Linking Permit Markets Multilaterally*

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Abstract

Linkages between emissions trading systems (ETSs) are crucial for the cost-effective implementation of the Paris Agreement. Yet we know little about the determinants of economic gains in a multilaterally linked system, how they are shared among participating jurisdictions and less still about their magnitude. We characterize these gains for an arbitrary linkage group, decompose them into gains in the group's internal bilateral linkages and prove linkage is superadditive. Relative to autarky linkage reduces permit price volatility on average but not necessarily for individual linkage group members. In a quantitative application calibrated to five hypothetical ETSs covering the power sectors in Canada, continental Europe, South Korea, the UK and the USA, linking generates gains of up to $370 million (constant 2005US$) per year relative to autarky. Focusing on linkage groups with two and three members which are themselves not linked, we find that maximum aggregate gains decline by $43-178 million.

Keywords: Climate change policy; International emissions trading systems; Multilateral linking; Effort sharing; Risk sharing.

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1 Introduction

Markets for emission permits have long been an important policy tool in responding to the climate change externality. A patchwork of emissions trading systems (ETSs), covering almost a quarter of global emissions, are now operational in jurisdictions including the EU, Switzerland, South Korea, China as well as several US states and Canadian provinces. Many more are in the pipeline. For the most part permits cannot be traded across the existing systems and the observed autarky prices for permits differ significantly. If these ETSs can be integrated through linking, substantial cost savings can in principle become available, which presents an important opportunity for achieving the ambitious goals of the Paris agreement cost-effectively (e.g., Bodansky et al. (2016) and Mehling et al. (2018)). So far the economic analysis of linking has primarily focused on two ETSs linking bilaterally (e.g., Pizer & Yates (2015)) at one extreme and the global market (e.g., Carbone et al. (2009)) at the other. In practice, linkages between three or more ETSs are starting to emerge. At the same time, the economist's holy grail, the global market, remains a distant dream.

In this paper we propose a novel and general model to describe and study what can happen along the full spectrum of possible linkages. That is, we analyze multilateral linking rigorously. Our analysis quantifies the economic gains from linking accruing to every individual jurisdiction participating in an arbitrary linkage group. There are two independent sources of these gains, namely the differences in the ambition levels of the group members and the uncertainty which affects the individual group members' demand for permits. They can be interpreted as effort-sharing and risk-sharing gains, respectively.

Next, we decompose the aggregate gains in any linkage group into gains in its internal bilateral linkages. This decomposition result enables us to (1) easily compute the gains generated by an arbitrary linkage group, which is crucial for our quantitative application discussed in detail below, (2) analyze the determinants of linkage gains and preferences, and (3) characterize the aggregate gains from the union of disjoint linkage groups which we prove to be no less than the sum of separate groups' gains, i.e. linkage is superadditive.

Superadditivity implies that the global market generates the highest aggregate gains. Absent inter-jurisdictional transfers, however, there is no guarantee that the global market is the most preferred linkage group from the perspective of an individual jurisdiction. In fact, the conditions for the global market to be the most preferred group universally are unlikely to be satisfied in practice. Finally, we show that relative to autarky, linkage reduces price volatility on average but not necessarily for each individual group member.

We illustrate the quantitative implications of our model by focusing on possible linkages between hypothetical ETSs covering carbon dioxide emissions from the power sector of five real-world jurisdictions. Specifically, we calibrate our model to Canada, the EU aggregate excluding the UK, South Korea, the UK and the USA under the assumption that each jurisdiction implements its Paris Agreement commitments. We find that the linkage group which includes all five jurisdictions, what we refer to as the grand linkage, generates aggregate economic gains of $370 million (constant 2005US$) per annum which is split between risk- and effort-sharing components in a ratio of approximately 5:1.

This amount is $43 million greater than the sum of the gains generated by the linkage groups consisting of Canada and the UK, on the one hand and South Korea, the US and the EU, on the other. These two linkage groups are special in the sense that together they generate the *greatest* gains among the non-trivial multilateral linkage groups which is not the grand linkage, what we term a complete polycentric linkage structure. At the other extreme, the *smallest* gains generated by a complete polycentric linkage structure are $178 million smaller than those in the grand linkage. Put differently, moving from the grand linkage to a complete polycentric structure results in losses in the range of $43-178 million. Finally, we note that in our calibrated model the grand linkage is not the most preferred option unanimously.

Our model explores the gains from linking ETSs multilaterally under uncertainty. To do so, we introduce idiosyncratic shocks à la Weitzman (1974) and Yohe (1976, 1978). Moreover, to isolate these gains that are directly due to linkage, we assume that domestic emissions caps are exogenous and fixed permanently. Therefore, there is no strategic interaction between jurisdictions' linking decisions and no anticipation of linkage when caps are selected.

We also abstract from economic and political costs of linking which could preclude linkages that are otherwise beneficial. For example, large and persistent differences in ambition levels of jurisdictions imply some jurisdictions are net permit buyers in mutually beneficial transactions but which nonetheless trigger ongoing financial transfers. Both the financial transfers in the buying jurisdictions and the persistently stricter-than-cap emission levels in the selling jurisdictions can face domestic political resistance. In fact, the balance between the economic gains and political costs may be one reason why some jurisdictions are already linked (e.g., California, Québec & Ontario) while other links are expected to take a long time to emerge (e.g., EU-ETS & the Chinese national ETS). In this paper we exclusively study the potential economic gains not because we think economic and political costs are negligible but because the economic gains provide a strong incentive for jurisdictions to overcome them.

First and foremost, our paper is related to the literature on the economics of linking which has primarily emphasized two important determinants of gains from bilateral linking agreements, namely the cost-effective reallocation of abatement efforts and the reduction of permit price volatility (Flachsland et al., 2009; Jaffe et al., 2009; Fankhauser & Hepburn, 2010; Pizer & Yates, 2015; Ranson & Stavins, 2016; Doda & Taschini, 2017). Our paper formalizes and refines these arguments in a model of multilaterally linked ETSs by viewing any linkage group as the union of the group's building blocks, i.e. internal bilateral linkages. We offer a precise characterization of both effort-sharing and risk-sharing from linkage, and qualify the results in Caillaud & Demange (2017), who obtain a result similar to Proposition 1 but stop short of analyzing the distribution of gains among the participating jurisdictions as well as the properties of linkage we describe in Propositions 2, 3 and 4.

Our modelling approach is similar in spirit to the multinational production-location decision studied in de Meza & van der Ploeg (1987) and the desirable degree of decentralization in permit markets analyzed by Yates (2002). There are, however, conceptual differences with respect to our analysis of jurisdictional gains from linkage. Specifically, in de Meza & van der Ploeg (1987) a multinational firm maximizes expected profits by relocating production across plants situated in different countries with plant-specific shocks but crucially plant-specific technology and production capacity are irrelevant. In Yates (2002) a single regulator decides whether to allow trading across firms within a given jurisdiction but the implications of decentralization at the level of the regulated entity are not analyzed.

Our analysis is static and we assume invariant caps. This distinguishes our approach from the literature on international environmental agreements (Carraro & Siniscalco, 1993; Barrett, 1994) and international emissions trading (Helm, 2003; Carbone et al., 2009), dynamic and sequential linkage with strategic cap negotiation (Holtsmark & Midttømme, 2015; Caparrós & Péreau, 2017; Heitzig & Kornek, 2018), and delegation of cap selection with and without linking (Habla & Winkler, 2017). Our work also relates to the use of efficiency-improving trading ratios for a global carbon market (Holland & Yates, 2015) as well as to the growing policy literature that explores how to facilitate linking (Mehling & Görlach, 2016; Burtraw et al., 2017; Quemin & de Perthuis, 2017; Rose et al., 2018) and linking of heterogeneous climate policies (Metcalf & Weisbach, 2012; Mehling et al., 2017).

Finally, our paper characterizes certain features of linkage in terms of risk sharing. In this respect, it relates to several recent studies focusing on efficient risk sharing through international finance and macroeconomics perspectives (Callen et al., 2015; Farhi & Werning, 2017; Malamud & Rostek, 2017). Moreover, our risk-sharing results align with those of Jacks et al. (2011) and Caselli et al. (2017) who empirically focus on the impact of international trade on commodity price and GDP volatility, respectively.

The rest of the paper is organized as follows. Section 2 describes the economic environment in which we study linkage formally. Section 3 presents the general model of multilateral linkages. It also states and discusses our main theoretical results. Section 4 provides an analytical example in a world consisting of three jurisdictions and Section 5 contains a calibrated quantitative application. Section 6 concludes. All numbered tables and figures are provided at the end. There are three appendixes dealing with the analytical derivations and proofs (A), the description of our calibration methodology (B) and a more detailed discussion of the analytical example in Section 4 (C). Finally, in Appendix D we list several extensions and generalizations regarding linkage costs (D.1), the analysis of linkage sequentially (D.2) and strategic cap selection without and with anticipation of linkage (D.3 & D.4).

2 Modelling framework

We consider a standard static model of competitive markets for emission permits designed to regulate uniformly-mixed pollution in several jurisdictions. We make five key assumptions. First, markets for permits and for other goods and services are separable. That is, we conduct a partial-equilibrium analysis focusing exclusively on the jurisdictions' regulated emissions and abstract from interactions with the rest of the economy. Second, the only uncertainty is in the form of additive shocks affecting jurisdictions' unregulated emission levels. These two assumptions are somewhat restrictive but standard (Weitzman, 1974; Yohe, 1976). Third, jurisdictions' benefits from emissions are quadratic functional forms, which facilitate the derivation of analytical results and can be viewed as local approximations of more general functional specifications (Newell & Pizer, 2003). Fourth, the international political economy dimension is omitted. Each jurisdiction has a regulatory authority that can design policies independently of authorities in other jurisdictions with no anticipation of linkage. Fifth, we focus on interior market equilibria only. This simplifies the exposition of the model and some of our analytical derivations but it is innocuous for our analysis.[1]

Jurisdictions There are n jurisdictions and $\mathcal{I} = \{1, \dots, n\}$ denotes the set of jurisdictions. Aggregate benefits from emissions in jurisdiction $i \in \mathcal{I}$ are a function of the jurisdiction-wide

[1] Lecuyer & Quirion (2013) and Goodkind & Coggins (2015) provide an explicit treatment of corner solutions in related contexts, namely optimal climate policy mix and instrument choice, and argue they can be of importance. See the discussion in Appendix B for why the assumption is innocuous in our setup.

level of emissions $q_i \geq 0$ and are also subject to the idiosyncratic shock θ_i such that

$$B_i(q_i;\theta_i) = (\beta_i + \theta_i)q_i - q_i^2/(2\gamma_i), \tag{1}$$

where the parameters $\beta_i > 0$ and $\gamma_i > 0$ control the intercept and slope of i's linear marginal benefit schedule, respectively.[2] We refer to γ_i as i's flexibility in abatement at the margin, hereafter flexibility for short. Indeed, note that i's optimal level of emissions in response to an arbitrary permit price $p > 0$ is $q_i^*(p) = \gamma_i(\beta_i + \theta_i - p)$. Then, in absolute terms, the variation in emissions consecutive to a price variation τ is $\gamma_i \tau$ and thus proportional to flexibility. Further note that flexibility compounds two distinct characteristics, namely abatement technology and volume of regulated emissions. For instance, comparing two jurisdictions i and j with identical technology, $\gamma_i > \gamma_j$ reflects that i regulates a larger volume of emissions than j. Symmetrically, when regulated emissions are of identical volume in both i and j, $\gamma_i > \gamma_j$ means that i has access to a lower-cost abatement technology than j.

For analytical convenience and without loss of generality, we assume that jurisdictional shocks are mean-zero with constant variance and that they may be correlated across jurisdictions. Specifically, for any pair of jurisdictions $(i, j) \in \mathcal{I}^2$, we let

$$\mathbb{E}\{\theta_i\} = 0, \ \mathbb{V}\{\theta_i\} = \sigma_i^2, \text{ and } \mathrm{Cov}\{\theta_i;\theta_j\} = \rho_{ij}\sigma_i\sigma_j \text{ with } \sigma_i \geq 0 \text{ and } \rho_{ij} \in [-1;1]. \tag{2}$$

These shocks capture the net effect of stochastic factors that may influence emissions and their associated benefits, e.g. business cycles, technology shocks, jurisdiction-specific events, changes in prices of factors of production, weather fluctuations, etc. To see this, note that jurisdiction i's laissez-faire and baseline emissions are respectively defined by

$$\tilde{q}_i \doteq q_i^*(0) = \gamma_i(\beta_i + \theta_i), \text{ and } \bar{q}_i \doteq \mathbb{E}\{\tilde{q}_i\} = \gamma_i\beta_i. \tag{3}$$

Therefore, the idiosyncratic shock θ_i affects the intercept of i's linear marginal benefit schedule which in turn affects laissez-faire emissions $\tilde{q}_i$. For instance, $\theta_i > 0$ may reflect a favorable productivity shock that increases jurisdiction i's benefits from emissions, and as a consequence, laissez-faire emissions relative to baseline.

[2] Jurisdiction i's benefits correspond to the aggregate benefits accruing to all emitting firms located within its boundaries. Indeed, covered firms are all united by a uniform price on emissions, which causes their marginal benefits to equalize. By horizontal summation, individual marginal benefit curves can thus be combined into one aggregate marginal benefit curve. Therefore, only the efficiency side of linking is covered here and the intra-jurisdictional distributional aspects are outside the scope of the paper.

Emissions caps The emissions cap profile $(\omega_i)_{i\in\mathcal{I}}$ is exogenous. This implies domestic caps are independent of the decision to link.[3] That is, jurisdictional caps are fixed once and for all, upheld in all linkage scenarios, and do not constitute a part of the linkage negotiation process. This anchors the aggregate level of emissions at $\Omega_{\mathcal{I}} = \sum_{i\in\mathcal{I}} \omega_i$ and rules out spillovers attributable to linkage. Although this assumption is restrictive, it allows us to (1) have well-defined, stable autarky outcomes that serve as references throughout, (2) isolate the economic gains directly due to linkage, and (3) compare these gains across linkages and jurisdictions in a meaningful way. For clarity, we express caps as proportional to flexibility by an ambition parameter such that

$$\omega_i = \alpha_i \gamma_i, \text{ where } \alpha_i \in (0; \beta_i) \text{ for all } i \in \mathcal{I}, \tag{4}$$

which implies that jurisdictional caps are all – but not equally – stringent relative to baseline. In particular, notice the negative relationship between α_i and the level of ambition implicitly embedded in i's domestic cap, specifically as $\omega_i \to \bar{q}_i$ when $\alpha_i \to \beta_i$.

Autarky equilibria Under autarky, jurisdictions comply with their own caps. We assume that $\theta_i > \alpha_i - \beta_i$ for all $i \in \mathcal{I}$ and all shock realizations to focus on interior autarky equilibria exclusively. That is, there are weak restrictions on idiosyncratic shocks such that domestic caps are always binding. Specifically, autarky permit prices are positive and read

$$p_i = \bar{p}_i + \theta_i > 0 \text{ for all } i \in \mathcal{I}, \tag{5}$$

where $\bar{p}_i \doteq \beta_i - \alpha_i > 0$ denotes i's expected autarky price and notice $\bar{p}_i$ is lower for jurisdictions with higher α_i.[4] First, note that for a positive (resp. negative) shock realization θ_i, i's autarky price is above (resp. below) $\bar{p}_i$. Second, note that when autarky prices differ – whether it be due to differences in ambition measured by $\bar{p}_i$ or shock realizations – the aggregate abatement effort is not efficiently allocated among jurisdictions. In particular, cost-efficiency could be improved by shifting some abatement away from relatively high-ambition (resp. high-shock) to low-ambition (resp. low-shock) jurisdictions until autarky price differentials are eliminated.

[3] In practice, caps result from complex domestic negotiations and ETSs usually work in conjunction with supplemental policies (Flachsland et al., 2009). It thus seems unlikely that jurisdictions select their caps with an eye on linkage in the future. If, however, they do factor in linkage, it can be argued that this will be in a bid to align ambition levels across partnering jurisdictions and thereby render linkage politically feasible, rather than as a way to strategically inflate their gains from linkage. Therefore, we take cap selection as a decision of fundamentally domestic and political nature, and place it beyond the scope of this work. In Appendices D.3 and D.4, we discuss the implications of allowing for alternative cap selection mechanisms and strategic manipulation of domestic caps in anticipation of future linkage, respectively.

[4] In Appendix B which describes the model calibration for our quantitative application in detail, we show that autarky zero-price corners are typically rare since $\bar{p}_i > 2\sigma_i$ for all $i \in \mathcal{I}$.

As we elaborate in the next section, this is precisely the function linkage performs.

Costs of compliance Compliance with domestic emissions caps is costly because they are binding relative to laissez-faire emissions. Let $\tilde{a}_i \doteq \tilde{q}_i - \omega_i > 0$ and $C_i(\tilde{a}_i)$ denote i's domestic abatement level under autarky and associated abatement costs. By definition,

$$C_i(\tilde{a}_i) \doteq B_i(\tilde{q}_i; \theta_i) - B_i(\tilde{q}_i - \tilde{a}_i; \theta_i) = \tilde{a}_i^2/(2\gamma_i). \tag{6}$$

By convexity of C_i, Jensen's inequality implies that an increase in uncertainty about laissez-faire emissions and associated degrees of cap stringency raises the expected domestic costs of compliance under autarky. Specifically, these can be decomposed as

$$\mathbb{E}\{C_i(\tilde{a}_i)\} = C_i(\bar{q}_i - \omega_i) + \mathbb{E}\{C_i(\tilde{q}_i - \bar{q}_i)\} = \gamma_i(\bar{p}_i^2 + \sigma_i^2)/2, \tag{7}$$

where the first term measures compliance costs absent uncertainty, which are proportional to the cap's ambition level, and the second term captures the increase in compliance costs due to uncertainty, which are proportional to the shock variance. As will be developed further in the next section, for any group of linked jurisdictions, linkage mitigates the aggregate costs of compliance in linked jurisdictions via a reduction in both these components.

3 Theory

3.1 Definitions and terminology

Let $\mathbf{G} \doteq \{\mathcal{G} : \mathcal{G} \subseteq \mathcal{I}, \mathcal{G} \neq \varnothing\}$ be the set of non-empty subsets of $\mathcal{I}$ with generic element $\mathcal{G}$ and cardinality $|\mathbf{G}| = 2^n - 1$. Let also $\mathbf{G}_\star \doteq \{\mathcal{G} : \mathcal{G} \in \mathbf{G}, |\mathcal{G}| \geq 2\}$ with cardinality $|\mathbf{G}_\star| = |\mathbf{G}| - n$ denote the set whose generic element $\mathcal{G}$ we call a linkage group. Finally, denote by $\mathbf{S}$ the set of partitions of $\mathcal{I}$ whose generic element $\mathcal{S}$ we call a linkage structure.[5] Formally, $\mathcal{S}$ is a structure i.f.f. $\varnothing \notin \mathcal{S}$, $\bigcup_{\mathcal{G}\in\mathcal{S}} \mathcal{G} = \mathcal{I}$, and $\forall(\mathcal{G}, \mathcal{G}') \in \mathcal{S} \times \mathcal{S}_{-\mathcal{G}}, \mathcal{G} \cap \mathcal{G}' = \varnothing$. For instance, among a set of three jurisdictions $\{i, j, k\}$, there exist five linkage structures, namely

$$\underbrace{\Big\{\{i\},\{j\},\{k\}\Big\}}_{\text{complete autarky}}, \quad \underbrace{\Big\{\{i,j,k\}\Big\}}_{\text{grand linkage}}, \quad \underbrace{\Big\{\{i,j\},\{k\}\Big\},\ \Big\{\{i,k\},\{j\}\Big\} \text{ and } \Big\{\{j,k\},\{i\}\Big\}}_{\text{3 incomplete linkages}}.$$

[5] By definition linkage structures only comprise disjoint linkage groups. This is without loss of generality because our machinery is also able to handle situations where jurisdictions belong to several linkage groups simultaneously, i.e. indirect linkages as defined in Jaffe et al. (2009) and Tuerk et al. (2009) inter alia.

