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Essais sur les Liaisons Spatiales et Temporelles entre et au sein des Systèmes d'Échange de Quotas d'Émission

Résumé

Les systèmes d'échange de quotas d'émission (SEQEs) sont un instrument de régulation environnementale important et ont un rôle clef à jouer dans la réduction des émissions de gaz à effet de serre pour l'atténuation du changement climatique. Cette thèse a une double orientation : les liaisons spatiales entre SEQEs d'une part et les échanges intertemporels de quotas au sein d'un SEQE d'autre part.

Les liaisons entre SEQEs peuvent aider à établir un futur cadre de politique climatique mondiale coût-efficient. Cependant, ces liaisons sont difficiles à mettre en place et peu nombreuses à ce jour. Dans un premier temps, à l'aide d'un modèle simple et unifié et en se basant sur des expériences réelles de SEQEs, nous comparons différentes restrictions à l'échange comme éléments facilitant une transition vers le libre échange de quotas. Dans un deuxième temps, nous construisons un modèle qui décrit et caractérise analytiquement les effets et gains associés à des liaisons multilatérales sous incertitude. Le modèle est ensuite calibré sur émissions historiques de différentes juridictions dans le but d'illustrer les déterminants des préférences de liaison.

Les SEQEs sont sujets à une forte incertitude, notamment de type règlementaire, ce qui peut affaiblir le signal-prix de long terme et nuire à l'efficience-coût dynamique. La prévalence d'une telle incertitude peut être assimilée à une situation d'ambiguïté. Afin de prendre en compte son influence, nous supposons les entités couvertes par un SEQE averses à l'ambiguïté, puis analysons leurs décisions intertemporelles et les distorsions induites sur le fonctionnement du système. Nous rapprochons enfin l'éclairage apporté par ces résultats des observations faites sur le fonctionnement des SEQEs existants.

Mots Clés : Échange de quotas d'émission, Politique climatique, Liaisons inter-systèmes, Échange intertemporel de quotas, Restrictions à l'échange, Incertitude, Ambiguïté.

Essays on Spatial and Temporal Interconnections between and within in Emissions Trading Systems

Abstract

Emissions Trading Systems (ETSs) are an important instrument in regulating pollution and have a key role to play in reducing greenhouse gas emissions to mitigate climate change. This dissertation has a twin focus: Spatial linkages between ETSs at a point in time and intertemporal emissions trading within an ETS.

Linkages between ETSs are crucial for the cost-effectiveness of the future climate policy architecture. Complete linkages, however, are difficult to agree and to date, few and far between. Here, our contribution is twofold. First, using a simple and unified model and drawing on experiences with real-world ETSs, we compare alternative permit trading restrictions as transitional and facilitative mechanisms toward unrestricted bilateral linkages. Second, we develop a model able to describe and analytically characterize the effects and gains from multilateral linkages under uncertainty. The model is then calibrated to historical emissions of real-world jurisdictions to illustrate the determinants of linkage preferences.

ETSs are subject to considerable uncertainty, especially of a regulatory nature, which can disrupt dynamic cost-effectiveness and undermine the long-term price signal. The prevalence of such uncertainty can be assimilated to a situation of ambiguity. Here, our contribution is to introduce ambiguity aversion on the part of liable firms to account for the influence of such uncertainty, analyze their intertemporal decisions, and discuss how the induced distortions in market functioning can help explain observations from existing ETSs.

Keywords: Emissions trading, Climate change policy, Inter-system linkage, Intertemporal emissions trading, Permit trade restrictions, Uncertainty, Ambiguity.

Table of Contents

List of Figures

List of Tables

* * *

«Il y a une solitude dans la pauvreté, mais une solitude qui rend son prix à toute chose. À un certain degré de richesse, le ciel lui-même et la nuit pleine d'étoiles semblent des biens naturels. Mais au bas de l'échelle, le ciel reprend tout son sens : une grâce sans prix.»

—Albert Camus, Entre oui et non *in* L'envers et l'endroit.

«Qui peut donc vouloir selon une formule ? [. . .] *Car deux et deux font quatre, ce n'est déjà plus la vie, messieurs, c'est le début de la mort.»*

—Fiodor Mikhaïlovitch Dostoïevski, Les carnets du sous-sol.

«Vous aussi, utilitaristes, n'aimez tout ce qui est utile *que comme* charrette *de vos inclinations, – vous aussi trouvez en réalité le grincement de ses roues intolérables ?»*

—Friedrich Nietzsche, Par-delà bien et mal §174.

«Car seul le cylindre offre des certitudes et au-dehors rien que mystère.»

—Samuel Beckett, Le dépeupleur.

* * *

General Introduction

Anthropogenic greenhouse gas emissions and induced changes in climate have had widespread impacts on human and natural systems. There is consensus that little can still be emitted into the atmosphere to contain severe, pervasive and irreversible consequences (IPCC, 2014, AR5: SYR, SPM1&2). Limiting climate change and related risks would require substantial and sustained reductions in greenhouse gas emissions. In turn, the attendant need for profound and rapid changes in our economies and infrastructures would involve large shifts in investment patterns as well as cooperative approaches, for instance in the form of linkages between climate policy initiatives (IPCC, 2014, AR5: WGIII, SPM5).

In this context, the Paris Agreement symbolizes a new era for international climate action and constitutes a soft-law, bottom-up guidance framework for the future global climate policy architecture (UNFCCC, 2015). The attainment of the ambitious objective of holding the increase in global average temperature between 1.5 and 2°C above pre-industrial levels will necessitate an extensive rollout and swift take-up of dedicated economic instruments. Although the primary focus of this dissertation lies on Emissions Trading Systems (ETSs, or more commonly referred to as 'carbon markets'), these programs are but one economic tool available to mitigate climate change impacts, and other market-based or non-commoditized approaches are also recognized under the agreement, c.f. Article 6.8.

Emissions trading is now a well-established instrument to rein in greenhouse gas emissions. By early next year, more than seven billion tons of carbon dioxide equivalent should be regulated under nineteen ETSs operating worldwide according to the International Carbon Action Partnership (ICAP, 2017). These systems function at various supranational, regional, national and subnational levels (henceforth jurisdictions). For instance, with annual emission caps of almost two billion tons of CO_2e, the European Union ETS has by far been the largest system in operation since its inception in 2005. In terms of volume, China shall take over the EU's pole position when its national ETS enters into force later this year, with annual caps about twice as large. Moreover, ETSs are expected to grow in number as focus gradually shifts from country promises in the form of Nationally Determined Contributions made under the Paris Agreement to practical questions of delivering on them.

Against this backdrop, linkages between jurisdictional ETSs are deemed to be a key element on the route toward a global climate policy regime (Flachsland et al., 2009a; Redmond & Convery, 2015; Bodansky et al., 2016).[1] Although international climate negotiations and emissions trading have largely evolved on separate tracks, the two may well reinforce one another, as attest language and trading-related provisions set out in Article 6.2 of the Paris Agreement evoking the concept of 'internationally transferred mitigation outcomes'. In a budget-constrained world, linkage indeed has potential to cost-effectively reduce the costs of curbing emissions, and is also seen as a means of promoting both the geographical expansion of a carbon price signal and an increase in environmental ambition.

It is also crucial that the price signal conveyed by an ETS be reflective of the long-term objective of emission reductions for today's investments to be accordingly channelled into low-carbon technologies. For, if that is not the case, investment decisions would be out of line with long-term carbon budgets, technological innovation and learning would be slowed down, and economies could lock into carbon-intensive infrastructures whose emissions would have to be abated at higher costs in the future. In an ETS, one way this is theoretically being achieved is by allowing for intertemporal permit trading so that the market price is the vehicle that equalizes long-term supply and demand of permits.[2]

Therefore, if ETSs are to help work toward the 1.5-2°C objective, they must spur the enlargement of climate cooperation in a cost-effective manner and provide adequate incentives to alter current investment patterns. In spite of favorable political rhetoric, however, inter-ETS linkages have proven difficult to agree and to date, remain few and far between. In addition, ETSs have recently come under fire for failing to deliver proper long-term price signals, most notably in Europe. This dissertation thus aims at contributing to the debate on these two issues, by first addressing spatial linkages between ETSs at a point in time (Chapters 1 and 2) before turning to intertemporal trading within an ETS (Chapter 3).

Brief History and Theory of Emissions Trading

Economists have long advocated for market-based instruments to incite economic agents to internalize and thereby reduce the social impact associated with their individual production of negative externalities like environmental pollution (Pigou, 1920; Coase, 1960). The essential common feature of these endeavors (i.e., the incentive) is ultimately to establish a monetary cost (i.e., a price) on the generation of these negative externalities.

[1] Broadly speaking, linkage refers to interconnections between policies that allow for mitigation outcomes to be redistributed across systems in a way that reduces aggregate costs of achieving the overall target.

[2] Note that there is consensus that technology policy need complement mitigation policies to address market failures related to innovation and technology diffusion (IPCC, 2014, AR5: WGIII, SPM5).

About fifty years ago or so, however, virtually all pollution regulations followed command-and-control approaches in the form of requirements to install specific pollution control equipments or to abide by performance standards, e.g. limits on emission levels or rates. At about the same time, a few economists challenged these conventional approaches and put forth the idea of 'tradable pollution rights' as a novel way of attaining environmental objectives. Already implicit in the work of Coase (1960), this concept crystallized in the seminal contributions by Crocker (1966), Dales (1968) and Montgomery (1972). A system of tradable rights was deemed better able to tap into the heterogeneity in abatement costs across emission sources and therefore touted as a more cost-effective policy.[3]

The principal approach to implementing such a policy is a cap-and-trade system whose three core elements are: (*i*) the establishment by the regulatory agency of the total volume of pollution that liable entities are allowed to emit and the creation of a commensurate amount of pollution rights (called permits or allowances); (*ii*) the distribution of permits to covered entities, either through auction or free allocation; and (*iii*) the provision for permit trading. Cap and trade therefore harnesses market forces by fixing a cap on emissions and then leaving it to covered entities to ferret out the least expensive abatement opportunities through permit trading. The price that emerges on the market is reflective of the stringency of the cap and permit trading is conducive to the equalization of marginal abatement costs across emission sources which, in theory, ensures that the overall abatement target is achieved at minimum cost (Baumol & Oates, 1988; Cropper & Oates, 1992).

The implementation of cap and trade has grown steadily since the 1980s, starting in the United States as a way to carry out the phasedown of lead in gasoline at the federal level. Since then, cap and trade has also been employed to regulate local and criteria pollutants, and has become an important instrument for the control of greenhouse gas emissions. The reader may refer to Schmalensee & Stavins (2017) for a recent article covering the history of cap and trade over the last three decades, the Winter 2013's Symposium on 'Trading Pollution Permits' in the *Journal of Economic Perspectives* (Goulder, 2013; Newell et al., 2013; Schmalensee & Stavins, 2013) as well as Ellerman et al. (2000) and Ellerman et al. (2010) for comprehensive, in-depth descriptions and evaluations of the first three years' experiences with the U.S. Acid Rain Program and the EUETS, respectively.

The dual approach to permit trading – a pollution tax – directly places a price on emissions. Under idealized textbook assumptions, these two approaches are essentially equivalent, but in real-world situations where imperfect information, uncertainty and transaction costs

[3] Goulder & Schein (2013) note that command-and-control regulations may remain more advantageous when emissions are difficult to monitor. In such situations, it can be less costly for the regulator to impose the installation of a particular equipment and monitor its use in lieu of directly monitoring emissions.

prevail, there are noticeable differences, which has notably given rise to a large body of literature on instrument choice.[4] In recent years, however, the observed policy preference for permit trading over taxes is primarily driven by political economy considerations: Cap and trade is easier to implement politically (Ellerman, 2012). For instance, free allocation of permits is often key to garner industry support. That said, the choice between price and quantity instruments is not strict since permit markets often incorporate price-based design features, e.g. price floors and ceilings, which essentially amounts to changing the slope of the permit supply curve and is a core issue of policy design.

The provision for trading is key to improving upon cost efficiency as compared to less flexible approaches. The complement to flexibility to trade emissions across space – and equally important – is flexibility to spread emissions over time. In a similar fashion, intertemporal trading increases the performance of permit markets and implements the least discounted cost solution as the aggregate abatement effort is spread cost-effectively across time periods (Rubin, 1996; Cronshaw & Kruse, 1996; Kling & Rubin, 1997). For this reason, most ETSs allow for some degree of intertemporal trading through banking and (limited) borrowing of permits. As a consequence, given that the aggregate long-term supply of permits is fixed by the trajectory of the emissions cap, i.e. permits are an exhaustible resource, the current permit price should reflect the net present value of the last permit used in the system and the optimal price path should grow at the interest rate (Hotelling, 1931).[5]

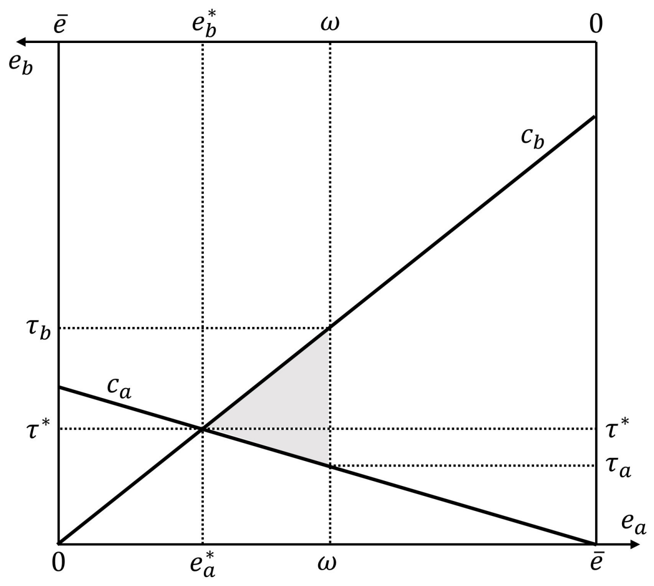
Whether it be spatial or temporal flexibility, the underlying rationale originates in the so called 'Equal Marginal Value Principle', which is best illustrated with the standard graphical analysis presented in Figure A. Consider a permit market with two divisions a and b, each characterized by a linear marginal abatement schedule of slope c_i, $i \in \{a, b\}$.[6] The two divisions have the same level of unregulated emissions $\bar{e}$ and are endowed with a similar quantity of permits $\omega < \bar{e}$. Emissions in division a are measured from left to right on the bottom horizontal axis; those in division b from right to left on the top horizontal axis. The width of the graph denotes the combined abatement effort. When inter-division permit trading is not authorized, each division faces an autarkic shadow price of compliance of $\tau_i = c_i(\bar{e} - \omega)$. Allowing trading results in permits flowing from the lower-price division (a)

[4] The key reference remains Weitzman's seminal article published in 1974. The reader may also refer to Hepburn (2006) and Goulder & Schein (2013) for a general literature review and to Metcalf (2009) for a nontechnical, propaedeutic piece. See also Hoel & Karp (2001), Newell & Pizer (2003) and Fell et al. (2012b) for an extension to the case of stock pollutants such as greenhouse gases. Note also the importance of corner solutions, e.g. due to (practically relevant) uncertainty about cap bindingness, in comparing prices and quantities (Goodkind & Coggins, 2015) and defining the optimal policy mix (Lecuyer & Quirion, 2013).

[5] Because permits are commodities with negligible storage costs and by absence of arbitrage opportunity, the cost-of-carry price of permits must correspond to the spot price grown at the interest rate.

[6] For the purpose of this example, we borrow the terminology of Yates (2002) who thinks of 'natural divisions' in a given permit market as «time periods, regions, pollutants, or even individual firms.»

Figure A: The Equal Marginal Value Principle



to the higher-price division (b) until marginal abatement costs are equated across divisions and the initial autarkic price differential is arbitraged away. The equilibrium price of permits is $\tau^* = 2c(\bar{e} - \omega)$ with $1/c = 1/c_a + 1/c_b$ and reflects the shadow price of the two divisions jointly attaining the aggregate cap 2ω. In equilibrium, the aggregate effort of abatement is allocated efficiently across divisions which emit up to $e_i^* = \bar{e} - \tau^*/c_i$. Permit trading reduces aggregate compliance costs and is beneficial for both divisions, whose (immediate) economic gains from trade are demarcated by the two grey-shaded triangles and proportional to the square of the difference in divisional autarkic prices.

Spatial Linkages between Emissions Trading Systems

A large body of literature studying linkages between ETSs has accumulated since the early 2000s, a time when signatory states to the Kyoto Protocol contemplated market-based regulations as part of their compliance options, thereby mirroring the flexibility mechanisms introduced under the Protocol.[7] At that time, early contributions set out the definitions of linkage concepts and modalities.[8] By the late 2000s, after years of stagnating international climate negotiations and with a shift in dominant paradigm away from traditional multilateralism, scholars and analysts alike began to see the developments of emissions trading and

[7]Throughout this dissertation, linkage is considered in its typical framework, i.e. between ETSs, but linkage among heterogeneous systems may also be feasible (Metcalf & Weisbach, 2012).

[8]In its most simple rendition, linkage necessitates the formal recognition that permits issued by a foreign regulatory authority can be surrendered as valid compliance instruments domestically. When recognition is reciprocal, jurisdictional permits become equivalent, i.e. fungible commodities.

links between emerging jurisdictional ETSs as a feasible alternative bottom-up pathway to a global climate policy regime. As a consequence, this period witnessed the publication of a number of empirical case studies of possible bilateral linkages focused on the identification of conditions and mechanisms for links to be established seamlessly. More recently, as progress on linkage has shown to be slower than anticipated, the focus of investigation has shifted to the political, legal, institutional and technical impediments encountered in practice, notably through careful ex-post assessments of linkage experiences.

The reader may refer to Step 9 in the emissions trading handbook by the PMR & ICAP (2016) for a concise, thorough and practice-oriented propaedeutic piece as well as the special issue on 'Linking GHG Trading Systems' in *Climate Policy*, especially Flachsland et al. (2009b) and Tuerk et al. (2009). In a similar vein, Jaffe et al. (2009), Mehling & Haites (2009) and Fankhauser & Hepburn (2010b) describe the basic tenets of linkage and related design issues. A literature review can be found in Kachi et al. (2015) and especially Mehling (2016) for a historical emphasis, along with a focus on the role of law and institutions. Also of particular interest are the lessons drawn from linkage experiences contained in Jevnaker & Wettestad (2016), Ranson & Stavins (2016) and Tuerk & Gubina (2016).

Linkage is ascribed with a number of potential benefits as compared to standalone systems (i.e., autarky). On the economic side, the essential argument is that linking generates immediate cost-efficiency savings by equalization of marginal abatement costs across systems. Linkage can also increase market liquidity and depth, placate concerns about exercise of market power and reduce overall permit price volatility as jurisdictional shocks are spread over a larger market, especially for small systems. Additionally, it can generate economies of scale through sharing of administrative costs associated with running the system and, if linking partners are also trade partners, assuage fears about carbon leakage by levelling the playing field. On the political side, linkage might help build domestic support for emissions trading, reinforce the credibility of the scheme by making it more durable and resilient to weakening or dismantling in the future, as well as signal leadership.

The foregoing (economic) advantages, however, have proven difficult to leverage in practice. A link between California and Québec entered into force in January 2014, following a great deal of cooperation through the Western Climate Initiative as the separate programs were designed and implemented. Other jurisdictions have expressed their interest in following suit, and Ontario should soon join the linked system. Three members of the European Free Trade Association (Iceland, Liechtenstein and Norway) were integrated into the EUETS upon their inclusion in the European Economic Area in 2007, as access to the EU's internal market is granted in exchange for implementation of relevant EU legislation. As is common with the fourth EFTA member, Switzerland-EU relations are regulated by a series of bilateral agreements and linkage negotiations – initiated in 2010 – were no exception. An agreement was struck by late 2016 but the link has yet to be operationalized.[9]

In addition, the Regional Greenhouse Gas Initiative (RGGI) can be seen as a linked system in which constituent northeastern US states developed their ETSs through joint negotiation of a model rule. The same goes for the EUETS, especially during the first two trading phases (2005-2012) in which Member States determined their domestic caps and permit distribution through National Allocation Plans (subject to approval by the European Commission), before the system's degree of centralization increased as of Phase III.[10] Thus far, linkages have only occurred between motivated partners mostly seeing eye to eye and yet, negotiations lasted several years.[11,12] In sum, linkages are difficult to agree.

What economic theory suggests to be an attractive and natural policy option is, in effect, of a multi-faceted nature, hence politically complex and procedurally demanding (Mehling, 2016; Ranson & Stavins, 2016). By way of example, Article 25 of the EU Directive 2003/87/EC (§1a), which regulates linkage arrangements, stipulates that «agreements may be made to provide for the recognition of allowances between the Community scheme and compatible mandatory greenhouse gas emissions trading systems with absolute emissions caps established in any other country or in sub-federal or regional entities». While it is explicit that potential partnering systems must be mandatory and have absolute caps on emissions in place, the term *compatible* is not defined. What makes a system compatible to link with the EUETS, therefore, fundamentally resides in the political domain.

In the words of Fankhauser & Hepburn (2010b) «there are factors that may counsel against full liberalization of markets across space». Three principal factors can be identified. First and foremost, different ambition levels – that manifest themselves in price discrepancies – can be deemed unacceptable.[13] While gains from linkage are higher the larger the difference in autarkic prices, large price disparities may connote different ambition and policy choices that seem hardly reconcilable.[14] Indeed, even regardless of ambition concerns, jurisdictions may prefer different price levels reflecting different views about the role of the carbon price. For instance, a jurisdiction may view a high price as desirable, e.g. to spark innovation and

[9]Linkage was negotiated as part of a policy package, which slowed down the process (Rutherford, 2014).

[10]This notably led Ellerman (2010) to consider the EUETS as a 'prototype global system'.

[11]The functioning link between Tokyo and Saitama municipal ETSs and the aborted attempt to connect the now defunct Carbon Pricing Mechanism in Australia to the EUETS complete the list.

[12]Jevnaker & Wettestad (2016), Ranson & Stavins (2016) and Tuerk & Gubina (2016) identify geographical proximity (i.e., prior economic and political ties) and similarity in policy and market design (i.e., prior commitments to coordinating climate policies) as key determinants of existing linkages.

[13]Associated financial flows can also be politically challenging. From the perspective of permit importing firms, for instance, this is all the more unpalatable that this suggests lower ambition abroad is tolerable.

[14]Relatedly, the possibility that (current) foreign caps might be non-binding and the associated existence of accumulated surpluses of unused permits can also have a dampening effect on the chances of linking.

investment, drive its climate agenda or raise revenues. By contrast, another jurisdiction may prefer a low-price system working in conjunction with complementary regulations and incentives, e.g. to protect against detrimental distributional outcomes. Therefore, as prices across linked systems converge, high-price jurisdictions may fear that the link might weaken the stimulus to innovate, restrain other ancillary benefits of domestic abatements, or undermine environmental integrity by diluting ambition. Symmetrically, low-price jurisdictions may dislike link-induced price increases and associated consequences.

Second and related, different market designs – as currently observed in existing ETSs – hinder linkage in that a sufficient degree of design harmonization is required to ensure market compatibility and avoid disruptions to the linked system. Market design features, however, reflect jurisdictional circumstances and have often been critical to striking an internal political deal, which may complicate inter-system design alignment.[15] Third, although linkage should reduce overall price volatility, it will also create exposure to shocks occurring abroad as they propagate through the linked system. These 'imported risks' can be driven by natural market fluctuations or policy changes originating in one partnering system.[16] Linkage may thus lead to unforeseen and potentially unpalatable consequences in the event that externally-driven price variations conflict with domestic policy priorities.

In view of the foregoing elements, the first two Chapters of this dissertation tackle the issue of spatial linkages between ETSs from two different angles: Chapter 1 deals with the case of bilateral linkages with restrictions on permit trading and Chapter 2 that of multilateral linkages under uncertainty. In both cases, we assume emissions caps are exogenously given and invariant. In practice, domestic caps indeed result from complex negotiation processes involving a host of stakeholders with vested interests that must accommodate jurisdiction-specific constraints of different sorts (Flachsland et al., 2009b). As a consequence, it seems unlikely that jurisdictions select their domestic caps with a eye on linkage in the future. In sum, we take cap selection as a decision of fundamentally domestic and political nature, which we place beyond the scope of this work and hence demote in our models.

[15] Many papers discuss the extent to which features need be harmonized across systems and categorize them by importance of alignment, albeit with various emphases. In particular, while jurisdictional allocation systems should theoretically not matter, it can be an important practical barrier (Tiche et al., 2014).

[16] Small systems are more vulnerable to these 'imported risks' as the influence of larger systems on the linked system will be relatively more pronounced. The example of the somewhat fortuitous indirect link between the EUETS and the New Zealand ETS through the Clean Development Mechanism is informative in this respect. Indeed, New Zealand had a soft domestic cap on emissions in place whereby covered entities could surrender an unlimited number of Kyoto credits for domestic compliance. As European permit prices plummeted by mid-2011, so did international offset prices since the EUETS happened to be the major, if not sole, source of Kyoto offset demand, which, in turn, mechanically depressed NZ permit prices. The decoupling between EU and NZ prices occurred when New Zealand announced its withdrawal from the second Commitment Period of the Kyoto Protocol in 2013 (World Bank, 2015).

In addition, this assumption implies that strategic interactions and anticipatory effects associated with linkage are assumed away. While we take account of the large body of literature on International Environmental Agreements initiated by Carraro & Siniscalco (1993) and Barrett (1994), we believe this to be more congruent with a top-down approach to international climate negotiations than with inter-ETS linkages from the bottom up.[17] Indeed, in a linkage context, jurisdictions have the ability to carefully choose their linking partners, whose emissions caps' trajectories are often already in place.

In Chapter 1, we consider a bilateral link with various types of restrictions on interjurisdictional permit trading. Restrictions can be employed to limit inter-system trading and associated consequences or to impose that linking be conducive to a net increase in emissions reductions (Rehdanz & Tol, 2005; Jaffe et al., 2009). In practice, restrictions have mostly been used to regulate offset credits for 'supplementarity' reasons, e.g. quantitative and qualitative limits on offset compliance usage and discount rates on offset compliance value. Although permit trade restrictions were extensively discussed during the Kyoto era, they recently gained renewed attention from scholars in the context of linking, e.g. Burtraw et al. (2013) and Gavard et al. (2016), especially in a bid to foster linkage.

Restrictions are distortionary and cost-efficiency does not obtain. That is, a restricted link creates a trade-off between eliminating some impediments to a full link and undermining a fundamental economic reason for linking permit markets in the first place. As restrictions provide levers to adjust for the depth of the link, they could therefore be used as a means of gradually approaching a full link. For instance, they could be loosened over time and eventually removed as the effects of the link materialize (Mehling & Haites, 2009). In the sense of «linking by degrees» (Burtraw et al., 2013), this could help initiate and facilitate linkage through progressive steps by testing the effects of the link while containing its reach as well as providing more time and flexibility in circumventing barriers to a full link, e.g. convergence in ambition levels or harmonization of market designs.

Three main types of link restrictions are considered, namely quantitative restrictions on net permit transfers, border taxes on permit exchanges and exchange rates on permits' compliance values. Their relative implications are evaluated through a partial-equilibrium model of bilateral linkage in a static and deterministic framework, in comparison with two

[17] We will nonetheless review this important strand of literature in Section 2.2 and consider the impacts of allowing for strategic interactions and anticipation of linkage in Appendices 2.B.3 and 2.B.4. In short, because of their global public good nature, domestic abatement efforts are always strategic substitutes in a pure emissions game. Anticipation of linkage further alters cap selection and reinforces the substitutability of abatement efforts, which may lead to both lower ambition and cost-efficiency (Helm, 2003; MacKenzie, 2011; Holtsmark & Sommervoll, 2012), i.e. a short of 'race to the bottom'.

reference scenarios, viz. autarky and full linkage.[18] Because our approach is not normative, we lack a formal criterion to be able to establish a clear ranking between restrictions. However, although our stylized model is very simple, it is structured enough to highlight key differences between restrictions and their implications. This allows us to compare them in a unified framework and greatly enhances insight. Additionally, our model is meant to serve, in conjunction with lessons drawn from real world experiences with ETSs and linkage, as a basis for a policy-oriented discussion of the comparative merits of each restriction in their ability to initiate linkage and transition to a full link.

By fixing a ceiling on the net authorized permit transfer, a quantitative restriction provides a direct quantity handle on the reach of the link but the ratio of inter-system price convergence is unknown ex ante. Symmetrically, a border tax sets the price ratio but there is uncertainty about the resulting permit transfers. In both cases, the restricted link outcomes are comprised between autarky and full linkage, and aggregate emissions are constant. Just like a border tax, an exchange rate specifies the ratio of jurisdictional marginal abatement costs in equilibrium but further changes the relative compliance value of permits. Overall emissions are thus allowed to vary as a result of inter-system permit trading.

On the face of it, quantitative restrictions seem to be the natural route to full linkage between two quantity instruments. As two jurisdictional prices coexist, however, inter-system transaction prices may not reflect marginal abatement costs, which can generate uncertainty about price formation and undesirable price fluctuations. Relatedly, the distribution of the scarcity rent (associated with the binding restriction) across jurisdictions and firms is not clear ex ante. Quantitative restrictions can thus lead to uncertain distributional effects and weakened price signals, which may impair the transition to a full link.

Some of these aspects can be mitigated under a border tax on permits. Indeed, distributional outcomes can be better managed as a tax raises revenues where a quantity restriction creates a scarcity rent instead. These revenues can be seen as a form of interjurisdictional transfers and might thus help spur cooperation. Additionally, because the price ratio is conveyed by the tax rate, there should be less undesirable price fluctuations and better information on jurisdictional marginal abatement costs. Border permit taxes, however, may be more complicated to pursue legislatively speaking.

By altering the fungibility of jurisdictional abatements, exchange rates can be employed

[18]The analysis is limited to a bilateral link for clarity. The insights gained from this simple framework, however, can help understand the effects of restrictions in the context of multilateral linkages or networked ETSs (Keohane et al., 2015; Mehling & Görlach, 2016) as further discussed in Chapter 1.

to adjust for differences in programs' stringencies and potentially other economic and non-economic criteria.[19] In addition, we show how exchange rates, when skillfully selected, have potential to increase ambition over time. On the flip side, however, difficulties precisely pertain to the selection and subsequent adjustment of the exchange rate, which might possibly lead to environmental and economic outcomes that are worse than autarky.

This analysis thus enables us to identify comparative advantages and weaknesses for each link restriction. Although there is no 'ideal' transitional restricted linkage, we finally show how experience suggests that unilateral linkage – whereby permits can flow in one direction but not vice versa – can be a practical and promising way of gradually approaching a full, two-way link. For instance, both the Norway-EU and (aborted) Australia-EU one-way links served as a transitory step in aligning programs for a later full-link scale-up.

In Chapter 2, we develop a model to describe and analytically characterize the effects of and economic gains from multilateral linkages under conditions of uncertainty. By contrast, the literature has primarily focused on the simpler case of bilateral linkages and uncertainty is rarely formally introduced.[20] The uncertainty analyzed here takes the reduced form of idiosyncratic shocks on the intercepts of jurisdictional marginal abatement cost schedules à la Weitzman (1974) and Yohe (1976).[21] In essence, this Chapter extends and generalizes the work of Doda & Taschini (2017) on bilateral linkages under uncertainty.

There are potential gains from linkage whenever there exists a price differential between jurisdictions under autarky, which can in turn result from varying jurisdiction-specific ambition levels or cost shocks. Most analyses of linkage concentrate on the former as the sole source of gains. In this Chapter, however, we argue that these two sources of gains exist independently of each other, and devote most of our attention to characterizing the latter. Irrespective of the magnitude of the first source, i.e. even when jurisdictions have identical ambition, the second source reinforces the Pareto argument in favor of linking relative to autarky.[22] Indeed, these two sources show up as two non-negative components of linked jurisdictions' expected linkage gains: the former is proportional to the square of the difference between the autarky and linking expected permit prices and the latter is proportional

[19] The reader may refer to the documentation provided via the Network Carbon Markets initiative by the World Bank for a list of criteria that can be used to define the 'mitigation value' of various carbon assets.

[20] When looking for prospective linking partners, however, one is likely to consider their expected autarkic prices, which reflect their underlying ambition levels, as well as their autarkic price volatilities (i.e., higher-order moments of the autarkic price), which reflect other jurisdictional characteristics.

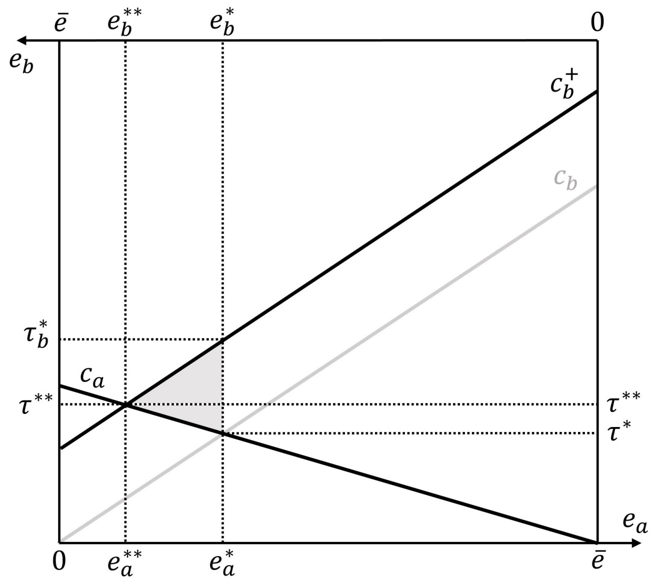
[21] In our setup, a positive cost shock can be interpreted as an increase in laissez-faire emissions.

[22] Under uncertainty, autarkic compliance costs increase so that linking becomes all the more so relevant. Indeed, if $\bar{e}$ is random and abatement costs C are convex functions of abatement, Jensen's inequality yields $C(\mathbb{E}\{\bar{e}\} - \omega) \leq \mathbb{E}\{C(\bar{e} - \omega)\}$. Note that the higher the uncertainty, the larger the compliance costs.

to the variance of the difference between the autarky and linking permit prices.

To see this, consider again Figure A but now assume that abatement costs are uncertain and that c_i (resp. τ_i) corresponds to the expected marginal abatement cost (resp. expected autarkic price) in jurisdiction i. The two grey triangles thus indicate the first component of jurisdictional gains from linkage. Now assume this equilibrium is attained and fixed. As depicted in Figure B, further assume a positive cost shock occurs in jurisdiction b, i.e. the realized marginal abatement cost in b becomes c_b^+ while that in a remains unchanged. This

Figure B: The Equal Marginal Value Principle under Uncertainty



opens up another price differential $\tau_b^* - \tau^*$ between the two jurisdictions. Again, linkage eliminates the post-shock price wedge and, as exchange opportunities are being exhausted, prices converge to τ^{**} and jurisdictions emit up to e_i^{**} in the new equilibrium. Starting from a situation where expected prices are equal across jurisdictions, the two grey triangles in Figure B demarcate the second component of jurisdictional gains from linkage, which will depend on the shock characteristics, viz. volatility and pairwise correlation.

We then establish the theoretical foundations for gains in bilateral linkages, which prove to be intuitive. That is, linkages with larger systems are more beneficial, all else constant.[23] A jurisdiction also prefers the permit demand in its partner's system to be variable and weakly correlated with its own. Our formal approach is useful as we show that these insights do not translate easily to multilateral linkages. Additionally, the number of possible coalitions of linked systems and structures thereof escalate rapidly as the number of jurisdictions

[23]The term 'large' refers to the size of jurisdictions, which only measures the volume of regulated emissions by jurisdictional systems under autarky, and not other economic dimensions such as GDP or population.

available to link with increases. In many ways, however, we will see that bilateral linkages constitute the cornerstone of our analysis of multilateral linkages.

Our model can in principle handle an arbitrary number of linked jurisdictions and complex coalition structures. Indeed, as a novel and extremely useful tool, we show that any multilateral linkage can be decomposed into its internal bilateral linkages. Such a decomposition enables us to characterize and quantify the aggregate and individual gains in any linkage coalition as a size-weighted function of the gains in all bilateral links that can be formed among its constituents. Moreover, we show that linkage is superadditive, i.e. the aggregate expected gains from the union of disjoint coalitions of linked ETSs is no less than the sum of the separate coalitions' expected gains, and further provide an analytical formula for this gain as a function of coalitional sizes and shock characteristics.

A natural consequence of superadditivity is that the global market generates the highest aggregate expected gains. Absent inter-jurisdictional transfers, however, there is no guarantee that it is the most preferred linkage coalition from a jurisdictional perspective. In fact, the conditions for the global market to be the most preferred linkage coalition universally are restrictive and thus unlikely to be satisfied in practice. The combination of superadditivity and impracticality of transfers, say due to the prevalence of political-economy constraints, implies that jurisdictional linkage preferences within an arbitrary coalition may not be aligned. This could be one reason why linkages are rarely observed in practice.

Additionally, the volatility of the permit price is a well-defined object in our model and we can study its properties. Because idiosyncratic shocks affecting individual jurisdictions are correlated, there is no reason to expect the linking price variance to decline as the number of linked jurisdictions increases. However, we show that high-volatility jurisdictions will always experience reduced price volatility under linking relative to autarky as their domestic shocks are spread over a larger market and thus better buffered. Conversely, as linking creates exposure to shocks occurring abroad, low-volatility jurisdictions may face an increase in price volatility under linking, especially when they are relatively small and the influence of larger jurisdictions on the linked system is more pronounced.

Our model is apt for policy analysis shedding light on questions like which jurisdictions gain the most by linking their existing or planned ETSs. We thus take the model to the data to provide some quantitative implications of our analytical results using a real-world example. The model is loosely calibrated to historical emissions of five jurisdictions, which allows us to provide a quantitative illustration of their linkage preferences.[24] We concentrate our analysis on the ambition-independent source of linkage gains by equating expected autarkic

[24] We consider only five jurisdictions for clarity of exposition and emphasize that, to a large extent, our sample spans the diversity of jurisdictional characteristics present in the data. Jurisdictions' sizes and

prices across jurisdictions.[25] This quantitative exercise notably provides some validity to the fact that the global market is not everyone's most preferred option.

Recognizing that linking can be a lengthy and costly process in terms of political negotiation and design harmonization, we finally extend the policy application by introducing linkage costs as a way to bring in minimal realism. In the presence of linkage costs, whose magnitude is endogenous to the formation of linkage coalitions, we identify the nature of linkage coalition structures that are socially efficient with alternative assumptions about how costs are shared among partnering jurisdictions. We also find noticeable differences across cost-sharing arrangements, which, in a world where outright permit or cash transfers can run into significant political-economy hurdles, can have important policy implications for initiatives aiming to steer jurisdictions towards efficient policy architectures.

Temporal Linkages within Emissions Trading Systems

Most permit markets allow for some degree of intertemporal trading through banking and borrowing of permits. In general, there is lenient or no restriction at all on banking whereas individual borrowing is often severely limited or simply prohibited, lest it be incompatible with the attainment of the environmental target or that firms may shirk.[26] When caps are declining, however, it is rational for firms to decrease emissions below the cap at the start, accumulating a 'permit bank' and then drawing it down as the cap gets more stringent in order to cost minimize over time. The reader may refer to Chevallier (2012) and Hasegawa & Salant (2015) for a literature review on intertemporal emissions trading and to Holland & Moore (2013), PMR & ICAP (2016) and ICAP (2017) for details on market designs, e.g. holding limits in California or implicit year-on-year borrowing in the EUETS.

Under conditions of uncertainty, intertemporal permit trading allows a smoothing of abatement efforts across time periods, which should reduce the costs associated with otherwise 'unresponsive' short-run permit supplies.[27] Indeed, as firms cost minimize, the opportunity

shocks are calibrated using the level and fluctuation of their historical emissions obtained with the Hodrick-Prescott filter, which is congruent with our interpretation that jurisdictional shocks capture the net effect of stochastic factors that may influence their laissez-faire emissions, e.g. business cycles and technology shocks, jurisdiction-specific events, changes in the price of factors of production, weather fluctuations, etc.

[25] Given our calibration exercise, we believe we can say something reasonable about the often under-appreciated nature and magnitude of linkage gains arising due to uncertainty. This also enables us to include jurisdictions that do not have an ETS or any other form of absolute abatement objectives in place.

[26] Note that, as compared to the situation where the overall abatement effort is evenly apportioned across compliance periods, a descending cap can be seen as a market-wide borrowing mechanism.

[27] Much has been written about the problem of vertical permit supply curves since the seminal contributions by Roberts & Spence (1976) and Weitzman (1978). Changing the slope of the permit supply curve (e.g., by introducing steps) is a central issue of policy design, see e.g. Fankhauser & Hepburn (2010a) for a

to bank (resp. borrow) permits for (resp. from) future periods implies an arbitrage condition between present and discounted expected future permit prices. Therefore, in a rational expectations stochastic market equilibrium, the least discounted expected cost solution obtains, i.e. expected marginal abatement costs have the same present value at any point in time (Samuelson, 1971; Schennach, 2000).[28] Furthermore, because permits have negligible storage costs, the cost-of-carry price coincides with the spot price grown at the interest rate. In other words, the optimal permit price path grows at the interest rate.

The permit price, therefore, is the vehicle that equates the expected long-term supply and demand of permits. This underlines an often under-appreciated feature of permit markets with intertemporal trading relative to emissions taxes. In a normative setting, for instance, Pizer & Prest (2016) exploit the ability of the former in equating current and expected future prices (as compared to the latter that cannot do so) to establish the first best in all periods by an adequate selection of a sequence of quantity policy updates.[29] In practice, this means that firms' anticipation and perception of the program's future stringency will guide their abatement, compliance and investment strategies through time.

In practice, however, ETSs are subject to considerable uncertainty. Indeed, these systems do not function in a vacuum and are influenced by external factors and policies outside their perimeters, e.g. macroeconomic conditions, the usage of offset credits to partly acquit compliance obligations and the reach of complementary policies (Newell et al., 2013; de Perthuis & Trotignon, 2014; Tvinnereim, 2014; Borenstein et al., 2016; Chèze et al., 2016; Ellerman et al., 2016; Lecuyer & Quirion, 2016). Policy overlap can be fortuitous as (deplored) in the EUETS or explicitly built into an open regulatory system as in California where the ETS operates in conjunction with a set of complimentary measures, thereby constituting a safety net ensuring that the state-wide target is attained and that no low-cost abatements are left behind.[30] In turn, the above factors can erode the cap stringency as there exists significant uncertainty about baseline emission levels which Borenstein et al. (2016) estimate to be «at least as large as uncertainty about the effect of abatement measures».[31]

review. The standard way this can be accomplished is by imposing price collars or corridors, i.e. contingent price-triggered adjustments to the aggregate supply (Pizer, 2002; Burtraw et al., 2010; Fell et al., 2012a).

[28]This is the general line of reasoning for stock pollutants. However, if stocks of, say greenhouse gasses, happen to generate a flow of damages in each time period, then the least discounted cost solution will not minimize the more appropriate welfare function, i.e. the discounted sum of abatement costs and damages, as shown by Kling & Rubin (1997) and Leiby & Rubin (2001).

[29]This tilts the standard prices-*vs*-quantities comparative advantage formula toward quantities and prices can never be preferred. Similarly, Newell et al. (2005) explore alternative cap adjustment mechanisms based on shock realizations that allow for intertemporally tradable quantities to replicate a price policy.

[30]Note that policy overlap is not limited to climate change and energy related policies. For instance, Schmalensee & Stavins (2013) underline the impact of railway deregulation on the US SO_2 trading program.

[31]Borenstein et al. (2016, 2017) show that significant baseline uncertainty coupled with little price elasticity is likely to generate either very high or very low price levels with high price volatility.

As it turned out, baselines have been lower than anticipated in most existing ETSs. Consequently, as a general rule, permit prices have declined and now keep hovering at low levels or just above price floors when such price support mechanisms exist. If agents are rational, however, lower-than-expected price levels should be inconsequential for intertemporal cost efficiency. Indeed, a positive (resp. negative) permit demand shock would shift the optimal price path upwards (resp. downwards), but its slope would be preserved and it would remain efficient. Additionally, if there is a desire, prices could be increased by cutting the future cap: forward-looking agents would anticipate higher requirements and bank more permits, thereby raising the current price. In the EUETS, however, the announcement that the cap stringency will be increased from 2021 onwards had little impact on current prices (Koch et al., 2014) and concern remains that these are not sending appropriate signals.

Indeed, it is difficult to ascertain whether low prices are attributable to external demand shocks or to intrinsic market and regulatory imperfections. Prices may thus not be 'right' in that they may not reflect intertemporal marginal abatement costs. As a case in point, Hintermann et al. (2016) review the literature on the price determinants in the EUETS and find that «there is a complex interaction between BAU emissions, abatement quantities and allowance prices». Put otherwise, our understanding of these determinants is limited. For instance, Koch et al. (2014) find that abatement-related fundamentals were responsible for only 10% of the permit price variation. Present market and regulatory imperfections, low prices can be of consequence for intertemporal efficiency. Importantly, interactions between such imperfections and exogenous shocks could impair permit price formation and undermine the long-term price signal conveyed by the system.

In the EUETS, a scan of the literature indicates that three types of imperfections are at the center of attention, viz. limited foresight, excessive discounting and regulatory uncertainty. First, if agents have truncated time horizons and permits are relatively more abundant today than they will be in the future, prices will not reflect the long-term permit scarcity and be lower than they ought to, which raises overall compliance costs (Ellerman et al., 2015). Second, it can be that discount rates higher than the interest rate are applied for banking strategies outside a 'hedging corridor' due to institutional or corporate constraints (Neuhoff et al., 2012; Schopp et al., 2015). Additionally, when future abatement costs are uncertain, risk premia can be associated with holding permits when firms are risk averse (Kollenberg & Taschini, 2016). In turn, these 'too high' discount rates would encourage lower banking and sustain lower price today, as compared to the cost-effective pathway. Relatedly, Bredin & Parsons (2016) find that the EUETS has been in contango since early Phase II in 2008. That is, futures prices have been higher than cost-of-carry prices with implied premiums (i.e., negative convenience yields) of significant sizes.

Third, regulatory uncertainty about permit supply adjustments has shown to bear on price formation. To give but a few examples thereof, consider first the increase in RGGI prices when the 2014 45% slash in the cap was under discussion, but before it was actually passed. Similarly, the price rise in early 2016 in the New Zealand ETS relates to the announcement that the one-permit-for-two-tons compliance rule should be abolished at some point in the future. More recently, the downward pressure on prices currently observed in the Chinese ETS pilots results from uncertainty about the nationwide rollout, especially regarding the carry-over provisions for pilot permits into the national market.[32]

This shows that market participants can anticipate, if not speculate, about future policy changes. In turn, this distorts intertemporal optimality of agents' decisions, i.e. intertemporal cost efficiency (and possibly other desirable elements of the policy) are impaired.[33] In the best case, this may be a necessary consequence of a policy update, i.e. when agents fully understand the objectives of the regulator (Kydland & Prescott, 1977).[34] However, this may be a needless cost when agents regard regulatory actions as somewhat random (Salant & Henderson, 1978), i.e. when the policy update is poorly managed or worse, when speculation is unfounded. Additionally, low price levels have sparked short-term interventions (e.g., ex post supply management) as well as structural design reforms (e.g., price collars) in all existing ETSs, which further feeds regulatory uncertainty.

With a focus on the EUETS, Salant (2016) shows how, in a rational expectations market equilibrium, regulatory uncertainty weighs on price formation.[35] Koch et al. (2016) and Creti & Joëts (2017) provide empirical support and find the EUETS responsive to political events and announcements. That is, not only the announced cap level will hold sway over price formation, but also speculation about the attendant regulatory commitment may cause prices to fluctuate.[36] Koch et al. (2016) also present evidence that market participants tend to belittle, if not ignore, announcements that should be indicative of higher future prices. The above further suggests that firms cannot entirely hedge against regulatory risks.

In view of the foregoing elements, the third and last Chapter of this dissertation takes account of the considerable uncertainty – especially regulatory uncertainty – firms covered

[32] An even more recent example, although it has not had bearing on prices and market functioning yet, is the fate of UK-issued European Allowances under Brexit, which could possibly be seized or cancelled from accounts across the bloc. Indeed, there is little precedent concerning the legal ownership status of EUAs.

[33] For instance, Harstad & Eskeland (2010) develop a model with signaling where firms anticipate that the regulator will allocate future permits in proportion to the firms' needs and thus select their present emission levels in a bid to influence their future endowments.

[34] See Helm et al. (2003), Brunner et al. (2012) and Jakob & Brunner (2014) for an application to climate change of the the long-running debate on 'rules versus discretion' initiated by Kydland & Prescott (1977).

[35] Salant (2016) draws on his analysis of the spot price of gold in the 70's (Salant & Henderson, 1978).

[36] Positive prices in oversupplied Phase II indicate banking as firms expect the emission constraint to be binding in the future and also reflect «their awareness of regulatory uncertainty» (Hintermann et al., 2016).

under an ETS are faced with. In particular, we argue that firms lack confidence and/or relevant information to assign a probability measure uniquely describing the stochastic nature of their decision problems, which corresponds to a situation characterized by ambiguity. By contrast, risk refers to situations where such distributions are perfectly known and unique. For instance, Hoffmann et al. (2008) define regulatory uncertainty as «an individual's perceived inability to predict the future state of the regulatory environment» where the term 'uncertainty' is deliberately used in the Knightian sense (Knight, 1921). As a novel way of accounting for both the prevalence and influence of regulatory uncertainty, we further propose to consider that ETS-liable firms exhibit ambiguity aversion.

Chapter 3 therefore sets out to examine intertemporal abatement decisions by a risk neutral ambiguity averse firm covered under a two-period ETS.[37] We assume an interior banking solution between dates 1 and 2, i.e. a descending cap. We also consider that at date 1 both the date-2 market permit price and the firm's demand for permits are ex-ante ambiguous and exogenous to the firm. This reflects that regulatory uncertainty directly bears on price formation (Salant, 2016) and that there is significant uncertainty about permit demands, e.g. via direct or indirect policy overlaps (Borenstein et al., 2016).[38] Ambiguity neutrality is our natural benchmark, in which the firm's optimal abatement stream is congruent with the least discounted expected cost solution (Schennach, 2000) and permit carry-over arbitrage conditions solely depend on expected future prices (Samuelson, 1971).

Ambiguity resolves at the start of date 2. We solve the firm's intertemporal cost minimization program by backward induction and compare the optimal level of date-1 abatement (i.e., banking) under ambiguity aversion relative to ambiguity neutrality. We consider a smooth ambiguity model of choice à la Klibanoff et al. (2005) in which the firm is confronted with different possible scenarios about the future regulatory framework, i.e. objective probabilities for the related permit price and demand forecasts, and has subjective beliefs over this set of scenarios.[39] Ambiguity neutrality ensures linearity between objective and subjective lotteries, thereby collapsing to a Savagian framework (Savage, 1954). Attitudes toward ambiguity originate in the relaxation of such linearity and ambiguity aversion corresponds to the (additional) aversion (w.r.t. risk aversion) to being unsure about the probabilities. This will incite the firm to favor abatement streams that reduce the level of ambiguity.

[37]The firm thus displays aversion toward model uncertainty in the sense of Marinacci (2015).

[38]Although regulatory uncertainty could bear on the firm's permit allocation, we prefer to keep this as a parameter in the model to be able to measure its influence on banking decisions. Indeed, neutrality of allocation does not hold under ambiguity aversion. Note, however, that because we let the demand be ambiguous, the firm's gross effort of abatement (baseline minus allocation) is also affected by ambiguity.

[39]Typically, consider for instance that these objective scenarios are provided by groups of experts, e.g. BNEF, Energy Aspects, ICIS-Tschach, Point Carbon, diverse academic fora or think tanks, etc.

Ambiguity aversion drives equilibrium abatement stream choices away from intertemporal cost efficiency. Before examining joint market price and firm's baseline ambiguities we consider each source of ambiguity in isolation. This enables us to separate out two ambiguity aversion induced effects. First, with risky price and individual baseline ambiguity, we note that from the perspective of the risk neutral firm the cap and trade can be assimilated to an emissions tax where the tax rate is set at the expected permit price. Ambiguity aversion induces an upward (resp. downward) shift in the firm's discount factor when it exhibits Decreasing (resp. Increasing) Absolute Ambiguity Aversion. Therefore, early overabatement (resp. underabatement) occurs relative to the benchmark under DAAA (resp. IAAA).[40]

Second, with price ambiguity and risky individual baseline, ambiguity aversion induces another effect by which the firm pessimistically distorts its subjective beliefs and overweights 'detrimental' scenarios. Intuitively, when the firm expects to be net short (resp. long) it overemphasizes scenarios where high (resp. low) prices are relatively more likely. This raises (resp. lowers) the firm's estimate of the future price relative to the benchmark and raises (resp. lowers) its incentive for early abatement accordingly. Relative to the benchmark the ambiguity averse firm does not solely base its present abatement decisions on the expected future price but also on its expected future market position. This ultimately hinges upon permit allocation and we identify allocation thresholds below (resp. above) which pessimism unconditionally leads the firm to overabate (resp. underabate) early on.

Third, with both price and individual baseline ambiguities, we show that early overabatement occurs when the conditions for early overabatement under sole price ambiguity obtain and, additionally, high-price scenarios coincide with high-baseline scenarios. We then extend the model and consider a continuum of firms identical but for permit allocation where the market price is endogenously determined by the market-wide baseline ambiguity. We can refine the threshold condition on permit allocation and we show that pessimism generates early overabatement under a symmetric allocation of permits. This can be a behavioral factor that contributes to the formation of a permit bank, e.g. in the EUETS.

The two ambiguity aversion induced effects can be aligned or antagonistic, the direction and magnitude of which depend on the degree of ambiguity aversion and permit allocation. In particular, a higher degree of ambiguity aversion is not necessarily conducive to a larger adjustment in early abatement (in absolute terms).[41] With a parametrical example we numerically show that early abatement decreases with allocation and that the magnitude

[40]Thus, we define DAAA as ambiguity prudence following Berger (2014) and Gierlinger & Gollier (2017).

[41]An increase in ambiguity aversion always increases the magnitude of the pessimistic distortion in the sense of a monotone likelihood ratio deterioration (Gollier, 2011) and we show that it can increase that of ambiguity prudence only when ambiguity prudence is not too strong relative to ambiguity aversion.

of distortion due to pessimism is generally greater than that due to the shift in the discount factor. This shows that, under ambiguity aversion, early abatement is higher under auctioning than free allocation and suggests that the distortion away from intertemporal efficiency is greater under a cap and trade than an emissions tax.[42]

Finally, we discuss our results in relation to the literature.[43] Note that we extend the work of Baldursson & von der Fehr (2004) to ambiguity aversion. Similarly, Baldursson & von der Fehr show that risk averse firms that expect to be short (resp. long) on the permit market overinvest (resp. underinvest) in abatement technology relative to risk neutrality. However, we show that both price and quantity regulations deteriorate under ambiguity aversion while a price instrument remains intertemporally efficient under risk aversion. Additionally, in our setup firms expecting to be net long (resp. short) can still overabate (resp. underabate) when they exhibit DAAA (resp. IAAA). In particular, the DAAA (resp. IAAA) induced increase (resp. decrease) in the discount factor can create a downward pressure on future (resp. present) prices. In our setup, therefore, the hypothesis of excessive discounting found in the literature to account for the current price depreciation in the EUETS (either due to a hedging corridor (Neuhoff et al., 2012; Schopp et al., 2015) or due to risk aversion (Kollenberg & Taschini, 2016)) coincides with IAAA, i.e. 'imprudence toward ambiguity'. However, this does not imply that IAAA-firms under-bank permits as pessimism can dominate the shift in discounting depending on their permit endowment.

As a final note, we consider three extensions to the model. First, we show that introducing forward contracts cannot restore intertemporal efficiency, perhaps indicating that regulatory risks cannot be entirely hedged. Although forwards have potential to partially mitigate pessimism, the shift in discounting always persists. Second, we show that the volume of trade is reduced when allocation is sufficiently asymmetrical across ambiguity averse firms. Third, we show that the equilibrium in a market populated by a mix of ambiguity neutral and averse firms should be brought further away from intertemporal efficiency.

[42] We compare how price or quantity controls affect intertemporal decisions in terms of distortion magnitude. Jumping back to Pizer & Prest (2016) and footnote 29, we note that Pizer & Prest show that with the introduction of exogenous noises in policy updates (which can be thought of as an analog of regulatory uncertainty), prices can be preferred again (because the adverse effect of policy noises is at least delayed before policy is actually implemented), especially when the variance of noise shocks is high.

[43] Economic theory suggests that there is an option value to postpone investments under uncertainty (Dixit & Pindyck, 1994). Note that Dorsey (2017) empirically validates that regulatory uncertainty increases compliance costs by delaying investments in the context of EPA's Clean Air Interstate Rule.

* * *

Chapter 1

Transitional Restricted Linkages

* * *

Full linkages between Emissions Trading Systems are difficult to agree. A full link could be approached gradually through transitory restrictions on permit trading. This may allow to test the effects of the link while containing its reach, provide more time and flexibility in circumventing impediments to unrestricted linkage as well as spur cooperation. Thanks to a simple and unified modeling framework, we descriptively analyze and compare the implications of various link restrictions, namely quantitative restrictions and border taxes on inter-system permit transfers, exchange and discount rates on permit compliance values, and unilateral linkage. Drawing from both our modeling exercise and real-world experiences with linkage and trade restrictions in ETSs, we then discuss the comparative merits of each link restriction in facilitating linkage and transitioning to a full link.

This analysis allows us to identify comparative advantages and weaknesses for each link restriction. While quantitative restrictions seem to be the natural route to full linkage, they can lead to uncertain distributional effects and weaken price signals. These aspects are mitigated under a border tax, but this policy seems harder to implement. Exchange rates have potential to adjust for discrepancies in systems' stringencies and increase environmental ambition, but can be challenging to select. As experience corroborates, unilateral linkage can be a practical and promising way of gradually approaching a full, two-way link.

* * *

This Chapter is an adaptation of a collaboration with Christian de Perthuis.

1.1 Introduction

As discussed in the General Introduction, full linkages are difficult to agree and to date, few and far between. Indeed, the multi-faceted nature of linkage as well as growing heterogeneity in market designs and governance frameworks pose many challenges to prospective partners. First and foremost, discrepancies in autarkic prices reflect different ambition levels and/or views about the desirable price signal, which impede on the political feasibility of linkage although this would increase attendant economic gains (Flachsland et al., 2009b; Fankhauser & Hepburn, 2010b). Second, a certain degree of design harmonization is required to ensure market compatibility and avoid disruptions to the linked system (Jaffe et al., 2009; Tiche et al., 2016). However, market designs reflect jurisdictional circumstances and have often been critical to striking an internal political deal, which may complicate inter-system design alignment.[1] Third, even when jurisdictions have compatible systems and are seeing eye to eye in terms of ambition and price levels, there are still risks that link outcomes do not unfold as anticipated. Indeed, linkage creates exposures to developments originating abroad that propagate throughout the linked system (Flachsland et al., 2009b).

Forging linkage agreements that reconcile and accommodate every party's interests is thus likely to prove difficult (Tuerk et al., 2009). As a consequence, the most suitable way for interconnection may fall short of a full link, at least in the near term. In particular, two types of approaches can be contemplated to palliate the acknowledged difficulties in initiating linkage. First, connections to a common hub might constitute a first step toward further market integration, e.g. indirect linkage through offsetting or networking.[2] As a

[1] One can expect this issue to be magnified when jurisdictions of comparable large sizes explore linking opportunities. Indeed, they might not be as much inclined to cede sovereign control over deeply entrenched policy objectives and design features as smaller jurisdictions (thus with a stronger interest in linking) can be. For instance, given its sheer size and political weight, the EU imposed its policy objective and market design to its linkage partners that had no choice but to conform with (almost) no leeway.

[2] The concept of networking ETSs has recently emerged as a substitute for direct multilateral linkages (Keohane et al., 2015; Mehling & Görlach, 2016), notably under the auspices of the Networked Carbon Markets initiative by the World Bank. The idea is to allow for trades of 'carbon assets' between systems

case in point, Jaffe et al. (2009), Tuerk et al. (2009) and Fankhauser & Hepburn (2010b) conceived of a progressive mechanism of market integration through unilateral connections to the Clean Development Mechanism, envisaged as a common hub in the Kyoto era. Such an international offsetting mechanism, however, is currently missing.[3]

Second, transitional link restrictions might be established in the perspective of a full link.[4] According to Mehling & Haites (2009), «a bilateral link can be approached gradually; quantity restrictions could be applied to the other scheme's units initially and can be loosened over time as the effects [associated with the link] become clear». On the face of it, restrictions may provide levers to adjust for the reach of the link and test its effects. They could also facilitate negotiations by breaking down a lengthy linking process into progressive steps in the sense of «linking by degrees» (Burtraw et al., 2013).[5] We also note that, in practice, linkage has sometimes been initiated via trade restrictions, as attest transitional one-way links integrating Norway and the European aviation sector to the EUETS.

This Chapter compares three main types of link restrictions, namely quantitative transfer restrictions, border taxes on permit imports/exports and exchange rates on permits' compliance values. Unilateral linkage and discount rates – two other forms of restrictions – will also be discussed. To evaluate the effects of each restriction we use a partial-equilibrium model of linkage between two same-sized permit markets in a static and deterministic framework. Their relative implications are measured against four indicators, namely cost-efficiency, location and volume of abatement, price formation and distributional aspects, in comparison with two reference scenarios, namely autarky and full linkage.

We assume all types of markets are competitive, except in the case of quantitative restrictions where the market structure we consider is a bilateral monopoly. We abstract from market designs to single out restriction-specific effects.[6] We limit the analysis to a bilateral link to facilitate exposition but we note that this is not entirely innocuous.[7] However, the insights gained from this simple framework can help understand the effects of restrictions

that are inherently different (e.g., in terms of design, ambition, MRV standards) by placing a 'mitigation value' on assets that account for these differences and possibly using trade restrictions as analyzed herein.

[3]The Sustainable Development Mechanism or 'revamped-CDM' established under Article 6.4 of the Paris Agreement could offer such opportunities for indirect links, but has yet to be developed.

[4]As discussed in Jaffe et al. (2009), restrictions can also be used «to reduce inter-system trading, or if there is a desire, to require that trading with other systems lead to a net reduction in emissions».

[5]Symmetrically, link restrictions may provide levers to maneuver if partners are not satisfied with the link and wish it be severed. That is, they offer additional ways to terminate the link, whose organisation affects intertemporal cost-effectiveness and price formation in the linked scheme (Pizer & Yates, 2015).

[6]Note that price containment mechanisms affect permit price formation (Holt & Shobe, 2016) and that full inter-scheme price convergence may not obtain under unrestricted linkage when such mechanisms are divergent across systems (EPRI, 2006; Jaffe et al., 2009; Grüll & Taschini, 2012).

[7]For instance, in a multilateral setup, permit importers may benefit from binding quantitative restrictions on imports in other jurisdictions/sectors as this reduces the permit price but not their own demands.

in a multilateral link. Finally, for comparability, we assume domestic caps on emissions are exogenously given and enforced in every situation considered.Our stylized model is thus simple enough to allow for analytical solutions and enables us to compare link restrictions in a unified framework, which greatly enhances insight. Crucially, it has enough structure to highlight key differences between the various restrictions considered.

Restrictions distort market incentives by driving a wedge between jurisdictional prices and are thus always detrimental relative to full linkage in aggregate terms. Note, however, that we adopt a descriptive approach in comparing the relative implications of restrictions with a policy-oriented focus. Because we do not follow a normative approach, we lack a formal criterion to be able to establish a ranking between restrictions from a social perspective. That said, restrictions can improve upon full linkage when viewed from a jurisdictional perspective and we characterize jurisdictions' optimal restrictions.

Restricted linkage creates a trade-off between eliminating some impediments to full linkage and undermining a fundamental reason for linking ETSs in the first place, i.e. cost efficiency. This justifies a temporary use of restrictions moving toward unrestricted linkage. Transitional restricted linkage can be envisaged to test the effects of the link, assuage some of the risks associated with a full link, incite jurisdictions to cooperate, as well as give more time and flexibility for parties to reconcile their policy differences and bring their schemes further into alignment for a full link to be established seamlessly.

Drawing on both our modeling exercise and real-world experiences with restrictions and linkage, we then set out to discuss the comparative merits of each link restriction. We focus on their ability in facilitating linkage, i.e. their potential to both mitigate risks associated with linkage and inform the extension to a full link. We also envisage restrictions and induced rents as possible coordinating mechanisms to spur cooperation.

By fixing the maximum authorized net permit transfer, a quantitative restriction provides a direct quantity handle on the reach of the link but the ratio of inter-system price convergence is unknown ex ante. Symmetrically, a border tax sets the price ratio but there is uncertainty about the resulting permit transfers. In both cases, the restricted link outcomes are comprised between autarky and full linkage, and aggregate emissions are constant. Just like a border tax, an exchange rate specifies the ratio of jurisdictional marginal abatement costs in equilibrium but further changes the relative compliance value of permits. Overall emissions are thus allowed to vary as a result of inter-system permit trading.

On the face of it, quantitative restrictions seem to be the natural route to full linkage between two quantity instruments. As two jurisdictional prices coexist, however, inter-system transaction prices may not reflect marginal abatement costs, which can generate uncertainty about price formation and undesirable price fluctuations. Relatedly, the distribution of the scarcity rent (associated with the binding restriction) across jurisdictions and firms is not clear ex ante. Quantitative restrictions can thus lead to uncertain distributional effects and weakened price signals, which may impair the transition to a full link.

Some of these aspects can be mitigated under a border tax on permits. Indeed, distributional outcomes can be better managed as a tax raises revenues where a quantity restriction creates a scarcity rent instead. These revenues can be seen as a form of interjurisdictional transfers and might thus help spur cooperation. Additionally, because the price ratio is conveyed by the tax rate, there should be less undesirable price fluctuations and better information on jurisdictional marginal abatement costs. Border taxes, however, may be more complicated to pursue legislatively speaking, for instance at the EU level.

By altering the fungibility of jurisdictional abatements, exchange rates can be employed to adjust for differences in programs' stringencies – and potentially other economic and non-economic criteria. In addition, we show how exchange rates, when skillfully selected, have potential to increase ambition over time. On the flip side, however, difficulties precisely pertain to the selection and subsequent adjustment of the exchange rate, which might possibly lead to environmental and economic outcomes worse than autarky.

This analysis thus allows us to identify comparative advantages and weaknesses for each link restriction. Although there is no 'ideal' transitional restricted linkage, we finally show how experience suggests that unilateral linkage – whereby permits can flow in one direction but not vice versa – can be a practical and promising way of gradually approaching a full, two-way link. For instance, both the Norway-EU and (aborted) Australia-EU one-way links served as a transitory step in aligning programs for a later full-link scale-up.

The remainder of this Chapter proceeds as follows. Section 1.2 reviews the related literature and the use of restrictions in practice. Section 1.3 presents our modeling framework and two reference scenarios, viz. autarky and full linkage. Section 1.4 analytically describes the implications of each link restriction. Section 1.5 illustrates these results with numerical simulations. Section 1.6 discusses the relative merits of each restriction with a special focus on the transition to full linkage. Section 1.7 concludes. An Appendix contains the analytical derivations and proofs (1.A), details about the numerical simulations (1.B) and domestic cap selection (1.C), and a general modeling framework for linkage (1.D).

1.2 Related literature and practical use of restrictions

Related literature. This Chapter complements and provides an analytical underpinning to Lazarus et al. (2015) who discuss the use of three similar link restrictions, viz. quantitative restrictions, exchange and discount rates. Closer to our model is Rehdanz & Tol (2005) who consider a bilateral link in which the importing jurisdiction can unilaterally impose link restrictions as an expedient to deter the exporting jurisdiction from issuing additional permits relative to autarky, if not influence it to adopt a more ambitious target.[8] Rehdanz & Tol show that the importing jurisdiction is better off under a border tax or a quantitative limit on imports than under a discount rate. They also find that importing jurisdictions should aim at keeping abatement imports constant – rather than overall abatement – and that quantitative restrictions best meet this purpose.[9] However, our approach differs in spirit as our focus is on linked market functioning when restrictions are in place with the perspective of a fully-fledged link in the future.

During the Kyoto era the literature was mostly slanted toward import restrictions on both permits from the ex-USSR bloc (with a eye on limiting so-called 'hot air' sales and related ambition dilution) and offset credits (for 'supplementarity' reasons).[10] An exception is Forner & Jotzo (2002) who instead discuss the benefits of limiting offset supply. With CGE models, Bernstein et al. (1999), Bollen et al. (1999) and Criqui et al. (1999) have compared the economic consequences of different emissions trading scenarios to understand the opportunity cost of trade restrictions. In general, they show that trade has significant potential to reduce compliance costs and that the less restricted trading is, the greater is that potential. They note, however, that even though restrictions unconditionally reduce global welfare as compared to unrestricted trading, within that total, some jurisdictions may actually be better off from restricted trading. In particular, exporting jurisdictions are always worse off when trade is restricted as compared to free trade while importing jurisdictions may be better off for some levels of restriction. This is because the latter are able to capture the scarcity rent associated with the restriction.

Ellerman & Sue Wing (2000) were the first to formally account for the existence of these rents and underlined the monopsonistic effects of restrictions on permit imports. More recently, Gavard et al. (2016) envisage quantitative restrictions, along with the rents they

[8] In essence, Rehdanz & Tol (2005) revisit the classical International Environmental Agreement (IEA) model à la Helm (2003) in which cap selection is conditional upon the future permit trade regime. However, note that the strategic interaction dimension is somewhat 'moot' in their model. In particular, they cannot solve for the cap-selection stage analytically and have to proceed numerically.

[9] Similarly, when jurisdictions exhibit reluctance to trade Eyckmans & Kverndokk (2010) show that import quotas may lead to lower global emissions although cost-efficiency is impaired.

