \psi_1\epsilon \\
&= \frac{\psi_1\psi_2^2}{(\psi_1+\psi_2)^2}\frac{(\theta_2-\theta_1)^2}{2b_2} - \psi_1\epsilon \\
&= \frac{\psi_2}{\psi_1+\psi_2}\Delta + (\psi_2-\psi_1)\epsilon.
\end{aligned}$$

Evaluating the second line of Equation (4), we obtain

$$\delta_2 = \frac{\psi_1}{\psi_1+\psi_2}\Delta + (\psi_1-\psi_2)\epsilon.$$

And the expected country-specific EA is

$$\mathbb{E}[\delta_i] = \frac{\psi_j}{\psi_i+\psi_j}\mathbb{E}[\Delta] + (\psi_j-\psi_i)\epsilon.$$

Finally, while n is identical under cooperative and non-cooperative quotas, comparing (3) and (A.9) we note that $p_L \neq p_L^c$. However, this difference has no implication for δ_i above. To see this note that in moving from the first to the second line in the derivation of δ_1, the terms generating the difference cancel out.

Proof of Proposition 2

Let us first evaluate the variance of the equilibrium prices using (1), (2), and (3). The autarky and linking price volatilities are

$$\begin{aligned} var(p_{A1}) &= \sigma_1^2; \\ var(p_{A2}) &= \sigma_2^2; \\ var(p_L) &= \frac{1}{(\psi_1+\psi_2)^2}\Big(\psi_1^2\sigma_1^2+\psi_2^2\sigma_2^2+2\psi_1\psi_2\sigma_1\sigma_2\rho\Big). \end{aligned}$$

Assume $0 \leq \sigma_1 < \sigma_2$ and, without loss of generality, let $\psi_1 = 1$. The volatility of the autarky permit price in country 2 is larger than the volatility of the linking permit price if

$$\begin{aligned} \sigma_2^2(1+\psi_2)^2 &> \sigma_1^2+\psi_2^2\sigma_2^2+2\psi_2\sigma_1\sigma_2\rho \\ \sigma_2^2+2\psi_2\sigma_2^2+\psi_2^2\sigma_2^2 &> \sigma_1^2+\psi_2^2\sigma_2^2+2\psi_2\sigma_1\sigma_2\rho \\ (\sigma_2^2-\sigma_1^2)+2\psi_2(\sigma_2^2-\sigma_1\sigma_2\rho) &> 0. \end{aligned}$$

which trivially holds under the assumption $\sigma_2 > \sigma_1 \geq 0$. and for $\forall \rho \in [-1, 1]$. We now turn to the second part of Proposition 2. The volatility of the autarky permit price in country 1 is smaller than the volatility of the linking permit price, $var(p_{A1}) < var(p_L)$, if

$$\begin{aligned} \sigma_1^2+2\psi_2\sigma_1^2+\psi_2^2\sigma_1^2 &< \sigma_1^2+\psi_2^2\sigma_2^2+2\psi_2\sigma_1\sigma_2\rho \\ \psi_2 &> \frac{2(\sigma_1^2-\sigma_1\sigma_2\rho)}{(\sigma_2^2-\sigma_1^2)}. \end{aligned}$$