Structures in which there are singletons, i.e. some jurisdictions remain in autarky, are referred to as incomplete linkages, e.g. $\{\{i,k\},\{j\}\}$. Among a set of four jurisdictions $\{i,j,k,l\}$, richer variation in structures emerges consisting of multiple linkage groups, e.g. $\{\{i,j\},\{k,l\}\}$. Structures in which groups coexist are referred to as polycentric structures. Note that polycentric structures may also contain singletons and therefore exhibit linkage incompleteness. Table 1 illustrates that the difference in the number of possible linkage groups and structures grows exponentially with the number of jurisdictions.

Next, we introduce the concept of structure coarsening that is helpful in comparing different structures. To define it formally, we first introduce and define a unitary linkage between two disjoint groups. Then, a structure coarsening coincides with a sequence of unitary linkages.

Definition 1. ***(Unitary linkage)*** *For $\mathcal{S} \in \mathbf{S}$ with $|\mathcal{S}| \geq 2$, a unitary linkage is a mapping*

$$\begin{cases} \mathbf{S} \longrightarrow \mathbf{S} \\ \mathcal{S} \longmapsto \mathcal{S}' = \{\mathcal{G}' \cup \mathcal{G}''\} \cup \mathcal{S}\backslash\{\mathcal{G}', \mathcal{G}''\}, \end{cases}$$

for some $(\mathcal{G}', \mathcal{G}'') \in \mathcal{S} \times \mathcal{S}\backslash\{\mathcal{G}'\}$. That is, the linkage structure $\mathcal{S}'$ obtains from $\mathcal{S}$ by merging exactly two disjoint linkage groups in $\mathcal{S}$ and $|\mathcal{S}| - |\mathcal{S}'| = 1$.

Definition 2. ***(Coarsening)*** *For any $\mathcal{S}$ and $\mathcal{S}'$ in $\mathbf{S}^2$ with $|\mathcal{S}| \geq 2$ and $d = |\mathcal{S}| - |\mathcal{S}'| \geq 1$, $\mathcal{S}'$ is coarser than $\mathcal{S}$ if there exists a sequence $(\mathcal{S}_i)_{i \in [\![0;d]\!]} \in \mathbf{S}^{d+1}$ such that $\mathcal{S}_0 = \mathcal{S}'$, $\mathcal{S}_d = \mathcal{S}$ and for all $i \in [\![1;d]\!]$, $\mathcal{S}_{i-1}$ obtains from $\mathcal{S}_i$ via unitary linkage. That is, for all $i \in [\![1;d]\!]$, there exist $(\mathcal{G}'_i, \mathcal{G}''_i)$ in $\mathcal{S}_i \times \mathcal{S}_i\backslash\{\mathcal{G}'_i\}$ such that $\mathcal{S}_{i-1} = \{\mathcal{G}'_i \cup \mathcal{G}''_i\} \cup \mathcal{S}_i\backslash\{\mathcal{G}'_i, \mathcal{G}''_i\}$.*

Linkage is therefore congruent with a coarsening of the underlying structure. In particular, when structure $\mathcal{S}'$ obtains from structure $\mathcal{S}$ through linkage, the set of newly formed linkage groups is $\mathcal{S}'\backslash\{\mathcal{S}' \cap \mathcal{S}\}$ and has cardinality $|\mathcal{S}| - |\mathcal{S}'|$ at most. Finally, note that the number of structures that are strictly coarser than $\mathcal{S}$ is $2^{|\mathcal{S}|} - |\mathcal{S}| - 1$.

3.2 Multilateral linkage equilibrium

For all $\mathcal{G}$ in $\mathbf{G}_\star$, we call $\mathcal{G}$-linkage the formation of a linked market between all jurisdictions in group $\mathcal{G}$. By extension, $\mathcal{I}$-linkage coincides with the grand linkage. An interior $\mathcal{G}$-linkage equilibrium consists of the $(|\mathcal{G}|+1)$-tuple $(p_\mathcal{G}, (q_{\mathcal{G},i})_{i \in \mathcal{G}})$, where $p_\mathcal{G}$ is the equilibrium permit price in the linked market and $q_{\mathcal{G},i}$ denotes jurisdiction i's equilibrium level of emissions.[6]

[6]Specifically, we further assume all idiosyncratic shocks are bounded from above such that zero-emissions corners do not occur as a result of a link. In Appendix B, we show that such corners are typically rare since

The equilibrium is characterized by the equalization of marginal benefits across jurisdictions in $\mathcal{G}$ (to the $\mathcal{G}$-linkage equilibrium price) and linked market clearing, that is

$$\beta_i + \theta_i - q_{\mathcal{G},i}/\gamma_i = p_{\mathcal{G}} \text{ for all } i \text{ in } \mathcal{G}, \text{ and } \sum_{i\in\mathcal{G}} q_{\mathcal{G},i} = \Omega_{\mathcal{G}} \doteq \sum_{i\in\mathcal{G}} \omega_i, \tag{8}$$

where $\Omega_{\mathcal{G}}$ denotes $\mathcal{G}$'s cap. Therefore, cost-efficiency obtains as any jurisdiction $i \in \mathcal{G}$ abates in proportion to its flexibility, i.e. $\tilde{q}_i - q_{\mathcal{G},i} = \gamma_i p_{\mathcal{G}}$. In particular, the $\mathcal{G}$-linkage equilibrium price can be expressed as the flexibility-weighted average of autarky prices, that is

$$p_{\mathcal{G}} = \bar{p}_{\mathcal{G}} + \hat{\Theta}_{\mathcal{G}}, \text{ with } \bar{p}_{\mathcal{G}} \doteq \Gamma_{\mathcal{G}}^{-1} \sum_{i\in\mathcal{G}} \gamma_i \bar{p}_i \text{ and } \hat{\Theta}_{\mathcal{G}} \doteq \Gamma_{\mathcal{G}}^{-1} \sum_{i\in\mathcal{G}} \gamma_i \theta_i \tag{9}$$

where $\Gamma_{\mathcal{G}} \doteq \sum_{i\in\mathcal{G}} \gamma_i$ measures $\mathcal{G}$'s flexibility. Individual net demands for permits in the linked market are proportional to flexibility and the difference between the autarky and prevailing linking prices, e.g. for $i \in \mathcal{G}$

$$q_{\mathcal{G},i} - \omega_i = \gamma_i (p_i - p_{\mathcal{G}}). \tag{10}$$

In particular, jurisdiction i is a net permit importer (resp. exporter) under $\mathcal{G}$-linkage provided that $p_i > p_{\mathcal{G}}$ (resp. $p_i < p_{\mathcal{G}}$), i.e. the linking price is lower (resp. higher) than its autarky price. Ceteris paribus, this shows that $\mathcal{G}$-linkage is observationally equivalent to an increase (resp. decrease) in i's effective cap relative to autarky.

3.3 Gains from trade in multilateral linkages

Because aggregate emissions are constant and do not vary with the underlying linkage structure, the economic gains accruing to $i \in \mathcal{G}$ correspond to the difference between its benefits under $\mathcal{G}$-linkage (including permit trading in the linked market) and autarky, that is

$$\begin{aligned} \delta_{\mathcal{G},i} &\doteq B_i(q_{\mathcal{G},i};\theta_i) - p_{\mathcal{G}}(q_{\mathcal{G},i} - \omega_i) - B_i(\omega_i;\theta_i) \\ &= (q_{\mathcal{G},i} - \omega_i)^2/(2\gamma_i) = \gamma_i (p_i - p_{\mathcal{G}})^2/2, \end{aligned} \tag{11}$$

and are further characterized in the following proposition.

$\beta_i > \bar{p}_{\mathcal{G}} + 2\mathbb{V}\{\hat{\Theta}_{\mathcal{G}}\}^{1/2}$ for all $i \in \mathcal{I}$ and $\mathcal{G} \in \mathbf{G}_\star$. Our focus on interior market equilibria is thus without loss of generality for our analysis and allows simplification in (1) computing expected gains from linkage as damages from aggregate emissions are constant and (2) determining the linking price uniquely.

Proposition 1. *Linkage is mutually beneficial almost surely. In particular, under $\mathcal{G}$-linkage, the expected economic gains accruing to jurisdiction $i \in \mathcal{G}$ can be decomposed into ambition and uncertainty components such that*

$$\begin{aligned}\mathbb{E}\{\delta_{\mathcal{G},i}\} = \gamma_i \mathbb{E}\{(p_i - p_{\mathcal{G}})^2\}/2 &= \gamma_i \Big(\underbrace{(\mathbb{E}\{p_i\} - \mathbb{E}\{p_{\mathcal{G}}\})^2}_{\text{ambition comp.}} + \underbrace{\mathbb{V}\{p_i - p_{\mathcal{G}}\}}_{\text{uncertainty comp.}} \Big)\Big/2, \\ &= \gamma_i \Big((\bar{p}_i - \bar{p}_{\mathcal{G}})^2 + \mathbb{V}\{\theta_i - \hat{\Theta}_{\mathcal{G}}\} \Big)\Big/2 \geq 0.\end{aligned} \tag{12}$$

Proof. Relegated to Appendix A.1. □

Jurisdiction i's expected economic gains from $\mathcal{G}$-linkage are proportional to the expectation of the square of the difference in autarky and $\mathcal{G}$-linkage prices, i.e. the square of the distance in autarky-linking prices. Notice the quantity $\mathbb{E}\{\delta_{\mathcal{G},i}\}$ is non-negative and positive provided that i's autarky and $\mathcal{G}$-linkage prices differ almost surely.[7] That is, every partnering jurisdiction in any multilateral linkage is always at least as well off as under autarky. In other words, linking induces a (weak) Pareto-improvement relative to autarky.

It is noteworthy that $\mathbb{E}\{\delta_{\mathcal{G},i}\}$ can be decomposed into two non-negative components. The ambition, or equivalently effort-sharing, component is proportional to the square of the *expected autarky-linking price wedge*, relates to the intra-group variation in domestic ambition levels (i.e., expected autarky prices) and is independent of the shock structure. Intuitively, the larger this wedge, the larger the gains associated with the equalization of jurisdictional marginal benefits *on average*. In practice, however, significant disparities in expected autarky prices can compromise the political feasibility of a link for two reasons. First, they imply sizeable, persistent and politically-unpalatable monetary transfers associated with permit flows across jurisdictions. Second, they may connote different preferences in terms of environmental ambition or role of the carbon price signal as a domestic climate policy instrument.

The uncertainty, or equivalently risk-sharing, component is proportional to the *variance of the autarky-linking price wedge*, relates to jurisdictional and $\mathcal{G}$-wide shock characteristics, and is independent of jurisdictions' ambition levels.[8] Provided that idiosyncratic shock realizations

[7] This result is the analog of the expected gains from merging ETSs obtained by Caillaud & Demange (2017). Note also that summing $\delta_{\mathcal{G},i} = (q_{\mathcal{G},i} - \omega_i)^2/(2\gamma_i)$ over $i \in \mathcal{G}$ would yield the comparative advantage of decentralization w.r.t. centralization for uniformly-mixed pollutants in Yates (2002).

[8] In other words, the second component is invariant, irrespective of how caps are selected. In particular, when in a linkage group $\mathcal{G}$, $\bar{p}_i = \bar{p}$ for all $i \in \mathcal{G}$, then the first component of gains from $\mathcal{G}$-linkage shrinks to zero. In general, jurisdiction i is a net permit seller in expectation i.f.f. $\bar{p}_i \leq \bar{p}_{\mathcal{G}}$, i.e. its ambition level is lower than $\mathcal{G}$'s. As first shown by Helm (2003) and here in Appendix D.3, this creates an incentive for expected net selling (resp. buying) jurisdictions to inflate (resp. deflate) their domestic caps in anticipation of linkage. Appendix D.4 further shows that such strategic selection of domestic caps can increase aggregate emissions,

differ across partnering systems, linking induces a strictly positive gain compared to the case without uncertainty, which is a strict Pareto-improvement due to the absorption of shocks. Intuitively, controlling for the intra-group variation in expected autarky prices, the larger the ex-post wedge in realized autarky and linking prices, the larger the gains associated with risk sharing. For instance, all else equal, a jurisdiction will prefer to be part of linkage groups in which the price happens to be high w.r.t. expectation when its (counterfactual) domestic price would have happened to be low w.r.t. expectation, and vice versa.[9]

Moreover, since the $\mathcal{G}$-linkage price is the flexibility-weighted average of internal autarky prices, it is primarily driven by those of relatively flexible jurisdictions, all else equal. Similarly, for jurisdictions of similar flexibilities, it is in large part determined by those jurisdictions whose permit demand is highly variable. Thus, only considering the uncertainty component of gains, one may expect relatively flexible and volatile jurisdictions to prefer linking with several jurisdictions in a bid to augment their autarky-link price distances. Conversely, relatively non-flexible (resp. non-volatile) jurisdictions may prefer to link exclusively with one relatively flexible (resp. volatile) jurisdiction, for otherwise the influence of that flexible (resp. volatile) jurisdiction on the link outcome is likely to be mitigated.

Before analyzing in more detail the determinants of jurisdictional gains in the next section, we briefly discuss the sources of the two components of the total gains in a group. Specifically, $\mathcal{G}$'s expected costs of compliance with its cap under $\mathcal{G}$-linkage amount to

$$\sum_{i \in \mathcal{G}} \mathbb{E}\{C_i(\tilde{q}_i - q_{\mathcal{G},i})\} = \Gamma_{\mathcal{G}}(\bar{p}_{\mathcal{G}}^2 + \mathbb{V}\{\hat{\Theta}_{\mathcal{G}}\})/2. \tag{13}$$

Note that summing Equation (7) over $i \in \mathcal{G}$ gives the corresponding aggregate costs of compliance under autarky. In particular, we have $\sum_{i \in \mathcal{G}} \mathbb{E}\{C_i(\tilde{q}_i - q_{\mathcal{G},i})\} \leq \sum_{i \in \mathcal{G}} \mathbb{E}\{C_i(\tilde{q}_i - \omega_i)\}$ as it jointly holds that $\Gamma_{\mathcal{G}}\bar{p}_{\mathcal{G}}^2 \leq \sum_{i \in \mathcal{G}} \gamma_i \bar{p}_i^2$ and $\Gamma_{\mathcal{G}}\mathbb{V}\{\hat{\Theta}_{\mathcal{G}}\} \leq \sum_{i \in \mathcal{G}} \gamma_i \sigma_i^2$.[10] In words, given a cap, linkage induces a cost-efficient reduction in the group's expected costs of compliance by spreading the expected aggregate abatement effort in proportion to each member's flexibility and by improving the absorption of shocks within the linked system.

thereby possibly rendering linkage detrimental, relative to complete autarky.

[9] Loosely speaking, the more 'variable' the linking price relative to autarky price, the larger the second component of gains, i.e. the more a jurisdiction benefits from the link. Note that in other economic contexts, Waugh (1944) and Oi (1961) observed that variability could be beneficial.

[10] Note that the first and second inequalities hold with strictness provided that there exists $(i, j) \in \mathcal{G}^2$ such that $\bar{p}_i \neq \bar{p}_j$ and respectively $\rho_{ij} < 1$ and/or $\sigma_i \neq \sigma_j$. See Appendix A.5 for more details.

3.4 Bilateral decomposition of gains in multilateral linkages

Equation (12) offers a compact and intuitive interpretation of individual gains in terms of autarky-linking price distance. While this clarifies the behavior of the ambition component, it is unclear prima facie how the uncertainty component relates to jurisdictional characteristics. To illuminate this further, we unpack Equation (12). In order to focus momentarily on the determinants of the uncertainty component, we assume identical ambition across jurisdictions so that autarky-linking price wedges arise only due to shocks, i.e. $p_i - p_{\mathcal{G}} = \theta_i - \hat{\Theta}_{\mathcal{G}}$. Substituting this into Equation (11) and using the definition of $\hat{\Theta}_{\mathcal{G}}$, we obtain

$$\delta_{\mathcal{G},i} = \gamma_i (2\Gamma_{\mathcal{G}}^2)^{-1} \left(\sum_{j \in \mathcal{G}_{-i}} \gamma_j \left(\theta_i - \theta_j\right) \right)^2. \tag{14}$$

Expanding the above and taking expectations then yields

$$\begin{aligned} \mathbb{E}\{\delta_{\mathcal{G},i}\} = \gamma_i (2\Gamma_{\mathcal{G}}^2)^{-1} \Bigg(& \sum_{j \in \mathcal{G}_{-i}} \gamma_j^2 \left(\sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j\right) \\ & + \sum_{(j,k) \in \mathcal{G}_{-i} \times \mathcal{G}_{-i}} \gamma_j \gamma_k \left(\sigma_i^2 + \rho_{jk}\sigma_j\sigma_k - \rho_{ik}\sigma_i\sigma_k - \rho_{ij}\sigma_i\sigma_j\right) \Bigg). \end{aligned} \tag{15}$$

For clarity of interpretation, we first consider the most elementary group $\mathcal{G} = \{i,j\}$, i.e. a unitary linkage between singletons i and j, or bilateral linkage. Letting $\Delta_{\{i,j\}} \doteq \delta_{\{i,j\},i} + \delta_{\{i,j\},j}$ denote the aggregate economic gains from $\{i,j\}$-linkage, Equation (15) simplifies and gives

$$\mathbb{E}\{\Delta_{\{i,j\}}\} = \gamma_i \gamma_j (\sigma_i^2 + \sigma_j^2 - \rho_{ij}\sigma_i\sigma_j)/(2\Gamma_{\{i,j\}}) \geq 0, \text{ and} \tag{16a}$$

$$\mathbb{E}\{\delta_{\{i,j\},i}\}/\mathbb{E}\{\delta_{\{i,j\},j}\} = \gamma_j/\gamma_i. \tag{16b}$$

Intuitively and as described further in Doda & Taschini (2017), the aggregate risk-sharing gains from $\{i,j\}$-linkage are (1) positive as long as jurisdictional shocks are imperfectly correlated and jurisdictional volatility levels differ, for otherwise the two jurisdictions are identical in terms of shock characteristics and there is no gain from linkage, (2) increasing in both jurisdictional volatilities and flexibilities, (3) higher the more weakly correlated jurisdictional shocks are, and (4) for a given aggregate flexibility, maximal when jurisdictions have equal flexibilities. Additionally, note that aggregate gains are apportioned between jurisdictions in inverse proportion to flexibility. This is so because, for a given volume of trade, the distance between the autarky and linking prices is greater in the more flexible jurisdiction.