[10] Westskog (2002) discusses the relevance of various arguments for trading restrictions in this context.

create and their distribution, as a possible mechanism to help foster cooperation via inter-ETS linkage. With a CGE model, Gavard et al. assess the benefits of a quantity-restricted link between China and the US (or Europe) and find that directing the rents to China could steer the country toward the establishment a restricted link. Indeed, rents have potential to overcome the negative effects China otherwise faces under full linkage, that is a consumption loss that exceeds the gains from selling permits.[11] Finally Burtraw et al. (2013) quantify the impacts of a restricted link between the California ETS and RGGI with a 3-for-1 exchange rate in comparison with full linkage (1-for-1 trading).

Finally, while our model is static, we note that each link restriction should distort the jurisdictions' intertemporal decisions differently. For instance, Pizer & Yates (2015) compare how different rules for the treatment of banked permits in the context of a (possible) future delinking alter present price formation and cost-effectiveness. Additionally, Açıkgöz & Benchekroun (2017) analyze the anticipatory non-cooperative responses of signatories to various exogenously-given types of IEAs to be implemented in the future.

Use of restrictions in practice. Quantitative (and qualitative) limits have been extensively used to regulate the use of offset credits to favor domestic abatement and contain impacts on domestic permit prices, all the while allowing for reduction of firms' compliance costs and expansion of the price signal beyond the regulated perimeter. Note that although permits and offsets are supposed to be statutory substitutes, Certified Emission Reductions (CERs) have always been priced at a discount relative to European allowances (EUAs) and this spread has widened over time. This is due to an increase in the net supply of Kyoto credits, the fact that the usage limit becomes binding (Gronwald & Hintermann, 2016) and both offset-specific and transaction costs, especially for small firms (Trotignon, 2012; Braun et al., 2015; Naegele, 2015). In general, quantitative limits on offset usage do not exceed 15% of entities' compliance obligations.[12]

To the best of our knowledge, the closest example of border taxes on interjurisdictional abatement transfers is on exports of Chinese CERs. China has been the sole host country to systematically impose specific levies on China-based CDM projects in addition to income corporate taxes. The objective was to split the CDM rent between the government and projects owners (Liu, 2010). The Chinese CER tax system discriminates between project types with remarkably high rates for HFC-23/PFC and N_2O projects (65 and 30%,

[11] Our model ignores such general equilibrium effects of linking which can be of importance in assessing the relative performance of restrictions. See Carbone et al. (2009) and Marschinski et al. (2012) for general equilibrium models of linkage. Note also that we ignore interactions with other policies when we characterize jurisdictional optimal restrictions (Lipsey & Lancaster, 1956; Bovenberg & Goulder, 1996).

[12] Since usage quotas generally span several compliance periods, the use of offsets has to be timed.

respectively) and low rates for other project types (2%). Zhu (2014) finds that the Chinese discriminative rent-seeking border tax mechanism does not distort the market nor modify investors' preferences over project types (deterrent or channelling effects). However, Zhu (2014) does not investigate the tax-induced effects on importing countries.

So far, exchange rates have not been used in the case of uniformly mixed pollutants like carbon dioxide. However, discount rates have been employed to regulate the use of offset credits toward compliance in GHG ETSs, e.g. to favor domestic abatement or alleviate additionality downsides.[13] The use of trading ratios is usually advocated for non-uniformly mixed pollutants to account for the heterogeneity in both pollutants and reception points.[14] Trading ratios were considered in some cap-and-trade programs but not implemented in the end, e.g. in RECLAIM as discussed in Section 1.6.4 (Tietenberg, 1995; Fromm & Hansjürgens, 1996).[15] Using the US SO_2 Trading Program as a case in point, Muller & Mendelsohn (2009) show that trading at the ratio of marginal damages can improve efficiency as compared to one-for-one trading and generage cost savings.[16] Additionally, in the context of the NO_X Budget Trading Program, Fowlie & Muller (2017) show that the spatially uniform scheme (as implemented) is likely to have welfare-dominated damage-differentiated emissions trading because realized abatement costs have exceeded expectations.[17]

1.3 The modeling framework

There are two jurisdictions 1 and 2 with a domestic ETS in place.[18] Permit markets are competitive and we consider that jurisdictions have one representative polluting firm within

[13] By way of example the EU legislation authorizes the use of discount rates on Kyoto offset credits and France applies a 10% discount on Emission Reduction Units (ERUs) thereby only recognizing 90% of the abatement labelled as ERUs. In the US, the Waxman-Markey Bill (2009) included, as proposed, a 20% discount on international offsets that would have obliged covered entities to buy and turn in five offsets for every four tons emitted. Similar discounts exist for forestry offsets in voluntary markets.

[14] In this case, (volume) efficiency requires that trading ratios be set equal to the ratio of delivery coefficients so that marginal costs of emissions reduction vary across emission sources in accordance with the marginal damages caused by these emissions (Montgomery, 1972; Mendelsohn, 1986) although it follows that cost efficiency can generally not be achieved (Førsund & Nævdal, 1998).

[15] The REgional CLean Air Incentives Market was launched in 1994 to regulate ozone (a non-uniformly mixed pollutant) levels in the Los Angeles basin. Environmental objectives were reached (without hot spots) and compliance costs were reduced w.r.t. command-and-control approaches (Fowlie et al., 2012).

[16] We note that the ratio of delivery coefficients coincides with the ratio of marginal damages when ambient concentrations are held constant at other reception points. Holland & Yates (2015) show (*i*) that marginal damage ratios are optimal under full information on the part of the regulator and (*ii*) how optimal trading ratios differ from ratios of marginal damages when the regulator is uncertain about the shocks affecting marginal abatement costs of regulated sources of emissions.

[17] In line with Weitzman (1974), Fowlie & Muller (2017) show that a damage-differentiated tax would have welfare-dominated a non-differentiated tax regime because marginal damages are relatively flatter than marginal costs and uncertainty on costs does not influence the design the damage-differentiated tax.

[18] A more general modeling framework is relegated to Appendix 1.D.

their geographical boundaries (Montgomery, 1972; Krupnick et al., 1983). Jurisdictions have the same size that we proxy by their unregulated emission level $\bar{e}$ and we let $e_i \in [0;\bar{e}]$ denote jurisdiction i's level of emission for $i \in \{1,2\}$. For clarity and without loss of generality for the purpose of our model, jurisdictions face the same binding cap on emissions $\omega < \bar{e}$ or domestic abatement objective $a = \bar{e} - \omega > 0$.[19] For comparability, we assume caps are enforced under autarky, full linkage and all other forms of restricted linkages.

Abatement costs, denoted C_i in jurisdiction i, are increasing and convex functions of the abatement level $a_i = \bar{e} - e_i$ with $C_i(0) = 0$. For analytical tractability and as is standard practice, these functions are equipped with a quadratic specification (Newell & Stavins, 2003). Without loss of generality and up to a translation of the results the linear term is omitted for convenience and we let c_i denote jurisdiction i's linear marginal abatement cost slope. That is, the higher c_i the less sensitive (i.e., elastic) i's emissions ($\mathrm{d}e_i$) to a shift in the permit price ($\mathrm{d}\tau$) since $\mathrm{d}\tau = c_i \mathrm{d}e_i$. In other words, jurisdictions are identical but for abatement technology and $1/c_i$ measures jurisdiction i's flexibility in abatement.

Autarky. Compliance cost minimization under autarky in jurisdiction i requires

$$\min_{e_i \in (0;\bar{e})} \left\langle C_i(\bar{e} - e_i) \right\rangle \text{ subject to } e_i \leq \omega. \tag{1.1}$$

Because caps are binding and abatement is costly, jurisdictions emit up to their caps and $\tau_i = c_i a$ denotes i's autarkic equilibrium permit price. When autarkic prices differ across jurisdictions, cost-efficiency can be improved upon by relocating some share of the abatement effort from the high-price to the low-price jurisdiction. Unless specified otherwise, we let jurisdiction 1 (resp. 2) be the high-price (resp. low-price) jurisdiction, i.e. $\tau_1 > \tau_2$ and the natural direction of the net interjurisdictional permit flow is from 2 to 1. In out setup, jurisdiction 1 has less flexibility in abatement than jurisdiction 2, i.e. $1/c_1 < 1/c_2$.

Full linkage. Because jurisdictional permits are mutually recognized and can flow both ways, abatement occurs where it is the least expensive. Jurisdictions jointly minimize the aggregate abatement cost to attain the overall emissions cap 2ω, that is

$$\min_{(e_1,e_2) \in (0;\bar{e})^2} \left\langle C_1(\bar{e} - e_1) + C_2(\bar{e} - e_2) \right\rangle \text{ subject to } e_1 + e_2 \leq 2\omega. \tag{1.2}$$

We let $\Delta^* > 0$ denote the equilibrium variation in emissions in jurisdiction 1 as a result of

[19] We discuss jurisdictional cap selection in more details in Appendices 1.C and 2.B.3. See also Appendix 2.B.4 for a discussion on the strategic anticipatory effect of linkage on cap selection.

the full link relative to autarky. As the linked market clears, the full-linkage equilibrium is entirely characterized by the necessary first-order condition

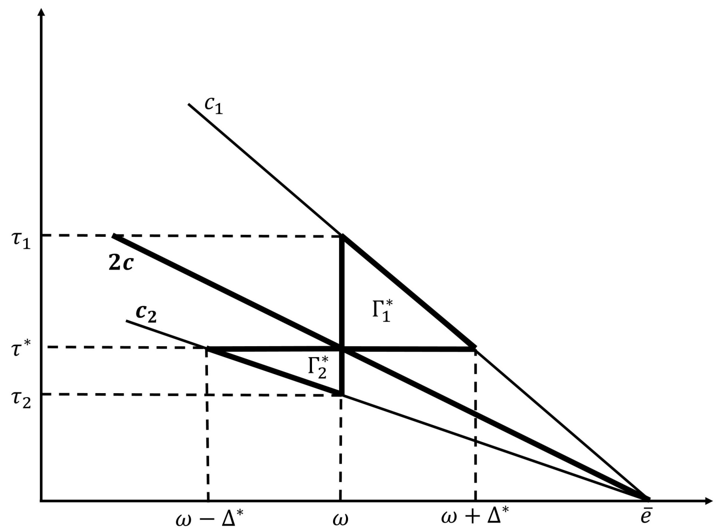
$$C_1'(a - \Delta^*) = \tau^* = C_2'(a + \Delta^*), \tag{1.3}$$

where τ^* is the full-link equilibrium price. With quadratic abatement costs it comes

$$\Delta^* = \frac{\tau_1 - \tau_2}{c_1 + c_2} = \frac{\tau_1 - \tau^*}{c_1} = \frac{\tau^* - \tau_2}{c_2} \text{ and } \tau^* = 2ca, \tag{1.4}$$

where $1/c = 1/c_1 + 1/c_2$ denotes the flexibility in abatement of the fully linked system. Overall abatement is the same as under autarky but is now apportioned across jurisdictions

Figure 1.1: Autarkic and full-linkage equilibria



Note: Area Γ_i^* measures the economic gain accruing to jurisdiction i under unrestricted permit trading.

in proportion to their flexibility in abatement, i.e. jurisdiction i abates τ^*/c_i in equilibrium. That is, cost efficiency obtains and the autarkic price differential is arbitraged away. The situation is graphically depicted in Figure 1.1 where the thick-edged triangles demarcate the jurisdictional gains from the full link, $\Gamma_i^* = c_i\Delta^{*2}/2 = (\tau_i - \tau^*)^2/(2c_i)$. Note that the jurisdictional gains from the link are proportional to the square of the difference in the autarkic and linking prices.[20] Note also that the aggregate gains are distributed across jurisdictions in inverse proportion to their abatement flexibility, i.e. $\Gamma_1^*/\Gamma_2^* = c_1/c_2$.[21]

[20]This result continues to hold under more general modeling assumptions and actually follows from the linearity of marginal abatement cost functions, c.f. Proposition 2.6.3 under uncertainty. See also Proposition 1.D.1 for a comparative static analysis of jurisdictional gains from full bilateral linkage.

[21]Even when jurisdictions have equal autarkic prices and there are no ‘immediate’ gains from trade due to the equalization of marginal abatement costs, linkage still brings about benefits in terms of increased

1.4 Implications of link restrictions

1.4.1 Linkage with quantitative restrictions on permit transfers

Consider that jurisdiction 1 limits net imports of 2-permits as valid domestic compliance instruments, or alternatively, that jurisdiction 2 imposes a limit on the net quantity of domestic permits it is willing to export. Either way, we assume the restriction is binding and let $\alpha \in [0; 1]$ denote the allowed share of the cost-efficient transfer.[22] Abatement transfer is thus restricted to

$$\bar{\Delta}(\alpha) = \alpha \Delta^*. \tag{1.5}$$

As depicted in Figure 1.2, the level of abatement undertaken by jurisdiction 1 (resp. 2) is $a - \bar{\Delta}(\alpha)$ (resp. $a + \bar{\Delta}(\alpha)$). On the face of it, a quantitative restriction should thus limit the reach of the link and associated impacts, i.e. its implications should be comprised between autarky and full linkage. As it turns out, there are more subtle implications.

Cost-efficiency does not obtain because the convergence in jurisdictional shadow prices is incomplete. The restriction $\alpha \in (0; 1)$ drives a wedge between these two prices denoted $\bar{\tau}_1(\alpha) = c_1(a - \bar{\Delta}(\alpha))$ and $\bar{\tau}_2(\alpha) = c_2(a + \bar{\Delta}(\alpha))$ such that $\tau_1 > \bar{\tau}_1(\alpha) > \tau^* > \bar{\tau}_2(\alpha) > \tau_2$. This generates a deadweight loss $L(\alpha) \propto (1 - \alpha)^2$ that is the sum of the deadweight losses on the importer and exporter's sides of the market (triangles L_1 and L_2 in Figure 1.2), the magnitude of which depends on jurisdictional abatement flexibilities. Because overall abatement is maintained, cost-efficiency relative to full linkage can be measured by the index

$$I(\alpha) = (\Gamma_1^* + \Gamma_2^* - L(\alpha))/(\Gamma_1^* + \Gamma_2^*) = \alpha(2 - \alpha). \tag{1.6}$$

Even a stringent limit can bring about a high share of the full-link gains, e.g. $I\,(10\%) = 19\%$ and $I\,(50\%) = 75\%$. The laxer the restriction, the bigger the overall economic gain from the restricted link, but the lower the increase in gain at the margin (I is concave). This is so because when α increases, interjurisdictional price disparities narrow down and net gains per permit exchanged decrease accordingly. Note that the economic gains from constrained abatement relocation accruing jurisdictions reduce to $\bar{\Gamma}_i(\alpha) = \alpha^2 \Gamma_i^*$.

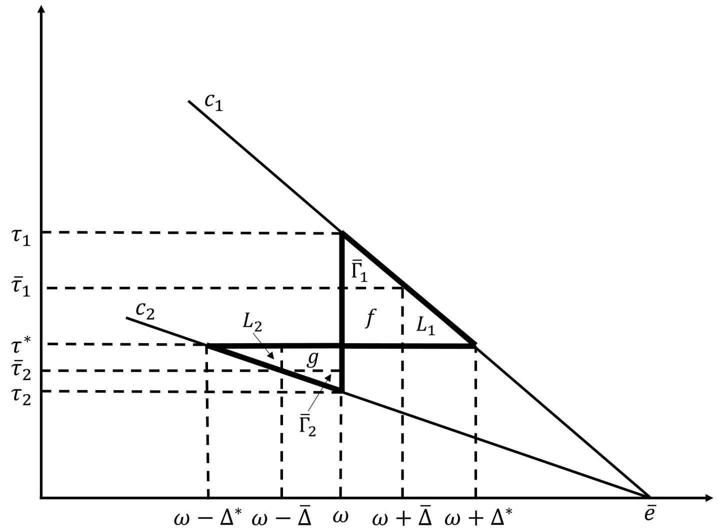
Crucially, there are two related implications of the price wedge. First, jurisdiction 1 is willing to buy up 2-permits for a price at most as high as $\bar{\tau}_1$ while jurisdiction 2 is willing

market liquidity (Fankhauser & Hepburn, 2010b). Indeed, jurisdictional permits are fully fungible and the linked market is 'thicker' than each system in isolation, which should reduce bid-ask spreads.

[22] In reality restrictions are likely to be expressed in the form of concrete ceilings on the share of domestic emission caps that can be outsourced or exported. This notation clarifies exposition because we describe the continuum of quantity-constrained link equilibria between autarky and full linkage when α spans $[0; 1]$.

to sell off 2-permits for a price at least as high as $\bar{\tau}_2$. This means that transaction prices are undetermined in the present model (they can settle anywhere in $[\bar{\tau}_2; \bar{\tau}_1]$) and that jurisdictional permits are not fungible.[23] Second, there exists a scarcity rent $S(\alpha) \propto \alpha(1-\alpha)$ of size $f+g$ in Figure 1.2 whose apportionment ultimately depends on these transaction prices. Note that the scarcity rent is relatively sizeable when the restriction is close to 50% and exceeds the aggregate economic gains from trade $\bar{\Gamma}_1 + \bar{\Gamma}_2$ when $\alpha \leq 2/3$.

Figure 1.2: Quantity and tax restricted linkage equilibria



Note: Area $\bar{\Gamma}_i$ measures the economic gains from restricted permit trading accruing to i. Area L_i is the deadweight loss associated with the restriction on i's side of the market. Area $f+g$ alternatively measures the scarcity rent under quantity restriction or the tax revenues collected by jurisdiction 1.

To pin down both the rent extraction and transaction prices we must specify something about bargaining. The market structure we consider is a bilateral monopoly and we assume a Nash bargaining game for the rent extraction (Nash, 1950) with zero-value outside options where $\theta \in [0; 1]$ (resp. $1-\theta$) denotes the bargaining power of jurisdiction 1 (resp. 2).[24] In this case jurisdictions capture a share of the rent that is proportional to their respective bargaining power

$$S_1(\alpha; \theta) = \theta S(\alpha), \text{ and } S_2(\alpha; \theta) = (1-\theta) S(\alpha), \tag{1.7}$$

which also determines the permit transaction price

$$\bar{\tau}(\alpha; \theta) = \theta \bar{\tau}_2(\alpha) + (1-\theta) \bar{\tau}_1(\alpha). \tag{1.8}$$

[23] We note that this could limit the gains in liquidity as compared to unrestricted linkage.

[24] Following the seminal contribution of Hahn (1984) the literature on permit markets generally focuses on the potential exercise of market power in view of permit price manipulation in relation with the initial allocation of permits. An exception is Ellerman & Sue Wing (2000).

By contrast, the literature generally considers that the apportionment of the rent ultimately depends on the way the restriction is set. Typically, it is assumed that a restriction on imports, i.e. on demand for 2-permits in jurisdiction 1, grants monopsony power ($\theta = 1$) to jurisdiction 1 which captures the entire rent. Symmetrically, a restriction on exports, i.e. on supply of 2-permits for jurisdiction 1, grants monopoly power ($\theta = 0$) to jurisdiction 2 which pockets the entire rent. For instance, Ellerman & Sue Wing (2000) consider the case of a competitive supply with restricted demand and Forner & Jotzo (2002) that of a competitive demand with restricted supply. There is, however, no reason to postulate the existence of a link between the definition of the restriction and the market structure itself.[25]

It is noteworthy that one jurisdiction may be better off from the restricted link relative to full linkage. To see this, fix $\theta = 1$, i.e. jurisdiction 1 has monopsony power and makes the price. We reason around the full-link equilibrium to analyze the effects of a restriction on jurisdictions' total compliance costs, denoted TC_i in jurisdiction i. Consider a restriction that is binding by a slightly enough margin. This leads to an infinitesimally small increase in abatement in jurisdiction 1 ($\mathrm{d}\varepsilon > 0$) and decrease in the permit price ($\mathrm{d}\tau < 0$). Any such active restriction changes the total costs of compliance in both jurisdictions. In particular for jurisdiction 1,

$$\mathrm{d}TC_1 = \Big(C_1'(a - \Delta^* + \mathrm{d}\varepsilon) - \tau^*\Big)\mathrm{d}\varepsilon + \Delta^*\mathrm{d}\tau. \tag{1.9}$$

The first term on the right-hand side of Equation (1.9) is positive and corresponds to the incremental increase in domestic abatement costs due to more expensive domestic abatement being substituted for imported permits. The second term is negative and measures the incremental cost savings on remaining imports. The sign of $\mathrm{d}TC_1$ is thus ambiguous and depends on the relative magnitude of these two antagonistic effects. When the restriction is lax (i.e., α close to 1), the import price effect dominates the domestic abatement effect and jurisdiction 1 is better off under the restriction than unrestricted linkage. The converse holds when the restriction is stringent (i.e., α close to 0). By a continuity argument there exists an optimal restriction from the perspective of the monopsonistic jurisdiction. Note that the price effect is absent in the case of price-taking jurisdiction 2 and the sign of $\mathrm{d}TC_2$ is unambiguous

$$\mathrm{d}TC_2 = -\Delta^*\mathrm{d}\tau > 0. \tag{1.10}$$

This corresponds to a direct income transfer to jurisdiction 1. By the same token, we can define jurisdictions' optimal restrictions in the general case.

[25] For instance, when demand is restricted, the standard argument is that the linked market is a pure buyers' market (buyers' cartel) in which acquiescent sellers are compelled to compete to sell off their permits (and vice versa for a restricted supply). But one could as well conceive of the situation where sellers collude and/or buyers compete so that the model is underspecified without further assumptions on bargaining.

Proposition 1.4.1. *Given $\theta \in [0;1]$ jurisdictional optimal quantitative restrictions read*

$$\alpha_1^*(\theta) = \begin{cases} \dfrac{(c_1+c_2)\theta}{2(c_1+c_2)\theta - c_1} & \text{if } \theta \geq \bar{\theta} \doteq \dfrac{c_1}{c_1+c_2}, \\ 1 & \text{otherwise,} \end{cases} \tag{1.11a}$$

$$\text{and, } \alpha_2^*(\theta) = \begin{cases} \dfrac{(c_1+c_2)(1-\theta)}{2(c_1+c_2)(1-\theta) - c_2} & \text{if } \theta \leq \bar{\theta}, \\ 1 & \text{otherwise.} \end{cases} \tag{1.11b}$$

In the relevant ranges, α_1^* (resp. α_2^*) is a decreasing (resp. increasing), convex function of θ with $\alpha_1^*(1) > \alpha_2^*(0)$, $\inf\{\alpha_1^*\} = \lim_{c_1 \to c_2^+} \alpha_1^*(1) = 2/3$ and $\inf\{\alpha_2^*\} = \lim_{c_2 \to 0^+} \alpha_2^*(0) = 1/2$.

Proof. Relegated to Appendix 1.A.1. □

First, because α_1^* and α_2^* intersect once at $\theta = \bar{\theta}$, the two jurisdictions can never prefer a quantity-restricted linkage simultaneously (relative to full linkage). Second, the range of relative bargaining powers over which the high-cost jurisdiction prefers a quantity-restricted link over full linkage is smaller than for the low-cost jurisdiction. This is so because the former gains relatively more from the full link than the latter. Third, optimal restrictions always authorize at least 50% of the full-link volume of transfers and that under monopoly power is more stringent than under monopsony power ($\alpha_2^*(0) < \alpha_1^*(1)$).

1.4.2 Linkage with border taxes on permit transfers

A border tax on interjurisdictional permit transfers corresponds to the dual link restriction of a quantitative limit (see Appendix 1.A.2). That is, to each tax rate there corresponds a unique authorized share of permit transfers and vice versa. While both instruments are formally equivalent in our deterministic framework (i.e., in terms of equilibrium characterization) they will nonetheless differ in their distributional aspects as well as political and linkage implications. In particular, the effects of a tax on permit imports (resp. exports) levied by jurisdiction 1 (resp. 2) can be assimilated to those of an equivalent quantitative restriction with $\theta = 1$ (resp. $\theta = 0$). Without loss of generality, consider that jurisdiction 1 imposes a proportional tax μ on 2-permit imports.[26] This tariff only concerns interjurisdictional transfers and there is no levy on domestic transactions.[27] The restricted equilibrium

[26] The alternative situation where jurisdiction 2 imposes a tax μ on permit exports would also satisfy the tax restricted-linkage equilibrium in Equation (1.12) but with symmetric distributional aspects.

[27] Heindl et al. (2014) consider a bilateral link where one jurisdiction levies an domestic tax on intrajurisdictional emissions on top of the linked market price. Some abatement undertaken in this jurisdiction is thus attributable to this tax system, which undermines the price signal in the linked permit system.

is defined by the triplet $(\bar{\tau}_1, \bar{\tau}_2, \bar{\Delta})$ and, depending on the dispersion in autarkic prices, satisfies

$$(\bar{\tau}_1, \bar{\tau}_2, \bar{\Delta}) = \begin{cases} \left(\tau_1 - c_1\bar{\Delta}, (1-\mu)\bar{\tau}_1, \dfrac{(1-\mu)\tau_1 - \tau_2}{(1-\mu)c_1 + c_2}\right) & \text{if } \mu \in [0; 1 - \tau_2/\tau_1], \\ (\tau_1, \tau_2, 0) & \text{otherwise.} \end{cases} \tag{1.12}$$

Again, the situation is depicted in Figure 1.2. Equilibrium (1.12) is constrained to autarky if the tax rate is set at too high a level for given autarkic prices. For instance, when $\tau_1 = 2\tau_2$ then the tax rate on permit imports should not exceed 50% for some transfers to occur. The border tax thus locates the restricted link outcome between autarky ($\mu \geq 1 - \tau_2/\tau_1$) and full linkage ($\mu = 0$). Cost-efficiency does not obtain as the border tax is distortionary and the spread in jurisdictional prices is linearly proportional to the tax rate. Overall abatement is constant but some mutually beneficial transfers absent the tax do not take place ($\bar{\Delta} \leq \Delta^*$, where $\bar{\Delta}$ is decreasing with the tax rate). Relative to full linkage the increase in the permit price in 1 is less than the tax because part of it is passed on to 2 where the permit price declines. The magnitude of these price variations depends on relative jurisdictional abatement flexibilities.

However, there are two key crucial differences from quantitative restrictions. First, a border tax allows for trading of permits whose jurisdictional prices differ as jurisdiction 1 pays a markup on each 2-permit it imports. That is, jurisdictional permits are fungible. Second, a border tax raises revenues where a quantitative restriction generates a scarcity rent instead. Distributional aspects of the restriction are thus clearer. Relative to full linkage the imposition of a border tax by jurisdiction 1 is unambiguously detrimental to jurisdiction 2. This is attributable to impeded interjurisdictional trade (L_2) and diminished terms of trade (g). Although its economic gains from trade are reduced, jurisdiction 1 also raises tax revenues equal to $f + g$. That is, jurisdiction 1 is better off with the tax than under full linkage provided that $g > L_1$. This holds true for small tax rates and highlights the standard trade-off between the level of the tax rate (μ) and the width of the tax base ($\bar{\Delta}$).

Corollary 1.4.2. *The optimal tax rate on imports is* $\mu^* = (c_1 - c_2)/(3c_1)$ *and jurisdiction 1 is better off from the border tax regime than full linkage if* $\mu \in [0; \bar{\mu}]$ *where* $\bar{\mu} > \mu^*$.

Proof. Special case of Proposition 1.4.1 with $\theta = 1$. See also Appendix 1.A.2. □

1.4.3 Linkage with exchange rates on relative permit values

We let $\rho > 0$ denote the rate at which emission reductions occurring in 1 are converted into emission reductions occurring in 2 through interjurisdictional exchange of permits. That is, one unit of abatement in 1 is worth ρ unit of abatement in 2. We define the linked market ρ-equilibrium by the following joint compliance cost minimization program

$$\min_{(e_1,e_2)\in(0;\bar{e})^2} \Big\langle C_1(\bar{e}-e_1)+C_2(\bar{e}-e_2)\Big\rangle \text{ subject to } \rho e_1+e_2 \leq (1+\rho)\omega. \tag{1.13}$$

We assume the aggregate constraint on emissions binds and let $\bar{\Delta}_i(\rho)$ denote the variation in emissions in jurisdiction i in the ρ-equilibrium relative to autarky. Market closure yields $\bar{\Delta}_2(\rho) = -\rho\bar{\Delta}_1(\rho)$ and the interior ρ-equilibrium is characterized by the necessary first-order condition

$$C_1'(\bar{e}-\omega-\bar{\Delta}_1(\rho)) = \rho C_2'(\bar{e}-\omega+\rho\bar{\Delta}_1(\rho)). \tag{1.14}$$

With quadratic abatement cost functions, abatement unit transfers from 2 to 1 satisfy

$$\bar{\Delta}_1(\rho) = \frac{\tau_1-\rho\tau_2}{c_1+\rho^2 c_2} \geq 0 \;\Leftrightarrow\; \rho \leq \tau_1/\tau_2. \tag{1.15}$$

There are two effects consecutive to the introduction of an exchange rate: fungibility of jurisdictional abatement units does not hold (emission conversion, or EC effect) and jurisdictional marginal abatement costs are adjusted for the exchange rate in equilibrium (MAC effect). First, for a given volume of interjurisdictional permit transfer, an exchange rate specifies a rate of conversion between emission reductions in 1 and 2, thereby changing overall abatement. Accounting for the sole EC effect, more or less overall abatement occurs in equilibrium relative to the benchmark. Second, the ratio of jurisdictional marginal abatement costs in equilibrium is determined by the exchange rate. Accounting for the sole MAC effect, an exchange rate induces a deadweight loss and modifies incentives for interjurisdictional abatement transfers in a fashion akin to a border tax.

Proposition 1.4.3. *Relative to full linkage, in any interior linked market ρ-equilibrium,*
(i) jurisdiction 1 raises emissions i.f.f. $\rho < 1$;
(ii) jurisdiction 2 reduces emissions i.f.f. $(\rho-1)(\rho-\bar{\rho}) < 0$ with $\bar{\rho} \doteq \frac{c_1(\tau_1-\tau_2)}{c_1\tau_2+c_2\tau_1} \in (0;\tau_1/\tau_2)$;
(iii) the additional aggregate abatement satisfies $\gamma(\rho) \doteq (\rho-1)\bar{\Delta}_1(\rho)$, which is positive i.f.f. $\rho \in (1;\tau_1/\tau_2)$ and maximal at $\rho = \hat{\rho} \doteq \sqrt{\tau_1/\tau_2}$ where $\gamma(\hat{\rho}) = \frac{a(\sqrt{c_1}-\sqrt{c_2})^2}{2\sqrt{c_1 c_2}}$.

Proof. Relegated to Appendix 1.A.3. □

When parity does not hold, jurisdictional abatements are not equivalent and the aggregate cap on emissions varies as a result of interjurisdictional permit trading. We see from Equation (1.15) that permits flow in the natural direction provided that the exchange rate is smaller than the ratio of autarkic prices. We also note from Equation (1.14) that cost-efficiency obtains only under parity ($\rho = 1$) and that the (τ_1/τ_2)-equilibrium replicates autarky. Indeed, this exchange rate makes up for the differential in autarkic jurisdictional marginal abatement costs and there is no incentive to trade. These observations delineate three trading regimes depending on the value of the exchange rate w.r.t. parity (full linkage) and τ_1/τ_2 (autarky), whose relative properties are listed in Table 1.1.[28]

Table 1.1: Relative properties of the three trading regimes

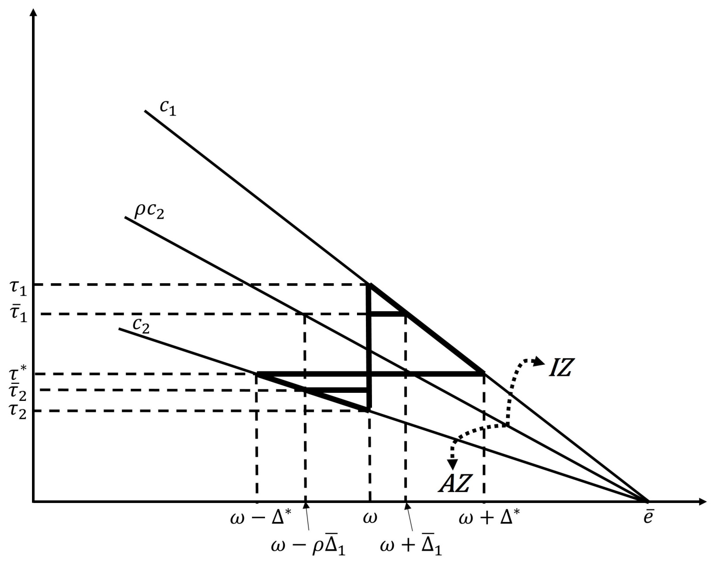
	Reduction zone	Amplification zone	Inversion zone
Relative permit value	J1>J2	J2>J1	J1≫J2
Permit flow	J1→J2	J1→J2	J2→J1
Overall abatement	higher than A/FL	lower than A/FL	lower than A/FL
Cost-efficiency	higher than A lower than FL	higher than A† lower than FL	lower than A lower than FL
Emissions w.r.t. FL	J1: lower J2: higher i.f.f. $\rho > \bar{\rho}$	J1: higher J2: higher i.f.f. $\rho < \bar{\rho}$	J1: lower J2: higher
Permit prices	$\tau^* < \bar{\tau}_1 < \tau_1$; $\bar{\tau}_2 > \tau_2$ $\bar{\tau}_2 < \tau^*$ i.f.f. $\rho > \bar{\rho}$	$\bar{\tau}_1 < \tau^*$; $\bar{\tau}_2 > \tau_2$ $\bar{\tau}_2 < \tau^*$ i.f.f. $\rho < \bar{\rho}$	$\bar{\tau}_1 > \tau_1$ $\bar{\tau}_2 < \tau_2$
Gains from trade‡	$\bar{\Gamma}_1 > \bar{\Gamma}_2$ i.f.f. $\rho < \hat{\rho}$	$\bar{\Gamma}_1 > \bar{\Gamma}_2$	$\bar{\Gamma}_2 > \bar{\Gamma}_1$

Note: Ji: jurisdiction i; FL: full linkage; A: autarky; †: except for very small rates; ‡: not a welfare measure (only account for economic gains from permit trade and ignore shifts in overall emission levels).

Reduction zone ($1 \leq \rho \leq \tau_1/\tau_2$). The dispersion in jurisdictional marginal abatement costs adjusted for the exchange rate is *reduced* and the conversion rate is favorable to jurisdiction 1. The linked market ρ-equilibrium is depicted in Figure 1.3. Controlling for the EC effect, this is conducive to less abatement transfers than is mutually beneficial under full linkage. Controlling for the MAC effect, the 1-permit value is inflated, i.e. the exchange rate reduces the demand for 2-permits in jurisdiction 1 while increasing the demand for 1-permits in both jurisdictions (but jurisdiction 2 remains the net permit exporter). Consequently, holding 2-permit imports constant, less emissions are allowed into jurisdiction 1 than under full linkage. In other words, holding abatement transfers constant, jurisdiction 2 undertakes more abatement (ρ-as-many). These two effects combined yield higher overall abatement relative to the benchmark. Relative to full linkage, jurisdiction 1 emits less while jurisdiction 2 may emit more ($\rho > \bar{\rho}$) or less ($\rho < \bar{\rho}$) but overall, total abatement increases.

[28] Lazarus et al. (2015) identify the three same trading zones but name them differently.

Figure 1.3: Restricted linkage equilibrium in the reduction zone (with $\rho > \bar{\rho} > 1$)



Note: The two curved dotted arrows rotate the line of slope ρc_2 to the amplification zone (AZ) and the inversion zone (IZ) and point outside of the reduction zone represented by the hull $\langle \bar{e}c_2, \bar{e}c_1 \rangle$.

Amplification zone ($\rho \leq 1$). The dispersion in jurisdictional marginal abatement costs adjusted for the exchange rate is *amplified* and the conversion rate is favorable to jurisdiction 2. Controlling for the EC effect, this leads to more exchanges of abatement than under full linkage. Controlling for the MAC effect, the 1-permit value is deflated. Permits keep on flowing in the natural direction but since one 2-permit is worth ρ-as-many 1-permit more emissions occur overall. These two effects combined yield less aggregate abatement than in the benchmark. Relative to full linkage, jurisdiction 1 emits more while jurisdiction 2 may emit more ($\rho < \bar{\rho}$) or less ($\bar{\rho} < \rho$) but overall, total abatement decreases.

Inversion zone ($\rho > \tau_1/\tau_2$). The dispersion in jurisdictional marginal abatement costs adjusted for the exchange rate is *inverted* and the conversion rate is favorable to jurisdiction 1 (even more so than in the reduction zone). The exchange rate sufficiently reduces the demand for 2-permits in jurisdiction 1 and increases the demand for 1-permits in both jurisdictions for jurisdiction 1 to become the net permit exporter. This regime is less cost-efficient than autarky since abatement occurs where it is most expensive.[29] Relative to autarky, jurisdiction 1 (resp. 2) abates (resp. emits) more. Since the exchange rate inflates the 1-permit value, this results in aggregate emissions higher than in the benchmark.

[29]The 3-for-1 exchange rate between California and RGGI as modeled in Burtraw et al. (2013) reverses the natural direction of abatement flows and thus belongs to the inversion zone.

Note that aggregate gains from trade no longer reflect gains in cost-efficiency since overall abatement varies with the exchange rate. Loosely speaking, the more distant ρ from parity, the bigger the dispersion in jurisdictional marginal abatement costs at the ρ-equilibrium and the lower the degree of cost-efficiency.[30] An exchange rate affects both the size of the aggregate gains from trade and its repartition across jurisdictions in the following manner

$$\bar{\Gamma}_1(\rho) + \bar{\Gamma}_2(\rho) = \frac{(\tau_1 - \rho\tau_2)^2}{2\,(c_1 + \rho^2 c_2)} \text{ with } \bar{\Gamma}_1(\rho)/\bar{\Gamma}_2(\rho) = c_1/(c_2\rho^2). \tag{1.16}$$

Aggregate gains from trade decrease with ρ as long as $\rho \leq \tau_1/\tau_2$, are nil at $\rho = \tau_1/\tau_2$ and increase with ρ thereafter. In addition, jurisdiction 1 (resp. 2) gets a higher share of these gains when $\rho \leq$ (resp. $\geq$)$\hat{\rho}$, i.e. jurisdiction 1 (resp. 2) wants the exchange rate to be as low (resp. high) as possible. This line of reasoning, however, does not account for the attendant variation in aggregate emissions. In Appendix 1.C we show that factoring in this shift in emissions mitigates jurisdictions preferences for too high or too low rates. Here, we illustrate the flexibility in overall emissions with the following special case.

Corollary 1.4.4. *The two jurisdictions are better off under full linkage with adjusted caps* $(\omega_1, \omega_2) = (\omega, \omega - \gamma(\hat{\rho}))$ *than under* $\hat{\rho}$*-equilibrium with initial caps* $(\omega_1, \omega_2) = (\omega, \omega)$.

Proof. Relegated to Appendix 1.A.3. □

A possible interpretation is that exchange rates have potential to increase environmental ambition over time. Consider that jurisdictions initiate linkage with an exchange rate that triggers additional abatement relative to autarky. All else equal, both jurisdictions then have an incentive to transition to full linkage with domestic caps adjusted so as to generate overall abatement commensurate with that under the exchange rate.

1.5 Numerical illustrations

Parameters are set such that $c_1 = 3c_2$, i.e. $\tau_1 = 3\tau_2$, which also ensures that $\bar{\rho} = 1$. The numerical results are presented in relative values with full linkage or autarky as benchmark and hold irrespective of the stringency of the common abatement objective.

Border taxes on permit transfers

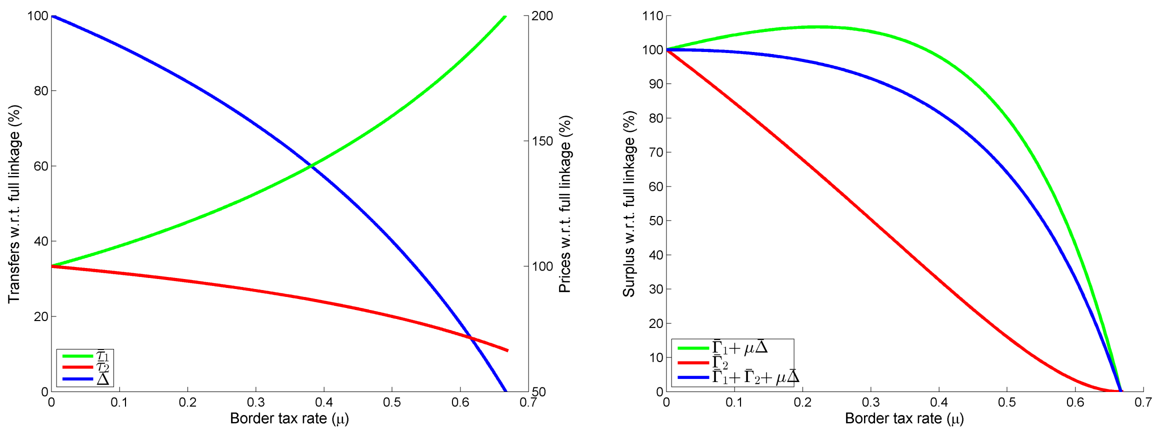
Relative to full linkage, the implications of a border tax on permit imports in the admissible tax range $[0; 2/3]$ are displayed in Figure 1.4. This also depicts the effects of a quantitative

[30] Gains in liquidity should be similar to those under full linkage because permits are fungible.

restriction on transfers when jurisdiction 1 has monopsony power ($\theta = 1$). As the tax

Figure 1.4: Effects of a border tax set by jurisdiction 1 on 2-permit imports

(a) Permit prices and transfers (b) Gains from trade + tax revenues



rate rises, Figure 1.4a shows that trade decreases while the price wedge increases, i.e. cost-efficiency decreases. In particular, $\mu = 0$ corresponds to full linkage and for $\mu \geq 2/3$ the tax regime replicates autarky. Figure 1.4b shows that jurisdiction 1's surplus (gains from trade + tax revenues) is increasing with μ as long as $\mu < \mu^* \simeq .22$ and at that $\bar{\mu} \simeq .40$ it is indifferent between a tax $\bar{\mu}$ and full linkage. Both aggregate and jurisdiction 2's surpluses decrease with the tax rate and remain positive. However, note that jurisdiction 2's surplus is quasi linearly decreasing while the aggregate surplus is concave and relatively flat for small tax rates.[31] For instance, when the tax rate is $\mu \simeq .3$ jurisdiction 2 loses about half of its full-link gains while the deadweight loss remains small (∼10%).

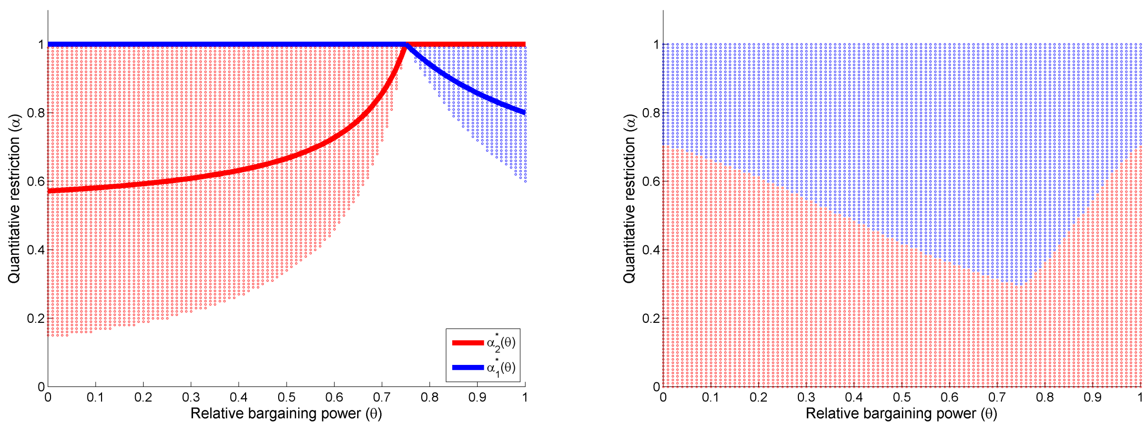
Quantitative transfer restrictions

Figure 1.5a graphically depicts the optimal quantitative restrictions for jurisdiction 1 (thick blue line) and 2 (thick red line) as a function of the relative bargaining power. The blue and red circles denote restrictions that constitute an improvement w.r.t. full linkage for jurisdictions 1 and 2, respectively. Note that the range of such quantity-restricted linkages is wider for the low-cost jurisdiction. Although both jurisdictions cannot simultaneously be better off under a quantitative restriction w.r.t. full linkage, one jurisdiction may accept to lose out a share of its full-link gains if this is necessary for the other jurisdiction to initiate linking. In this respect, the blue circles in Figure 1.5b indicate quantitative restrictions that are *potentially acceptable* in the sense that jurisdictions are willing to give up on (at most)

[31] Were the tax mutually agreed upon and revenues shared in proportion to the c_i's (1 gets f and 2 gets g in Fig. 1.2 where $f/g = c_1/c_2$) jurisdictional surpluses would evolve like the blue line in Fig. 1.4b.

Figure 1.5: Jurisdictional preferences for quantitative linkage restrictions

(a) Optimal and better-than-autarky restrictions (b) Potential agreement on restrictions



Note: Fig. 1.5a: thick blue and red lines are optimal quantitative restrictions for jurisdiction 1 and 2, respectively, and intersect at $\theta = \bar{\theta} = .75$; blue and red circles indicate volume-restricted linkages better than full linkage for jurisdiction 1 and 2, respectively. Fig. 1.5b: blue (red) bullets denote restrictions that are (not) *potentially acceptable* at a 50% level of full-linkage gains from trade by both jurisdictions.

half of their full-linkage gains in the restricted link. In this case, $\alpha \simeq .7$ (resp. $\alpha \simeq .3$) is the most stringent limit to be potentially acceptable when $\theta = \{0; 1\}$ (resp. $\theta = \bar{\theta}$).

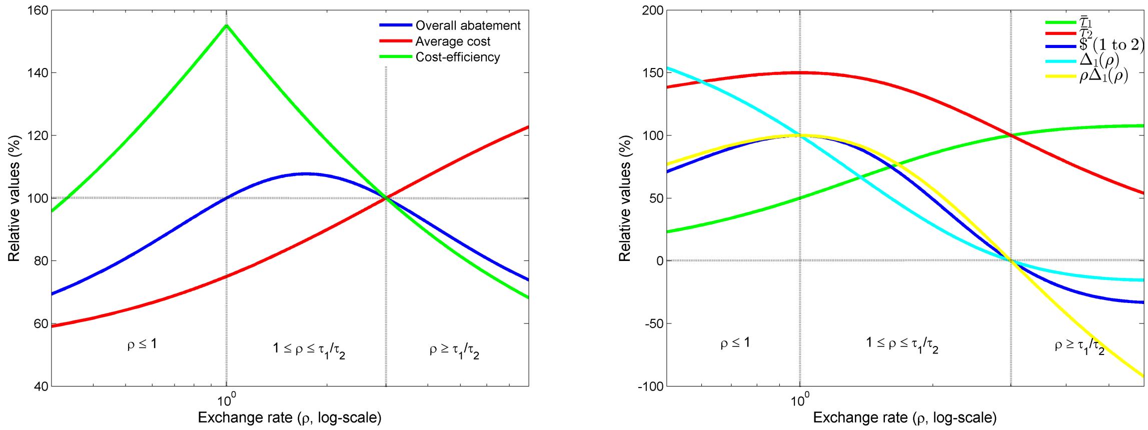
Linkage with exchange rates

Figure 1.6 describes both the economic and environmental outcomes along the continuum of ρ-equilibria. The green curve in Figure 1.6a shows that the degree of cost-efficiency is the lower the farther away the exchange rate from parity, where it is maximal.[32] The blue curve in Figure 1.6a shows that overall abatement is higher than in the benchmark provided that the exchange rate lies in $[1; \tau_1/\tau_2]$ and is maximal at $\rho = \hat{\rho}$. Another way to see this is to consider Figure 1.6b. In the reduction zone, overall abatement is higher than in the benchmark since the volume of abatement undertaken in jurisdiction 2 is higher than the corresponding increase in emissions occurring in jurisdiction 1 (the yellow line is above the cyan one and the spread between them is maximal at $\rho = \hat{\rho}$). The converse holds outside of this zone. Note also that as the exchange rate runs from autarky to parity both abatement and permit flows from 2 to 1 increase. In the amplification zone the wedge in jurisdictional prices (relative to autarky) widens out as compared to full linkage while it is reversed in the inversion zone. In the latter zone, the negative values associated with the blue, cyan and yellow lines indicate that permit trading occurs opposite to the natural direction.

[32] More details on the definition of this index are relegated to Appendix 1.B.

Figure 1.6: Relative implications of an exchange rate (with $\bar{\rho} = 1$)

(a) Overall abatement and cost-efficiency (b) Prices and abatement transfers

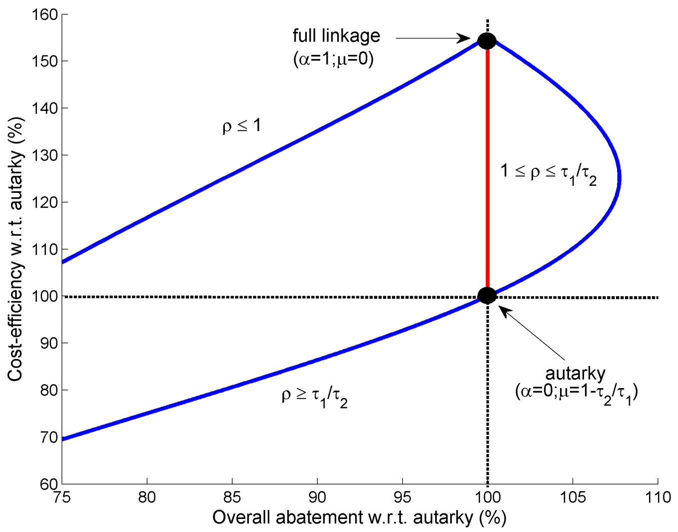


Note: All values relative to autarky except transfers in Fig. 1.6b that are measured w.r.t. full linkage. Due to the abatement cost quadratic specification, jurisdictional abatements and prices have identical variations.

Comparative effects of the three restrictions

Figure 1.7 displays the comparative effects of the three types of link restriction in the overall-abatement−cost-efficiency space relative to autarky. The red line describes the economic

Figure 1.7: Comparative effects of the three link restrictions relative to autarky



(and fixed environmental) outcomes along the continuum of quantitative restrictions and border tax rates. The blue curve plots relative cost-efficiency as a function of relative overall abatement along the continuum of exchange rates. It delineates the reduction zone in the upper-right quadrant, the amplification zone in the upper-left quadrant and the inversion zone in the lower-left quadrant. Figure 1.7 clearly shows that both quantitative restrictions and border taxes affect cost-efficiency but preserve overall abatement while exchange rates have an impact along these two dimensions.

1.6 Comparative analysis of link restrictions

This section draws on our modeling exercise and real-world experiences to underline the comparative merits and political feasibility of each type of link restriction. Two additional restrictions, namely unilateral linkage and discount rates, will also be discussed as special cases of quantitative restrictions and exchange rates, respectively.

1.6.1 Quantitative transfer restrictions

Under a quantitative restriction transfers are restricted up to the authorized limit if it binds; if not, full linkage should obtain. Therefore, because transfers are confined within a predefined range a quantitative restriction is an attractive instrument if jurisdictions seek to have a direct handle on the quantity-side consequences of a full link and retain a certain degree of oversight over their domestic systems. On the one hand, a high-price environmentally-inclined jurisdiction may want to limit imports to avoid those link-induced consequences potentially pitting the economic gains from linkage against broader environmental or equity concerns. This would ensure that a certain volume of abatement occurs domestically (e.g., ancillary benefits, reputational aspects) or assuage fears about over-allocation in exporting jurisdictions that could dilute domestic ambition. On the other hand, a low-price jurisdiction may desire to limit exports in a bid to contain the link-induced price rise.

That said, some implications of quantitative restrictions are not as straightforward as they seem to be on the face of it. This is attributable to the coexistence of different price signals and undetermined transaction prices. Since one permit may have two distinct prices whether it is sold domestically ($\bar{\tau}_i(\alpha)$) or abroad ($\bar{\tau}(\alpha;\theta)$) quantitative restrictions may create perverse incentives for firms to make profits on secondary markets that are disconnected from abatement-related fundamentals. This might lead to purely speculative trades and contribute to the financialization of the market. A related issue is the existence of a scarcity rent whose apportionment among firms is not clear ex ante.

To mitigate these uncertain distributional effects public authorities may devise mechanisms to allocate the rent between firms. Restrictions could be formulated at the firm level, e.g. as a percentage of firms' individual compliance obligations. Alternatively, authorities could issue a certain number of trade licenses and require that firms attach, say, one such license to each foreign permit they surrender domestically.[33] Because the rent distribution may serve as a negotiation lever, linkage can be facilitated if jurisdictions are able to agree on how to allocate these licenses between them (Gavard et al., 2016). While this parallel license market may offer a better management of the distributional aspects of the restricted link it does not determine how transaction license prices are fixed and, ultimately, the share of the total rent one can get. We also note that administrative and transaction costs associated with setting up and running this parallel market might shrink the gross benefits of linkage. A hybrid approach where licenses are auctioned off or sold at a fixed price may limit these costs and further redirects the rent to the regulatory authorities. In particular, fixed-price licenses may solve the issue of undetermined transaction prices.

Under conditions of uncertainty, note that a restriction that turns out to be non-binding ex post might still affect permit trading and price formation. For instance, Gronwald & Hintermann (2016) show that the probability of non-bindingness of the usage quota on Kyoto credits does affect the EUA-CER price spread in the EUETS. In this respect, a relatively stringent restriction has joint potential to bring about an important share of the full-link aggregate economic gains, effectively contain the reach of the link as well as reduce uncertainty about its bindingness and related impact on price formation. However they may maintain a relatively wide price wedge and thus a wide range over which prices can vary. By contrast, a relatively lax restriction reduces this wedge but would risk sustaining uncertainty relative to its bindingness and not protecting from the full-link effects.

As a transitory linkage mechanism, quantity restrictions seem to be the natural route to gradually allow for unlimited trading between two quantity instruments. However, the ratio of jurisdictional shadow prices is undetermined ex ante, hard to infer ex post and transaction prices may fluctuate independently of abatement-related fundamentals. Permit prices may thus no longer reflect jurisdictional marginal abatement costs, which is essential information in both assessing and transitioning to a full link.

1.6.2 Border taxes on permit transfers

Although there is a bijection between price and quantity restrictions in terms of equilibrium transfers, distributional and other link-related effects of the two restrictions differ. Because the ratio of jurisdictional prices is fixed by the tax rate, price signals better reflect marginal abatement costs, which is key information in the perspective of a full link. In addition, a

[33] It is the combination of one foreign permit and one trade license that frees up one additional permit that is valid for domestic compliance. See also the ‘Implementation’ section in Appendix 1.A.1.

border tax raises revenues. That is, authorities have a better handle on the distributional effects of their policy as compared to quantitative restrictions which generate scarcity rents whose distribution is unclear a priori.[34] Controlling for the deadweight loss, a border tax operates an interjurisdictional surplus transfer. In other words, taxes have a redistributive potential that may serve as leverage and spur linkage negotiations.[35]

Under conditions of uncertainty, the dual property between price and quantity restrictions would vanish (Weitzman, 1974). In practice, this relates to the comparative advantage of having a fixed level of permit transfers with a variable ratio of jurisdictional prices versus a fixed price ratio and variable permit transfers. Note that because a border tax concerns permit prices the link equilibrium will always be affected and potentially brought to autarky if the rate is set at too high a level. By contrast, quantitative restrictions may turn out to be non-binding (even though this would still bear on price formation).

As a transitory linkage mechanism, border taxes may be more seamless than quantitative restrictions both in informing a full-link scale-up and managing associated distributional aspects. Note that small tax rates generate a sizeable share of the full-link gains but do not reduce much of its effects. Conversely, too high a tax rate risks turning out to be detrimental (w.r.t. full linkage) even for the jurisdiction that collects revenues. Finally note a border tax is a fiscal policy and might thus be relatively more complicated to pursue legislatively speaking than a quantity-based approach, for instance in the EU.[36]

1.6.3 Linkage with exchange rates

As with a border tax an exchange rate sets the ratio of jurisdictional marginal abatement costs (MAC effect). Additionally, it also modifies the one-for-one compliance value of jurisdictional permits, i.e. jurisdictional abatement efforts are not equivalent (EC effect). As noted by Burtraw et al. (2013), exchange rates thus have potential to adjust for programs' stringencies even though cost-efficiency is reduced.[37] Note that taking this line of reasoning

[34]Note that unless tax revenues are redistributed to firms, they will always be worse off as a result of the tax-restricted link and might oppose it.

[35]They can be seen as surrogates for otherwise politically unpalatable lump-sum transfers (Victor, 2015).

[36]Indeed, pursuant to Article 192 §2 of the Lisbon Treaty signed in 2007, policies that are deemed to be 'primarily of a fiscal nature' require unanimity between Member States to be enacted. In addition, we also note the indirect but related concern about WTO-compatibility voiced in the more general case of border (tax) adjustments for correct for carbon leakage.

[37]Burtraw et al. (2013) implement a 3-for-1 rate in linking California and RGGI (one CCA is worth three RGAs) arguing that this «provides a rough adjustment for the relative stringencies of the two programs but reduces the opportunities for cost savings from shifting CO_2 emissions from RGGI to California».

to its logical extreme (i.e., $\rho \sim \tau_1/\tau_2$) would conduce the link to resemble autarky. Additionally, an exchange rate may also serve as a means to accommodate other economic criteria or types of political and environmental preferences.[38]

Cost-efficiency may be higher or lower than under autarky, but will always be lower than under full linkage. In addition, due to the emission conversion effect, the overall level of emissions varies as a result of interjurisdictional trading. In particular, the volume of interjurisdictional transfers can increase, decrease or even be reversed relative to full linkage. As compared to autarky, the aggregate implications of an exchange rate in both economic and environmental terms could therefore happen to be beneficial (reduction zone) as well detrimental (inversion zone). In loose terms, the reduction zone is likely to be targeted by regulators. In particular, if they prioritize environmental outcomes they should aim for a rate close to $\hat{\rho}$. If, instead, they wish to increase liquidity without bearing much of the other effects of a full link, they should set ρ close to τ_1/τ_2.

Under conditions of uncertainty, however, selecting an exchange rate may prove to be difficult and have unintended, possibly detrimental, consequences. The difficulty is indeed twofold. First, due to ex-ante uncertainty about programs' actual stringencies (hence autarkic prices) it is complicated to select the rate right in the first place.[39] Second, it is also challenging to duly adjust the rate ex post since autarkic prices that would have prevailed absent the link restriction are not directly observable. Although counterfactual autarkic prices could be constructed, it could only be so with a lag of one compliance period at best. The risk of error and detrimental outcomes (e.g., associated with the inversion zone) in selecting the policy handle is higher than for the other two restrictions where policy outcomes are always confined within autarky and full linkage.

As a transitory linkage mechanism, an exchange rate has potential to increase environmental ambition over time when emissions cap diminution is not directly feasible. Indeed, penalized schemes have an incentive to raise domestic ambition provided that their abatement units become (gradually) traded with parity. In fact, Corollary 1.4.4 shows that it is in the interest of each party. We also note that since an exchange rate does not induce explicit rents, the transition to a full link may be easier than for the other two restrictions.

[38] In this respect, we refer the reader to the documentation provided under the auspices of the World Bank's Globally Networked Carbon Markets Initiative.

[39] This issue is somewhat mitigated if markets to be linked are already in operation as past price levels can help guide the selection of the exchange rate.

1.6.4 Two special cases of link restrictions

Unilateral (or conditional) linkage. Unilateral linkage is a special case of quantitative restrictions whereby entities in one jurisdiction can surrender foreign permits for domestic compliance but not the other way around. Should the unilateral link be established in the natural direction of trade its implications would closely resemble those of a full link save for the non-fungibility of permits. Conversely, it may also be that the unilateral link is not active, i.e. an autarky-like situation persists, as attests the so far inactive unilateral integration of the European aviation sector into the EUETS as of 2012. Unilateral linkage is thus of a conditional nature, which may incite jurisdictions to increase ambition.[40] Additionally, unilateral linkage can mitigate price uncertainty and distributional aspects (there is no scarcity rent) associated with quantitative restrictions.

Both the Norway-EU and aborted Australia-EU unilateral links were envisaged as initial, transitory steps toward fully-fledged links. During Phase I of the EUETS and until the extension of the EUETS to EEA-EFTA countries by late 2007, Norwegian firms could surrender EUAs domestically but not vice versa.[41] This one-way link originated in a unilateral decision on the part of Norway to help prepare for full integration to the EUETS, e.g. gradual market design alignment. In mid-2012 Australia and the EU Commission agreed to link up their domestic ETSs following a two-step process whereby Australia would first be unilaterally linked to the EU (EUAs recognized in Australia, but not vice versa) before the link would become two-way 3 years later. For compatibility with the EUETS, each of these two steps were to contingent upon gradual design adjustments in Australia.[42]

These two experiences indicate that unilateral links (*i*) can be established pursuant to unilateral or joint decisions; (*ii*) do not require market designs to be as much aligned as for bilateral links; (*iii*) may help initiate linkage while giving more time to bring schemes into sufficient alignment deemed necessary for bilateral links to be established seamlessly.

The elaboration of the RECLAIM program also underlines the practical merits of unilateral linkage. To take spatial factors into account the Los Angeles air basin was initially divided

[40]Imagine a unilateral link between a 'high-ambition' system A and a 'low-ambition' system B whereby only A can purchase B-units. In this sense, full linkage is conditional on B increasing ambition. Also note that the unilateral link provides a soft price floor for system A.

[41]Only one EUA transaction was recorded and the price for Norwegian permits was well below the price of CERs (Mehling & Haites, 2009) and the unilateral link can be seen as a de facto soft price ceiling.

[42]For instance, Australia committed to gradually scrap its price floor and ceiling. See Jotzo & Betz (2009) for more details on the compatibility between the EUETS and Australia Carbon Pricing Mechanism (CPM). Although linkage negotiations were conducted pursuant to Article 25 of the EUETS Directive concessions pertaining to design alignment were exclusively envisaged on the Australian side of the link because Europe had more political weight and thus 'design pull'. The project of an intercontinental link between Australia and Europe stalled when the CPM was officially repealed in mid-2014.

into 38 zones with interzonal trade restrictions. This would have massively reduced gains from using a market-based policy relative to command-and-control approaches. One alternative was to create a single market with trading ratios accounting for spatial discrepancies but quantification of these ratios proved complicated and the resulting scheme altogether would have been cumbersome and unworkable. The final program solely comprised two geographical zones (upwind sources, located near the coast and contributing more to elevated ozone levels and downwind sources, located inland) with interzonal trading allowed only from upwind to downwind sources (Tietenberg, 1995; Fromm & Hansjürgens, 1996).

Discount rates. Discount rates are the unilateral version of exchange rates. That is, when jurisdiction A applies a given conversion ratio to permits from jurisdiction B, B need not impose a conversion ratio to A-permits that is equal to the inverse of A's ratio on B-permits. Discount rates may thus be asymmetrical, i.e. of different magnitudes depending on the jurisdictions considered and the direction of the permit flow. When the differential in autarkic prices surpasses the discount rate its implications are similar to those of an equivalent exchange rate (same EC and MAC effects) but full permit fungibility does not obtain. As noted by Lazarus et al. (2015) this asymmetry may have potential to overcome some challenges inherent to exchanges rates. First, discount rates need not be mutually agreed upon so that jurisdictions can maintain relatively more flexibility in selecting and adjusting the discount rates they use. Second, if both jurisdictions were to implement discount rates higher than unity on inflowing foreign permits, then, whatever the realized direction of the permit flow, overall abatement and cost-efficiency would increase relative to autarky, which is congruent with the 'desirable' characteristics of the reduction zone.

1.7 Conclusion

This Chapter has compared the implications of various restrictions on permit trading in the context of a bilateral link as possible mechanisms for a gradual approach of an unrestricted link. This trial phase may allow to test the effects of the link while limiting its reach and associated effects as well as give more time and flexibility for partners to reconcile their policy differences and bring their respective schemes further into alignment for a full link to be established seamlessly. A few years down the road, partners may decide to scale up the link. Otherwise, should trial not be conclusive the link may also be severed.[43]

[43] Because restrictions are distortionary and the existence of restriction-induced rents may not incentivize recipients for a link rollout, it should be clear on both sides of the connection (and ideally spelt out in the linkage agreement) that the use of restrictions is only temporary.

On the face of it, quantitative restrictions seem to be the most implementation-friendly route to a full link between quantity instruments. In particular, they provide a direct quantity handle on the reach of the link. However, there is uncertainty about price formation and the distribution of the scarcity rent, which may impair the transition to a full link. These aspects are mitigated with a border a tax, which should ensure a better management of distributional outcomes, less undesirable price fluctuations and better information on jurisdictional marginal abatement costs. Exchange rates can be used to correct for discrepancies in programs' stringencies and have potential to increase ambition over time. However, they can be challenging to select and adjust, which might lead detrimental outcomes.

This analysis therefore identified comparative advantages and weaknesses for each link restriction. In order to hammer out a linkage agreement as workable and wieldy as possible, regulators can pick the instrument (or combination thereof) that best assuages dominant link-related risks and fits the negotiation and domestic contexts. As experience corroborates, transitory unilateral linkage may well strike a good balance between the 'ideal' and the 'practical' in translating economic theory into specific policy design elements. This echoes the words of Tietenberg (2006) that «in practice, one common approach to resolving spatial concerns involves a system of directional trading».

In addition, the insights gained in this simple framework can help evaluate the effects of trade restrictions as proposed in the context of networked ETSs. An recent example is the ICAR Platform proposed by Füssler et al. (2016), which provides a structure to which ETSs may dock on a voluntary basis contingent upon their meeting a set of predefined requirements. Docked ETSs retain some discretion in the form of unilateral imposition of both quantitative restrictions on permit outflows and inflows and qualitative restrictions (e.g., discount rates) determining compliance values assigned to foreign permits.

Finally, although we treat jurisdictions as monolithic entities and abstract from intrajurisdictional distributional issues, we stress that this deserves more attention.[44] Relatedly, the way restricted linkage affects firms and other jurisdictional constituencies will certainly shape regulators' room for maneuver in selecting and implementing restrictions. Note also that different regimes of revenue recycling can have important implications in assessing link restrictions as is the case with first-best instrument selection (Pezzey & Jotzo, 2012).

[44]Moreover, recent contributions underline that taking regulators to act as single, social welfare maximizing entities may constitute an oversimplification (Habla & Winkler, 2017; Marchiori et al., 2017).

Appendices of Chapter 1

1.A Analytical derivations and collected proofs

1.A.1 Quantity-restricted linkage

Let $\alpha \in [0;1]$ be the authorized share of interjurisdictional abatement transfers w.r.t. full linkage. In the constrained link, jurisdiction 1 (resp. 2) abates $a-\alpha\Delta^*$ (resp. $a+\alpha\Delta^*$) and the equilibrium marginal abatement cost is $\bar{\tau}_1(\alpha) = c_1(a-\alpha\Delta^*)$ (resp. $\bar{\tau}_2(\alpha) = c_2(a+\alpha\Delta^*)$). Notice that $\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha) = (1-\alpha)(\tau_1 - \tau_2)$ and $|\tau_i - \bar{\tau}_i(\alpha)| = c_i\alpha\Delta^*$, for $i = 1, 2$. The scarcity rent S, the deadweight loss L and jurisdictional economic gains from trade $\bar{\Gamma}_i$ then obtain from simple area computations, e.g. from Figure 1.2, that is

$$S(\alpha) = \alpha\Delta^*(\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha)) = \Delta^*(\tau_1 - \tau_2)\alpha(1-\alpha), \tag{1.A.1a}$$

$$2L(\alpha) = (1-\alpha)\Delta^*(\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha)) = \Delta^*(\tau_1 - \tau_2)(1-\alpha)^2, \tag{1.A.1b}$$

$$2\bar{\Gamma}_i(\alpha) = \alpha\Delta^*|\tau_i - \bar{\tau}_i(\alpha)| = c_i\Delta^{*2}\alpha^2. \tag{1.A.1c}$$

The scarcity rent is increasing (resp. decreasing) in α for $\alpha \leq$(resp. $\geq$)$1/2$. The deadweight loss is decreasing in α at a decreasing rate. Jurisdictional economic gains from trade are increasing in α less than linearly but at an increasing rate. Further notice that

$$S(\alpha) \geq \bar{\Gamma}_1(\alpha) + \bar{\Gamma}_2(\alpha) \Leftrightarrow \tau_1 - \tau_2 \leq 3(\bar{\tau}_1(\alpha) - \bar{\tau}_2(\alpha)) \Leftrightarrow \alpha \leq 2/3. \tag{1.A.2}$$

That is, the size of the scarcity rent relative to economic gains from trade accruing to jurisdictions is significant for a wide range of quantitative restrictions. The way the rent is apportioned among jurisdictions is thus of political importance in terms of linkage design. Finally note that since overall abatement is constant the degree of cost-efficiency relative to full linkage can be measured by the ratio of the total surplus under the restriction α to the total surplus under full linkage. This is measured by the index

$$I(\alpha) \doteq \frac{\Gamma_1^* + \Gamma_2^* - L(\alpha)}{\Gamma_1^* + \Gamma_2^*} = \frac{\alpha\Delta^*(\tau_1 + \bar{\tau}_1(\alpha) - (\tau_2 + \bar{\tau}_2(\alpha)))}{\Delta^*(\tau_1 - \tau_2)} = \alpha(2 - \alpha). \tag{1.A.3}$$

Any binding quantitative restriction is detrimental in aggregate terms. As shown below, this is not necessarily when considered from a jurisdictional perspective.