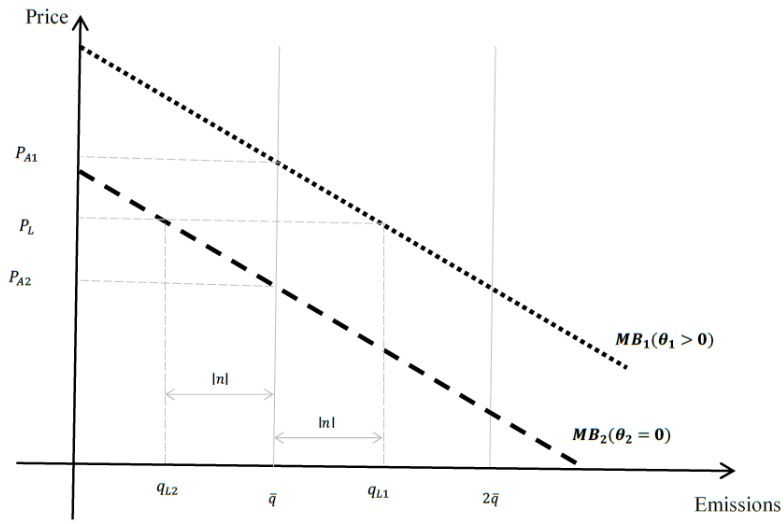
C Interior equilibrium

We use a simple graphical example to illustrate interior equilibrium. Let $\psi_1 = \psi_2 = 1$ which implies $\bar{q}_1 = \bar{q}_2 = \bar{q}$. The top panel of Figure C.5 illustrates the permit market equilibria under autarky and linking for a given pair of shock realizations where $0 = \theta_2 < \theta_1$. Country 1 faces a positive shock; the dotted line represents the marginal benefit curve consistent with $\theta_1 > 0$. Country 2 faces a zero shock and its marginal benefit curve is described by the dashed line. When the two systems are linked, country 1 imports $|n|$ permits from country 2. In this case LE is interior because $|n| < \bar{q}$ and $p_L > 0$. Similarly, both AE are interior because $0 < p_{A2} < p_{A1}$.[17]

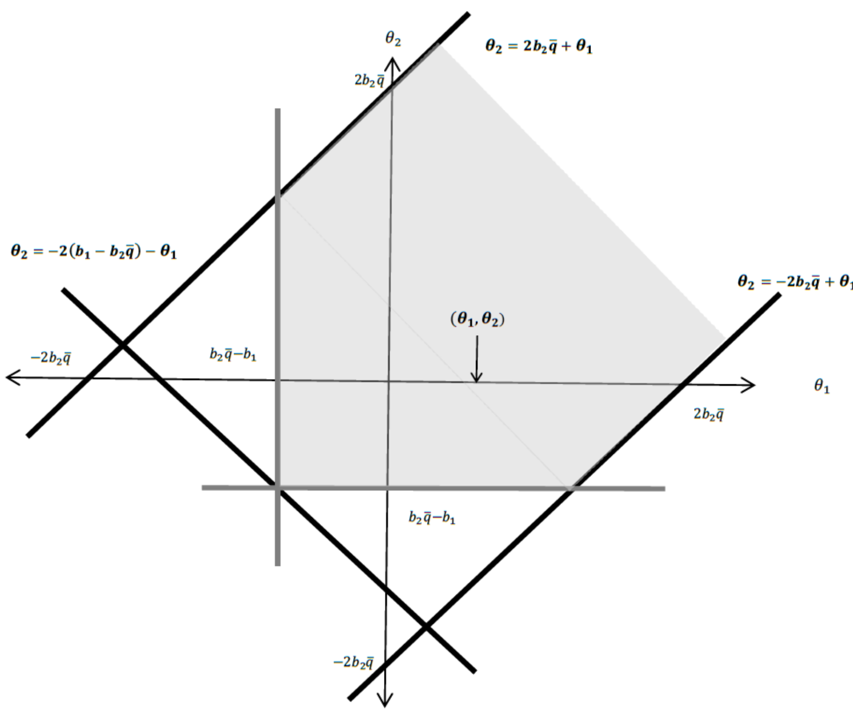
The bottom panel of Figure C.5 illustrates a (θ_1, θ_2) pair consistent with the equilibrium solutions just discussed. In addition, the shaded area in the figure indicates all shock pairs for which both AE and LE are simultaneously interior. AE are interior for all (θ_1, θ_2) pairs in the region to the northeast of the intersection of the grey lines perpendicular to the x-axis and the y-axis. Similarly, LE is interior for all (θ_1, θ_2) pairs between the two positively-sloped parallel black lines lines *and* to the northeast of the negatively-sloped black line. The positively-sloped lines constrain n to the interval $(-\bar{q}, \bar{q})$. However, a subset of this region must be excluded because below the negatively sloped line, where both shocks are large and negative, $p_L = 0$.

[17]The standard theoretical approach to comparing price and quantity policies is strictly interior. Goodkind and Coggins (2015) extend the comparison to account for the possibility of corner outcomes.

Figure C.5: Autarky and Linking



TOP PANEL: Permit Market Equilibrium



BOTTOM PANEL: Intersection of interior AE and interior LE