Returning to the general case of any $\mathcal{G}$-linkage, we could pursue a similar approach to compute $\mathbb{E}\{\delta_{\mathcal{G},i}\}$ as i's expected gains from a unitary linkage between i and $\mathcal{G}_{-i}$. However, the nature of the entity $\mathcal{G}_{-i}$ becomes exceedingly complex as the cardinality of $\mathcal{G}$ increases – see Appendix C for the case of trilateral linkage. In this respect, one of our contributions is to recognize that bilateral linkages constitute the building blocks of the multilateral linkage analysis. Specifically, in a given linkage group, we show that it is more convenient to express the associated quantities as a function of the group's internal bilateral linkage quantities. That is, with the convention that for any $i \in \mathcal{I}$ $\Delta_{\{i,i\}} = 0$, gains in $\mathcal{G}$-linkage (inclusive of both ambition and uncertainty components) accruing to jurisdiction $i \in \mathcal{G}$ write

$$\delta_{\mathcal{G},i} = \Gamma_{\mathcal{G}}^{-2} \sum_{j \in \mathcal{G}_{-i}} \left\{ \Gamma_{\mathcal{G}_{-i}} \Gamma_{\{i,j\}} \Delta_{\{i,j\}} - (\gamma_i/2) \sum_{k \in \mathcal{G}_{-i}} \Gamma_{\{j,k\}} \Delta_{\{j,k\}} \right\}. \tag{17}$$

Therefore, jurisdiction i is better off linking with sets of jurisdictions such that on the one hand, the aggregate gains in bilateral links between i and each jurisdiction in these sets are high, and on the other hand, the aggregate gains in bilateral links internal to these sets are low. In particular, referring to the description of the determinants of the uncertainty component of gains in bilateral links discussed above, these desirable sets, from the perspective of i, should comprise of jurisdictions that are (1) similar to each other, (2) more volatile and flexible than i, and (3) negatively correlated with i. At the extreme and considering only the uncertainty component of gains, i would ideally like to link with as many replicas of its most preferred bilateral linking partner as possible.

Then, summing Equation (17) over all $i \in \mathcal{G}$ gives the following proposition.

Proposition 2. *Any $\mathcal{G}$-linkage can be decomposed into its internal bilateral linkages, that is*

$$\Delta_{\mathcal{G}} \doteq \sum_{i \in \mathcal{G}} \delta_{\mathcal{G},i} = (2\Gamma_{\mathcal{G}})^{-1} \sum_{(i,j) \in \mathcal{G}^2} \Gamma_{\{i,j\}} \Delta_{\{i,j\}}. \tag{18}$$

The number of such internal bilateral links is triangular and equals $\binom{|\mathcal{G}|+1}{2}$.

Proof. Relegated to Appendix A.2. □

In words, the aggregate gains from $\mathcal{G}$-linkage write as a flexibility-weighted sum of all gains from bilateral linkages within $\mathcal{G}$. This decomposition result allows a more practical formulation and quantification of gains generated by any arbitrarily large group. In the next section we study what enlarging linkage groups implies for aggregate expected gains.

3.5 Superadditivity and linkage between linkage groups

We define the aggregate gains generated by any structure $\mathcal{S}$ in $\mathbf{S}$ by $\Delta_{\mathcal{S}} \doteq \sum_{\mathcal{G}\in\mathcal{S}} \Delta_{\mathcal{G}}$ and we adopt the convention that $\Delta_{\mathcal{G}} = 0$ whenever $\mathcal{G} \in \mathbf{G}\backslash\mathbf{G}_{\star}$. Let $(\mathcal{G}, \mathcal{G}') \in \mathbf{G}_{\star} \times \mathbf{G}$ with $\mathcal{G}' \subset \mathcal{G}$ and denote by $\mathcal{G}''$ the complement of $\mathcal{G}'$ in $\mathcal{G}$, i.e. $\mathcal{G} = \mathcal{G}' \cup \mathcal{G}''$ and $\mathcal{G}' \cap \mathcal{G}'' = \varnothing$. Then, we can express the aggregate gains in $\mathcal{G}$ as a function of those in $\mathcal{G}'$ and $\mathcal{G}''$ by unpacking Equation (18), that is

$$\Delta_{\mathcal{G}} = \Gamma_{\mathcal{G}}^{-1}\left(\Gamma_{\mathcal{G}'}\Delta_{\mathcal{G}'} + \Gamma_{\mathcal{G}''}\Delta_{\mathcal{G}''} + \sum_{(i,j)\in\mathcal{G}'\times\mathcal{G}''} \Gamma_{\{i,j\}}\Delta_{\{i,j\}}\right). \tag{19}$$

Note that the third term in the parenthesis captures the interaction among jurisdictions in $\mathcal{G}'$ and $\mathcal{G}''$, which is precisely the quantity we want to isolate. To do so, we consistently denote the aggregate gains of merging groups $\mathcal{G}'$ and $\mathcal{G}''$ by $\Delta_{\{\mathcal{G}',\mathcal{G}''\}}$ and define them such that

$$\Delta_{\{\mathcal{G}',\mathcal{G}''\}} \doteq \Delta_{\mathcal{G}} - \Delta_{\mathcal{G}'} - \Delta_{\mathcal{G}''}. \tag{20}$$

With this definition, we can establish the following proposition.

Proposition 3. *Linkage is superadditive in the sense that for any $(\mathcal{S}, \mathcal{S}') \in \mathbf{S}^2$ such that $|\mathcal{S}| \geq 2$ and $\mathcal{S}'$ is a coarsening of $\mathcal{S}$ as in Definition 2 with $d = |\mathcal{S}| - |\mathcal{S}'|$*

$$\mathbb{E}\{\Delta_{\mathcal{S}'}\} - \mathbb{E}\{\Delta_{\mathcal{S}}\} = \sum_{i=1}^{d}\Big\{\mathbb{E}\{\Delta_{\mathcal{S}_i}\} - \mathbb{E}\{\Delta_{\mathcal{S}_{i-1}}\}\Big\} = \sum_{i=1}^{d}\mathbb{E}\{\Delta_{\{\mathcal{G}_i',\mathcal{G}_i''\}}\} \geq 0, \tag{21}$$

where in particular, for all intermediary unitary linkages $i \in [\![1; d]\!]$,

$$\mathbb{E}\{\Delta_{\{\mathcal{G}_i',\mathcal{G}_i''\}}\} = \Gamma_{\{\mathcal{G}_i'\cup\mathcal{G}_i''\}}^{-1}\left(\sum_{(j,k)\in\mathcal{G}_i'\times\mathcal{G}_i''}\Gamma_{\{j,k\}}\mathbb{E}\{\Delta_{\{j,k\}}\} - \Gamma_{\mathcal{G}_i''}\mathbb{E}\{\Delta_{\mathcal{G}_i'}\} - \Gamma_{\mathcal{G}_i'}\mathbb{E}\{\Delta_{\mathcal{G}_i''}\}\right) \geq 0. \tag{22}$$

Proof. Relegated to Appendix A.3. □

In words, the aggregate expected gains from the union of disjoint groups is no less than the sum of the separate groups' aggregate expected gains.[11] Intuitively, the non-negative sign in Equation (22) follows from the mutually beneficial nature of any unitary linkage.[12]

We now illustrate several implications of superadditivity. In particular, because singletons

[11] Because we can characterize linkages between two or more linkage groups, we note that our analysis can be extended to sequential linkages. We discuss this issue further in Appendix D.2.

[12] In a permit market covering firms whose emissions are stochastic, Hennessy & Roosen (1999) also find that merging firms is superadditive but they stop short of a finer description of this property.

have zero value, linkage exhibits monotonicity, that is

$$\forall(\mathcal{G},\mathcal{G}') \in \mathbf{G}^2,\ \mathcal{G}' \subseteq \mathcal{G} \Rightarrow \mathbb{E}\{\Delta_{\mathcal{G}'}\} \leq \mathbb{E}\{\Delta_{\mathcal{G}}\}. \tag{23}$$

Therefore, $\mathcal{I}$-linkage is the linkage group that is the most advantageous in aggregate expected terms. Superadditivity, in fact, provides a stronger result than monotonicity, i.e. that linkage displays cohesiveness

$$\forall\mathcal{S} \in \mathbf{S},\ \mathbb{E}\{\Delta_{\mathcal{I}}\} \geq \mathbb{E}\{\Delta_{\mathcal{S}}\}. \tag{24}$$

Therefore, $\mathcal{I}$-linkage is the linkage structure that is conducive to the highest aggregate cost savings in complying with the aggregate cap $\Omega_{\mathcal{I}}$.[13] In aggregate terms, a single linkage group consisting of all jurisdictions linked together thus outperforms any other linkage structure. Additionally, superadditivity allows us to characterize jurisdictional preferences in terms of linkage groups in the absence of inter-jurisdictional transfers.

Corollary 1. *Assume inter-jurisdictional monetary transfers away. Then, jurisdictional linkage preferences are not aligned in the sense that*
(a) $\mathcal{I}$-linkage may not be the most preferred linkage group for all jurisdictions in $\mathcal{I}$;
(b) any $\mathcal{G} \in \mathbf{G}_\star \backslash \{\mathcal{I}\}$ cannot be the most preferred linkage group for all jurisdictions in $\mathcal{G}$.

Proof. Relegated to Appendix A.4. □

Statement (a) implies that there exists a non-empty set of jurisdictional characteristics such that $\mathcal{I}$-linkage is the most preferred linkage group unanimously. That said, Sections 4 and 5 will illustrate that this is unlikely to be the case in practice. In other words, although grand linkage is the most cost-efficient outcome from an aggregate perspective, it is unlikely to emerge endogenously absent inter-jurisdictional transfers as some jurisdictions may prefer to form smaller groups and thus voice opposition.[14] Such smaller groups can form provided that jurisdictional linkage preferences tally with one another. However, as Statement (b) indicates, one jurisdiction's most preferred group cannot simultaneously be the favourite

[13]Formally, cohesiveness requires that aggregate gains from grand linkage be larger than under no agreement (i.e., complete autarky) or any partial agreement (i.e., incomplete linkage). Superadditivity is a stronger property as it requires that this holds for all intermediary linkage structures as well. We also note that the particular functional forms that are assumed in the literature on International Environmental Agreements generally imply cohesiveness but not necessarily superadditivity.

[14]When inter-jurisdictional transfers are feasible, cohesiveness ensures that it is always possible to find a transfer scheme that satisfies 'grand coalition' rationality, i.e. no subgroup is better off deviating from grand linkage. In other words, there exists (at least) one allocation of the gains from grand linkage that lies in the core of the coalitional game, i.e. grand linkage can be sustained (Helm, 2001).

group for every jurisdiction thereof. Note that this is to be expected because partners in the desirable sets a jurisdiction wants to link with the most, do not benefit much from the link themselves. In a world where monetary transfers can run into significant political-economy obstacles and thereby prove unwieldy, this non-alignment result can in part explain why linkage negotiations do not readily result in the formation of large linkage groups.[15]

3.6 Risk-sharing and permit price properties under linkage

In our model, the permit price is a well-defined object whose properties we can analyze. First, we describe the two terms constituting the $\mathcal{G}$-linkage price $p_{\mathcal{G}} = \bar{p}_{\mathcal{G}} + \hat{\Theta}_{\mathcal{G}}$. The first term $\bar{p}_{\mathcal{G}}$ is commensurate with the stringency of the group's cap relative to its baseline emissions. It measures the marginal cost of abatement when the group's expected abatement effort is allocated cost-efficiently. The second term $\hat{\Theta}_{\mathcal{G}} = \Gamma_{\mathcal{G}}^{-1} \sum_{i \in \mathcal{G}} \gamma_i \theta_i$ quantifies the price impact due to the variability of the stringency of the group's cap relative to laissez-faire emissions that would be consistent with a profile of realized shocks. Indeed, given $(\theta_i)_{i \in \mathcal{G}}$, the quantity $\sum_{i \in \mathcal{G}} \gamma_i \theta_i$ measures the difference in the group's laissez-faire and baseline emissions. Then, dividing it by the group-wide flexibility gives the corresponding price impact.

Next, we establish two properties of permit price volatility that allow us to characterize the features of linkage in terms of risk-sharing in the following proposition.

Proposition 4. *Linkage reduces permit price volatility on average in groups and structures, but not necessarily for each of their member jurisdictions. That is,*
(a) For any $\mathcal{S} \in \mathbf{S}$, let $\mathcal{V}_{\mathcal{S}} = \Gamma_{\mathcal{S}}^{-1} \sum_{\mathcal{G} \in \mathcal{S}} \Gamma_{\mathcal{G}} \mathbb{V}\{p_{\mathcal{G}}\}^{1/2}$ where $\Gamma_{\mathcal{S}} = \sum_{\mathcal{G} \in \mathcal{S}} \Gamma_{\mathcal{G}}$. Linkage diversifies risk in the sense that for any $\mathcal{G} \in \mathbf{G}_{\star}$, $\mathbb{V}\{p_{\mathcal{G}}\}^{1/2} \leq \Gamma_{\mathcal{G}}^{-1} \sum_{i \in \mathcal{G}} \gamma_i \mathbb{V}\{p_i\}^{1/2}$ and any $(\mathcal{S}, \mathcal{S}') \in \mathbf{S}^2$ such that $|\mathcal{S}| \geq 2$ and $\mathcal{S}'$ is a coarsening of $\mathcal{S}$, $\mathcal{V}_{\mathcal{S}'} \leq \mathcal{V}_{\mathcal{S}}$.
(b) Under $\mathcal{G}$-linkage, only when shocks are independent does it hold that $\text{p-lim}_{|\mathcal{G}| \to +\infty} p_{\mathcal{G}} = \bar{p}_{\mathcal{G}}$. *In particular, relative to autarky, linkage always reduces price volatility in higher volatility jurisdictions but may increase it in lower volatility jurisdictions.*

Proof. Relegated to Appendix A.5. □

As shown in Statement (a), linkage improves shock absorption and reduces price volatility on average relative to autarky. Indeed, in a given group, the linking price volatility is smaller

[15] Again, we emphasize that inter-jurisdictional transfers could ensure both internal and external stability of groups as defined in Cartel games (D'Aspremont et al., 1983; Nagashima et al., 2009; Lessmann et al., 2015). Here, in fact, all groups are 'potentially internally stable' in the sense of Carraro et al. (2006).

than the flexibility-weighted average of autarky price volatilities. That is, the variability of the group's cap stringency is less than the one implied by its members' individual cap stringencies taken together. As discussed earlier, this in turn mitigates the variability of the group-wide costs of compliance with the group's target relative to autarky. Importantly, we also prove that this diversification property translates to structures: the coarser a structure, the more diversified the domestic shocks on average.[16] Obviously, on the flip side reduced price volatility implies jurisdictional emission levels are now uncertain and contingent on own and linkage partners' shock realizations. This, however, can be desirable as it introduces some responsiveness in domestic caps much like a hybrid instrument does.[17]

Although linkage-induced diversification guarantees that price volatility is reduced on average in a group, this by no means implies every jurisdiction experiences a reduction in volatility relative to autarky. As clarified in Statement (b), on the one hand relatively volatile jurisdictions always experience reduced price volatility w.r.t. autarky as domestic shocks are spread over a thicker market and thus better cushioned. On the other hand, because linkage also creates exposure to shocks occurring abroad, relatively stable jurisdictions may face higher price volatility w.r.t. autarky. All else equal, this is more likely to occur in low-flexibility jurisdictions, i.e. jurisdictions regulating a small volume of emissions or having access to a high-cost abatement technology at the margin, or both. For instance, from the perspective of small-volume jurisdictions, the influence of larger-volume jurisdictions on the link outcomes tends to be more pronounced. However, we emphasize that linkage is always preferred to autarky, even when it leads to higher price volatility domestically. As will become clearer in the quantitative application in Section 5, even the jurisdictions that 'import' volatility as a result of the link experience a reduction in expected costs of compliance.

Relatedly, enlarging a group does not imply that the associated linking price tends to converge in probability towards its expected value. This would be true if and only if domestic shocks are independent. In other words, there is no reason that price volatility should gradually diminish as the cardinality of a group increases. As a case in point, consider the situation where sufficiently volatile and large-volume jurisdictions join in as the group expands.

[16] Making a parallel with portfolio theory where a structure is a portfolio whose assets are jurisdictions that can be pooled into groups, greater risk diversification would coincide with coarser structures as they tend to comprise larger groups and thus mix a wider variety of jurisdictions together.

[17] In the normative framework of instrument selection, much has been written about the problem of vertical permit supply curves since the seminal contributions by Roberts & Spence (1976) and Weitzman (1978). In general, hybrid instruments have been shown to outperform both pure price and pure quantity instruments.

4 Qualitative illustration

In this section we illustrate our theoretical results with the aid of a stylized three-jurisdiction world $\{i, j, k\}$. Taking jurisdiction i's perspective, we compare its linkage options graphically in Figure 1. Throughout we assume that jurisdictions have identical ambition levels, i.e. autarky prices are equal in expectation and the ambition component of linkage gains is zero. The calibrated quantitative application in the next section relaxes this assumption and provides monetary evaluations of both ambition and uncertainty components of gains.

We start by describing the key features of Figure 1. The axes are identical across the panels of the figure and measure γ_j and γ_k with respect to the innocuous normalization $\gamma_i = 1$. The dot in the center of each panel identifies the point of γ-symmetry, i.e. $\gamma_i = \gamma_j = \gamma_k = 1$. Throughout we also refer to the case where $\sigma_i = \sigma_k = \sigma_j > 0$ and $\rho_{ij} = \rho_{ik} = \rho_{jk} = 0$ as the symmetric uncertainty benchmark (SUB).

In Panel 1a we rule out the possibility of grand linkage to focus on the simpler case of i's possible bilateral linkage groups, namely $\{i, j\}$ and $\{i, k\}$. In this case, the 45° line depicts the indifference frontier along which $\{i, j\}$ and $\{i, k\}$ generate the same linkage gains for i. Above the frontier i prefers to link with k because k offers more flexible abatement opportunities at the margin than j does. All else constant, deviations from SUB such as $\sigma_i = \sigma_j < \sigma_k$ or $\rho_{ij} = 0 > \rho_{ik}$ distort the indifference frontier to the dashed curve.[18] These deviations imply that k is i's preferred partner in a larger region of the $\{\gamma_j, \gamma_k\}$-space.

In Panel 1b we revert back to SUB but now allow for the formation of the grand linkage in addition to the bilateral links just discussed. We make two observations. First, at the point of γ-symmetry, i prefers the grand linkage over the bilateral linkages. This is to be expected because with j and k ex ante identical, the grand linkage offers greater abatement flexibility than the bilateral linkages by virtue of its greater market size, access it provides to lower cost abatement technologies at the margin, or a combination of both. Now note that i's indifference point between grand linkage and bilateral linkages – denoted by a diamond – is such that $\gamma_i < \gamma_j = \gamma_k$. Indeed, given the restrictions implicit in SUB, it must be that j and k are individually able to offer abatement opportunities sufficiently more flexible than i's to render bilateral linkages at least as rewarding as grand linkage for i.