Proof of Proposition 1.4.1. Fix $\theta \in [0; 1]$. The surplus accruing to jurisdiction 1 under the restriction α consists of gains from trade and a share of the scarcity rent, that is

$$\Gamma_1(\alpha; \theta) \doteq \bar{\Gamma}_1(\alpha) + S_1(\alpha; \theta) = \Gamma_1^* \alpha^2 + \theta S(\alpha). \tag{1.A.4}$$

The optimal restriction from jurisdiction 1's perspective thus satisfies

$$\alpha_1^*(\theta) \doteq \arg \max_{\alpha \in [0;1]} \Big\langle \Gamma_1(\alpha; \theta) \Big\rangle, \tag{1.A.5}$$

for which the first-order condition simplifies to

$$(c_1 + c_2)\theta = (2(c_1 + c_2)\theta - c_1)\alpha_1^*, \tag{1.A.6}$$

as long as α_1^* belongs to $[0; 1]$. When this is not the case, full linkage is preferred (i.e., $\alpha_1^* = 1$). Note that $\alpha_1^* \geq 0$ and $\alpha_1^* \leq 1$ require $\theta \geq \bar{\theta}/2$ and $\theta \geq \bar{\theta}$, respectively, where $\bar{\theta} \doteq c_1/(c_1 + c_2) \geq 1/2$. Equation (1.A.6) thus holds for θ higher than the threshold $\bar{\theta}$ and this gives Equation (1.11a). The proof proceeds similarly for jurisdiction 2 where $\alpha_2^*(\theta) \doteq \arg \max_{\alpha \in [0;1]} \langle \Gamma_2(\alpha; \theta) \doteq \Gamma_2^* \alpha^2 + (1 - \theta) S(\alpha) \rangle$ and is therefore omitted.

Implementation. Quantitative restrictions should concern the net permit flow. In practice, quantitative restrictions could be implemented in a fashion akin to the «gateway mechanism» originally proposed by Sterk et al. (2006) to facilitate the establishment of links between the EUETS and another non-Kyoto-ratifying jurisdictional ETSs. Because EUAs were backed up by Kyoto units (AAUs) and AAU transfers with non-Annex B countries were not permitted under the Protocol, the gateway mechanism was envisioned as a repository whose functions would have been (*i*) to hold (and potentially cancel) AAUs when EUAs flew out to non-Annex B countries − an operation by which outgoing EUAs were stripped of their AAU characteristic to avoid that certificates were used twice ('double counting'); (*ii*) to attach AAUs to any inflowing non-Annex-B permits provided that there were sufficient AAUs available in the repository − thereby ensuring compliance with the

Protocol. On net, the repository should have played the role of a clearinghouse making sure that net permit flows could only occur in the allowed direction and up to the allowed quota. Another option is to create additional markets for import/export licenses which must be used when importing/exporting permits as e.g. in Bernstein et al. (1999) or Gavard et al. (2016). If licenses are distributed in excess, i.e. the restriction is not binding, the price of licenses is zero. If the restriction is binding, the license price is determined by Equation (1.8). Note that (*i*) the way the licenses are distributed between firms allocates the scarcity rent between them; (*ii*) the regulator can capture the rent (otherwise accruing to firms) if it auctions off these licenses. Finally note that the costs associated with setting up and running this parallel market may outweigh the initial benefits of linkage.

1.A.2 Border tax-restricted linkage

Consider that jurisdiction 1 unilaterally taxes imports of 2-permits at a proportional rate μ and does not share any of the revenues it collects. In the admissible tax range $[1; 1-\tau_2/\tau_1]$, permit imports are restrained to a volume of $\bar{\Delta}(\mu)$ such that

$$0 \leq \bar{\Delta}(\mu) = \frac{(1-\mu)\tau_1 - \tau_2}{(1-\mu)c_1 + c_2} \leq \Delta^*, \;\; \bar{\Delta}'(\mu) = -\frac{c_1\tau_2 + c_2\tau_1}{((1-\mu)c_1 + c_2)^2} < 0, \text{ and } \bar{\Delta}''(\mu) < 0. \tag{1.A.7}$$

This reduces jurisdictional economic gains from trade to $\bar{\Gamma}_i(\mu) = c_i(\bar{\Delta}(\mu))^2/2$ which are decreasing functions of μ. The total surplus accruing to jurisdiction 1 is $\Gamma_{1,t}(\mu) = \bar{\Gamma}_1(\mu) + \mu\bar{\tau}_1(\mu)\bar{\Delta}(\mu) = c_1(\bar{\Delta}(\mu))^2/2 + \mu\bar{\Delta}(\mu)(\tau_1 - c_1\bar{\Delta}(\mu))$ where the second term corresponds to tax revenues. Therefore, jurisdiction 2 is worse off w.r.t. full linkage but better off w.r.t. autarky ($\Gamma_2^* = \bar{\Gamma}_2(0) \geq \bar{\Gamma}_2(\mu) \geq 0$) while jurisdiction 1 can be better or worse off w.r.t. full linkage as the diminution in gains from trade can be more or less than offset by tax revenues. Indeed,

$$\Gamma'_{1,t}(\mu) = \bar{\Delta}'(\mu)\left[c_1\bar{\Delta}(\mu) + \mu(\tau_1 - 2c_1\bar{\Delta}(\mu))\right] + \bar{\Delta}(\mu)\left[\tau_1 - c_1\bar{\Delta}(\mu)\right], \tag{1.A.8}$$

where the two bracketed terms are positive for all admissible rate μ. The sign of $\Gamma'_{1,t}$ is thus ambiguous. However, by continuity of both $\Gamma_{1,t}$ and $\Gamma'_{1,t}$ and by noting that

$$\Gamma'_{1,t}(0) = \frac{c_2(c_2\tau_1 + c_1\tau_2)}{(c_1+c_2)^3}(\tau_1 - \tau_2) > 0 \text{ and } \Gamma'_{1,t}\Big(1 - \frac{\tau_2}{\tau_1}\Big) = \bar{\Delta}'\Big(1 - \frac{\tau_2}{\tau_1}\Big)(\tau_1 - \tau_2) < 0, \tag{1.A.9}$$

along with $\Gamma_{1,t}\left(1 - \frac{\tau_2}{\tau_1}\right) = 0 < \Gamma_{1,t}(0)$, there exist $\mu_1^* \leq \bar{\mu}_1$ both admissible such that jurisdiction 1's surplus is maximized at μ_1^* ($\bar{\Gamma}'_1(\mu_1^*) = 0$) and jurisdiction 1 is indifferent between a tax on imports at a rate $\bar{\mu}_1 > \mu_1^*$ and no tax at all ($\Gamma_{1,t}(\bar{\mu}_1) = \Gamma_{1,t}(0) = \Gamma_1^*$).[45] In aggregate, the tax on 2-permit imports results in a deadweight loss of

$$L(\mu) = (\Delta^* - \bar{\Delta}(\mu))(\bar{\tau}_1(\mu) - \bar{\tau}_2(\mu)) = \mu(\Delta^* - \bar{\Delta}(\mu))(\tau_1 - c_1\bar{\Delta}(\mu)), \quad (1.A.10)$$

and taking the derivative gives

$$L'(\mu) = (\Delta^* - \bar{\Delta}(\mu))(\tau_1 - c_1\bar{\Delta}(\mu)) - \bar{\Delta}'(\mu)\mu(\tau_1 - c_1\bar{\Delta}(\mu)) - c_1\bar{\Delta}'(\mu)\mu(\Delta^* - \bar{\Delta}(\mu)) > 0, \quad (1.A.11)$$

which is the sum of three positive terms. The deadweight loss is hence increasing with the tax rate or, equivalently, the aggregate surplus from the link is decreasing with the tax rate.

Relationship between price and quantity restrictions. In our deterministic framework, there exists a bijection between binding quantitative restrictions and admissible tax rates. The tax rate that restricts net permit transfers up to an authorized share $\alpha \in [0;1]$ is such that

$$\bar{\Delta}(\mu) = \alpha\Delta^* \Leftrightarrow \mu = \frac{(1-\alpha)(c_1^2 - c_2^2)}{c_1(c_1(1-\alpha) + c_2(1+\alpha))}. \quad (1.A.12)$$

Note that $\mu = 0 \Leftrightarrow \alpha = 1$ and $\mu = 1 - c_2/c_1 \Leftrightarrow \alpha = 0$. In aggregate terms, quantity and price tax policies linked via Equation (1.A.12) are equivalent.[46] As explained in Chapter 1, this is not the case from the perspective of one jurisdiction (although for equivalent quantitative restrictions and border taxes the sizes of the scarcity rent and tax revenues are equal, distributional aspects differ as the rent apportionment depends on relative bargaining powers) or in terms of market functioning (e.g., transaction price formation). In particular, the optimal tax rate on permit imports obtains as a special case of Equation (1.11a) with $\theta = 1$, that is

$$\bar{\Delta}(\mu_1^*) = \alpha_1^*(1)\Delta^* \Leftrightarrow \mu_1^* = (c_1 - c_2)/3c_1. \quad (1.A.13)$$

There is no particular interest in determining an analytical value for $\bar{\mu}_1$. In the symmetric case where jurisdiction 2 unilaterally imposes a tax μ_2 on 2-permit exports and keeps all the revenues to itself the optimal tax rate would satisfy $\bar{\Delta}(\mu_2^*) = \alpha_2^*(0)\Delta^* \Leftrightarrow \mu_2^* = \frac{c_1 - c_2}{c_1 + 2c_2} > \mu_1^*$.

[45] Similar results are found by Bernstein et al. (1999) in a general-equilibrium framework, where the authors add a markup to Russia's domestic permit price when permits are sold abroad (much like an export tariff) to be able to model market power exercise on the part of Russia.

[46] Introducing uncertainty (e.g., on abatement costs) or asymmetric information between 'an assumed global regulator' and regulated jurisdictions would make this dual property vanish (Weitzman, 1974).

1.A.3 Linkage with exchange rates

Proof of Proposition 1.4.3. From Equation (1.14) and market closure, in any interior linked market ρ-equilibrium it holds that

$$\Delta_1(\rho) = \frac{\tau_1 - \rho\tau_2}{c_1 + \rho^2 c_2} \geq 0 \Leftrightarrow \rho \leq \frac{\tau_1}{\tau_2}, \text{ and } \Delta_2(\rho) = \frac{\rho^2\tau_2 - \rho\tau_1}{c_1 + \rho^2 c_2} \geq 0 \Leftrightarrow \rho \geq \frac{\tau_1}{\tau_2}. \tag{1.A.14}$$

Since $\Delta_1(\rho) \sim_{0^+} \frac{\tau_1}{c_1}$ and $\Delta_1(\rho) \sim_{+\infty} \frac{-\tau_2}{\rho c_2} \to_{+\infty} 0^-$, one has that $\lim_{0^+} e_1(\rho) = \bar{e}$ and $\lim_{+\infty} e_1(\rho) = \omega$. The only relevant (positive) root of $\Delta_1'(\rho) = 0$ is $\rho^+ = \frac{\tau_1}{\tau_2} + \sqrt{\frac{\tau_1^2}{\tau_2^2} + \frac{c_1}{c_2}}$. Similarly, $\Delta_2(\rho) \sim_{+\infty} \frac{\tau_2}{c_2}$ and $\Delta_2(\rho) \sim_{0^+} \frac{\rho^2\tau_2}{c_1} \to_{0^+} 0$ so that $\lim_{+\infty} e_2(\rho) = \bar{e}$ and $\lim_{0^+} e_2(\rho) = \omega$. The only relevant (positive) root of $\Delta_2'(\rho) = 0$ is $\rho^{++} = \frac{c_1\tau_2}{c_2\tau_1}\left(\sqrt{1 + \frac{c_2\tau_1}{c_1\tau_2}} - 1\right)$. Noting that $\rho = 1$ is an obvious root of $\Delta_i(\rho) = \Delta^*$ for $i = 1, 2$, it follows that

$$\Delta_1(\rho) \geq \Delta^* \;\Leftrightarrow\; (\rho - 1)(\rho + \bar{\rho}_1) \leq 0, \tag{1.A.15a}$$

$$\rho\Delta_1(\rho) \geq \Delta^* \;\Leftrightarrow\; (\rho - 1)(\rho - \bar{\rho}_2) \leq 0, \tag{1.A.15b}$$

where $\bar{\rho}_1 \doteq \frac{c_1\tau_2 + c_2\tau_1}{c_2(\tau_1 - \tau_2)} > 0$ and $\bar{\rho}_2 \doteq \frac{c_1(\tau_1 - \tau_2)}{c_1\tau_2 + c_2\tau_1} \in (0; \tau_1/\tau_2)$. Statements (i) and (ii) follow immediately: Jurisdiction 1 increases its emissions relative to full linkage provided that the exchange rate is less than unitary. Jurisdiction 2 decreases its emissions relative to full linkage provided that $(\rho - 1)(\rho - \bar{\rho}_2) < 0$. Note that the threshold $\bar{\rho}_2$ satisfies

$$\bar{\rho}_2 \leq 1 \;\Leftrightarrow\; \frac{\tau_1}{\tau_2} \leq \frac{2c_1}{c_1 - c_2} \;\Leftrightarrow\; \frac{c_1}{c_2} \leq \frac{2(\bar{e} - \omega_2) + (\bar{e} - \omega_1)}{\bar{e} - \omega_1} = 1 + 2\frac{\bar{e} - \omega_2}{\bar{e} - \omega_1}. \tag{1.A.16}$$

In our special case where $\omega_1 = \omega_2$, $\bar{\rho} = 1 \Leftrightarrow \tau_1 = 3\tau_2 \Leftrightarrow c_1 = 3c_2$. Note that when $\bar{\rho} = 1$ emissions in jurisdiction 2 never pass below their full-linkage level.

Relative to the benchmark, additional aggregate abatement $\gamma(\rho)$ obtains as the difference between aggregate emissions in the benchmark and in the ρ-equilibrium, that is

$$\gamma(\rho) \doteq 2\omega - \left(\omega + \bar{\Delta}_1(\rho) + \omega - \rho\bar{\Delta}_1(\rho)\right) = (\rho - 1)\bar{\Delta}_1(\rho). \tag{1.A.17}$$

Recall that $\bar{\Delta}_1(\rho) \geq 0$ i.f.f. $\rho \in [0; \tau_1/\tau_2]$. Hence $\gamma(\rho) \geq 0$ i.f.f. $\rho \in [1; \tau_1/\tau_2]$. We then solve for

$$\gamma'(\rho) = 0 \;\Leftrightarrow\; \rho^2 c_2(\tau_1 + \tau_2) - 2\rho(c_2\tau_1 - c_1\tau_2) - c_1(\tau_1 + \tau_2) = 0. \tag{1.A.18}$$

Noting that by assumption $\tau_i = c_i a$, $i = 1, 2$, then $c_2\tau_1 = c_1\tau_2$ and additional aggregate abatement is maximized at $\rho = \hat{\rho} \doteq (\tau_1/\tau_2)^{1/2}$. Computing $\gamma(\hat{\rho})$ establishes Statement (iii).

Proof of Corollary 1.4.4. In the linked market $\hat{\rho}$-equilibrium variations in jurisdictional emission levels as compared to autarky are such that

$$\hat{\Delta}_1 = \frac{\sqrt{c_1} - \sqrt{c_2}}{2\sqrt{c_1}} a, \text{ and } \hat{\Delta}_2 = -\sqrt{\frac{c_1}{c_2}} \hat{\Delta}_1 = \frac{\sqrt{c_2} - \sqrt{c_1}}{2\sqrt{c_2}} a. \tag{1.A.19}$$

In total, aggregate abatement increases by

$$\gamma(\hat{\rho}) \doteq (\hat{\rho} - 1)\Delta_1(\hat{\rho}) = \hat{\Delta}_1 - \hat{\Delta}_2 = a(\sqrt{c_1} - \sqrt{c_2})^2/(2\sqrt{c_1 c_2}). \tag{1.A.20}$$

Assume that in lieu of implementing the exchange rate regime $\hat{\rho}$ jurisdictions were to agree upon a full link where jurisdiction 2 reduced its domestic cap in such a fashion that aggregate abatement would be equal to that in the $\hat{\rho}$-equilibrium. That is, jurisdictional caps would be such that $\hat{\omega}_1 = \omega$ and $\hat{\omega}_2 = \omega - \gamma(\hat{\rho})$. Under full linkage with jurisdictional caps $(\hat{\omega}_1, \hat{\omega}_2)$ permits continue to flow in the natural direction and unit transfers amount to

$$\hat{\Delta} = \Delta^* - c_2\gamma(\hat{\rho})/(c_1 + c_2). \tag{1.A.21}$$

These two linkage regimes can be compared in terms of sole associated gains from trade because they are generative of the same aggregate level of emissions. In particular, jurisdiction i prefers the full link with domestic caps $(\hat{\omega}_1, \hat{\omega}_2)$ over the $\hat{\rho}$-equilibrium with domestic caps (ω, ω) i.f.f. $\hat{\Delta} \geq |\hat{\Delta}_i|$, which holds for $i = 1, 2$ since

$$\hat{\Delta}_1 - \hat{\Delta} = \frac{c_2 - c_1}{2(c_1 + c_2)} a < 0, \text{ and } |\hat{\Delta}_2| - \hat{\Delta} = \frac{c_2 - c_1 - 3\sqrt{c_1 c_2}}{2\sqrt{c_1 c_2}} a < 0. \tag{1.A.22}$$

Another interpretation than that proposed in the body of the Chapter is that, if the two jurisdictions establish a link with an exchange rate aimed at correcting for too low an ambition level in jurisdiction 2, then they would both be better off from a full link with an equivalent downward-adjusted cap in jurisdiction 2.

1.B Numerical simulations and indexes

Jurisdictions have the same domestic abatement objective, thus $c_1/c_2 = \tau_1/\tau_2$. Equating this ratio to 3 ensures that $\bar{\rho}_2 = 1$ and provides clear-cut results in terms of emission variations for jurisdiction 2 (see Equation (1.A.15b)). Below are defined three indexes that measure overall abatement (1.B.1a), average abatement cost (1.B.1b) and cost-efficiency (1.B.1c) relative to autarky. This means that only relative parameter values matter. Without loss of generality we set $\bar{e} = 1000$, $\omega = 900$ and $c_1 = 3c_2 = 0.3$, which gives $\tau_1 = 3\tau_2 = 30$.

$$I^A = \frac{2\bar{e} - (2\omega + (1-\rho)\Delta_1(\rho))}{2(\bar{e}-\omega)} = 1 + \frac{(\rho-1)\Delta_1(\rho)}{2(\bar{e}-\omega)} \tag{1.B.1a}$$

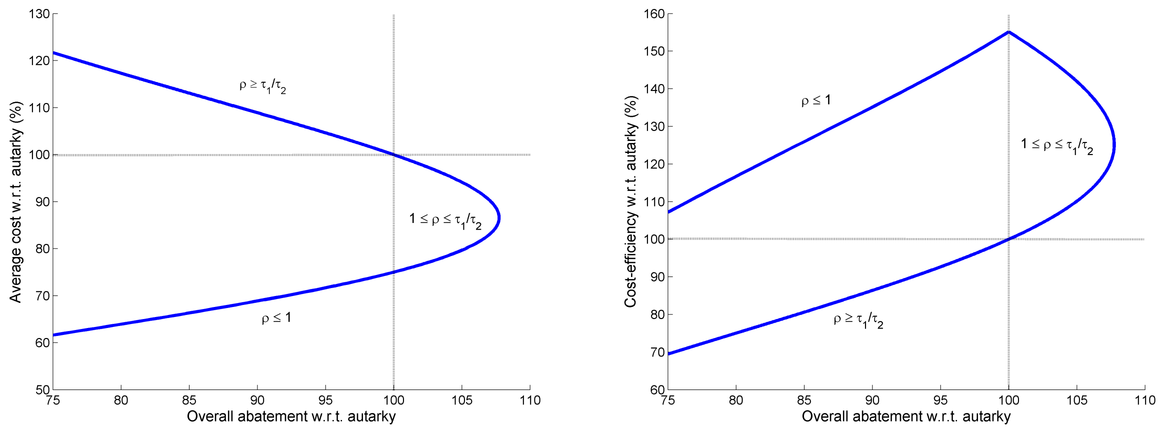
$$I^{AC} = \frac{1}{I^A} \times \frac{C_1(\bar{e}-\omega-\Delta_1(\rho)) + C_2(\bar{e}-\omega+\rho\Delta_1(\rho))}{C_1(\bar{e}-\omega) + C_2(\bar{e}-\omega)} \tag{1.B.1b}$$

$$I^{CE} = \ln\left(\frac{C_1'(\bar{e}-\omega)}{C_2'(\bar{e}-\omega)} + 1\right) \Big/ \ln\left(\frac{\max_i C_i'(\bar{e}-\omega-\Delta_i(\rho))}{\min_i C_i'(\bar{e}-\omega-\Delta_i(\rho))} + 1\right) \tag{1.B.1c}$$

Note that I^{CE} merely gives an indication (and not a proper measure) of the degree of cost-

Figure 1.B.1: Overall abatement, average abatement cost and cost-efficiency w.r.t. autarky

(a) $I^{AC} = f\left(I^A\right)$ (b) $I^{CE} = f\left(I^A\right)$



efficiency. The kink at $\rho = 1$ is due to the max operator: at this point there is a discontinuity since the higher marginal abatement cost jurisdiction switches ($\bar{\tau}_1 \geq \bar{\tau}_2 \Leftrightarrow \rho \geq 1$).

1.C Cap selection and environmental damages

We let $d_i > 0$ denote jurisdiction i's constant marginal damage from aggregate emissions. Linear damage functions ensure that jurisdictional cap reaction functions are orthogonal, i.e. jurisdictions select the same domestic cap whatever the other jurisdiction's choice. This is a mild assumption as there is evidence that marginal benefits from mitigation are much flatter than marginal abatement costs over the range of annual emissions (Newell & Stavins, 2003). Without loss of generality we assume that cap selection is non-cooperative and the Cournot-Nash jurisdictional emission caps satisfy

$$\omega_i \doteq \arg\min_{\omega\in[0;\bar{e}]} \left\langle C_i(\bar{e}-\omega) + d_i(\omega+\omega_{-i}) \right\rangle = \bar{e} - d_i/c_i, \text{ for } i = 1,2. \tag{1.C.1}$$

Note that each domestic cap is strictly binding ($\omega_i < \bar{e}$) and independent of the cap-setting decision in the other jurisdiction (ω_{-i}). We abstract from corners by assuming that $d_i < c_i\bar{e}$, i.e. $\omega_i > 0$ for $i = 1, 2$. Note that our assumption of identical caps in the main text obtains if we assume that $c_1/c_2 = d_1/d_2$. Note also that jurisdictions do not internalize the negative externality generated by their emissions on the other jurisdiction. By contrast, cooperative caps are socially efficient and satisfy $\omega_i^* = \bar{e} - (d_i + d_{-i})/c_i < \omega_i$.

The optimal exchange rate ρ_i^* for jurisdiction i maximizes the difference in compliance costs between autarky and ρ_i^*-equilibrium, knowing how both jurisdictions react to a rate ρ, that is

$$\rho_i^* \doteq \arg\max_{\rho>0} \Big\langle C_i(\bar{e} - \omega) - C_i(\bar{e} - \omega - \bar{\Delta}_i(\rho)) + d_i(\rho - 1)\bar{\Delta}_1(\rho)\Big\rangle. \tag{1.C.2}$$

This mitigates jurisdictional preferences for too high or too low rates as mentioned in the main text. We do not provide an analytical solution to Program (1.C.2) and refer the reader to the literature on optimal intertemporal trading ratios, e.g. Leiby & Rubin (2001), Yates & Cronshaw (2001), Innes (2003) and Feng & Zhao (2006), for similar analytical problems.

Note that the socially efficient level of emissions $2\bar{e} - (d_1 + d_2)/c$ need not coincide with that triggered under $\hat{\rho}$-linkage. In particular, we numerically show that when d_i/c_i is relatively small (resp. big) then the two jurisdictions overabate (resp. underabate) at the $\hat{\rho}$-equilibrium as compared to the social optimum. Finally, we numerically show that jurisdictionally-preferred exchange rates defined in Program (1.C.2) that are *potentially acceptable* at a 50% level of full-link gains are centred around parity within the range $[0.61; 1.44]$.

1.D Linkage: A general modeling framework

We are interested in the regulation of uniformly-mixed pollutants (e.g., GHGs) for which only global concentration levels matter insofar as climate change damages are concerned. In other words, the location of these emissions should not matter.[47] Therefore, we consider ‘simple’ permit markets in which there is a single type of permit that trades freely across

[47]In a linkage context, however, location of emissions matters since jurisdictions want some level of abatement (e.g., for ancillary benefits and attendant technology investments) to occur domestically. In a domestic market context, we also note that because market forces determine where GHG abatements occur, cap-and-trade systems are sometimes criticized for exacerbating inequalities to pollution exposure. This criticism is in part misplaced in the sense that co-pollutants do have direct, local health impacts, but not GHG emissions per se. One therefore needs to ponder whether inequalities in local pollution exposure ought to be addressed by separate (prescriptive) regulations or by distorting climate change policies. See Fowlie (2016) for a discussion in the context of the California cap-and-trade program.

space on a one-for-one basis.[48] The reader may refer to Itkonen (2014) for an extension of this modeling framework to a network of linked markets using graph theory.

1.D.1 General case: Multilateraly-linked permit markets

We consider a set of n jurisdictions $\mathcal{I} = \{1, \ldots, n\}$. In each jurisdiction i in $\mathcal{I}$, there is a continuum $\mathcal{S}_i = [0; s_i]$ of polluting firms, where the mass of firms s_i measures the size of jurisdiction i. We denote by $\bar{e}_{ij}$ the unregulated level of emissions of firm j in $\mathcal{S}_i$ and $\bar{e}_i = \int_{\mathcal{S}_i} \bar{e}_{ij}\mathrm{d}j$ is that of jurisdiction i.[49] Each jurisdiction regulates its domestic emissions with a pure quantity instrument: the regulator in jurisdiction i imposes a cap on domestic emissions ω_i and distributes it in the form of pollution permits according to the allocation profile $(\omega_{ij})_{j\in\mathcal{S}_i}$ where each firm $j \in \mathcal{S}_i$ is endowed with ω_{ij} permits and $\omega_i = \int_{\mathcal{S}_i} \omega_{ij}\mathrm{d}j$. These caps are given, fixed once and for all and assumed binding. Denote by $a_i = \bar{e}_i - \omega_i > 0$ jurisdiction i's domestic abatement target. To demonstrate compliance, firms may either abate emissions or purchase permits on the market.[50] Let $a_{ij} \geq 0$ denote the abatement level undertaken by firm $j \in \mathcal{S}_i$. Abatement costs incurred by firm $j \in \mathcal{S}_i$ are denoted by the function C_{ij}, and are assumed to be increasing and convex, i.e. $C'_{ij} > 0$ and $C''_{ij} > 0$. For analytical tractability, the quadratic abatement cost specification below will be used

$$C_{ij}(a_{ij}) = c_{ij}a_{ij}^2/2, \text{ for all } j \in \mathcal{S}_i \text{ and } i \in \mathcal{I}, \tag{1.D.1}$$

where firm-specific cost coefficients $c_{ij} > 0$ reflect the decreasing returns in abatement. The higher c_{ij} the less sensitive (i.e., elastic) firm j's abatement decisions to a shift in the permit price. In other words, $1/c_{ij}$ measures the flexibility in abatement of firm $j \in \mathcal{S}_i$.

[48] Other market designs are possible, e.g. ambient permit systems in which there exist as many types of permits – and thus associated markets – as there are receptor locations (Montgomery, 1972) or pollution-offset systems in which there is only one permit type but restrictions on feasible trades apply (Krupnick et al., 1983). Note that these systems are more demanding in terms of market design for the regulator.

[49] To see how size affects jurisdictional baseline levels of emissions in a simple situation consider that $\bar{e}_{ij} = e$ for all i and j. In this case, baselines are proportional to size, i.e. $\bar{e}_i = e \cdot s_i$.

[50] Firms basically have two strategies to curb pollution: one is to reduce gross emissions by directly cutting production; the other is to maintain production constant while reducing emissions by employing an abatement technology. In general, a combination of both will be optimal. Many papers in the literature assume separability between permit and product markets. We do the same throughout this dissertation. This means that we implicitly assume that output is fixed. Alternatively, one needs to assume competitive product markets. In this case, optimal adjustments in output can be incorporated into abatement cost functions that are derived from firms' joint cost functions of both production and abatement. A compelling (and formal) argument is developed in Requate (2005), Section 2.1. In this sense, abatement costs are nothing but foregone profits attributable to the curtailment of emissions.

Autarkic permit markets

Assume permit markets are competitive. Because abatement is costly, domestic abatement requirements hold with equality. For a given abatement objective $a_i > 0$ in jurisdiction $i \in \mathcal{I}$, the optimal domestic abatement profile $(\hat{a}_{ij}(a_i))_{j\in\mathcal{S}_i}$ satisfies

$$C'_{ij}(\hat{a}_{ij}(a_i)) = C'_{ik}(\hat{a}_{ik}(a_i)) \text{ for all } (j,k) \in \mathcal{S}_i^2 \text{ and } \int_{\mathcal{S}_i} \hat{a}_{ij}(a_i)\mathrm{d}j = a_i. \tag{1.D.2}$$

The positive number τ_i such that $C'_{ij}(\hat{a}_{ij}(a_i)) = \tau_i$ for all $j \in \mathcal{S}_i$ is commensurate with the stringency of the domestic cap on emissions. This shadow price is the equilibrium autarkic price at which permits trade on jurisdiction i's domestic market. Note that it is an implicit decreasing function of the domestic emissions cap, i.e. $\tau_i \equiv \tau_i(\omega_i)$ with $\tau_i' < 0$. Montgomery (1972) formally showed that the market equilibrium defined in Equation (1.D.2) implements the cost-effective solution in which firms jointly minimize abatement costs to comply with the aggregate abatement objective, and that this holds irrespective of the initial allocation of permits. In other words, firms regulated under i's permit market can be aggregated into representative firm whose abatement cost function C_i satisfies

$$C_i(a_i) \doteq \min_{(a_{ij})_{j\in\mathcal{S}_i}} \int_{\mathcal{S}_i} C_{ij}(a_{ij})\mathrm{d}j \text{ subject to } a_i = \int_{\mathcal{S}_i} a_{ij}\mathrm{d}j. \tag{1.D.3}$$

Quadratic costs (1.D.1). Cost-efficiency in i's autarkic regime requires that $c_{ij}\hat{a}_{ij}(a_i) = \tau_i$ for all $j \in \mathcal{S}_i$ and domestic market closure yields $\tau_i = c_i a_i$ where $1/c_i = \int_{\mathcal{S}_i} \mathrm{d}j/c_{ij}$ denotes i's aggregate flexibility in abatement.[51] Note that the domestic effort of abatement is efficiently apportioned between firms, i.e. in proportion to their flexibility in abatement,

$$\hat{a}_{ij}(a_i) = c_i a_i / c_{ij} \text{ for all } j \in \mathcal{S}_i, \tag{1.D.4}$$

and that i's representative firm's abatement cost function simply reads $C_i(a_i) = c_i a_i^2/2$.

Linked permit markets

Let $\mathcal{C}$ be a subset of $\mathcal{I}$ of cardinality larger than two. Denote by $\omega = \sum_{i\in\mathcal{C}} \omega_i$ and $\bar{e} = \sum_{i\in\mathcal{C}} \bar{e}_i$ the aggregate permit supply and level of baseline emissions in $\mathcal{C}$. Consider that jurisdictions in $\mathcal{C}$ link their domestic systems to form a unique permit market, which we assume is competitive. By the same token as for autarkic regimes, the linked market

[51] To see how size affects jurisdictional abatement flexibility in a simple situation consider that $c_{ij} = \gamma$ for all i and j. In this case, flexibilities are proportional to size, i.e. $1/c_i = s_i/\gamma$. That is, for any given common technology, the larger the jurisdiction, the larger its flexibility in abatement.

equilibrium obtains either by joint abatement cost minimization on the part of jurisdictional representative firms or by each jurisdictional representative firm minimizing its compliance costs. In the latter case, representative firm i takes the market price τ and its allocation ω_i as given and solves

$$\min_{a_i \geq 0} \Big\langle C_i(a_i) + \tau(\bar{e}_i - \omega_i - a_i)\Big\rangle, \tag{1.D.5}$$

where the second term is the net cost of buying permits on the linked market. By linked market closure the linkage equilibrium functional solution is defined by

$$a_i^*(\omega) = (C_i')^{-1}(\tau^*(\omega)) \text{ for all } i \in \mathcal{C}, \tag{1.D.6a}$$

$$\text{and, } \tau^*(\omega) = \Big(\textstyle\sum_{i\in\mathcal{C}} (C_i')^{-1}\Big)^{-1}(\bar{e} - \omega). \tag{1.D.6b}$$

By assumption, both the equilibrium market price and jurisdictional abatement levels are decreasing functions of the aggregate emissions cap. For instance, differentiating Equation (1.D.6b) w.r.t. ω yields

$$\frac{\mathrm{d}\tau^*}{\mathrm{d}\omega} = -\left(\sum_{i\in\mathcal{C}} \frac{1}{C_i''(a_i^*(\omega))}\right)^{-1} < 0. \tag{1.D.7}$$

Therefore, in terms of jurisdictional abatement variations, one has that

$$\frac{\mathrm{d}a_i^*}{\mathrm{d}\omega} = \frac{1}{C_i''(a_i^*(\omega))}\frac{\mathrm{d}\tau^*}{\mathrm{d}\omega} \in (-1;0) \text{ for all } i \in \mathcal{I} \text{ with } \sum_{i\in\mathcal{C}} \frac{\mathrm{d}a_i^*}{\mathrm{d}\omega} = -1. \tag{1.D.8}$$

When the aggregate cap on emissions increases, the linked market price decreases in inverse proportion to the market-wide flexibility in abatement and jurisdiction's abatements decrease in proportion to their flexibility in abatement. If we et $\Delta_i^* = a_i - a_i^*$ be jurisdiction i's net permit imports (if $\Delta_i^* \leq 0$, i is a net exporting jurisdiction and market clearing requires $\sum_{i\in\mathcal{C}} \Delta_i^* = 0$), jurisdictional gains from the link are non-negative and write

$$\Gamma_i^* = \int_{a_i}^{a_i^*} \Big[\tau^* - C_i'(x)\Big]\mathrm{d}x = \int_0^{\Delta_i^*} \Big[C_i'(a_i - x) - \tau^*\Big]\mathrm{d}x \geq 0. \tag{1.D.9}$$

That is, when jurisdictional caps are binding and fixed prior to linking, the formation of the link generates non-negative gains from trade for all jurisdictions involved. In other words, linkage constitutes a Pareto-improvement with respect to autarky. Note that gains accruing to jurisdiction $i \in \mathcal{C}$ are positive provided that $\Delta_i^* \neq 0$, i.e. the link actually affects i.

Quadratic costs (1.D.1). The linked market equilibrium is characterized by

$$\tau^*(\omega) = c(\bar{e} - \omega), \text{ and } a_i^*(\omega) = c(\bar{e} - \omega)/c_i \text{ for all } i \in \mathcal{C}, \tag{1.D.10}$$

where $1/c = \sum_{i \in \mathcal{C}} 1/c_i$ is the linked market abatement flexibility. Abatement costs to meet the aggregate objective $a = \bar{e} - \omega$ are minimized as it is efficiently apportioned across jurisdictions, that is in proportion to their abatement flexibility. Jurisdictional net permit imports thus write

$$\Delta_i^* = (\tau_i - \tau^*)/c_i \text{ for all } i \in \mathcal{C}. \tag{1.D.11}$$

There are two implications. First, jurisdiction i is a net permit importer i.f.f. the price that would have prevailed under autarky (τ_i) is higher than the linked price (τ^*). Second, variations in jurisdictional abatements as a result of the link are proportional to both jurisdictional abatement flexibilities and the difference in autarkic and linked prices. Invoking market closure, the linked price writes as the flexibility-weighted average of autarkic prices, that is

$$\tau^* = c \sum_{i \in \mathcal{C}} \tau_i / c_i \in \Big(\min_{i \in \mathcal{C}} \tau_i ; \max_{i \in \mathcal{C}} \tau_i \Big). \tag{1.D.12}$$

The linked price will be closer to autarkic prices of those jurisdictions with relatively high abatement flexibility. In particular, jurisdictional gains from the link simplify to

$$\Gamma_i^* = c_i \Delta_i^{*2}/2 = (\tau_i - \tau^*)^2/(2c_i) \text{ for all } i \in \mathcal{C}, \tag{1.D.13}$$

and are proportional to both jurisdictional flexibility in abatement and the square of the difference between autarkic and linked prices. Moving back to firm level, all firms contribute to the aggregate abatement effort in proportion to their flexibility in abatement, that is

$$\hat{a}_{ij}(a_i^*(\omega)) = c_i a_i^*(\omega)/c_{ij} = c(\bar{e} - \omega)/c_{ij} \text{ for all } j \in \mathcal{S}_i \text{ and } i \in \mathcal{C}. \tag{1.D.14}$$

All happens as if linkage unfolded in two subsequent stages: a first stage where jurisdictions trade between themselves until all inter-jurisdictional exchange opportunities are exhausted; a second stage where jurisdictional equilibrium abatement levels are then efficiently distributed between liable firms within each jurisdiction.

The above has laid out the underlying mechanism of linkage. Economic and distributional effects of linkage then depend on jurisdictional characteristics, namely flexibility in abatement, size and ambition level. In this respect, how these effects relate to jurisdictional characteristics are best illustrated in a two-jurisdiction setup.

1.D.2 Special case: Bilaterally-linked permit markets

There are two jurisdictions, 1 and 2, whose domestic emission caps are binding and fixed. We let jurisdiction 1 be the higher-cost jurisdiction, i.e. autarkic prices are such that $\tau_1 > \tau_2$. That is, jurisdiction 1 (resp. 2) is net permit buyer (resp. seller) on the linked market and undertakes less (resp. more) abatement domestically relative to autarky. Indeed, it has a net incentive to import (resp. export) permits at a price below (resp. above) its domestic marginal abatement cost. This continues until marginal abatement costs equalize across systems, i.e. the autarkic price differential is arbitraged away.

With our quadratic abatement cost specification, jurisdiction i's permit market is entirely characterized by three parameters: its abatement flexibility $1/c_i$, its size proxied by its level of baseline emissions $e_{0,i}$ and the stringency of its emission cap γ_i, defined by $\omega_i = (1-\gamma_i)\bar{e}_i$. For the remainder of this Appendix, jurisdiction 2 will serve as our reference. We let β and γ be 1's size and cap stringency relative to 2, i.e. $\bar{e}_1 = \beta\bar{e}_2$ and $\gamma_1 = \gamma\gamma_2$. Note that the parameter c_i incorporates two distinct dimensions, namely a size dimension and a technology dimension. For an abatement technology common to the two jurisdictions, if jurisdiction 1 is twice as large as jurisdiction 2, then $c_2 = 2c_1$. Similarly, for two same-sized jurisdictions, if 1's abatement technology is twice as efficient as 2's, then again $c_2 = 2c_1$. We thus let $\bar{c}_i$ denote i's linear marginal abatement cost curve slope corrected for relative size, i.e. $1/\bar{c}_i$ is a measure of i's sole abatement technology. If we let $1/\bar{c}$ characterize 1's technology relative to 2, then $c_1 = \bar{c}\bar{c}_2/\beta$ and $c_2 = \bar{c}_2$. Finally note that $\tau_1 > \tau_2$ requires $\bar{c}\gamma > 1$. Irrespective of the relative size, 1 is the higher cost jurisdiction when the relative cap stringency γ is larger the relative abatement technology $1/\bar{c}$.

Interior bilateral linkage equilibrium. We let $\Delta^* > 0$ denote the equilibrium volume of permits imported by 1.[52] It is uniquely defined by joint abatement cost minimization, that is

$$\Delta^* \doteq \arg\min_{\Delta > 0} \Big\langle C_1(a_1 - \Delta) + C_2(a_2 + \Delta) \Big\rangle. \tag{1.D.15}$$

With τ^* the linked permit price, the attendant necessary first-order condition writes

$$C_1'(a_1 - \Delta^*) = \tau^* = C_2'(a_2 + \Delta^*). \tag{1.D.16}$$

We let $a = a_1 + a_2$ and $1/c = 1/c_1 + 1/c_2$ be the aggregate abatement effort and the abatement flexibility of the linked system, respectively. Note that linkage results in higher

[52] With quadratic abatement costs, corners occur when 1 emits up to its baseline, or 2 cuts down emissions to zero, before marginal abatement costs could equalize across systems.

abatement flexibility in the linked system than in each system taken separately, i.e. $1/c > 1/c_i$, for $i = 1, 2$. With quadratic abatement costs, it follows from Section 1.D.1 that

$$\tau^* = ca = \frac{c_2\tau_1 + c_1\tau_2}{c_1 + c_2} = \frac{\beta\tau_1 + \bar{c}\tau_2}{\beta + \bar{c}} \in (\tau_2; \tau_1), \tag{1.D.17a}$$

$$\text{and, } \Delta^* = \frac{\tau_1 - \tau_2}{c_1 + c_2} = \frac{\tau_1 - \tau}{c_1} = \frac{\tau - \tau_2}{c_2} > 0. \tag{1.D.17b}$$

That is, price convergence is complete and inter-system trading makes up for the discrepancy in autarkic prices. In particular, the overall objective a is allocated in proportion to jurisdictional abatement flexibilities, i.e. jurisdiction i abates ca/c_i in equilibrium. For a given $\bar{c}$, note also that $\tau \to_{\beta\to\infty} \tau_1$ and $\tau \to_{\beta\to 0^+} \tau_2$, i.e. the linked price is closer to the autarkic price of the bigger jurisdiction. This shows that linkage will have less of an impact on the larger system than on the smaller one, in terms of both price variations and relative shifts in the (post-trade) effective cap.[53] This also suggests that the smaller system will be more subject to shocks originating in the larger system than vice versa.[54] As shown below, however, smaller systems will gain relatively more from the link precisely because the distance in the autarkic and linking prices is relatively bigger, see e.g. Equation (1.D.13).

Determinants of gains from linkage. With our quadratic abatement cost specification, jurisdictional and aggregate gains from the link satisfy

$$\Gamma^* = \Gamma_1^* + \Gamma_2^* = \frac{(\tau_1 - \tau_2)^2}{2(c_1 + c_2)} = \frac{\beta\bar{c}_2(\gamma\bar{e}_2(\bar{c}\gamma - 1))^2}{2(\beta + \bar{c})} \text{ with } \Gamma_1^*/\Gamma_2^* = c_1/c_2 = \bar{c}/\beta. \tag{1.D.18}$$

Two insights are readily apparent from the above. First, the distribution of the overall surplus is only influenced by the ratio of abatement flexibilities and independent of the relative target stringency. In particular, a larger share of the overall surplus accrues to the smaller and more abatement-efficient jurisdiction. Second, the overall surplus is proportional to the square of the wedge in autarkic prices, which in turn depends on the three ETS parameters.

To better illustrate the underlying mechanisms of linkage, we first detail surplus computations when jurisdictions solely differ in abatement technology ($\gamma = \beta = 1$ and $\bar{c} > 1$).[55] The situation is depicted in Figure 1.1 where linkage gains readily obtain by simple triangle area computations. It is instructive, however, to compute the difference between compliance

[53]The future connection between the Swiss and the EU ETSs is a case in point since the Swiss cap amounts to 0.2% of the EU's. The link will thus have imperceptible effects on the EU ETS, if any.

[54]This intuition will be confirmed in Chapter 2, see Section 2.4.2 in particular.

[55]When jurisdictions only differ in their target stringency ($\bar{c} = \beta = 1$ and $\gamma > 1$) both the aggregate abatement effort $(\gamma + 1)\gamma_2\bar{e}_2$ and the overall surplus are evenly distributed between them. Intuitively, this is so because they have the same abatement flexibility. When jurisdictions only differ in volume or size ($\bar{c} = \gamma = 1$ and $\beta = 1$), autarkic prices are equal and there is no incentive to trade.

costs under autarky and linkage. For instance, in jurisdiction 1

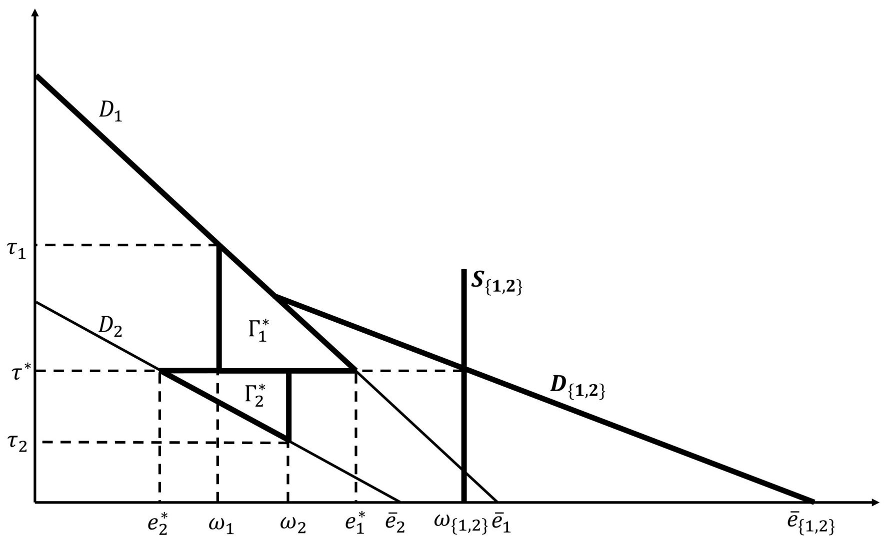
$$2\Gamma_1^* = (\bar{e} - \omega) \cdot \tau_1 - ((\bar{e} - e_1^*) + 2(e_1^* - \omega)) \cdot \tau^* \tag{1.D.19a}$$

$$= (\bar{e} - \omega) \cdot (\tau_1 - \tau^*) - \tau^* \cdot \Delta^*. \tag{1.D.19b}$$

The first term on the right-hand side of Equation (1.D.19b) measures the link-related economic gain in abating the autarky target $\bar{e} - \omega$, which is reflected by the rotation of the marginal abatement cost curve around $\bar{e}$ from slope c_1 to $2c$. The second term is the cost incurred by 1 from purchasing Δ^* 2-permits at price τ^*. The sum of these two terms is positive, i.e. the gain in abatement flexibility outweighs the loss associated with the purchase of 2-permits on the linked market to demonstrate compliance in 1. In other words, abatement costs in 1 decrease as the effective cap is less stringent than under autarky, which more than makes up for the monetary loss associated with the permit purchase. Similarly, linkage is also beneficial on net in jurisdiction 2 in which revenues from permit sales accrue, notwithstanding the associated increase in abatement costs.

Now consider the general case with heterogeneity in the three ETS parameters. The situation is depicted in Figure 1.D.1. Aggregate permit supply and demand curves are denoted

Figure 1.D.1: Bilateral linkage in the general case



Note: D_i: i's permit demand or marginal abatement cost; $\omega_i = S_i$: i's permit supply or emission cap; $\bar{e}_i$: i's unregulated emission for $i = \{1, 2, \{1, 2\}\}$. Aggregate quantities obtain by horizontal summation.

by the subscript {1,2} and obtain by horizontal summation. Their intersection determines the equilibrium on the linked market. Above considerations are summarized below.

Proposition 1.D.1. *In terms of comparative statics in a bilateral link,*
(*i*) *the bigger the size of the linked market, the bigger the aggregate gains from linkage;*
(*ii*) *the wider the relative dispersion in autarkic prices (i.e., in both abatement technologies and cap stringencies), the bigger the aggregate gains from linkage;*
(*iii*) *the smaller and less abatement flexible jurisdiction receives a relatively higher share of the aggregate gains from linkage;*
(*iv*) *there exists a relative size threshold above which the larger jurisdiction's gains from linkage decline consecutive to further interjurisdictional heterogeneity in size.*

Proof. Partially differentiating the aggregate linkage gains gives

$$\begin{aligned}
\left.\frac{\partial\Gamma^*}{\partial\gamma}\right|_{\bar{c},\beta} &= \frac{\beta\bar{c}\bar{c}_2(\gamma\bar{e}_2)^2(\bar{c}\gamma-1)}{\beta+\bar{c}} > 0 \text{ i.f.f. } \bar{c}\gamma > 1,\\
\left.\frac{\partial\Gamma^*}{\partial\beta}\right|_{\bar{c},\gamma} &= \frac{\bar{c}\bar{c}_2(\gamma\bar{e}_2)^2(\bar{c}\gamma-1)}{2(\beta+\bar{c})^2} > 0 \text{ for all}\,\beta,\\
\left.\frac{\partial\Gamma^*}{\partial\bar{c}}\right|_{\beta,\gamma} &= \frac{\beta\bar{c}_2(\gamma\bar{e}_2)^2(\gamma(2\beta+\bar{c})+1)(\bar{c}\gamma-1)}{2(\beta+\bar{c})^2} > 0 \text{ i.f.f. } \bar{c}\gamma > 1.
\end{aligned} \tag{1.D.20}$$

Under the assumption that $\bar{c}\gamma > 1$, the aggregate gain increases in the discrepancy in both cap stringency and abatement technology levels. Combined together, this means that the wider apart autarkic prices, the larger the overall gain. Γ^* also increases in β and $e_{0,2}$ unconditionally, i.e. the larger the linked market, the larger Γ^*. Note that similar results obtain for the net-selling jurisdiction 2. This is so because jurisdiction 2 is the reference.

We now turn to the net-purchasing jurisdiction 1 for which $\Gamma_1^* = \bar{c}\Gamma^*/(\beta+\bar{c})$

$$\begin{aligned}
\left.\frac{\partial\Gamma_1^*}{\partial\gamma}\right|_{\bar{c},\beta} &= \frac{\beta\bar{c}^2\bar{c}_2(\gamma\bar{e}_2)^2(\bar{c}\gamma-1))}{(\beta+\bar{c})^2} > 0 \text{ i.f.f. } \bar{c}\gamma > 1,\\
\left.\frac{\partial\Gamma_1^*}{\partial\beta}\right|_{\bar{c},\gamma} &= \frac{\bar{c}\bar{c}_2((\gamma\bar{e}_2)(\bar{c}\gamma-1))^2(\bar{c}-\beta)}{2(\beta+\bar{c})^3} > 0 \text{ i.f.f. } \beta < \bar{c},\\
\left.\frac{\partial\Gamma_1^*}{\partial\bar{c}}\right|_{\beta,\gamma} &= \frac{\beta\bar{c}_2(\gamma\bar{e}_2)^2(\bar{c}\gamma-1)(\gamma\bar{c}^2+(3\beta\gamma+1)\bar{c}-\beta)}{2(\beta+\bar{c})^3} > 0 \text{ i.f.f. } \bar{c}\gamma > 1.
\end{aligned} \tag{1.D.21}$$

First, under the assumption that $\bar{c}\gamma > 1$, 1's gain increases in 1's relative cap stringency. Indeed, for fixed $\bar{c}$ and β, the gain repartition is unchanged. In this case, an increase in γ leads to an increase in Γ^* which unambiguously leads to an increase in Γ_1^*. Second, 1's gain increases in 1's size provided 1 is not too big relative to 2, i.e. $\beta < \bar{c}$. While an increase in β always increases Γ, it also reduces the share of the overall gain that 1 gets. Third, 1's gain increases in 1's marginal abatement cost slope provided that $\bar{c} > \max\{\gamma^{-1}; \bar{c}^+\}$, where

$2\gamma\bar{c}^{+} = \sqrt{9\beta^2\gamma^2 + 10\beta\gamma + 1} - 3\beta\gamma - 1$. But note that $\bar{c}^{+}\gamma < 1$. Thus Γ_1^* increases in $\bar{c}$ by the assumption that $\bar{c}\gamma > 1$. □

Linkage is beneficial on net. While linkage is beneficial on net for the two jurisdictions, it is important to note that there are 'losers' and 'winners' within each jurisdiction. This point is made by Jaffe et al. (2009) and backed up by the laboratory experiments conducted by Cason & Gangadharan (2011). We consider the simple case where there are only two firms in jurisdiction 1, a and b. They have the same abatement technology $1/c_1$ but a is endowed with all the permits (ω_1) and b gets nothing. The net selling firm (a) is worse off as a result of the link because it sells its permits at a lower price. Conversely, the net buying firm (b) is better off because it acquires permits at a lower price. Because jurisdiction 1 as a whole is better off in the linked market, the gains of firm b outweigh the losses of firm a.

* * *

Chapter 2

Multilateral Linkages under Uncertainty

* * *

We propose a general model to describe and analytically study multilateral linkages between Emissions Trading Systems under uncertainty. We first show how the introduction of uncertainty reinforces the Pareto argument in favor of linking ETSs. As a novel and extremely useful tool, we also show that the gains in any multilateral linkage can be decomposed into gains in its internal bilateral linkages. This decomposition result enables us to characterize and quantify the individual and aggregate gains for an arbitrary number of linked jurisdictions and to demonstrate how linkage is a superadditive mechanism. Our theoretical results also imply that the global market, despite generating the largest aggregate savings, may not emerge endogenously and that jurisdictions' linkage preferences are not aligned. This makes our model apt for policy analysis shedding light on questions like which regions gain the most by linking their existing or planned ETSs.

We thus take the model to the data and calibrate it to jurisdictions' historical emissions to illustrate our theory and linkage preferences in a real-world context. In particular, this quantitative exercise provides some validity to the fact that the global market is not everyone's most preferred option. We further extend the policy application by introducing political costs associated with link formation. We then identify the nature of linkage coalition structures that are socially efficient and compare the ability of alternative inter-jurisdictional cost-sharing arrangements in steering jurisdictions towards these structures.

* * *

This Chapter is an adaptation of a collaboration with Baran Doda and Luca Taschini.

2.1 Introduction

As in Chapter 1, current research on linking Emissions Trading Systems has primarily focused on bilateral linkages. By comparison, a formal study of multilateral linkages poses numerous challenges, as discussed in Mehling & Görlach (2016), who consider different options for a successful management of these linkages. In this Chapter, we propose a language and develop a model that allows us to describe and study multilateral linkages between ETSs under uncertainty, thereby generalizing Doda & Taschini (2017), whose analysis solely focuses on bilateral linkages. In particular, this Chapter makes two contributions to the intensifying debate on system integration in the post Paris Agreement era.

First, from a theory perspective, we propose a language and develop a general theory that allows us to describe and study multilateral linkages among ETSs. A novel and extremely useful tool that emerges from our analysis is the formula we derive for decomposing the gains in a multilateral linkage into gains in its internal bilateral linkages. This decomposition result enables us to characterize and quantify the individual and aggregate gains for an arbitrary number of linked jurisdictions, and to demonstrate how linkage is a superadditive mechanism. This makes our model apt for policy analysis shedding light on questions like which regions gain the most by linking their existing or planned ETSs.

Second, we take the model to the data and illustrate the quantitative implications of our general theory using a real-world example. In particular, we show that despite generating the largest aggregate savings, the global market may not be everyone's most preferred option. We further extend the policy application by introducing linkage costs and comparing the ability of alternative inter-jurisdictional cost-sharing arrangements in obtaining the socially efficient structure of linkage coalitions.

Our model explores the gains from linking under uncertainty by introducing idiosyncratic shocks à la Weitzman (1974) and Yohe (1976, 1978). To isolate those gains that are directly attributable to linkage, we assume that jurisdictional emissions caps are exogenous and fixed permanently. Therefore, there is no strategic interaction between jurisdictions' linking decisions and no anticipation of linkage when emissions caps are selected. This assumption is deliberate. Indeed, our aim is to understand the determinants of the economic gains from multilateral linkage and to be able to characterize them analytically.

In practice, emissions caps result from complex negotiation processes involving a host of domestic stakeholders with vested interests that must accommodate jurisdiction-specific constraints of different sorts (Flachsland et al., 2009b). Jurisdictions may also implement policies that are supplemental to ETSs, which can further reflect different priorities on both the appropriate level of domestic abatement efforts and the desirable level of the underlying price signal. As a consequence, it seems unlikely that jurisdictions select their domestic 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.

With invariant jurisdictional emissions caps, we can proceed with a combinatorial approach to analyzing all possible multilateral linkages. By construction, linkage is always mutually beneficial, i.e. jurisdictions are always better off in any linkage coalition than under autarky. However, they gain more when participating in some linkage coalitions than in others. In this respect, our analysis allows us to rank alternative coalitions from a jurisdictional perspective and thereby characterize jurisdictional linkage preferences.

There are potential gains from linkage whenever there exists a price differential between jurisdictions under autarky. In turn, this autarkic price wedge can be the result of varying jurisdiction-specific ambition levels or jurisdiction-specific shocks. Most existing analyses of linkage concentrate on the former as the sole source of gains. For instance, the determinants of the former source of gains were analyzed in Chapter 1, cf. Proposition 1.D.1.

In this Chapter, we argue that these two sources of gains exist independently of each other, and devote most of our attention to characterizing the latter. We will formally show how this choice is inconsequential for our theoretical results. We also show that regardless of the magnitude of the first source, i.e. even when jurisdictions have identical ambition, the second source reinforces the Pareto-argument in favor of linking relative to autarky. Analytically, these two sources show up as two non-negative components of the jurisdictional expected linkage gains: the first component is proportional to the square of the difference between the autarky and linking expected permit prices and the second component is proportional to the variance of the difference between the autarky and linking permit prices.

The theoretical foundations for gains in bilateral linkages are well-understood and intuitive: linkages with larger systems are more beneficial, all else constant.In addition, a jurisdiction prefers the permit demand in its partner's system to be variable and weakly correlated with its own. Our formal approach is useful as we show that these insights do not translate easily to multilateral linkages. In many ways, however, we will see that bilateral linkages constitute the cornerstone of our analysis of multilateral linkage.

To see why, consider a special case with three jurisdictions which have independent shocks with identical variances. Also, let two jurisdictions have same size and the third one be larger. When evaluating possible linkages, the larger jurisdiction has little incentive to link exclusively with a single smaller jurisdiction and prefers to be part of the trilaterally linked market instead. Conversely, smaller jurisdictions prefer a bilateral linkage with the larger jurisdiction. Intuitively, this is because in all possible linking arrangements the linking price will settle closer to the autarky price of the large jurisdiction. Therefore, its gains from trade will be greater in the trilateral link as its own impact on the linking price is attenuated relative to bilateral linkages. This argument reverses for the two smaller jurisdictions.

In general, however, the identification of multilateral linkage outcomes and jurisdictional preferences in these linkages are not clear when one moves away from the special cases. Moreover, the number of possible linkage coalitions and coalition structures (i.e., partitions of the set of jurisdictions) increases exponentially with the number of jurisdictions. For instance, with four jurisdictions there are six possible bilateral linkages (with two jurisdictions in autarky), three groups of two bilateral linkages, four trilateral linkages (with one jurisdiction in autarky), one quadrilateral linkage, and complete autarky where each system operates in isolation; i.e. 15 coalition structures in total. With 10 jurisdictions, there are already 1,013 and 115,975 possible linkage coalitions and coalition structures.

Despite this apparent complexity, our model can in principle handle a significant number of jurisdictions and complex coalition structures. Indeed, we show that any multilateral linkage can be decomposed into its internal bilateral linkages. This decomposition result allows us to characterize aggregate and jurisdictional gains from any linkage coalition as a size-weighted function of aggregate gains from all bilateral links that can be formed within this coalition. Moreover, we show that linkage is superadditive, i.e. the aggregate expected gains from the union of disjoint coalitions of linked ETSs is no less than the sum of separate coalitions' expected gains. In particular, we provide an analytical formula for this economic gain as a function of coalitional sizes and shock characteristics.

A natural consequence of superadditivity is 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 coalition from the perspective of an individual jurisdiction. In fact, the conditions for the global market to be the most preferred coalition universally are unlikely to be satisfied in practice. The combination of superadditivity and impracticality of transfers, say due to the prevalence of political-economy constraints, implies that the jurisdictional linkage preferences within an arbitrary coalition may not be aligned. This could be one reason why linkages are rarely observed in practice.

In our model the volatility of the permit price in any linkage coalition is a well-defined object, whose properties we study. When the shocks affecting individual jurisdictions are correlated, there is no reason to expect the variance of the linkage price to decline as the number of jurisdictions participating in the coalition increases. However, we show that the most volatile jurisdictions will always experience reduced price volatility under linking relative to autarky as their domestic shocks are spread over a larger market and thus better buffered. Conversely, jurisdictions with the least volatile shocks may face an increase in price volatility under linking because links create exposure to shocks occurring abroad. This is more likely to be the case when these jurisdictions are small as the influence of larger jurisdictions on the link outcome will be relatively more pronounced.

Finally, we take the model to the data in order to provide some quantitative implications of our general theory and demonstrate the potential shortcomings of the existing theory of bilateral linkages using a real-world example. The model is loosely calibrated to historical emissions of five jurisdictions, which allows us to provide a quantitative illustration of the determinants of their linkage preferences. We concentrate our analysis on the ambition-independent source of linkage gains by equating expected autarkic prices across jurisdictions. In this quantitative exercise, despite generating the largest aggregate savings, the global market turns out *not* to be the most preferred coalition for every jurisdiction.

As another application of the model, we explore further policy implications by introducing linkage costs to account for political-economy frictions and thus bring in minimal realism. Indeed, the few practical instances of linkage were bilateral in nature and occurred between (*i*) jurisdictions with aligned ETSs (e.g., California and Québec) and thus relatively low linkage costs; (*ii*) one small jurisdiction wishing to join a much larger system, the former thus ready to bear all the costs associated with the link (e.g., Europe and Norway or Europe and Switzerland). We take explicit account of this observation and assume linkage costs have two components: implementation costs that are higher the larger the jurisdictions involved and negotiation costs that are higher the larger the number of participants. The magnitude of linkage costs is thus endogenous to linkage coalition formation. This reflects that (*i*) it is more costly for large jurisdictions to harmonize their domestic schemes in accordance with the linked system blueprint; (*ii*) the more numerous the parties sitting at the negotiation table, the more difficult to find a compromise (Keohane & Victor, 2016). In the literature, these considerations have given rise to concepts such as minilateralism (Falkner, 2016) or polycentrism (Ostrom, 2009; Dorsch & Flachsland, 2017).

In the presence of linkage costs and with alternative assumptions about how they are shared between partnering jurisdictions, we show how non-degenerate linkage coalition structures may yield higher aggregate net gains than the global market. We observe that such structures may feature some jurisdictions that remain in autarky unlinked as well as coexisting linkage coalitions. We also find noticeable differences across cost-sharing arrangements. In a world where outright permit or cash transfers can run into significant political-economy hurdles, these differences can have far-reaching policy implications for initiatives aiming to steer jurisdictions towards efficient policy architectures, such as the World Bank's Partnership for Market Readiness and the G7 Carbon Market Platform.

The rest of this Chapter is organized as follows. Section 2.2 reviews the related literature. Section 2.3 presents the modeling framework. Section 2.4 offers a primer on bilateral linkages and builds intuition for linking under uncertainty. Section 2.5 discusses complexities that arise in multilateral settings using a simple three-jurisdiction world. Section 2.6 then presents the general theory of multilateral linkages and states our main analytical results. The quantitative illustration of the model is in Section 2.7. Section 2.8 contains a policy application in the presence of linkage costs and cost-sharing arrangements. Section 2.9 concludes. An Appendix contains the analytical derivations and proofs (2.A), discusses the generalization of the model (2.B), provides the analytical forms for linkage indifference frontiers (2.C) and finally describes our calibration methodology (2.D).

2.2 Related literature

Our model 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). First, de Meza & van der Ploeg (1987) consider a multinational firm whose objective is to maximize its expected profits by relocating production across plants situated in different countries with plant-specific shocks but crucially, the sizes of plants are irrelevant. There is thus a conceptual difference with our analysis of jurisdictional economic gains from linkage. Second, Yates (2002) develops a similar framework where a single regulator decides whether to allow trading across firms within a given jurisdiction in the presence of asymmetric information on abatement costs between firms and the regulator. Yates finds that full decentralization is socially optimal in the case of uniformly-mixed pollutants, anticipating our result that the global market is the most desirable outcome from an aggregate perspective.[1] However, he does not analyze the effects of decentralization at the firm level.

Regarding linkage, a recent theoretical study of the optimal scope of price and quantity policies by Caillaud & Demange (2017) analyzes the effect of merging ETSs on a global scale. Caillaud & Demange obtain the analog of Proposition 2.6.3 but do not decompose gains from merging ETSs any further nor do they study the mechanisms governing multilateral linkages and how the benefits are shared among participating jurisdictions. Analogously, Hennessy & Roosen (1999) study merger incentives among firms subject to a permit market when emissions are stochastic. Hennessy & Roosen find merging firms is beneficial almost surely for both risk-neutral and risk-averse firms. However, in their model the incentive to merge arises from the non-linearity in firms' objective functions induced by penalties charged above a predetermined emission threshold. Interestingly, they also find that merging is superadditive (i.e., total expected profits for the merged firms can be no less than the sum of expected profits for separate firms) but stop short of the description of the properties of this mechanism (as we do in Proposition 2.6.6) and its implications for merging firms.

Additionally, using a computable general equilibrium model, Carbone et al. (2009) generate estimates of economy-wide gains from linkage by considering the formation of a single coalition of linked ETSs with endogenous selection of non-cooperative emissions caps. Similarly, Heitzig (2013) numerically explores the dynamic process of formation of coalitions of linked ETSs where jurisdictions also have the possibility to coordinate on emissions cap selection. These last two contributions, however, do not characterize multilateral linkage analytically nor do they investigate the determinants of gains from linkage.

Flachsland et al. (2009b), Jaffe et al. (2009), Fankhauser & Hepburn (2010b) and Pizer & Yates (2015) argue that linkage ought to reduce overall permit price volatility by pointing out that domestic shocks are dispersed over a larger market.[2] Empirically, this claim is supported by Jacks et al. (2011) who find that gradual market integration has reduced overall commodity price volatility over time since 1700. At the same time these three studies note that this by no means imply that price volatility experienced by linked jurisdictions is actually lowered as some may face greater exposure to link-transmitted shocks. Empirically, similar results have been established by Caselli et al. (2015) in the international trade

[1]In fact, Yates (2002) analyzes trading across 'natural divisions' of the considered permit market, e.g. compliance periods, firms, regions, etc. With the interpretation that divisions correspond to time periods, Yates & Cronshaw (2001), Feng & Zhao (2006) and Fell et al. (2012b) show that providing for intertemporal trading of permits can be an optimal regulatory response to abatement cost shocks.

[2]Relatedly, Colla et al. (2012) show that the presence of speculators with whom risk averse firms can trade permits augments the risk bearing capacity of the market and tends to reduce permit price volatility.

context. They show that openness to international trade has potential to lower GDP volatility when country-specific shocks are the most significant source of volatility (i.e., 'diversification through trade') but underline that this is not guaranteed in general.

Finally, because we assume invariant caps to solely capture economic gains from linkage, our model deviates from the literature on self-enforcing international environmental agreements (IEA) initiated by Carraro & Siniscalco (1993) and Barrett (1994) in three important ways. First, we rule out strategic interactions and spillovers associated with linkage. For instance, Helm (2003) shows how anticipation of linkage alters jurisdictional incentives in the determination of their domestic caps (see Appendix 2.B.4).[3] Second, most of this literature studies a Cartel game where only one single coalition can form and sets aside the question of multiple coalitions. It typically assumes that coalition members choose their emission caps cooperatively (the coalition is a metaplayer).[4] Third, we abstract from coalition stability considerations. In general, the literature finds somewhat pessimistic results regarding the size of stable coalitions and identifies a trade-off between efficiency and stability.[5] We also note that the different coalition membership rules and equilibrium concepts in the literature lead to different predictions regarding stability.[6]

We note that transfers can increase participation in and stability of coalitions (Nagashima et al., 2009; Lessmann et al., 2015). We approach transfers indirectly via alternative linkage cost-sharing rules rather than via alternative permit allocation rules as is usual (Altamirano-Cabrera & Finus, 2006).[7] Finally note that a recent contribution by Caparrós & Péreau (2017) shows that a sequential negotiation process always leads to the grand coalition even when it is not stable in a multilateral (one-shot) negotiation stage.

[3]Consider also two more recent contributions. For instance, Habla & Winkler (2017) show that a principal-agent problem leads to an over-issuance of permits and may undermine the incentives to link. By contrast, Holtsmark & Midttømme (2015) manage to incentivize tighter permit issuances through time across linked ETSs by tying the dynamic emissions game to the dynamics of investments in renewables.

[4]Absent uncertainty, however, interjurisdictional emissions trading has no effect on the overall emissions level as the effort sharing is already efficient from the coalition's perspective. Notable exceptions include Finus & Maus (2008) and Carbone et al. (2009), e.g. via non-cooperative cap-setting by coalition members.

[5]McGinty (2007) notes that these pessimistic conclusions stem in part from the assumption that jurisdictions are symmetric. He finds that larger coalitions can be stable when allowing for asymmetry.

[6]For instance, Ray & Vohra (1997) study equilibrium binding agreements where coalitions can break up into smaller sub-coalitions, but not vice versa. Ray & Vohra (1999) consider some kind of Rubinstein-type bargaining game for coalition formation. Bloch (1995) and Bloch (1996) analyzes an alternative-offers bargaining game and an infinite-horizon coalition formation game, respectively, both requiring unanimity for a coalition to form. Yi (1997) considers alternative coalition membership rules, e.g. open membership, unanimity and equilibrium bindingness. In the climate context, Osmani & Tol (2009) analyze farsightedly stable linkage coalitions in the sense of Chwe (1994). Finally, Konishi & Ray (2003) consider a dynamic coalition formation process with farsighted players. With a similar sequential linking process, Heitzig (2013) allows for coalition members to simply link markets but also coordinate on cap selection.

[7]On a different but related note, Gersbach & Winkler (2011) analyze the ability of refunding schemes to improve upon standard international permit markets. They show that jurisdictions are relatively better off with refunding than without and further have an incentive to tighten their issuance of permits.

2.3 The modeling framework

We consider a standard static model of competitive markets for emission permits designed to regulate uniformly-mixed pollution in several jurisdictions with independent regulatory authorities. We make four key assumptions. First, we assume separability between markets for permits and markets for other goods and services. 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, we assume that the only uncertainty is in the form of additive shocks affecting the jurisdictions' unregulated levels of emissions. These two assumptions are somewhat restrictive but relatively standard in the literature (Weitzman, 1974; Yohe, 1976). Third, we represent jurisdictions' benefits from emissions assuming quadratic functional forms. This is standard, allows for derivation of analytical results and can be viewed as a local approximation of more general functional specifications (Newell & Stavins, 2003). Fourth, the international political economy dimension is omitted. Each jurisdiction has a regulatory authority who can design policies independently of authorities in other jurisdictions with no anticipation of linkage.