Second, deviations from SUB which do not break symmetry would move the point of indifference along the 45° line. For example, $\sigma_i < \sigma_j = \sigma_k$ would move the point of indifference

[18] Appendix C contains the analytical expressions for the indifference frontiers as well as simple analytical examples that further characterize the influence of jurisdictional parameters on linkage preferences.

northeast, thereby expanding the region in which grand linkage is the preferred option symmetrically around the 45º line, and vice versa. Additionally, Panel 1c shows the implications of breaking the symmetry implicit in *SUB*. The case depicted in this panel distorts the indifference frontier in favor of the bilateral group $\{i, k\}$ which is consistent with deviations from *SUB* such that $\sigma_i = \sigma_j < \sigma_k$ or $\rho_{ik} < \rho_{ij} = \rho_{jk} = 0$.

Finally, it is informative to characterize j and k's linkage preferences in the same $\{\gamma_j, \gamma_k\}$-space. Panel 1d superimposes the linkage indifference frontiers for the three jurisdictions in *SUB*. The dark grey area at the center represents the zone where grand linkage is simultaneously preferred by all three jurisdictions and should thus endogenously emerge. This is the case when the γ_i's do not deviate much from γ-symmetry. The light grey areas at the top and in the southwest corner represent the zones where i and k respectively prefer $\{i, k\}$-linkage the most. Because these zones do not overlap, $\{i, k\}$-linkage cannot form endogenously without transfers. This is consistent with Corollary 1 which implies that no bilateral linkage can simultaneously be the most preferred option for the two jurisdictions involved.

In general, for a given set of jurisdictions, it is not clear prima facie whether jurisdictional characteristics are such that grand linkage is the most preferred linkage option for all jurisdictions simultaneously. As Panel 1d suggests, we can surmise that this is the case only when the degree of asymmetry between jurisdictions is low enough. With more than three jurisdictions the problem becomes analytically cumbersome so in the next section we provide a quantitative illustration calibrated to a set of five real-world jurisdictions.

5 Quantitative application

In this section we illustrate the quantitative implications of our theoretical findings by considering possible linkages between hypothetical ETSs regulating carbon dioxide emissions from the power sector of several real-world jurisdictions. We assume that compliance must take place annually without banking and borrowing of permits across compliance periods. This implies that the per-annum monetary gains from trade due to linkage computed below should be taken as illustrative only.

Data description and model calibration Our calibration strategy is described in detail in Appendix B. Here we provide a succinct overview. We obtained estimates of the annual baseline emissions and marginal abatement cost curves (MACCs) for the power sector of eleven jurisdictions in 2030 from Enerdata, a private research and consulting firm whose clients include national governments of the UK and Canada and international organizations such as the UNDP and the European Commission among other public and private sector organizations. Based on the Ener-Blue scenario of the POLES model, the company also provided us with its estimates of the annual emission caps consistent with the achievement of the 2030 targets defined in the Nationally Determined Contributions as announced at the Conference of Parties in Paris.

Equipped with caps and MACCs, we compute the expected autarky permit prices using our model and restrict our attention to five jurisdictions with similar expected autarky prices. This ensures that the ambition component of linkage gains, which is exogenously given in our model, does not swamp the uncertainty component. Moreover, focusing on jurisdictions which have broadly comparable ambition and uncertainty components helps ease political-economy concerns by limiting large and persistent one-way permit/financial flows. The five jurisdictions we study are Canada (CAN), the continental European countries currently participating in the European Union Emission Trading System excluding the UK (EUR), South Korea (KOR), the United Kingdom (GBR) and the United States (USA).[19]

The annual baselines ($\bar{q}_i$) and emission caps (ω_i) as well as the corresponding expected autarky permit prices ($\bar{p}_i$) are reported in Table 2, which also reports the flexibility coefficients (γ_i) and linear intercepts (β_i) we calibrate using power sector MACCs from Enerdata. It is not straightforward to compare γ_i across jurisdictions because this parameter is a combination of available abatement technologies and the volume of regulated emissions in each jurisdiction.

We calibrate the shock properties based on the cyclical variation in historical power sector emissions using data from the International Energy Agency. Table 3 provides the volatility of the autarky permit prices as measured by the coefficient of variation, as well as the pairwise shock correlations implied by our theory. We emphasize the fact that there is large cross-jurisdiction variation in autarky prices and that there exist instances where the correlation between shocks is negative, e.g. between KOR and EUR.

Discussion Thanks to the bilateral decomposition result in Proposition 2 we can adopt a combinatorial approach to quantifying the *annual monetary gains* to every jurisdiction in every possible linkage group.

Proposition 1 indicates that jurisdictional gains are proportional to the sum of an ambition component and an uncertainty component. In this quantitative section we refer

[19] The remaining six jurisdictions are Australia, China, Japan, Mexico, New Zealand, and South Africa. We report their expected autarky permit prices $\bar{p}_i$'s in Appendix B.

to the gains associated with the two components as effort-sharing and risk-sharing gains. These are illustrated in Figure 2 using three distinct linkage structures, namely the grand linkage and the two structures which generate the *greatest* and *smallest* gains among the ten possible complete polycentric linkage structures, {{CAN,GBR}, {EUR,KOR,USA}} and {{GBR,KOR}, {CAN,EUR,USA}}, respectively. The figure shows (1) how a group's gains are shared among the member jurisdictions and (2) the sources of gains for each jurisdiction. The areas of the various rectangles are proportional to the magnitude of the gains.[20] They are comparable across the gains components, jurisdictions and panels of the figure. Different colors indicate jurisdictions and different shades of a given color indicate the effort-sharing (light) and risk-sharing (dark) gains for a given jurisdiction. The grey areas in the lower two panels are the reduction in gains due to the move away from the grand linkage.

In the grand linkage (top panel of Figure 2), the aggregate effort-sharing gains amount to \$60 million, and those associated with risk sharing are \$310 million, totalling \$370 million.[21] Risk sharing is the dominant source of gains in all jurisdictions but CAN. At \$46 million CAN's effort-sharing gains are sizeable and account for almost 80% of aggregate effort-sharing gains. This is not surprising because the expected autarky-linking price wedge in CAN is the largest (113.7 vs 92.7 \$/tCO_2). Conversely, KOR captures the largest risk-sharing gains which amount to \$177 million or approximately half of the aggregate risk-sharing gains.

The complete polycentric structure (middle panel of Figure 2) consists of the bilateral and trilateral linkage groups {CAN,GBR} and {EUR,KOR,USA}, respectively. The former includes the two jurisdictions with the largest difference in $\bar{p}_i$ so the effort-sharing gains in this group are greater than the risk-sharing gains. Moreover, since the calibrated flexibility coefficient of GBR is smaller, it captures the lion's share of the total gains of about \$60 million. For effort-sharing gains this is so because the expected linking price settles at \$105/tCO_2 which is closer to CAN's $\bar{p}_i$. By contrast, at about \$5 million the aggregate effort-sharing gains are tiny in the trilateral linkage because the differences between $\bar{p}_i$ are small among EUR, KOR and USA. As in the grand linkage, the risk-sharing gains mostly accrue to KOR (\$175 million), followed by EUR (\$64 million) and USA (\$23 million). The aggregate gains generated in this linkage group are approximately \$267 million.

Comparing the aggregate gains in the complete polycentric structure to those in the grand linkage illustrates superadditivity of linkage established in Proposition 3. To see this, observe

[20]The small squares are an exception, e.g. KOR's effort-sharing gains in the grand linkage, and indicate gains too small to be visible in the graph.

[21]All monetary quantities are expressed in constant 2005US\$ and all gains accrue annually.

that the sum of the gains in bilateral and trilateral linkages in the former correspond to approximately 89% of total gains in the grand linkage. That is, additional gains of about $43 million, represented by the grey area in the middle panel, can be generated by linking the two disjoint groups.

As indicated above, in a set of five jurisdictions there are ten distinct complete polycentric linkage structures. These generate a wide range of aggregate gains, as well as distributions of these gains across jurisdictions and gains components. Among these, the structure {{GBR,KOR},{CAN,EUR,USA}} generates the smallest gains (lower panel of Figure 2). In this case, observe that the risk-sharing gains that accrue to KOR ($3 million) are significantly lower. The aggregate gains generated in this structure are $192 million of which only about $133 million is due to risk sharing because most of the risk-sharing gains that would have otherwise been available are dissipated by linking the volatile jurisdiction KOR with the inflexible jurisdiction GBR. The risk-sharing gains which go unrealized account for the bulk of the $178 million decline in aggregate gains generated in this structure, once again represented by the grey area in the lower panel. To summarize, moving from the grand linkage to a complete polycentric structure results in losses in the range of $43-178 million.

Corollary 1 indicates that jurisdictional linkage preferences are not necessarily aligned. We can make a number of related observations regarding this point using the aggregate gains CAN, GBR and EUR's receive in alternative linkage groups as reported in the left column of Figure 3. First, the grand linkage is not the most desirable group for any of these jurisdictions. Instead, the most preferred option of CAN is the trilateral link {CAN,GBR,KOR}, that of GBR is the bilateral link {CAN,GBR}, and that of EUR is the quadrilateral link {CAN,EUR,KOR,USA}. Second, linkage preferences do not tally: GBR would prefer to be in a bilateral link with CAN, which in turn would rather have KOR join in to form a trilateral link. In its turn, KOR (not shown) prefers the grand linkage over all other groups.

Third, the effect of a change in the cardinality of a group is not monotonic. Starting from any group, entry by a new jurisdiction, say at the insistence of one of the partnering jurisdictions, may increase or decrease the gains of another group member. For example, adding USA to {CAN,GBR} improves the gains of CAN more than five-fold to almost $70 million but reduces those of GBR by about 30% to about $35 million. Put differently, no simple and transparent relationship exists between the characteristics of a given jurisdiction and the impact its entry will have on the gains of the existing members of a group. Taken together, these observations underline the need for a model to evaluate the gains from linking ETSs multilaterally.

Finally, Proposition 4 indicates that although linkage improves shock absorption on average, it may increase price volatility in some jurisdictions. This is shown in the right panel of Figure 3, which depicts the volatility of permit prices as measured by the coefficient of variation in alternative groups. Loosely speaking, linkage-induced shock absorption can be observed in the general downward trend in average volatility as the cardinality of groups increases. Regarding individual jurisdictions, both GBR and EUR experience reduced price volatility relative to autarky in their most preferred groups. In GBR, volatility declines from about 0.49 to about 0.15 in {GBR,CAN} and for EUR it declines from about 0.12 to 0.08 in {EUR,USA,CAN,KOR}. Conversely, in its most preferred groups, CAN experiences increased price volatility relative to autarky. Note also that the most preferred groups for all three jurisdictions feature significantly greater price variability than the grand linkage where the volatility is approximately 0.07. We emphasize that in our model an increase in permit price volatility relative to autarky does not have any negative implications, which for many jurisdictions in the real world can be an important consideration.

6 Conclusion

Linkages between ETSs has an important role to play in the successful, cost-effective implementation of the Paris Agreement. In this paper we advance the frontier of research on permit markets integration by proposing a general model to describe and analyze multilaterally linked ETSs. In our model, the magnitude of individual linkage gains and the volatility of permit prices in any linkage group are well-defined objects. We study their analytical properties. We first show how two independent components together constitute the gains from trade in multilateral linkages. The first one is determined by the inter-jurisdictional variation in domestic ambition levels (i.e., effort-sharing gains). The second one is driven by the nature of the uncertainty affecting the demand for permits in individual jurisdictions (i.e., risk-sharing gains). We then show that relative to autarky, linkage reduces permit price volatility on average but not necessarily for individual group members.

Importantly, we decompose any multilateral linkage into its internal bilateral linkages. That is, we characterize aggregate and jurisdictional gains in any linkage group as a weighted average of aggregate gains from all bilateral links that can be formed among its constituents. The decomposition formula is a practical tool to compute the gains generated in arbitrary linkage groups, which in turn allows us to rank groups from the perspective of individual jurisdictions. We analyze the determinants of linkage preferences and characterize the aggregate gains from the union of disjoint groups. We prove these gains to be no less than the sum of separate groups' gains. In other words, we prove linkage is superadditive.

A quantitative application calibrated to hypothetical ETSs covering the power sector emissions of five real-world jurisdictions illustrates that our model can be used to identify the sources of linkage gains and quantify the aggregate and jurisdiction-specific cost-savings. Specifically, we calibrate our model to Canada, the EU aggregate excluding the UK, South Korea, the UK and the USA under the assumption that each jurisdiction implements its Paris Agreement commitments. In the grand linkage the aggregate effort-sharing gains amount to \$60 million (constant 2005US\$) and risk-sharing gains are \$310 million, totalling \$370 million per annum relative to autarky. In comparison, the complete polycentric structures {{CAN,GBR},{EUR,KOR,USA}} and {{GBR,KOR},{CAN,EUR,USA}} generate gains whose magnitudes are lower by \$43 and \$178 million per annum, respectively. This provides evidence on the practical relevance of our theoretical findings and shows how our model can readily be used for policy-oriented applications.

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Tables

Table 1: Number of linkage groups and structures

Number of jurisdictions (n)	3	4	5	10	15
Number of linkage groups ($\|\mathbf{G}_\star\|$)	4	11	26	1,013	32,752
Number of linkage structures ($\|\mathbf{S}\|$)	5	15	52	115,975	1,382,958,545

Note: The cardinality of $\mathbf{S}$ is given by the n^{th} Bell number given n agents.

Table 2: Annual baseline emissions ($\bar{q}_i$, $10^6 tCO_2$) and annual emissions caps (ω_i, $10^6 tCO_2$) obtained from Enerdata. Calculated expected autarky permit prices ($\bar{p}_i$, 2005US$/$tCO_2$), calibrated flexibility coefficients (γ_i, $10^3(tCO_2)^2$/2005US$), linear intercepts ($\beta_i$, 2005US$/tCO_2) and ambition coefficients ($\alpha_i = \omega_i/\gamma_i$, 2005US$/tCO_2) obtained using Enerdata data.

	EUR	GBR	USA	CAN	KOR
$\bar{q}_i$	841.8	48.3	1,946.8	90.2	287.5
ω_i	724.1	44.2	1,469.3	66.3	225.8
$\bar{p}_i$	89.8	75.3	92.8	113.7	92.6
β_i	642.5	876.1	378.2	428.9	432.0
γ_i	1,309.9	55.2	5,146.4	210.2	665.3
α_i	552.7	801.0	285.5	315.4	339.5

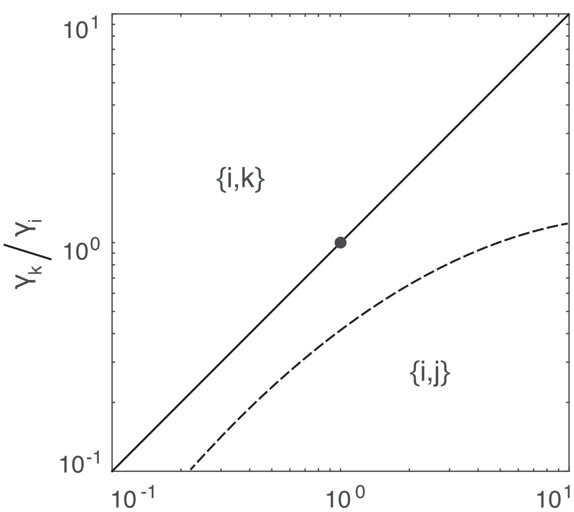
Table 3: Coefficients of variation of autarky permit prices ($\sigma_i/\bar{p}_i$) and pairwise correlation coefficients (ρ_{ij})

	EUR	GBR	USA	CAN	KOR
$\sigma_i/\bar{p}_i$	0.12	0.42	0.08	0.15	0.26
EUR	1.000				
GBR	0.557	1.000			
USA	0.270	0.213	1.000		
CAN	0.183	-0.003	0.521	1.000	
KOR	-0.181	-0.043	0.080	0.049	1.000

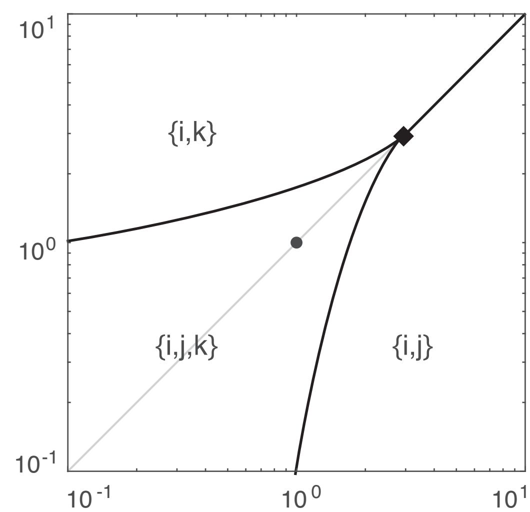
Figures

Figure 1: Linkage preferences in the three-jurisdiction world $\mathcal{T} = \{i, j, k\}$

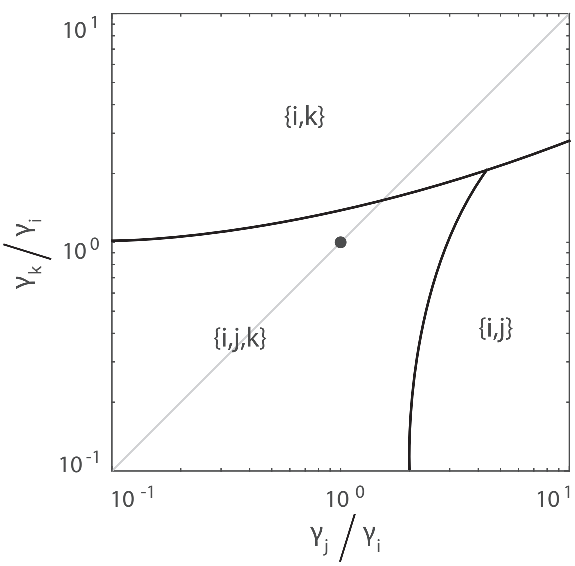
(a) Bilateral linkages only



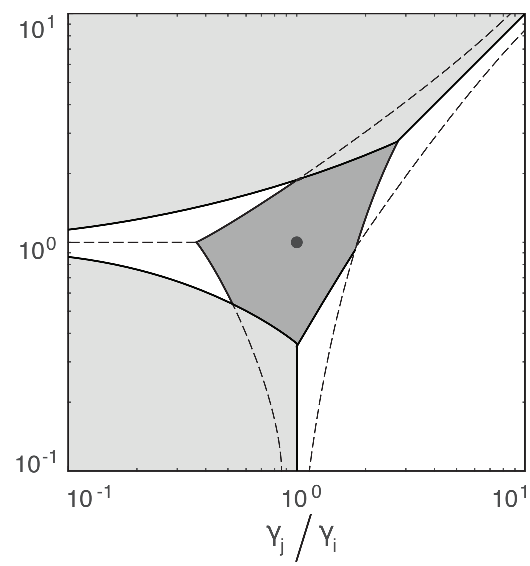
(b) Bilateral and grand linkages (*SUB*)



(c) Bilateral and grand linkages (no *SUB*)