Jurisdictions. There are n jurisdictions and $\mathcal{I} = \{1, \ldots, n\}$ denotes the set of jurisdictions. Benefits from emissions in jurisdiction $i \in \mathcal{I}$ are a function of its level of emissions $q_i \geq 0$. Additionally, a jurisdiction-specific shock θ_i affects the intercept of the marginal benefit schedule such that

$$B_i(q_i; \theta_i) = (b_1 + \theta_i)q_i - \frac{b_2}{2\psi_i} q_i^2. \tag{2.3.1}$$

The parameters $b_1, b_2 > 0$ are identical across jurisdictions and $\psi_i > 0$ is a parameter specific to jurisdiction i. The ratio b_2/ψ_i controls the slope of i's linear marginal benefit schedule. We adopt the interpretation that b_2 characterizes the abatement technology and that ψ_i is a measure of the volume of emissions to be regulated in jurisdiction i.[8] To see this, note that jurisdiction i's optimal emissions in response to an arbitrary permit price $p > 0$ are given by $q_i^*(p) = \psi_i(b_1 + \theta_i - p)/b_2$. Then jurisdiction i's laissez-faire emissions (i.e., when $p = 0$) amount to

$$\tilde{q}_i = \psi_i(b_1 + \theta_i)/b_2, \tag{2.3.2}$$

which are proportional to ψ_i. Below we refer to ψ_i as the size of jurisdiction i and emphasize it is imperfectly correlated with the jurisdiction's other relevant economic dimensions such as GDP or population. Business-as-usual emissions in i are defined by $\bar{q}_i \doteq \mathbb{E}\{\tilde{q}_i\} = \psi_i b_1/b_2$.

[8] With a common b_2 parameter, an alternative, observationally-equivalent interpretation is that a high ψ represents a jurisdiction who has access to low-cost abatement opportunities at the margin.

For analytical convenience and without loss of generality, we assume that jurisdictional shocks are mean-zero with constant variance and may be correlated across jurisdictions, i.e.

$$\mathbb{E}\{\theta_i\} = 0,\ \mathbb{V}\{\theta_i\} = \sigma_i^2,\ \text{and } \mathrm{Cov}\{\theta_i;\theta_j\} = \rho_{ij}\sigma_i\sigma_j \text{ with } \rho_{ij} \in [-1;1]. \tag{2.3.3}$$

These shocks capture the net effect of stochastic factors that may influence emissions and their associated benefits, e.g. business cycles and technology shocks, jurisdiction-specific events, changes in the price of factors of production, weather fluctuations, etc. For instance, $\theta_i > 0$ can be a favorable productivity shock that increases jurisdiction i's benefits from emissions, and as a consequence, emissions relative to baseline. We assume that $\theta_i > -b_1$ for every jurisdiction and shock realization. This is innocuous and guarantees that $\tilde{q}_i$ is always positive. In sum, jurisdictions are identical up to size and shock.

Emissions caps. The emissions cap profile $(\omega_i)_{i\in\mathcal{I}}$ is exogenous. By implication, caps are independent of the decision to link, i.e. they 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 thereby rules out spillovers attributable to linkage. While this assumption is restrictive, it allows us to (*i*) have well-defined (i.e., stable) autarky outcomes; (*ii*) isolate the economic gains directly due to linkage; and (*iii*) compare these gains across multilateral linkages in a meaningful way.

In order to focus our analysis on the benefits of linkage arising from shocks, we further restrict jurisdictional caps to be proportional to jurisdictional size by a common factor of proportionality, that is

$$\omega_i = A \cdot \psi_i \text{ for all } i \in \mathcal{I}, \tag{2.3.4}$$

where $A \in (0; b_1/b_2)$, which means that caps are stringent relative to baseline. Notice the negative relationship between A and the level of ambition implicitly embedded in domestic caps (specifically, as $A \to b_1/b_2$, $\omega_i \to \bar{q}_i$). Moreover, our assumption that A is common to all jurisdictions implies that *expected* autarkic permit prices are equal across jurisdictions. This sets the linkage gains associated with the equalization of *expected* marginal benefits across partnering jurisdictions to zero, and limits the benefits of linking only to those arising from shocks. In Appendix 2.B we show that different ambition levels across jurisdictions is inconsequential for our results and discuss the implications of both alternative cap selection mechanisms and strategic manipulation of caps in anticipation of linkage.

Autarkic equilibria. Under autarky, each jurisdiction complies with its domestic cap. We assume that $\theta_i > b_2\omega_i/\psi_i - b_1$ for all $i \in \mathcal{I}$ to exclusively focus on interior equilibria.[9] That is, restrictions on shocks are such that all domestic caps are binding and autarkic permit prices are positive

$$\bar{p}_i = \bar{p} + \theta_i > 0 \text{ for all } i \in \mathcal{I}, \tag{2.3.5}$$

where $\bar{p} = b_1 - b_2 A$ is the expected autarkic permit price, and as noted above, is equal across jurisdictions. Therefore, jurisdictions with positive (resp. negative) shock realizations have autarkic prices higher (resp. lower) than $\bar{p}$. When autarkic prices differ, 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- to low-shock jurisdictions until the autarkic price differential is arbitraged away. As shown below, this is precisely the function that linkage performs.

2.4 Bilateral linkage

2.4.1 Bilateral linkage equilibria

Consider a bilateral link between two jurisdictions i and j and call it $\{i, j\}$-linkage. An interior $\{i, j\}$-linkage equilibrium consists of the triple $(p_{\{i,j\}}, q_{\{i,j\},i}, q_{\{i,j\},j})$ where $p_{\{i,j\}}$ is the equilibrium permit price on the linked market $\{i, j\}$ and $q_{\{i,j\},i}$ (resp. $q_{\{i,j\},j}$) is the equilibrium emissions level in jurisdiction i (resp. j). The $\{i, j\}$-linkage equilibrium price reads

$$p_{\{i,j\}} = \bar{p} + \hat{\Theta}_{\{i,j\}} = \frac{\psi_i\bar{p}_i + \psi_j\bar{p}_j}{\psi_i + \psi_j}, \text{ where } \hat{\Theta}_{\{i,j\}} = \frac{\psi_i\theta_i + \psi_j\theta_j}{\psi_i + \psi_j} \tag{2.4.1}$$

is the size-averaged shock in the linked system $\{i, j\}$. Because the linking price is also the size-weighted average of autarkic prices, it will be closer to that of the larger jurisdiction. Abatement reallocation under $\{i, j\}$-linkage is such that jurisdictional marginal benefits are equalized and the aggregate constraint on emissions $\Omega_{\{i,j\}} = \omega_i + \omega_j$ is met (market closure).

[9] In a corner, when jurisdiction i's domestic cap happens to be slack for instance, its autarkic price is zero and it emits up to its laissez-faire emissions. In this case, linking jurisdiction i to a another positive-price jurisdiction would result in higher aggregate emission levels than operating these two systems in isolation. We note that this could reduce the benefits from linking. However, restricting our attention to interior equilibria allows substantial analytical simplification (i) in computing expected gains from linkage as pollution damages are constant and thus cancel out; (ii) because we can uniquely determine the linking price without arbitrarily specifying bargaining power between permit sellers and buyers, i.e. who is making the price. We could replace the assumption about interior equilibrium with one about bargaining power and proceed numerically. We would find similar results because corners are typically rare. See Goodkind & Coggins (2015) for an extension of Weitzman (1974) accounting for corner solutions. See also Lecuyer & Quirion (2013, 2016) for a characterization of an optimal policy mix in the presence of uncertainty about cap bindingness and possible price-zero corners.

In particular, net jurisdictional demands for permits under $\{i, j\}$-linkage write

$$q_{\{i,j\},i} - \omega_i = \frac{\psi_i}{b_2}(\bar{p}_i - p_{\{i,j\}}) = \frac{\psi_i \psi_j}{b_2\,(\psi_i + \psi_j)}(\theta_i - \theta_j), \tag{2.4.2a}$$

$$q_{\{i,j\},j} - \omega_j = \frac{\psi_j}{b_2}(\bar{p}_j - p_{\{i,j\}}) = \frac{\psi_i \psi_j}{b_2\,(\psi_i + \psi_j)}(\theta_j - \theta_i). \tag{2.4.2b}$$

Linkage thus eliminates the post-shock wedge in realized autarkic prices, the magnitude of which is measured by $|\theta_i - \theta_j|$. For given shock realizations, the high-shock (i.e., high-price) jurisdiction will 'import' permits from the low-shock (i.e., low-price) jurisdiction because it values them more. In essence, bilateral linkage increases the effective cap in the high-shock jurisdiction and reduces that of the low-shock jurisdiction by the same amount, thereby leaving the aggregate emissions cap $\Omega_{\{i,j\}}$ unchanged.

Because aggregate emissions are constant, the difference between jurisdictional benefits under $\{i, j\}$-linkage and autarky corresponds to the jurisdictional gains from the bilateral link. We denote these as $\delta_{\{i,j\},i}$ and $\delta_{\{i,j\},j}$ and show in Appendix 2.A.1 that

$$\delta_{\{i,j\},i} = \frac{b_2}{2\psi_i}(q_{\{i,j\},i} - \omega_i)^2, \tag{2.4.3a}$$

$$\delta_{\{i,j\},j} = \frac{b_2}{2\psi_j}(q_{\{i,j\},j} - \omega_j)^2. \tag{2.4.3b}$$

These are non-negative quantities, i.e. $\{i, j\}$-linkage is always mutually beneficial. Plugging Equations (2.4.2a) and (2.4.2b) into Equations (2.4.3a) and (2.4.3b) respectively gives

$$\delta_{\{i,j\},i} = \frac{\psi_i}{2b_2}(\bar{p}_i - p_{\{i,j\}})^2 = \frac{\psi_i \psi_j^2}{2b_2(\psi_i + \psi_j)^2}(\theta_i - \theta_j)^2, \tag{2.4.4a}$$

$$\delta_{\{i,j\},j} = \frac{\psi_j}{2b_2}(\bar{p}_j - p_{\{i,j\}})^2 = \frac{\psi_j \psi_i^2}{2b_2(\psi_i + \psi_j)^2}(\theta_i - \theta_j)^2. \tag{2.4.4b}$$

By summation, aggregate gains from $\{i, j\}$-linkage amount to

$$\Delta_{\{i,j\}} \doteq \delta_{\{i,j\},i} + \delta_{\{i,j\},j} = \frac{\psi_i \psi_j}{2b_2(\psi_i + \psi_j)}(\theta_i - \theta_j)^2. \tag{2.4.5}$$

Taking expectations then yields

$$\mathbb{E}\{\Delta_{\{i,j\}}\} = \underbrace{\frac{\psi_i \psi_j}{2b_2(\psi_i + \psi_j)}}_{PSE_{\{i,j\}}} \Big(\underbrace{\sigma_i^2 + \sigma_j^2}_{VE_{\{i,j\}}} \underbrace{-2\rho_{ij}\sigma_i\sigma_j}_{DE_{\{i,j\}}} \Big) \geq 0, \tag{2.4.6}$$

where adapt the terminology in Doda & Taschini (2017) to indicate the pair size effect

($PSE_{\{i,j\}}$), volatility effect ($VE_{\{i,j\}}$) and dependence effect ($DE_{\{i,j\}}$) associated with $\{i,j\}$-linkage. We observe that the influence of jurisdictional sizes (resp. shocks) is confined to PSE (resp. VE and DE). We also observe that the aggregate expected gain is (i) 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,[10] (ii) increasing in both jurisdictional volatilities and sizes, (iii) is higher the more weakly correlated jurisdictional shocks are, and (iv) for a given aggregate size, maximal when jurisdictions have equal sizes.

In addition, we note that the aggregate gross gain is apportioned between jurisdictions in inverse proportion to size.[11] Formally, $\mathbb{E}\{\delta_{\{i,j\},i}\}/\mathbb{E}\{\delta_{\{i,j\},j}\} = \psi_j/\psi_i$. This is so because, for a given volume of permit trade, the *distance* between the autarkic and linkage prices is relatively greater in the smaller jurisdiction. This is a crucial point to which we will come back further on. For future reference, we write i's gains from $\{i,j\}$-linkage as

$$\mathbb{E}\{\delta_{\{i,j\},i}\} = PSE_{\{i,j\},i} \times \Big(VE_{\{i,j\}} + DE_{\{i,j\}}\Big), \tag{2.4.7}$$

where $PSE_{\{i,j\},i} = \psi_j PSE_{\{i,j\}}/(\psi_i + \psi_j)$ and note that $VE_{\{i,j\}} = VE_{\{i,j\},i} = VE_{\{i,j\},j}$ as well as $DE_{\{i,j\}} = DE_{\{i,j\},i} = DE_{\{i,j\},j}$. In sum, a jurisdiction prefers a link with a relatively larger jurisdiction whose permit demand is volatile and weakly correlated to its own.

2.4.2 Bilateral linkage with binary shocks

Assume that jurisdictional shocks in i and j are binary. Using conventional notations for lotteries and given Equation (2.3.3), it must thus be that $\theta_i = (+\sigma_i, .5; -\sigma_i, .5)$ and $\theta_j = (+\sigma_j, .5; -\sigma_j, .5)$. We will consider two cases in turn.

Case 1: $\boldsymbol{\psi_i = 2\psi_j = 2\psi}$, $\boldsymbol{\sigma_i = \sigma_j = \sigma}$ **with arbitrary** $\boldsymbol{\rho_{ij}}$

In this case, the shock affecting the joint system $\{i,j\}$ satisfies

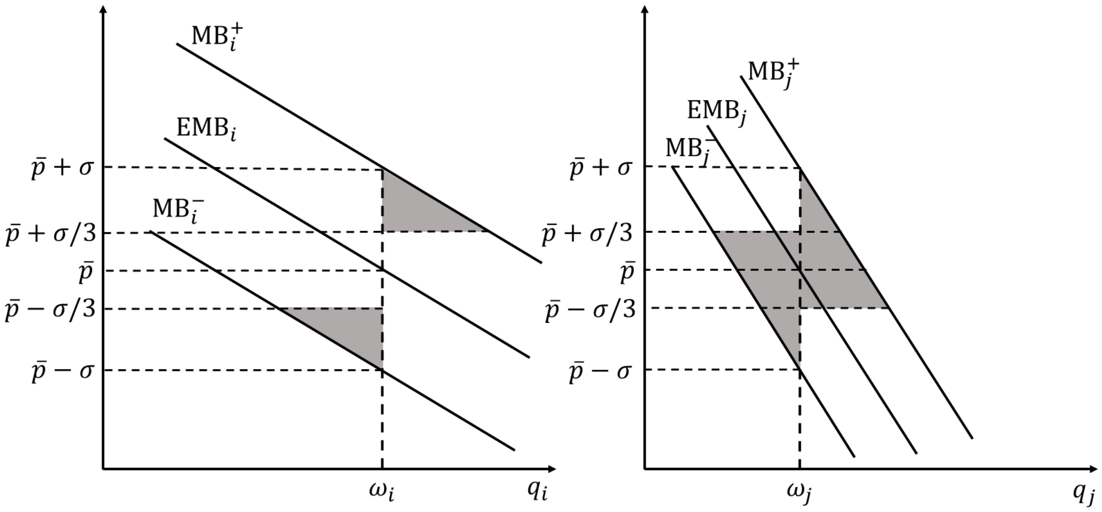
$$\hat{\Theta}_{\{i,j\}} = \Big(+\sigma, (1+\rho_{ij})/4; \sigma/3, (1-\rho_{ij})/4; -\sigma/3, (1-\rho_{ij})/4; -\sigma, (1+\rho_{ij})/4 \Big). \tag{2.4.8}$$

Assume the positive shock $+\sigma$ occurs in i. It also occurs in j with probability $(1+\rho_{ij})/2$, in which case autarkic 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 $\bar{p}_i - \bar{p}_j = 2\sigma \neq 0$ and there are positive gains from linkage. Note that the linking price settles at $p_{\{i,j\}} = (2\bar{p}_i + \bar{p}_j)/3 =$

[10]Even when jurisdictional shocks are perfectly correlated, differences in shock volatilities can generate gains from linkage. Then, the larger the difference in volatility levels, the larger the gains from the link.

[11]With the alternative interpretation that ψ measures jurisdictional abatement technology level, the jurisdiction with a higher-cost abatement technology gains relatively more from the link.

Figure 2.1: Expected jurisdictional gains from $\{i,j\}$-linkage



Note: Jurisdictional caps are such that $\omega_i = A\psi_i = 2A\psi_j = 2\omega_j$. $\text{EMB}_i = b_1 - b_2 q_i/\psi_i$ denotes the expected marginal benefits from emissions in i, $\text{EM}_i^+ = \text{EMB}_i + \sigma$ and $\text{EM}_i^- = \text{EMB}_i - \sigma$.

$\bar{p}+\sigma/3$ because i is twice as large as j. The case of the negative shock occurring in i is symmetric. Jurisdictional price wedges between autarky and $\{i,j\}$-linkage thus read

$$|\bar{p}_i - p_{\{i,j\}}| = \Big(+2\sigma/3, (1-\rho_{ij})/2; 0, (1+\rho_{ij})/2\Big), \tag{2.4.9a}$$

$$|\bar{p}_j - p_{\{i,j\}}| = \Big(+4\sigma/3, (1-\rho_{ij})/2; 0, (1+\rho_{ij})/2\Big). \tag{2.4.9b}$$

The situation is graphically depicted in Figure 2.1 where the shaded triangles represent gains from linkage when shock realizations do open up a price wedge across jurisdictions. Each triangle occurs with probability $(1-\rho_{ij})/4$ and those in jurisdiction i have an area equal to $\frac{1}{2} \times |\bar{p}_i - p_{\{i,j\}}| \times \frac{\psi_i}{b_2}|\bar{p}_i - p_{\{i,j\}}|$. We can thus infer that i's expected gains from $\{i,j\}$-linkage write

$$\mathbb{E}\{\delta_{\{i,j\},i}\} = \frac{\psi_i}{2b_2}\mathbb{E}\{(\bar{p}_i - p_{\{i,j\}})^2\}. \tag{2.4.10}$$

This also obtains by directly taking expectations in Equation (2.4.4a) and will carry over to multilateral linkage – cf. Proposition 2.6.3. Thus, j benefits more from $\{i,j\}$-linkage than i does because the expected autarky-link price wedge is wider for j than for i. Intuitively, this is because the linking price settles closer to the autarkic price of the larger jurisdiction.

Also note that correlation solely influences the probabilities of realization of possible price wedges, but not their magnitude. 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 $\rho_{ij} = 0$, jurisdictional gains from $\{i,j\}$-linkage amount to $\mathbb{E}\{\delta_{\{i,j\},i}\} = 2\psi\sigma^2/(9b_2)$ and $\mathbb{E}\{\delta_{\{i,j\},j}\} = 4\psi\sigma^2/(9b_2)$.

Case 2: $\boldsymbol{\psi_i = \psi_j = \psi}$, $\boldsymbol{\sigma_i = 2\sigma_j = 2\sigma}$ **with arbitrary** $\boldsymbol{\rho_{ij}}$

In this case, the shock affecting the joint system $\{i,j\}$ satisfies

$$\hat{\Theta}_{\{i,j\}} = \Big(+3\sigma/2, (1+\rho_{ij})/4; \sigma/2, (1-\rho_{ij})/4; -\sigma/2, (1-\rho_{ij})/4; -3\sigma/2, (1+\rho_{ij})/4\Big). \quad (2.4.11)$$

Assume the positive shock $+2\sigma$ occurs in i. When the positive shock $+\sigma$ also occurs in j (with probability $(1+\rho_{ij})/2$) a positive price wedge exists because jurisdictional volatility levels differ ($\bar{p}_i - \bar{p}_j = \sigma$) 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 ($\bar{p}_i - \bar{p}_j = 3\sigma$) with linking price $p_{\{i,j\}} = \bar{p} + \sigma/2$. Again, the case of the negative shock occurring in i is symmetric. For all shock realizations, the linking price is equidistant from the two autarkic prices because jurisdictions have same size. Jurisdictional price wedges thus coincide and read

$$|\bar{p}_i - p_{\{i,j\}}| = |\bar{p}_j - p_{\{i,j\}}| = \Big(+3\sigma/2, (1-\rho_{ij})/2; +\sigma/2, (1+\rho_{ij})/2\Big). \quad (2.4.12)$$

In turn, this means that expected jurisdictional gains are equal. In other words, two jurisdictions of equal size benefit equally from a higher VE. Therefore, for given aggregate gains from a bilateral link, only relative jurisdictional sizes matter in determining how they are apportioned between jurisdiction. In particular, when $\rho_{ij} = 0$, jurisdictional gains from $\{i,j\}$-linkage amount to $\mathbb{E}\{\delta_{\{i,j\},i}\} = \mathbb{E}\{\delta_{\{i,j\},j}\} = 5\psi\sigma^2/(8b_2)$.

2.4.3 Bilateral linkage preferences in a three-jurisidiction world

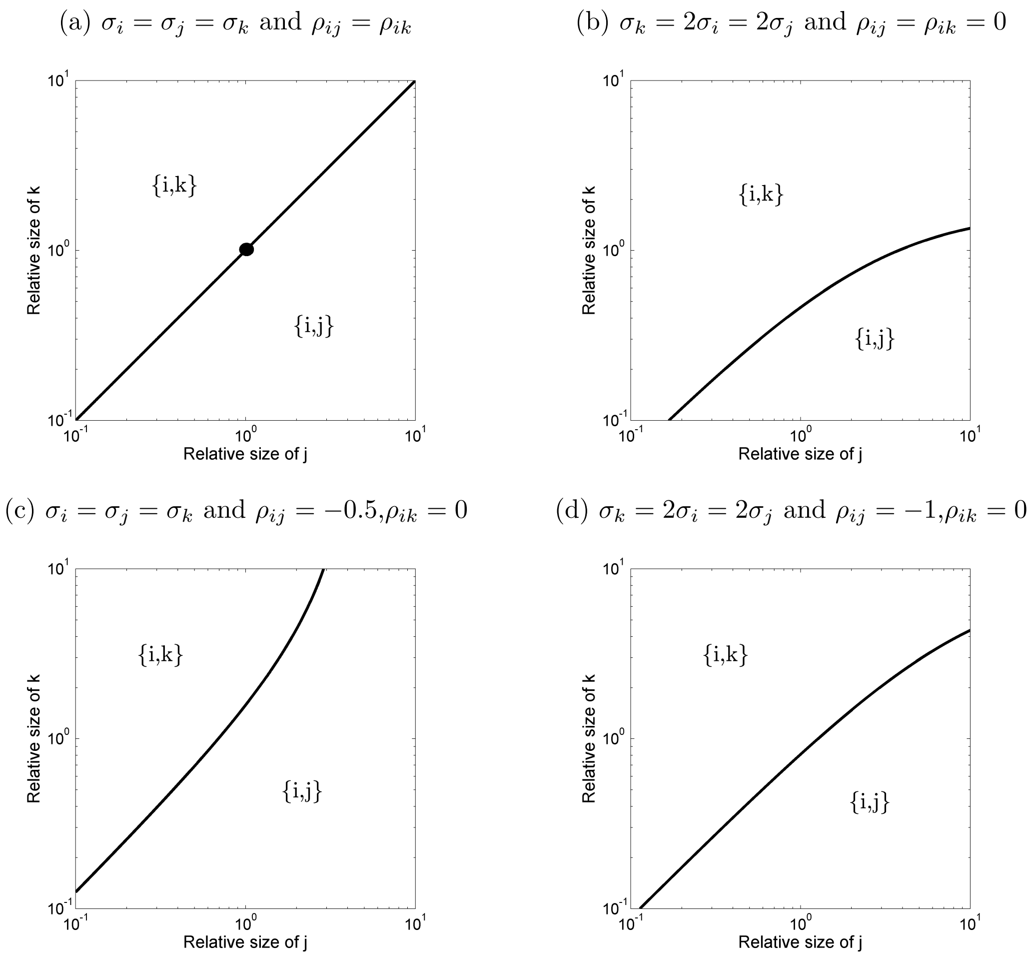
There are three jurisdictions denominated by i, j and k. We consider that jurisdiction i can choose between linking with either jurisdiction j or k and we analyze its relative bilateral linkage preferences. That is, we characterize the sets of jurisdictional characteristics such that i prefers a link with j or k (or is indifferent between them). To this end, sizes of j and k are expressed relative to the size of i. Figure 2.2 plots different linkage indifference frontiers for i in the j-k relative size space for various volatility and correlation parameters. Note that above (resp. below) the frontier i prefers to link with k (resp. j).[12]

In Figure 2.2a interjurisdictional correlations and volatility levels are equal so that jurisdictions only differ by size. That is, $VE_{\{i,j\}} = VE_{\{i,k\}}$ and $DE_{\{i,j\}} = DE_{\{i,k\}}$ and we single out PSE. The indifference frontier coincides with the 45-degree line and the central dot represents the point where jurisdictions are identical. All else equal, this shows that i is better off linking with the larger jurisdiction. Formally, when $\psi_j \geq \psi_k$,

[12] We derive analytical solutions for indifference frontiers that are provided in Appendix 2.C. In the main text, however, we limit exposition to a graphical analysis for readability.

$PSE_{\{i,j\},i} \geq PSE_{\{i,k\},i}$. Next, Figure 2.2b isolates VE by considering that shocks are independent and that k is twice as volatile as i and j. This distorts the 45-degree line in favour of $\{i,k\}$ because $VE_{\{i,k\}} > VE_{\{i,j\}}$. There is an observationally equivalent frontier distortion when we isolate DE. For instance, with equal volatility levels, Figure 2.2c considers that shocks in i and j are negatively correlated while those in i and k are independent, i.e. $DE_{\{i,j\}} > DE_{\{i,k\}} = 0$. Finally, Figure 2.2d is indicative of the trade-off between VE and DE. In this case, VE 'dominates' DE because the volatility in k is sufficiently high for $VE_{\{i,k\}} + DE_{\{i,k\}} > VE_{\{i,j\}} + DE_{\{i,j\}}$ to hold.

Figure 2.2: Bilateral linkage preferences for jurisdiction i



In sum, from a jurisdictional perspective, ranking bilateral linkages given a set of jurisdictional characteristics is relatively straightforward and intuitive. As can be expected, this gets more arduous a task when considering multilateral linkages. However, as we shall see further on, some lines of reasoning developed for bilateral linkages can be generalized and, analytically, bilateral linkages will constitute the very basic elements of our analysis of multilateral linkage. We turn to the intermediary case of trilateral linkage beforehand.

2.5 Trilateral linkage

2.5.1 Linkage preferences in a three-jurisdiction world

We consider the three-jurisdiction economy $\mathcal{I} = \{i, j, k\}$ but we now also contemplate the formation of the trilateral link. Rather than characterizing the $\mathcal{I}$-linkage equilibrium we will solely focus on how jurisdiction i fares under the trilateral link $\mathcal{I}$ as compared to the two bilateral links $\{i, j\}$ and $\{i, k\}$. By an extension of both notations and Equation (2.4.10) the expected gains from $\mathcal{I}$-linkage relative to autarky accruing to i amount to

$$\mathbb{E}\{\delta_{\mathcal{I},i}\} = \frac{\psi_i}{2b_2}\mathbb{E}\{(\theta_i - \hat{\Theta}_{\mathcal{I}})^2\}, \text{ where } \hat{\Theta}_{\mathcal{I}} = \frac{\psi_i\theta_i + \psi_j\theta_j + \psi_k\theta_k}{\psi_i + \psi_j + \psi_k}. \tag{2.5.1}$$

By definition of the size-averaged shocks, note that the above rewrites

$$\mathbb{E}\{\delta_{\mathcal{I},i}\} = \frac{\psi_i(\psi_j + \psi_k)^2}{2b_2(\psi_i + \psi_j + \psi_k)^2}\mathbb{E}\{(\theta_i - \hat{\Theta}_{\{j,k\}})^2\}. \tag{2.5.2}$$

Therefore, insofar as i is concerned, the trilateral link $\mathcal{I}$ is equivalent to a bilateral link with the joint system $\{j, k\}$. By this artefact and from a jurisdictional perspective, we can apply our analysis of bilateral linkage to that of trilateral linkages. In other words, we can compare PSE, VE and DE across bilateral and trilateral linkages in a meaningful way. Direct computation of $\mathbb{V}\{\hat{\Theta}_{\{j,k\}}\}$ and $\text{Cov}\{\theta_i; \hat{\Theta}_{\{j,k\}}\}$ the yields

$$\mathbb{E}\{\delta_{\mathcal{I},i}\} = \underbrace{\frac{\psi_i(\psi_j + \psi_k)^2}{2b_2(\psi_i + \psi_j + \psi_k)^2}}_{PSE_{\mathcal{I},i}}\Bigg(\underbrace{\sigma_i^2 + \frac{\psi_j^2\sigma_j^2 + \psi_k^2\sigma_k^2 + 2\rho_{jk}\psi_j\psi_k\sigma_j\sigma_k}{(\psi_j + \psi_k)^2}}_{VE_{\mathcal{I},i}} \underbrace{-2\sigma_i\frac{\rho_{ij}\psi_j\sigma_j + \rho_{ik}\psi_k\sigma_k}{\psi_j + \psi_k}}_{DE_{\mathcal{I},i}}\Bigg) \tag{2.5.3}$$

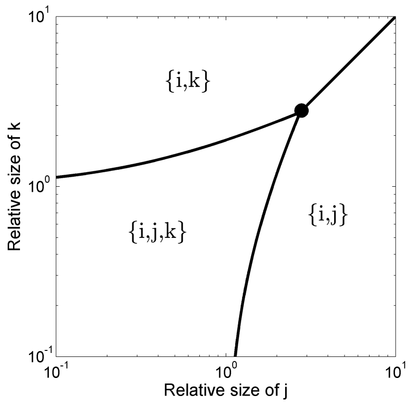
As compared to a bilateral link between two jurisdictions, first note that the influence of jurisdictional sizes is no longer limited to PSE as sizes now affect VE and DE.[13] In a trilateral link with j and k, note also that i is better off it is when negatively correlated with both j and k. As for a bilateral link, this increases DE. A novelty is that i prefers j and k to be positively correlated with one another. Intuitively, this reinforces the magnitude of the demand volatility in the joint system $\{j, k\}$ and thus increases VE.

Figure 2.1 illustrates i's linkage preferences by plotting i's linkage indifference frontiers. Note that a finer characterization of these frontiers is provided in Appendix 2.C. Figure 2.1a is the reference situation where jurisdictions are equally volatile and shocks and independent

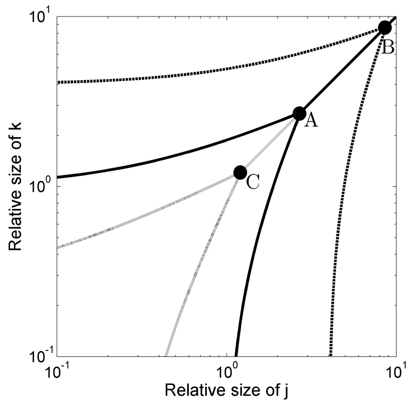
[13] For instance, we see from $DE_{\mathcal{I},i}$ in Equation (2.5.3) that when $\sigma_j \sim \sigma_k$, $\rho_{ij} > 0$ and $\rho_{ik} < 0$ then i is negatively correlated with the joint system $\{j, k\}$ provided that k is large enough relative to j.

Figure 2.1: Bi- and trilateral linkage preferences for jurisdiction i

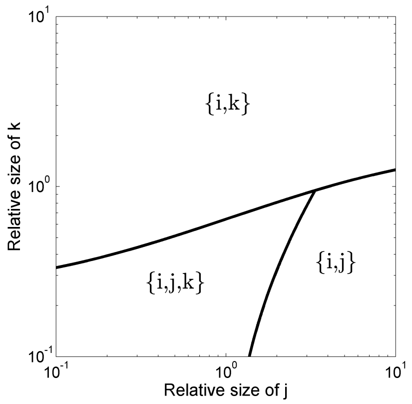
(a) $\sigma_i = \sigma_j = \sigma_k$ and $\rho_{ij} = \rho_{ik} = \rho_{jk} = 0$



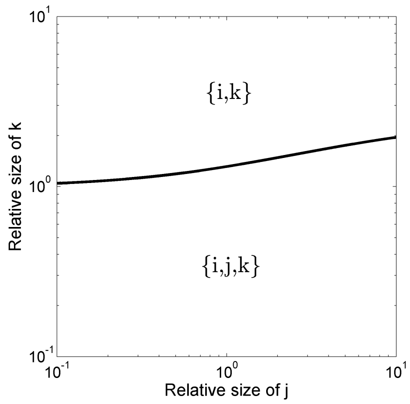
(b) B:$\sigma_i = 2\sigma_j = 2\sigma_k$ and C:$2\sigma_i = \sigma_j = \sigma_k$



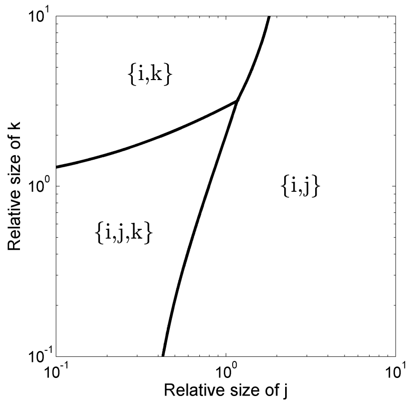
(c) $\sigma_k = 2\sigma_i = 2\sigma_j$ and $\rho_{ij} = \rho_{ik} = \rho_{jk} = 0$



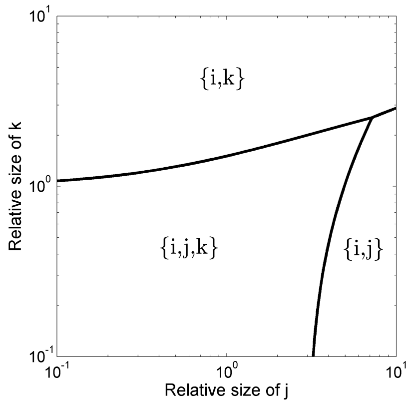
(d) $\sigma_i = \sigma_k$,$\sigma_j = 0$ and $\rho_{ij} = \rho_{ik} = \rho_{jk} = 0$



(e) $\sigma_i = \sigma_j = \sigma_k$, $\rho_{ij} = \rho_{jk} = 0$ and $\rho_{ik} = .5$



(f) $\sigma_i = \sigma_j = \sigma_k$, $\rho_{ij} = \rho_{jk} = 0$ and $\rho_{ik} = -.5$



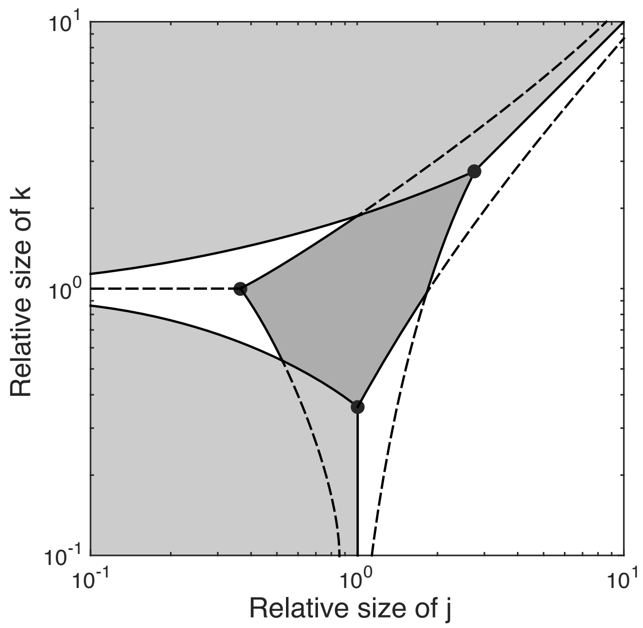
(the dot represents the point where i is indifferent between the three possible links). All else equal, this shows that i prefers the trilateral link when it is of similar or larger size than the other two jurisdictions. Otherwise, it prefers a bilateral link with the largest jurisdiction.

Figure 2.1b considers two alternative situations where i is twice (resp. half) as volatile as both j and k where the indifference point is B (resp. C). This shows i prefers the trilateral link when it is similarly or more volatile than the other two jurisdictions. Otherwise, it prefers a bilateral link with the most volatile jurisdiction. There is an observationally equivalent interpretation of Figure 2.1b where, relative to the case of independent shocks (A) the indifference point becomes B (resp. C) when j and k are positively (resp. negatively) correlated as this increases (resp. decreases) $VE_{\mathcal{I},i}$.

As compared to Figure 2.1a, Figure 2.1c depicts the effects of doubling σ_k. All else equal, this makes $\{i,k\}$ more attractive than $\{i,j\}$ and, interestingly, also reduces the region where $\mathcal{I}$ is preferred. Moreover, in the extreme case where $\sigma_j = 0$, Figure 2.1d shows that $\{i,j\}$ is never the most preferred link for jurisdiction i in the considered size ranges. Note that i's preference between $\{i,k\}$ and $\mathcal{I}$ does not vary much with j's size – in particular, $\{i,k\}$ will always be the preferred link provided that $\psi_k \geq 2\psi_i$. Next, we analyze the impact of correlation. In Figure 2.1e we consider that i and k are positively correlated, which deteriorates both $\{i,k\}$ and $\mathcal{I}$ relative to $\{i,j\}$. Conversely, when i and k are negatively correlated as in Figure 2.1f, $\{i,j\}$ becomes less attractive than both $\{i,k\}$ and $\mathcal{I}$.

Finally, it is also informative to characterize j and k's linkage preferences. Figure 2.2

Figure 2.2: Linkage preferences for the three jurisdictions



superimposes the linkage indifference frontiers for the three jurisdictions when they are equally volatile with independent shocks. First, the dark grey area at the center represents the zone where $\mathcal{I}$-linkage is simultaneously preferred by the three jurisdictions and should thus endogenously emerge. This is the case when heterogeneity in size is not too pronounced. Second, the light grey areas at the top and in the south-east corner represent the zones where i and k prefer $\{i,k\}$-linkage the most, respectively. These zones do not overlap, which means that $\{i,k\}$-linkage cannot form endogenously without lump-sum transfers. In fact, no bilateral linkage can simultaneously be the preferred link for the two jurisdictions involved. Non-alignment of jurisdictional linkage preferences will generalize to multilateral linkage as a consequence of superadditivity and infeasibility of interjurisdictional transfers.

2.5.2 Trilateral linkage with binary shocks

We now illustrate why the largest and/or most volatile jurisdiction (say i) tends to prefer the trilateral link over bilateral links. Intuitively, this is the case because the trilateral-link price is 'less driven' by i's autarkic price relative to a bilateral link, i.e. the 'distance' (or variability) between i's autarkic price and the linking price is greater. To do so, we consider two similar cases as those in Section 2.4.2 for comparison purposes. Without loss of generality, we also assume that shocks are independent, i.e. $\rho_{ij} = \rho_{ik} = \rho_{jk} = 0$.

Case 1: $\boldsymbol{\psi_i = 2\psi_j = 2\psi_k = 2\psi}$, $\boldsymbol{\sigma_i = \sigma_j = \sigma_k = \sigma}$ **with** $\boldsymbol{\rho_{ij} = \rho_{ik} = \rho_{jk} = 0}$
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 same probability which drive a wedge in autarkic prices $\bar{p}_i - \bar{p}_j = \bar{p}_i - \bar{p}_k = 2\sigma$. By symmetry and with complementary probability 1/2 opposed shocks occur in j and k and linking price reads $p_{\mathcal{I}} = (2\bar{p}_i + \bar{p}_j + \bar{p}_k)/4 = \bar{p} + \sigma/2$. By symmetry, jurisdictional price wedges between autarky and $\mathcal{I}$-linkage read

$$|\bar{p}_i - p_{\mathcal{I}}| = \Big(\sigma, 1/4; \sigma/2, 1/2; 0, 1/4\Big), \tag{2.5.4a}$$

$$|\bar{p}_j - p_{\mathcal{I}}| = |\bar{p}_k - p_{\mathcal{I}}| = \Big(3\sigma/2, 1/4; \sigma, 1/4; \sigma/2, 1/4; 0, 1/4\Big), \tag{2.5.4b}$$

and gains from $\mathcal{I}$-linkage are $\mathbb{E}\{\delta_{\mathcal{I},i}\} = 3\psi\sigma^2/(8b_2)$ and $\mathbb{E}\{\delta_{\mathcal{I},j}\} = \mathbb{E}\{\delta_{\mathcal{I},k}\} = 7\psi\sigma^2/(16b_2)$. Comparing with Case 1 in Section 2.4.2 we see that the largest jurisdiction (i) prefers the trilateral link while the small jurisdictions (j and k) prefer to form a bilateral link with i.

Case 2: $\boldsymbol{\psi_i = \psi_j = \psi_k = \psi}$, $\boldsymbol{\sigma_i = 2\sigma_j = 2\sigma_k = 2\sigma}$ **with** $\boldsymbol{\rho_{ij} = \rho_{ik} = \rho_{jk} = 0}$
Assume the positive shock $+2\sigma$ occurs in i. Then, positive shocks $+\sigma$ occur in both j and k with probability 1/4 and autarkic price wedges are such that $\bar{p}_i - \bar{p}_j = \bar{p}_i - \bar{p}_k = \sigma$. Negative shocks $-\sigma$ occur in both j and k with same probability but higher autarkic price wedges $\bar{p}_i - \bar{p}_j = \bar{p}_i - \bar{p}_k = 3\sigma$. By symmetry and with complementary probability 1/2 opposed shocks occur in j and k and linking price reads $p_{\mathcal{I}} = (\bar{p}_i + \bar{p}_j + \bar{p}_k)/3 = \bar{p} + 2\sigma/3$.

By symmetry, jurisdictional price wedges between autarky and $\mathcal{I}$-linkage read

$$|\bar{p}_i - p_{\mathcal{I}}| = \Big(2\sigma, 1/4; 4\sigma/3, 1/2; 2\sigma/3, 1/4\Big), \tag{2.5.5a}$$

$$|\bar{p}_j - p_{\mathcal{I}}| = |\bar{p}_k - p_{\mathcal{I}}| = \Big(5\sigma/3, 1/4; \sigma, 1/4; \sigma/3, 1/2\Big), \tag{2.5.5b}$$

and gains from $\mathcal{I}$-linkage are $\mathbb{E}\{\delta_{\mathcal{I},i}\} = \psi\sigma^2/b_2$ and $\mathbb{E}\{\delta_{\mathcal{I},j}\} = \mathbb{E}\{\delta_{\mathcal{I},k}\} = \psi\sigma^2/(2b_2)$. Comparing with Case 1 in Section 2.4.2, the most volatile jurisdiction (i) now prefers the trilateral link while less volatile jurisdictions (j and k) prefer a bilateral link with i.

In the above cases, while $\mathcal{I}$-linkage increases the autarky-linking price variability for i relative to bilateral linkages, it does just the opposite for j and k. These examples further illustrate that jurisdictional linkage preferences are not aligned. We now generalize the model to the case of multilateral linkage and set forth our main theoretical contributions.

2.6 Multilateral linkage

2.6.1 Definitions and terminology

Let $\mathbf{C} \doteq \{\mathcal{C} : \mathcal{C} \subseteq \mathcal{I}, \mathcal{C} \neq \varnothing\}$ be the set of non-empty coalitions in $\mathcal{I}$ with generic element $\mathcal{C}$ and cardinality $|\mathbf{C}| = 2^n - 1$. Let also $\mathbf{C}_\star$ denote the set of non-trivial coalitions, i.e. $\mathbf{C}_\star \doteq \{\mathcal{C} : \mathcal{C} \in \mathbf{C}, |\mathcal{C}| \geq 2\}$ with cardinality $|\mathbf{C}_\star| = |\mathbf{C}| - n$, whose generic element $\mathcal{C} \in \mathbf{C}_\star$ we call linkage coalition. Denote by $\mathbf{S}$ the set of coalition structures, where a coalition structure corresponds to a partition of $\mathcal{I}$.[14] Formally, $\mathcal{S}$ is a coalition structure i.f.f. $\varnothing \notin \mathcal{S}$, $\bigcup_{\mathcal{C}\in\mathcal{S}} \mathcal{C} = \mathcal{I}$, and $\forall(\mathcal{C}, \mathcal{C}') \in \mathcal{S} \times \mathcal{S}_{-\mathcal{C}}, \mathcal{C} \cap \mathcal{C}' = \varnothing$. For instance, among a group of three jurisdictions $\{i, j, k\}$, there exist five coalition structures, namely

$$\underbrace{\{\{i\},\{j\},\{k\}\}}_{\text{complete autarky}}\ ,\quad \underbrace{\{\{i,j,k\}\}}_{\text{global market}}\ ,\quad \underbrace{\{\{i,j\},\{k\}\},\ \{\{i,k\},\{j\}\}, \text{ and } \{\{j,k\},\{i\}\}}_{\text{3 incomplete linkages}}.$$

The first and second coalition structures are the complete autarky and the global market, respectively. Coalition structures in which there are singletons, i.e. some jurisdictions remain in autarky, are referred to as incomplete linkage, e.g. $\{\{i, k\}, \{j\}\}$. Among a group of four jurisdictions $\{i, j, k, l\}$, richer variation in coalition structures emerge consisting of

[14] For the sake of expositional clarity and consistently with the language of cooperative game theory, coalition structures can only comprise disjoint coalitions. This is without loss of generality and our machinery can characterize situations where jurisdictions belong to several coalitions. In other words, this could represent an 'indirect linkage' as defined in Jaffe et al. (2009) and Tuerk et al. (2009).

multiple linkage coalitions, e.g. $\{\{i,j\},\{k,l\}\}$. Coalition structures in which linkage coalitions coexist are referred to as polycentric structures. Note that polycentric structures may also contain singletons and therefore exhibit incomplete linkage.

Further, let $\mathbf{S}_i$ denote the set of coalition structures containing exactly $i \in [\![1;n]\!]$ coalitions, whose cardinality is given by the Stirling number of the second kind $\left\{ {n \atop i} \right\}$. The cardinality of $\mathbf{S}$ is thus given by the n^{th} Bell number given n agents, that is

$$|\mathbf{S}| \doteq \sum_{i=1}^{n} |\mathbf{S}_i| = \sum_{i=1}^{n} \left\{ {n \atop i} \right\} = \sum_{i=1}^{n} \frac{1}{i!} \sum_{j=0}^{i} (-1)^{i-j} \binom{i}{j} j^n. \tag{2.6.1}$$

As shown in Table 2.1, the difference in the number of possible linkage coalitions and coalition structures grows exponentially as the number of jurisdictions increases.

Table 2.1: Number of linkage coalitions and coalition structures

Number of jurisdictions	3	4	5	10	15
Number of linkage coalitions	4	11	26	1,013	32,752
Number of coalition structures	5	15	52	115,975	1,382,958,545

Before presenting our general model of multilateral linkage, we define the concept of coarsening (i.e., coalition structure refinement) so as to compare different coalition structures. First, we formally define a unitary linkage between two disjoint coalitions.

Definition 2.6.1. (Unitary linkage) Let $\mathcal{S} \in \mathbf{S}$ such that $|\mathcal{S}| \geq 2$. A unitary linkage is a mapping

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

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

Observe that a bilateral linkage coincides with a unitary linkage between two singletons. Next, a structure coarsening can be defined as a sequence of unitary linkages.[15]

Definition 2.6.2. (Coarsening) Let $\mathcal{S}$ and $\mathcal{S}'$ in $\mathbf{S}^2$ such that $|\mathcal{S}| \geq 2$ and $d = |\mathcal{S}| - |\mathcal{S}'| \geq 1$. $\mathcal{S}'$ is coarser than $\mathcal{S}$ if there exists $(\mathcal{S}_i)_{i \in [\![0;d]\!]} \in \mathbf{S}^{d+1}$ 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 $(\mathcal{C}'_i, \mathcal{C}''_i)$ in $\mathcal{S}_i \times \mathcal{S}_i \backslash \{\mathcal{C}'_i\}$ such that $\mathcal{S}_{i-1} = \{\mathcal{C}'_i \cup \mathcal{C}''_i\} \cup \mathcal{S}_i \backslash \{\mathcal{C}'_i, \mathcal{C}''_i\}$.

[15] Another criterion to compare coalition structures is that of concentration. Formally, $\mathcal{S}'$ is a concentration of $\mathcal{S}$ if it obtains from $\mathcal{S}$ by moving one jurisdiction at a time from a coalition in $\mathcal{S}$ to another coalition of equal or larger cardinality. Notice, the relation 'coarser than' implies 'is a concentration of' while the opposite is not true. The key difference is that concentration allows for coalitions to be gradually dissolved.

In this sense, linkage can be interpreted as a refinement of the underlying coalition structure. When a coalition structure $\mathcal{S}'$ obtains from $\mathcal{S}$ through linkage, the set of newly formed linkage coalitions is $\mathcal{S}'\backslash\{\mathcal{S}'\cap\mathcal{S}\}$ and has cardinality $|\mathcal{S}|-|\mathcal{S}'|$ at most. Note also that the number of coalition structures that are strictly finer than $\mathcal{S}$ is $2^{|\mathcal{S}|}-|\mathcal{S}|-1$.

2.6.2 Multilateral linkage equilibria

For all $\mathcal{C}$ in $\mathbf{C}_\star$, we call $\mathcal{C}$-linkage the formation of a linked market for permits between all jurisdictions in $\mathcal{C}$. By extension, $\mathcal{I}$-linkage corresponds to the global market. An interior $\mathcal{C}$-linkage equilibrium consists of the $(|\mathcal{C}|+1)$-tuple $(p_\mathcal{C},(q_{\mathcal{C},i})_{i\in\mathcal{C}})$, where $p_\mathcal{C}$ is the equilibrium price in the linked market and $q_{\mathcal{C},i}$ denotes jurisdiction i's equilibrium emissions level. The equilibrium is fully characterized by the equalization of marginal benefits across partnering jurisdictions (to the $\mathcal{C}$-linkage equilibrium price) and the linked market clearing condition, that is

$$b_1+\theta_i-\frac{b_2}{\psi_i}q_{\mathcal{C},i}=p_\mathcal{C} \text{ for all } i \text{ in } \mathcal{C}, \text{ and } \sum_{i\in\mathcal{C}}q_{\mathcal{C},i}=\Omega_\mathcal{C}, \tag{2.6.2}$$

where $\Psi_\mathcal{C}\doteq\sum_{i\in\mathcal{C}}\psi_i$ and $\Omega_\mathcal{C}\doteq\sum_{i\in\mathcal{C}}\omega_i=A\cdot\Psi_\mathcal{C}$. After rearranging, the $\mathcal{C}$-linkage equilibrium price can be expressed as the size-weighted average of jurisdictional autarkic prices, that is

$$p_\mathcal{C}=\bar{p}+\hat{\Theta}_\mathcal{C}=\Psi_\mathcal{C}^{-1}\sum_{i\in\mathcal{C}}\psi_i\bar{p}_i, \text{ with } \hat{\Theta}_\mathcal{C}\doteq\Psi_\mathcal{C}^{-1}\sum_{i\in\mathcal{C}}\psi_i\theta_i. \tag{2.6.3}$$

Jurisdictional net demands for permits are proportional to both jurisdictional size and the difference between the jurisdictional autarkic price and the prevailing linkage price, e.g. for jurisdiction $i\in\mathcal{C}$

$$q_{\mathcal{C},i}-\omega_i=\psi_i(\bar{p}_i-p_\mathcal{C})/b_2. \tag{2.6.4}$$

Ex post, jurisdiction i imports permits under $\mathcal{C}$-linkage i.f.f. $\bar{p}_i>p_\mathcal{C}$, i.e. the linking price happens to be lower than its autarkic price. All else equal, this is equivalent to an increase in jurisdiction i's effective cap. Relative to autarky, the gains from $\mathcal{C}$-linkage accruing to jurisdiction $i\in\mathcal{C}$ are

$$\delta_{\mathcal{C},i}=\frac{b_2}{2\psi_i}(q_{\mathcal{C},i}-\omega_i)^2=\frac{\psi_i}{2b_2}(\bar{p}_i-p_\mathcal{C})^2. \tag{2.6.5}$$

We summarize the above in the following proposition.

Proposition 2.6.3. *Under $\mathcal{C}$-linkage, the expected economic gains accruing to jurisdiction $i\in\mathcal{C}$ amount to*

$$\mathbb{E}\{\delta_{\mathcal{C},i}\}=\frac{\psi_i}{2b_2}\mathbb{E}\{(\bar{p}_i-p_\mathcal{C})^2\}\geq 0. \tag{2.6.6}$$

Proof. Relegated to Appendix 2.A.1. □

Jurisdiction i's expected gains from $\mathcal{C}$-linkage are always non-negative – and positive provided that the i's autarkic price differs from the $\mathcal{C}$-linkage price almost surely.[16] That is, every partnering jurisdiction in any multilateral linkage is always at least as well off as compared to autarky. Note that jurisdictional gains are proportional to both jurisdictional size and the expectation of the square of the difference in autarkic and $\mathcal{C}$-linkage price realizations. In loose terms, the more 'variability' in the linking price relative to its autarkic price, the more a jurisdiction benefits from the link.[17,18] For instance, controlling for size, a jurisdiction will prefer to be part of linkage coalitions in which the linking price happens to be relatively high when its domestic price happens to be relatively low and vice versa.

Also note from Equation (2.6.3) that the linking price is mostly driven by the autarkic prices of the relatively large jurisdictions. Similarly, for jurisdictions of equal sizes, it is intuitive that the linking price is more affected by those autakic prices whose variation ranges are wide. In other words, large and highly volatile jurisdictions will prefer to link with many jurisdictions in a bid to augment their autarky-link price distances. Conversely, small jurisdictions may prefer to link exclusively with one relatively large jurisdiction, for otherwise the influence of that large jurisdiction on the link outcome is likely to be mitigated.

In addition, note that Equation (2.6.6) can be decomposed into two non-negative components, namely

$$\mathbb{E}\{\delta_{\mathcal{C},i}\} = \frac{\psi_i}{2b_2}\Big((\mathbb{E}\{\bar{p}_i\} - \mathbb{E}\{p_{\mathcal{C}}\})^2 + \mathbb{V}\{\bar{p}_i - p_{\mathcal{C}}\}\Big). \tag{2.6.7}$$

The first component relates to the difference in expected autarky/link prices, i.e. in jurisdictional cap stringencies or ambition levels.[19] Intuitively, the larger this difference, the larger the benefits associated with the equalization of marginal benefits on average. The second component relates to the variance of the difference in autarly/link prices. That is, linking ETSs induces a positive additional gain relative to the case without uncertainty as soon as shocks are different across linked jurisdictions, which can be seen as a strict Pareto-improvement due to the absorption of shocks. In this Chapter, we neutralize the first component of linkage gains by setting expected autarkic prices equal across jurisdictions through Equation (2.3.4) and only focus on those gains that arise due to uncertainty.

Finally, we have the following result regarding the properties of the $\mathcal{C}$-linkage price which is a generalization of Proposition 2 in Doda & Taschini (2017).

[16]This result is the analog of the expected gains from merging ETSs obtained by Caillaud & Demange (2017). Note also that summing $\delta_{\mathcal{C},i} = b_2\,(q_{\mathcal{C},i} - \omega_i)^2/(2\psi_i)$ over $i \in \mathcal{C}$ would yield the comparative advantage of decentralization w.r.t. centralization for uniformly-mixed pollutants in Yates (2002).

[17]In other economic contexts, Waugh (1944) and Oi (1961) observed that variability could be beneficial.

[18]Formally, the adequate term is 'distance'. Indeed, if $\mathcal{L}^2 = \{f|\mathbb{E}\{f^2\} < \infty\}$ then $(\mathcal{L}^2, \langle\cdot\rangle)$ is a Hilbert space with inner product $\langle f, g\rangle = \mathbb{E}\{fg\}$ and $(f,g) \mapsto (\langle f-g, f-g\rangle)^{1/2}$ is the distance induced by $\langle\cdot\rangle$.

[19]More details can be found in Appendix 2.B.1 – see Equation (2.B.5) in particular.

Proposition 2.6.4. *Under $\mathcal{C}$-linkage, the permit price volatility is bounded from above*

$$\mathbb{V}\{p_{\mathcal{C}}\} \leq \Psi_{\mathcal{C}}^{-1} \sum_{i \in \mathcal{C}} \psi_i \mathbb{V}\{\bar{p}_i\} \text{ with } \mathbb{E}\{p_{\mathcal{C}}\} = \bar{p}.$$

Only when shocks are independent does it hold that $\text{p-lim}_{|\mathcal{C}| \to +\infty} p_{\mathcal{C}} = \bar{p}$. *Linkage always lowers price volatility in higher volatility jurisdictions but may increase it in lower volatility jurisdictions, especially when the latter are relatively small.*

Proof. Relegated to Appendix 2.A.2. □

The first statement places an upper bound on the linking price volatility. Moreover, the inequality holds strictly provided that at least two jurisdictions in $\mathcal{C}$ are not perfectly positively correlated and/or have different volatility levels. This illustrates the shock absorption mechanism associated with linkage and suggests that overall permit price volatility is reduced as a result of the link. The second statement, however, clarifies this point and shows that as the linkage coalition expands, the linking price converges in probability towards its expected value $\bar{p}$ only when shocks are independent. In other words, in the general case, there is no reason that the linking price volatility should gradually diminish and converge to zero as the number of linked jurisdictions increases.

Proposition 2.6.4 also substantiates the effects of linking on price volatility from a jurisdictional perspective. Highly volatile jurisdictions experience reduced price volatility as domestic shocks are spread over a deeper market and thus better cushioned. By contrast, as links create exposure to shocks occurring abroad, jurisdictions with little volatility may face higher price volatility relative to autarky. All else equal, this is more likely to be the case when these jurisdictions are small as the influence of larger jurisdictions on the link outcomes is relatively more salient. However, we stress that linkage is always preferred to autarky despite that it might lead to higher price volatility. This is so because jurisdictions that 'import' some volatility as a result of the link are well compensated for doing so.

2.6.3 Bilateral decomposition of multilateral linkages

Jurisdictional expected gains in Equation (2.6.6) are in a compact form that provides an intuitive interpretation in terms of autarky-link price distance. However, this does not directly relate to jurisdictional characteristics so we might want to unpack it. Then, as per our definition of emissions caps in Equation (2.3.4) the autarky-linking price wedge solely relates to shocks, that is

$$\bar{p}_i - p_{\mathcal{C}} = \theta_i - \hat{\Theta}_{\mathcal{C}}. \tag{2.6.8}$$

Plugging Equation (2.6.8) into Equation (2.6.5) and using the definition of $\hat{\Theta}_{\mathcal{C}}$, we obtain

$$\delta_{\mathcal{C},i} = \frac{\psi_i}{2b_2\Psi_{\mathcal{C}}^2}\left(\sum_{j\in\mathcal{C}_{-i}} \psi_j\left(\theta_i - \theta_j\right)\right)^2. \tag{2.6.9}$$

Expanding the above and taking expectations then yields

$$\begin{aligned}\mathbb{E}\{\delta_{\mathcal{C},i}\} = \frac{\psi_i}{2b_2\Psi_{\mathcal{C}}^2}\Bigg(&\sum_{j\in\mathcal{C}_{-i}} \psi_j^2\left(\sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j\right)\\ &+ \sum_{(j,k)\in\mathcal{C}_{-i}\times\mathcal{C}_{-i}} \psi_j\psi_k\left(\sigma_i^2 + \rho_{jk}\sigma_j\sigma_k - \rho_{ik}\sigma_i\sigma_k - \rho_{ij}\sigma_i\sigma_j\right)\Bigg).\end{aligned} \tag{2.6.10}$$

The above expression, however, is relatively cumbersome and does not lend itself to an easy interpretation. We could also pursue a similar approach as in Section 2.5 to write $\mathbb{E}\{\delta_{\mathcal{C},i}\}$ as the expected gains from a bilateral link between i and $\mathcal{C}_{-i}$, but the nature of the entity $\mathcal{C}_{-i}$ is already hard to grasp for quadrilateral links. In general, when it comes to a multilateral link, it will be more convenient to express the associated quantities as a function of its internal bilateral linkage quantities. By an argument of symmetry and with the convention that for all $i \in \mathcal{I}$, $\Delta_{\{i,i\}} = 0$, Appendix 2.A.1 shows that $\mathcal{C}$-linkage gains accruing to jurisdiction $i \in \mathcal{C}$ write

$$\delta_{\mathcal{C},i} = \Psi_{\mathcal{C}}^{-2}\sum_{j\in\mathcal{C}_{-i}}\left\{\Psi_{\mathcal{C}_{-i}}(\psi_i+\psi_j)\Delta_{\{i,j\}} - \frac{\psi_i}{2}\sum_{k\in\mathcal{C}_{-i}}(\psi_j+\psi_k)\Delta_{\{j,k\}}\right\}. \tag{2.6.11}$$

Therefore, jurisdiction i is better off linking with groups of jurisdictions such that bilateral gains (a) between i and each jurisdiction in these groups are high; (b) internal to these groups are low. Then, summing over all $i \in \mathcal{C}$ yields the following result.

Proposition 2.6.5. *Any $\mathcal{C}$-linkage can be decomposed into its internal bilateral linkages, that is*

$$\Delta_{\mathcal{C}} \doteq \sum_{i\in\mathcal{C}}\delta_{\mathcal{C},i} = (2\Psi_{\mathcal{C}})^{-1}\sum_{(i,j)\in\mathcal{C}^2}(\psi_i+\psi_j)\Delta_{\{i,j\}}. \tag{2.6.12}$$

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

Proof. Relegated to Appendix 2.A.3. Appendix 2.B.1 shows that Proposition 2.6.5 continues to hold for jurisdictional cap profiles that do not satisfy Equation (2.3.4). □

In words, the aggregate gain from $\mathcal{C}$-linkage writes as a size-weighted function of all gains from bilateral links between jurisdictions belonging to the linkage coalition $\mathcal{C}$. This shortens equations and provides a convenient way to compute gains associated with large coalitions.

However, it is not clear from Equation (2.6.12) what are the implications (e.g., in terms of aggregate expected gains) of enlarging a linkage coalition. This is what we analyze next.

2.6.4 Linkage between linkage coalitions

We define the aggregate gains generated by any coalition structure $\mathcal{S}$ in $\mathbf{S}$ by $\Delta_{\mathcal{S}} \doteq \sum_{\mathcal{C}\in\mathcal{S}} \Delta_{\mathcal{C}}$ and we adopt the convention that $\Delta_{\mathcal{C}} = 0$ whenever $\mathcal{C} \in \mathbf{C}\backslash\mathbf{C}_\star$. Now let $(\mathcal{C}, \mathcal{C}') \in \mathbf{C}_\star \times \mathbf{C}$ such that $\mathcal{C}' \subset \mathcal{C}$ and denote by $\mathcal{C}''$ the complement of $\mathcal{C}'$ in $\mathcal{C}$, i.e. $\mathcal{C} = \mathcal{C}' \cup \mathcal{C}''$ and $\mathcal{C}' \cap \mathcal{C}'' = \varnothing$. Then, we can express the aggregate gains in $\mathcal{C}$ as a function of those in $\mathcal{C}'$ and $\mathcal{C}''$ by unpacking Equation (2.6.12), that is

$$\Delta_{\mathcal{C}} = \Psi_{\mathcal{C}}^{-1}\left(\Psi_{\mathcal{C}'}\Delta_{\mathcal{C}'} + \Psi_{\mathcal{C}''}\Delta_{\mathcal{C}''} + \sum_{(i,j)\in\mathcal{C}'\times\mathcal{C}''}(\psi_i + \psi_j)\Delta_{\{i,j\}}\right). \tag{2.6.13}$$

Note that the third term in the above captures the interaction among jurisdictions in $\mathcal{C}'$ and $\mathcal{C}''$, which is what we want to isolate. To do so, we denote the aggregate gains of linking coalitions $\mathcal{C}'$ and $\mathcal{C}''$ by $\Delta_{\{\mathcal{C}',\mathcal{C}''\}}$ and define them such that

$$\Delta_{\{\mathcal{C}',\mathcal{C}''\}} \doteq \Delta_{\mathcal{C}} - \Delta_{\mathcal{C}'} - \Delta_{\mathcal{C}''}. \tag{2.6.14}$$

With this definition, we can establish the following result.

Proposition 2.6.6. *Let $\mathcal{S}$ and $\mathcal{S}'$ be as in Definition 2.6.2 where $\mathcal{S}'$ is coarser than $\mathcal{S}$ and $d = |\mathcal{S}| - |\mathcal{S}'| \geq 1$. Linkage is a superadditive mechanism, that is*

$$\mathbb{E}\{\Delta_{\mathcal{S}'}\} - \mathbb{E}\{\Delta_{\mathcal{S}}\} = \sum_{i=1}^{d}\Big\{\mathbb{E}\{\Delta_{\mathcal{S}_i}\} - \mathbb{E}\{\Delta_{\mathcal{S}_{i-1}}\}\Big\} = \sum_{i=1}^{d}\mathbb{E}\{\Delta_{\{\mathcal{C}_i',\mathcal{C}_i''\}}\} \geq 0, \tag{2.6.15}$$

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

$$\mathbb{E}\{\Delta_{\{\mathcal{C}_i',\mathcal{C}_i''\}}\} = \Psi_{\{\mathcal{C}_i'\cup\mathcal{C}_i''\}}^{-1}\left(\sum_{(j,k)\in\mathcal{C}_i'\times\mathcal{C}_i''}(\psi_j + \psi_k)\mathbb{E}\{\Delta_{\{j,k\}}\} - \Psi_{\mathcal{C}_i''}\mathbb{E}\{\Delta_{\mathcal{C}_i'}\} - \Psi_{\mathcal{C}_i'}\mathbb{E}\{\Delta_{\mathcal{C}_i''}\}\right) \geq 0. \tag{2.6.16}$$

Proof. Relegated to Appendix 2.A.4. Appendix 2.B.1 shows that Proposition 2.6.6 continues to hold for jurisdictional cap profiles that do not satisfy Equation (2.3.4). □

In words, the aggregate expected gain from the union of disjoint (linkage) coalitions is no less than the sum of the separate (linkage) coalitions' aggregate expected gains. The proof for the non-negativity of $\mathbb{E}\{\Delta_{\{\mathcal{C}_i',\mathcal{C}_i''\}}\}$ in Equation (2.6.16) intuitively follows from the definition and beneficial nature of bilateral linkage – here generally considered between two coalitions in lieu of two jurisdictional markets (i.e., singletons).

We now illustrate the implications of superadditivity. In particular, because singletons have zero value, linkage also satisfies monotonicity, that is

$$\forall(\mathcal{C},\mathcal{C}') \in \mathbf{C}^2,\ \mathcal{C}' \subseteq \mathcal{C} \Rightarrow \mathbb{E}\{\Delta_{\mathcal{C}'}\} \leq \mathbb{E}\{\Delta_{\mathcal{C}}\}. \tag{2.6.17}$$

Therefore, $\mathcal{I}$-linkage is the linkage coalition that is the most advantageous in aggregate expected terms.[20] Superadditivity, in fact, provides the stronger result that linkage satisfies cohesiveness, that is

$$\forall\mathcal{S} \in \mathbf{S},\ \mathbb{E}\{\Delta_{\mathcal{I}}\} \geq \mathbb{E}\{\Delta_{\mathcal{S}}\}. \tag{2.6.18}$$

Therefore, $\mathcal{I}$-linkage is the socially optimal linkage coalition structure in that it is conducive to the highest aggregate gross cost savings in meeting the aggregate emissions cap $\Omega_{\mathcal{I}}$.[21] In words, from a global perspective a single linkage coalition consisting of all jurisdictions linked together outperforms any possible grouping of disjoint linkage coalitions.

In addition, superadditivity allows to generalize the observations made for trilateral links in Section 2.5 regarding jurisdictional linkage preferences absent interjurisdictional transfers.

Corollary 2.6.7. *Assume interjurisdictional lump-sum transfers away. Then, jurisdictional linkage preferences are not aligned in the sense that*
(i) $\mathcal{I}$-linkage may not be the most preferred linkage coalition for all jurisdictions in $\mathcal{I}$;
(ii) any $\mathcal{C} \in \mathbf{C}_\star \backslash \mathcal{I}$ cannot be the most preferred linkage coalition for all jurisdictions in $\mathcal{C}$.

Proof. Relegated to Appendix 2.A.5. □

Statement (i) can be reformulated as follows: There exists a set of jurisdictional characteristics such that $\mathcal{I}$-linkage is the most preferred link for all jurisdictions. We can infer from the trilateral case in Section 2.5.1 that this set is such that jurisdictions are homegenous enough in terms of size and volatility, which is not the case in practice. Therefore, although $\mathcal{I}$-linkage is the most efficient outcome from an aggregate perspective, it is unlikely that

[20] As mentioned in Appendix 2.A.3, $\mathcal{I}$ maximizes aggregate expected gains but may not reduce (let alone minimize) the associated variability in gains. One could thus envision to define an 'optimal portfolio' of bilateral linkages à la Markowitz (1952) that best meets a certain mean-variance criterion. Two differences are that allowing an additional jurisdiction into an existing linkage coalition (i) is a binary decision and (ii) adds as many bilateral links into the portfolio as there presently are jurisdictions inside the coalition.