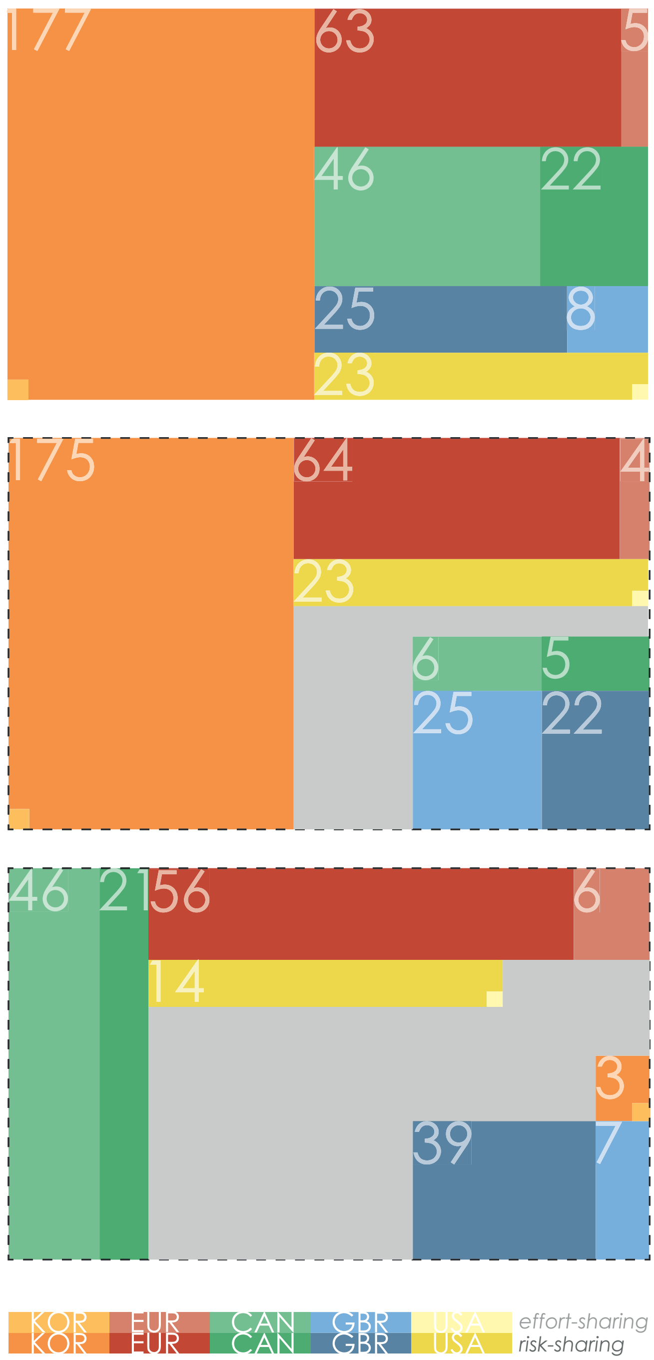


(d) Joint preferences (*SUB*)



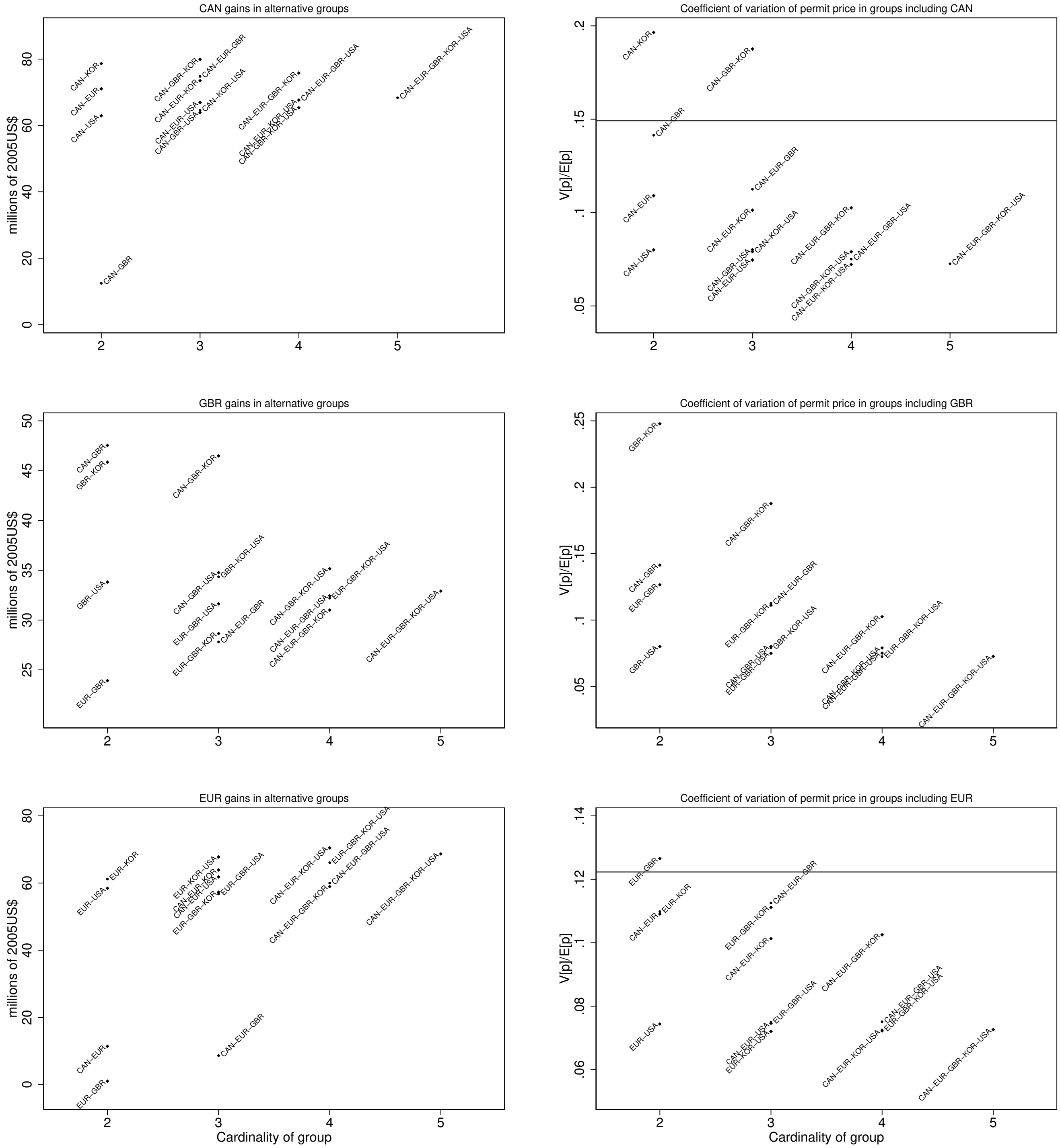
Note: SUB refers to the symmetric uncertainty benchmark defined in text.

Figure 2: Distribution and sources of economic gains in the grand linkage (upper panel) and in the complete polycentric linkage structure that generates the largest (middle panel) and lowest gains (lower panel). Color codes identify jurisdictions and color shades identify uncertainty component (dark) and ambition component (light).



Note: Expected permit prices ($\bar{p}_{\mathcal{G}}$, 2005US$/t$CO_2$) are respectively 92.7 in {EUR,GBR,USA,CAN,KOR}, 92.2 in {EUR,USA,KOR}, 105.7 in {GBR,CAN}, 92.9 in {EUR,USA,CAN} and 91.3 in {GBR,KOR}. See Figure 3 for the volatility of prices in these linkage groups.

Figure 3: Expected gains and coefficients of variation of prices in alternative linkage groups



Note: The horizontal lines in the right column indicate the coefficients of variation of autarky permit prices except for GBR where $\sigma/\bar{p} = 0.42$.

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Appendices & Supplemental Material

A Analytical derivations and collected proofs

Throughout Appendix A and w.l.o.g., we fix $\mathcal{G} = \{1, 2, \dots, m\} \in \mathbf{G}_\star$ for some $m \in [\![3; n]\!]$.

A.1 Proof of Proposition 1 (two components of linkage gains)

Recalling the definition of i's economic gains from $\mathcal{G}$-linkage in Equation (11), we have

$$\begin{aligned}\delta_{\mathcal{G},i} &\doteq B_i(q_{\mathcal{G},i};\theta_i) - p_{\mathcal{G}}(q_{\mathcal{G},i} - \omega_i) - B_i(\omega_i;\theta_i) \\ &= (\beta + \theta_i - p_{\mathcal{G}})(q_{\mathcal{G},i} - \omega_i) - (q_{\mathcal{G},i}^2 - \omega_i^2)/(2\gamma_i) \\ &= q_{\mathcal{G},i}(q_{\mathcal{G},i} - \omega_i)/\gamma_i - (q_{\mathcal{G},i}^2 - \omega_i^2)/(2\gamma_i) \\ &= (q_{\mathcal{G},i} - \omega_i)^2/(2\gamma_i) = \gamma_i(p_i - p_{\mathcal{G}})^2/2,\end{aligned} \tag{A.1}$$

where the third and fifth equalities obtain via the first-order condition in Equation (8) and the net permit demand in Equation (10), respectively. Taking expectations and observing that $\mathbb{V}\{p_i - p_{\mathcal{G}}\} = \mathbb{E}\{(p_i - p_{\mathcal{G}})^2\} - \mathbb{E}\{p_i - p_{\mathcal{G}}\}^2$ concludes. Alternatively, $\delta_{\mathcal{G},i}$ can be defined in terms of reduction in total costs of compliance, namely $\delta_{\mathcal{G},i} \doteq C_i(\tilde{q}_i - \omega_i) - C_i(\tilde{q}_i - q_{\mathcal{G},i}) - p_{\mathcal{G}}(q_{\mathcal{G},i} - \omega_i)$.

A.2 Proof of Proposition 2 (bilateral decomposition)

We first establish Equation (17). Substituting $p_{\mathcal{G}} = \Gamma_{\mathcal{G}}^{-1} \sum_{i\in\mathcal{G}} \psi_i p_i$ into Equation (11) yields

$$\begin{aligned}\delta_{\mathcal{G},i} &= \gamma_i(2\Gamma_{\mathcal{G}}^2)^{-1}\left(\sum_{j=1,j\neq i}^{m} \gamma_j(p_i - p_j)\right)^2 \\ &= \gamma_i(2\Gamma_{\mathcal{G}}^2)^{-1}\sum_{j=1,j\neq i}^{m} \gamma_j\left\{\gamma_j(p_i - p_j)^2 + 2\sum_{k>j,k\neq i}^{m}\gamma_k(p_i - p_j)(p_i - p_k)\right\}.\end{aligned} \tag{A.2}$$

It is useful to note that the two following identities hold true

$$\begin{aligned}2(p_i - p_j)(p_i - p_k) &= (p_i - p_k + p_k - p_j)(p_i - p_k) + (p_i - p_j)(p_i - p_j + p_j - p_k) \\ &= (p_i - p_j)^2 + (p_i - p_k)^2 - (p_j - p_k)^2, \text{ and}\end{aligned} \tag{A.3}$$

$$\sum_{j=1,j\neq i}^{m}\sum_{k>j,k\neq i}^{m}\gamma_j\gamma_k\left\{(p_i - p_j)^2 + (p_i - p_k)^2\right\} = \sum_{j=1,j\neq i}^{m}\sum_{k=1,k\neq i,j}^{m}\gamma_j\gamma_k(p_i - p_j)^2. \tag{A.4}$$

Using these identities and rearranging the sums in Equation (A.2), we obtain that

$$\delta_{\mathcal{G},i} = \gamma_i(2\Gamma_{\mathcal{G}}^2)^{-1} \sum_{j=1,j\neq i}^{m} \gamma_j \left\{ (\Gamma_{\mathcal{G}} - \gamma_i)(p_i - p_j)^2 - \sum_{k>j,k\neq i}^{m} \gamma_k (p_j - p_k)^2 \right\}. \tag{A.5}$$

Since the total $\{i,j\}$-linkage gains read $\Delta_{\{i,j\}} = \gamma_i\gamma_j(p_i - p_j)^2/(2\Gamma_{\{i,j\}})$ and $\Gamma_{\mathcal{G}_{-i}} = \Gamma_{\mathcal{G}} - \gamma_i$, Equation (A.5) coincides with Equation (17). Summing over all $i \in [\![1;m]\!]$ then gives

$$\Delta_{\mathcal{G}} \doteq \sum_{i=1}^{m} \delta_{\mathcal{G},i} = \Gamma_{\mathcal{G}}^{-2} \sum_{i=1}^{m} \left\{ \sum_{j=1,j\neq i}^{m} \left\{ \Gamma_{\mathcal{G}_{-i}}(\gamma_i + \gamma_j)\Delta_{\{i,j\}} - \gamma_i \sum_{k>j,k\neq i}^{m} (\gamma_j + \gamma_k)\Delta_{\{j,k\}} \right\} \right\}. \tag{A.6}$$

Regrouping terms by bilateral linkages, Equation (A.6) rewrites

$$\begin{aligned} \Delta_{\mathcal{G}} &= \Gamma_{\mathcal{G}}^{-2} \sum_{1\leq i<j\leq m} \left\{ \left(\Gamma_{\mathcal{G}_{-i}} + \Gamma_{\mathcal{G}_{-j}}\right)\Gamma_{\{i,j\}}\Delta_{\{i,j\}} - \sum_{k=1,k\neq i,j}^{m} \gamma_k \Gamma_{\{i,j\}}\Delta_{\{i,j\}} \right\} \\ &= \Gamma_{\mathcal{G}}^{-2} \sum_{1\leq i<j\leq m} \left\{ \left(\Gamma_{\mathcal{G}_{-i}} + \Gamma_{\mathcal{G}_{-j}} - \Gamma_{\mathcal{G}_{-\{i,j\}}}\right)\Gamma_{\{i,j\}}\Delta_{\{i,j\}} \right\} = \Gamma_{\mathcal{G}}^{-1} \sum_{1\leq i<j\leq m} \Gamma_{\{i,j\}}\Delta_{\{i,j\}}. \end{aligned} \tag{A.7}$$

By symmetry, i.e. $\Delta_{\{i,j\}} = \Delta_{\{j,i\}}$, Equation (A.7) finally coincides with Equation (18).

As a side note, because variance is a symmetric bilinear operator, it holds that

$$\mathbb{V}\{\Delta_{\mathcal{G}}\} = (2\Gamma_{\mathcal{G}})^{-2} \sum_{(i,j)\in\mathcal{G}\times\mathcal{G}} \Gamma_{\{i,j\}} \sum_{(k,l)\in\mathcal{G}\times\mathcal{G}} \Gamma_{\{k,l\}} \mathrm{Cov}\{\Delta_{\{i,j\}};\Delta_{\{k,l\}}\}. \tag{A.8}$$

Intuitively, although it is clear that $\mathcal{I} = \arg\max_{\mathcal{G}\in\mathbf{G}_\star} \mathbb{E}\{\Delta_{\mathcal{G}}\}$, there is no reason that forming larger groups reduces volatility of gains and a fortiori that $\mathcal{I} = \arg\min_{\mathcal{G}\in\mathbf{G}_\star} \mathbb{V}\{\Delta_{\mathcal{G}}\}$.

A.3 Proof of Proposition 3 (superadditivity)

Equation (21) obtains by linearity of the expectation operator and telescoping the sequence $(\Delta_{\mathcal{S}_i})_{i\in[\![0;d]\!]}$ with $(\mathcal{S}_i)_{i\in[\![0;d]\!]} \in \mathbf{S}^{d+1}$ with $\mathcal{S}_0 = \mathcal{S}'$ and $\mathcal{S}_d = \mathcal{S}$ as in Definition 2. It is thus sufficient to prove Equation (22) for any $i \in [\![1;d]\!]$. Fix $\mathcal{G}$ and $\mathcal{G}'$ in $\mathbf{G}_\star$ with $\mathcal{G}' \subset \mathcal{G}$ and $\mathcal{G}''$ the complement of $\mathcal{G}'$ in $\mathcal{G}$, i.e. $\mathcal{G}'' = \mathcal{G}\backslash\mathcal{G}'$. Note that expanding Equation (18) gives

$$\begin{aligned} \Delta_{\mathcal{G}} &= (2\Gamma_{\mathcal{G}})^{-1} \left(\sum_{(i,j)\in\mathcal{G}'\times\mathcal{G}'} \Gamma_{\{i,j\}}\Delta_{\{i,j\}} + \sum_{(i,j)\in\mathcal{G}''\times\mathcal{G}''} \Gamma_{\{i,j\}}\Delta_{\{i,j\}} + 2 \sum_{(i,j)\in\mathcal{G}'\times\mathcal{G}''} \Gamma_{\{i,j\}}\Delta_{\{i,j\}} \right) \\ &= \Gamma_{\mathcal{G}}^{-1} \left(\Gamma_{\mathcal{G}'}\Delta_{\mathcal{G}'} + \Gamma_{\mathcal{G}''}\Delta_{\mathcal{G}''} + \sum_{(i,j)\in\mathcal{G}'\times\mathcal{G}''} \Gamma_{\{i,j\}}\Delta_{\{i,j\}} \right). \end{aligned} \tag{A.9}$$

The aggregate gains from linking $\mathcal{G}'$ and $\mathcal{G}''$ are $\Delta_{\{\mathcal{G}',\mathcal{G}''\}} \doteq \Delta_{\mathcal{G}} - \Delta_{\mathcal{G}'} - \Delta_{\mathcal{G}''}$ so that

$$\begin{aligned}\Delta_{\{\mathcal{G}',\mathcal{G}''\}} &= \Gamma_{\mathcal{G}}^{-1}\Big(\sum_{(i,j)\in\mathcal{G}'\times\mathcal{G}''}\Gamma_{\{i,j\}}\Delta_{\{i,j\}} + \Big(\Gamma_{\mathcal{G}'}-\Gamma_{\mathcal{G}}\Big)\Delta_{\mathcal{G}'} + \Big(\Gamma_{\mathcal{G}''}-\Gamma_{\mathcal{G}}\Big)\Delta_{\mathcal{G}''}\Big)\\ &= \Gamma_{\mathcal{G}}^{-1}\Big(\sum_{(i,j)\in\mathcal{G}'\times\mathcal{G}''}\Gamma_{\{i,j\}}\Delta_{\{i,j\}} - \Gamma_{\mathcal{G}''}\Delta_{\mathcal{G}'} - \Gamma_{\mathcal{G}'}\Delta_{\mathcal{G}''}\Big).\end{aligned} \tag{A.10}$$

Finally, by transposing Equation (16a) from two singletons to two groups, Equation (A.11) below holds, which is non negative by definition and thus proves superadditivity.

$$\mathbb{E}\{\Delta_{\{\mathcal{G}',\mathcal{G}''\}}\} = \Gamma_{\mathcal{G}'}\Gamma_{\mathcal{G}''}\Big(\mathbb{V}\{p_{\mathcal{G}'}\} + \mathbb{V}\{p_{\mathcal{G}''}\} - 2\mathrm{Cov}\{p_{\mathcal{G}'};p_{\mathcal{G}''}\}\Big)\Big/(2\Gamma_{\mathcal{G}}) \geq 0. \tag{A.11}$$

A.4 Proof of Corollary 1 (non alignment of preferences)

Fix $\mathcal{G}' \in \mathbf{G}_\star\backslash\mathcal{I}$. Let $\mathcal{G} \supset \mathcal{G}'$ be a proper superset of $\mathcal{G}'$ and denote by $\mathcal{G}'' = \mathcal{G}\cap\mathcal{G}'$ the complement of $\mathcal{G}'$ in $\mathcal{G}$. By way of contradiction, assume that $\mathbb{E}\{\delta_{\mathcal{G}',i}\} \geq \mathbb{E}\{\delta_{\mathcal{G},i}\}$ holds for all $i \in \mathcal{G}'$, with at least one inequality holding strictly. By summation over $i \in \mathcal{G}'$

$$\sum_{i\in\mathcal{G}'}\mathbb{E}\{\delta_{\mathcal{G}',i}\} = \mathbb{E}\{\Delta_{\mathcal{G}'}\} > \sum_{i\in\mathcal{G}'}\mathbb{E}\{\delta_{\mathcal{G},i}\} = \mathbb{E}\{\Delta_{\mathcal{G}}\} - \sum_{i\in\mathcal{G}''}\mathbb{E}\{\delta_{\mathcal{G},i}\} \tag{A.12}$$

Recalling the definition of the gains in a link between $\mathcal{G}'$ and $\mathcal{G}''$ in Equation (20), Equation (A.12) imposes

$$\mathbb{E}\{\Delta_{\mathcal{G}''}\} + \mathbb{E}\{\Delta_{\{\mathcal{G}',\mathcal{G}''\}}\} - \sum_{i\in\mathcal{G}''}\mathbb{E}\{\delta_{\mathcal{G},i}\} < 0, \tag{A.13}$$

and contradicts superadditivity, which requires the above expression to be non-negative. That is, $\mathcal{G}'$ cannot be the most weakly preferred linkage coalition for all jurisdictions thereof.