[21] Formally, cohesiveness requires the aggregate gains from the grand coalition (i.e., $\mathcal{I}$-linkage) to 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 coalition structures as well. We also note that the particular functional forms that are assumed in the IEA literature generally imply cohesivess but not necessarily superadditivity.

it will be the most preferred outcome jurisdictionally speaking. In other words, absent interjurisdictional transfers, the global market is unlikely to emerge endogenously as some jurisdictions will oppose it and prefer to form smaller linkage coalitions.[22] Such smaller coalitions can form provided that jurisdictional linkage preferences happen to tally with one another. However, statement (*ii*) indicates that one jurisdiction's most preferred linkage coalition cannot simultaneously be the favourite coalition for every jurisdiction thereof. 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 fall short of leading to large linkage coalitions in the short run.[23]

Finally note that our analysis naturally extends to linkages between more than two linkage coalitions by rewriting Equation (2.6.11). That is, for any linkage coalition $\mathcal{C} = \bigcup_i \mathcal{C}_i$ where for all $i \neq j$, $\mathcal{C}_i \cap \mathcal{C}_j = \varnothing$, the gain accruing to coalition $\mathcal{C}_i$ in forming $\mathcal{C}$ reads

$$\Delta_{\mathcal{C},\mathcal{C}_i} = \Psi_{\mathcal{C}}^{-2} \sum_{\mathcal{C}' \in \mathcal{C}_{-\mathcal{C}_i}} \left\{ \Psi_{\mathcal{C}_{-\mathcal{C}_i}} \Big(\Psi_{\mathcal{C}_i} + \Psi_{\mathcal{C}'} \Big) \Delta_{\{\mathcal{C}_i,\mathcal{C}'\}} - \frac{\Psi_{\mathcal{C}_i}}{2} \sum_{\mathcal{C}'' \in \mathcal{C}_{-\mathcal{C}_i}} \Big(\Psi_{\mathcal{C}'} + \Psi_{\mathcal{C}''} \Big) \Delta_{\{\mathcal{C}',\mathcal{C}''\}} \right\}. \quad (2.6.19)$$

Note also that we deliberately abstain from characterizing how this gain is apportioned within linkage coalitions. As discussed in Appendix 2.B.2, this would require additional assumptions on the definition of linkage coalitions, namely the degree of consolidation.

2.7 Quantitative illustration

In this section we illustrate the quantitative implications of our theory using historical emissions data to discipline the selection of model parameters for five real-world jurisdictions: China (CHN), the United States (USA), the block of European countries currently participating in the EUETS (EUR), Korea (KOR) and Egypt (EGY). We assume that there is a hypothetical ETS which covers all carbon emissions in each jurisdiction. In this five-jurisdiction economy, we call 'global market' the pentalateral link.

[22] If interjurisdictional transfers were feasible, cohesiveness ensures that it would always be possible to find a transfer scheme that satisfies 'grand' coalition rationality, i.e. no subcoalition is better off deviating from the global market. In other words, there exists (at least) one allocation of the gains from the global market that lies in the core of the coalitional game, i.e. the global market can be sustained. Note that, utilizing the solution concept of Partial Agreement Nash Equilibrium, Chander & Tulkens (1995, 1997) prove non-emptiness of the (γ)-core precisely by pointing out a specific stabilizing transfer scheme in the standard coalition coalitional game with transboundary externalities. Helm (2001) generalizes this result by showing that such a game is 'balanced' provided that cohesivess and standard convexity assumptions about the payoff functions hold. Invoking the Bondareva-Shapley theorem, the core is non-empty.

[23] Again, note that interjurisdictional transfers could stabilize linkage coalitions in the sense of both internal and external stability as defined in Cartel games (D'Aspremont et al., 1983). In fact, all linkage coalitions are 'potentially internally stable' in the sense of Carraro et al. (2006).

Our calibration strategy is similar to Doda & Taschini (2017) and described in more detail in Appendix 2.D. We calibrate jurisdictions' sizes and shock properties using the level and fluctuation of jurisdictionsal historical emissions. The results are reported in Tables 2.1 and 2.2. Specifically, Table 2.1 provides jurisdictions' sizes, where China's size is normalized to 100, and shock volatilities. Table 2.2 lists the pairwise jurisdictional shock correlations.

Table 2.1: Calibration results: Size and volatility (ψ_i and σ_i)

	CHN	USA	EUR	KOR	EGY
ψ_i	100	55.038	38.699	6.645	2.356
σ_i	0.028	0.019	0.017	0.034	0.050

Table 2.2: Calibration results: Pairwise correlation coefficients (ρ_{ij})

	CHN	USA	EUR	KOR	EGY
CHN	1.000				
USA	0.525	1.000			
EUR	0.460	0.652	1.000		
KOR	0.247	0.419	0.277	1.000	
EGY	-0.395	-0.186	-0.101	-0.397	1.000

We consider only five jurisdictions for clarity of exposition and emphasize that our sample selection is deliberate.[24] One of the jurisdictions, CHN, is very large relative to the rest. Two other jurisdictions are large and approximately of equal size, USA and EUR. The remaining two, KOR and EGY, are relatively small and substantially more volatile than the larger jurisdictions. Finally, EGY is negatively correlated with all other jurisdictions to varying degrees. To a large extent, our sample spans the diversity present in the data.

We adopt a combinatorial approach to evaluating the gains from, or equivalently the *value* of, every possible linkage arrangement to illustrate the mechanisms that govern multilateral linkage. At this level of abstraction, value is measured in arbitrary units but its magnitude is comparable across jurisdictions, linkage coalitions, and linkage coalition structures. This ensures that we can compare multilateral linkages in a consistent way and thus, that we can characterize jurisdictional linkage preferences.

Our theoretical results indicate that the global market always generates the largest aggregate value. However, by Corollary 2.6.7, it may not be the most preferred link for each jurisdiction. Indeed, in our sample the global market is not each jurisdiction's best option.

[24]For instance, see also Appendix 2.D for a set of eight jurisdictions.

This is shown in Table 2.3 which illustrates the jurisdictions' linkage preferences by listing their most and second most preferred linkage coalitions.

Table 2.3: Jurisdictional rankings of linkage coalitions

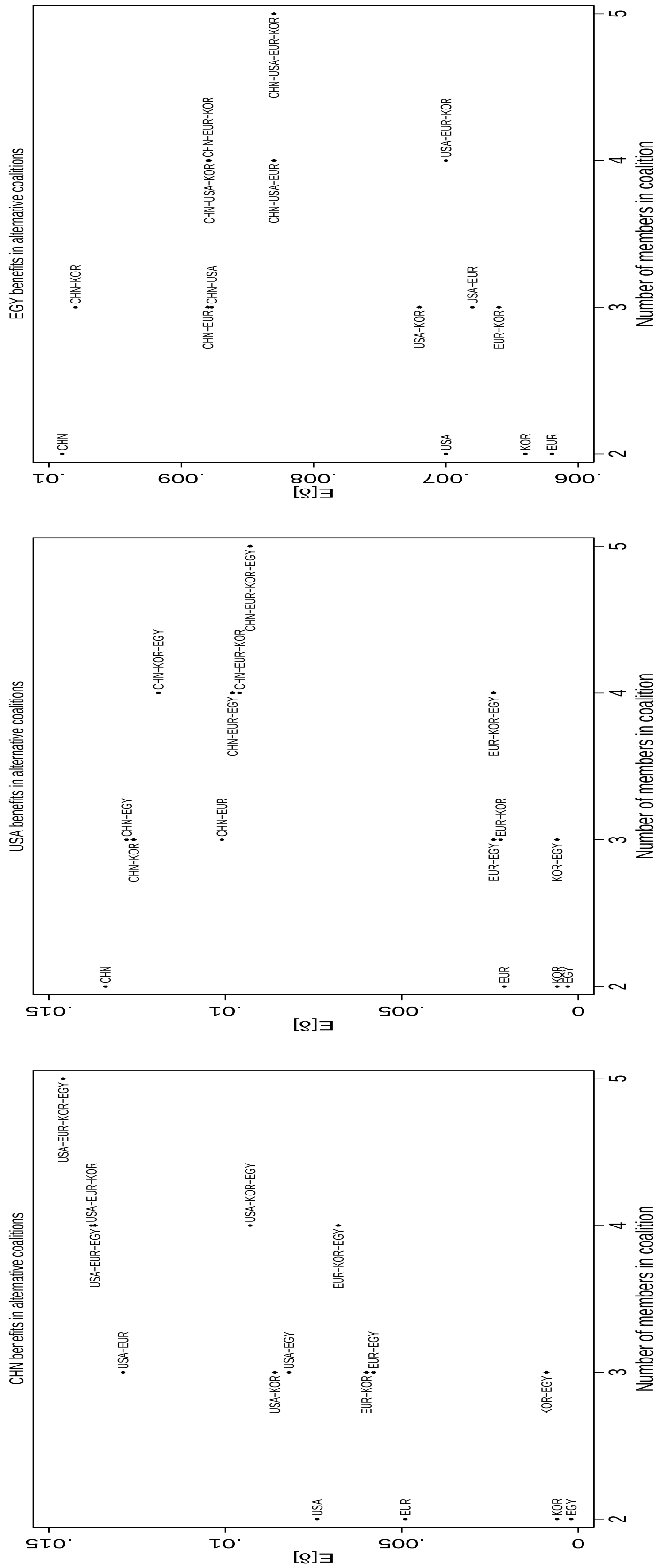
	Most preferred coalition	Second most preferred coalition
CHN	{CHN,USA,EUR,KOR,EGY}	{CHN,USA,EUR,KOR}
USA	{CHN,USA}	{CHN,USA,EGY}
EUR	{CHN,EUR}	{CHN,EUR,KOR,EGY}
KOR	{CHN,KOR}	{CHN,KOR,EGY}
EGY	{CHN,EGY}	{CHN,KOR,EGY}

In particular, Table 2.3 shows that size is a key factor determining the most preferred coalition. The size of CHN is so dominant that only when all others join CHN in a global market, the value CHN receives is the highest. This is in line with Doda & Taschini (2017) who show that a jurisdiction prefers a larger partner, all else equal. For the remaining jurisdictions, however, a bilateral link with CHN is preferred to all other coalitions. This is true despite the fact that adding other jurisdictions to the bilateral link with CHN increases the overall size of the market. This demonstrates why it may be misleading to apply the results and intuition derived in a bilateral setting to a multilateral context.

Although Table 2.3 reveals much about the complex interactions that determine jurisdictional linkage preferences, this is only part of a much richer story. To illustrate this, Figure 2.1 provides more detailed information by illustrating the gains from every linkage coalition for CHN, USA and EGY. The gains CHN derives from being a member of a linkage coalition is increasing in the total size of the remaining members of the coalition of a given cardinality, which is intuitive. Moreover, CHN always prefers to expand the present linkage coalition by including the largest partner among those available.

For USA and EGY, the effects of coalitional cardinality are more subtle. First, for these jurisdictions the global market is far from being a desirable coalition. Second, starting from their most preferred coalition, a bilateral link with CHN, entry by a new jurisdiction in the coalition, say at the insistence of CHN, implies marginal losses which are increasing in the new member's size. Third and conversely, starting from their second most preferred bilateral coalition under the assumption that CHN is not available to link, entry by a new jurisdiction can actually improve the gains USA and EGY obtain. Fourth, the gain improvements highlighted in the previous sentence, which is realized when EGY joins the USA-EUR link and KOR joins the EGY-USA link respectively, do not require the entry of the largest jurisdiction that is available to link. Taken together these four observations reinforce the message of Table 2.3 that the general model of multilateral linking presented above is essential for ranking alternative coalitions from a jurisdiction's perspective.

Figure 2.1: Jurisdictional preferences in terms of linkage coalition



Finally, we highlight the existence of preference clusters in Figure 2.1. There are three such clusters for CHN. An upper cluster where it partners with the two other large jurisdictions (USA and EUR), a middle cluster where CHN is linked with either USA or EUR but not both, and a lower cluster where CHN is only linked to small jurisdictions (KOR and EGY). In each of these clusters, CHN prefers linkage coalitions with the largest members available. For USA, two such clusters exist.[25] An upper cluster where CHN is in the linkage coalition and a lower cluster where it is not. Note again the effect of size: in the lower cluster where USA is the largest jurisdiction, it prefers links with the largest jurisdictions available while in the upper cluster where it is not the largest jurisdiction, it prefers links with the smallest jurisdictions available. For EGY, the smallest jurisdiction in our sample, such clusters are more circumscribed. We observe that the dispersion of jurisdictional gains across linkage coalitions is modest, suggesting that a clear ranking of links for small jurisdictions can be more arduous. In this case, a combination of sizes and shock characteristics govern the ranking of the possible multilateral linkages, which illustrates that without a theory it is difficult to determine their net effect.

2.8 Policy application: Multilateral linkage with costs

Linkage coalitions that generate high gains involve large partners or many partners, or both. In practice, however, these could be relatively costly to form. In particular, in the presence of costs associated with the formation of linkage coalitions, hereafter linkage costs, it might well be that a coalition structure different from the global market yields the highest aggregate payoff, net of costs. In this section we look at two aspects of this question. First, given such linkage costs, we explore the nature of globally efficient coalition structures, or GECS for short. Second, we compare the ability of various inter-jurisdictional cost-sharing arrangements in making GECS Pareto-improving with respect to autarky.[26]

We model the linkage costs as having two distinct variable components: (*i*) a linkage implementation part capturing that the larger the potential jurisdictions involved, the larger are the implementation-related administrative costs, e.g. the costs of harmonizing the rules of the previously independent systems; and (*ii*) a linkage negotiation part reflecting that costs in forging and establishing climate policy linkage agreements are increasing in the number of participating jurisdictions. Fixed per-link sunk costs are not considered as they are blind to both the composition of coalitions and the architecture of coalition structures,

[25] Although EUR is not in Figure 2.1, it displays a similar pattern with a smaller distance between the two clusters, suggesting that 'dispersion' in terms of linkage gain is lower for smaller jurisdictions.

[26] This analysis could also be applied to any other 'desirable' coalition structures.

thereby unable to discriminate between them. We capture these elements in the following cost structure

$$\kappa(\mathcal{C};\varepsilon_0,\varepsilon_1) \doteq \varepsilon_0 \cdot \Psi_{\mathcal{C}} + \varepsilon_1 \cdot |\mathcal{C}|^2, \text{ for all } \mathcal{C} \in \mathbf{C}_\star, \tag{2.8.1}$$

where $(\varepsilon_0,\varepsilon_1) \in \mathbb{R}^2_+$ are scaling parameters for the implementation and negotiation costs, respectively. Given these costs, we define the efficient structure as follows.

Definition 2.8.1. (Globally efficient coalition structure, GECS) Given cost parameters $(\varepsilon_0,\varepsilon_1) \in \mathbb{R}^2_+$ net aggregate economic gains from any $\mathcal{S} \in \mathbf{S}$ write

$$\tilde{\Delta}_{\mathcal{S}}(\varepsilon_0,\varepsilon_1) \doteq \Delta_{\mathcal{S}} - \sum_{\mathcal{C}\in\mathcal{S}} \kappa(\mathcal{C};\varepsilon_0,\varepsilon_1). \tag{2.8.2}$$

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

$$\mathcal{S}^*(\varepsilon_0,\varepsilon_1) \doteq \arg\max_{\mathcal{S}\in\mathbf{S}} \left\langle \mathbb{E}\{\tilde{\Delta}_{\mathcal{S}}(\varepsilon_0,\varepsilon_1)\} \right\rangle. \tag{2.8.3}$$

Although our definition of linkage costs in Equation (2.8.1) is exogenously imposed, we emphasize that costs associated with the formation of coalition structures are endogenous to the optimization program in Equation (2.8.3). On the one hand, for a pair of cost parameters low enough, linkage may remain superadditive and GECS correspond to the global market. In particular, $\mathcal{S}^*(0,0) = \mathcal{I}$. On the other hand, for a pair of cost parameters high enough, linkage may become subadditive and GECS correspond to complete autarky. For cost parameters such that linkage is neither superadditive nor subadditive, below we numerically explore the nature of GECS in terms of polycentricity and incompleteness of linkage. To that end, we first introduce alternative inter-jurisdictional cost-sharing arrangements and adopt a criterion to discriminate between alternative arrangements.

Definition 2.8.2. (Cost-sharing arrangements) Given $\mathcal{C} \in \mathbf{C}_\star$, a cost-sharing arrangement is a collection of non-negative weights $(\phi_{\mathcal{C},i})_{i\in\mathcal{C}}$ such that $\sum_{i\in\mathcal{C}} \phi_{\mathcal{C},i} = 1$ where $\phi_{\mathcal{C},i}$ is the share of the aggregate cost of forming coalition $\mathcal{C}$ incurred by jurisdiction $i \in \mathcal{C}$.

For any cost-sharing arrangement, net gains from forming any $\mathcal{C}$ in $\mathbf{C}_\star$ accruing to i in $\mathcal{C}$ thus write

$$\tilde{\delta}_{\mathcal{C},i}(\varepsilon_0,\varepsilon_1) \doteq \delta_{\mathcal{C},i} - \phi_{\mathcal{C},i} \cdot \kappa(\mathcal{C};\varepsilon_0,\varepsilon_1). \tag{2.8.4}$$

We consider seven cost-sharing arrangements that are listed and described in Table 2.1. These rules apportion costs equally, based on size, on cost type, on the gains that a jurisdiction obtains, etc. They are not meant to be exhaustive but simply illustrative. Notice that cost-sharing arrangements can be assimilated to inter-jurisdictional transfer schemes.

Table 2.1: Alternative inter-jurisdictional cost-sharing arrangements

Rule number	Share of total costs incurred by jurisdiction i ($\phi_{\mathcal{C},i}$)†
$R1$	$\lvert\mathcal{C}\rvert^{-1}$
$R2$	$\psi_i \cdot \Psi_{\mathcal{C}}^{-1}$
$R3$	$\psi_i^{-1} \cdot \left(\sum_{i\in\mathcal{C}} \psi_i^{-1}\right)^{-1}$
$R4$	$\varepsilon_0 \cdot \psi_i + \varepsilon_1 \cdot \lvert\mathcal{C}\rvert$
$R5$	$\mathbb{E}\{\delta_{\mathcal{C},i}\} \cdot \mathbb{E}\{\Delta_{\mathcal{C}}\}^{-1}$
$R6$	$\left(\mathbb{E}\{\Delta_{\mathcal{C}}\} - \mathbb{E}\{\Delta_{\mathcal{C}_{-i}}\}\right)^{-1} \cdot \left(\sum_{j\in\mathcal{C}} \left(\mathbb{E}\{\Delta_{\mathcal{C}}\} - \mathbb{E}\{\Delta_{\mathcal{C}_{-j}}\}\right)^{-1}\right)^{-1}$
$R7$	$\left(\mathbb{E}\{\Delta_{\mathcal{C}}\} - \mathbb{E}\{\Delta_{\mathcal{C}_{-i}}\}\right) \cdot \left(\lvert\mathcal{C}\rvert \cdot \mathbb{E}\{\Delta_{\mathcal{C}}\} - \sum_{j\in\mathcal{C}} \mathbb{E}\{\Delta_{\mathcal{C}_{-j}}\}\right)^{-1}$

Note: †: except for $R4$ where the total linkage costs incurring to jurisdiction i are indicated.
Legend: $R1$ is an egalitarian rule: all jurisdictions incur the same costs. With $R2$ and $R3$ linkage costs are shared in proportion to size or inverse of size, respectively. $R4$ is a mixed rule where implementation costs are shared in proportion to size and negotiation costs are evenly shared among jurisdictions. Under $R5$ jurisdictions incur costs in proportion to what they gain from the coalition. $R6$ (resp. $R7$) considers that the more desirable one jurisdiction is, the less (resp. more) it contributes to linkage cost payment.

We adopt a weak notion of incentive-compatibility 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 $(\varepsilon_0, \varepsilon_1) \in \mathbb{R}_+^2$, GECS is said to be Pareto-improving with respect to autarky if it holds that, for all $\mathcal{C}$ in $\mathcal{S}^*(\varepsilon_0, \varepsilon_1)$ and all i in $\mathcal{C}$

$$\mathbb{E}\{\tilde{\delta}_{\mathcal{C},i}(\varepsilon_0, \varepsilon_1)\} \geq 0. \tag{2.8.5}$$

Next we compare the seven cost-sharing arrangements in their ability to implement GECS, that is to make GECS Pareto-improving w.r.t. autarky.

Introducing linkage costs requires us to parametrize the cost function in Equation (2.8.1). This is difficult even at this level of abstraction because there is very little empirical guidance to select the pair $(\varepsilon_0, \varepsilon_1)$. To discipline the parametrization, we report three sets of results which are comparable in the sense that the most costly coalition structure, i.e. that where jurisdictions negotiate a global market, generates costs equal to 75% of the gross benefits it delivers. Note that this does not identify $(\varepsilon_0, \varepsilon_1)$ individually. To pin down a unique pair, we further assume that a share z of the linkage costs are implementation costs, and report results for $z \in \{0, 0.5, 1\}$. In particular, the aggregate gross gain from the global market is 0.0473 with coalition cardinality 5 and aggregate size 202.738. With $z = 1$ there are only implementation costs and $(\varepsilon_0, \varepsilon_1)$ is uniquely determined $(1.75 \cdot 10^{-4}, 0)$. Conversely, with $z = 0$, there are only negotiation costs and we have the parameter pair $(0, 1.42 \cdot 10^{-3})$. Finally, with $z = 0.5$ the parameter pair is $(8.75 \cdot 10^{-5}, 7.01 \cdot 10^{-4})$.

Table 2.2 presents the results of combining these cost assumptions with the seven cost-sharing arrangements. In particular, we report GECS ($\mathcal{S}^*$) and the associated expected aggregate net gains $\mathbb{E}\{\tilde{\Delta}_{\mathcal{S}^*}\}$. We say that $\mathcal{S}^*$ is blocked by a jurisdiction i under a rule $R\#$, if i receives negative net benefits, i.e. it is worse off under $\mathcal{S}^*$ than autarky. Table 2.2 also reports the blocking jurisdictions, if any, under a given rule.

Table 2.2: Multilateral linkage with costs and alternative cost-sharing rules ($x = 0.75$)

	$\mathcal{S}^*$	$\mathbb{E}\{\tilde{\Delta}_{\mathcal{S}^*}\}$	Set of blocking jurisdiction under R#
$z = 0$	{{CHN,USA,EUR},{KOR,EGY}}	0.0221	$R3$ and $R5$: $\emptyset$ $R1$, $R2$, $R4$, $R6$ and $R7$: {KOR}
$z = 0.5$	{{CHN,USA,EUR},{KOR,EGY}}	0.0137	$R1$, $R4$, $R5$ and $R7$: $\emptyset$ $R2$: {KOR}; $R3$: {EUR} $R6$: {EUR,KOR}
$z = 1$	{{CHN,USA,EUR,KOR,EGY}}	0.0118	$R5$: $\emptyset$; $R1$: {KOR}; $R7$: {CHN} $R2$ and $R4$: {CHN,USA} $R3$ and $R6$: {KOR,EGY}

Note: Cost parameters are set such that linkage costs (i) amount to a share x of the aggregate gains from the global market; (ii) are composed of a share z (resp. $1-z$) of implementation (resp. negotiation) costs.

First, when only linkage negotiation costs are involved ($z = 0$), GECS corresponds to a linked system among the three largest jurisdictions on the one hand, and another system consisting of the two smallest jurisdictions on the other, i.e. GECS is a polycentric complete linkage. If we were to increase cost parameters further, a GECS where some jurisdictions remain in autarky, i.e. an incomplete linkage, would emerge. However, only rules $R3$ and $R5$ are consistent with no jurisdiction blocking this efficient structure. If any other rule were adopted ex ante, KOR would block its linkage coalition with EGY thereby precluding the implementation of GECS. Thus, cost-sharing rules are critical for whether GECS is a Pareto-improvement w.r.t. autarky, i.e. whether GECS is implementable or not.

Second, we observe that when $z = 0.5$, GECS is unchanged. Although the net gains from GECS are half those that obtain with $z = 0$, GECS is now feasible under cost-sharing rules $R1$, $R4$, $R5$ and $R7$. This shows that high aggregate gains from GECS do not necessarily make incentive-compatibility easier to achieve. Additionally, KOR is no longer the sole blocking jurisdiction, as EUR might also oppose GECS under certain cost-sharing rules.

Third, when only linkage implementation costs are involved ($z = 1$), GECS corresponds to the global market. However, it is only achievable under $R5$ and all jurisdictions but EUR may block it depending on the rule considered. Although GECS with $z = 1$ corresponds to the global market, it brings about half the aggregate gains as GECS with $z = 0$, which differs from the global market. In addition, it seems less likely to obtain because there are more potential blocking jurisdictions and fewer cost-sharing rules that can implement it.

The above suggests that polycentric GECSs are likely when the share of negotiation costs is larger, while the level of implementation costs determines whether system integration is complete or incomplete. Among the cost specifications and cost-sharing rules considered in Table 2.2, $R5$ always renders GECS viable. That is, splitting linkage costs in proportion to jurisdictional linkage gains might facilitate the implementation of efficient structures. In practice, however, the determination of the associated cost shares might not be as straightforward as it is for simpler rules, e.g. egalitarian or per size.

2.9 Conclusion

While the theory of bilateral linkages is well established, we know relatively little about multilaterally linked systems. This Chapter has advanced the frontier of research on this topic by proposing a general theory to describe and analyze multilateral linkages between ETSs. In our theory, the magnitude of individual gains in linkages and the variance of prices in linkage equilibria are well defined objects, whose analytical properties we study. In particular, we provide a formula for the gains from trade in multilaterally linked ETSs as a function of coalitional sizes and shock characteristics. Importantly, we decompose any multilateral linkage into its internal bilateral linkages. We use this decomposition to characterize aggregate and jurisdictional gains from any linkage coalition as a size-weighted function of aggregate gains from all bilateral links that can be formed within it. Finally, this decomposition formula allows us to analytically characterize the aggregate expected gains from the union of disjoint coalitions of linked ETSs, which we show to be no less than the sum of separate coalitions' expected gains, i.e. linkage is superadditive.

A direct consequence of superadditivity is that the global market is the efficient coalition structure from a social perspective. Absent inter-jurisdictional transfer arrangement, however, the global market is not necessarily the most preferred linkage coalition when viewed from the perspective of a single jurisdiction. Therefore, even without linkage costs it is not a forgone conclusion that the globally linked market will endogenously emerge. In a world where inter-jurisdictional transfers are politically unpalatable, this may be an important reason why multilateral linkages are uncommon.

A quantitative illustration loosely calibrated to five real-world jurisdictions provides evidence on the potential practical relevance of our theoretical findings. For example, the global market is *not* the most preferred coalition of every jurisdiction in our numerical analysis. When we additionally introduce reasonably parametrized linkage costs, linkage coalition structures different from the global market may be efficient but not necessarily implementable depending on how linkage costs are shared. This is clearly an area where additional academic and policy work would be useful.

As a final note, we would like to underline that in our model, it is always 'desirable' to link with a jurisdiction whose price volatility is high. However, as Fankhauser & Hepburn (2010b) put it, «in some cases, price volatility is a direct consequence of market design and/or policy shocks, rather than being caused by natural market fluctuations». Therefore, link-induced price volatility can also be perceived as 'bad' because it may appear somewhat unfounded and/or conflict with domestic objectives. One such example is the unanticipated 'CER flood' in the New Zealand ETS as discussed in footnote 16 in the General Introduction. In our model, we thus somehow fail to distinguish between 'good' and 'bad' price volatility. Although indirectly treated, the idea that permit price variations may not be related to market fundamentals will be the subject of the next Chapter.

Appendices of Chapter 2

2.A Collected proofs

2.A.1 Proof of Proposition 2.6.3 (compact form of linkage gains)

For the remainder and without loss of generality, we fix $\mathcal{C} \in \mathbf{C}_\star$ such that $\mathcal{C} = \{1, 2, \ldots, m\}$ with $m \in [\![3; n]\!]$. Because aggregate pollution is fixed and does not vary with the underlying linkage coalition structure, the economic gross gains from $\mathcal{C}$-linkage accruing to jurisdiction $i \in \mathcal{C}$ is given by the difference between its benefits under $\mathcal{C}$-linkage and autarky, that is

$$\begin{aligned}
\delta_{\mathcal{C},i} &= (b_1 + \theta_i - p_{\mathcal{C}})(q_{\mathcal{C},i} - \omega_i) - \frac{b_2}{2\psi_i}(q_{\mathcal{C},i}^2 - \omega_i^2) \\
&= \frac{b_2}{\psi_i} q_{\mathcal{C},i}(q_{\mathcal{C},i} - \omega_i) - \frac{b_2}{2\psi_i}(q_{\mathcal{C},i}^2 - \omega_i^2) \\
&= \frac{b_2}{2\psi_i}(q_{\mathcal{C},i} - \omega_i)^2 = \frac{\psi_i}{2b_2}(\bar{p}_i - p_{\mathcal{C}})^2,
\end{aligned} \tag{2.A.1}$$

where the second and fourth equalities obtain via the necessary first-order condition in Equation (2.6.2) and the net demand for permits in Equation (2.6.4), respectively. This is Equation (2.6.5) and taking expectations proves Proposition 2.6.3. Since $\bar{p}_i - p_{\mathcal{C}} = \theta_i - \hat{\Theta}_{\mathcal{C}}$, applying the definition of $\hat{\Theta}_{\mathcal{C}}$ then gives Equation (2.6.9). Expanding further yields

$$\delta_{\mathcal{C},i} = \frac{\psi_i}{2b_2\Psi_{\mathcal{C}}^2} \sum_{j=1, j\neq i}^{m} \psi_j \left\{ \psi_j(\theta_i - \theta_j)^2 + 2 \sum_{k>j, k\neq i}^{m} \psi_k(\theta_i - \theta_j)(\theta_i - \theta_k) \right\}. \tag{2.A.2}$$

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

$$\begin{aligned}
2(\theta_i - \theta_j)(\theta_i - \theta_k) &= (\theta_i - \theta_k + \theta_k - \theta_j)(\theta_i - \theta_k) + (\theta_i - \theta_j)(\theta_i - \theta_j + \theta_j - \theta_k) \\
&= (\theta_i - \theta_j)^2 + (\theta_i - \theta_k)^2 - (\theta_j - \theta_k)^2,
\end{aligned} \tag{2.A.3}$$

$$\sum_{j=1, j\neq i}^{m} \sum_{k>j, k\neq i}^{m} \psi_j\psi_k \left\{ (\theta_i - \theta_j)^2 + (\theta_i - \theta_k)^2 \right\} = \sum_{j=1, j\neq i}^{m} \sum_{k=1, k\neq i,j}^{m} \psi_j\psi_k(\theta_i - \theta_j)^2. \tag{2.A.4}$$

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

$$\delta_{\mathcal{C},i} = \frac{\psi_i}{2b_2\Psi_{\mathcal{C}}^2} \sum_{j=1,j\neq i}^{m} \psi_j \Big\{ (\Psi_{\mathcal{C}} - \psi_i)(\theta_i - \theta_j)^2 - \sum_{k>j,k\neq i}^{m} \psi_k(\theta_j - \theta_k)^2 \Big\}. \tag{2.A.5}$$

Recall that the aggregate gross economic gains from $\{i,j\}$-linkage read

$$\Delta_{\{i,j\}} = \frac{\psi_i\psi_j}{2b_2(\psi_i+\psi_j)}(\theta_i-\theta_j)^2. \tag{2.A.6}$$

Finally noting that $\Psi_{\mathcal{C}_{-i}} = \Psi_{\mathcal{C}} - \psi_i$, Equation (2.A.5) coincides with Equation (2.6.11).

2.A.2 Proof of Proposition 2.6.4 (linking price properties)

Since the variance is a symmetric bilinear form, it jointly holds that

$$\mathbb{V}\{p_{\mathcal{C}}\} = \mathbb{V}\{\hat{\Theta}_{\mathcal{C}}\} = \Psi_{\mathcal{C}}^{-2}\Bigg(\sum_{i=1}^{m}\psi_i^2\sigma_i^2 + 2\sum_{1\leq i<j\leq m}\psi_i\psi_j\rho_{ij}\sigma_i\sigma_j\Bigg), \text{ and} \tag{2.A.7a}$$

$$\Psi_{\mathcal{C}}\sum_{j=1}^{m}\psi_j\mathbb{V}\{\theta_j\} = \sum_{i=1}^{m}\sum_{j=1}^{m}\psi_i\psi_j\sigma_j^2 = \sum_{i=1}^{m}\psi_i^2\sigma_i^2 + \sum_{1\leq i<j\leq m}\psi_i\psi_j(\sigma_i^2+\sigma_j^2). \tag{2.A.7b}$$

It follows that $\mathbb{V}\{p_{\mathcal{C}}\} \leq \Psi_{\mathcal{C}}^{-1}\sum_{i\in\mathcal{C}}\psi_i\mathbb{V}\{\bar{p}_i\}$ since $\sigma_i^2+\sigma_j^2 \geq 2\rho_{ij}\sigma_i\sigma_j$ and $\mathbb{V}\{\bar{p}_i\} = \mathbb{V}\{\theta_i\}$. The inequality thus holds strictly when $\exists(i,j)\in\mathcal{C}^2$ such that $\rho_{ij}<1$ and/or $\sigma_i\neq\sigma_j$. The statement on price variability is verified for bilateral links. The argument naturally extends to multilateral links. Then, by definition,

$$\mathbb{V}\{p_{\{i,j\}}\} = (\psi_i+\psi_j)^{-2}\Big(\psi_i^2\mathbb{V}\{\bar{p}_i\} + \psi_j^2\mathbb{V}\{\bar{p}_j\} + 2\rho_{ij}\psi_i\psi_j(\mathbb{V}\{\bar{p}_i\}\mathbb{V}\{\bar{p}_j\})^{1/2}\Big). \tag{2.A.8}$$

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. $\mathbb{V}\{\bar{p}_j\} \geq \mathbb{V}\{p_{\{i,j\}}\}$, that is i.f.f.

$$\psi_i(\sigma_j-\sigma_i)\Big(\psi_i(\sigma_i+\sigma_j) + 2\psi_j\sigma_j(1-\rho_{ij})\Big) \geq 0, \tag{2.A.9}$$

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

$$\psi_j(\sigma_j-\sigma_i)\Big(\psi_j(\sigma_i+\sigma_j) + 2\psi_i\sigma_i(\rho_{ij}-1)\Big) \leq 0 \;\Leftrightarrow\; \frac{\psi_j}{\psi_i} \leq \frac{2\sigma_i(1-\rho_{ij})}{\sigma_i+\sigma_j}. \tag{2.A.10}$$

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 is not too large in comparison.

Now assume that $\mathcal{C}$ is ordered such that $\psi_1 \leq \cdots \leq \psi_m$ and let $\bar{\sigma} = \max_{i\in\mathcal{C}} \sigma_i$. Fix $\varepsilon > 0$. We have the following chain of inequalities

$$\begin{aligned} \mathbb{P}\Big(|\hat{\Theta}_{\mathcal{C}} - \mathbb{E}\{\hat{\Theta}_{\mathcal{C}}\}| > \varepsilon\Big) &\leq \varepsilon^{-2}\mathbb{E}\Big\{(\hat{\Theta}_{\mathcal{C}} - \mathbb{E}\{\hat{\Theta}_{\mathcal{C}}\})^2\Big\} = \varepsilon^{-2}\mathbb{V}\{\hat{\Theta}_{\mathcal{C}}\} \\ &= \varepsilon^{-2}\psi_{\mathcal{C}}^{-2}\sum_{i=1}^{m}\left\{\psi_i^2\sigma_i^2 + \sum_{j=1}^{m}\rho_{ij}\psi_i\psi_i\sigma_i\sigma_j\right\} \\ &\leq \left(\frac{\psi_m\bar{\sigma}}{\psi_1\varepsilon}\right)^2\left[\frac{1}{m}+1\right], \end{aligned} \tag{2.A.11}$$

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

2.A.3 Proof of Proposition 2.6.5 (bilateral decomposition)

Summing Equation (2.6.11) over all $i \in [\![1;m]\!]$ gives

$$\Delta_{\mathcal{C}} \doteq \sum_{i=1}^{m}\delta_{\mathcal{C},i} = \Psi_{\mathcal{C}}^{-2}\sum_{i=1}^{m}\left\{\sum_{j=1,j\neq i}^{m}\left\{\Psi_{\mathcal{C}_{-i}}(\psi_i+\psi_j)\Delta_{\{i,j\}} - \psi_i\sum_{k>j,k\neq i}^{m}(\psi_j+\psi_k)\Delta_{\{j,k\}}\right\}\right\}. \tag{2.A.12}$$

Regrouping terms by bilateral linkages, Equation (2.A.12) rewrites

$$\begin{aligned} \Delta_{\mathcal{C}} &= \Psi_{\mathcal{C}}^{-2}\sum_{1\leq i<j\leq m}\left\{\Big(\Psi_{\mathcal{C}_{-i}} + \Psi_{\mathcal{C}_{-j}}\Big)(\psi_i+\psi_j)\Delta_{\{i,j\}} - \sum_{k=1,k\neq i,j}^{m}\psi_k(\psi_i+\psi_j)\Delta_{\{i,j\}}\right\} \\ &= \Psi_{\mathcal{C}}^{-2}\sum_{1\leq i<j\leq m}\Big\{\Big(\Psi_{\mathcal{C}_{-i}} + \Psi_{\mathcal{C}_{-j}} - \Psi_{\mathcal{C}_{-\{i,j\}}}\Big)(\psi_i+\psi_j)\Delta_{\{i,j\}}\Big\} \\ &= \Psi_{\mathcal{C}}^{-1}\sum_{1\leq i<j\leq m}(\psi_i+\psi_j)\Delta_{\{i,j\}}. \end{aligned} \tag{2.A.13}$$

By symmetry, i.e. $\Delta_{\{i,j\}} = \Delta_{\{j,i\}}$, Equation (2.A.13) coincides with Equation (2.6.12). Expectation and variance are linear and symmetric bilinear operators respectively, hence

$$\mathbb{E}\{\Delta_{\mathcal{C}}\} = (2\Psi_{\mathcal{C}})^{-1}\sum_{(i,j)\in\mathcal{C}\times\mathcal{C}}\Psi_{\{i,j\}}\mathbb{E}\{\Delta_{\{i,j\}}\}, \tag{2.A.14a}$$

$$\mathbb{V}\{\Delta_{\mathcal{C}}\} = (2\Psi_{\mathcal{C}})^{-2}\sum_{(i,j)\in\mathcal{C}\times\mathcal{C}}\Psi_{\{i,j\}}\sum_{(k,l)\in\mathcal{C}\times\mathcal{C}}\Psi_{\{k,l\}}\mathrm{Cov}\{\Delta_{\{i,j\}};\Delta_{\{k,l\}}\}. \tag{2.A.14b}$$

The following will establish that $\mathcal{I} = \arg\max_{\mathcal{C}\in\mathbf{C}_\star}\mathbb{E}\{\Delta_{\mathcal{C}}\}$ but there is no reason that forming larger coalitions reduces volatility of gains and a fortiori that $\mathcal{I} = \arg\min_{\mathcal{C}\in\mathbf{C}_\star}\mathbb{V}\{\Delta_{\mathcal{C}}\}$.

2.A.4 Proof of Proposition 2.6.6 (superadditivity)

Given $\mathcal{S}$ and $\mathcal{S}'$ as in Definition 2.6.2, Equation (2.6.15) obtains by telescope and it is sufficient to establish Equation (2.6.16) for any $i \in [\![1; d]\!]$. Fix $\mathcal{C}$ and $\mathcal{C}'$ in $\mathbf{C}_\star$ with $\mathcal{C}' \subset \mathcal{C}$ and $\mathcal{C}''$ the complement of $\mathcal{C}'$ in $\mathcal{C}$, i.e. $\mathcal{C} = \mathcal{C}' \cup \mathcal{C}''$ and $\mathcal{C}' \cap \mathcal{C}'' = \varnothing$. Expanding Equation (2.6.12) gives

$$\begin{aligned}\Delta_{\mathcal{C}} &= (2\Psi_{\mathcal{C}})^{-1}\left(\sum_{(i,j)\in\mathcal{C}'\times\mathcal{C}'}\Psi_{\{i,j\}}\Delta_{\{i,j\}} + \sum_{(i,j)\in\mathcal{C}''\times\mathcal{C}''}\Psi_{\{i,j\}}\Delta_{\{i,j\}} + 2\sum_{(i,j)\in\mathcal{C}'\times\mathcal{C}''}\Psi_{\{i,j\}}\Delta_{\{i,j\}}\right)\\ &= \Psi_{\mathcal{C}}^{-1}\left(\Psi_{\mathcal{C}'}\Delta_{\mathcal{C}'} + \Psi_{\mathcal{C}''}\Delta_{\mathcal{C}''} + \sum_{(i,j)\in\mathcal{C}'\times\mathcal{C}''}\Psi_{\{i,j\}}\Delta_{\{i,j\}}\right).\end{aligned} \tag{2.A.15}$$

The aggregate gain from merging $\mathcal{C}'$ and $\mathcal{C}''$ is $\Delta_{\{\mathcal{C}',\mathcal{C}''\}} \doteq \Delta_{\mathcal{C}} - \Delta_{\mathcal{C}'} - \Delta_{\mathcal{C}''}$ so that

$$\begin{aligned}\Delta_{\{\mathcal{C}',\mathcal{C}''\}} &= \Psi_{\mathcal{C}}^{-1}\left(\sum_{(i,j)\in\mathcal{C}'\times\mathcal{C}''}\Psi_{\{i,j\}}\Delta_{\{i,j\}} + \left(\Psi_{\mathcal{C}'} - \Psi_{\mathcal{C}}\right)\Delta_{\mathcal{C}'} + \left(\Psi_{\mathcal{C}''} - \Psi_{\mathcal{C}}\right)\Delta_{\mathcal{C}''}\right)\\ &= \Psi_{\mathcal{C}}^{-1}\left(\sum_{(i,j)\in\mathcal{C}'\times\mathcal{C}''}\Psi_{\{i,j\}}\Delta_{\{i,j\}} - \Psi_{\mathcal{C}''}\Delta_{\mathcal{C}'} - \Psi_{\mathcal{C}'}\Delta_{\mathcal{C}''}\right).\end{aligned} \tag{2.A.16}$$

By transposition of the definition (and beneficial nature) of bilateral linkage between singletons to (disjoint) coalitions, it is the case that

$$\mathbb{E}\{\Delta_{\{\mathcal{C}',\mathcal{C}''\}}\} = \frac{\Psi_{\mathcal{C}'}\Psi_{\mathcal{C}''}}{2b_2\Psi_{\mathcal{C}}}\left(\mathbb{V}\{p_{\mathcal{C}'}\} + \mathbb{V}\{p_{\mathcal{C}''}\} - 2\mathrm{Cov}\{p_{\mathcal{C}'}; p_{\mathcal{C}''}\}\right) \geq 0. \tag{2.A.17}$$

2.A.5 Proof of Corollary 2.6.7 (non alignment of preferences)

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

$$\sum_{i\in\mathcal{C}'}\mathbb{E}\{\delta_{\mathcal{C}',i}\} = \mathbb{E}\{\Delta_{\mathcal{C}'}\} > \sum_{i\in\mathcal{C}'}\mathbb{E}\{\delta_{\mathcal{C},i}\} = \mathbb{E}\{\Delta_{\mathcal{C}}\} - \sum_{i\in\mathcal{C}''}\mathbb{E}\{\delta_{\mathcal{C},i}\} \tag{2.A.18}$$

Recalling the definition of a link between $\mathcal{C}'$ and $\mathcal{C}''$ in Equation (2.6.14), Equation (2.A.18) imposes

$$\mathbb{E}\{\Delta_{\mathcal{C}''}\} + \mathbb{E}\{\Delta_{\{\mathcal{C}',\mathcal{C}''\}}\} - \sum_{i\in\mathcal{C}''}\mathbb{E}\{\delta_{\mathcal{C},i}\} < 0, \tag{2.A.19}$$

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

2.B Model generalization and extensions

2.B.1 The two components of linkage gains

We consider the general case where jurisdictions in $\mathcal{C}$ have different domestic ambition levels, i.e. the exogenous cap profile $(\omega_i)_{i\in\mathcal{C}}$ does not satisfy Equation (2.3.4) and expected autarkic prices differ across jurisdictions in $\mathcal{C}$. In this case, the $\mathcal{C}$-linkage equilibrium permit price reads

$$p_{\mathcal{C}} = b_1 - b_2\Omega_{\mathcal{C}}\Psi_{\mathcal{C}}^{-1} + \hat{\Theta}_{\mathcal{C}}, \tag{2.B.1}$$

Considering the difference between the $\mathcal{C}$-linkage price and the autarky price in jurisdiction $i \in \mathcal{C}$, we obtain

$$\bar{p}_i - p_{\mathcal{C}} = \theta_i - \hat{\Theta}_{\mathcal{C}} - b_2\Big(\Omega_{\mathcal{C}}\Psi_{\mathcal{C}}^{-1} - \omega_i\psi_i^{-1}\Big). \tag{2.B.2}$$

Note that Equation (2.B.2) reduces to Equation (2.6.8) when $\Omega_{\mathcal{C}}\Psi_{\mathcal{C}}^{-1} = \omega_i\psi_i^{-1}$. This occurs when Equation (2.3.4) holds, i.e. when $\exists A > 0$ such that $\omega_i = A \cdot \psi_i$ for all $i \in \mathcal{C}$.

Before showing how our results in the main text generalize, we illustrate how they hold irrespective of the common stringency parameter A To this end, we compare $\mathcal{C}$-linkage equilibria with two ambition parameters A and A' such that A is more stringent than A', i.e. $A' > A$. This implies that both autarky and $\mathcal{C}$-linkage prices under A are higher than under A', that is

$$p_{\mathcal{C}}^{A} = b_1 - b_2 A + \hat{\Theta}_{\mathcal{C}} > p_{\mathcal{C}}^{A'} = b_1 - b_2 A' + \hat{\Theta}_{\mathcal{C}}. \tag{2.B.3}$$

However, jurisdictional net permit demands, and consequently the linkage gains, are unaltered. In fact,

$$q_{\mathcal{C},i}^{A} - \omega_i^{A} = q_{\mathcal{C},i}^{A'} - \omega_i^{A'} = \psi_i(\theta_i - \hat{\Theta}_{\mathcal{C}})/b_2, \tag{2.B.4}$$

holds for all $i \in \mathcal{C}$ and is independent of the coalition-wide stringency parameter.

In the general case, plugging Equation (2.B.2) into Equation (2.6.5) and taking expectations gives

$$\mathbb{E}\{\delta_{\mathcal{C},i}\} = \underbrace{\frac{b_2\psi_i}{2}\Big(\Omega_{\mathcal{C}}\Psi_{\mathcal{C}}^{-1} - \omega_i\psi_i^{-1}\Big)^2}_{\text{stringency-dependent only}} + \underbrace{\frac{\psi_i}{2b_2}\mathbb{E}\{(\theta_i - \hat{\Theta}_{\mathcal{C}})^2\}}_{\text{shock-dependent only}}. \tag{2.B.5}$$

As in Equation (2.6.7), the expected gains from $\mathcal{C}$-linkage of $i \in \mathcal{C}$ can be decomposed into two components. The first source of gains directly relates to the within-coalition differences in jurisdiction-specific ambition levels (i.e., wedges in expected autarky prices) and is *independent* of the shocks. The second source of gains, which is our primary focus, directly relates to jurisdiction-specific uncertainty and is *independent* of the ambition levels.

Because both the first and second components of gains are non-negative, it is straightforward to show that Proposition 2.6.6 (superadditivity) continues to hold. However, a formal proof is required to show that Proposition 2.6.5 (bilateral decomposition) is maintained. For this purpose, consider that shocks are absent. In this case, aggregate gains from $\mathcal{C}$-linkage read

$$\Delta_{\mathcal{C}} = \frac{b_2}{2}\sum_{i=1}^{m}\psi_i\Big(\Omega_{\mathcal{C}}\Psi_{\mathcal{C}}^{-1} - \omega_i\psi_i^{-1}\Big)^2 = \frac{b_2}{2}\Big(\sum_{i=1}^{m}\omega_i^2\psi_i^{-1} - \Omega_{\mathcal{C}}^2\Psi_{\mathcal{C}}^{-1}\Big). \tag{2.B.6}$$

Applying Equation (2.B.6) for bilateral linkages, it follows that

$$\begin{aligned}
\sum_{1\le i<j\le m}\Psi_{\{i,j\}}\Delta_{\{i,j\}} &= \frac{b_2}{2}\sum_{1\le i<j\le m}\Big\{\Psi_{\{i,j\}}(\omega_i^2\psi_i^{-1}+\omega_j^2\psi_j^{-1}) - \Omega_{\{i,j\}}^2\Big\}\\
&= \frac{b_2}{2}\Big(\sum_{i=1}^{m}\sum_{j=1,j\neq i}^{m}\Psi_{\{i,j\}}\omega_i^2\psi_i^{-1} - \sum_{1\le i<j\le m}\Omega_{\{i,j\}}^2\Big)\\
&= \frac{b_2}{2}\sum_{i=1}^{m}\Big\{\Big(\Psi_{\mathcal{C}} + (m-2)\psi_i\Big)\omega_i^2\psi_i^{-1} - \sum_{j=1,j\neq i}^{m}\Big\{\omega_i^2+\omega_i\omega_j\Big\}\Big\} \qquad (2.B.7)\\
&= \frac{b_2}{2}\Big(\Psi_{\mathcal{C}}\sum_{i=1}^{m}\omega_i^2\psi_i^{-1} - \sum_{i=1}^{m}\Big\{\omega_i^2 + 2\sum_{j>i}\omega_i\omega_j\Big\}\Big)\\
&= \frac{b_2}{2}\Big(\Psi_{\mathcal{C}}\sum_{i=1}^{m}\omega_i^2\psi_i^{-1} - \Omega_{\mathcal{C}}^2\Big).
\end{aligned}$$

Multiplying both sides by $\Psi_{\mathcal{C}}^{-1}$ shows that Equations (2.6.12) and (2.B.6) coincide.

2.B.2 Distribution of gains between and within linkage coalitions

To analyze how linkage gains are apportioned within linkage coalitions it is implicit that they must have developed into an integrated system beforehand for otherwise the entity 'linkage coalition' would be ill-defined. To be able to pin down how coalition-wide gains are shared, we therefore consider that linkage coalitions consolidate in the sense that when jurisdictions form a linkage coalition they essentially transmute into one new, single entity (Caparrós & Péreau, 2017). Because there is no explicit appearance of time in our model, consolidation can be envisaged as commitment in the sense of Carraro & Siniscalco (1993).

As in the main text, consider the situation where two disjoint linkage coalitions $\mathcal{C}'$ and $\mathcal{C}''$ link. Let $\mathcal{C} = \mathcal{C}' \cup \mathcal{C}''$ and assume that $\mathcal{C}'$ and $\mathcal{C}''$ have consolidated prior to linking. By definition of bilateral linkage the aggregate gross gains $\mathbb{E}\{\Delta_{\{\mathcal{C}',\mathcal{C}''\}}\}$ is shared between $\mathcal{C}'$ and $\mathcal{C}''$ in inverse proportion to linkage coalition size. To understand how these gains are then shared within each linkage coalition, first note that the aggregate abatement effort required of, say, $\mathcal{C}'$ must be apportioned between internal jurisdictions according to optimality within that coalition, i.e. in proportion to jurisdictional flexibilities in abatement flexibilities.

Note that the ratio ψ_i/b_2 measures the flexibility in abatement of jurisdiction jurisdiction $i \in \mathcal{C}'$. By summation, the flexibility in abatement of the consolidated linkage coalition $\mathcal{C}'$ is $\Psi_{\mathcal{C}'}/b_2$. Within-$\mathcal{C}'$ optimality thus requires that jurisdiction i's net permit demand under $\{\mathcal{C}',\mathcal{C}''\}$-linkage satisfies $q_{\{\mathcal{C}',\mathcal{C}''\},i} - \omega_i = (\psi_i/\Psi_{\mathcal{C}'})(q_{\{\mathcal{C}',\mathcal{C}''\},\mathcal{C}'} - \Omega_{\mathcal{C}'})$. In turn, the gains in $\mathcal{C}'$ are divided between internal jurisdictions in proportion to size as well. For instance, the gains accruing to jurisdiction $i \in \mathcal{C}'$ amount to $(\psi_i/\Psi_{\mathcal{C}'})(\Psi_{\mathcal{C}''}/\Psi_{\mathcal{C}})\mathbb{E}\{\Delta_{\{\mathcal{C}',\mathcal{C}''\}}\}$.

Special case: Unitary accretion. It is also of interest to characterize the special case where a linkage coalition is linked to an individual jurisdiction (i.e., singleton). This clarifies how overall gross gains from the link are distributed between jurisdictions. Fix $\mathcal{C} \in \mathbf{C}$ and $i \in \mathcal{I}_{-\mathcal{C}}$ and let $\mathcal{C}' = \mathcal{C}$ and $\mathcal{C}'' = \{i\}$ in Equation (2.6.16), then

$$\mathbb{E}\{\Delta_{\{\mathcal{C},\{i\}\}}\} = \mathbb{E}\{\Delta_{\mathcal{C}\cup\{i\}}\} - \mathbb{E}\{\Delta_{\mathcal{C}}\} = \Psi_{\mathcal{C}\cup\{i\}}\Psi_{\mathcal{C}}^{-1}\mathbb{E}\{\delta_{\mathcal{C}\cup\{i\},i}\} = (1 + \psi_i\Psi_{\mathcal{C}}^{-1})\mathbb{E}\{\delta_{\mathcal{C}\cup\{i\},i}\}. \tag{2.B.8}$$

In words, linking jurisdiction $i \notin \mathcal{C}$ to the linkage coalition $\mathcal{C}$ generates an overall gross gain equal to $\mathbb{E}\{\delta_{\mathcal{C}\cup\{i\},i}\} + \psi_i\mathbb{E}\{\delta_{\mathcal{C}\cup\{i\},i}\}/\Psi_{\mathcal{C}}$ where the first term accrues to jurisdiction i and the second one accrues to the linkage coalition $\mathcal{C}$. Put differently, jurisdictions in $\mathcal{C}$ get a portion $\psi_i/\Psi_{\mathcal{C}\cup\{i\}}$ of the overall gross gain $\mathbb{E}\{\Delta_{\{\mathcal{C},\{i\}\}}\}$ that they share in proportion to size.

We provide an alternative direct proof of Equation (2.B.8). Fix w.l.o.g. $i = m$ such that $\mathcal{C}_{-i} = \{1, 2, \ldots, m-1\}$. By subtracting Equation (2.6.12) for coalitions $\mathcal{C}$ and $\mathcal{C}_{-i}$, we obtain

$$\begin{aligned}
\Delta_{\mathcal{C}} - \Delta_{\mathcal{C}_{-i}} &= \Psi_{\mathcal{C}}^{-1}\sum_{1\le j<k\le i}(\psi_j+\psi_k)\Delta_{\{j,k\}} - \Psi_{\mathcal{C}_{-i}}^{-1}\sum_{1\le j<k\le i-1}(\psi_j+\psi_k)\Delta_{\{j,k\}}\\
&= \Psi_{\mathcal{C}}^{-1}\sum_{j=1}^{i-1}(\psi_j+\psi_i)\Delta_{\{j,i\}} - \sum_{1\le j<k\le i-1}(\Psi_{\mathcal{C}_{-i}}^{-1} - \Psi_{\mathcal{C}}^{-1})(\psi_j+\psi_k)\Delta_{\{j,k\}}\\
&= \Psi_{\mathcal{C}}^{-1}\Psi_{\mathcal{C}_{-i}}^{-1}\left(\sum_{j=1}^{i-1}\Psi_{\mathcal{C}_{-i}}(\psi_j+\psi_i)\Delta_{\{j,i\}} - \psi_i\sum_{1\le j<k\le i-1}(\psi_j+\psi_k)\Delta_{\{j,k\}}\right)\\
&= \Psi_{\mathcal{C}}\Psi_{\mathcal{C}_{-i}}^{-1}\delta_{\mathcal{C},i},
\end{aligned} \tag{2.B.9}$$

where the last line follows from Equation (2.6.11). Also note that telescoping Equation (2.B.9) provides an alternative way of computing gains from merging two disjoint coalitions.

2.B.3 Alternative domestic cap selection mechanisms

This appendix considers various cap selection mechanisms. In the case of a uniformly-mixed stock pollutant, environmental damages are a function of aggregate emissions $Q_{\mathcal{I}} = \sum_{i\in\mathcal{I}} q_i$.

Assume for the moment that each jurisdiction incurs the same damages from pollution

$$D(Q_{\mathcal{I}}) = d_1 Q_{\mathcal{I}} + d_2 (Q_{\mathcal{I}})^2/2, \tag{2.B.10}$$

where d_1, d_2 are positive parameters. For instance, jurisdictional caps on emissions can be set non-cooperatively under risk neutrality. That is, jurisdiction $i \in \mathcal{I}$ maximizes its net expected benefits from operating its permit market under autarky, taking other jurisdictions' cap levels $(\omega_j)_{j \in \mathcal{I}_{-i}}$ as given. With $\Omega_{-i} = \sum_{j \in \mathcal{I}_{-i}} \omega_j$, these Cournot-Nash jurisdictional caps satisfy

$$\omega_i \doteq \arg\max_{\omega \geq 0} \mathbb{E}\Big\{ B_i(\omega; \theta_i) - D\left(\omega + \Omega_{-i}\right) \Big\} \text{ for all } i \in \mathcal{I}. \tag{2.B.11}$$

In this case, jurisdictional caps are proportional to jurisdictional size

$$\omega_i = A_1 \cdot \psi_i \text{ for all } i \in \mathcal{I}, \text{ where } A_1 = \frac{b_1 - d_1}{b_2 + d_2 \Psi_{\mathcal{I}}} > 0 \tag{2.B.12}$$

measures the non-cooperative abatement effort that is common to all jurisdictions (we assume $b_1 > d_1$). As long as damages are identical and there is no anticipation of linkage, similar results obtain under various cooperation levels and alternative conjectural variations.

Let $\mathcal{C} \in \mathbf{C}$ be a coalition on cap selection, i.e. jurisdictions in $\mathcal{C}$ set their caps cooperatively. Denote by $\bar{\mathcal{C}}$ the complement of $\mathcal{C}$ in $\mathbf{C}$ and assume members of $\bar{\mathcal{C}}$ behave as singletons w.r.t. cap selection. We assume Stackelberg conjectural variations where $\mathcal{C}$ behaves as the leader. Note that 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 $\Omega_{\mathcal{C}}$ selected by $\mathcal{C}$ reads

$$\Omega^r_{\bar{\mathcal{C}}}(\Omega_{\mathcal{C}}) = \frac{(b_1 - d_1 - d_2 \Omega_{\mathcal{C}})}{b_2 + d_2 \Psi_{\bar{\mathcal{C}}}} \cdot \Psi_{\bar{\mathcal{C}}}. \tag{2.B.13}$$

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

$$\max_{(\omega_i)_{i \in \mathcal{C}}} \left\{ \sum_{i \in \mathcal{C}} B_i(\omega_i; \theta_i) - |\mathcal{C}| D\Big(\Omega_{\mathcal{C}} + \Omega^r_{\bar{\mathcal{C}}}(\Omega_{\mathcal{C}})\Big) \right\}. \tag{2.B.14}$$

Solving Equation (2.B.14) and summing over i in $\mathcal{C}$ gives the $\mathcal{C}$-coalition aggregate cap

$$\Omega_{\mathcal{C}} = A_{\mathcal{C}} \cdot \Psi_{\mathcal{C}}, \text{ with } A_{\mathcal{C}} \doteq \frac{b_1 (b_2 + d_2 \Psi_{\bar{\mathcal{C}}})^2 - b_2 |\mathcal{C}| \Big(d_1 (b_2 + d_2 \Psi_{\bar{\mathcal{C}}}) + d_2 (b_1 - d_1) \Psi_{\mathcal{C}} \Big)}{b_2 \Big((b_2 + d_2 \Psi_{\bar{\mathcal{C}}})^2 + b_2 d_2 |\mathcal{C}| \Psi_{\mathcal{C}} \Big)}. \tag{2.B.15}$$

Substituting the above in Equation (2.B.13) gives the $\bar{\mathcal{C}}$-aggregate cap

$$\Omega_{\bar{\mathcal{C}}} = A_{\bar{\mathcal{C}}} \cdot \Psi_{\bar{\mathcal{C}}}, \text{ with } A_{\bar{\mathcal{C}}} \doteq \frac{b_1 - d_1 - d_2 A_{\mathcal{C}} \cdot \Psi_{\mathcal{C}}}{b_2 + d_2 \Psi_{\bar{\mathcal{C}}}}. \tag{2.B.16}$$

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

$$\frac{\partial A_{\mathcal{C}}}{\partial |\mathcal{C}|} < 0, \text{ and } \frac{\partial A_{\bar{\mathcal{C}}}}{\partial |\mathcal{C}|} = -\frac{d_2 \Psi_{\mathcal{C}}}{b_2 + d_2 \Psi_{\bar{\mathcal{C}}}} \frac{\partial A_{\mathcal{C}}}{\partial |\mathcal{C}|} > 0. \tag{2.B.17}$$

The first inequality tells us that the higher the number of cooperating jurisdictions, the more pollution externalities are internalized, and thus the larger partnering jurisdictions' 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.[27] That is, in response to higher abatement efforts from jurisdictions in $\mathcal{C}$, jurisdictions in $\bar{\mathcal{C}}$ will lower their own. In particular, $\mathcal{C} = \mathcal{I}$ corresponds to full cooperation where the common abatement effort is $A_n = \frac{b_1 - nd_1}{b_2 + nd_2 \Psi_{\mathcal{I}}} > 0$ (we assume $b_1 > nd_1$). Symmetrically, $\bar{\mathcal{C}} = \mathcal{I}$ coincides with the Cournot-Nash solution in Equation (2.B.11) with $A_1 = \frac{b_1 - d_1}{b_2 + d_2 \Psi_{\mathcal{I}}} > A_n$ as jurisdictions do not internalize the negative externality generated by their pollution on the other $n-1$ jurisdictions.

2.B.4 Cap selection in anticipation of linkage

First note that differentiating Equation (2.B.5) w.r.t. ω_i gives

$$\frac{\partial \mathbb{E}\{\delta_{\mathcal{C},i}\}}{\partial \omega_i} = b_2 \psi_i \Big(\Omega_{\mathcal{C}} \Psi_{\mathcal{C}}^{-1} - \omega_i \psi_i^{-1}\Big)\Big(\Psi_{\mathcal{C}}^{-1} - \psi_i^{-1}\Big) \geq 0 \Leftrightarrow \omega_i \psi_i^{-1} \geq \Omega_{\mathcal{C}} \Psi_{\mathcal{C}}^{-1}. \tag{2.B.18}$$

Irrespective of the shock structure, jurisdictions with size-adjusted cap stringency lower than that of $\mathcal{C}$ (i.e., $\omega_i \psi_i^{-1} \geq \Omega_{\mathcal{C}} \Psi_{\mathcal{C}}^{-1}$) are net permit sellers in expectations (i.e., $\mathbb{E}\{\bar{p}_i\} \leq \Psi_{\mathcal{C}}^{-1} \sum_{j \in \mathcal{C}} \psi_j \mathbb{E}\{\bar{p}_j\}$). These jurisdictions have an incentive to inflate their domestic caps to increase permit sales and thus economic gains from linkage (Helm, 2003). Note that this incentive is limited by the contrasting downward pressure exerted on the linked permit price. Conversely, jurisdictions whose ambition levels are above the $\mathcal{C}$-average are net permit buyers in expectations and have the incentive to strengthen ambition.

As an illustration we consider the situation where jurisdictions anticipate $\mathcal{C}$-linkage when selecting their domestic cap. This corresponds to a two-stage game where jurisdictions

[27] This will always be the case in a pure emissions game. In an international market for permits, note that 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.

determine 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 marginal benefits across jurisdictions and linked market closure. Given cap and realized shock profiles $(\omega_i)_{i\in\mathcal{C}}$ and $(\theta_i)_{i\in\mathcal{C}}$, respectively, we denote by $q^*_{\mathcal{C},i}$ and $p^*_{\mathcal{C}}$ the equilibrium emission level in i and linking price

$$q^*_{\mathcal{C},i} \equiv q^*_{\mathcal{C},i}(\Omega_{\mathcal{C}}; (\theta_i)_{i\in\mathcal{C}}) = \psi_i(\theta_i - \hat{\Theta}_{\mathcal{C}})/b_2 + \psi_i \Omega_{\mathcal{C}} \Psi_{\mathcal{C}}^{-1}, \tag{2.B.19a}$$

$$p^*_{\mathcal{C}} \equiv p^*_{\mathcal{C}}(\Omega_{\mathcal{C}}; (\theta_i)_{i\in\mathcal{C}}) = b_1 + \hat{\Theta}_{\mathcal{C}} - b_2 \Omega_{\mathcal{C}} \Psi_{\mathcal{C}}^{-1}. \tag{2.B.19b}$$

As is standard, we note that $\partial p^*_{\mathcal{C}}/\partial_{\Omega_{\mathcal{C}}} = -b_2\Psi_{\mathcal{C}}^{-1} < 0$ and $\partial q^*_{\mathcal{C},i}/\partial_{\Omega_{\mathcal{C}}} = \psi_i \Psi_{\mathcal{C}}^{-1} \in (0;1)$. For simplicity, 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 size.

Stage 1: Non-cooperative jurisdictional cap selection with linkage anticipation.

Each jurisdiction recognizes the effects of its domestic cap decision on both the linked permit price and its own market position. We consider Cournot conjectural variations (i.e., caps are announced simultaneously) and each jurisdiction takes other jurisdictional caps as given. Jurisdictional caps with strategic anticipation of linkage $(\hat{\omega}_i)_{i\in\mathcal{C}}$ satisfy, for all i in $\mathcal{C}$,

$$\begin{aligned} \hat{\omega}_i \doteq \arg\max_{\omega} \mathbb{E}\Big\{ & B_i\Big(q^*_{\mathcal{C},i}(\omega + \Omega_{\mathcal{C}_{-i}}; (\theta_i)_{i\in\mathcal{C}}); \theta_i\Big) - \psi_i d_1(\omega + \Omega_{\mathcal{C}_{-i}}) \\ & + p^*_{\mathcal{C}}(\Omega_{\mathcal{C}}; (\theta_i)_{i\in\mathcal{C}})\Big(\omega - q^*_{\mathcal{C},i}(\omega + \Omega_{\mathcal{C}_{-i}}; (\theta_i)_{i\in\mathcal{C}})\Big)\Big\}. \end{aligned} \tag{2.B.20}$$

Now assume that $\mathcal{C} = \{i, j\}$ where $\psi_j > \psi_i$, i.e. j is the larger and higher-damage jurisdiction. By stage-2 optimality, i.e. $\partial B_i(q^*_{\mathcal{C},i}; \theta_i)/\partial q_i = p^*_{\mathcal{C}}$, and taking expectations, the necessary first-order condition associated with Program (2.B.20) writes

$$-b_2 \Psi_{\{i,j\}}^{-2}(\psi_j \hat{\omega}_i - \psi_i \hat{\omega}_j) + b_1 - b_2(\hat{\omega}_1 + \hat{\omega}_2)\Psi_{\{i,j\}}^{-1} - d_1 \psi_i = 0. \tag{2.B.21}$$

Summing over i and j gives $\hat{\omega}_1 + \hat{\omega}_2 = \Psi_{\{i,j\}}(2b_1 - d_1\Psi_{\{i,j\}})/(2b_2)$ and substituting in the above yields

$$\hat{\omega}_i = \psi_i(b_1 - d_1\Psi_{\{i,j\}})/b_2 + d_1\psi_j\Psi_{\{i,j\}}/(2b_2). \tag{2.B.22}$$

When there is no anticipation of linkage, caps are determined by Equation (2.B.11), i.e. $\omega_i = \psi_i(b_1 - d_1\psi_i)/b_2$. 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 since

$$\hat{\omega}_i + \hat{\omega}_j \geq \omega_i + \omega_j \Leftrightarrow (\psi_i - \psi_j)^2 \geq 0. \tag{2.B.23}$$

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

2.C Linkage indifference frontiers

We define the relative size and volatility parameters by $\psi_j = x\psi_i$, $\psi_k = y\psi_i$, $\sigma_j = \alpha\sigma_j$ and $\sigma_k = \beta\sigma_i$. Then, jurisdiction i prefers $\{i,j\}$ over $\{i,k\}$, $\{i,j\}$ over $\mathcal{I} = \{i,j,k\}$ and $\{i,k\}$ over $\mathcal{I}$ i.f.f. the following inequalities respectively hold

$$y \leq \frac{x\sqrt{1+\alpha^2-2\rho_{ij}\alpha}}{\sqrt{1+\beta^2-2\rho_{ik}\beta} + x\left(\sqrt{1+\beta^2-2\rho_{ik}\beta} - \sqrt{1+\alpha^2-2\rho_{ik}\alpha}\right)} \tag{2.C.1a}$$

$$y \leq \frac{2x(1+x)\left(x(1+\alpha^2-2\rho_{ij}\alpha) - (1+x)(1-\rho_{ij}\alpha-\rho_{ik}\beta+\rho_{jk}\alpha\beta)\right)}{(1+x)^2(1+\beta^2-2\rho_{ik}\beta) - x^2(1+\alpha^2-2\rho_{ij}\alpha)} \tag{2.C.1b}$$

$$x \leq \frac{2y(1+y)\left(y(1+\beta^2-2\rho_{ik}\beta) - (1+y)(1-\rho_{ij}\alpha-\rho_{ik}\beta+\rho_{jk}\alpha\beta)\right)}{(1+y)^2(1+\alpha^2-2\rho_{ij}\alpha) - y^2(1+\beta^2-2\rho_{ik}\beta)}, \tag{2.C.1c}$$

and define the indifference frontiers depicted in Figures 2.2, 2.1 and 2.2. Similarly, we could define indifference frontiers for j and k. We can obtain comparative statics results by directly differentiating the frontiers in Equation (2.C.1) but we prefer to proceed graphically to explain the movements of the frontiers when jurisdictional characteristics vary.

In particular, to better discipline our characterization of i's relative preferences for the trilateral link w.r.t. bilateral links it is useful to consider the following ratio

$$\frac{\mathbb{E}\{\delta_{\mathcal{I},i}\}}{\mathbb{E}\{\delta_{\{i,j\},i}\}} = \frac{PSE_{\mathcal{I},i}}{PSE_{\{i,j\},i}} \times \frac{VE_{\mathcal{I},i} + DE_{\mathcal{I},i}}{VE_{\{i,j\},i} + DE_{\{i,j\},i}}. \tag{2.C.2}$$

First note that the coefficient PSE is always higher for the trilateral link than for an internal bilateral link, that is

$$PSE_{\mathcal{I},i} > PSE_{\{i,j\},i}. \tag{2.C.3}$$

In addition, the ratio $PSE_{\mathcal{I},i}/PSE_{\{i,j\},i}$ increases with ψ_i and ψ_k but decreases with ψ_j. The implications of this are twofold. First, all else equal, when i is relatively larger than both j and k, the PSE ratios are such that i prefers the trilateral link over the two bilateral links. Second, all else equal, when j (resp. k) is relatively larger than both i and k (resp. j), the PSE ratios steer i's preferences towards the bilateral link $\{i,j\}$ (resp. $\{i,k\}$).