A.5 Proof of Proposition 4 (linking price properties)

For any $\mathcal{G} \in \mathbf{G}_\star$, first note that price volatilities satisfy $\mathbb{V}\{p_{\mathcal{G}}\}^{1/2} \leq \Gamma_{\mathcal{G}}^{-1}\sum_{i\in\mathcal{G}}\gamma_i\mathbb{V}\{p_i\}^{1/2}$ with a strict inequality provided that there exists $(i,j) \in \mathcal{G}^2$ such that $\rho_{ij} < 1$. Indeed,

$$\begin{aligned}\mathbb{V}\{p_{\mathcal{G}}\} &= \Gamma_{\mathcal{G}}^{-2}\sum_{(i,j)\in\mathcal{G}^2}\gamma_i\gamma_j\mathrm{Cov}\{p_i;p_j\}\\ &\leq \Gamma_{\mathcal{G}}^{-2}\sum_{(i,j)\in\mathcal{G}^2}\gamma_i\gamma_j\sigma_i\sigma_j = \Gamma_{\mathcal{G}}^{-2}\Big(\sum_{i\in\mathcal{G}}\gamma_i\mathbb{V}\{p_i\}^{1/2}\Big)^2.\end{aligned} \tag{A.14}$$

Note that we have a similar inequality for price variances. Indeed, it jointly holds that

$$\mathbb{V}\{p_{\mathcal{G}}\} = \Gamma_{\mathcal{G}}^{-2}\left(\sum_{i=1}^{m} \gamma_i^2 \sigma_i^2 + 2 \sum_{1\leq i<j\leq m} \gamma_i \gamma_j \rho_{ij} \sigma_i \sigma_j\right), \text{ and} \tag{A.15a}$$

$$\Gamma_{\mathcal{G}} \sum_{j=1}^{m} \gamma_j \mathbb{V}\{p_j\} = \sum_{i=1}^{m}\sum_{j=1}^{m} \gamma_i \gamma_j \sigma_j^2 = \sum_{i=1}^{m} \gamma_i^2 \sigma_i^2 + \sum_{1\leq i<j\leq m} \gamma_i \gamma_j (\sigma_i^2 + \sigma_j^2). \tag{A.15b}$$

Then, $\mathbb{V}\{p_{\mathcal{G}}\} \leq \Gamma_{\mathcal{G}}^{-1} \sum_{i\in\mathcal{G}} \gamma_i \mathbb{V}\{p_i\}$ follows since $\sigma_i^2 + \sigma_j^2 \geq 2\rho_{ij}\sigma_i\sigma_j$ and observe that the inequality holds strictly when there exists $(i,j) \in \mathcal{G}^2$ such that $\rho_{ij} < 1$ and/or $\sigma_i \neq \sigma_j$.

It suffices to establish the rest of Statement (a) for a unitary linkage since the proof extends to a more general case by transitivity over the relevant sequence of unitary linkages. Thus, let $\mathcal{S} = \{\mathcal{G}_1, \ldots, \mathcal{G}_z\}$ and assume w.l.o.g. that $\mathcal{S}' = \{\mathcal{G}_1 \cup \mathcal{G}_2, \mathcal{G}_3, \ldots, \mathcal{G}_z\}$. Then, it holds that

$$\mathcal{V}_{\mathcal{S}'} = \Gamma_{\mathcal{S}'}^{-1}\left(\sum_{k=3}^{z} \Gamma_{\mathcal{G}_k} \mathbb{V}\{p_{\mathcal{G}_k}\}^{1/2} + \left(\Gamma_{\mathcal{G}_1}^2 \mathbb{V}\{p_{\mathcal{G}_1}\} + \Gamma_{\mathcal{G}_2}^2 \mathbb{V}\{p_{\mathcal{G}_2}\} + 2\Gamma_{\mathcal{G}_1}\Gamma_{\mathcal{G}_2} \mathrm{Cov}\{p_{\mathcal{G}_1}; p_{\mathcal{G}_2}\}\right)^{1/2}\right). \tag{A.16}$$

Note that $\Gamma_{\mathcal{S}} = \Gamma_{\mathcal{S}'}$ holds by definition and that $|\mathrm{Cov}\{p_{\mathcal{G}_1}; p_{\mathcal{G}_2}\}| \leq \mathbb{V}\{p_{\mathcal{G}_1}\}^{1/2} \mathbb{V}\{p_{\mathcal{G}_2}\}^{1/2}$ holds via the Cauchy-Schwarz inequality. This proves $\mathcal{V}_{\mathcal{S}'} \leq \mathcal{V}_{\mathcal{S}}$ and establishes Statement (a).

We now turn to Statement (b). Note that it is sufficient to verify the claim on jurisdictional price variability as a result of linkage for bilateral links – the argument naturally extends to multilateral links. Then, by applying Equation (A.15a) to $\{i,j\}$-linkage it holds that

$$\mathbb{V}\{p_{\{i,j\}}\} = \left(\gamma_i^2 \mathbb{V}\{p_i\} + \gamma_j^2 \mathbb{V}\{p_j\} + 2\rho_{ij}\gamma_i\gamma_j (\mathbb{V}\{p_i\}\mathbb{V}\{p_j\})^{1/2}\right) \Big/ \Gamma_{\mathcal{G}}^2. \tag{A.17}$$

Assume w.l.o.g. that jurisdiction i is the less volatile jurisdiction, i.e. $\sigma_j \geq \sigma_i$. Then, $\{i,j\}$-linkage reduces price volatility in the high-volatility jurisdiction i.f.f. $\mathbb{V}\{p_j\} \geq \mathbb{V}\{p_{\{i,j\}}\}$, that is i.f.f.

$$\gamma_i(\sigma_j^2 - \sigma_i^2) + 2\gamma_j\sigma_j(\sigma_j - \rho_{ij}\sigma_i) \geq 0, \tag{A.18}$$

and unconditionally holds, i.e. for all γ_i, γ_j, $\sigma_j \geq \sigma_i$ and $\rho_{ij} \in [-1; 1]$. For the low-volatility jurisdiction, however, $\mathbb{V}\{p_i\} \geq \mathbb{V}\{p_{\{i,j\}}\}$ holds if and only if

$$\gamma_j(\sigma_i^2 - \sigma_j^2) + 2\gamma_i\sigma_i(\sigma_i - \rho_{ij}\sigma_j) \geq 0 \;\Leftrightarrow\; \frac{\gamma_j}{\gamma_i} \leq \frac{2\sigma_i(\sigma_i - \rho_{ij}\sigma_j)}{\sigma_j^2 - \sigma_i^2}. \tag{A.19}$$

For a given triple $(\sigma_i, \sigma_j, \rho_{ij})$, $\{i,j\}$-linkage effectively reduces volatility in the low-volatility jurisdiction provided that the high-volatility jurisdiction's γ is relatively not too large.

Finally, to establish the claim on price convergence in probability, we let $\mathcal{G}$ be ordered such that $\gamma_1 \leq \cdots \leq \gamma_m$, let $\bar{\sigma} = \max_{i \in \mathcal{G}} \sigma_i$. Fix $\varepsilon > 0$. Then, it holds that

$$\begin{aligned}\mathbb{P}\Big(|\hat{\Theta}_{\mathcal{G}} - \mathbb{E}\{\hat{\Theta}_{\mathcal{G}}\}| > \varepsilon\Big) &\leq \varepsilon^{-2}\mathbb{E}\Big\{(\hat{\Theta}_{\mathcal{G}} - \mathbb{E}\{\hat{\Theta}_{\mathcal{G}}\})^2\Big\} = \varepsilon^{-2}\mathbb{V}\{\hat{\Theta}_{\mathcal{G}}\} \\ &= \varepsilon^{-2}\gamma_{\mathcal{G}}^{-2}\sum_{i=1}^{m}\left\{\gamma_i^2\sigma_i^2 + \sum_{j=1}^{m}\rho_{ij}\gamma_i\gamma_i\sigma_i\sigma_j\right\} \\ &\leq \left(\frac{\gamma_m\bar{\sigma}}{\gamma_1\varepsilon}\right)^2\left[\frac{1}{m}+1\right],\end{aligned} \tag{A.20}$$

where the first inequality is Chebyshev's inequality and the second follows by construction. Since γ_m and $\bar{\sigma}$ are finite, only when the second term in the above bracket is nil (i.e., shocks are independent) does it hold that $p_{\mathcal{G}}$ converges in probability towards $\bar{p}_{\mathcal{G}}$ as $|\mathcal{G}|$ tends to infinity, that is $\lim_{m\to+\infty}\mathbb{P}\Big(|\hat{\Theta}_{\mathcal{G}} - \mathbb{E}\{\hat{\Theta}_{\mathcal{G}}\}| > \varepsilon\Big) = 0$, i.e. $\lim_{m\to+\infty}\mathbb{P}\Big(|\hat{\Theta}_{\mathcal{G}} - \mathbb{E}\{\hat{\Theta}_{\mathcal{G}}\}| \leq \varepsilon\Big) = 1$.

B Calibration methodology

This appendix describes the calibration of jurisdictional emission caps (ω_i), baseline emissions ($\bar{q}_i$), abatement flexibility (γ_i) and intercepts (β_i) based on proprietary data we have obtained from Enerdata and the calibration of price shock volatility (σ_i) and the pairwise correlations across jurisdictions (ρ_{ij}) primarily based on IEA data on power sector emissions.

We obtained annual emissions caps and MACCs of the power sector for 11 jurisdictions from Enerdata. First, Enerdata models emission caps consistent to three possible scenarios. The Ener-Brown scenario describes a world with durably low fossil fuel energy prices. The Ener-Blue scenario provides an outlook of energy systems based on the achievement of the 2030 targets defined in the NDCs as announced at COP 21. The Ener-Green scenario explores the implications of more stringent energy and climate policies to limit the global temperature increase at around 1.5-2ºC by the end of the century. We selected annual emission caps consistent with the INDCs (Ener-Blue scenario). Second, Enerdata also generates MACCs and annual emission baselines using the Prospective Outlook on Long-term Energy Systems (POLES) model. MACCs are available for four time periods (2025, 2030, 2035 and 2040). We selected emission baselines and the MACCs available for 2030.

Using these annual caps and MACCs, we compute the expected autarky permit prices, which range from around 13\$/tCO_2 (China and Mexico) to over 100\$/tCO_2 (Canada).[22] Large deviations from a jurisdiction's cap under linkage can compromise the political feasibility of the

[22] All monetary quantities are expressed in constant 2005US\$.

constructed linkage examples. To minimize this concern, we focus on five jurisdictions whose expected autarky prices are similar: the block of European countries currently participating in the European Union Emission Trading System without the UK (EUR), the United Kingdom (GBR), the United States (USA), Canada (CAN) and South Korea (KOR).[23] Table 2 reports the annual baseline emissions ($\bar{q}_i$) and emissions caps (ω_i) as well as the corresponding expected autarky permit prices ($\bar{p}_i$) of the five jurisdictions.

Equipped with annual emissions caps and MACCs, we proceed with the calibration of jurisdictional characteristics. A linear interpolation of jurisdictional MACCs around domestic caps gives the linear intercept β_i and slope $1/\gamma_i$, reported in Table 2. Table 2 also contains ambition coefficients $\alpha_i = \omega_i/\gamma_i$, which help us compare volume-adjusted opportunity costs of abatement at the margin across jurisdictions in the vicinity of domestic caps.

The remaining jurisdictional characteristics are calibrated using historical times series of carbon dioxide emissions from the power sector. We obtain annual data covering 1972-2015 from the International Energy Agency. We denote observed emissions from jurisdiction i in year t by $e_{i,t}$. We identify historical emission levels with laissez-faire emissions, i.e. we assume that no or relatively lax regulations on CO_2 emissions were in place prior to 2015.

In Equation (3) laissez-faire emissions $\tilde{q}_i$ comprise a constant term, the baseline $\bar{q}_i = \gamma_i\beta_i$, and a variable term, $\tilde{q}_i - \bar{q}_i = \gamma_i\theta_i$. Assuming the latter is small enough relative to the former, we obtain the following linear Taylor approximation for the natural logarithm of laissez-faire emissions

$$\ln(\tilde{q}_i) \simeq \ln(\bar{q}_i) + (\tilde{q}_i - \bar{q}_i)/\bar{q}_i. \tag{B.1}$$

We associate the variable term in the above to the cyclical component of historical emissions obtained using the Hodrick-Prescott (HP) filter with the penalty parameter $\lambda = 6.25$ for annual data – see Hodrick & Prescott (1997) and Ravn & Uhlig (2002) for details. This is in the spirit of Doda (2014) and congruent with our interpretation of variations in marginal benefits of emissions as being driven by business cycles, technology shocks, changes in the prices of factors of production, jurisdiction-specific events, weather fluctuations, etc.

The HP filter decomposes the observed series $\{\ln(e_{i,t})\}$ into two time series $\{e^t_{i,t}\}$ and $\{e^c_{i,t}\}$ where $\ln(e_{i,t}) = e^t_{i,t} + e^c_{i,t}$ in each year t. To calibrate shock characteristics, we assume that the cyclical components $\{e^c_{i,t}\}$'s provide information about the distributions of the underlying shocks θ_i's. Then, given our modelling framework, $e^c_{i,t}$ is related to a draw from the

[23] To limit the variation in $\bar{p}_i$, we thus dropped Australia (27.1US\$2005/tCO_2), China (13.5), Japan (29.4), Mexico (12.3), New Zealand (27.0), and South Africa (15.1) from our sample.

distribution of θ_i such that

$$e^c_{i,t} = (\tilde{q}_i - \bar{q}_i)/\bar{q}_i = \theta_i/\beta_i. \tag{B.2}$$

We note that $\{e^c_{i,t}\}$ obtained using the HP filter are stationary time series. We can therefore compute the standard deviation of θ_i consistent with the model using

$$\sigma_i = \sigma(\beta_i e^c_{i,t}), \tag{B.3}$$

and the standard deviation of domestic laissez-faire power-sector emissions simply obtain by the rescaling $\gamma_i\sigma_i$. Table 4 below reports the standard deviations of autarky permit prices (σ_i) and normalized standard deviations of laissez-faire emissions ($\sigma(e^c_{i,t}) = \gamma_i\sigma_i/\bar{q}_i$).

Table 4: Standard deviations of autarky prices (σ_i, 2005US\$/tCO_2) and normalized standard deviations of laissez-faire emissions from domestic power sectors ($\sigma(e^c_{i,t}) = \gamma_i\sigma_i/\bar{q}_i$)

	EUR	GBR	USA	CAN	KOR
σ_i	10.9	31.6	7.4	17.0	24.5
$\sigma(e^c_{i,t}) = \gamma_i\sigma_i/\bar{q}_i$	0.0171	0.0359	0.0196	0.0395	0.0566

Note that price shock variabilities are such that $\bar{p}_i > 2\sigma_i$ and $\beta_i > \bar{p}_{\mathcal{G}} + 2\mathbb{V}\{\hat{\Theta}_{\mathcal{G}}\}^{1/2}$ for any jurisdiction i and any possible group in our sample, i.e. zero-price and zero-emissions corners can safely be neglected.[24] Therefore, our focus on interior autarky and linking market equilibria is of negligible consequence for our analysis of linkage gains.

Finally, we calibrate pairwise correlation between shocks in i and j using

$$\rho_{ij} = \text{Corr}(\beta_i e^c_{i,t}, \beta_j e^c_{j,t}). \tag{B.4}$$

and note that the ρ_{ij}'s – reported in Table 3 – can be positive, negative or approximately zero. We also note that this large variation in inter-jurisdictional correlation is to be expected.

To see why note that emissions of 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 Calderón et al. (2007) which provides evidence on international business

[24]Note that a sufficient condition for the second type of inequalities to hold is $\beta_i > \bar{p}_i + 2\sigma_i$ for all i.

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.

We highlight the following three points regarding our calibration strategy and results. 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 effect 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 & King (1999), the random walk band pass filter recommended by Christiano & Fitzgerald (2003) or the simpler log quadratic/cubic detrending procedures. However, their effect on the results are minimal so we restrict our attention to the HP filter. Third, we take the calibrated ρ_{ij}'s at face value in our computations, rather than setting insignificant correlations to zero, which does not alter the results in a meaningful way.

C Linkages in a three-jurisdiction world in detail

In this appendix we consider the three-jurisdiction world of Section 4 in greater detail. Specifically, we provide the analytical expressions of the linkage indifference frontiers in Figure 1 and consider four special cases. Throughout we denote the set of jurisdictions by $\mathcal{T} = \{i, j, k\}$ and assume identical ambition. That is, we let $\bar{p} = \bar{p}_i = \bar{p}_j = \bar{p}_k$ denote the expected price that is common to all jurisdictions and linkage groups.

Recall that risk-sharing gains in a bilateral link are given in Equations (16a) and (16b). In the case of $\mathcal{T}$-linkage we specialize Equation (12) in Proposition 1, which yields

$$\mathbb{E}\{\delta_{\mathcal{T},i}\} = \gamma_i \mathbb{E}\{(\theta_i - \hat{\Theta}_{\mathcal{T}})^2\}/2, \text{ where } \hat{\Theta}_{\mathcal{T}} = (\gamma_i\theta_i + \gamma_j\theta_j + \gamma_k\theta_k)/\Gamma_{\mathcal{T}}, \tag{C.1}$$

and using the definition of the γ-averaged shock $\hat{\Theta}_{\mathcal{T}}$, this can be rewritten as

$$\mathbb{E}\{\delta_{\mathcal{T},i}\} = \gamma_i \Gamma^2_{\{j,k\}} \mathbb{E}\{(\theta_i - \hat{\Theta}_{\{j,k\}})^2\}/(2\Gamma^2_{\mathcal{T}}). \tag{C.2}$$

That is, insofar as i is concerned, $\mathcal{T}$-linkage is equivalent to a unitary linkage with the group $\{j,k\}$. With this in mind, we can apply the formula for gains in bilateral linkages, namely Equations (16a) and (16b). Direct computation of $\mathbb{V}\{\hat{\Theta}_{\{j,k\}}\}$ and $\text{Cov}\{\theta_i; \hat{\Theta}_{\{j,k\}}\}$ then yields

$$\mathbb{E}\{\delta_{\mathcal{T},i}\} = \frac{\gamma_i \Gamma^2_{\{j,k\}}}{2\Gamma^2_{\mathcal{T}}}\left(\sigma_i^2 + \frac{\gamma_j^2\sigma_j^2 + \gamma_k^2\sigma_k^2 + 2\rho_{jk}\gamma_j\gamma_k\sigma_j\sigma_k}{\Gamma^2_{\{j,k\}}} - 2\sigma_i \frac{\rho_{ij}\gamma_j\sigma_j + \rho_{ik}\gamma_k\sigma_k}{\Gamma_{\{j,k\}}}\right). \tag{C.3}$$

Note that relative to a bilateral linkage between two jurisdictions as described in Equations (16a) and (16b) an important difference is the presence of partners' γ's in the term inside the parenthesis because they determine the properties of $\mathbb{V}\{\hat{\Theta}_{\{j,k\}}\}$ and $\text{Cov}\{\theta_i; \hat{\Theta}_{\{j,k\}}\}$.