Next, in order to analyze the relative VE, assume that $\rho_{jk} = 0$ to start with. In this case

$$VE_{\{i,j\},i} \geq VE_{\mathcal{I},i} \Leftrightarrow \sigma_j \sqrt{\psi_k + 2\psi_j} \geq \sigma_k \sqrt{\psi_k}, \tag{2.C.4}$$

which holds unconditionally when $\sigma_j \sim \sigma_k$ since $\sigma_j^2 > \mathbb{V}\{\hat{\Theta}_{\{j,k\}}\}$ or provided that $\sqrt{3}\sigma_j \geq \sigma_k$ when $\psi_j = \psi_k$. All else equal, note that $VE_{\{i,j\},i}/VE_{\mathcal{I},i} \geq 1$ is more (resp. less) likely to hold when $\rho_{jk} < 0$ (resp. $\rho_{jk} > 0$), i.e. i prefers to link with both j and k when the latter are positively correlated. In addition, the ratio $VE_{\{i,j\},i}/VE_{\mathcal{I},i}$ increases with σ_j, decreases with σ_k and decreases with σ_i i.f.f. Inequality (2.C.4) holds. Finally, in terms of relative DE, it holds that

$$DE_{\{i,j\},i} \geq DE_{\mathcal{I},i} \Leftrightarrow \rho_{ij}\sigma_j \leq \rho_{ik}\sigma_k, \tag{2.C.5}$$

which is always the case when $\rho_{ik} > 0$ and $\rho_{ij} < 0$, and conversely never holds when $\rho_{ik} < 0$ and $\rho_{ij} > 0$. Note also that $DE_{\{i,j\},i}/DE_{\mathcal{I},i} \geq 1$ provided that j is more (resp. less) volatile than k when $\rho_{ij} = \rho_{ik} < 0$ (resp. $\rho_{ij} = \rho_{ik} > 0$). In addition, the ratio $DE_{\{i,j\},i}/DE_{\mathcal{I},i}$ increases in σ_j (resp. σ_k) provided that $\rho_{ij} \cdot \rho_{ik} > 0$ (resp. $\rho_{ij} \cdot \rho_{ik} < 0$).

Figure 2.1 illustrates these results by graphically representing i's linkage preferences. Figure 2.1a is the reference situation where jurisdictions are equally volatile and shocks and independent. The solid dot represents the point where i is indifferent between the three possible links, that is

$$\frac{\mathbb{E}\{\delta_{\mathcal{I},i}\}}{\mathbb{E}\{\delta_{\{i,j\},i}\}} = \underbrace{\frac{PSE_{\mathcal{I},i}}{PSE_{\{i,j\},i}}}_{>1} \times \underbrace{\frac{VE_{\mathcal{I},i}}{VE_{\{i,j\},i}}}_{<1} = 1. \tag{2.C.6}$$

Then, an increase in ψ_i, i.e. moving south-west, increases the PSE ratios and leaves the VE ratios unchanged so that i prefers $\mathcal{I}$-linkage. Similarly, an increase in ψ_j, i.e. moving east, decreases $PSE_{\mathcal{I},i}/PSE_{\{i,j\},i}$ more than it increases $VE_{\mathcal{I},i}/VE_{\{i,j\},i}$ and i prefers $\{i,j\}$-linkage. All else equal, i prefers the trilateral link when of similar or larger size than the other two jurisdictions. Otherwise, it prefers a bilateral link with the largest jurisdiction.

Figure 2.1b considers two alternative situations where i is twice (resp. half) as volatile as both j and k with indifference point B (resp. C). Given that the ratio $VE_{\mathcal{I},i}/VE_{\{i,j\},i}$ increases with σ_i, all else equal, the larger σ_i, the wider the range of sizes such that i prefers $\mathcal{I}$-linkage and vice versa. Thus, i prefers the trilateral link when similarly or more volatile than the other two jurisdictions. Otherwise, it prefers a bilateral link with the most volatile jurisdiction. There is an observationally-equivalent interpretation of Figure 2.1b. Relative to the case of independent shocks (A) the indifference point is B (resp. C) when j and k are positively (resp. negatively) correlated as this increases (resp. decreases) $VE_{\mathcal{I},i}$.

As compared to Figure 2.1a, Figure 2.1c depicts the effects of doubling σ_k. All else equal, $VE_{\{i,k\},i}$ is strengthened against both $VE_{\mathcal{I},i}$ and $VE_{\{i,j\},i}$ and $VE_{\mathcal{I},i}$ also appreciates relative to $VE_{\{i,j\},i}$. Graphically, this means that the $\{i,k\}$-$\mathcal{I}$ and $\{i,j\}$-$\{i,k\}$ frontiers go southwards and that the $\{i,j\}$-$\mathcal{I}$ frontier moves eastwards. In the extreme case where $\sigma_j = 0$, Figure 2.1d shows that $\{i,j\}$ is never the most preferred link for jurisdiction i in the considered size ranges. Note that i's preference between $\{i,k\}$ and $\mathcal{I}$ does not vary much with j's size – in particular, $\{i,k\}$ will always be the preferred link provided that $\psi_k \geq 2\psi_i$.

Finally, we analyze the impact of correlation. In Figure 2.1e we consider that i and k are positively correlated. All else equal, this deteriorates both $DE_{\{i,k\},i}$ and $DE_{\mathcal{I},i}$ relative to $DE_{\{i,j\},i}$ as well as $DE_{\{i,k\},i}$ relative to $DE_{\mathcal{I},i}$. Graphically, this means that the $\{i,j\}$-$\mathcal{I}$ and $\{i,j\}$-$\{i,k\}$ frontiers move eastwards and that the $\{i,k\}$-$\mathcal{I}$ frontier is shifted northwards. In Figure 2.1f, the converse holds when we let i and k be negatively correlated instead.

2.D Calibration methodology

This appendix describes the steps we take in calibrating jurisdictional characteristics. We consider three additional jurisdictions as compared to the main text, namely Japan (JPN), Mexico (MEX) and a supranational sector, the International Aviation Bunker (IAB).

We obtain annual country level carbon dioxide emissions data covering 1950-2012 from the World Resources Institute – observed emissions from jurisdiction i in year t is denoted e_{it}. For China we exclude observations from 1950-1975 because this period features uncharacteristic fluctuations associated with the Great Leap Forward and Cultural Revolution.

Taking the natural logarithm of laissez-faire emissions given in Equation (2.3.2) gives

$$\ln(\tilde{q}_i) = \ln(b_2/\psi_i) + \ln(b_1 + \theta_i). \tag{2.D.1}$$

We associate each component of $\ln(\tilde{q}_i)$ with the trend and cyclical components of 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 variation 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 $\{\ln(e_{it})\}$ into two time series $\{e^t_{it}, e^c_{it}\}$ where $\ln(e_{it}) = e^t_{it} + e^c_{it}$ in each year t. We acknowledge that assuming jurisdictions have identical technology (b_2) lacks realism. However, it reduces the data required to calibrate the model substantially and we consider this assumption to be a reasonable first pass. Since our model is static, we also assume that the final observation of the trend component is related to size of jurisdiction i through

$$\ln(b_2/\psi_i) = e^t_{i,2012}. \tag{2.D.2}$$

Given our assumptions that jurisdictions are identical up to size and shock, we can normalize $\psi_{CHN} = 100$ and set $b_2 = 0.5$. These amount to choosing the units in which gains are measured. Consequently, the quantitative results in the main text are comparable across linkage coalitions and jurisdictions. However, the value of the gain from a particular link and how it is shared between jurisdictions, remains sensitive to technology differences and, given those differences, to the calibration of ψ_i. Jurisdictional sizes are listed in Table 2.D.1.

Table 2.D.1: Calibration results: Size and volatility (ψ_i and σ_i)

	CHN	USA	EUR	JPN	KOR	IAB	MEX	EGY
ψ_i	100	55.038	38.699	12.966	6.645	5.089	4.904	2.356
σ_i	0.028	0.019	0.017	0.033	0.034	0.028	0.026	0.050

To calibrate σ_i and ρ_{ij} we assume that the cyclical components e^c_{it} provide information about the distribution of the underlying jurisdiction-specific shocks θ_i. Then, given our modelling framework, e^c_{it} is related to a draw from the distribution of θ_i so that

$$\ln(b_1 + \theta_i) = e^c_{it}. \tag{2.D.3}$$

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

$$\sigma_i = \sigma(\exp(e^c_{it})). \tag{2.D.4}$$

Jurisdictional volatilities are given in Table 2.D.1. Finally, we calibrate ρ_{ij} using

$$\rho_{ij} = \text{Corr}(\exp(e^c_{it}), \exp(e^c_{jt})). \tag{2.D.5}$$

and highlight that ρ_{ij} – reported in Table 2.D.2 – can be positive, approximately zero, or negative. We note that this large variation in ρ_{ij} 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

Table 2.D.2: Calibration results: Pairwise correlation coefficients (ρ_{ij})

	CHN	USA	EUR	JPN	KOR	IAB	MEX	EGY
CHN	1.000							
USA	0.525⋆	1.000						
EUR	0.460⋆	0.652⋆	1.000					
JPN	0.394⋆	0.347⋆	0.461⋆	1.000				
KOR	0.247	0.419⋆	0.277⋆	0.360⋆	1.000			
IAB	0.496⋆	0.637⋆	0.507⋆	0.315⋆	0.041	1.000		
MEX	-0.244	0.080	0.086	0.269⋆	-0.138	0.185	1.000	
EGY	-0.395⋆	-0.186	-0.101	-0.123	-0.397⋆	-0.279⋆	-0.174	1.000

⋆: statistically different from zero at 10% level.

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 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.

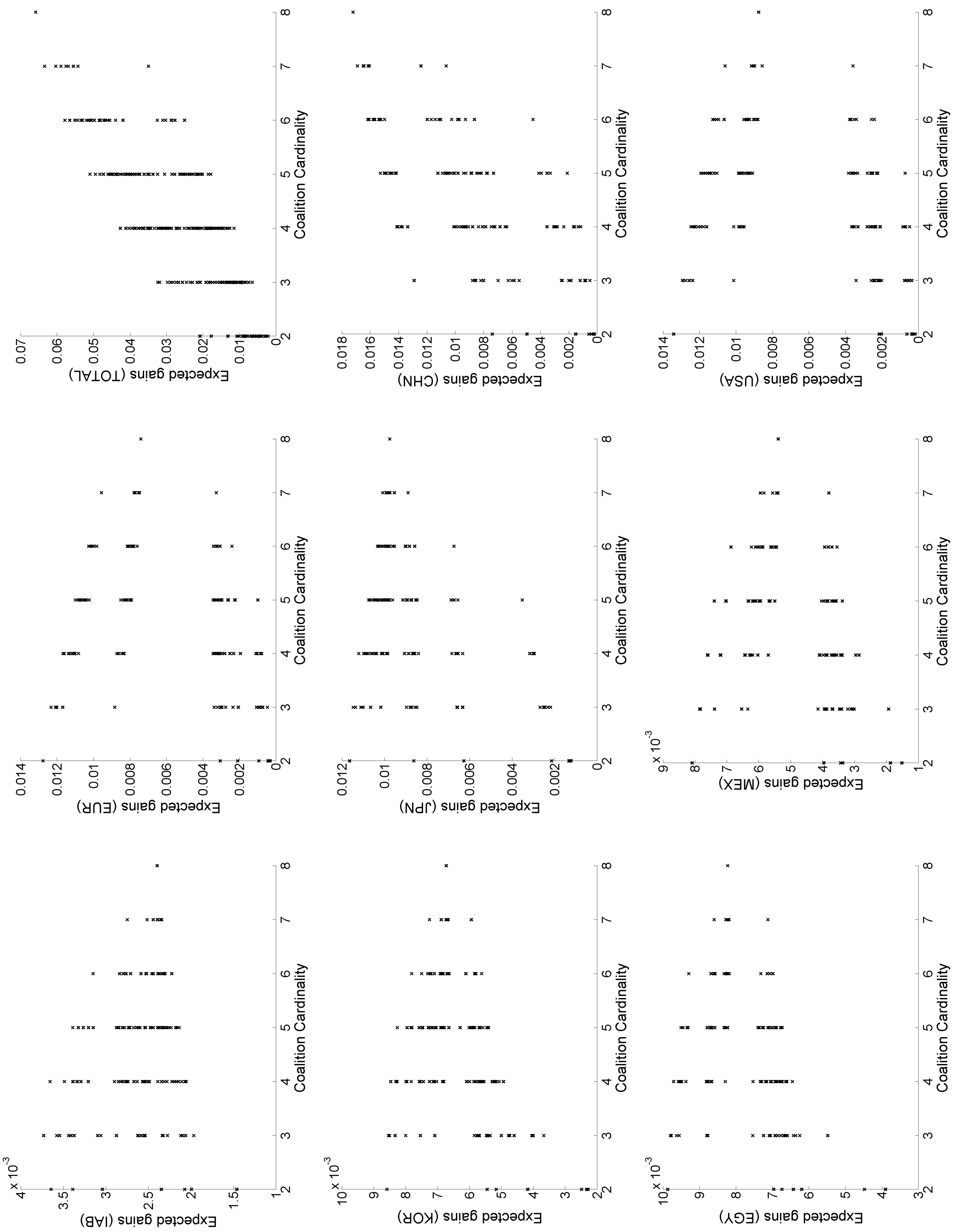
We highlight the following three points regarding our calibration strategy and results. First, we assume that the pair characteristics are not affected by the recent introduction of climate change policies. Some emitters in some of the jurisdictions in our sample are regulated under these policies. We 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 we discuss below 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.

Finally, Figure 2.D.1 depicts aggregate and jurisdictional expected gains from all possible linkage coalitions among the eight jurisdictional ETSs considered in this appendix.

Figure 2.D.1: Multilateral linkage with eight jurisdictions



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Chapter 3

Intertemporal Abatement Decisions under Ambiguity Aversion

* * *

Emissions Trading Systems are subject to considerable uncertainty, especially of a regulatory nature. This can disrupt intertemporal efficiency and undermine the long-term price signal. We first argue that the prevalence of such uncertainty can be assimilated to a situation of ambiguity and then propose to assume ambiguity aversion on the part of covered firms to account for its influence. We consider that ambiguity bears on both the future permit price and firm's permit demand. Ambiguity aversion drives equilibrium choices away from intertemporal efficiency and induces two effects, viz. a pessimistic distortion of the firm's beliefs overemphasizing 'detrimental' outcomes and a shift in the firm's discount factor.

We find that the firm's intertemporal decisions do not solely depend on the expected future permit prices, but also on its own expected future market position. In particular, pessimism leads the firm to overabate (resp. underabate) early on relative to intertemporal efficiency when it expects to be short (resp. long) on the market. We show that, in general, pessimism provides an incentive for early overabatement, and that it is more pronounced under auctioning that under free allocation. This can be a behavioral factor that contributes to the accumulation of permit banks or surpluses in existing ETSs. In our setup, the hypothesis of excessive discounting found in the literature to account for the current permit price depreciation in the EUETS coincides with 'imprudence toward ambiguity'. Finally, we show that forward contracts cannot restore intertemporal efficiency. Forwards have potential to partially mitigate the effect of pessimism but the shift in discounting always persists.

* * *

3.1 Introduction

Emissions Trading Systems allow for some degree of temporal flexibility through banking and borrowing of permits. As firms cost minimize, the opportunity to bank (resp. borrow) permits for (resp. from) future compliance periods implies an arbitrage condition between present and discounted future permit prices. That is, the price is the vehicle that equates the long-term supply and demand of permits. In a competitive market where firms have perfect foresight and information, the aggregate abatement effort is efficiently spread through time and the least discounted cost solution obtains (Rubin, 1996; Cronshaw & Kruse, 1996; Kling & Rubin, 1997). Because permits have negligible storage costs, the cost-of-carry price must correspond to the spot price grown at the interest rate. Therefore, the current permit price should reflect the net present value of the last permit surrendered and the optimal price path should grow at the interest rate (Hotelling, 1931).

In practice, however, ETSs are subject to considerable uncertainty. Indeed, these systems do not function in a vacuum and are influenced by external factors and policies outside their perimeters, e.g. macroeconomic conditions, the usage of offset credits to partly acquit compliance obligations and the reach of complementary policies (Newell et al., 2013; de Perthuis & Trotignon, 2014; Tvinnereim, 2014; Borenstein et al., 2016; Chèze et al., 2016; Ellerman et al., 2016; Lecuyer & Quirion, 2016). Policy overlap can be fortuitous as (deplored) in the EUETS or explicitly built into an open regulatory system as in California where the ETS operates in conjunction with a set of complimentary measures, thereby constituting a safety net ensuring that the state-wide target is attained and that no low-cost abatements are left behind.[1] In turn, the above factors can erode the cap stringency as there exists significant uncertainty about baseline emission levels which Borenstein et al. (2016) estimate to be «at least as large as uncertainty about the effect of abatement measures».[2]

[1]Note that policy overlap is not limited to climate change and energy related policies. For instance, Schmalensee & Stavins (2013) underline the impact of railway deregulation on the US SO_2 trading program.

[2]Borenstein et al. (2016, 2017) show that significant baseline uncertainty coupled with little price elasticity is likely to generate either very high or very low price levels with high price volatility.

As it turned out, baselines have been lower than anticipated in most existing ETSs. Consequently, as a general rule, permit prices have declined and now keep hovering at low levels or just above price floors when such price support mechanisms exist. If agents are rational, however, lower-than-expected price levels should be inconsequential for intertemporal cost efficiency. Indeed, a positive (resp. negative) permit demand shock would shift the optimal price path upwards (resp. downwards), but its slope would be preserved and it would remain efficient. In other words, even if abatement costs were subject to random shocks, the cap would still be achieved at least discounted expected cost (Schennach, 2000; Salant, 2016). Moreover, in a rational expectations market equilibrium, permit carry-over arbitrage conditions would solely depend on expected future permit prices (Samuelson, 1971).

However, it is difficult to ascertain whether low prices are attributable to external demand shocks or to intrinsic market and regulatory imperfections. Prices may thus not be 'right' in that they may not reflect intertemporal marginal abatement costs. As a case in point, Hintermann et al. (2016) review the literature on the price determinants in the EUETS and find that «there is a complex interaction between BAU emissions, abatement quantities and allowance prices». Put otherwise, our understanding of these determinants is limited. For instance, Koch et al. (2014) find that abatement-related fundamentals were responsible for only 10% of the permit price variation. Present market and regulatory imperfections, low prices can be of consequence for intertemporal efficiency. Importantly, interactions between such imperfections and exogenous shocks could impair permit price formation and undermine the long-term price signal conveyed by the system.

A scan of the literature indicates that three types of imperfections are at the center of attention, viz. limited foresight, excessive discounting and regulatory uncertainty.[3,4] First, if agents have truncated time horizons and permits are relatively more abundant today than they will be in the future, prices will not reflect the long-term permit scarcity and be lower than they ought to, which raises overall compliance costs (Ellerman et al., 2015). Second, it can be that discount rates higher than the interest rate are applied for banking strategies outside a 'hedging corridor' due to institutional or corporate constraints (Neuhoff et al., 2012; Schopp et al., 2015).[5] Additionally, when future abatement costs are uncertain, risk

[3] Hintermann et al. (2016) underline that the alleged wedge between permit prices and intertemporal marginal abatement costs can also be sustained by other factors such as transaction costs or market power.

[4] Relative to 'standard' markets a specificity of permit markets is that the supply of permits is exogenously imposed by the regulatory authority, i.e. permits are not natural commodities with intrinsic value. Rather, they can be limited, modified or simply cancelled. Hence our analysis could also apply to other types of 'insecure, ill-defined' natural resource tradable property rights, see e.g. Grainger & Costello (2014).

[5] Firms can bank permits (or purchase forward contracts) at the opportunity cost of capital for their hedging strategies. Beyond this 'hedging corridor' higher rates (up to 15%) should apply because holding permits is regarded as a risky investment, i.e. speculation. However, Neuhoff et al. (2012) and Schopp et al. (2015), who report results from a dozen interviews with representatives of the European power sector, do

premia can be associated with holding permits when firms are risk averse (Kollenberg & Taschini, 2016). In turn, these 'too high' discount rates would encourage lower banking and sustain lower price today, as compared to the cost-effective pathway. As a case in point, Bredin & Parsons (2016) find that the EUETS has been in contango since early Phase II in 2008. That is, futures prices have been higher than cost-of-carry prices with implied premiums (i.e., negative convenience yields) of significant sizes.[6]

Third, regulatory uncertainty about permit supply adjustments has shown to bear on price formation. With a focus on the EUETS, Salant (2016) shows how, in a rational expectations market equilibrium, regulatory uncertainty weighs on price formation.[7] Empirical support is provided by Koch et al. (2016) and Creti & Joëts (2017) who find the EUETS responsive to political events and announcements. In other words, not only the announced cap level will hold sway over price formation, but also speculation about the attendant regulatory commitment may cause prices to fluctuate.[8] Koch et al. (2016) also present evidence that market participants tend to belittle, if not ignore, announcements that should be indicative of higher future prices. This further suggests that firms cannot entirely hedge against regulatory risks. Additionally, low price levels have sparked short-term interventions (e.g., ex post supply management) as well as structural design reforms (e.g., price collars) in all existing ETSs, which contributes to sustaining regulatory uncertainty.

Faced with such uncertainty, we argue that firms lack confidence and/or relevant information to assign a probability measure uniquely describing the stochastic nature of their decision problems. This corresponds to a situation characterized by ambiguity while, by contrast, risk refers to situations where such distributions are perfectly known and unique.[9] This Chapter thus examines intertemporal abatement decisions by a risk neutral ambiguity averse firm to take account of the prevalence of regulatory uncertainty.[10] Ambiguity neutrality is our natural benchmark, in which the firm's optimal abatement stream is congruent with the least discounted expected cost solution (Schennach, 2000) and permit carry-over arbitrage conditions solely depend on expected future prices (Samuelson, 1971).

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not provide an explanation for why such a high rate of return would be required. Note that banking can be also limited at the institutional level, e.g. in South Korea and via holding limits in California.

[6]Interestingly, Bredin & Parsons (2016) note that this term structure reflects a 'sort of fear' that is not consistent with the types of reforms discussed at the EU level. For instance, changes in the permit supply via the Market Stability Reserve or an adjustment of the annual cap-decreasing factor should shift the term structure as a whole, not just its slope. A change in permit bankability, by contrast, could shift the slope.

[7]Salant (2016) draws on his analysis of the spot price of gold in the 70's (Salant & Henderson, 1978).

[8]Positive prices in oversupplied Phase II indicate banking as firms expect the emission constraint to be binding in the future and also reflect «their awareness of regulatory uncertainty» (Hintermann et al., 2016).

[9]For instance, Hoffmann et al. (2008) define regulatory uncertainty as «an individual's perceived inability to predict the future state of the regulatory environment» where Hoffmann et al. deliberately use the term 'uncertainty' in the Knightian sense (Knight, 1921), i.e. ambiguity.

[10]The firm thus displays aversion toward model uncertainty in the sense of Marinacci (2015).

We consider a firm covered under a two-period ETS that starts at the beginning of date 1 and terminates at the end of date 2. We assume that the firm is already compliant at date 1 but can still undertake additional abatement and bank permits into date 2 in anticipation of (higher) date-2 requirements. At date 1, however, both the date-2 market permit price and the firm's demand for permits are ex-ante ambiguous and exogenous to the firm. This reflects that regulatory uncertainty directly bears on price formation (Salant, 2016) and that there is significant uncertainty about permit demands, e.g. via direct or indirect policy overlaps (Borenstein et al., 2016). One could expect regulatory uncertainty to bear on the firm's endowment of permits. However we choose to keep permit allocation as a parameter in the model to be able to measure its influence on intertemporal abatement decisions.[11] Indeed, we show that neutrality of allocation does not hold under ambiguity aversion.[12]

Ambiguity resolves at the start of date 2. We solve the firm's intertemporal cost minimization program by backward induction and compare the optimal level of date-1 abatement (i.e., banking) under ambiguity aversion relative to ambiguity neutrality. We consider a smooth ambiguity model of choice à la Klibanoff et al. (2005) in which the firm is confronted with different possible scenarios about the future regulatory framework, i.e. objective probabilities for the related permit price and demand forecasts, and has subjective beliefs over this set of scenarios.[13] Ambiguity neutrality ensures linearity between objective and subjective lotteries, thereby collapsing to a Savagian framework (Savage, 1954). Attitudes toward ambiguity originate in the relaxation of such linearity and ambiguity aversion corresponds to the (additional) aversion (w.r.t. risk aversion) to being unsure about the probabilities. This will incite the firm to favor abatement streams that reduce the level of ambiguity.

Ambiguity aversion drives equilibrium abatement stream choices away from intertemporal cost efficiency. Before examining joint market price and firm's baseline ambiguities we consider each source of ambiguity in isolation. This enables us to separate out two ambiguity aversion induced effects. First, with risky price and individual baseline ambiguity, we note that from the perspective of the risk neutral firm the cap and trade can be assimilated to an emissions tax where the tax rate is set at the expected permit price. Ambiguity aversion induces an upward (resp. downward) shift in the firm's discount factor when it exhibits Decreasing (resp. Increasing) Absolute Ambiguity Aversion. Therefore, early overabatement

[11] Ultimately, it is the firm's gross effort of abatement (baseline minus allocation) that is impacted by regulatory uncertainty, which we already capture by letting the baseline be ambiguous.

[12] Permit allocation is not neutral as soon as one of the assumptions sustaining the market equilibrium solution of Montgomery (1972) is relaxed. See Hahn & Stavins (2011) for a literature review and Fowlie & Perloff (2013) for an empirical study in the RECLAIM program providing empirical support to neutrality.

[13] Typically, consider for instance that these objective scenarios are provided by groups of experts, e.g. BNEF, Energy Aspects, ICIS-Tschach, Point Carbon, diverse academic fora or think tanks, etc.

(resp. underabatement) occurs relative to the benchmark under DAAA (resp. IAAA).[14]

Second, with price ambiguity and risky individual baseline, ambiguity aversion induces another effect by which the firm pessimistically distorts its subjective beliefs and overweights 'detrimental' scenarios. Intuitively, when the firm expects to be net short (resp. long) it overemphasizes scenarios where high (resp. low) prices are relatively more likely. This raises (resp. lowers) the firm's estimate of the future price relative to the benchmark and raises (resp. lowers) its incentive for early abatement accordingly. Relative to the benchmark the ambiguity averse firm does not solely base its present abatement decisions on the expected future price but also on its expected future market position. This ultimately hinges upon permit allocation and we identify allocation thresholds below (resp. above) which pessimism unconditionally leads the firm to overabate (resp. underabate) early on.

Third, with both price and individual baseline ambiguities, we show that early overabatement occurs when the conditions for early overabatement under sole price ambiguity obtain and, additionally, high-price scenarios coincide with high-baseline scenarios. We then extend the model and consider a continuum of firms identical but for permit allocation where the market price is endogenously determined by the market-wide baseline ambiguity. We can refine the threshold condition on permit allocation and we show that pessimism generates early overabatement under a symmetric allocation of permits. This can be a behavioral factor that contributes to the formation of a permit bank, e.g. in the EUETS.

The two ambiguity aversion induced effects can be aligned or antagonistic, the direction and magnitude of which depend on the degree of ambiguity aversion and permit allocation. In particular, a higher degree of ambiguity aversion is not necessarily conducive to a larger adjustment in early abatement (in absolute terms).[15] With a parametrical example we numerically show that early abatement decreases with allocation and that the magnitude of distortion due to pessimism is generally greater than that due to the shift in the discount factor. This shows that, under ambiguity aversion, early abatement is higher under auctioning than free allocation and suggests that the distortion away from intertemporal efficiency is greater under a cap and trade than an emissions tax.[16]

As a final note, we consider three extensions to the model. First, we show that introducing forward contracts cannot restore intertemporal efficiency, perhaps indicating that

[14]We thus define DAAA as ambiguity prudence following Berger (2014) and Gierlinger & Gollier (2017).

[15]An increase in ambiguity aversion always increases the magnitude of the pessimistic distortion in the sense of a monotone likelihood ratio deterioration (Gollier, 2011) and we show that it can increase that of ambiguity prudence only when ambiguity prudence is not too strong relative to ambiguity aversion.

[16]We compare how price or quantity controls affect intertemporal decisions in terms of distortion magnitude. See Pizer & Prest (2016) for a normative approach to comparing price and intertemporally tradable quantity regulations. Present exogenous noises in policy updates (i.e., the analog of regulatory uncertainty) they show that prices (resp. quantities) dominate when the noise variance is high (resp. low).

regulatory risks cannot be entirely hedged. Although forwards have potential to partially mitigate pessimism, the shift in discounting always persists. Second, we show that the volume of trade is reduced when allocation is sufficiently asymmetrical across ambiguity averse firms. Third, we show that the equilibrium in a market populated by a mix of ambiguity neutral and averse firms should be brought further away from intertemporal efficiency.

The remainder of this Chapter is organized as follows. Section 3.2 reviews the related literature. Section 3.3 presents the modeling framework. Section 3.4 analyzes the effects of ambiguity aversion on intertemporal abatement decisions relative to ambiguity neutrality. In particular, Section 3.4.1 considers the case of pure firm-level baseline ambiguity and Section 3.4.2 that of pure market price ambiguity. The case of joint price and baseline ambiguities is next presented in Section 3.4.3 and that of market-wide demand ambiguity with endogenous permit price is considered in Section 3.4.4. Section 3.5 illustrates our results numerically and Section 3.6 concludes. An Appendix contains the analytical derivations and proofs (3.A), some extensions to the model (3.B), discusses the use of other representation theorems under ambiguity (3.C), provides additional details on both the two ambiguity aversion induced effects (3.D) and the case of joint price and baseline ambiguities (3.E), and finally considers the special case of binary price ambiguity (3.F).

3.2 Related literature

The Chapter combines two strands of literature, namely abatement and investment incentives under environmental regulations and decision-making under ambiguity aversion.

Dynamic abatement and investment incentives. First, we extend the results of Baldursson & von der Fehr (2004) to ambiguity aversion. Similarly, Baldursson & von der Fehr show that risk averse firms that expect to be short (resp. long) on the permit market overinvest (resp. underinvest) in abatement technology relative to risk neutrality.[17] However, both price and quantity regulations deteriorate under ambiguity aversion while a price instrument remains intertemporally efficient under risk aversion. Additionally, in our setup firms expecting to be net long (resp. short) can still overabate (resp. underabate) when they exhibit DAAA (resp. IAAA).[18] In particular, the DAAA (resp. IAAA) induced increase (resp. decrease) in the discount factor can create a downward pressure on future

[17]With a different modeling framework, we note that Ben-David et al. (2000) find similar results.

[18]With reference to Phase I of the EUETS, Ellerman et al. (2010) note that there is an asymmetry between long and short entities since the former are under no compulsion to sell and can adopt a passive wait-and-see attitude as long as uncertainty is high and experience is being gained.

(resp. present) prices. In our setup, the hypothesis of 'excessive discounting' found in the literature to account for the current price depreciation in the EUETS (either due to a hedging corridor (Neuhoff et al., 2012; Schopp et al., 2015) or due to risk aversion (Kollenberg & Taschini, 2016)) coincides with IAAA, i.e. 'imprudence toward ambiguity'.[19] However, our results do not imply that IAAA-firms necessarily under-bank permits as pessimism can dominate the shift in discounting depending on their permit endowment. Finally, we also extend Chevallier et al. (2011) who examine the impacts of risky permit allocations on banking decisions and find that banking increases consecutive to an increase in risk if, and only if, the third derivative of the firm's production function is positive.[20]

We follow the literature on dynamic investment incentives under environmental regulations in that it generally considers exogenous shocks on permit prices and firms' demands – see Requate (2005) for a review.[21] In general, partial equilibrium models tend to favor taxes over ETSs essentially because in the latter the permit price comprises a real option value and thus deviates from marginal abatement costs – see e.g. Xepapadeas (2001) with permit price uncertainty and Chao & Wilson (1993) with aggregate demand uncertainty. This literature further distinguishes between irreversible and reversible investments and generally shows that the former tend to decrease with uncertainty (Blyth et al., 2007) while the latter can be used as a hedge and tend to increase with uncertainty (Chen & Tseng, 2011).[22] For instance, Zhao (2003) finds that, in a general equilibrium model, irreversible investments decrease in the level of abatement cost uncertainty, but more so under a tax than an ETS. Finally, Albrizio & Costa (2014) explicitly analyze the effects of policy uncertainty on irreversible and reversible investments by ETS-liable firms in a model where the cap set by the regulator is observed only once firms have made their investment decisions.

[19]More precisely, Kollenberg & Taschini (2016) study the continuum of convex combinations between a pure price and pure quantity instrument in a dynamic framework where there is uncertainty about abatement costs. When firms are risk averse, firms' risk premium is the highest (resp. lowest) under a pure quantity (resp. price) instrument because the burden to adjust to shocks is entirely borne by firms (resp. the regulator). They find that aggregate compliance costs are minimized somewhere in between these two polar cases, which reflects a trade-off between the inability to take advantage of the differences in marginal abatement costs through time via intertemporal trading (under a tax) and significant costs for firms of having to adjust their strategies in response to shock realizations (under a permit market).

[20]Chevallier et al. (2011) describe how banking can be a risk-management tool, and, provided that firms can pool risks, define optimal risk-sharing rules between firms. Relatedly, Hennessy & Roosen (1999) show that when pollution is random, firms subject to a permit market have an incentive to merge (i.e., consolidate) for permit management purposes under both risk neutrality and risk aversion.

[21]Economic theory suggests that there is an option value to postpone investments under uncertainty (Dixit & Pindyck, 1994). Note that Dorsey (2017) empirically validates that regulatory uncertainty increases compliance costs by delaying investments in the context of EPA's Clean Air Interstate Rule.

[22]In the words of Laffont & Tirole (1996) low-emission investment are a 'bypass' of permit markets.

Decision-making under ambiguity. Since Ellsberg's seminal article in 1961 it has been well documented that most individuals treat ambiguity differently than objective risk and prefer gambles with known rather than unknown probabilities.[23] There exist alternatives to Subjective Expected Utility (Savage, 1954) – see Etner et al. (2012) and Machina & Siniscalchi (2014) for a review. These models of choice differ in their treatments of objective and subjective probabilities and preferences are no longer linear in probabilities. They can roughly be grouped into three categories. The first category represents non-additive beliefs, i.e. the probability of an outcome depends on its ranking among all possible outcomes (Schmeidler, 1989; Chateauneuf et al., 2007). The second category considers that agents have a set of multiple subjective priors. Gilboa & Schmeidler (1989) provided behavioral foundations for Multiple-priors (or Maximin) Expected Utility (MEU) preferences. Ghirardato et al. (2004) later axiomatized the α-maxmin model of choice which considers a convex combination of maximal and minimal expected utilities over the set of priors.

The third category corresponds to Recursive Expected Utility models, in which agents have a second-order subjective prior over a set of first-order objective measures and are EU-maximizers over the two layers of uncertainty (Klibanoff et al., 2005, or KMM). A KMM model of choice has the advantage of disentangling ambiguity itself (or 'beliefs') from attitudes (or 'tastes') toward ambiguity. It also comes with nice comparative statics and tractability properties to which the decision-making under risk machinery readily applies, can be embedded in a dynamic framework (Klibanoff et al., 2009) and nests other models of choice under ambiguity aversion as special cases.[24]

Ambiguity aversion has been applied to a variety of fields in economics, such as finance (Gollier, 2011; Gierlinger & Gollier, 2017), formation of precautionary savings (Berger, 2014), self-insurance and self-protection (Alary et al., 2013; Berger, 2016) or health (Treich, 2010; Berger et al., 2013), and can explain otherwise unaccounted for empirical facts such as the equity premium puzzle (Collard et al., 2016) or the negative correlation between asset prices and returns (Ju & Miao, 2012). Closer to our model is the theory of the competitive firm à la Sandmo (1971) under ambiguity aversion (Wong, 2015a) and the integration of risk and model uncertainty in Integrated Assessment Models (Millner et al., 2013; Berger et al., 2017). There is also evidence that individuals tend to display ambiguity aversion and especially DAAA, see e.g. Berger & Bosetti (2016) and references therein.

We develop a two-period model to analyze what is fundamentally a fully-fledged dynamic

[23] Ellsberg (1961) showed that rational decision-makers behaved in ways incongruent with the Savagian axiomatization, and especially the sure-thing principle.

[24] When ϕ displays CAAA with $\phi(x) = \frac{e^{-\alpha x}}{-\alpha}$, Klibanoff et al. (2005) show that, under some conditions, the KMM model approaches the MEU criterion when the ambiguity aversion coefficient α tends to infinity.

problem. This is sufficient to capture the essence of the two ambiguity aversion induced effects and simplifies the problem at hand in two respects. First, considering more than two periods is technically difficult. For instance, Collard et al. (2016) assume CAAA to simplify Euler equations but this means that solely pessimistic distortions are considered while shifts in levels are abstracted away. Second, another difficulty relates to the incorporation of new information to update beliefs and preferences. This issue is mechanically absent in our two-period model. Millner et al. (2013) opt for two polar exogenous learning scenarios: One where ambiguity resolves after the first period, the other with persistent and unchanged ambiguity throughout. Guerdjikova & Sciubba (2015) consider two similar types of learning structures, one where the true scenario is determined in the first period, another where the 'hidden' scenario is a Markov process and cannot never be identified (so do Ju & Miao (2012)). Alternatively, Gierlinger & Gollier (2017) and Traeger (2014) use a one-step-ahead formulation consisting of nested sets of identical ambiguity structures.

3.3 The modeling framework

We consider a firm whose production's by-product is atmospheric pollution. The firm is regulated under a permit market. To demonstrate compliance it can abate emissions and/or buy permits on the market. There are two dates $t = 1, 2$. At date 1, the date-2 permit price τ and the firm's date-2 baseline level of emissions b (or production output) are ambiguous to the firm in a sense that will be defined below. Ambiguity resolves at the beginning of date 2.[25] The firm's date-2 abatement depends on its date-1 abatement as well as on price and baseline realizations. We analyze the firm's optimal level of date-1 abatement under ambiguity aversion relative to ambiguity neutrality.

The economic environment. Regulation is effective at both dates and terminates at the end of date 2. As in Chevallier et al. (2011) we assume date-1 compliance is effective and that all inter-firm trading opportunities are exhausted. The firm can still undertake additional date-1 abatement ($a_1 \geq 0$) in the perspective of more stringent date-2 requirements, which frees up a corresponding amount of permits that are banked into date 2.[26] This assumption ensures that the Rubin-Schennach banking condition is always satisfied and assumes corner solutions away (Rubin, 1996; Schennach, 2000). There are two alternative descriptions of this framework where regulation is effective at date 2 only: a_1 may also correspond to

[25] Learning is perfect and exogenous to the firm because it can readily observe the prevailing market price and its own demand at date 2, and cannot influence the extent of learning by its date-1 actions.

[26] In the case of the EUETS presented in the Introduction, date 1 corresponds to Phase II with a non-binding constraint on emissions and date 2 to Phase III and beyond with an expected permit scarcity.

investments in abatement technology in anticipation of future regulation or 'early reduction permits' handed out to the firm for its early abatements.[27]

Given an abatement stream $(a_1; a_2)$ the firm's date-2 emission level is $b - a_1 - a_2$. Letting ω denote the firm's endowment of permits at date 2, a positive (resp. negative) value for $b - a_1 - a_2 - \omega$ corresponds to a short (resp. long) market position, i.e. the amount of permits it buys (resp. sells) on the market at date 2. Abatement cost functions are given by twice continuously differentiable functions C_1 and C_2. Abatement is said to have long-term effect in the sense that C_2 also depends on the level of date-1 abatement, i.e. $C_2 \equiv C_2(a_1, a_2)$. Therefore, the marginal cost of date-1 abatement is $\partial_{a_1}(C_1 + C_2)$. Abatement costs are assumed to be strictly increasing and convex on $[0; \infty)$ with no fixed cost, i.e. $C_1', C_1'' > 0$ with $C_1(0) = C_1'(0) = 0$ and $\partial_{a_2} C_2, \partial^2_{a_2 a_2} C_2 > 0$ with $C_2(\cdot, 0) = 0$. The firm also faces decreasing abatement opportunities, i.e. $\partial^2_{a_1 a_2} C_2 \geq 0$ (Bréchet & Jouvet, 2008). This is compensated by a positive learning-by-doing effect which is captured by assuming that $\partial^2_{a_1 a_1}(C_1 + C_2) \geq \partial^2_{a_1 a_2} C_2$ and $\partial^2_{a_2 a_2} C_2 \geq \partial^2_{a_1 a_2} C_2$ (Slechten, 2013). When we want to derive analytical results, we will assume that abatement cost functions are equipped with the following quadratic specification, where for all $a_1, a_2 \geq 0$

$$C_1(a_1) = c_1 a_1^2/2 \text{ and } C_2(a_1, a_2) = c_2 a_2^2/2 + \gamma a_1 a_2, \tag{3.3.1}$$

with $c_1, c_2 > 0$ and $c_2 > \gamma$ for our assumptions on cost functions to obtain. Note that a quadratic specification is a usual and mild assumption (Newell & Stavins, 2003). Here, this also allows us to single out the effects of ambiguity aversion on optimal abatement streams as it guarantees intertemporal efficiency under ambiguity neutrality (see Proposition 3.4.3). Note that $1/c_t$ measures the firm's flexibility in abatement at date t and γ denotes the long-term abatement effect coefficient. For tractability, we will sometimes need to assume that there is no long-term effect of abatement, i.e. $\partial_{a_1} C_2 \equiv 0$ or $\gamma = 0$.

The firm's objective under uncertainty. We consider a partial equilibrium model that focuses solely on the firm's abatement and permit trading decisions. The model ignores both the interactions with the goods' market and the firm's production decisions.[28] Denote by $\zeta_t > 0$ the firm's net profits on the goods' market at date $t = 1, 2$ that are independent of the

[27] These interpretations are equivalent provided that a given level of abatement or investment cuts down emissions by a corresponding amount, and that date-1 abatement or investment reduces both date-1 and date-2 emissions by the same amount. In this respect, note that Slechten (2013) underlines a 'partial' substitutability between banked abatements and low-carbon technology investments.

[28] This is a restrictive yet usual assumption, see e.g. Zhao (2003) and Baldursson & von der Fehr (2004). It can be justified if firms produce different goods and/or belong to different sectors. While an interaction between the goods' market and environmental policy undoubtedly exists, its direction and magnitude are uncertain. For instance, Martin et al. (2014) show that the UK carbon tax has reduced both energy use and

firm's volume of emissions. To solve for the firm's optimal abatement stream we proceed in two steps using backward induction. At date 2 the firm observes the couple (τ, b) of realized permit price and individual demand for permits. Given its date-1 abatement $a_1 \geq 0$, the firm maximizes its date-2 profits, that is

$$\max_{a_2 \geq 0} \pi_2(a_1, a_2; \tau, b) = \zeta_2 - C_2(a_1, a_2) - \tau(b - a_1 - a_2 - \omega). \tag{3.3.2}$$

Date-2 optimality requires that $\partial_{a_2} C_2(a_1, a_2^*) = \tau$, where the optimal date-2 abatement is implicitly defined by $a_2^* \equiv a_2^*(a_1; \tau)$. With cost specification (3.3.1) it comes

$$a_2^*(a_1; \tau) = (\tau - \gamma a_1)/c_2. \tag{3.3.3}$$

At date 1, however, both the date-2 permit price and baseline emissions are uncertain. Let the price risk $\tilde{\tau}$ be described by the objective cumulative distribution G^0 supported on $\mathrm{T} = [\underline{\tau}; \bar{\tau}]$ with $0 < \underline{\tau} < \bar{\tau} < \infty$. Let also the baseline risk $\tilde{b}$ be described by the objective cumulative distribution L^0 with support on $\mathrm{B} = [\underline{b}; \bar{b}]$ with $0 < \underline{b} < \bar{b} < \infty$. These two risks are assumed to be independent, i.e. there is no connection between the prevailing market price and the firm's baseline.[29] This parallels a frequent assumption in the literature on firms' decisions under uncertainty that price and production shocks are independent stochastic variables (Viaene & Zilcha, 1998; Dalal & Alghalith, 2009). We consider that the firm is risk neutral. The firm's date-1 optimal abatement decision thus satisfies

$$\bar{a}_1 \doteq \arg \max_{a_1 \geq 0} \left\langle \pi_1(a_1) + \beta \mathbb{E}_{G^0, L^0} \left\{ \pi_2(a_1, a_2^*(a_1; \tilde{\tau}); \tilde{\tau}, \tilde{b}) \right\} \right\rangle, \tag{3.3.4}$$

where $\beta \in [0; 1]$ is the firm's discount factor and $\pi_1(a_1) = \zeta_1 - C_1(a_1)$ is the date-1 profit (note the absence of trade terms). Combining optimality conditions at both dates yields

$$C_1'(\bar{a}_1) + \beta \mathbb{E}_{G^0} \left\{ \partial_{a_1} C_2(\bar{a}_1, a_2^*(\bar{a}_1; \tilde{\tau})) \right\} = \beta \langle \tilde{\tau} \rangle = \beta \mathbb{E}_{G^0} \left\{ \partial_{a_2} C_2(\bar{a}_1, a_2^*(\bar{a}_1; \tilde{\tau})) \right\}, \tag{3.3.5}$$

where $\langle \tilde{\tau} \rangle \doteq \mathbb{E}_{G^0}\{\tilde{\tau}\}$ is the expected permit price. Intertemporal efficiency obtains in expectations since expected marginal abatement costs are equated at both dates. For a price realization $\tau \in \mathrm{T}$ the abatement stream $(\bar{a}_1; a_2^*(\bar{a}_1; \tau))$ coincides with the Rubin-Schennach least discounted cost solution (Rubin, 1996; Schennach, 2000). Note that Equation (3.3.5)

intensity, but find no evidence of impacts on employment or production. See Requate (1998) and Baldursson & von der Fehr (2012) for a treatment of the interaction between permit trading and the output market.

[29] The cap stringency is determined by the difference between the aggregate demand fro permits and the cap and the permit price should reflect the shadow price associated with this constraint. Independence can be justified if the permit market is competitive. Alternatively, it may reflect that «there is a complex interaction between BAU emissions, abatement quantities, and allowance prices» (Hintermann et al., 2016). In Section 3.4.4 we consider the case of an endogenous price that solely reflects the cap stringency.

is independent of both the firm's baseline risk and permit allocation ω and with cost specification (3.3.1) it comes

$$\bar{a}_1 = \frac{(c_2 - \gamma)\beta \langle \tilde{\tau} \rangle}{c_1 c_2 - \beta\gamma^2}. \tag{3.3.6}$$

With quadratic cost functions the optimal level of date-1 abatement under uncertainty $\bar{a}_1$ is invariant to any mean-preserving spread in $\tilde{\tau}$, cf. Proposition 3.4.3. It is also clear from Equation (3.3.6) that $\bar{a}_1$ is solely dictated by the discounted expected date-2 permit price and does not depend on the expected market position at date 2.

Introduction of ambiguity. Ambiguity is introduced in the sense of Klibanoff et al. (2005), i.e. the firm is uncertain about G^0 and L^0. Formally, the firm is confronted with a set of objective probability measures for both $\tilde{\tau}$ and $\tilde{b}$ and is uncertain about which of those truly govern the two risks. For each realization θ (called θ-scenario) of the random variable $\tilde{\theta}$, let $G(\cdot;\theta)$ and $L(\cdot;\theta)$ denote the objective probability measures for $\tilde{\tau}_\theta$ and $\tilde{b}_\theta$, the θ-scenario price and baseline risks, respectively. Ambiguity is represented by a second-order subjective probability distribution for $\tilde{\theta}$ denoted F with support on $\Theta = [\underline{\theta}; \bar{\theta}]$. The measure F represents the firm's beliefs about which scenario it feels will materialize. While we consider that G and L are second-order dependent across θ-scenarios we assume for consistency with the uncertain case that G and L are first-order independent given a θ-scenario, i.e. $\mathbb{E}_{G,L}\{\cdot|\theta\} \equiv \mathbb{E}_G\{\cdot|\theta\}\mathbb{E}_L\{\cdot|\theta\}$. An ambiguity neutral firm compounds first and second order lotteries, i.e. it is a Savagian expected profit maximizer w.r.t. the compound risk measures $\bar{G} \doteq \mathbb{E}_F\{G(\cdot;\tilde{\theta})\}$ and $\bar{L} \doteq \mathbb{E}_F\{L(\cdot;\tilde{\theta})\}$. We assume there is no bias in the ambiguity neutral firm's beliefs, i.e. $\bar{G} \equiv G^0$ and $\bar{L} \equiv L^0$. That is, an ambiguity neutral firm is not affected by the introduction of ambiguity nor a shift in the level of ambiguity.

Ambiguity aversion. Attitudes towards ambiguity originate in the relaxation of the reduction of compound first and second order lotteries. The construction of the firm's objective can be decomposed into three steps. First, in any given θ-scenario the firm computes its expected date-2 profits w.r.t. $G(\cdot;\theta)$ and $L(\cdot;\theta)$. Second, each θ-scenario first-order expected date-2 profits are transformed by an increasing function ϕ. Third, the firm's second-order expected date-2 profits obtain by taking the expectation of the ϕ-transformed first-order expected date-2 profits w.r.t. F. Ambiguity aversion is characterized by a concave function ϕ. As defined in Equation (3.3.9), denote by $\mathcal{V}(a_1;\theta)$ the firm's expected profit at date 2 in scenario $\theta \in \Theta$ when it abates a_1 at date 1. Under ambiguity aversion, Jensen's inequality yields

$$\phi^{-1}\Big(\mathbb{E}_F\{\phi(\mathcal{V}(a_1;\tilde{\theta}))\}\Big) \leq \mathbb{E}_F\{\mathcal{V}(a_1;\tilde{\theta})\}. \tag{3.3.7}$$

The left-hand side of Inequality (3.3.7) is the date-2 ϕ-certainty equivalent expected profit and the right-hand side corresponds to ambiguity neutrality (ϕ is linear) since expectations is taken w.r.t. compound probability distributions. In words, the ambiguity averse firm dislikes any mean-preserving spread in the space of second-order expected profits. Finally note that since the firm is taken to be risk neutral the function ϕ actually characterizes aversion towards model uncertainty (Marinacci, 2015).[30] Because ambiguity aversion requires stronger aversion towards model uncertainty than towards risk our assumption leads to an overestimation of the effects of ambiguity aversion (Berger & Bosetti, 2016). However this assumption allows us to derive clear analytical results.[31]

The firm's objective under ambiguity. Note that date-2 optimality and Equation (3.3.3) hold irrespective of both the presence of ambiguity and the firm's attitude towards ambiguity. However the optimal date-1 abatement decision under ambiguity aversion hinges upon the ambiguity level, as perceived from date 1, in conjunction with the degree of ambiguity aversion. We use the recursive smooth ambiguity model of choice of Klibanoff et al. (2009).[32] Because ambiguity is resolved at the beginning of date 2 the firm's program writes

$$\max_{a_1 \geq 0} \pi_1(a_1) + \beta\phi^{-1}\Big(\mathbb{E}_F\{\phi(\mathcal{V}(a_1;\tilde{\theta}))\}\Big), \tag{3.3.8}$$

where the θ-scenario-expected profitability from date-1 abatement $\mathcal{V}(a_1;\tilde{\theta})$ satisfies

$$\mathcal{V}(a_1;\theta) \doteq \mathbb{E}_{G,L}\{\tilde{V}(a_1;\theta)|\theta\} \text{ with } \tilde{V}(a_1;\theta) \doteq \max_{a_2} \pi_2(a_1, a_2; \tilde{\tau}_\theta, \tilde{b}_\theta). \tag{3.3.9}$$

In the above $\mathbb{E}_F$ denotes expectation taken w.r.t. F conditional on all relevant information available to the firm at date 1. Similarly $\mathbb{E}_{G,L}\{\cdot|\theta\}$ denotes expectation taken w.r.t. $G(\cdot;\theta)$ and $L(\cdot;\theta)$ conditional on the true scenario being θ. Note that Program (3.3.8) is well-defined provided that ambiguity tolerance $-\phi'/\phi''$ is concave (Gierlinger & Gollier, 2017;

[30]See Guetlein (2016) for comparative static results on risk aversion under smooth ambiguity aversion. That firms are risk neutral is a standard assumption as they should be able to diversify risk. Firms can still exhibit ambiguity aversion which is a different psychological trait. Note that there is empirical evidence of ambiguity aversion for actuaries (Cabantous, 2007). Brunette et al. (2015) also show that individuals are less risk averse but more ambiguity averse in a group than alone. Seeing firms as groups of individuals making joint decisions may help underpin our assumption of a risk-neutral ambiguity-averse firm.

[31]If the firm was risk averse and maximized the utility of its profits at each date, joint conditions on both the utility and ambiguity functions would emerge to determine the direction of the date-1 abatement adjustment, see e.g. Gierlinger & Gollier (2017), Berger (2016) and Wong (2015a). In particular, the criterion to sign pessimism in Proposition 3.4.4 would have to be restated. In our case this also renders the firm's optimization program ill-defined since e.g. the date-1 profit is a decreasing function of abatement.

[32]Note that in Klibanoff et al. (2009) the scenario space Θ is finite. Here we consider its continuous extension with a continuous subjective distribution F. Note also that the KMM axiomatization is based on acts rather than probability distribution on the outcome spaces T and B.

Berger, 2016). Because this condition is satisfied for the ϕ functions we use for numerical simulations in Section 3.5 we assume that it holds throughout. By the Envelop Theorem applied to $\tilde{V}$, it comes, for all $a_1 \geq 0$ and $\theta \in \Theta$

$$\tilde{V}_{a_1}(a_1;\theta) = \tilde{\tau}_\theta - \partial_{a_1} C_2(a_1, a_2^*(a_1;\tilde{\tau}_\theta)). \tag{3.3.10}$$

With cost specification (3.3.1) the θ-scenario-expected marginal profitability from date-1 abatement reads

$$\mathcal{V}_{a_1}(a_1;\theta) = ((c_2 - \gamma)\bar{\tau}_\theta + \gamma^2 a_1)/c_2, \tag{3.3.11}$$

where $\bar{\tau}_\theta \doteq \mathbb{E}_G \{\tilde{\tau}_\theta | \theta\}$ denotes the expected permit price at date 2 in scenario $\theta \in \Theta$. By construction $\mathcal{V}_{a_1}$ is positive, i.e. the firm always have an incentive to bank at date 1.

3.4 Abatement decisions under ambiguity aversion

3.4.1 Tax regime: Cap and trade under firm's baseline ambiguity

First consider that $\partial_\theta G(\cdot;\theta) \equiv 0$. Since the firm is risk neutral the situation can be assimilated to a tax regime where the date-2 proportional tax rate on emissions is $\mu \doteq \mathbb{E}_{\bar{G}}\{\tilde{\tau}\}$.[33] In this case, ω can be interpreted as a tax-threshold liability where the tariff is charged only on the difference between emissions and the threshold (Pezzey & Jotzo, 2013). Note that the θ-scenario-expected marginal profitability from date-1 abatement satisfies $\mathcal{V}_{a_1}(a_1;\theta) = \mu - \partial_{a_1} C_2(a_1, a_2^*(a_1;\mu)) > 0$ where both μ and $\partial_{a_1} C_2$ are deterministic. Hence $\mathcal{V}_{a_1}$ is deterministic and does not depend on the θ-scenario considered.

Ambiguity neutrality. With ϕ linear the necessary first-order condition for Program (3.3.8) defines the optimal level of date-1 abatement under ambiguity neutrality by

$$-C_1'(\bar{a}_1^\mu) + \beta \mathcal{V}_{a_1}(\bar{a}_1^\mu) = 0. \tag{3.4.1}$$

Combining optimality conditions at both dates then yields

$$C_1'(\bar{a}_1^\mu) + \beta \partial_{a_1} C_2(\bar{a}_1^\mu, a_2^*(\bar{a}_1^\mu, \mu)) = \beta\mu = \beta \partial_{a_2} C_2(\bar{a}_1^\mu, a_2^*(\bar{a}_1^\mu;\mu)). \tag{3.4.2}$$

[33] The date-2 tax rate is thus certain and exogenously given. The tax regime is such that the date-1 tax rate is zero. This is without loss of generality and roughly captures that tax rates generally rise over time.

The (aggregate) marginal date-1 abatement cost is equated to the marginal date-2 abatement cost, i.e. intertemporal efficiency obtains. With cost specification (3.3.1) the optimal abatement stream is $(\bar{a}_1^{\mu}; a_2^*(\bar{a}_1^{\mu}; \mu))$, where $\bar{a}_1^{\mu}$ obtains from Equation (3.3.6) with $\mu = \langle\tilde{\tau}\rangle$. With no long-term dependency (i.e., $\gamma = 0$), a_2^* is independent of a_1 and the firm's overall level of abatement under ambiguity neutrality is $\bar{a}_1^{\mu} + a_2^*(\mu) = \beta\mu/c$ where $1/c = 1/c_1 + 1/(\beta c_2)$ is the firm's aggregate flexibility in abatement over the two dates. The overall abatement volume is efficiently apportioned between the two dates

$$\bar{a}_1^{\mu} = \frac{c}{c_1}\Big(\frac{\beta\mu}{c}\Big) \text{ and } a_2^*(\mu) = \frac{c}{\beta c_2}\Big(\frac{\beta\mu}{c}\Big), \tag{3.4.3}$$

that is in proportion to each date abatement flexibility. The ambiguity neutral benchmark corresponds to a decision under risk – here for a risk neutral firm. Under risk aversion, Baldursson & von der Fehr (2004) show that intertemporal efficiency continues to hold in a tax regime. As exposed below, however, this does not carry over to ambiguity aversion.

Ambiguity Aversion. With ϕ concave the necessary first-order condition for Program (3.3.8) defines the optimal level of date-1 abatement under ambiguity aversion by

$$-C_1'(\hat{a}_1^{\mu}) + \beta\mathcal{A}(\hat{a}_1^{\mu})\mathcal{V}_{a_1}(\hat{a}_1^{\mu}) = 0, \tag{3.4.4}$$

where the shift in levels $\mathcal{A}$ is a function defined by

$$\mathcal{A}(a_1) \doteq \frac{\mathbb{E}_F\{\phi'(\mathcal{V}(a_1; \tilde{\theta}))\}}{\phi' \circ \phi^{-1}(\mathbb{E}_F\{\phi(\mathcal{V}(a_1; \tilde{\theta}))\})}. \tag{3.4.5}$$

Proposition 3.4.1 characterizes the impact of ambiguity aversion on the firm's optimal date-1 abatement decision relative to ambiguity neutrality.

Proposition 3.4.1. *Ambiguity aversion is conducive to higher (resp. lower) date-1 abatement than under ambiguity neutrality if, and only if, the firm displays Decreasing (resp. Increasing) Absolute Ambiguity Aversion. Under Constant Absolute Ambiguity Aversion, the introduction of ambiguity aversion does not affect the firm's date-1 abatement decision.*

Proof. Relegated to Appendix 3.A.1. □

Except when the firm displays CAAA the tax regime is not intertemporally efficient under ambiguity aversion. This suggests that the relative merits of price versus quantity instruments showed by Baldursson & von der Fehr (2004) under risk aversion would tend to fade away under ambiguity aversion. Moreover, Proposition 3.4.1 is in line with the literature on the formation of precautionary saving under ambiguity aversion, e.g. Osaki & Schlesinger (2014) and Gierlinger & Gollier (2017). Because the firm overabates at date 1 relative ambiguity neutrality i.f.f. it exhibits DAAA, we follow Berger (2014) and Gierlinger & Gollier (2017) in assimilating DAAA with prudence towards ambiguity.[34] With this definition,

Corollary 3.4.2. *The firm overabates at date 1 relative to ambiguity neutrality, i.e. forms precautionary date-1 abatement, if, and only if, it displays prudence towards ambiguity.*

Comparing optimality conditions under ambiguity neutrality (Equation (3.4.1)) and ambiguity aversion (Equation (3.4.4)) we see a shift in the firm's discount factor from β to $\beta\mathcal{A}$. A value higher than unity for function $\mathcal{A}$ indicates ambiguity prudence and the discount factor is shifted up (resp. down) when the firm exhibits DAAA (resp. IAAA). In words, ambiguity prudence puts relatively more weight on date-2 profits than under ambiguity neutrality − lowering impatience, as it were − which leads to date-1 overabatement.[35]

3.4.2 Cap and trade under pure permit price ambiguity

Now let $\partial_\theta L(\cdot;\theta) \equiv 0$. This corresponds to a cap and trade under pure price ambiguity, i.e. ambiguity is extrinsic to the firm and transmitted via the permit price only. Without loss of generality further let the firm's baseline b be certain for convenience.

Ambiguity neutrality. With ϕ linear the necessary first-order condition for Program (3.3.8) defines the optimal level of date-1 abatement under ambiguity neutrality by

$$-C_1'(\bar{a}_1) + \beta\mathbb{E}_F\{\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\} = 0. \tag{3.4.6}$$

Since the ambiguity neutral firm compounds lotteries and we assume its beliefs are unbiased, Equation (3.4.6) coincides with the first-order condition for Program (3.3.4) under uncertainty. Intertemporal efficiency hence obtains in expectations, see Equation (3.3.5). As is standard the effects of uncertainty on optimal decisions relate to the third derivative of the profit (in general, utility) function (Leland, 1968; Kimball, 1990).

[34] We note that this definition is presently unsettled. For instance, Baillon (2017) defines ambiguity prudence by the less demanding condition that ϕ''' be positive (DAAA $\Rightarrow$ $\phi''' > 0$). This definition parallels that of risk prudence under Expected Utility and can be defined in terms of lotteries. However, $\phi''' > 0$ is not sufficient to guarantee the formation of precautionary banking with the KMM certainty equivalent representation theorem we use. For instance, adopting an approach similar to Kimball (1990), Osaki & Schlesinger (2014) show that only under DAAA is the ambiguity precautionary premium bigger than the ambiguity premium. DAAA is thus the 'natural' definition for ambiguity prudence in our analysis. Finally note that there is empirical evidence for DAAA (Berger & Bosetti, 2016).

[35] Another interpretation is that DAAA intensifies the importance of any date-2 profit risk and can be assimilated to a «preference for an earlier resolution of uncertainty», see e.g. Theorem 4 in Strzalecki (2013).

Proposition 3.4.3. *Assume time separability, i.e.* $\partial_{a_1} C_2 \equiv 0$*. Then, in the face of an increase in risk in the sense of a mean-preserving spread (Rothschild & Stiglitz, 1971), the ambiguity neutral firm overabates at date 1 if, and only if,* $C_2''' > 0$*.*

Proof. Relegated to Appendix 3.A.2 □

Therefore, date-1 overabatement under ambiguity neutrality is conditional on the positivity of the third derivative of the abatement cost function. Note again from Equation (3.3.6) that $\bar{a}_1$ does not depend on the expected market position at date 2 and that, with the quadratic abatement costs, it is also invariant to any mean-preserving spread in $\tilde{\tau}$.

Ambiguity aversion. With ϕ concave the necessary first-order condition for Program (3.3.8) defines the optimal level of date-1 abatement under ambiguity aversion by

$$-C_1'(\hat{a}_1) + \beta \frac{\mathbb{E}_F\{\phi'(\mathcal{V}(\hat{a}_1;\tilde{\theta}))\mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\}}{\phi' \circ \phi^{-1}(\mathbb{E}_F\{\phi(\mathcal{V}(\hat{a}_1;\tilde{\theta}))\})} = 0. \tag{3.4.7}$$

Normalizing and decomposing the fraction in Equation (3.4.7) into two terms yields

$$-C_1'(\hat{a}_1) + \beta \mathcal{A}(\hat{a}_1)\mathbb{E}_F\{\mathcal{D}(\hat{a}_1;\tilde{\theta})\mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\} = 0, \tag{3.4.8}$$

where function $\mathcal{A}$ is defined in Equation (3.4.5) and $\mathcal{D}$ is a distortion function satisfying, for all $a_1 \geq 0$ and $\theta \in \Theta$,

$$\mathcal{D}(a_1;\theta) \doteq \frac{\phi'\left(\mathcal{V}(a_1;\theta)\right)}{\mathbb{E}_F\{\phi'(\mathcal{V}(a_1;\tilde{\theta}))\}}. \tag{3.4.9}$$

In addition to the shift in levels $\mathcal{A}$, ambiguity aversion distorts the subjective prior F via $\mathcal{D}$. By concavity of ϕ the distortion function $\mathcal{D}$ overweights those θ-scenarios with low-$\mathcal{V}$ values. This can be interpreted as pessimism in the sense of a monotone likelihood ratio (MLR) deterioration (Gollier, 2011; Gierlinger & Gollier, 2017) and the pessimistically distorted second-order subjective measure H is such that, for all $a_1 \geq 0$ and $\theta \in \Theta$,

$$H(a_1;\theta) \doteq \int_{\underline{\theta}}^{\theta} \mathcal{D}(a_1;X)\mathrm{d}F(X) = \frac{\mathbb{E}_F\{\phi'(\mathcal{V}(a_1;\tilde{X}))|\tilde{X} \leq \theta\}}{\mathbb{E}_F\{\phi'(\mathcal{V}(a_1;\tilde{\theta}))\}}F(\theta), \tag{3.4.10}$$

with $H(\cdot;\underline{\theta}) = 0$, $H(\cdot;\bar{\theta}) = 1$ and $\partial_\theta H(\cdot;\theta) > 0$. By concavity of the objective function,

$$\hat{a}_1 \geq \bar{a}_1 \;\Leftrightarrow\; \mathcal{A}(\bar{a}_1)\mathbb{E}_H\{\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\} \geq \mathbb{E}_F\{\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\}. \tag{3.4.11}$$

Controlling for the shift in levels $\mathcal{A}$, introducing ambiguity in the ambiguity averse firm's decision is identical to a shift in the ambiguity neutral firm's subjective beliefs from F to

H, where H overemphasizes low-profit θ-scenarios relative to F. Intuitively, this will incite the ambiguity averse firm to overabate at date 1 provided that these low-profit scenarios have high marginal profitabilities from date-1 abatement.

Proposition 3.4.4. *Under CAAA, pessimism raises date-1 abatement relative to ambiguity neutrality if, and only if,* $(\mathcal{V}(\bar{a}_1;\theta))_\theta$ *and* $(\mathcal{V}_{a_1}(\bar{a}_1;\theta))_\theta$ *are anticomonotone. Under DAAA (resp. IAAA) ambiguity aversion is conducive to higher (resp. lower) date-1 abatement than under ambiguity neutrality only if anticomonotonicity (resp. comonotonicity) holds.*

Proof. Relegated to Appendix 3.A.3. □

In words, anticomonotonicity requires that low-$\mathcal{V}$ scenarios coincide with high-$\mathcal{V}_{a_1}$ scenarios. Controlling for the shift in levels $\mathcal{A}$, this ensures that the firm overabates at date 1 relative to ambiguity neutrality. Note that similar (anti)comonotonicity criteria obtain with other representation theorems to sign the effects of ambiguity aversion – see Appendix 3.C for MEU and α-maxmin preferences. The underlying relation between (anti)comonotonicity and pessimism is further illustrated in Examples 3.4.5 and 3.4.6.

Example 3.4.5. Let $\Theta = \{\theta_1, \theta_2\}$, $F = (q, \theta_1; 1-q, \theta_2)$ with $0 \le q \le 1$ and ϕ exhibit CAAA ($\mathcal{A} \equiv 1$). Assume that $\mathcal{V}(\cdot;\theta_2) \ge \mathcal{V}(\cdot;\theta_1)$. Pessimism thus overweights scenario θ_1 relative to θ_2, i.e. $H = (\hat{q}, \theta_1; 1-\hat{q}, \theta_2)$ with $q \le \hat{q} \le 1$.[36] Then, under ambiguity neutrality, date-1 abatement with the subjective prior H ($\bar{a}_{1,H}$) is higher than with F ($\bar{a}_{1,F}$) i.f.f.

$$\hat{q}\mathcal{V}_{a_1}(\bar{a}_{1,F};\theta_1) + (1-\hat{q})\mathcal{V}_{a_1}(\bar{a}_{1,F},\theta_2) \ge q\mathcal{V}_{a_1}(\bar{a}_{1,F};\theta_1) + (1-q)\mathcal{V}_{a_1}(\bar{a}_{1,F},\theta_2),$$

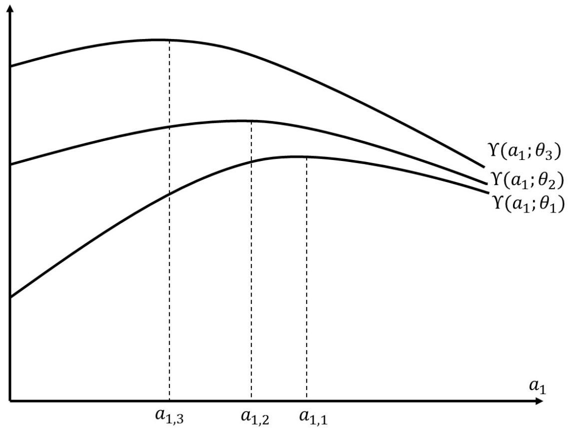
which is true when anticomonotonicity holds, i.e. $\mathcal{V}_{a_1}(\cdot;\theta_1) \ge \mathcal{V}_{a_1}(\cdot;\theta_2)$.

Example 3.4.6. Let $\Theta = \{\theta_1, \theta_2, \theta_3\}$ and $\Upsilon(a_1;\theta_i)$ denote the net intertemporal expected profit from date-1 abatement $a_1 \ge 0$ in scenario θ_i, i.e. $\Upsilon(a_1;\theta_i) = \pi_1(a_1) + \beta\mathcal{V}(a_1;\theta_i)$. Let Θ be ordered such that $\Upsilon(\cdot;\theta_i)$ is increasing in i. Assume that anticomonotonicity holds, i.e. $\Upsilon_{a_1}(\cdot;\theta_i)$ is decreasing in i, as depicted in Figure 3.1 where $a_{1,i}$ is the optimal date-1 abatement in scenario θ_i. Anticomonotonicity implies that $a_{1,i}$ is decreasing with i and that the higher date-1 abatement the narrower the spread in $\Upsilon(\cdot;\theta)$ across θ-scenarios.

The ambiguity averse firm dislikes any mean-preserving spread in the space of second-order expected profit. Accordingly, pessimism adjusts date-1 abatement in the direction of a reduced spread in $\mathcal{V}(\cdot;\theta)$ across θ-scenarios. We note that anticomonotonicity is quite

[36] Note that $\hat{q} = 1$ with MEU preferences. This illustrates that a KMM model of choice converges to MEU in the limiting case of infinite ambiguity aversion (Klibanoff et al., 2005).

Figure 3.1: The effect of pessimism under anticomonotonicity (Example 3.4.6)



Note: $\mathcal{V}(\cdot;\theta)$ and $\mathcal{V}_{a_1}(\cdot;\theta)$ (and thus $\Upsilon(\cdot;\theta)$ and $\Upsilon_{a_1}(\cdot;\theta)$) are anticomonotonic w.r.t. θ-scenarios; $a_{1,i}$ denotes the optimal level of date-1 abatement for a risk neutral firm solely considering scenario θ_i.

demanding a condition because it requires that $\mathcal{V}(\cdot;\theta)$ do not cross between θ-scenarios to clearly sign the covariance in Proof 3.A.3, and could be relaxed somewhat. It might be sufficient that the discrepancy in $\mathcal{V}(\cdot;\theta)$ across θ-scenarios diminishes with date-1 abatement in some rough sense for pessimism to raise it relative to ambiguity neutrality.[37]

Proposition 3.4.4 also indicates that the two ambiguity aversion induced effects can be aligned or antagonistic. To further account for the shift in levels $\mathcal{A}$, momentarily assume for clarity that there is no long-term effect of abatement, i.e. $\partial_{a_1} C_2 \equiv 0$. Then, Condition (3.4.11) rewrites

$$\hat{a}_1 \geq \bar{a}_1 \Leftrightarrow \mathcal{A}(\bar{a}_1)\left(\langle\tilde{\tau}\rangle + \mathcal{P}(\bar{a}_1)\right) \geq \langle\tilde{\tau}\rangle\,, \tag{3.4.12}$$

where $\mathcal{P}$ can be interpreted as a pessimism-only price distortion function satisfying, for all $a_1 \geq 0$,

$$\mathcal{P}(a_1) \doteq \frac{\mathrm{Cov}_\theta\{\phi'(\mathcal{V}(a_1;\tilde{\theta}));\mathcal{V}_{a_1}(a_1;\tilde{\theta})\}}{\mathbb{E}_F\{\phi'(\mathcal{V}(a_1;\tilde{\theta}))\}}. \tag{3.4.13}$$

Note that anticomonotonicity is equivalent to a non-negative $\mathcal{P}$. In other words, the ambiguity averse firm adjusts date-1 abatement upwards (resp. downwards) when its pessimistically-distorted estimate of the date-2 permit price is higher (resp. lower) than under ambiguity neutrality. Additionally, it directly follows from Equation (3.4.12) that

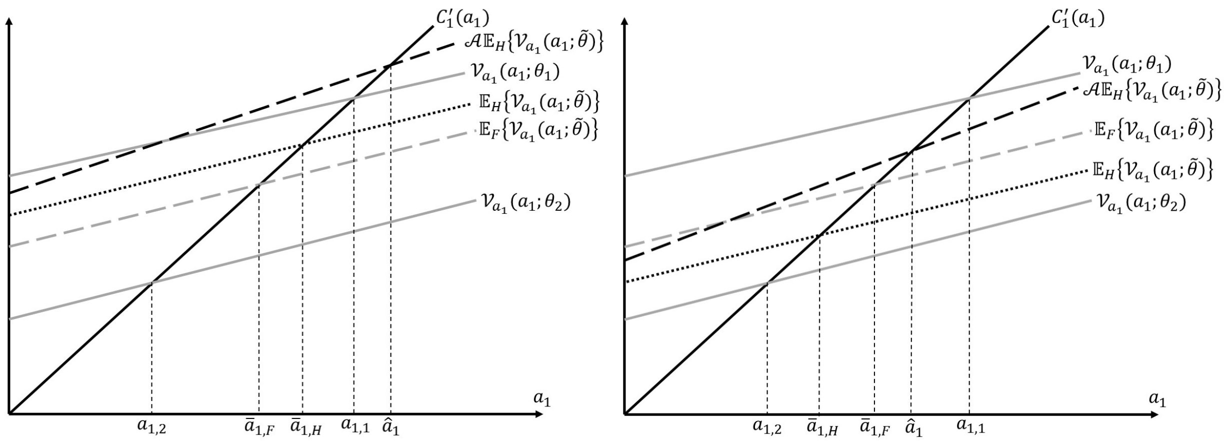
[37] We could not get there analytically but this is illustrated with numerical simulations in Section 3.5. In this respect, note that Berger et al. (2017) transform the anticomonotonicity criterion into a 'convergence effect' between scenarios. They are able to do so because they use a binary structure, i.e. a good and a bad state, and ambiguity bears solely on the chances that these two states occur.

Proposition 3.4.7. *Let $\partial_{a_1} C_2 \equiv 0$. Then, the following equivalence conditions obtain*
(i) When ϕ displays CAAA, $\hat{a}_1 \geq \bar{a}_1$ if, and only if, $\mathcal{P}(\bar{a}_1) \geq 0$;
(ii) When ϕ displays DAAA, $\hat{a}_1 \geq \bar{a}_1$ if, and only if, $\mathcal{P}(\bar{a}_1) \geq (1-\mathcal{A}(\bar{a}_1)) \langle \tilde{\tau} \rangle / \mathcal{A}(\bar{a}_1) < 0$;
(iii) When ϕ displays IAAA, $\hat{a}_1 \leq \bar{a}_1$ if, and only if, $\mathcal{P}(\bar{a}_1) \leq (1-\mathcal{A}(\bar{a}_1)) \langle \tilde{\tau} \rangle / \mathcal{A}(\bar{a}_1) > 0$.

Proposition 3.4.7 characterizes the conditions about the relative strengths and directions of the pessimistic price distortion $\mathcal{P}$ and the shift in levels $\mathcal{A}$ in determining the direction of the date-1 abatement adjustment under ambiguity aversion. Note that these two effects can be aligned or antagonistic. For an instance of the latter case, let ϕ display DAAA and assume that $\mathcal{P}(\bar{a}_1) \in [(1-\mathcal{A}(\bar{a}_1)) \langle \tilde{\tau} \rangle / \mathcal{A}(\bar{a}_1); 0]$. Anticomonotonicity does not hold and pessimism only would lead to date-1 underabatement. However the upward shift in the firm's discount factor is large enough for precautionary date-1 abatement to form overall.

Figure 3.2: Joint effects of pessimism and shift in levels under DAAA

(a) Aligned effects (b) Antagonistic effects



Note: $\Theta = \{\theta_1, \theta_2\}$, $\mathcal{V}_{a_1}(\cdot;\theta_1) \geq \mathcal{V}_{a_1}(\cdot;\theta_2)$ and $F = (.5, \theta_1; .5, \theta_2)$. Fig. 3.2a: anticomonotonicity holds so that H overweights θ_1 relative to θ_2 as compared to F, and the two effects are aligned. Fig. 3.2b: comonotonicity holds so that H overweights θ_2 relative to θ_1 relative to F, and the two effects are antagonistic. In this case, the shift in levels dominates pessimism in terms of adjustment magnitude.

Figure 3.2 graphically depicts the joint effects of pessimism and shift in levels under DAAA where for clarity we let $H(\cdot;\theta)$ and $\mathcal{A}$ be constant functions of date-1 abatement − see Appendix 3.D when they are allowed to vary. Note that Figure 3.2 separates the pessimism effect ($\bar{a}_1 = \bar{a}_{1,F} \to \bar{a}_{1,H}$) from the shift in levels ($\bar{a}_{1,H} \to \hat{a}_1$) in terms of date-1 abatement adjustment. Pessimism operates a vertical translation of the F-averaged expected marginal profitability from date-1 abatement within the $\mathcal{V}_{a_1}(\cdot;\theta_2)$-$\mathcal{V}_{a_1}(\cdot;\theta_1)$ band in the direction of the lower $\mathcal{V}$-value scenario. The DAAA-induced shift in levels then increases the slope of the H-averaged expected marginal profitability from date-1 abatement.

While Propositions 3.4.4 and 3.4.7 are intuitively appealing the anticomonotonicity criterion lacks some concreteness. Proposition 3.4.8 provides more tangible conditions under which this criterion holds and characterizes how it translates with cost specification (3.3.1).

Proposition 3.4.8. *Let ϕ exhibit CAAA and abatement costs be quadratic. Then, the ambiguity averse firm overabates at date 1 relative to ambiguity neutrality if, and only if*
(i) it expects to be in a net short position at date 2 under the abatement stream $(\bar{a}_1; a_2^*(\bar{a}_1; \tau_\theta^*))$ *in all θ-scenarios where* $\tau_\theta^* \doteq \int_{\mathrm{T}} x \partial_\theta G(x;\theta)\mathrm{d}x \Big/ \int_{\mathrm{T}} \partial_\theta G(x;\theta)\mathrm{d}x$;
(ii) for a given date-2 permit allocation ω, it abates too little at date 1 under ambiguity neutrality $\bar{a}_1 \leq \min_{\theta\in\Theta} \langle a_{1,\theta} \doteq b - \omega - a_2^*(\bar{a}_1; \tau_\theta^*)\rangle$, *or reciprocally,*
(iii) its date-2 allocation is relatively small $\omega \leq \omega^* \doteq \min_{\theta\in\Theta} \langle \omega_\theta^* \doteq b - \bar{a}_1 - a_2^*(\bar{a}_1; \tau_\theta^*)\rangle$.

Proof. Relegated to Appendix 3.A.4. □

Proposition 3.4.8 shows that pessimism can alternatively lead to overabatement or underabatement at date 1 relative to ambiguity neutrality, which depends on the expected market position at date 2. This ultimately relates to the firm's endowment of permits, which is thus non neutral under ambiguity aversion. By contrast, the optimal level of date-1 abatement under ambiguity neutrality is solely driven by the $\bar{G}$-expected permit price. While we can intuitively appreciate that the level of date-1 abatement under ambiguity aversion should be decreasing with permit allocation, Appendix 3.A.8 shows that no clear results of comparative statics obtain.[38] Section 3.5 will confirm this in a numerical example.

Note that date-1 overabatement occurs only in those 'unfavorable' situations where the firm expects to be a net buyer of permits under abatement streams $(\bar{a}_1; a_2^*(\bar{a}_1; \tau_\theta^*))$ in all θ-scenarios. In these situations pessimism overweights those θ-scenarios in which high permit prices are relatively more likely. In turn, this inflates the firm's estimate of the future permit price and thus leads to overabatement. Put otherwise, evaluated at $a_1 = \bar{a}_1$, the marginal benefit of date-1 abatement (a lowering of the likelihood of effectively being net short and of the volume of permit purchases) outweighs the marginal cost of date-1 abatement for sure. Symmetrically, in those 'favorable' situations where the firm expects to be net long in all θ-scenarios pessimism overemphasizes low-price θ-scenarios, which leads to a smaller price estimation than in the benchmark and in turn to underabatement. Otherwise, when the firm is net long in some θ-scenarios and net short in others we cannot conclude a priori.[39]

[38] Clear comparative statics results under ambiguity aversion are hard to come by. One difficulty is that H and $\mathcal{A}$ values are endogenous to the optimization program, which ultimately hinges upon initial conditions. For instance, signing pessimism requires restrictive threshold conditions on allocation.

[39] Again, this suggests that anticomonotonicity might actually be too strong a criterion to sign pessimism.

Anticomonotonicity translates into threshold criteria on initial conditions, i.e. $\bar{a}_1$ or ω. Similarly, Berger (2016) obtains threshold conditions in translating anticomonotonicity in the case of self-insurance and self-protection under ambiguity aversion, in the specific case where ambiguity is concentrated on one state.[40] Note that pessimism acts in line with a 'two-sided' precautionary principle. If date-2 permit allocation is sufficiently high (resp. low) for the firm to expect to be net short (resp. long) in all θ-scenarios $\omega < \omega^*$ (resp. $\omega > \omega^*$) then the pessimistic firm will overabate (resp. underabate) at date 1.[41]

Corollary 3.4.9. *Under DAAA, conditions (i-iii) in Proposition 3.4.8 are sufficient, but not necessary, for ambiguity aversion to raise date-1 abatement relative to neutrality.*

In other words, ambiguity prudence (DAAA) is in line with a 'one-sided' precautionary principle whereby a sufficiently high allocation ($\omega > \omega^*$) does not guarantee that there is underabatement while overabatement always occurs when allocation is low enough ($\omega < \omega^*$).

Increase in ambiguity aversion. In the sense of Klibanoff et al. (2005) firm 2 is more ambiguity averse than firm 1 if firm 2's ambiguity function ϕ_2 writes as an increasing, concave transformation of that of firm 1, ϕ_1. Denote by $\mathcal{A}_i$ and $\mathcal{D}_i$ firm i's shift in levels and distortion function. If we let $\hat{a}_i$ denote firm i's optimal level of date-1 abatement under ambiguity aversion, then, by concavity of the firms' objective functions,

$$\hat{a}_2 \geq \hat{a}_1 \Leftrightarrow \mathcal{A}_2(\hat{a}_1)\mathbb{E}_F\{\mathcal{D}_2(\hat{a}_1;\tilde{\theta})\mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\} \geq \mathcal{A}_1(\hat{a}_1)\mathbb{E}_F\{\mathcal{D}_1(\hat{a}_1;\tilde{\theta})\mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\}. \quad (3.4.14)$$

Proposition 3.4.10 separates out two effects consecutive to an increase in ambiguity aversion.

Proposition 3.4.10. *Consider two ambiguity averse firms 1 and 2 and assume that there exists a function ψ such that $\phi_2 = \psi \circ \phi_1$ with $\psi' > 0$ and $\psi'' \leq 0$. Then,*
(i) (Gollier, 2011) firm 2 is more pessimistic than firm 1 in the sense of a monotone likelihood ratio deterioration;
(ii) assuming that ψ is almost quadratic (i.e., $\psi''' \simeq 0$) a necessary condition for a larger upward shift in levels for firm 2 is that firm 1's ambiguity prudence is not too strong relative to ambiguity aversion, that is $-\phi_1''/\phi_1' \leq -\phi_1'''/\phi_1'' \leq -3\phi_1''/\phi_1'$.

Proof. Relegated to Appendix 3.A.5. □

[40] There is also a noticeable parallel between permit banking and both self-insurance and self-protection. Banking is costly but it reduces the likelihood of being in a net short position at date 2 (role of self-protection) and, for a given date-2 net position, it increases date-2 profits by either increasing sales or reducing purchases of permits (role of self-insurance).

[41] The characterization of the cut-off allocation volume ω^* will be refined in Section 3.4.4. Appendix 3.F shows that when price ambiguity is binary the conditions to sign pessimism are milder although not unequivocal as is the case in Snow (2011), Alary et al. (2013), Wong (2015a) and Berger (2016).

First, point (*i*) states that an increase in ambiguity aversion induces an increase in pessimism, i.e. a relatively more concave ϕ_2 places relatively more weight on those low-profit scenarios than ϕ_1. Therefore, assuming CAAA on the part of both firms, an increase in ambiguity aversion is always conducive to a larger adjustment date-1 abatement (in absolute terms).[42] Second, point (*ii*) only provides a necessary condition regarding the direction of the shift in levels because it is difficult to characterize when $\mathcal{A}_2$ is uniformly larger than $\mathcal{A}_1$. Moreover, ψ must be equipped with an additional property and we impose the simplest one, namely $\psi''' = 0$. In words, point (*ii*) states that when the ambiguity prudence effect for firm 1 is already relatively strong, increasing ambiguity aversion might not further increase the upward shift in levels (that of firm 2). Note that Guerdjikova & Sciubba (2015) also find a cut-off condition on the strength of ambiguity prudence in a market survival context.[43] This result motivates further work on higher-order ambiguity prudence (Baillon, 2017).

3.4.3 Cap and trade under price and firm's baseline ambiguities

This section considers the case where the two first-order independent ambiguities on the firm's baseline and the market permit price are simultaneously present. Note that the baseline ambiguity can be interpreted as a multiplicative background risk.

Proposition 3.4.11. *Let ϕ exhibit CAAA. Then, the ambiguity averse firm overabates at date 1 relative to ambiguity neutrality if, and only if, its date-2 permit allocation is relatively small $\omega \leq \min_{\theta\in\Theta} \left\langle \bar{b}_\theta - \bar{a}_1 - a_2^*(\bar{a}_1;\tau_\theta^*) \right\rangle$ and $\mathrm{Cov}_\theta\{G, L\} \geq 0$.*

Proof. Relegated to Appendix 3.A.6. □

The first difference with Proposition 3.4.8 relates to the definition of the allocation threshold which now comprises $\bar{b}_\theta \doteq \mathbb{E}_L\{\tilde{b}_\theta|\theta\}$, the θ-scenario expected baseline. The second difference is the additional covariance criterion. It states that θ must rank $G(\cdot;\theta)$ and $L(\cdot;\theta)$ in the same order in the sense of first-order stochastic dominance. In words, pessimism triggers overabatement when allocation is low enough, i.e. the firm expects to be net short, and those θ-scenarios where high prices are more likely coincide with those θ-scenarios where high firm-level demand for permits is more likely. Symmetrically, pessimism triggers underabatement when allocation is high enough, i.e. the firm expects to be net long, and high-price scenarios

[42] A similar result for precautionary saving formation is in Proposition 3 of Osaki & Schlesinger (2014).

[43] Consider a market populated by both ambiguity neutral (i.e., SEU-maximizers) and ambiguity averse agents. The latter tend to disappear with time because they form 'wrong beliefs' as compared to SEU-maximizers. Guerdjikova & Sciubba (2015) show that only those ambiguity averse agents displaying strong ambiguity prudence relative to ambiguity aversion will survive in the market, $-\phi'''/\phi'' > -2\phi''/\phi'$.

coincide with low firm-level demand scenarios. When neither of the above holds it is difficult to determine a clear-cut condition to sign pessimism for sure.[44]

3.4.4 Cap and trade under pure market-wide baseline ambiguity

Consider a continuum $\mathcal{S}$ of infinitesimally small and competitive firms indexed by s. The mass of firms is S. All firms have the same abatement technology (C_1, C_2), subjective beliefs F and ambiguity functions ϕ.[45] Therefore, firms are identical but for their initial allocation $\omega(s)$ which is one key determinant of the date-1 abatement adjustment under ambiguity aversion. Firms are subject to individual baseline ambiguity and we consider that the market-wide ambiguity on firms' baselines is the sole determining factor of the permit price ambiguity which endogenously emerges on the market.

To be able to derive clear analytical results we let abatement cost functions be time separable and the θ-scenario firm-level baseline uncertainty $\tilde{b}_\theta(s)$ be equipped with a specific structure such that for all $\theta \in \Theta$ and $s \in \mathcal{S}$, $\tilde{b}_\theta(s) = \bar{b}_\theta + \tilde{\epsilon}_\theta(s)$.[46] That is, individual baselines comprise a first term $\bar{b}_\theta$ common to all firms but specific to any given θ-scenario, and an idiosyncratic term $\tilde{\epsilon}_\theta(s)$ such that for all $\theta \in \Theta$, $(\tilde{\epsilon}_\theta(s))_{s\in\mathcal{S}}$ are i.i.d. with $\mathbb{E}_L\{\tilde{\epsilon}_\theta(s)|\theta\} = 0$ and finite variance. Now fix a θ-scenario. By the Law of Large Numbers for a continuum of i.i.d. variables the θ-scenario aggregate level of baseline emissions level is deterministic and given by

$$\int_{\mathcal{S}} \tilde{b}_\theta(s)\mathrm{d}s = \int_{\mathcal{S}} \bar{b}_\theta \mathrm{d}s + \int_{\mathcal{S}} \tilde{\epsilon}_\theta(s)\mathrm{d}s = S\bar{b}_\theta. \tag{3.4.15}$$

Fix an aggregate emission cap Ω and an allocation profile $(\omega(s))_{s\in\mathcal{S}}$. Date-2 optimality requires that all firms abate up to the realized market price τ whatever their baseline realizations, i.e. $C_2'(a_2^*(s)) = \tau$ for all s $\in \mathcal{S}$. All firms abate by the same amount $a_2^* \equiv a_2^*(s)$, for all $s \in \mathcal{S}$. Date-2 market closure in the considered θ-scenario thus yields

$$\int_{\mathcal{S}} \Big(\tilde{b}_\theta(s) - a_1(s) - a_2(\theta) - \omega(s)\Big)\mathrm{d}s = 0 \Rightarrow a_2^*(A_1; \bar{b}_\theta) = \bar{b}_\theta - \frac{A_1 + \Omega}{S}, \tag{3.4.16}$$

where A_1 is the aggregate date-1 abatement volume carried into date 2. The resulting θ-scenario permit price is $\tau_\theta = C_2'(a_2^*(A_1; \bar{b}_\theta)) > 0$ and thus deterministic. Noting that individual date-1 abatement decisions have no influence on the date-2 permit price,

[44] Appendix 3.E contains numerical simulations with joint market price and firm's demand ambiguities.

[45] It is difficult to define the market equilibrium when firms have heterogeneous attitudes towards ambiguity and subjective beliefs, see e.g. Danan et al. (2016). In Appendix 3.B we consider the case of a permit market populated by a mix of (equally) ambiguity averse and neutral firms.

[46] With long-term dependency our results carry over if we suppose symmetric allocation of permits. This ensures that all firms abate the same at both dates. However no trade occurs in equilibrium since firms are identical along all relevant dimensions.

i.e. $\partial_{a_1}\tau_\theta = 0$, it follows that for all $a_1 \geq 0$ and $\theta \in \Theta$, $\mathcal{V}_{a_1}(a_1;\theta) = \tau_\theta$. Denote by $\Psi(s;\theta) \doteq \bar{a}_1 + a_2^*(\bar{A}_1;\bar{b}_\theta) + \omega(s) - \bar{b}_\theta$ firm s' expected net position on the market in scenario θ under ambiguity neutrality. Proposition 3.4.12 refines the cut-off condition for the formation of precautionary date-1 abatement under ambiguity aversion.

Proposition 3.4.12. *Let $\partial_{a_1}C_2 \equiv 0$. Pessimism will incite firm $s \in \mathcal{S}$ to overabate at date 1 provided that $\min_{\theta\in\Theta}\Psi(s;\theta) < C_2'(a_2^*(\bar{A}_1;\bar{b}_\theta))/C_2''(a_2^*(\bar{A}_1;\bar{b}_\theta))$. This is always the case under symmetric allocation of permits.*

Proof. Relegated to Appendix 3.A.7. □

First, given that firms are identical, symmetric allocation of permits coincides with grandfathering, in which case sole pessimism triggers date-1 overabatement. Controlling for shifts in levels, this result is suggestive of a general behavioral tendency towards precautionary permit banking which can contribute to the observed formation of permit surpluses in existing ETSs. Second, note that the anticomonotonicity criterion is laxer than under pure price ambiguity since net long positions under abatement streams $(\bar{a}_1; a_2^*(\bar{A}_1;\bar{b}_\theta))$ can be sufficient to trigger date-1 overabatement (provided that these positions are not too big).

3.5 Numerical illustration

For clarity we ignore long-term effects of abatement ($\gamma = 0$) and assume the firm has the same abatement technology at both dates which we normalize to unity, i.e. $c_1 = c_2 = 1$ and $\beta = 1$. When the firm exhibits CAAA (resp. DAAA) we take $\phi(x) = \frac{e^{-\alpha x}}{-\alpha}$ (resp. $\phi(x) = \frac{x^{1-\alpha}}{1-\alpha}$) where $\alpha > 0$ (resp. $\alpha > 1$) is the coefficient of absolute ambiguity aversion. If $\hat{a}_1^\alpha$ denotes the optimal date-1 abatement when the degree of ambiguity aversion is α, it solves the implicit equation

$$\hat{a}_1^\alpha = \mathcal{A}(\hat{a}_1^\alpha)\left(\langle\tilde{\tau}\rangle + \mathcal{P}(\hat{a}_1^\alpha)\right). \tag{3.5.1}$$

By extension, let $\hat{a}_1^\infty$ denote the optimal date-1 abatement with the MEU representation theorem and $\hat{a}_1^0 = \bar{a}_1$ under CAAA. Similarly $\hat{a}_1^1 = \bar{a}_1$ under DAAA.

We take a discrete scenario space $\Theta = [\![-\bar{\theta};\bar{\theta}]\!]$ and assume that F is uniform over Θ. For all scenario $\theta \in \Theta$, $G(\cdot;\theta)$ is uniform over $\mathrm{T}_\theta = [\underline{\tau}+\theta;\bar{\tau}+\theta]$ where $0 < \bar{\theta} < \underline{\tau}$ and $\bar{\tau} > \underline{\tau} > 0$. Similarly $L(\cdot;\theta)$ is uniform over $\mathrm{B}_\theta = [\underline{b}+\theta;\bar{b}+\theta]$ where $0 < \bar{\theta} < \underline{b}$ and $\bar{b} > \underline{b} > 0$. The parameters are set such that $\underline{\tau} = 10$, $\bar{\tau} = 30$, $\underline{b} = 50$, $\bar{b} = 150$ and $\bar{\theta} = 9$. Date-2 permit allocation is such that $\omega \in [0;120]$. By construction, for all $\theta \in \Theta$, $\bar{\tau}_\theta = \langle\tilde{\tau}\rangle + \theta$ and $\bar{b}_\theta = \langle\tilde{b}\rangle + \theta$ where $\langle\tilde{\tau}\rangle = (\bar{\tau}+\underline{\tau})/2 = 20$ and $\langle\tilde{b}\rangle = (\bar{b}+\underline{b})/2 = 100$. Note that $\mathcal{V}_{a_1}(a_1;\theta) = \bar{\tau}_\theta = \langle\tilde{\tau}\rangle + \theta$, i.e. the θ-scenario expected marginal profitability from date-1 abatement is constant. Below we consider cap-and-trade regimes under pure price ambiguity (see Appendix 3.E for joint market price and firm's demand ambiguities). In this case, anticomonotonicity holds provided that, for all $\theta \in \Theta$,

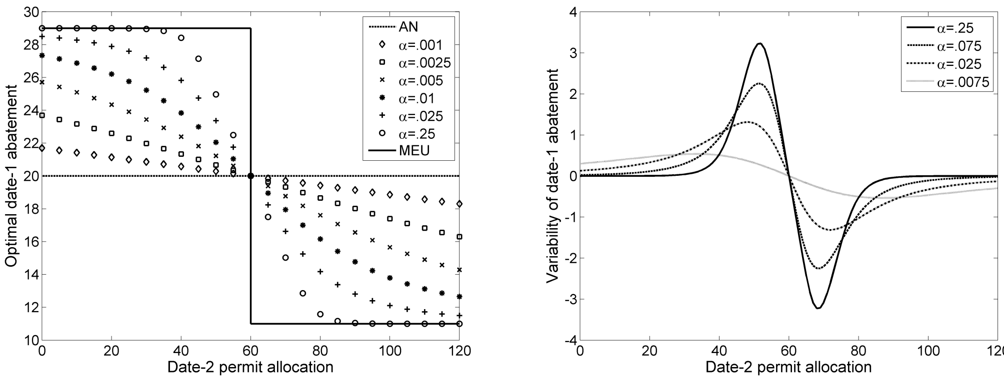
$$\partial_\theta \mathcal{V}(a_1;\theta) \leq 0 \Leftrightarrow \omega \leq \langle\tilde{b}\rangle - a_1 - \langle\tilde{\tau}\rangle - \theta. \tag{3.5.2}$$

Evaluated at $a_1 = \bar{a}_1 = \langle\tilde{\tau}\rangle$, anticomonotonicity holds i.f.f. $\omega \leq \omega^* = \langle\tilde{b}\rangle - 2\langle\tilde{\tau}\rangle - \bar{\theta} = 51$. Symmetrically, comonotonicity at $a_1 = \bar{a}_1$ holds i.f.f. $\omega \geq \langle\tilde{b}\rangle - 2\langle\tilde{\tau}\rangle + \bar{\theta} = 69$.

Cap-and-trade regime under CAAA. Equation (3.5.1) simplifies to $\hat{a}_1^\alpha = \langle\tilde{\tau}\rangle + \mathcal{P}(\hat{a}_1^\alpha)$. Figure 3.1a depicts the variations of $\hat{a}_1^\alpha$ w.r.t. α and ω. Since the codomain of the pessimistic

Figure 3.1: Cap-and-trade regime under CAAA

(a) $\hat{a}_1^\alpha = f(\omega)$ for different α (b) Optimal abatement variability



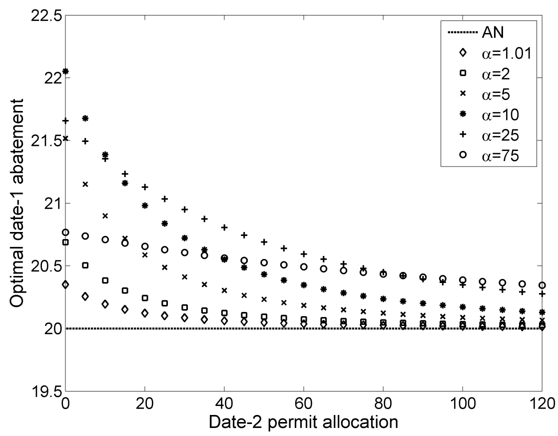
price distortion $\mathcal{P}$ is bounded to $[-\bar{\theta}, \bar{\theta}]$, $\hat{a}_1^\alpha$ is confined within the range $[\langle\tilde{\tau}\rangle - \bar{\theta}; \langle\tilde{\tau}\rangle + \bar{\theta}]$. The dotted line represents the optimal date-1 abatement under ambiguity neutrality $\hat{a}_1^0$ and is independent of the allocation. The solid line characterizes the optimal date-1 abatement level with the MEU representation theorem $\hat{a}_1^\infty$. It is a step function of the allocation: if $\omega < \bar{\omega} = 60$, $\hat{a}_1^\infty = \langle\tilde{\tau}\rangle + \bar{\theta}$; otherwise, $\hat{a}_1^\infty = \langle\tilde{\tau}\rangle - \bar{\theta}$. Other curves depict $\hat{a}_1^\alpha$ for various ambiguity aversion degrees α. First note that the KMM representation describes the continuum between the two polar cases of ambiguity neutrality and MEU. In particular, $\hat{a}_1^\alpha$ unambiguously decreases with ω with a clear threshold $\bar{\omega} = 60$ below (resp. above) which overabatement (resp. underabatement) occurs for all ambiguity aversion degrees. It is noteworthy that this condition is laxer than anticomonotonicity since $\omega^* < \bar{\omega}$.[47] Second, for any given permit allocation the magnitude of the date-1 abatement adjustment $|\hat{a}_1^\alpha - \bar{a}_1|$

[47] Again, this suggests that anticomonotonicity might be too strong a requirement to sign pessimism. From the simulations we can infer that $\bar{\omega} \doteq \mathbb{E}_F\{\omega_\theta^*\} = \langle\tilde{b}\rangle - 2\langle\tau\rangle$. That is, ambiguity aversion raises date-1 abatement relative to ambiguity neutrality i.f.f. anticomonotonicity holds in expectations over Θ w.r.t. F.

increases with α. For instance when $\omega < \bar{\omega}$, $\hat{a}_1^\alpha$-lines are ordered by increasing α and never cross each other, i.e. an increase in ambiguity aversion always leads to higher date-1 abatement.[48] Note also that the bigger α, the more sensitive the variations in $\hat{a}_1^\alpha$ w.r.t. ω around $\bar{\omega}$. In particular, for $\alpha = .25$, $\hat{a}_1^\alpha$ has already converged to its upper (resp. lower) limit when ω reaches 30 (resp. 90). Figure 3.1b depicts the variability of the date-1 abatement adjustment w.r.t. ω for various ambiguity aversion degrees.[49] The bigger α, the quicker $\hat{a}_1^\alpha$ reacts to ω in a smaller $\bar{\omega}$-centred range. For lower α, the incentive to adjust date-1 abatement is smaller and more evenly spread over the allocation range.

Tax regime under DAAA. Equation (3.5.1) rewrites $\hat{a}_1^\alpha = \mathcal{A}(\hat{a}_1^\alpha)\langle\tilde{\tau}\rangle$ and $\mathcal{V}_{a_1}(a_1;\theta) = \langle\tilde{\tau}\rangle$. Figure 3.2 depicts the variations of $\hat{a}_1^\alpha$ w.r.t. α and ω and isolates the effects of the shift in

Figure 3.2: Tax regime under DAAA



levels $\mathcal{A}$. For all $\alpha > 1$, $\hat{a}_1^\alpha$ unambiguously decreases with ω and is always above $\hat{a}_1^1$. That is, $\mathcal{A}$ is a decreasing function of allocation and has steeper variations for smaller ω. Note that for a standard tax regime, i.e. $\omega = 0$, higher ambiguity aversion degrees do not guarantee higher date-1 abatement levels. In particular, there exists a threshold $\bar{\alpha}$ such that $\hat{a}_1^\alpha$ increases (resp. decreases) with α provided that α is below (resp. above) $\bar{\alpha}$. Numerically we find $\bar{\alpha} \simeq 11.5$. For ω high enough, however, note that $\hat{a}_1^\alpha$ is ranked by increasing ambiguity aversion degrees. Note also that the ratio $\hat{a}_1^\alpha/\bar{a}_1 > 1$ is relatively smaller than for a cap and trade under CAAA. This suggests that the magnitude of the shift in levels $\mathcal{A}$ is relatively smaller than the pessimistic distortion $\mathcal{P}$.

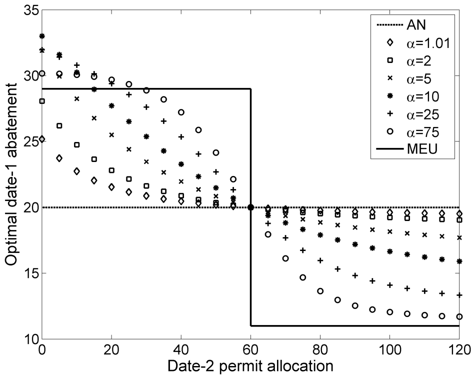
[48] Under CAAA, only point (i) in Proposition 3.4.10 holds. The effects of an increase in α are thus clear.

[49] Figure 3.1b plots $\mathcal{P}(\bar{a}_1) - \mathcal{P}(\hat{a}_1^\alpha)$ as a function of ω. From Equation (3.4.12) and injecting the first-order condition for $\hat{a}_1^\alpha$, overabatement occurs i.f.f. $\hat{a}_1^\alpha - \bar{a}_1 + \mathcal{P}(\bar{a}_1) - \mathcal{P}(\hat{a}_1^\alpha) > 0$. That is, $\mathcal{P}(\bar{a}_1) - \mathcal{P}(\hat{a}_1^\alpha)$ can be interpreted as a proxy of the incentive to increase $\hat{a}_1^\alpha$ relative to $\bar{a}_1$.

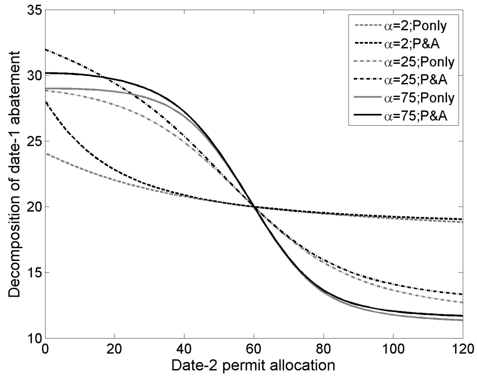
Cap-and-trade regime under DAAA. This case combines the joint effects of $\mathcal{A}$ and $\mathcal{P}$ and $\hat{a}_1^\alpha$ solves Equation (3.5.1). Figure 3.3 depicts the variations of $\hat{a}_1^\alpha$ w.r.t. α and ω. Figure 3.3a is similar to Figure 3.1a save for small disruptions due to the upward shift in

Figure 3.3: Cap-and-trade regime under DAAA

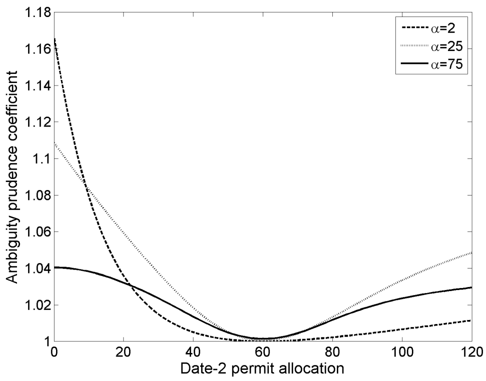
(a) $\hat{a}_1^\alpha = f(\omega)$ for different α



(b) Decomposition of $\mathcal{P}$ and $\mathcal{A}$ effects



(c) Magnitude of the $\mathcal{A}$ effect



level $\mathcal{A}$. It is noteworthy that this upward shift is asymmetric w.r.t. allocation. When $\omega > \bar{\omega}$, $\hat{a}_1^\alpha$ is pushed up towards the $\bar{a}_1$-line, although without breaching it, and the lower limit $\langle\tau\rangle - \bar{\theta}$ is never reached. When $\omega < \bar{\omega}$, date-1 abatement is further adjusted upwards. For relatively low allocation levels the upper limit $\langle\tau\rangle + \bar{\theta}$ can be exceeded. As in the tax regime, for ω low enough, higher ambiguity aversion degrees do not guarantee higher date-1 abatements. More precisely, as Figure 3.3c shows, the magnitude of the $\mathcal{A}$-adjustment is more pronounced for low α when ω is small. Note that the upward shift is relatively smaller when ω is big enough. Note also that within the $[40; 80]$ band, the $\mathcal{A}$-adjustment is very small and ordered by increasing α. That $\hat{a}_1^\alpha$-lines may cross each other when ω is low enough substantiates Proposition 3.4.10, i.e. the shift in levels $\mathcal{A}$ may disrupt the $\mathcal{P}$-adjustment. By contrast, no such crossings exist when $\omega > \bar{\omega}$, i.e. there is an asymmetry in the $\mathcal{A}$-adjustment. Relative adjustments in abatement attributable to $\mathcal{A}$ and $\mathcal{P}$ are illustrated in Figure 3.3b. It is clear that the $\mathcal{A}$-adjustment is more pronounced for lower than bigger ω and that it is almost nil within the $[40; 80]$ band. Except for low allocation levels, this further suggests that pessimism is the principal determinant of the deviation in date-1 abatement relative to ambiguity neutrality.

3.6 Conclusion and supplemental results

Summary. Emissions Trading Systems are subject to considerable uncertainty, especially of a regulatory nature, which can disrupt intertemporal cost efficiency and undermine the long-term price signal. As a novel approach, this Chapter has introduced ambiguity and ambiguity aversion on the part of covered firms as a way to account for the prevalence and influence of such large uncertainty. We note that this analysis could apply to other commodity markets under similar circumstances.

Considering exogenous ambiguity about the future permit price and the firm's permit demand, we analyze the impacts of ambiguity aversion on the firm's intertemporal decisions relative to the case of ambiguity neutrality (i.e., rational expectations). Ambiguity aversion distorts intertemporal efficiency and induces two effects, namely a pessimistic distortion of the firm's beliefs and a shift in the firm's discount factor. These two effects can be aligned or antagonistic, the direction and magnitude of which depend on the firm's degree of ambiguity aversion and its expected future market position. In particular, pessimism leads the firm that expects to be short (resp. long) on the market in the future to overabate (resp. underabate) early on relative to intertemporal efficiency because it overemphasizes situations where high (resp. low) permit prices are relatively more likely.

Furthermore, we show that under certain conditions, pessimism creates a general incentive to overabate early on that is more pronounced under auctioning than free allocation. This can be a behavioral factor that contributes to the formation of permit surpluses in existing ETSs that is adding to the 'physical' factors discussed in the Introduction. In our setup, the hypothesis of excessive discounting found in the literature to account for the current permit price depreciation in the EUETS coincides with 'imprudence toward ambiguity'.

As a final note, we underline that price collars (i.e., price-triggered contingent adjustments to the supply of permits) can reduce the range of ambiguity, but not the effects of ambiguity aversion itself.[50] However, because agents are forward-looking and will anticipate these adjustments, price collars will affect their intertemporal decisions even though they are non binding, what Salant et al. (2017) call an 'action at a distance'. As underlined by these

[50] In this respect, note that we make a first step toward characterizing the effects of an increase in the range of ambiguity in the simpler case of binary price ambiguity in Appendix 3.F.

authors, more research is needed to understand better how price containment mechanisms interact with the complicated intertemporal permit trading incentives.

Supplemental results in Appendix 3.B. We consider three extensions to the model. First, we introduce forward contracts and show that the possibility to trade forwards can mitigate the magnitude of the pessimism-induced effects. However, only under the assumption that forwards are fairly priced will pessimism completely vanish. Additionally, the shift in the firm's discount factor always persists. Therefore, this suggests that the introduction of forwards cannot (*i*) restore intertemporal cost efficiency and (*ii*) render a cap and trade and an emissions tax equivalent under ambiguity aversion on the part of firms.

Second, we show that if permit allocation is sufficiently asymmetrical across firms and firms are ambiguity averse, then the equilibrium volume of trade will be reduced relative to the benchmark. This can contribute to what Ellerman (2000) calls 'autarkic compliance' in nascent systems where traded volumes are thin and covered entities tend to cling on to their permit endowments. This is currently the case in South Korea where the government recently decided to limit the bankability of permits to force permit holders to sell in a bid to ensure there is enough supply on the market and avoid price spikes.

Third, we show that the equilibrium in a market populated by a mix of ambiguity neutral and averse firms should be brought further away from intertemporal efficiency. Although we cannot properly solve for the resulting equilibrium, we take our approach as a reasonable first pass. This also motivates further work toward the definition of a market equilibrium in which agents have heterogeneous beliefs and attitudes toward ambiguity.

Appendices of Chapter 3

3.A Collected proofs

3.A.1 Proof of Proposition 3.4.1

By concavity of the objective function, $\hat{a}_1^\mu \geq \bar{a}_1^\mu$ i.f.f. $-C_1'(\bar{a}_1^\mu) + \beta\mathcal{A}(\bar{a}_1^\mu)\mathcal{V}_{a_1}(\bar{a}_1^\mu) \geq 0$, which is here equivalent to $\mathcal{A}(\bar{a}_1^\mu) \geq 1$. The proof follows if we establish the following claim:

$$\begin{aligned}\text{DAAA (resp. IAAA,CAAA)} &\Leftrightarrow \mathbb{E}\{\phi'(\cdot)\} \geq (\text{resp. } \leq, =)\, \phi' \circ \phi^{-1}(\mathbb{E}\{\phi(\cdot)\}) \\ &\Leftrightarrow \mathcal{A} \geq (\text{resp. } \leq, =)\, 1.\end{aligned}$$

Let ϕ be thrice differentiable. An agent is said to display Decreasing Absolute Ambiguity Aversion (DAAA) i.f.f. its Arrow-Pratt coefficient of absolute ambiguity aversion $-\phi''/\phi'$ is non-increasing. This is the case when $-\phi'''\phi' + \phi''^2 \leq 0$ or, upon rearranging, when $-\phi'''/\phi'' \geq -\phi''/\phi'$. This is equivalent to $-\phi'$ being more concave than ϕ, i.e. absolute prudence w.r.t. ambiguity exceeds absolute ambiguity aversion. In terms of certainty equivalent this translates into $\phi^{-1}(\mathbb{E}\{\phi(\cdot)\}) \geq (-\phi')^{-1}(-\mathbb{E}\{\phi'(\cdot)\})$. Applying $-\phi'$ on both sides proves the claim. See also Osaki & Schlesinger (2014) and Guerdjikova & Sciubba (2015) for a proof based on the concepts of ambiguity premium and ambiguity precautionary premium extending similar notions under risk (Pratt, 1964; Kimball, 1990).

3.A.2 Proof of Proposition 3.4.3

For a probability measure G^i, define the function O^i by

$$0 = -C_1'(\bar{a}_1^i) + \beta\mathbb{E}_{G^i}\{C_2'(a_2^*(\tilde{\tau}))\} \doteq O^i(\bar{a}_1^i), \tag{3.A.1}$$

where $\bar{a}_1^i$ is the date-1 optimal abatement when the price risk is distributed according to G^i and a_2^* does not depend on a_1 since we assume time separability. Let the measure G^j be a mean-preserving spread of G^i, i.e. an increase in risk relative to G^i in the sense of

Rothschild & Stiglitz (1971). Concavity of the firm's objective function then yields

$$\bar{a}_1^j \geq \bar{a}_1^i \Leftrightarrow O^j(\bar{a}_1^i) \geq O^i(\bar{a}_1^i) = 0 \Leftrightarrow \mathbb{E}_{G^j}\{C_2'(a_2^*(\tilde{\tau}))\} \geq \mathbb{E}_{G^i}\{C_2'(a_2^*(\tilde{\tau}))\}. \tag{3.A.2}$$

By Jensen's inequality, the last inequality in Equation (3.A.2) holds true i.f.f. C_2' is convex.

3.A.3 Proof of Proposition 3.4.4

By concavity of the objective function, $\hat{a}_1 \geq \bar{a}_1$ is equivalent to

$$\mathbb{E}_F\{\phi'(\mathcal{V}(\bar{a}_1;\tilde{\theta}))\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\} \geq \phi' \circ \phi^{-1}(\mathbb{E}_F\{\phi(\mathcal{V}(\bar{a}_1;\tilde{\theta}))\})\mathbb{E}_F\{\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\}. \tag{3.A.3}$$

With ϕ displays DAAA, a sufficient condition for Inequality (3.A.3) to hold is

$$\mathbb{E}_F\{\phi'(\mathcal{V}(\bar{a}_1;\tilde{\theta}))\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\} \geq \mathbb{E}_F\{\phi'(\mathcal{V}(\bar{a}_1;\tilde{\theta}))\}\mathbb{E}_F\{\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\}. \tag{3.A.4}$$

This is exactly $\mathrm{Cov}_\theta\{\phi'(\mathcal{V}(\bar{a}_1;\tilde{\theta}));\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\} \geq 0$. Noting that ϕ' is non-increasing concludes. The above holds with equality (resp. reverses) when ϕ is CAAA (resp. IAAA).

3.A.4 Proof of Proposition 3.4.8

The proof consists in signing $\mathrm{Cov}_\theta\{\mathcal{V}(\bar{a}_1;\tilde{\theta});\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\}$ and identifying under which conditions it is non-positive. With the quadratic cost specification (3.3.1), for all $\theta \in \Theta$, $\mathcal{V}_{a_1}(\bar{a}_1;\theta)$, $\bar{a}_1$, and a_2^* are given in Equations (3.3.11), (3.3.6) and (3.3.3), respectively. Differentiating $\mathcal{V}_{a_1}(\bar{a}_1;\theta)$ w.r.t. θ and then integrating by parts yields

$$\partial_\theta\mathcal{V}_{a_1}(\bar{a}_1;\theta) = \frac{c_2-\gamma}{c_2}\int_{\mathrm{T}} x\partial_\theta g(x;\theta)\mathrm{d}x = \frac{\gamma-c_2}{c_2}\int_{\mathrm{T}} G_\theta(x;\theta)\mathrm{d}x, \tag{3.A.5}$$

where $G_\theta(\cdot;\theta) \doteq \partial_\theta G(\cdot;\theta)$. Similarly, by the Envelop Theorem and differentiation w.r.t. θ,

$$\begin{aligned}\partial_\theta\mathcal{V}(\bar{a}_1;\theta) &= -\int_{\mathrm{T}} C_2(\bar{a}_1, a_2^*(\bar{a}_1;x)) + x\left(b-\bar{a}_1-a_2^*(\bar{a}_1;x)-\omega\right)\partial_\theta g(x;\theta)\mathrm{d}x \\ &= -\int_{\mathrm{T}} x\Big(b-\omega-\Big(1-\frac{\gamma}{c_2}\Big)\bar{a}_1-\frac{x}{2c_2}\Big)-\frac{\gamma^2\bar{a}_1^2}{2c_2}\partial_\theta g(x;\theta)\mathrm{d}x \\ &= \int_{\mathrm{T}}\Big(b-\omega-\Big(1-\frac{\gamma}{c_2}\Big)\bar{a}_1-\frac{x}{c_2}\Big)G_\theta(x;\theta)\mathrm{d}x,\end{aligned} \tag{3.A.6}$$

where the third equality obtains by integration by parts. For all $x \in \mathrm{T}$, let $k : x \mapsto b-\omega-\Big(1-\frac{\gamma}{c_2}\Big)\bar{a}_1-\frac{x}{c_2}$. We assume that $\underline{\tau} < c_2(b-\omega-\bar{a}_1) < \bar{\tau}$. Notice that k changes sign over T and by continuity there exists $\tau_0 \in \mathrm{T}$ such that $k(\tau_0) = 0$, i.e. $\tau_0 = c_2(b-\omega)-(c_2-\gamma)\bar{a}_1$.

For all $\theta \in \Theta$, let

$$\Gamma(\tau_0;\theta) \doteq \frac{1}{c_2}\int_{\mathrm{T}} (\tau_0 - x)\, G_\theta(x;\theta)\mathrm{d}x. \tag{3.A.7}$$

Differentiating w.r.t. τ_0 yields $\Gamma'_\theta(\tau_0) = \frac{1}{c_2}\int_{\mathrm{T}} G_\theta(x;\theta)\mathrm{d}x$. When $G_\theta > 0$, $\partial_\theta\Gamma(\cdot;\theta) > 0$ so that $\Gamma(\underline{\tau};\theta) < 0$ and $\Gamma(\bar{\tau};\theta) > 0$. Symmetrically, when $G_\theta < 0$, $\partial_\theta\Gamma(\cdot;\theta) < 0$ so that $\Gamma(\underline{\tau};\theta) > 0$ and $\Gamma(\bar{\tau};\theta) < 0$. In both cases, $\forall\theta \in \Theta$, by continuity of $\Gamma(\cdot;\theta)$ there exists a duple $(\tau^*_\theta; a_{1,\theta})$ such that $\tau^*_\theta = c_2(b-\omega) - (c_2-\gamma)a_{1,\theta}$ defined by $\Gamma(\tau^*_\theta;\theta) = 0$. By definition,

$$\int_{\mathrm{T}} (\tau^*_\theta - x)\, G_\theta(x;\theta)\mathrm{d}x = 0 \;\Rightarrow\; a_{1,\theta} = \frac{c_2}{c_2-\gamma}\left(b - \omega - \frac{\int_{\mathrm{T}} xG_\theta(x;\theta)\mathrm{d}x}{c_2\int_{\mathrm{T}} G_\theta(x;\theta)\mathrm{d}x}\right). \tag{3.A.8}$$

For a given ω, $a_{1,\theta}$ corresponds to the required date-1 abatement in scenario θ when the permit price prevailing at date 2 is $\tau^*_\theta \doteq \int_{\mathrm{T}} x\partial_\theta G(x;\theta)\mathrm{d}x \Big/ \int_{\mathrm{T}} \partial_\theta G(x;\theta)\mathrm{d}x$, i.e. when date-2 abatement is $a^*_2(\bar{a}_1;\tau^*_\theta)$. Two cases arise depending on the monotonicity of G w.r.t. θ.

1. $G_\theta > 0$: $\forall\theta \in \Theta$, $\partial_\theta\mathcal{V}_{a_1}(\bar{a}_1;\theta) < 0$ and $\partial_\theta\mathcal{V}(\bar{a}_1;\theta) > 0$ i.f.f. $\frac{c_2}{2}\Big(b-\omega-\Big(1-\frac{\gamma}{c_2}\Big)\bar{a}_1\Big) > \tau^*_\theta$, that is i.f.f. $\bar{a}_1 < a_{1,\theta}$;
2. $G_\theta < 0$: $\forall\theta \in \Theta$, $\partial_\theta\mathcal{V}_{a_1}(\bar{a}_1;\theta) > 0$ and $\partial_\theta\mathcal{V}(\bar{a}_1;\theta) < 0$ i.f.f. $\frac{c_2}{2}\Big(b-\omega-\Big(1-\frac{\gamma}{c_2}\Big)\bar{a}_1\Big) > \tau^*_\theta$, that is i.f.f. $\bar{a}_1 < a_{1,\theta}$.

In both cases, $\hat{a}_1 > \bar{a}_1$ i.f.f. $\bar{a}_1 < a_{1,\theta}$ for all $\theta \in \Theta$, that is i.f.f. $\bar{a}_1 < \min_{\theta\in\Theta} a_{1,\theta}$, which proves (*ii*). Points (*i*) and (*iii*) follow straightforwardly.

3.A.5 Proof of Proposition 3.4.10

Assume that $\mathcal{V}(\cdot;\tilde{\theta})$ and $\mathcal{V}_{a_1}(\cdot;\tilde{\theta})$ are anticomonotone, i.e. both firms form precautionary date-1 abatement. For all θ in Θ it holds that

$$\frac{\mathcal{D}_2(\hat{a}_1;\theta)}{\mathcal{D}_1(\hat{a}_1;\theta)} = \psi'\circ\phi_1(\mathcal{V}(\hat{a}_1;\theta))\frac{\mathbb{E}_F\{\phi'_1(\mathcal{V}(\hat{a}_1;\tilde{\theta}))\}}{\mathbb{E}_F\{\phi'_2(\mathcal{V}(\hat{a}_1;\tilde{\theta}))\}} \propto \psi'\circ\phi_1(\mathcal{V}(\hat{a}_1;\theta)). \tag{3.A.9}$$

W.l.o.g. let $\mathcal{V}(\hat{a}_1;\theta)$ be non-decreasing in θ. By definition $\psi'\circ\phi_1(\mathcal{V}(\hat{a}_1;\theta))$ and thus $\mathcal{D}_2/\mathcal{D}_1$ are non-increasing in θ. That is, firm 2 displays a stronger pessimism than firm 1 in the sense that it overemphasises low-$\mathcal{V}$ scenarios even further. Since we assume anticomonotonicity $\mathcal{V}_{a_1}(\hat{a}_1;\theta)$ is non-increasing in θ. Therefore, it holds that

$$\mathbb{E}_F\{\mathcal{D}_2(\hat{a}_1;\tilde{\theta})\mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\} \geq \mathbb{E}_F\{\mathcal{D}_1(\hat{a}_1;\tilde{\theta})\mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\}. \tag{3.A.10}$$

Comparing Equations (3.4.14) and (3.A.10), it is always true that $\hat{a}_2 \geq \hat{a}_1$ provided that $\mathcal{A}_2(\hat{a}_1) \geq \mathcal{A}_1(\hat{a}_1)$. However it is not easy to determine when $\mathcal{A}_2 \geq \mathcal{A}_1$. We note that a necessary condition for this to hold is that firm 2's coefficient of absolute ambiguity prudence be higher than that of firm 1, i.e. $-\phi_2'''/\phi_2'' \geq -\phi_1'''/\phi_1''$. Assuming $\psi''' = 0$ then yields

$$\phi_2'' = (\psi'' \circ \phi_1)\,\phi_1'^2 + (\psi' \circ \phi_1)\,\phi_1'', \text{ and } \phi_2''' = 3\,(\psi'' \circ \phi_1)\,\phi_1'\phi_1'' + (\psi' \circ \phi_1)\,\phi_1'''. \tag{3.A.11}$$

Noting that $-\phi_2'''/\phi_2'' \geq -\phi_1'''/\phi_1''$ rewrites $-\phi_1'''/\phi_1'' \leq -3\phi_1''/\phi_1'$ concludes.

3.A.6 Proof of Proposition 3.4.11

When both the date-2 market price and the firm's baseline are ambiguous, the θ-scenario expected profitability from date-1 abatement writes

$$\mathcal{V}(a_1;\theta) = \iint_{\mathrm{B,T}} \Big(\zeta_2 - C_2(a_1, a_2^*(a_1;x)) - x(y - a_1 - a_2^*(a_1;x) - \omega)\Big) g(x;\theta) l(y;\theta) \mathrm{d}x\mathrm{d}y. \tag{3.A.12}$$

With quadratic cost specification (3.3.1), because G and L are first-order independent, differentiating Equation (3.A.12) w.r.t. θ, integrating by parts and evaluating at $a_1 = \bar{a}_1$ gives

$$\partial_\theta \mathcal{V}(\bar{a}_1;\theta) = \int_{\mathrm{T}} \Big(\bar{b}_\theta - \omega - \Big(1 - \frac{\gamma}{c_2}\Big)\bar{a}_1 - \frac{x}{c_2}\Big) G_\theta(x;\theta)\mathrm{d}x + \bar{\tau}_\theta \int_{\mathrm{B}} L_\theta(y;\theta)\mathrm{d}y, \tag{3.A.13}$$

where $\bar{b}_\theta \doteq \mathbb{E}_L\{\tilde{b}_\theta|\theta\}$ and $L_\theta(\cdot;\theta) \doteq \partial_\theta L(\cdot;\theta)$. Note that $\partial_\theta \mathcal{V}_{a_1}(\bar{a}_1;\theta)$ is given by Equation (3.A.5). By the same token as in Proof 3.A.4 anticomonotonicity holds when $G_\theta > 0$ (resp. $G_\theta < 0$) if the allocation threshold condition is satisfied and $L_\theta > 0$ (resp. $L_\theta < 0$).

3.A.7 Proof of Proposition 3.4.12

Assume quadratic abatement cost specification (3.3.1). All ambiguity neutral firms abate by the same amount at date 1 $\bar{a}_1 = \beta \langle \tau_\theta \rangle / c_1$ where

$$\langle \tau_\theta \rangle \doteq \mathbb{E}_F\{\tau_\theta\} = c_2 \mathbb{E}_F\{a_2^*(\bar{A}_1;\bar{b}_\theta)\} = c_2\Big(\langle \tilde{b} \rangle - (\bar{A}_1 + \Omega)/S\Big). \tag{3.A.14}$$

Noting that $\bar{A}_1 = S\bar{a}_1$ then gives

$$\bar{a}_1 = c(\langle \tilde{b} \rangle - \Omega/S)/c_1 \text{ and } a_2^*(\bar{A}_1;\bar{b}_\theta) = \bar{b}_\theta - c\langle \tilde{b} \rangle / c_1 - c\Omega/(\beta c_2 S). \tag{3.A.15}$$

Note that the aggregate emission constraint is satisfied in every θ-scenario

$$\int_{\mathcal{S}} \Big(\tilde{b}_\theta(s) - \bar{a}_1 - \bar{a}_2^*(\bar{A}_1;\bar{b}_\theta)\Big)\mathrm{d}s = \Omega. \tag{3.A.16}$$

Note also that a positive permit price in each θ-scenario requires that, when $A_1 = \bar{A}_1$,

$$\Omega(c_1 - c) > S\Big(c_1 \max_{\theta\in\Theta} \bar{b}_\theta - c\langle\tilde{b}\rangle\Big), \tag{3.A.17}$$

which we assume is the case. Let us now sign $\mathrm{Cov}_\theta\{\mathcal{V}(\bar{a}_1;\tilde{\theta});\mathcal{V}_{a_1}(\bar{a}_1;\tilde{\theta})\}$. We have

$$\mathcal{V}(\bar{a}_1;\theta) = \zeta_2 - C_2(a_2^*(\bar{A}_1;\bar{b}_\theta)) - \tau_\theta\Big(\bar{b}_\theta - \bar{a}_1 - a_2^*(\bar{A}_1;\bar{b}_\theta) - \omega(s)\Big) \tag{3.A.18a}$$

$$\partial_\theta\mathcal{V}_{a_1}(\bar{a}_1;\theta) = \partial_\theta\tau_\theta = C_2''(a_2^*(\bar{A}_1;\bar{b}_\theta))\partial_\theta a_2^*(\bar{A}_1;\bar{b}_\theta) = C_2''(a_2^*(\bar{A}_1;\bar{b}_\theta))\partial_\theta\bar{b}_\theta, \tag{3.A.18b}$$

$$\partial_\theta\mathcal{V}(\bar{a}_1;\theta) = \Big(C_2'''(a_2^*(\bar{A}_1;\bar{b}_\theta))\Psi(s;\theta) - C_2'(a_2^*(\bar{A}_1;\bar{b}_\theta))\Big)\,\partial_\theta\bar{b}_\theta, \tag{3.A.18c}$$

since $\partial_\theta\bar{A}_1 = \partial_\theta\bar{a}_1 = 0$ (both $\bar{A}_1$ and $\bar{a}_1$ are decided ex ante) and where $\Psi(s;\theta) \doteq \bar{a}_1 + a_2^*(\bar{A}_1;\bar{b}_\theta) + \omega(s) - \bar{b}_\theta$ is firm s' expected net position on the market in scenario θ under ambiguity neutrality. Anticomonotonicity holds provided that for all $\theta\in\Theta$, $\Psi(s;\theta) < \frac{C_2'(a_2^*(\bar{A}_1;\bar{b}_\theta))}{C_2'''(a_2^*(\bar{A}_1;\bar{b}_\theta))}$. Note that this allows a net long (i.e., positive) market position which was not the case under pure price ambiguity. Injecting Equation (3.A.15) gives $\Psi(s;\theta) = \omega(s) - \frac{\Omega}{S}$ which is nil for a symmetric allocation plan. Therefore, when allocation is symmetric anticomonotonicity holds unconditionally. Assume for simplicity that the ratio of abatement technology between the two dates is unitary, i.e. $c_1 = \beta c_2$. Then,

$$\Psi(s;\theta) < \frac{C_2'(a_2^*(\bar{A}_1;\bar{b}_\theta))}{C_2''(a_2^*(\bar{A}_1;\bar{b}_\theta))} \;\Leftrightarrow\; \omega(s) < \min_{\theta\in\Theta}\Big\langle\omega_\theta \doteq (\Omega/S + 2\bar{b}_\theta - \langle\tilde{b}\rangle)/2\Big\rangle, \tag{3.A.19}$$

Noting from Equation (3.A.17) that $\omega_\theta > \Omega/S$ for all $\theta\in\Theta$ concludes.

3.A.8 Comparative statics w.r.t. permit allocation

With ϕ CAAA and no long-term effect of abatement, Equation (3.4.7) rewrites

$$-C_1'(\hat{a}_1) + \beta\frac{\mathbb{E}_F\{\phi'(\mathcal{V}(\hat{a}_1;\tilde{\theta}))\mathcal{V}_{a_1}(\hat{a}_1;\tilde{\theta})\}}{\mathbb{E}_F\{\phi'(\mathcal{V}(\hat{a}_1;\tilde{\theta}))\}} = 0. \tag{3.A.20}$$

Taking the total differential of Equation (3.A.20) yields

$$\frac{\mathrm{d}\hat{a}_1}{\mathrm{d}\omega} = \frac{\beta\Phi(\hat{a}_1)}{C_1''(\hat{a}_1) - \beta\Phi(\hat{a}_1)}, \tag{3.A.21}$$

where, since $\mathcal{V}_\omega = \mathcal{V}_{a_1} = \bar{\tau}_\theta$, and omitting arguments so as to avoid cluttering,

$$\Phi(a_1) = \frac{\mathbb{E}_F\{\mathcal{V}_{a_1}^2\phi''(\mathcal{V})\}\mathbb{E}_F\{\phi'(\mathcal{V})\} - \mathbb{E}_F\{\mathcal{V}_{a_1}\phi'(\mathcal{V})\}\mathbb{E}_F\{\mathcal{V}_{a_1}\phi''(\mathcal{V})\}}{\mathbb{E}_F\{\phi'(\mathcal{V})\}^2}. \tag{3.A.22}$$

In particular, note that $\frac{\mathrm{d}\hat{a}_1}{\mathrm{d}\omega} \in]-1;0[$ i.f.f. $\Phi(\hat{a}_1) < 0$. We can show that

$$\begin{aligned}\Phi(\hat{a}_1) &\propto \mathrm{Cov}_\theta \left\{\mathcal{V}_{a_1}; \mathcal{V}_{a_1}\phi''(\mathcal{V})\right\} \mathbb{E}_F \left\{\phi'(\mathcal{V})\right\} - \mathrm{Cov}_\theta \left\{\mathcal{V}_{a_1}; \phi'(\mathcal{V})\right\} \mathbb{E}_F \left\{\mathcal{V}_{a_1}\phi''(\mathcal{V})\right\} \\ &\propto \mathcal{P}(\hat{a}_1) - \mathcal{P}_2(\hat{a}_1) = \frac{\mathrm{Cov}_\theta \left\{\mathcal{V}_{a_1}; \phi'(\mathcal{V})\right\}}{\mathbb{E}_F \left\{\phi'(\mathcal{V})\right\}} - \frac{\mathrm{Cov}_\theta \left\{\mathcal{V}_{a_1}; \mathcal{V}_{a_1}\phi''(\mathcal{V})\right\}}{\mathbb{E}_F \left\{\mathcal{V}_{a_1}\phi''(\mathcal{V})\right\}},\end{aligned} \tag{3.A.23}$$

where $\mathcal{P}$ is the pessimism-only price distortion and $\mathcal{P}_2$ can be interpreted as a second-order pessimism-only price distortion. These two distortions have positive values when anticomonotonicity holds in which case $\Phi(\hat{a}_1) \leq 0$ i.f.f. $\mathcal{P}_2(\hat{a}_1) \geq \mathcal{P}(\hat{a}_1)$. It is difficult to determine the variations of $\hat{a}_1$ w.r.t. ω because it is hard to sign $\mathcal{P}_2(\hat{a}_1) - \mathcal{P}(\hat{a}_1)$ in general. In line with intuition numerical simulations in Section 3.5 show that the level of optimal date-1 abatement unambiguously decreases with allocation, with intensities depending on the degree of ambiguity aversion and the allocation volume itself. This would suggest that $\mathcal{P}_2$ is larger than $\mathcal{P}$. Again, this calls for studying higher orders for ambiguity prudence.

3.B Model extensions and supplemental results

This appendix first extends our model by allowing for trades of forward contracts. It then analyses the impacts of (i) ambiguity aversion on the equilibrium volume of permit trade; (ii) having a mix of ambiguity averse and neutral firms on the market for permits.

Forward trading. It is natural to investigate to which extent the introduction of a forwards market can diminish the effects of ambiguity aversion and restore intertemporal efficiency. In practice, ETS-liable firms liable have recourse to forward contracts for hedging purposes, e.g. power companies in the EUETS. We consider that firms now have the possibility to trade permits in a forward market at date 1. Let a_f and p_f denote the volume of permits contracted in the forward market and the forward price, respectively. Note that this does not change the optimal abatement decision at date-2. Then, the firm's recursive program rewrites

$$\max_{a_1 \geq 0, a_f} \left\langle \zeta_1 - C_1(a_1) - p_f a_f + \beta\phi^{-1}\Big(\mathbb{E}_F\{\phi(\mathcal{V}(a_1, a_f; \tilde{\theta}))\}\Big)\right\rangle, \tag{3.B.1}$$

where $\mathcal{V}(a_1, a_f; \theta) = \mathbb{E}_G \left\{\zeta_2 - C_2(a_1, a_2^*(a_1; \tilde{\tau}_\theta)) - \tilde{\tau}_\theta(b - a_1 - a_f - a_2^*(a_1; \tilde{\tau}_\theta) - \omega)|\theta\right\}$ for all $\theta \in \Theta$. The two necessary first-order conditions for $\hat{a}_1$ and $\hat{a}_f$ are given by

$$-C_1'(\hat{a}_1) + \beta\frac{\mathbb{E}_F\{\phi'(\mathcal{V}(\hat{a}_1, \hat{a}_f; \tilde{\theta}))\mathcal{V}_{a_1}(\hat{a}_1, \hat{a}_f; \tilde{\theta})\}}{\phi' \circ \phi^{-1}(\mathbb{E}_F\{\phi(\mathcal{V}(\hat{a}_1, \hat{a}_f; \tilde{\theta}))\})} = 0, \tag{3.B.2a}$$

$$\text{and } -p_f + \beta\frac{\mathbb{E}_F\{\phi'(\mathcal{V}(\hat{a}_1, \hat{a}_f; \tilde{\theta}))\mathcal{V}_{a_f}(\hat{a}_1, \hat{a}_f; \tilde{\theta})\}}{\phi' \circ \phi^{-1}(\mathbb{E}_F\{\phi(\mathcal{V}(\hat{a}_1, \hat{a}_f; \tilde{\theta}))\})} = 0. \tag{3.B.2b}$$

By the Envelop, $\mathcal{V}_{a_f}(\hat{a}_1, \hat{a}_f; \theta) = \bar{\tau}_\theta \geq \mathcal{V}_{a_1}(\hat{a}_1, \hat{a}_f; \theta) = \bar{\tau}_\theta - \mathbb{E}_G \{\partial_{a_1} C_2(\hat{a}_1, a_2^*(\hat{a}_1; \tilde{\tau}_\theta))|\theta\} > 0$, where $\bar{\tau}_\theta = \mathbb{E}_G \{\tilde{\tau}_\theta|\theta\}$. Thus, absent long-term effect of abatement, intertemporal efficiency in expectations is restored since it holds $\beta \langle\tilde{\tau}\rangle = C_1'(\bar{a}_1) = p_f = C_1'(\hat{a}_1)$ provided that $p_f \in \mathrm{T}$ is predetermined but irrespective of how p_f is priced. Otherwise, present long-term effect of abatement, combining Equations (3.B.2a) and (3.B.2b) gives

$$- C_1'(\hat{a}_1) - \beta\mathcal{A}(\hat{a}_1, \hat{a}_f)\mathbb{E}_F\{\mathcal{D}(\hat{a}_1, \hat{a}_f; \tilde{\theta})\mathbb{E}_G\{\partial_{a_1} C_2(\hat{a}_1, a_2^*(\hat{a}_1; \tilde{\tau}_\theta))|\theta\}\} + p_f = 0. \qquad (3.B.3)$$

Assume forward contracts are fairly priced, i.e. the forward price is unbiased $p_f \equiv \beta\langle\tilde{\tau}\rangle$. For any $a_1 \geq 0$, the optimal forward volume $a_f^*(a_1)$ solves $\langle\tilde{\tau}\rangle = \mathcal{A}(a_1, a_f^*)\mathbb{E}_F\{\mathcal{D}(a_1, a_f^*; \tilde{\theta})\tau_\theta\}$. Therefore, $\hat{a}_1 \geq \bar{a}_1$ holds if, and only if,

$$\mathbb{E}_{\bar{G}}\{\partial_{a_1} C_2(\bar{a}_1, a_2^*(\bar{a}_1; \tilde{\tau}))\} \geq \mathcal{A}(\bar{a}_1, a_f^*(\bar{a}_1))\mathbb{E}_F\{\mathcal{D}(\bar{a}_1, a_f^*(\bar{a}_1); \tilde{\theta})\mathbb{E}_G\{\partial_{a_1} C_2(\bar{a}_1, a_2^*(\bar{a}_1; \tilde{\tau}_\theta))|\theta\}\}. \qquad (3.B.4)$$

With quadratic cost specification (3.3.1), Inequality (3.B.4) is equivalent to

$$\langle\tilde{\tau}\rangle + \gamma(\mathcal{A}(\bar{a}_1, a_f^*(\bar{a}_1)) - 1)\bar{a}_1 \geq \mathcal{A}(\bar{a}_1, a_f^*(\bar{a}_1))\mathbb{E}_F\{\mathcal{D}(\bar{a}_1, a_f^*(\bar{a}_1); \tilde{\theta})\tau_\theta\}, \qquad (3.B.5)$$

which, under the fair price assumption, is equivalent to $\mathcal{A}(\bar{a}_1, a_f^*(\bar{a}_1)) \geq 1$. In summary,

Proposition 3.B.1. *Consecutive to the introduction of forward contracts,*
(i) absent long-term effect of abatement, intertemporal efficiency in expectations is restored irrespective of how forward contracts are priced;
(ii) present long-term effect of abatement and assuming that forward contracts are fairly priced, intertemporal efficiency in expectations obtains only under CAAA. In particular, under DAAA (resp. IAAA), date-1 overabatement (resp. underabatement) persists.