As in the main text, we take jurisdiction i's perspective. Also, we let j and k's flexibility and volatility parameters be defined relatively to i's, that is $\gamma_j = x\gamma_i$, $\gamma_k = y\gamma_i$, $\sigma_j = a\sigma_i$ and $\sigma_k = b\sigma_i$. Replacing this in Equations (16a), (16b) and (C.3) we obtain the following inequalities representing i's linkage preferences, namely

$$\{i,j\} \succcurlyeq_i \{i,k\} \Leftrightarrow y \leq \frac{x\sqrt{1+a^2-2\rho_{ij}a}}{\sqrt{1+b^2-2\rho_{ik}b} + x\left(\sqrt{1+b^2-2\rho_{ik}b} - \sqrt{1+a^2-2\rho_{ik}a}\right)}$$

$$\{i,j\} \succcurlyeq_i \mathcal{T} \Leftrightarrow y \leq \frac{2x(1+x)\left(x(1+a^2-2\rho_{ij}a) - (1+x)(1-\rho_{ij}a-\rho_{ik}b+\rho_{jk}ab)\right)}{(1+x)^2(1+b^2-2\rho_{ik}b) - x^2(1+a^2-2\rho_{ij}a)}$$

$$\{i,k\} \succcurlyeq_i \mathcal{T} \Leftrightarrow x \leq \frac{2y(1+y)\left(y(1+b^2-2\rho_{ik}b) - (1+y)(1-\rho_{ij}a-\rho_{ik}b+\rho_{jk}ab)\right)}{(1+y)^2(1+a^2-2\rho_{ij}a) - y^2(1+b^2-2\rho_{ik}b)}$$

It is straightforward to obtain the analogous sets of inequalities for j and k's linkage preferences, which taken together define the indifference frontiers depicted in Figure 1.

Now, we consider four special cases to build intuition for the determinants of the uncertainty component of gains in bilateral (cases 1 & 2) and trilateral (cases 3 & 4) links. We assume jurisdictional price shocks can take on only two values with equal probability and using the conventional notation for lotteries i's autarky price reads $p_i = (\bar{p}+\sigma_i, 0.5; \bar{p}-\sigma_i, 0.5)$.

Case 1: $\{i,j\}$-linkage with $\gamma_i = 2\gamma_j = 2\gamma$, $\sigma_i = \sigma_j = \sigma$ and arbitrary ρ_{ij}.

In this case, the shock affecting the $\{i,j\}$-linkage permit price satisfies

$$p_{\{i,j\}} = \bar{p} + \Big(\sigma, (1+\rho_{ij})/4; \sigma/3, (1-\rho_{ij})/4; -\sigma/3, (1-\rho_{ij})/4; -\sigma, (1+\rho_{ij})/4\Big). \tag{C.5}$$

Assume the positive shock $+\sigma$ occurs in i. It also occurs in j with probability $(1+\rho_{ij})/2$, in which case autarky prices are equal and there is no gain from linkage. The negative shock $-\sigma$ occurs in j with probability $(1-\rho_{ij})/2$, in which case $p_i - p_j = 2\sigma \neq 0$ and there are positive gains from linkage. Note that the linking price settles at $p_{\{i,j\}} = (2p_i + p_j)/3 = \bar{p} + \sigma/3$ because i is twice as flexible as j. The case of the negative shock occurring in i is symmetric. Thus, absolute jurisdictional price wedges between autarky and $\{i,j\}$-linkage read

$$|p_i - p_{\{i,j\}}| = \Big(2\sigma/3, (1-\rho_{ij})/2; 0, (1+\rho_{ij})/2\Big), \tag{C.6a}$$

$$|p_j - p_{\{i,j\}}| = \Big(4\sigma/3, (1-\rho_{ij})/2; 0, (1+\rho_{ij})/2\Big). \tag{C.6b}$$

Because jurisdictional gains are proportional to expected autarky-link price wedges, the above implies that j benefits more from $\{i,j\}$-linkage than i. Intuitively, this is because the linking price settles closer to the autarky price of the more flexible jurisdiction. Additionally, note that correlation solely influences the probabilities of realization of possible price wedges, but not their magnitudes. Indeed, all else equal, a link between two negatively-correlated jurisdictions increases the chances of non-nil price wedges as compared to a link between two positively-correlated jurisdictions. In particular, when $\rho_{ij} = 0$, expected jurisdictional gains from $\{i,j\}$-linkage amount to $\mathbb{E}\{\delta_{\{i,j\},i}\} = 2\gamma\sigma^2/9$ and $\mathbb{E}\{\delta_{\{i,j\},j}\} = 4\gamma\sigma^2/9$.

Case 2: $\{i,j\}$-linkage with $\gamma_i = \gamma_j = \gamma$, $\sigma_i = 2\sigma_j = 2\sigma$ and arbitrary ρ_{ij}.

In this case, the shock affecting the $\{i,j\}$-linkage permit price satisfies

$$p_{\{i,j\}} = \bar{p} + \Big(3\sigma/2, (1+\rho_{ij})/4; \sigma/2, (1-\rho_{ij})/4; -\sigma/2, (1-\rho_{ij})/4; -3\sigma/2, (1+\rho_{ij})/4\Big). \tag{C.7}$$

Assume the positive shock $+2\sigma$ occurs in i. Now, even when the positive shock $+\sigma$ also occurs in j (with probability $(1+\rho_{ij})/2$) there exists price wedge since jurisdictional volatility levels differ ($p_i - p_j = \sigma$) with linking price $p_{\{i,j\}} = \bar{p} + 3\sigma/2$. When the negative shock $-\sigma$ occurs in j (with probability $(1-\rho_{ij})/2$) the price wedge is wider ($p_i - p_j = 3\sigma$) with linking price $p_{\{i,j\}} = \bar{p} + \sigma/2$. Again, the case of the negative shock occurring in i is symmetric. Because jurisdictions are equally flexible, the linking price is equidistant from the two autarky prices for all realizations of shock pairs, and jurisdictional price wedges thus coincide, that is

$$|p_i - p_{\{i,j\}}| = |p_j - p_{\{i,j\}}| = \Big(3\sigma/2, (1-\rho_{ij})/2; \sigma/2, (1+\rho_{ij})/2\Big). \tag{C.8}$$

This implies equal expected jurisdictional gains. In other words, for given aggregate expected gains from a bilateral link, only relative jurisdictional flexibilities matter in determining how they are apportioned between jurisdiction. In particular, when $\rho_{ij} = 0$, expected jurisdictional gains from $\{i,j\}$-linkage amount to $\mathbb{E}\{\delta_{\{i,j\},i}\} = \mathbb{E}\{\delta_{\{i,j\},j}\} = 5\gamma\sigma^2/8$.

Why does the most flexible and/or volatile jurisdiction, say i, prefer the trilateral link over bilateral links? Because the trilateral-link price is 'less driven' by i's autarky price, i.e. the distance (or variability) between i's autarky price and the linking price is greater. To illustrate this and without loss of generality, we assume all shocks are independent in cases 3 and 4.

Case 3: $\mathcal{T}$-linkage with $\gamma_i = 2\gamma_j = 2\gamma_k = 2\gamma$, $\sigma_i = \sigma_j = \sigma_k = \sigma$ and independent shocks.

Assume the positive shock $+\sigma$ occurs in i. Then, positive shocks $+\sigma$ occur in both j and k with probability 1/4 and there is no gain from linkage. Conversely, negative shocks $-\sigma$ occur in both j and k with probability 1/4 which drives a wedge in autarky prices $p_i - p_j = p_i - p_k = 2\sigma$. By symmetry and with complementary probability 1/2, opposite shocks occur in j and k and the linking price reads $p_\mathcal{T} = (2p_i + p_j + p_k)/4 = \bar{p} + \sigma/2$. Therefore, absolute jurisdictional price wedges between autarky and $\mathcal{T}$-linkage read

$$|p_i - p_\mathcal{T}| = \Big(\sigma, 1/4; \sigma/2, 1/2; 0, 1/4\Big), \tag{C.9a}$$

$$|p_j - p_\mathcal{T}| = |p_k - p_\mathcal{T}| = \Big(3\sigma/2, 1/4; \sigma, 1/4; \sigma/2, 1/4; 0, 1/4\Big), \tag{C.9b}$$

and expected gains from $\mathcal{T}$-linkage are $\mathbb{E}\{\delta_{\mathcal{T},i}\} = 3\gamma\sigma^2/8$ and $\mathbb{E}\{\delta_{\mathcal{T},j}\} = \mathbb{E}\{\delta_{\mathcal{T},k}\} = 7\gamma\sigma^2/16$. Comparing with Case 1, the most flexible jurisdiction i prefers the trilateral link while the less flexible jurisdictions j and k prefer to form a bilateral link with i.

Case 4: $\mathcal{T}$-linkage with $\gamma_i = \gamma_j = \gamma_k = \gamma$, $\sigma_i = 2\sigma_j = 2\sigma_k = 2\sigma$ and independent shocks.

Assume the positive shock $+2\sigma$ occurs in i. Then, positive shocks $+\sigma$ occur in both j and k with probability 1/4 and autarky price wedges are such that $p_i - p_j = p_i - p_k = \sigma$. Negative shocks $-\sigma$ occur in both j and k with same probability but wider autarky price wedges $\bar{p}_i - \bar{p}_j = \bar{p}_i - \bar{p}_k = 3\sigma$. By symmetry and with complementary probability 1/2, opposite shocks occur in j and k and the linking price reads $p_\mathcal{T} = (p_i + p_j + p_k)/3 = \bar{p} + 2\sigma/3$. Therefore, absolute jurisdictional price wedges between autarky and $\mathcal{T}$-linkage read

$$|p_i - p_\mathcal{T}| = \Big(2\sigma, 1/4; 4\sigma/3, 1/2; 2\sigma/3, 1/4\Big), \tag{C.10a}$$

$$|p_j - p_\mathcal{T}| = |p_k - p_\mathcal{T}| = \Big(5\sigma/3, 1/4; \sigma, 1/4; \sigma/3, 1/2\Big), \tag{C.10b}$$

and expected gains from $\mathcal{T}$-linkage are $\mathbb{E}\{\delta_{\mathcal{T},i}\} = \gamma\sigma^2$ and $\mathbb{E}\{\delta_{\mathcal{T},j}\} = \mathbb{E}\{\delta_{\mathcal{T},k}\} = \gamma\sigma^2/2$. Comparing with Case 2, the most volatile jurisdiction i prefers the trilateral link while the less volatile jurisdictions j and k prefer to form a bilateral link with i.

Finally, note that in the above cases, while $\mathcal{T}$-linkage increases the autarky-linking price variability for i relative to bilateral linkages, it does just the opposite for j and k. These examples illustrate that jurisdictional linkage preferences are not aligned (Corollary 1).

D Model generalization and extensions

D.1 Multilateral linkage in the presence of costs

Our theoretical results indicate that relatively large groups and coarse structures generate relatively high gains. In practice, however, these could be relatively more costly to form. In particular, in the presence of costs associated with the formation of groups, hereafter linkage costs, it might well be that grand linkage does not yield the highest aggregate payoff, net of costs. Our theory can help better understand the policy implications of linkage costs.

In this appendix, we describe how our modelling framework can be extended to (1) explore the nature of efficient linkage structures, or ELS for short, present linkage costs; and (2) compare the ability of various inter-jurisdictional cost-sharing arrangements in making ELS Pareto-improving with respect to autarky.

Suppose linkage costs have two distinct components, namely (1) an implementation component reflecting that the larger the volume of regulated emissions of jurisdictions involved, the larger the implementation-related administrative costs, e.g. the costs of harmonizing the rules of the previously independent systems; and (2) a negotiation component reflecting that costs in forging and establishing policy agreements are increasing in the number of participating jurisdictions. In the literature, these considerations have given rise to concepts such as minilateralism (Falkner, 2016) or polycentrism (Ostrom, 2009; Dorsch & Flachsland, 2017) and can be captured by the following simple specification where forming any $\mathcal{G} \in \mathbf{G}_\star$ entails total costs

$$\kappa(\mathcal{G}; \varepsilon_0, \varepsilon_1) \doteq \varepsilon_0 \cdot \Omega_{\mathcal{G}} + \varepsilon_1 \cdot |\mathcal{G}|^2, \tag{D.1}$$

with $(\varepsilon_0, \varepsilon_1) \in \mathbb{R}_+^2$ scaling parameters for the implementation and negotiation components, respectively.[25] Note that fixed per-link sunk costs are not considered as they are blind to both the composition of groups and the architecture of structures, thereby unable to discriminate between them. Formally, given cost parameters $(\varepsilon_0, \varepsilon_1) \in \mathbb{R}_+^2$ net aggregate economic gains

[25] A fine parametrization of the pair $(\varepsilon_0, \varepsilon_1)$ is challenging because there is very little empirical guidance.

from any $\mathcal{S} \in \mathbf{S}$ write

$$\tilde{\Delta}_{\mathcal{S}}(\varepsilon_0, \varepsilon_1) \doteq \Delta_{\mathcal{S}} - \sum_{\mathcal{G} \in \mathcal{S}} \kappa(\mathcal{G}; \varepsilon_0, \varepsilon_1). \tag{D.2}$$

Then, the ELS, denoted $\mathcal{S}^*$, is unique and satisfies

$$\mathcal{S}^*(\varepsilon_0, \varepsilon_1) \doteq \arg\max_{\mathcal{S} \in \mathbf{S}} \left\langle \mathbb{E}\{\tilde{\Delta}_{\mathcal{S}}(\varepsilon_0, \varepsilon_1)\} \right\rangle. \tag{D.3}$$

Although our specification of costs in Equation (D.1) is exogenously imposed, we emphasize that costs associated with the formation of structures are endogenous to the optimization programme in Equation (D.3). On the one hand, for a pair of cost parameters low enough, linkage may remain superadditive and ELS correspond to grand linkage – in particular, note that $\mathcal{S}^*(0,0) = \mathcal{I}$. On the other hand, for a pair of cost parameters high enough, linkage may become subadditive and ELS correspond to complete autarky. For cost parameters such that linkage is neither superadditive nor subadditive, we can numerically explore the nature of ELS in terms of polycentricity and incompleteness of linkage.

To that end, we need to introduce alternative inter-jurisdictional cost-sharing arrangements. Formally, given $\mathcal{G} \in \mathbf{G}_\star$, a cost-sharing arrangement is a collection of non-negative weights $(\phi_{\mathcal{G},i})_{i \in \mathcal{G}}$ such that $\sum_{i \in \mathcal{G}} \phi_{\mathcal{G},i} = 1$ where $\phi_{\mathcal{G},i}$ is the share of the aggregate cost of forming group $\mathcal{G}$ incurred by jurisdiction $i \in \mathcal{G}$.[26] Then, given $(\phi_{\mathcal{G},i})_{i \in \mathcal{G}}$, i's net gains from forming $\mathcal{G}$ in $\mathbf{G}_\star$ write

$$\delta^{\kappa}_{\mathcal{G},i}(\varepsilon_0, \varepsilon_1) \doteq \delta_{\mathcal{G},i} - \phi_{\mathcal{G},i} \cdot \kappa(\mathcal{G}; \varepsilon_0, \varepsilon_1). \tag{D.4}$$

We adopt a weak concept of individual-rationality to discriminate between alternative outcomes and require that jurisdictions be at least as well off as under autarky, i.e. jurisdictional expected gains net of linkage costs must be non-negative. Formally, for given $(\varepsilon_0, \varepsilon_1) \in \mathbb{R}^2_+$, ELS is said to be Pareto-improving with respect to autarky if it holds that, for all $\mathcal{G}$ in $\mathcal{S}^*(\varepsilon_0, \varepsilon_1)$ and all i in $\mathcal{G}$

$$\mathbb{E}\{\delta^{\kappa}_{\mathcal{G},i}(\varepsilon_0, \varepsilon_1)\} \geq 0. \tag{D.5}$$

Equipped with this criterion, we can compare alternative cost-sharing arrangements in their ability to implement ELS, that is to make ELS Pareto-improving w.r.t. autarky. For instance, these rules can apportion costs equally or based on domestic market size, cost type, the gains that a jurisdiction obtains, jurisdictions' relative bargaining powers, etc. In a world where outright permit or cash transfers can run into significant political-economy hurdles, such a discrimination between alternative rules can have far-reaching policy implications for

[26] Note that cost-sharing arrangements can be assimilated to inter-jurisdictional transfer schemes.

initiatives aiming to steer jurisdictions towards efficient climate policy architectures.

D.2 Sequential linkage and distribution of gains within groups

As mentioned in the main text, our analysis naturally extends to linkages between more than two groups. Indeed, for any group $\mathcal{G} = \bigcup_i \mathcal{G}_i$ where for all $i \neq j$, $\mathcal{G}_i \cap \mathcal{G}_j = \varnothing$, rewriting Equation (17) gives the gains accruing to group $\mathcal{G}_i$ in forming $\mathcal{G}$

$$\Delta_{\mathcal{G},\mathcal{G}_i} = \Gamma_{\mathcal{G}}^{-2} \sum_{\mathcal{G}' \in \mathcal{G}\backslash\{\mathcal{G}_i\}} \left\{ \Gamma_{\mathcal{G}\backslash\{\mathcal{G}_i\}} \Gamma_{\{\mathcal{G}_i \cup \mathcal{G}'\}} \Delta_{\{\mathcal{G}_i,\mathcal{G}'\}} - (\Gamma_{\mathcal{G}_i}/2) \sum_{\mathcal{G}'' \in \mathcal{G}\backslash\{\mathcal{G}_i\}} \Gamma_{\{\mathcal{G}' \cup \mathcal{G}''\}} \Delta_{\{\mathcal{G}',\mathcal{G}''\}} \right\}. \quad \text{(D.6)}$$

We note that deploying our machinery in a repeated setting without inter-temporal permit trading could allow us to study sequential linkage.[27] To that end and in order to proceed with the analysis of how gains from linking groups are apportioned within groups, an assumption is required about the nature of the entity 'linkage group' which is otherwise ill-defined. An intuitive but strong assumption is to consider that groups, once they have formed, consolidate and transmute into a new, single entity (Caparrós & Péreau, 2017).[28]

As an illustration, consider the situation where two groups $\mathcal{G}'$ and $\mathcal{G}''$ link. Let $\mathcal{G} = \mathcal{G}' \cup \mathcal{G}''$ and assume that $\mathcal{G}'$ and $\mathcal{G}''$ have individually consolidated prior to linking. By definition of unitary linkage the gains $\mathbb{E}\{\Delta_{\{\mathcal{G}',\mathcal{G}''\}}\}$ are shared between $\mathcal{G}'$ and $\mathcal{G}''$ in inverse proportion to groups' flexibilities. Then, to understand how these gains are distributed within each group, note that the total abatement effort required of, say, $\mathcal{G}'$ must be apportioned among its constituents according to some optimality criterion, namely in proportion to jurisdictional abatement opportunities at the margin, i.e. flexibilities γ_i's. Thus, within-$\mathcal{G}'$ optimality requires that i's net permit demand under $\{\mathcal{G}',\mathcal{G}''\}$-linkage satisfies $q_{\{\mathcal{G}',\mathcal{G}''\},i} - \omega_i = (\gamma_i/\Gamma_{\mathcal{G}'})(q_{\{\mathcal{G}',\mathcal{G}''\},\mathcal{G}'} - \Omega_{\mathcal{G}'})$. In other words, the gains in $\mathcal{G}'$ are apportioned among internal jurisdictions in proportion to flexibility as well. Therefore, the gains accruing to jurisdiction $i \in \mathcal{G}'$ in $\{\mathcal{G}',\mathcal{G}''\}$-linkage would amount to $(\gamma_i/\Gamma_{\mathcal{G}'})(\Gamma_{\mathcal{G}''}/\Gamma_{\mathcal{G}})\mathbb{E}\{\Delta_{\{\mathcal{G}',\mathcal{G}''\}}\}$.

Unitary accretion. It is of interest to consider the special case where a group links to a singleton. This clarifies how aggregate gains from the link are distributed between jurisdictions. Fix $\mathcal{G} \in \mathbf{G}$ and $i \in \mathcal{I}\backslash\mathcal{G}$ and let $\mathcal{G}' = \mathcal{G}$ and $\mathcal{G}'' = \{i\}$ in Equation (22), then

$$\mathbb{E}\{\Delta_{\{\mathcal{G},\{i\}\}}\} = \mathbb{E}\{\Delta_{\mathcal{G}\cup\{i\}}\} - \mathbb{E}\{\Delta_{\mathcal{G}}\} = \Gamma_{\mathcal{G}\cup\{i\}}\Gamma_{\mathcal{G}}^{-1}\mathbb{E}\{\delta_{\mathcal{G}\cup\{i\},i}\} = (1 + \gamma_i\Gamma_{\mathcal{G}}^{-1})\mathbb{E}\{\delta_{\mathcal{G}\cup\{i\},i}\}. \quad \text{(D.7)}$$

[27] Heitzig & Kornek (2018) formally analyze bottom-up, sequential linking between carbon markets with various degrees of farsightedness, reversibility and coordination on domestic cap selection.

[28] Absent time, consolidation can be viewed as commitment in the sense of Carraro & Siniscalco (1993).

In words, linking jurisdiction $i \notin \mathcal{G}$ to the linkage group $\mathcal{G}$ generates an aggregate gain equal to $\mathbb{E}\{\delta_{\mathcal{G}\cup\{i\},i}\} + \gamma_i \mathbb{E}\{\delta_{\mathcal{G}\cup\{i\},i}\}/\Gamma_{\mathcal{G}}$ where the first term accrues to jurisdiction i and the second one accrues to group $\mathcal{G}$ as a whole. Put differently, jurisdictions in $\mathcal{G}$ get a portion $\gamma_i/\Gamma_{\mathcal{G}\cup\{i\}}$ of the aggregate gain $\mathbb{E}\{\Delta_{\{\mathcal{G},\{i\}\}}\}$ that is thus shared in proportion to flexibility.

We provide an alternative proof to arrive at Equation (D.7). Fix w.l.o.g. $i = m$ such that $\mathcal{G}_{-i} = \{1, 2, \ldots, m-1\}$. By subtracting Equation (18) for groups $\mathcal{G}$ and $\mathcal{G}_{-i}$, we obtain

$$\begin{aligned} \Delta_{\mathcal{G}} - \Delta_{\mathcal{G}_{-i}} &= \Gamma_{\mathcal{G}}^{-1} \sum_{1\le j<k\le i} \Gamma_{\{j,k\}}\Delta_{\{j,k\}} - \Gamma_{\mathcal{G}_{-i}}^{-1} \sum_{1\le j<k\le i-1} \Gamma_{\{j,k\}}\Delta_{\{j,k\}} \\ &= \Gamma_{\mathcal{G}}^{-1} \sum_{j=1}^{i-1} \Gamma_{\{j,i\}}\Delta_{\{j,i\}} - \sum_{1\le j<k\le i-1} (\Gamma_{\mathcal{G}_{-i}}^{-1} - \Gamma_{\mathcal{G}}^{-1})\Gamma_{\{j,k\}}\Delta_{\{j,k\}} \\ &= \Gamma_{\mathcal{G}}^{-1}\Gamma_{\mathcal{G}_{-i}}^{-1} \left(\sum_{j=1}^{i-1} \Gamma_{\mathcal{G}_{-i}}\Gamma_{\{j,i\}}\Delta_{\{j,i\}} - \gamma_i \sum_{1\le j<k\le i-1} \Gamma_{\{j,k\}}\Delta_{\{j,k\}} \right) \\ &= \Gamma_{\mathcal{G}}\Gamma_{\mathcal{G}_{-i}}^{-1}\delta_{\mathcal{G},i}, \end{aligned} \tag{D.8}$$

where the last line follows from Equation (17).

D.3 Alternative domestic cap selection mechanisms

We consider alternative domestic cap selection mechanisms. For example, jurisdictional caps could be set non-cooperatively without anticipation of linking. That is, jurisdiction $i \in \mathcal{I}$ maximizes the difference between expected benefits and damages from pollution by operating its own market for permit in autarky, taking other jurisdictions' cap levels $(\omega_j)_{j\in\mathcal{I}_{-i}}$ as given. In the case of a uniformly-mixed stock pollutant, pollution damages only depend on aggregate emissions $Q_{\mathcal{I}} = \sum_{i\in\mathcal{I}} q_i$. For the time being, assume every jurisdiction faces the same damages given by

$$D(Q_{\mathcal{I}}) = d_1 Q_{\mathcal{I}} + d_2 (Q_{\mathcal{I}})^2/2, \tag{D.9}$$

where d_1, d_2 are positive parameters. With $\Omega_{-i} = \sum_{j\in\mathcal{I}_{-i}} \omega_j$, these Cournot-Nash caps satisfy

$$\omega_i \doteq \arg\max_{\omega\ge 0} \mathbb{E}\Big\{ B_i(\omega;\theta_i) - D\left(\omega + \Omega_{-i}\right) \Big\} \text{ for all } i \in \mathcal{I}, \tag{D.10}$$

and are proportional to jurisdictional flexibility (w.l.o.g. we let $\beta_i = \beta$ for all $i \in \mathcal{I}$)

$$\omega_i = A_1 \cdot \gamma_i \text{ for all } i \in \mathcal{I}, \text{ where } A_1 = \frac{\beta - d_1}{1 + d_2 \Gamma_{\mathcal{I}}} > 0 \tag{D.11}$$

measures the common, non-cooperative abatement effort (we let $\beta > d_1$). As long as damage functions are identical across jurisdictions and there is no anticipation of linkage, similar results obtain under various degrees of cooperation and alternative conjectural variations.

Let $\mathcal{G} \in \mathbf{G}$ be a cooperative group, i.e. jurisdictions in $\mathcal{G}$ set their caps cooperatively. Denote by $\bar{\mathcal{G}}$ the complement of $\mathcal{G}$ in $\mathbf{G}$ and let $\bar{\mathcal{G}}$ members behave as singletons w.r.t. cap selection. Assume Stackelberg conjectural variations where $\mathcal{G}$ behaves as the leader – our results would slightly differ under alternative conjectural variations, see e.g. MacKenzie (2011) and Gelves & McGinty (2016). For instance, with Cournot conjectural variations we would solve for the coalitional Nash equilibrium in cap selection, see e.g. Bloch (2003). The aggregate reaction function of singletons to the emissions cap $\Omega_{\mathcal{G}}$ selected by $\mathcal{G}$ reads

$$\Omega^r_{\bar{\mathcal{G}}}(\Omega_{\mathcal{G}}) = \frac{(\beta - d_1 - d_2\Omega_{\mathcal{G}})}{1 + d_2\Gamma_{\bar{\mathcal{G}}}} \cdot \Gamma_{\bar{\mathcal{G}}}. \tag{D.12}$$

Group $\mathcal{G}$ recognizes $\Omega^r_{\bar{\mathcal{G}}}$ when jointly deciding upon $\Omega_{\mathcal{G}}$, that is

$$\max_{(\omega_i)_{i\in\mathcal{G}}} \left\{ \sum_{i\in\mathcal{G}} B_i(\omega_i;\theta_i) - |\mathcal{G}| D\Big(\Omega_{\mathcal{G}} + \Omega^r_{\bar{\mathcal{G}}}(\Omega_{\mathcal{G}})\Big) \right\}. \tag{D.13}$$

Solving Equation (D.13) and summing over i in $\mathcal{G}$ gives the $\mathcal{G}$-wide aggregate cap

$$\Omega_{\mathcal{G}} = A_{|\mathcal{G}|} \cdot \Gamma_{\mathcal{G}}, \text{ with } A_{|\mathcal{G}|} \doteq \frac{\beta(1 + d_2\Gamma_{\bar{\mathcal{G}}})^2 - |\mathcal{G}|\Big(d_1(1 + d_2\Gamma_{\bar{\mathcal{G}}}) + d_2(\beta - d_1)\Gamma_{\mathcal{G}}\Big)}{(1 + d_2\Gamma_{\bar{\mathcal{G}}})^2 + d_2|\mathcal{G}|\Gamma_{\mathcal{G}}}. \tag{D.14}$$

Substituting the above in Equation (D.12) gives the $\bar{\mathcal{G}}$-wide cap

$$\Omega_{\bar{\mathcal{G}}} = A_{|\bar{\mathcal{G}}|} \cdot \Gamma_{\bar{\mathcal{G}}}, \text{ with } A_{|\bar{\mathcal{G}}|} \doteq \frac{\beta - d_1 - d_2 A_{|\mathcal{G}|} \cdot \Gamma_{\mathcal{G}}}{1 + d_2\Gamma_{\bar{\mathcal{G}}}}. \tag{D.15}$$

Differentiating the abatement effort coefficients above w.r.t. the cardinality of $\mathcal{G}$ gives

$$\frac{\partial A_{|\mathcal{G}|}}{\partial|\mathcal{G}|} < 0, \text{ and } \frac{\partial A_{|\bar{\mathcal{G}}|}}{\partial|\mathcal{G}|} = -\frac{d_2\Gamma_{\mathcal{G}}}{1 + d_2\Gamma_{\bar{\mathcal{G}}}}\frac{\partial A_{|\mathcal{G}|}}{\partial|\mathcal{G}|} > 0. \tag{D.16}$$

The first inequality tells us that the higher the number of cap-cooperating jurisdictions, the the larger the proportion of pollution externalities that are internalized, and consequently the higher their individual abatement efforts. The second inequality reflects the standard free-rider problem and the crowding-out effect of domestic abatement efforts. Indeed, domestic abatement efforts are strategic substitutes.[29] That is, in response to higher abatement efforts from jurisdictions in $\mathcal{G}$, jurisdictions in $\bar{\mathcal{G}}$ will lower their own. In particular, $\mathcal{G} = \mathcal{I}$ corresponds to full cap-cooperation where the common abatement effort is $A_n = \frac{\beta - nd_1}{1+nd_2\Gamma_{\mathcal{I}}} > 0$ (we let $\beta > nd_1$). Symmetrically, $\bar{\mathcal{G}} = \mathcal{I}$ coincides with the Cournot-Nash solution in Equation (D.10) with $A_1 = \frac{\beta - d_1}{1+d_2\Gamma_{\mathcal{I}}} > A_n$ as jurisdictions do not internalize the negative externality generated by their pollution on the other $n-1$ jurisdictions.

D.4 Domestic cap selection in anticipation of linkage

First note that differentiating i's expected gains from $\mathcal{G}$-linkage w.r.t. ω_i gives

$$\frac{\partial \mathbb{E}\{\delta_{\mathcal{G},i}\}}{\partial \omega_i} = \gamma_i\Big(\Omega_{\mathcal{G}}\Gamma_{\mathcal{G}}^{-1} - \omega_i\gamma_i^{-1}\Big)\Big(\Gamma_{\mathcal{G}}^{-1} - \gamma_i^{-1}\Big) \geq 0 \Leftrightarrow \omega_i\gamma_i^{-1} \geq \Omega_{\mathcal{G}}\Gamma_{\mathcal{G}}^{-1}. \tag{D.17}$$

Irrespective of the shock structure, jurisdictions whose flexibility-adjusted cap stringency is below the group's (i.e., $\omega_i\gamma_i^{-1} \geq \Omega_{\mathcal{G}}\Gamma_{\mathcal{G}}^{-1}$) are expected net permit sellers (i.e., $\bar{p}_i \leq \bar{p}_{\mathcal{G}}$) and vice versa. As potential permit sellers, one would expect that these jurisdictions have an incentive to inflate their domestic caps in a bid to increase permit sales and thus economic gains from linkage (Helm, 2003). Note that such an incentive is mitigated by the contrasting downward pressure exerted by the extra supply of permits on the linked permit price. Conversely, jurisdictions whose ambition levels are above the group's are potential permit buyers on the linked market and have an incentive to strengthen ambition.

For illustration, we now consider the situation where jurisdictions anticipate $\mathcal{G}$-linkage when selecting their domestic caps. This is congruent with a two-stage game where jurisdictions set their caps at stage one and permit trading on the linked market occurs at stage 2. We solve the game using backward induction and focus on subgame perfect Nash equilibria.

Stage 2: Permit trading and jurisdictional emissions choices.

The linked market equilibrium obtains by equalization of jurisdictional marginal benefits and linked market closure. Given cap and realized shock profiles $(\omega_i)_{i\in\mathcal{G}}$ and $(\theta_i)_{i\in\mathcal{G}}$, respectively, we denote by $q^*_{\mathcal{G},i}$ and $p^*_{\mathcal{G}}$ the equilibrium emission level in i and linking price

$$q^*_{\mathcal{G},i} \equiv q^*_{\mathcal{G},i}(\Omega_{\mathcal{G}}; (\theta_i)_{i\in\mathcal{G}}) = \gamma_i(\theta_i - \hat{\Theta}_{\mathcal{G}} + \Omega_{\mathcal{G}}\Gamma_{\mathcal{G}}^{-1}), \tag{D.18a}$$

$$p^*_{\mathcal{G}} \equiv p^*_{\mathcal{G}}(\Omega_{\mathcal{G}}; (\theta_i)_{i\in\mathcal{G}}) = \beta + \hat{\Theta}_{\mathcal{G}} - \Omega_{\mathcal{G}}\Gamma_{\mathcal{G}}^{-1}. \tag{D.18b}$$

[29] This will always be the case in a pure emissions game. In the context of international market for permits, Holtsmark & Midttømme (2015) are able to transform domestic abatement efforts into strategic complements by tying the dynamic emissions game to the dynamics of (investments in) renewables.

As is standard, $\partial p^*_{\mathcal{G}}/\partial_{\Omega_{\mathcal{G}}} = -\Gamma^{-1}_{\mathcal{G}} < 0$ and $\partial q^*_{\mathcal{G},i}/\partial_{\Omega_{\mathcal{G}}} = \gamma_i \Gamma^{-1}_{\mathcal{G}} \in (0;1)$. For expositional clarity, we assume in the following that $d_2 = 0$, i.e. jurisdictional reaction functions for cap selection are orthogonal, and that jurisdictional damages are proportional to flexibility.

Stage 1: Non-cooperative jurisdictional cap selection with linkage anticipation.
Each jurisdiction recognizes the implications of its domestic cap decision on both the linked permit price and its own market position. Assuming Cournot conjectural variations (i.e., caps are announced simultaneously), each jurisdiction takes other jurisdictional caps as given. Jurisdictional caps with strategic anticipation of linkage $(\hat{\omega}_i)_{i\in\mathcal{G}}$ satisfy, for all i in $\mathcal{G}$,

$$\begin{aligned}\hat{\omega}_i \doteq \arg\max_{\omega\geq 0} \mathbb{E}\Big\{ & B_i\Big(q^*_{\mathcal{G},i}(\omega + \Omega_{\mathcal{G}_{-i}}; (\theta_i)_{i\in\mathcal{G}}); \theta_i\Big) - \gamma_i d_1(\omega + \Omega_{\mathcal{G}_{-i}}) \\ & + p^*_{\mathcal{G}}(\omega + \Omega_{\mathcal{G}_{-i}}; (\theta_i)_{i\in\mathcal{G}})\Big(\omega - q^*_{\mathcal{G},i}(\omega + \Omega_{\mathcal{G}_{-i}}; (\theta_i)_{i\in\mathcal{G}})\Big)\Big\}.\end{aligned} \tag{D.19}$$

Now let $\mathcal{G} = \{i, j\}$ where $\gamma_j > \gamma_i$, i.e. j is the higher-flexibility and higher-damage jurisdiction. By stage-2 optimality, i.e. $\partial B_i(q^*_{\mathcal{G},i}; \theta_i)/\partial q_i = p^*_{\mathcal{G}}$, and taking expectations, the necessary first-order condition associated with Programme (D.19) writes

$$\Gamma^{-2}_{\{i,j\}}(\gamma_j \hat{\omega}_i - \gamma_i \hat{\omega}_j) + \beta - (\hat{\omega}_1 + \hat{\omega}_2)\Gamma^{-1}_{\{i,j\}} - d_1\gamma_i = 0. \tag{D.20}$$

Summing over i and j gives $\hat{\omega}_1 + \hat{\omega}_2 = \Gamma_{\{i,j\}}(2\beta - d_1\Gamma_{\{i,j\}})/2$. Plugging this into Equation (D.20) then yields

$$\hat{\omega}_i = \gamma_i(\beta - d_1\Gamma_{\{i,j\}}) + d_1\gamma_j\Gamma_{\{i,j\}}/2. \tag{D.21}$$

Without anticipation of linkage, caps are determined by Equation (D.10), i.e. $\omega_i = \gamma_i(\beta - d_1\gamma_i)$. As in Helm (2003), it holds that $\hat{\omega}_i > \omega_i$ and $\hat{\omega}_j < \omega_j$, i.e. the low-damage (resp. high-damage) jurisdiction increases (resp. decreases) its domestic cap in the perspective of $\{i, j\}$-linkage. In aggregate, anticipation of linkage leads to increased emissions. Indeed, it holds that

$$\hat{\omega}_i + \hat{\omega}_j \geq \omega_i + \omega_j \;\Leftrightarrow\; (\gamma_i - \gamma_j)^2 \geq 0. \tag{D.22}$$

If additional damages associated with this increase in emissions are high enough, anticipated linkage can thus be suboptimal relative to autarky (Holtsmark & Sommervoll, 2012).