Absent long-term effect of abatement, the optimal level of date-1 abatement level does not depend on the underlying ambiguity level nor on the firm's attitude towards ambiguity. This is in line with recent extensions of the separation theorem under smooth ambiguity aversion (Wong, 2015b, 2016; Osaki et al., 2016).[51] Present long-term effect of abatement, the introduction of a fairly-priced market for forward contracts only corrects for pessimism but not for the shift in levels $\mathcal{A}$.[52] As far as date-1 abatement decisions are concerned a

[51] In the presence of pure price ambiguity for a risk-averse ambiguity-averse competitive firm, see Wong (2015b). In the presence of price ambiguity and additive background risk for a risk-neutral and ambiguity-averse competitive firm, see Osaki et al. (2016). In the presence of price ambiguity and additive or multiplicative background risk for a risk-averse ambiguity-averse competitive firm, see Wong (2016).

[52] This contrasts with Wong (2015b), Wong (2016) and Osaki et al. (2016) in that they use the static KMM formulation, hence without the shift in levels $\mathcal{A}$.

cap-and-trade regime with fairly-priced forward contracts is hence akin to a tax regime. When forwards are not priced fairly, however, pessimism does not (completely) vanish.

Equilibrium volume of trade. We investigate the impact of ambiguity aversion on the part of firms on the overall volume of trade. Assume CAAA for clarity. Then, when firm s (resp. l) is allocated less (resp. more) than $\min_{\theta\in\Theta}\omega^*_\theta$ (resp. $\max_{\theta\in\Theta}\omega^*_\theta$) it expects to be net short (resp. long) in all θ-scenarios under the abatement stream $(\bar{a}_1; a^*_2(\bar{a}_1;\tau^*_\theta))$. That is, $\hat{a}_1(s) \geq \bar{a}_1 \geq \hat{a}_1(l)$. At date 2, all firms equate their date-2 marginal abatement costs $\partial_{a_2}C_2(a_1;a^*_2)$ to the observed permit price τ. With quadratic cost specification (3.3.1), total abatements for the three types of firms rank such that

$$a^*_2(\hat{a}_1(s);\tau)+\hat{a}_1(s) = \Big(\tau+(c_2-\gamma)\hat{a}_1(s)\Big)/c_2 \geq a^*_2(\bar{a}_1;\tau)+\bar{a}_1 \geq a^*_2(\hat{a}_1(l);\tau)+\hat{a}_1(l). \quad (3.B.6)$$

Since the net buying (resp. selling) firm s (resp. l) abates more (resp. less) and buys (resp. sells) less permitss on the market than under ambiguity neutrality, one has

Proposition 3.B.2. *Let permits be non-symmetrically distributed such that at least some firms are endowed with* $\omega \notin [\min_{\theta\in\Theta}\omega^*_\theta; \max_{\theta\in\Theta}\omega^*_\theta]$. *Then, the equilibrium volume of trade is lower when firms are ambiguity averse than when they are ambiguity neutral.*

Similarly, Baldursson & von der Fehr (2004) find that risk aversion reduces the equilibrium volume of trade relative risk neutrality. Ambiguity and risk aversions may thus contribute to what Ellerman (2000) calls «autarkic compliance» in nascent ETSs, i.e. traded volumes are thin (e.g., presently in the Korean ETS or the Chinese pilots). Because covered entities are waiting for increased price discovery and due to high regulatory uncertainty they tend to hold on to their allocation so that trades are scarce. For instance, the volume of trades (both in spot EUAs and futures) increased steadily over Phase I of the EUETS as uncertainty gradually vanished, see e.g. Chapter 5 in Ellerman et al. (2010).

Different tastes for ambiguity. Consider a permit market populated by both ambiguity averse and neutral firms where $\varepsilon \in [0;1]$ denotes the share of ambiguity averse firms. Assume $\partial_{a_1}C_2 \equiv 0$. For any $\varepsilon \in (0;1)$ denote by $\hat{a}^\varepsilon_1$ and $\bar{a}^\varepsilon_1$ the optimal date-1 abatement levels for the ambiguity averse and neutral firms, respectively. Suppose also that ambiguity averse firms are allocated $\omega \leq \min_{\theta\in\Theta}\omega^*_\theta$ so that, in a market that contains either only ambiguity averse or ambiguity neutral firms, optimal date-1 abatement levels satisfy $\hat{a}^{\varepsilon=1}_1 = \hat{a}_1 \geq \bar{a}^{\varepsilon=0}_1 = \bar{a}_1$ and $\hat{A}_1 = S\hat{a}_1 \geq \bar{A}_1 = S\bar{a}_1$. For any mix ε, assume that market closure at date 2 gives the θ-scenario permit price by $\tau^\varepsilon_\theta = C'_2\Big(\bar{b}_\theta - (\varepsilon\hat{A}_1 + (1-\varepsilon)\bar{A}_1 + \Omega)/S\Big)$.[53] Denoting by $\bar{\tau}_\theta$ and

[53] This is a conservative assumption. As will be clear from Proposition 3.B.3, defining τ^ε_θ with $\hat{A}^\varepsilon_1$ and $\bar{A}^\varepsilon_1$ instead of $\hat{A}_1$ and $\bar{A}_1$ would further amplify the deviation.

$\hat{\tau}_\theta$ the θ-scenario permit price when $\varepsilon = 0$ and $\varepsilon = 1$, respectively, we have $\hat{\tau}_\theta \leq \tau^\varepsilon_\theta \leq \bar{\tau}_\theta$. Symmetrically, when ambiguity averse firms receive a large allocation $\omega \geq \max_{\theta\in\Theta} \omega^*_\theta$, $\hat{a}_1 \leq \bar{a}_1$, we have $\bar{\tau}_\theta \leq \tau^\varepsilon_\theta \leq \hat{\tau}_\theta$. By comparing the necessary first-order conditions for $\bar{a}_1$ and $\bar{a}^\varepsilon_1$ on the one hand, and for $\hat{a}_1$ and $\hat{a}^\varepsilon_1$ on the other hand, the following holds

Proposition 3.B.3. *Let $\varepsilon \in (0;1)$ denote the share of ambiguity averse firms. Then,*
(i) when they are allocated $\omega < \min_{\theta\in\Theta} \omega^*_\theta$, $\bar{a}^\varepsilon_1 < \bar{a}_1 < \hat{a}_1 < \hat{a}^\varepsilon_1$;
(ii) when they are allocated $\omega > \max_{\theta\in\Theta} \omega^*_\theta$, $\bar{a}^\varepsilon_1 > \bar{a}_1 > \hat{a}_1 > \hat{a}^\varepsilon_1$.

This shows that having a mix of ambiguity averse and neutral firms in the market where ambiguity averse firms are endowed with a relatively high or low number of permits brings the market further away from intertemporal efficiency. In particular, note that this also alters abatement decisions of ambiguity neutral firms.

3.C MEU preferences & anticomonotonicity

The anticomonotonicity criterion is robust in the sense that it obtains with other models of choice under ambiguity. This appendix considers the α-maxmin representation theorem (Gilboa & Schmeidler, 1989; Ghirardato et al., 2004). We stick to our interpretation of Θ as the set of possible objective probability distributions. The firm thus grants a weight $\alpha \in [0;1]$ to the worst θ-scenario in Θ and the complementary weight to the best θ-scenario.

Proposition 3.C.1. *Let the firm exhibit MEU preferences. The ambiguity averse firm overabates at date 1 relative to SEU preferences if, and only if, the sequences $(\mathcal{V}(\bar{a}_1;\theta))_\theta$ and $(\mathcal{V}_{a_1}(\bar{a}_1;\theta))_\theta$ are anticomonotone, where $\bar{a}_1$ denotes the SEU-optimal date 1-abatement.*

Proof. For the purpose of the proof, let Θ be a discrete finite set of cardinality $k = |\Theta|$ and ordered such that $\theta_1 \leq \cdots \leq \theta_k$. Let $(q_i)_{i=1,\dots,k}$ be the subjective prior where q_i denotes the firm's subjective probability that the θ_i-scenario will materialize and $\sum_i q_i = 1$. W.l.o.g. let the sequence $(\mathcal{V}(\bar{a}_1;\theta_i))_i$ be non-decreasing in i. We have

$$\bar{a}_1 \doteq \arg\max_{a_1\geq 0} \Big\langle \Upsilon_{\text{SEU}}(a_1) \doteq \pi_1(a_1) + \beta \sum_{i=1}^{k} q_i \mathcal{V}(a_1;\theta_i) \Big\rangle. \tag{3.C.1}$$

The α-maxmin objective function reads

$$\begin{aligned} \Upsilon_\alpha(a_1) &\doteq \pi_1(a_1) + \beta\Big(\alpha \min_{\theta\in\Theta} \mathcal{V}(a_1;\theta) + (1-\alpha)\max_{\theta\in\Theta} \mathcal{V}(a_1;\theta)\Big) \\ &= \pi_1(a_1) + \beta\left(\alpha\mathcal{V}(a_1;\theta_1) + (1-\alpha)\mathcal{V}(a_1;\theta_k)\right), \end{aligned} \tag{3.C.2}$$

and let $\hat{a}_1^\alpha$ be the unique maximizer of Υ_α. By concavity of Υ_α,

$$\hat{a}_1^\alpha \geq \bar{a}_1 \;\Leftrightarrow\; \alpha\mathcal{V}_{a_1}(\bar{a}_1;\theta_1) + (1-\alpha)\mathcal{V}_{a_1}(\bar{a}_1;\theta_k) \geq \sum_{i=1}^{k} q_i\mathcal{V}_{a_1}(\bar{a}_1;\theta_i). \tag{3.C.3}$$

By virtue of ambiguity aversion it holds $\Upsilon_\alpha \leq \Upsilon_{\text{SEU}}$. That is, for all $a_1 \geq 0$,

$$\alpha\mathcal{V}(a_1;\theta_1) + (1-\alpha)\mathcal{V}(a_1;\theta_k) \leq \sum_{i=1}^{k} q_i\mathcal{V}(a_1;\theta_i). \tag{3.C.4}$$

Rearranging Equation (3.C.4) gives

$$\begin{aligned}(\alpha - q_1)\mathcal{V}(a_1;\theta_1) &\leq \sum_{i=2}^{k-1} q_i\mathcal{V}(a_1;\theta_i) + (\alpha + q_k - 1)\mathcal{V}(a_1;\theta_k) \\ &\leq \Big(\alpha + \sum_{i=2}^{k} q_i - 1\Big)\mathcal{V}(a_1;\theta_k) = (\alpha - q_1)\mathcal{V}(a_1;\theta_k)\end{aligned} \tag{3.C.5}$$

since $(\mathcal{V}(a_1;\theta_i))_i$ is non-decreasing in i and $\sum_i q_i = 1$. Since $\mathcal{V}(\cdot;\theta_k) \geq \mathcal{V}(\cdot;\theta_1) > 0$, note that $\alpha \geq q_1$ is a sufficient condition for $\Upsilon_\alpha \leq \Upsilon_{\text{SEU}}$ to hold. Then,

$$\hat{a}_1^\alpha \geq \bar{a}_1 \;\Leftrightarrow\; (\alpha - q_1)\mathcal{V}_{a_1}(\bar{a}_1;\theta_1) \geq \sum_{i=2}^{k-1} q_i\mathcal{V}_{a_1}(\bar{a}_1;\theta_i) + (\alpha + q_k - 1)\mathcal{V}_{a_1}(\bar{a}_1;\theta_k). \tag{3.C.6}$$

Finally note that it is sufficient for Inequality (3.C.6) this to hold that $(\mathcal{V}_{a_1}(\bar{a}_1;\theta_i))_i$ be non-increasing in i since this would guarantee that

$$\begin{aligned}\sum_{i=2}^{k-1} q_i\mathcal{V}_{a_1}(\bar{a}_1;\theta_i) + (\alpha + q_k - 1)\mathcal{V}_{a_1}(\bar{a}_1;\theta_k) &\geq \Big(\alpha + \sum_{i=2}^{k} q_i - 1\Big)\mathcal{V}_{a_1}(\bar{a}_1;\theta_2) \\ &= (\alpha - q_1)\mathcal{V}_{a_1}(\bar{a}_1;\theta_2).\end{aligned} \tag{3.C.7}$$

This concludes the proof. □

W.l.o.g. fix $\alpha = 1$, i.e. MEU collapses to Wald's minimax criterion. An increase in the level of ambiguity correspond to an increase in the cardinality of Θ, say from $|\Theta|$ to $|\Theta'| \geq |\Theta|$. Note that this also corresponds to an increase in the degree of ambiguity aversion since

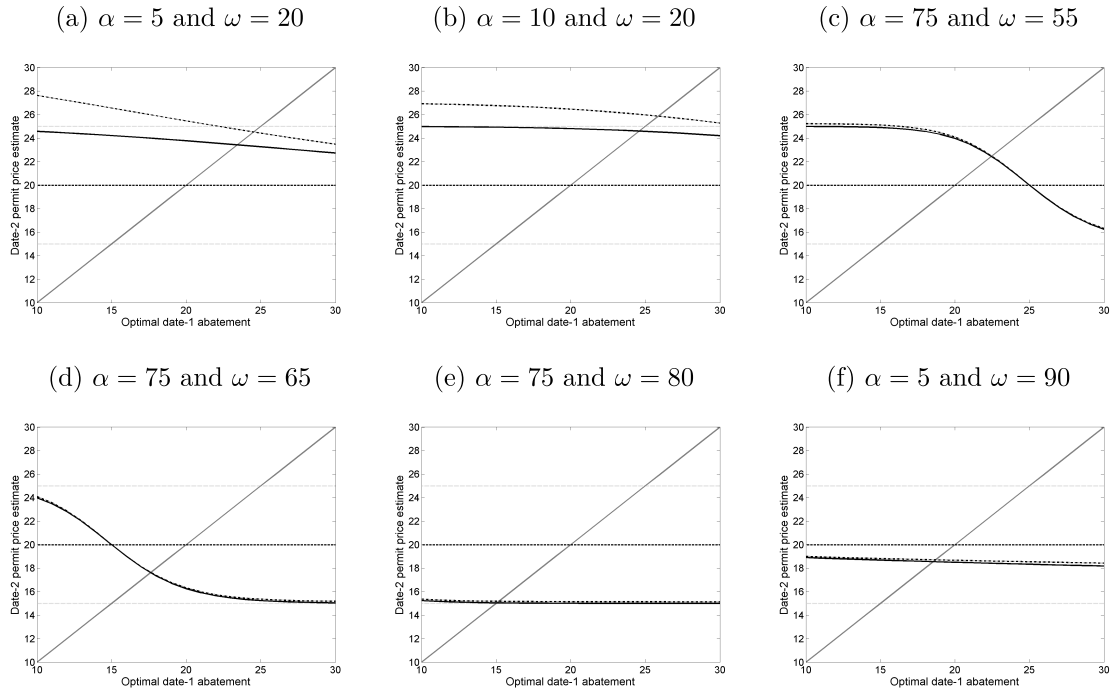
$$\min_{\theta\in\Theta'} \Big\langle \max_{a_1\geq 0} \mathcal{V}(a_1;\theta)\Big\rangle \leq \min_{\theta\in\Theta} \Big\langle \max_{a_1\geq 0} \mathcal{V}(a_1;\theta)\Big\rangle \;\Leftrightarrow\; |\Theta'| \geq |\Theta|. \tag{3.C.8}$$

That is, 'beliefs' and 'tastes' are not disentangled (this is attributable to the min operator). By linearity of the objective function, Proposition 3.C.1 also applies to the ϵ-contamination model of choice (Eichberger & Kelsey, 1999) which corresponds to a convex combination between a SEU criterion with a confidence degree or weight $\epsilon \in [0;1]$ and Wald's criterion with weight $1-\epsilon$. See also Gierlinger & Gollier (2017) for a treatment of multiplier preferences from robust control theory (Hansen & Sargent, 2001; Strzalecki, 2011).

3.D The two ambiguity aversion induced effects

With numerical simulations this appendix illustrates the decomposition of the two ambiguity aversion induced effects provided in Figure 3.2 when H and $\mathcal{A}$ are now allowed to vary with a_1. There are only two scenarios $\Theta = \{\theta_1 = +5, \theta_2 = -5\}$ with equal probability

Figure 3.D.1: Separation of pessimism and ambiguity prudence



Note: The upward-sloping grey solid line is C_1'. The two flat grey dotted lines are $\mathcal{V}_{a_1}(a_1;\theta_i)$. The flat dark dashed line is $\mathbb{E}_F\{\mathcal{V}_{a_1}(a_1;\tilde{\theta})\}$. The curved black solid line is $\mathbb{E}_H\{\mathcal{V}_{a_1}(a_1;\tilde{\theta})\}$. The curved black dotted line is $\mathcal{A}(a_1)\mathbb{E}_H\{\mathcal{V}_{a_1}(a_1;\tilde{\theta})\}$. The intersection between C_1' and $\mathcal{A}(a_1)\mathbb{E}_H\{\mathcal{V}_{a_1}(a_1;\tilde{\theta})\}$ gives $\hat{a}_1$.

under the subjective prior $F = (q_1, \theta_1; q_2, \theta_2)$, i.e. $q_1 = q_2 = .5$. We assume $\partial_{a_1} C_2 \equiv 0$ so that for all $\theta \in \Theta$ and $a_1 \geq 0$, $\mathcal{V}_{a_1}(a_1;\theta) = \langle\tilde{\tau}\rangle + \theta$ where the F-expected price is $\langle\tilde{\tau}\rangle = 20$. This means that $\mathcal{V}_{a_1}$-lines will be flat while they were upward-sloping in Figure 3.2. The pessimistically-distorted prior $H = (\hat{q}_1, \theta_1; \hat{q}_2, \theta_2)$ and shift in levels $\mathcal{A}$ satisfy, for all $a_1 \geq 0$

$$\hat{q}_i(a_1) = \frac{q_i \phi'\left(\mathcal{V}(a_1;\theta_i)\right)}{q_1 \phi'\left(\mathcal{V}(a_1;\theta_1)\right) + q_2 \phi'\left(\mathcal{V}(a_1;\theta_2)\right)} \text{ for } i = \{1,2\}, \tag{3.D.1a}$$

$$\text{and } \mathcal{A}(a_1) = \frac{q_1 \phi'\left(\mathcal{V}(a_1;\theta_1)\right) + q_2 \phi'\left(\mathcal{V}(a_1;\theta_2)\right)}{\phi' \circ \phi^{-1}\left(q_1 \phi\left(\mathcal{V}(a_1;\theta_1)\right) + q_2 \phi\left(\mathcal{V}(a_1;\theta_2)\right)\right)}. \tag{3.D.1b}$$

The necessary-first order condition for $\hat{a}_1$ in Equation (3.4.8) rewrites

$$-C_1'(\hat{a}_1) + \beta\mathcal{A}(\hat{a}_1)\Big(\langle\tilde{\tau}\rangle + \hat{q}_1(\hat{a}_1)\theta_1 + \hat{q}_2(\hat{a}_1)\theta_2\Big) = 0, \tag{3.D.2}$$

and is graphically depicted in Figure 3.D.1 for different combinations of α and ω. In this numerical example Figure 3.D.1 illustrates that the bulk of the variation in date-1 abatement level under ambiguity aversion relative to ambiguity neutrality is driven by pessimism. However note that the relative effects of ambiguity prudence can be relatively significant especially when α is low (Figs. 3.D.1a and 3.D.1b). Figures 3.D.1c and 3.D.1d highlight the high sensibility of $\hat{a}_1$ around the threshold $\bar{\omega} = 60$ for relatively high α. Figures 3.D.1e and 3.D.1f indicate that the pessimistic prior distortion is more pronounced when α is high. Finally, Figures 3.D.1b and 3.D.1e underline that when ω is outside of the $[40-80]$ band and α is relatively high pessimism redistributes almost all the weight to the worst scenario, i.e. θ_1 (resp. θ_2) when ω is small (resp. high).

3.E Joint market price and firm's demand ambiguities

As in Section 3.5 consider that $\mathrm{T}_\theta = [\underline{\tau}+\theta; \bar{\tau}+\theta]$ and $\mathrm{B}_\theta = [\underline{b}+\theta; \bar{b}+\theta]$, i.e. high-price scenarios coincide with high-demand scenarios. In this case it holds that $\partial_\theta\mathcal{V}_{a_1}(\bar{a}_1;\theta) = \langle\tilde{\tau}\rangle + \theta$ and

$$\partial_\theta\mathcal{V}(\bar{a}_1;\theta) \leq 0 \Leftrightarrow \omega \leq \langle\tilde{b}\rangle - \bar{a}_1 + \theta. \tag{3.E.1}$$

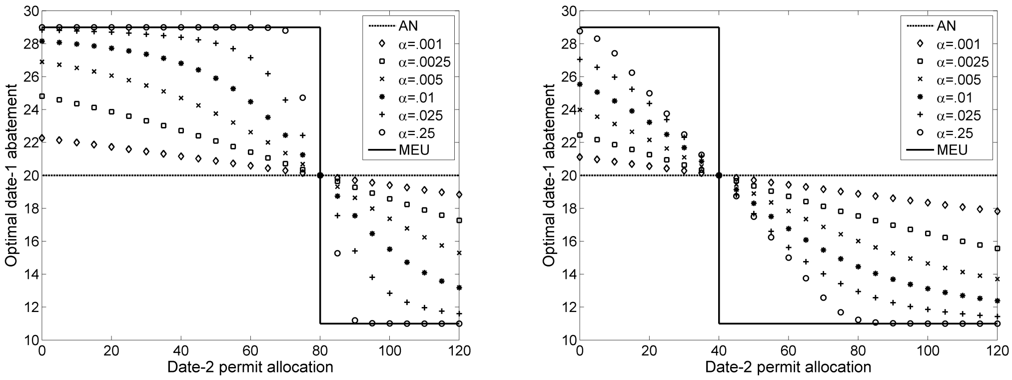
Anticomonotonicity (resp. comonotonicity) thus holds for sure if $\omega \leq 71$ (resp. $\omega \geq 89$). In expectations over Θ, anticomonotonicity (resp. comonotonicity) holds i.f.f. $\omega \leq$ (resp. $\geq$) 80. The situation is depicted in Figure 3.E.1a. Now consider that $\mathrm{T}_\theta = [\underline{\tau}+\theta; \bar{\tau}+\theta]$ and $\mathrm{B}_\theta = [\underline{b}-\theta; \bar{b}-\theta]$, i.e. high-price scenarios coincide with low-demand scenarios. In this case it holds that $\partial_\theta\mathcal{V}_{a_1}(\bar{a}_1;\theta) = \langle\tilde{\tau}\rangle + \theta$ and

$$\partial_\theta\mathcal{V}(\bar{a}_1;\theta) \leq 0 \Leftrightarrow \omega \leq \langle\tilde{b}\rangle - 2\langle\tilde{\tau}\rangle - \bar{a}_1 - 3\theta. \tag{3.E.2}$$

Anticomonotonicity (resp. comonotonicity) thus holds for sure if $\omega \leq 13$ (resp. $\omega \geq 67$). In expectations over Θ, anticomonotonicity (resp. comonotonicity) holds i.f.f. $\omega \leq$ (resp. $\geq$) 40. The situation is depicted in Figure 3.E.1b. Comparing Figures 3.E.1a and 3.E.1b, we see that date-1 overabatement occurs for a wider allocation range as the allocation threshold is higher (resp. lower) when $\mathrm{Cov}_\theta\{G, L\} >$ (resp. $<$) 0 as compared to pure price ambiguity (Figure 3.1a). Note also that the variability of the adjustment in date-1 abatement increases (resp. decreases) around the threshold when $\mathrm{Cov}_\theta\{G, L\} >$ (resp. $<$) 0.

Figure 3.E.1: Cap-and-trade regime under CAAA with joint price and demand ambiguities

(a) $\hat{a}_1^\alpha = f(\omega)$ with $\text{Cov}_\theta\{G, L\} > 0$ (b) $\hat{a}_1^\alpha = f(\omega)$ with $\text{Cov}_\theta\{G, L\} < 0$



3.F Special case: Binary price ambiguity

This appendix considers the case of binary price ambiguity, i.e. in all θ-scenarios $\tilde{\tau}_\theta$ either takes the value $\underline{\tau} > 0$ with probability $p(\theta) \in [0; 1]$ or $\bar{\tau}$ with complementary probability and $\Delta\tau = \bar{\tau} - \underline{\tau} > 0$. Let the underlying objective price lottery be $(p, \underline{\tau}; 1 - p, \bar{\tau})$. The no-ambiguity bias requires that $p = \mathbb{E}_F\{p(\tilde{\theta})\}$ and thus $\langle\tilde{\tau}\rangle = p\underline{\tau} + (1-p)\bar{\tau}$. W.l.o.g. assume for clarity that abatement cost functions are time separable. Let $\Upsilon(\cdot; \theta)$ denote the θ-scenario expected net intertemporal revenue from date-1 abatement. For all $a_1 \geq 0$ and $\theta \in \Theta$,

$$\begin{aligned}\Upsilon(a_1; \theta) &\doteq \pi_1(a_1) + \beta\mathcal{V}(a_1; \theta)\\ &= \zeta - C_1(a_1) - \beta p(\theta)(C_2(a_2^*(\underline{\tau})) + \underline{\tau}(b - a_1 - a_2^*(\underline{\tau}) - \omega))\\ &\quad - \beta(1 - p(\theta))(C_2(a_2^*(\bar{\tau})) + \bar{\tau}(b - a_1 - a_2^*(\bar{\tau}) - \omega)),\end{aligned} \tag{3.F.1}$$

where $\zeta = \zeta_1 + \beta\zeta_2$. With quadratic cost specification (3.3.1) Equation (3.F.1) rewrites

$$\Upsilon(a_1; \theta) = \zeta - C_1(a_1) + \beta\Big(p(\theta)\Delta\tau(b - a_1 - \omega - \langle\tau\rangle/c_2) - \bar{\tau}\Big(b - a_1 - \omega - \bar{\tau}/(2c_2)\Big)\Big), \tag{3.F.2}$$

where $\langle\tau\rangle \doteq (\bar{\tau} + \underline{\tau})/2$ denotes the date-2 average price when $p = .5$. Differentiating Equation (3.F.2) and evaluating it at $a_1 = \bar{a}_1 = \beta\langle\tilde{\tau}\rangle/c_1$ gives

$$\Upsilon_{a_1}(\bar{a}_1; \theta) = -C_1'(\bar{a}_1) + \beta\mathcal{V}_{a_1}(\bar{a}_1; \theta) = -C_1'(\bar{a}_1) + \beta(\bar{\tau} - p(\theta)\Delta\tau), \tag{3.F.3}$$

which is decreasing in θ i.f.f. $p(\theta)$ is increasing in θ. By optimality under ambiguity neutrality $\Upsilon_{a_1}(\bar{a}_1; \theta) = 0$ when $p(\theta) = p$. It follows that $\Upsilon_{a_1}(\bar{a}_1; \theta)$ changes sign from positive to negative at $p(\theta) = p$. Intuitively we see from Equation (3.F.2) that when the firm expects to be net short under the abatement stream $(\bar{a}_1; \langle\tau\rangle/c_2)$, $\Upsilon(\bar{a}_1;\theta)$ is relatively high (resp. low) when $p(\theta)$ is relatively large (resp. small). Therefore, for those θ-scenarios such that $p(\theta) < p$ where $\Upsilon(\bar{a}_1;\theta)$ is relatively low and $\Upsilon_{a_1}(\bar{a}_1;\theta) > 0$, an increase in a_1 will increase $\Upsilon(a_1;\theta)$. Conversely, for those θ-scenarios such that $p(\theta) > p$ where $\Upsilon(\bar{a}_1;\theta)$ is relatively high and $\Upsilon_{a_1}(\bar{a}_1;\theta) < 0$, an increase in a_1 will decrease $\Upsilon(a_1;\theta)$. In these two cases the spread in expected profits across θ-scenarios is reduced. Formally,

Proposition 3.F.1. *Let ϕ exhibit CAAA and assume abatement cost functions are quadratic and time separable. Under binary price ambiguity, the prevalence of ambiguity aversion raises date-1 abatement relative to ambiguity neutrality if, and only if,*
(i) the objective probability associated with the low-price scenario p is above the threshold $\bar{p} = (\beta c_2 \bar{\tau} + c_1 \langle\tau\rangle - c_1 c_2 (b-\omega))/(\beta c_2 \Delta\tau) \in [0;1]$; or equivalently,
(ii) the firm expects to be net buyer of permits under the abatement stream $(\bar{a}_1;\bar{a}_2)$ where $\bar{a}_1 = \beta\langle\tilde{\tau}\rangle/c_1$ and $\bar{a}_2 = \langle\tau\rangle/c_2$; or equivalently,
(iii) the firm's allocation ω is below the threshold $\bar{\omega} = b - \bar{a}_1 - \bar{a}_2$.

Proof. By differentiation w.r.t. θ we have, for all $a_1 \geq 0$ and $\theta \in \Theta$,

$$\partial_\theta \mathcal{V}(\bar{a}_1;\theta) = p'(\theta)\Delta\tau(b - \omega - \beta\langle\tilde{\tau}\rangle/c_1 - \langle\tau\rangle/c_2), \tag{3.F.4a}$$

$$\text{and } \partial_\theta \mathcal{V}_{a_1}(\bar{a}_1;\theta) = -p'(\theta)\Delta\tau. \tag{3.F.4b}$$

Therefore, anticomonotonicity holds i.f.f. $b - \omega - \beta\langle\tilde{\tau}\rangle/c_1 - \langle\tau\rangle/c_2 > 0$, i.e. the firm is net short of permits when it abates $(\bar{a}_1;\bar{a}_2)$. Note that by definition, $\langle\tilde{\tau}\rangle = \bar{\tau} - p\Delta\tau$, which is decreasing with p. Anticomonotonicity thus holds i.f.f.

$$2\beta c_2 (\bar{\tau} - p\Delta\tau) + c_1 (\bar{\tau} + \underline{\tau}) < 2 c_1 c_2 (b - \omega), \tag{3.F.5}$$

that is, i.f.f. $p > \bar{p}$. For $\bar{p}$ to be admissible we need that $\beta\underline{\tau} \leq c(b-\omega) \leq \beta\bar{\tau}$. To see why it makes sense to have such a price range, note that when the permit price is $c(b-\omega)$ the firm's gross abatement effort $b - \omega$ is optimally apportioned between the two dates. □

Initial allocation continues to dictate the direction of the date-1 abatement adjustment. This contrasts with results in Snow (2011), Alary et al. (2013), Wong (2015a) and Berger (2016) where the effect of pessimism is clear under a binary ambiguity structure. However the condition for anticomonotonicity to hold is milder than in Proposition 3.4.8. The ambiguity averse firm must expect to be net short under the sole the abatement stream $(\bar{a}_1;\bar{a}_2)$ – not across all θ-scenarios – for it to overabate. Note that this is akin to a situation where the ambiguity averse firm has no idea about the future price at all and thus considers the equiprobable price scenario. By contrast the ambiguity neutral firm is not affected by (the introduction of) ambiguity.

A novel insight from Proposition 3.F.1 is Condition (i). An explicit $\bar{p}$-threshold allows us to characterize the effects of an increase in the ambiguity level, here proxied by the price range $\Delta\tau$, for given degree of ambiguity aversion. To do so we determine the infinitesimal shift δp in $\bar{p}$ consecutive to an infinitesimal increase $\delta\tau > 0$ in $\Delta\tau$. For an upward shift in $\Delta\tau$, i.e. $\bar{\tau}$ increases by $\delta\tau$ with $\underline{\tau}$ fixed, $\bar{p}$ reacts such that

$$2\beta c_2 \left(\delta\tau - \bar{p}\delta\tau - \bar{\tau}\delta p - \delta p\delta\tau + \underline{\tau}\delta p\right) + c_1\delta\tau = 0, \text{ i.e. } R^{\uparrow} = \frac{\delta p}{\delta\tau} = \frac{2\beta c_2(1-\bar{p}) + c_1}{2\beta c_2\Delta\tau} > 0, \tag{3.F.6}$$

where $\delta p\delta\tau \simeq 0$ in the first order and $R^{\uparrow}$ denotes the rate of increase in $\bar{p}$ consecutive to an increase in $\bar{\tau}$ by $\delta\tau$. For a downward shift in $\Delta\tau$, i.e. $\underline{\tau}$ decreases by $\delta\tau$ with $\bar{\tau}$ fixed,

$$2\beta c_2 \left(\bar{p}\delta\tau + \bar{\tau}\delta p + \delta p\delta\tau - \underline{\tau}\delta p\right) + c_1\delta\tau = 0, \text{ i.e. } R^{\downarrow} = -\frac{\delta p}{\delta\tau} = \frac{2\beta c_2\bar{p} + c_1}{2\beta c_2\Delta\tau} > 0, \tag{3.F.7}$$

where $\delta p\delta\tau \simeq 0$ again and $R^{\downarrow}$ denotes the rate of decrease in $\bar{p}$ consecutive to a decrease in $\underline{\tau}$ by $\delta\tau$, in absolute terms. Therefore, it follows that

$$R^{\uparrow} - R^{\downarrow} = (1-2\bar{p})/\Delta\tau > 0 \Leftrightarrow \bar{p} < 1/2. \tag{3.F.8}$$

Consider a symmetric price range increase from $\Delta\tau$ to $\Delta\tau + 2\delta\tau$ which preserves $\langle\tau\rangle$ as well as the ambiguity neutral firm's price estimate $\langle\tilde{\tau}\rangle$. The ambiguity averse firm's price estimate, however, shifts from $\langle\tilde{\tau}\rangle_{\Delta\tau}$ to $\langle\tilde{\tau}\rangle_{\Delta\tau+2\delta\tau}$ where

$$\langle\tilde{\tau}\rangle_{\Delta\tau+2\delta\tau} = \langle\tilde{\tau}\rangle_{\Delta\tau} + \delta\tau(1-2p) \geq \langle\tilde{\tau}\rangle_{\Delta\tau} \Leftrightarrow p \leq 1/2 \Leftrightarrow \langle\tilde{\tau}\rangle_{\Delta\tau} \leq \langle\tau\rangle. \tag{3.F.9}$$

An increase in the range of price ambiguity hence always brings the ambiguity averse firm's price estimate (resp. $\bar{p}$) closer to $\langle\tau\rangle$ (resp. 1/2). This can be likened to a precautionary principle. More precisely under CAAA,
1. When $\bar{p} > 1/2$, the ambiguity averse firm overabates at date 1 i.f.f. $p \geq \bar{p} > 1/2$, i.e. i.f.f. $\langle\tilde{\tau}\rangle \leq \langle\tau\rangle$. That is, ambiguity aversion raises date-1 abatement when the ambiguity neutral firm foresees a price below $\langle\tau\rangle$ and does not abate enough relative to the $\langle\tau\rangle$-price scenario. Both $\bar{p}$ and $\langle\tilde{\tau}\rangle$ decrease consecutive to a symmetric increase in $\Delta\tau$, which makes the anticomonotonicity criterion relatively laxer.
2. When $\bar{p} < 1/2$, note that the ambiguity averse firm overabates i.f.f. $p \in [\bar{p}; 1/2]$, i.e. even though $\langle\tilde{\tau}\rangle > \langle\tau\rangle$ and the ambiguity neutral firm already abates more at date 1 than under

the $\langle\tau\rangle$-price scenario. Both $\bar{p}$ and $\langle\tilde{\tau}\rangle$ increase consecutive to a symmetric increase in $\Delta\tau$, which makes the anticomonotonicity criterion relatively more restrictive.

In other words, when the condition for pessimism to raise date-1 abatement relative to ambiguity neutrality is relatively demanding (resp. lax), an increase in the ambiguity range makes it laxer (resp. more demanding), which is in line with a precautionary principle.

* * *

General Conclusion

This dissertation has focused on Emissions Trading Systems as a climate policy instrument through the lens of inter-system linkages and intertemporal emissions trading. First, it makes two contributions to the debate on system integration in the Paris Agreement era. Chapter 1 begins by comparing alternative permit trading restrictions as transitional and facilitative mechanisms toward unrestricted bilateral linkages. Chapter 2 adopts a different approach by advancing the theory on multilateral linkages under uncertainty and providing a quantitative illustration based on a real-world example. Second, Chapter 3 proposes to introduce ambiguity and ambiguity aversion on the part of ETS-covered firms to account for the prevalence of the considerable uncertainty (especially of a regulatory nature) that they face and discusses how the induced intertemporal market distortions can help explain observations from existing systems. Two related comments follow.

On the one hand, one may argue that linking has potential to reduce regulatory uncertainty as it provides for political strengthening of separate programs. Indeed, the more integrated an ETS becomes, the more resilient it should become to future weakening, if not dismantling, e.g. by a lock-in of program reforms. On the other hand, one may also argue that regulatory uncertainty and associated difficulties in envisaging future developments abroad, especially of a political nature related to long-term policy commitment, is precisely what constitutes a strong impediment to linking in the first place. The instances of delinking from RGGI by New Jersey and the cessation of linking procedures between Europe and Australia, both in the wake of changes in political leaderships, are illustrative of the latter view.

Additionally, in a bid to manage price levels under conditions of uncertainty, a diversity of approaches to incorporating responsiveness and flexibility into domestic programs has emerged. Therefore, ETSs are never pure quantity instruments, which, in turn, complicates linking prospects as this raises 'linkability' issues, i.e. in terms of market compatibility. Such price stabilization mechanisms indeed span the entire rule-discretion spectrum, from a formal indexed regulation (Quirion, 2005; Newell & Pizer, 2008), to hard and soft price corridors (Pizer, 2002; Burtraw et al., 2010; Fell et al., 2012a) or indirect price controls via quantity collars in Europe, as well as independent carbon central banks (Whitesell, 2011;

Clò et al., 2013; de Perthuis & Trotignon, 2014; Grosjean et al., 2016). Reviewing the literature, Doda (2016) finds that «no single mechanism emerges as a dominant option for capturing the welfare gains associated with responsive carbon pricing instruments», which, he further notes, is not surprising as this ultimately depends on the properties of business cycle fluctuations in GDP and emissions, as well as on the institutional background and political economy realities. In this respect, although without delving too deeply into related 'linkability' issues, we would like to underline that the EU quantity-based Market Stability Reserve, due to its uniqueness, may pose serious challenges to future linking.

In a context marked by divergent price containment schemes and governance frameworks, apart from a few instances of linkages between jurisdictions having concordant interests, one is inclined to think that the observable multiplicity of announcements of cooperation and often attendant desire to work toward linking carbon markets fundamentally resides within the realm of political rhetoric. A glaring and now almost ironic example of this is the 2010 declared objective of the European Commission to develop an OECD-wide carbon market by 2015 (and with other developing economies by 2020) after the watershed 15th Conference of the Parties in Copenhagen (European Commission, 2010).

Furthermore, we would like to emphasize that a link necessitates continuous alignment and sustained cooperation, which has led some authors to draw a parallel between linkage and marriage. A recent example is the enactment of Assembly Bill 398 in California which extends the state's cap-and-trade program until 2030 and specifies design amendments. Among others, the Allowance Price Containment Reserve should remain operative, albeit with lower price thresholds, and will be complemented by a hard price ceiling mechanism. Although the introduction of this new price control instrument originated from California alone, its design will be elaborated by the Air Resource Board in conjunction with linked or soon-to-be-linked WCI partners (Québec and Ontario).

Although emissions trading as a climate policy instrument has been gaining momentum and attraction, the global landscape will continue to be characterized by a patchwork of different approaches tailored to local circumstances, at least in the short to medium term. For sure, linking will remain an important element on the international climate policy design and negotiations agenda. A significantly linked global carbon market, however, is most probably a long way off and ought perhaps to remain a 'distant dream'.

* * *

Résumé Long

Les systèmes d'échange de quotas d'émission (ETSs en anglais pour Emissions Trading Systems) sont un instrument de régulation environnementale important et ont un rôle clef à jouer dans la réduction des émissions de gaz à effet de serre pour l'atténuation du changement climatique. Selon l'International Carbon Action Partnership (ICAP, 2017), d'ici fin 2017, plus de sept milliards de tonnes de dioxide de carbonne équivalent seront régulées sous dix-neuf ETSs opérants à l'échelle mondiale. Ces systèmes fonctionnent à différents niveaux supranational, régional, national et infranational (désormais juridictions). Par exemple, avec des plafonds d'émission annuels d'environ deux milliards de tonnes, le système communautaire d'échange de quotas d'émission européen (EUETS) est de loin le plus grand système en opération depuis sa création en 2005. En termes de volume, la Chine reprendra la pole position à l'union européenne lorsque son ETS national entrera en vigueur plus tard cette année, avec des plafonds annuels d'environ deux fois plus importants.

On s'attend à ce que le nombre d'ETSs opérationnels augmente ces prochaines années avec les transpositions en pratique des contributions déterminées au niveau national (NDCs en anglais) en vertu de l'Accord de Paris. Dans ce contexte, les interactions et liaisons (*linkages* en anglais) entre politiques climatiques juridictionnelles sont considérées comme un élément central de la future architecture de politique climatique mondiale post-Paris (Bodansky et al., 2016), comme en attestent la terminologie contenue dans l'Article 6.2 de l'Accord de Paris évoquant «des démarches concertées passant par l'utilisation de résultats d'atténuation transférés au niveau international aux fins des contributions déterminées au niveau national».[1] Il est en effet d'importance, dans un monde de contraintes bugétaires et de disposition à payer limitée, que l'atténuation du changement climatique soit abordée de manière coût-efficiente; et les *linkages* ont précisemment ce potentiel.

[1]De façon générale, de telles liaisons correspondent à des interconnections entre systèmes de politique climatique juridictionnelles qui permettent de redistribuer les efforts d'atténuation entre ces systèmes de manière à réduire les coûts globaux de réalisation de l'objectif aggrégé. Tout au long de cette dissertation, les liaisons sont considérées dans leur cadre typique, c'est-à-dire entre ETSs, mais des liaisons entre les systèmes hétérogènes/hybrides peuvent également être réalisables (Metcalf & Weisbach, 2012).

Cependant, les liaisons entre ETSs sont difficiles à établir et à ce jour, peu nombreuses. Selon Fankhauser & Hepburn (2010b) «il existe des facteurs qui peuvent aviser contre la libéralisation complète des marchés à travers l'espace». Nous identifions trois facteurs principaux. En premier lieu et d'importance cruciale, les différents niveaux d'ambition qui se manifestent dans des écarts de prix jugés inacceptables et qui connotent différents choix politiques qui semblent difficilement réconciliables. Deuxièmement, les différents designs de marché comme nous l'observons actuellement dans les ETS existants entravent les possibilités de liaisons qui requièrent un degré suffisamment élevé d'harmonisation pour assurer la compatibilité des marchés et éviter de pertuber le système lié. Troisièmement, une liaison crée une exposition aux chocs qui se produisent à l'étranger, qu'ils soient d'origine politique ou de simples fluctuations naturelles, et peut donc conduire à des conséquences imprévues et potentiellement indésirables.

En nous basant sur ce qui précède, les deux premiers chapitres de cette dissertation abordent la question des liaisons spatiales entre ETSs sous deux angles différents. Dans le chapitre 1, nous utilisons un modèle simple et unifié et nous nous appuyons sur les expériences réelles d'ETSs pour comparer différentes restrictions à l'échange comme élément facilitants une transition vers le libre échange de quotas. Dans une optique de transition, de telles liaisons restreintes peuvent permettre de tester les effets du lien tout en contenant sa portée et de fournir plus de temps et de flexibilité pour contourner les obstacles relatifs à l'établissment d'une liaison complète (par exemple, différents niveaux d'ambition ou designs de marchés). Dans le chapitre 2, nous construsions un modèle qui décrit et caractérise analytiquement les effets et gains associés à des liaisons multilatérales sous incertitude. En particulier, nous isolons les gains qui sont indépendants des niveaux d'ambition des juridictions et qui sont seulement attribuables à l'absorption des chocs juridictionnels par le système lié, par rapport aux situations d'autarcie. Le modèle est ensuite calibré sur émissions historiques de différentes juridictions pour illustrer les déterminants des préférences de liaison.

De plus, les ETSs sont sujets à une incertitude importante. En effet, les ETSs ne sont pas des systèmes clôts et sont influencés par des facteurs externes et des politiques agissant en dehors de leur périmètre. Par exemple, il est prouvé que les conditions macroéconomiques, la portée de politiques environnementales complémentaires et l'utilisation des crédits de compensation peuvent éroder le niveau de contrainte exercé par le cap (Chèze et al., 2016). Comme ces facteurs sont par nature incertains, cela se traduit par une incertitude importante portant sur la demande de permis, que Borenstein et al. (2016) estiment être «au moins aussi importante que l'incertitude quant à l'effet des mesures d'abattement». En particulier, les chocs négatifs sur la demande de permis ont été courants dans la plupart des marchés de permis et, par conséquent, les prix des permis ont été inférieurs à ceux initialement prévus.

Dans les conditions idéales de fonctionnement d'un marché de permis, les bas niveaux de prix ne devraient pas avoir de conséquence pour l'efficacité coût intertemporelle : un choc de demande positif (resp. négatif) déplacerait le chemin de prix optimal vers le haut (resp. vers le bas), mais sa pente serait préservée et le chemin resterait efficient. En d'autres termes, même si les coûts d'abattement étaient soumis à des chocs aléatoires, le plafond serait encore atteint au moindre coût actualisé (Schennach, 2000; Salant, 2016). Dans la pratique, cependant, il est difficile de déterminer si les prix bas sont attribuables à des chocs de demande externes ou à des imperfections de marché intrinsèques.[2] Quand de telles imperfections sont présentes, des prix bas peuvent avoir une incidence néfaste sur l'efficacité coût intertemporelle. Il est important de noter que l'interaction entre ces imperfections et les chocs exogènes nuirait à la formation des prix et au signal de prix à long terme transmis par le système.

Une analyse de la littérature indique que trois types d'imperfections sont au centre de l'attention, à savoir un horizon temporel limité, une actualisation excessive et l'incertitude règlementaire. Tout d'abord, si les agents ont des horizons de temps tronqués et que les permis sont relativement plus abondants aujourd'hui qu'ils ne le seront à l'avenir, les prix ne reflètent pas la rareté à long terme des permis et sont plus bas qu'ils ne devraient l'être (Ellerman et al., 2015). Deuxièmement, il se peut que les agents appliquent des taux d'actualisation plus élevés que le taux d'intérêt à leurs stratégies de banking parce qu'ils font face à des contraintes institutionnelles ou corporatives sur leur banking (Neuhoff et al., 2012; Schopp et al., 2015) ou à cause de l'aversion au risque (Kollenberg & Taschini, 2016).[3] Cela favoriserait une baisse des niveaux de banking et des prix de permis actuels, par rapport au chemin optimal.

Troisièmement, les risques règlementaires associés aux éventuels ajustements du plafond, qu'ils soient à la hausse ou à la baisse, pèsent sur la formation des prix même lorsque les agents sont rationnels (Salant, 2016).[4] En outre, il est à noter que les bas niveaux de

[2]Dans le contexte de l'EUETS, Koch et al. (2014) estiment que les fondamentaux du marché n'ont été responsable que de 10% de la variation du prix du permis. Hintermann et al. (2016) examinent également la littérature empirique sur les déterminants des prix et concluent qu'«il existe une interaction complexe entre les émissions BAU, les quantités d'abattement et les prix des permis», c'est-à-dire que notre compréhension de ces déterminants est limitée.

[3]Bredin & Parsons (2016) ont trouvé que l'EUETS est en contango depuis 2008, c'est-à-dire que les prix à terme ont été supérieurs aux prix de cost and carry avec des primes implicites significatives (un convenience yield négatif).

[4]Koch et al. (2016) fournissent un appui empirique puisqu'ils établissent que l'EUETS est très sensibles aux événements politiques et aux effets d'annonce. C'est-à-dire que non seulement le niveau de plafond

prix ont déclenché des interventions règlementaires qui peuvent s'ajouter au niveau perçu d'incertitude règlementaire.

Compte tenu de ce qui précède, le troisième et dernier chapitre de cette thèse traite de la question de l'échange intertemporel de permis au sein d'un ETS sujet à de l'incertitude règlementaire. Dans le chapitre 3, nous établissons tout d'abord que la prévalence de l'incertitude règlementaire peut être assimilée à une situation d'ambiguïté. Ensuite, nous analysons les décisions d'abattement intertemporelles d'une entreprise couverte par un ETS, supposée averse à l'ambiguïté, où l'ambiguïté porte sur le futur prix des permis et la demande de la firme. Nous caractérisons ensuite les distorsions induites dans le fonctionnement du marché et discutons de l'éclairage apportés par ces résultats en rapport aux observations faites dans les ETSs existants.

Chapter 1: Transitional Restricted Linkages

Les liaisons complètes entre systèmes d'échange de quotas d'émission (ETSs) sont peu nombreuses. Le lien le plus accompli relie la Californie au Québec depuis fin 2013 et l'Ontario devrait s'y ajouter prochainement. Trois membres de l'Association européenne de libre-échange (Islande, Liechtenstein et Norvège) ont du être intégrés dans l'EUETS lorsqu'ils ont rejoint l'Espace économique européen en 2007. En outre, l'Europe est sur le point de concrétiser un lien bilatéral avec la Suisse, le quatrième membre de l'AELE, qui a préféré une série d'accords bilatéraux avec l'UE pour participer au marché intérieur plutôt que rejoindre l'EEE. Même si ces partenaires avaient une vision de politique climatique similaire et un désir d'établir les liaisons en question, les négociations ont duré plusieurs années.[5]

De fait, la nature multi-facette d'une liaison et l'hétérogénéité croissante des designs de marché et des cadres de gouvernance associés posent de nombreux défis aux partenaires potentiels. Tout d'abord, la liaison nécessite un certain degré d'harmonisation des designs pour garantir la compatibilité entre marchés et éviter des perturbations au système relié (Jaffe et al., 2009). Cependant, les designs de marché reflètent des circonstances locales et ont souvent été essentiels à la mise en place d'un accord politique interne, ce qui peut en

annoncé aura de l'influence sur la formation des prix, mais aussi la spéculation sur l'engagement des autorités associé à cette annonce peut entraîner des variations de prix.

[5] Ranson & Stavins (2016) identifient la proximité géographique et économique comme des déterminants clefs de la création de liaisons entre ETSs.

compliquer l'alignement inter-système.[6] Deuxièmement, même lorsque les juridictions ont des niveaux d'ambition similaires et des marchés compatibles, il existe tout de même des risques que les résultats de la liaison ne se déroulent pas comme prévu, puisque par définition une liaison crée une exposition à différents développements ou chocs se produisants à l'étranger (Flachsland et al., 2009b). Par conséquent, la création d'accords de liaison qui concilient les intérêts de chaque partie risque de s'avérer difficile (Tuerk et al., 2009).

La manière la plus appropriée d'interconnecter des marchés peut donc ne pas satisfaire au libre échange, au moins à court terme. Deux grands types d'approches peuvent être envisagés pour pallier les difficultés reconnues dans l'établissement de liaisons. Tout d'abord, les connexions à un hub commun peuvent constituer une première étape vers une plus grande intégration de marché, comme par exemple des liaisons indirectes via un système de crédits de compensation ou du networking.[7] Par exemple, Jaffe et al. (2009), Tuerk et al. (2009) et Fankhauser & Hepburn (2010b) avaient conçu un mécanisme d'interconnexion progressif via des liaisons unilatérales au Mécanisme de Développement Propre (MDP), considéré comme un hub commun potentiel durant l'ère Kyoto. Cependant, un tel mécanisme de compensation internationale est actuellement manquant.[8]

Deuxièmement, des restrictions transitoires à l'échange de permis peuvent également être établies dans la perspective du libre échange.[9] Selon Mehling & Haites (2009), «un lien bilatéral peut être approché de façon progressive; des restrictions quantitatives à l'échange pourraient être appliquées initialement puis être relâchées avec le temps alors que les effets [associés à la liaison] deviennent clairs». À première vue, les restrictions peuvent fournir des leviers pour ajuster la portée du lien et tester ses effets. Elles pourraient également faciliter les négociations en décomposant un long processus de liaison en étapes progressives dans le

[6]Nous pouvons nous attendre à ce que cette problématique soit amplifiée lorsque des juridictions de grandes tailles comparables explorent des possibilités de liaison. En effet, elles pourraient ne pas être aussi enclins à céder du contrôle souverain en termes de design et objectifs associés comme les juridictions plus petites (donc avec un plus fort intérêt à se lier) peuvent l'être. Par exemple, compte tenu de sa taille et de son poids politique, l'UE a imposé sa vision politique et spn design de marché à ses partenaires de liaison qui n'ont eu d'autre choix que d'ajuster les leurs avec (presque) aucune marge de manoeuvre.

[7]Le networking ETS a récemment émergé comme un substitut aux liens multilatéraux directs (Keohane et al., 2015; Mehling & Görlach, 2016) et pourrait impliquer des restrictions à l'échange telles qu'analysées ici. Un exemple est la plateforme ICAR (Füssler et al., 2016) qui fournit une structure à laquelle des ETSs peuvent s'accrocher sur une base volontaire à partir du moment où un ensemble d'exigences prédéfinies est rempli. Les ETSs ainsi accrochés conservent un certain niveau de discrétion sous la forme d'imposition unilatérale de restrictions quantitatives sur les entrées et sorties de permis et autres restrictions qualitatives (par exemple, les taux d'escompte) qui fixent les valeurs de conformité attribuées aux permis étrangers.

[8]Un MDP restructuré a été créé en vertu de l'article 6.4 de l'Accord de Paris (et déjà baptisé Mécanisme de développement durable ou SDM) et pourrait remplacer le MDP en offrant des possibilités de liens indirects, mais il doit encore être développé lors de prochaines Conférence des Parties.

[9]Comme l'indiquent Jaffe et al. (2009), des restrictions peuvent également être utilisées «pour réduire le volume d'échange entre systèmes, ou s'il existe un tel désir, pour exiger que le commerce avec d'autres systèmes entraîne une réduction nette des émissions».

sens d'un «linking by degrees» (Burtraw et al., 2013).[10] Nous notons également que, en pratique, certains liaisons ont été amorcées par des restrictions, comme attestent des liaisons unilatérales transitoires intégrant la Norvège et le secteur de l'aviation européen à l'EUETS.

Ce chapitre compare trois types principaux de restrictions à l'échange, à savoir les restrictions quantitatives, les taxes aux frontière sur les importations/exportations de permis et les taux de change sur les valeurs de conformité des permis. Deux autres formes proches de restrictions, à savoir les liaisons unilatérales (ou conditionnelles) et les taux de rabais seront également discutés. Pour évaluer les effets de chaque type de restriction, nous développons un modèle d'équilibre partiel de liaison entre deux marchés de permis de même taille dans un cadre statique et déterministe. Les implications de chaque restriction sont mesurées par rapport à quatre indicateurs principaux, à savoir l'efficience coût, la localisation et le volume des abattements, la formation des prix et les aspects distributifs, par rapport à deux scénarios de référence, à savoir l'autarcie et le libre échange.

Nous supposons que tous les types de marchés considérés sont compétitifs, sauf dans le cas des restrictions quantitatives où la structure de marché que nous considérons est un monopole bilatéral. Nous ignorons les designs de marché pour isoler les effets spécifiques aux restrictions.[11] Nous choisissons de limiter l'analyse à un lien bilatéral pour faciliter l'exposition et notons que ce n'est pas tout à fait anodin.[12] Cependant, les connaissances acquises dans ce cadre simple peuvent aider à comprendre les effets des restrictions dans une liaison multilatérale. Enfin, pour des raisons de comparabilité, le modèle suppose que des plafonds d'émissions sont exogènes et maintenus dans toutes les situations considérées.[13]

Notre modèle stylisé est assez simple pour avoir des solutions analytiques et nous permet de comparer les restrictions de liaisons dans un cadre unifié, ce qui aide considérablement à la compréhension. Cela dit, il a suffisamment de structure pour mettre en évidence les principales différences entre les différentes restrictions. Bien sûr, nos résultats dépendent

[10] Symétriquement, les restrictions à l'échange peuvent fournir des marges de manoeuvre si les partenaires ne sont pas satisfaits de la liaison et souhaitent qu'elle soit rompue. Autrement dit, elles offrent des moyens supplémentaires de mettre fin à une liaison, dont l'organisation affecte l'efficience intertemporelle et la formation des prix dans le système (Pizer & Yates, 2015).

[11] Il est à noter que même sous libre échange, des mécanismes de stabilisation des prix (par exemple les couloirs de prix) peuvent empêcher la convergence totale des prix entre systèmes (EPRI, 2006; Jaffe et al., 2009; Grüll & Taschini, 2012).

[12] En effet, dans un cadre multilatéral, nous notons que les restrictions à l'échange peuvent être différenciées et que leurs effets interfèrent. Par exemple, les importateurs peuvent bénéficier de restrictions contraignantes sur les importations dans d'autres juridictions/secteurs, car cela réduit le prix du permis, mais pas leurs propres demandes.

[13] Nous n'abordons donc pas les effets d'anticipation stratégique de liaisons (et des différents types de liaisons restreintes) sur la sélection des plafonds domestiques à la Helm (2003), mais les discutons plus en détail dans la Section 1.2.

directement des hypothèses, mais nous pensons que les résultats que nous obtenons dans ce cas simple se transposent, au moins dans une certaine mesure, à une situation plus réaliste.

Les restrictions à l'échange distordent l'équilibre de libre échange en induisant un écart entre les coûts marginaux d'abattement des deux juridictions et l'efficience coût n'a pas lieu. Cela signifie que dans notre cadre, les restrictions ont toujours des effets néfastes, en aggrégé, par rapport au libre échange. Cependant, il est important de noter que nous adoptons une approche descriptive pour décrire les implications comparatives des diverses restrictions, et que nous n'avons pas de questions normatives à l'esprit. Cela dit, les restrictions peuvent améliorer la situation d'une jurisdiction en particulier (par rapport à la situation de libre échange à nouveau) et nous caractérisons les restrictions optimales d'un point de vue juridictionnel.

Une liaison restreinte crée donc un compromis entre l'élimination de certains obstacles au libre échange et la raison fondamentale qui appelle à connecter les ETSs (l'efficience coût). Cela justifie donc un usage transitoire des restrictions dans une optique de mise en place du libre échange au bout de quelques années. En outre, puisque les restrictions créent des rentes économiques, elles peuvent entraver le déploiement du libre échange si celui-ci n'est pas clairement spécifié dans l'accord de liaison.

D'une manière similaire aux périodes d'essai dans les premières années d'opération des ETSs, une utilisation temporaire des restrictions pourrait être envisagée pour tester les effets d'une liaison, atténuer certains des risques associés à une liaison complète, inciter les juridictions à coopérer, ainsi que donner plus de temps et de flexibilité pour que les parties réconcilient leurs différents et alignent leurs designs respectifs afin qu'une liaison complète puisse être établie de manière harmonieuse. Après la période d'essai, les juridictions peuvent décider de passer au libre échange, mais, si la période d'essai n'est pas concluante, la liaison devrait être interrompue.

En s'appuyant sur nos résultats et des expériences pratiques de liaison et d'utilisation de restrictions, nous discutons ensuite les mérites comparatifs de chaque restriction à l'échange. En particulier, nous basons notre raisonnement sur les trois questions suivantes. Tout d'abord, quel risque associé à la liaison complète chaque restriction peut-elle atténuer en permettant ainsi de faciliter la mise en place de la liaison ? Deuxièmement, quel est le potentiel de chaque restriction à informer l'extension au libre échange et comment se différencient-elles en termes de faisabilité politique ? Troisièmement, les restrictions et les rentes induites peuvent-elles être envisagées comme un potentiel mécanisme de coordination pour stimuler la coopération via une liaison entre ETSs ?

Il n'y a pas de liaison restreinte transitoire idéale. Chaque restriction a ses propres mérites et inconvénients. Bien que les restrictions quantitatives semblent être la voie naturelle vers le libre échange, leurs implications peuvent être trompeuses car les aspects distributifs sont incertains et les signaux de prix sont affaiblis. En comparaison, ces aspects sont atténués avec une taxe aux frontières, mais cette politique peut être plus difficile à mettre en place sur le plan législatif. Les taux de change peuvent accomoder des niveaux de contraintes différents et ont le potentiel d'augmenter le niveau d'ambition environnementale. Cependant, ils sont difficiles à sélectionner et peuvent être à la source de situations plus défavorables que l'autarcie. Comme l'expérience le suggère, des liaisons unilatérales et transitoires peuvent constituer une approche pragmatique et prometteuse.

Chapter 2: Multilateral Linkages under Uncertainty

La litérature examinant les déterminants des avantages relatifs aux liaisons entre systèmes d'échange de quotas d'émission (ETSs) a surtout porté sur les liens bilatéraux. En comparaison, une étude formelle des liaisons multilatérales pose de nombreux défis, tels que décrits par Mehling & Görlach (2016), qui proposent différentes options pour une gestion réussie de telles liaisons. Dans ce chapitre, nous développons un modèle qui nous permet de décrire et d'étudier les liens multilatéraux entre ETSs dans des conditions d'incertitude. En substance, il s'agit d'une généralisation des travaux de Doda & Taschini (2017), dont l'analyse se concentre sur les liens bilatéraux.

Nous analysons les avantages de liaisons entre ETSs sous incertitude en introduisant des chocs idiosyncrasiques dans chaque juridiction à la Weitzman (1974) et Yohe (1976, 1978). Pour isoler les avantages qui sont directement attribuables à la formation de la liaison, nous supposons que les efforts d'abattement domestiques des juridictions (i.e., les plafonds d'émissions) sont donnés de façon exogène et fixés une fois pour toutes. En conséquence, nous considérons qu'il n'y a pas d'interactions stratégiques entre les juridictions dans leur décision de sélection de plafond domestique et qu'il n'y pas d'effets liés à l'anticipation de la mise en place d'une liaison dans le future (Helm, 2003). Ceci est délibéré parce que notre objectif est de comprendre les déterminants des gains économiques liés aux liaisons multilatérales et de les caractériser de façon analytique.

Dans la pratique, les plafonds domestiques sont issus de processus de négociation complexes (*i*) impliquants une foule d'acteurs juridictionnels (Flachsland et al., 2009b); (*ii*) qui doivent tenir compte des contraintes de différentes sortes et qui sont spécifiques à chaque juridiction. En outre, les juridictions peuvent également mettre en oeuvre des politiques complémentaires aux ETSs, ce qui peut refléter différentes opinions sur le niveau approprié d'effort d'abattement interne et sur un signal prix sous-jacent jugé acceptable/souhaitable.

Par conséquent, la sélection des plafonds est fondamentalement de nature domestique et politique, ce qui dépasse la portée de ce travail.[14]

Avec des plafonds juridictionnels invariants, nous pouvons procéder par une approche combinatoire pour analyser tous les liens multilatéraux possibles. En particulier, une liaison est toujours avantageuse, c'est-à-dire que les juridictions s'en sortent toujours mieux économiquement parlant dans n'importe quelle coalition de liaison que dans une situation d'autarcie. Cependant, elles gagnent davantage à faire partie de certaines coalitions de liaison plutôt que d'autres. À cet égard, notre analyse nous permet de classer les coalitions alternatives à l'échelle d'une juridiction et de caractériser ainsi les préférences de liaison.

Nous montrons que les gains économiques espérés relatifs à la formation d'une coalition d'ETSs reliés peuvent être décomposés en deux éléments positifs. Le premier est proportionnel au carré de la différence des prix espérés d'autarcie et de liaison, ce qui se rapporte uniquement à l'hétérogénéité des niveaux d'ambition au sein des juridictions liées. Le second est proportionnel à la variance de la différence de prix d'autarcie et de liaison, ce qui se rapporte uniquement à l'interaction entre les chocs spécifiques aux juridictions. En particulier, cela montre que la présence d'incertitude renforce l'argument de Pareto en faveur de formation de liaisons par rapport à conditions de certitude.

Nous nous concentrerons exclusivement sur la composante des gains de liaison qui surviennent en raison de l'incertitude. À cette fin, nous établissons des plafonds juridictionnels pour que les prix d'autarcie espérés soient égaux entre les juridictions. Encore une fois, cela est délibéré parce que nous croyons que notre contribution principale de notre travail concerne la compréhension des effets de la liaison sous incertitude.[15] Notez que nous montrerons comment ce choix est sans conséquence pour nos résultats théoriques. De plus, nous illustrerons nos résultats analytiques avec un exemple quantitatif en calibrant notre modèle sur émissions historiques de différentes juridictions, i.e. en indetifiant les caractéristiques des chocs spécifiques à ces juridictions. Nous pensons pouvons dire quelque chose d'empiriquement fondé sur la nature des gains liés aux chocs, alors que, comme nous l'avons noté ci-dessus nous avons une compréhension limitée des processus de sélection des caps domestiques (et donc de la première composante des gains). En outre, cela signifie également que nous pouvons inclure dans notre échantillon des juridictions qui n'ont pas d'ETS

[14]À la suite de cette observation, il semble peu probable que les juridictions choisissent leurs plafonds domestiques avec un oeil porté sur une possible liaison se matérialisant dans un futur proche. Si, toutefois, les juridictions intègrent une liaison future, on peut penser que cela ira dans le sens de l'alignement des niveaux d'ambition dans les juridictions partenaires et rendra ainsi la liaison politiquement réalisable (plutôt que comme un moyen de gonfler stratégiquement leurs gains issus de la liaison).

[15]À toute fin utile, il est à noter que les déterminants de la première composante des gains de liaison sont analysés dans la Proposition 1.D.1.

en place (ou toute autre forme d'objectif d'abattement domestique).

Dans le contexte d'une liaison bilatérale, Doda & Taschini (2017) établissent que les liaisons avec des systèmes plus grands sont plus bénéfiques, ceteris paribus.[16] En outre, une juridiction préfère que la demande de permis dans le système partenaire soit variable et faiblement corrélée à la sienne. Notre approche formelle est utile car les résultats pour les liens bilatéraux mis en évidence par Doda & Taschini ne se transposent pas facilement à des liens multilatéraux. En revanche et à bien des égards, nous verrons que les liens bilatéraux constituent la pierre angulaire de notre analyse des liaisons multilatérales.

Pour développer l'intuition, considérons un cas particulier avec trois juridictions où la variance des chocs affectant chaque juridiction est identique et les chocs sont indépendants. Laissons deux juridictions avoir la même taille et la troisième être plus grande. Lors de l'évaluation des liens possibles, la plus grande juridiction a peu d'incitation à se lier exclusivement à une seule des deux juridictions plus petites et préfère faire partie du marché trilatéralement lié. À l'inverse, les juridictions plus petites préfèrent un lien bilatéral avec la plus grande juridiction. Intuitivement, toutes choses étants égales par ailleurs, le prix de liaison se rapprochera du prix d'autarcie de la plus grande juridiction. Par conséquent, la variance de la différence des prix d'autarcie et de liaison sera plus grande dans le lien trilatéral pour la plus grande juridiction, car son impact sur le prix de liaison est atténué par rapport à une liaison bilatérale. Cet argument s'inverse pour les deux juridictions les plus petites.[17]

Cependant, en général, l'identification des résultats de liaison multilatérale n'est pas claire lorsque l'on s'éloigne de cas particuliers. En outre, le nombre de coalitions de liaison et de structures de coalitions possibles augmente de façon exponentielle avec le nombre de juridictions.[18] Par exemple, avec quatre juridictions, il existe six liens bilatéraux possibles (avec deux juridictions en autarcie), trois groupes de deux liens bilatéraux, quatre liens trilatéraux (avec une juridiction en autarcie), un lien quadrilatéral et une situation d'autarcie complète où chaque système opère isolement. Donc, 15 structures de coalition au total. Avec 10 juridictions, il y a déjà 1 013 et 115 975 coalitions de liaison et structures de coalition possibles.

Malgré cette complexité apparente, notre modèle peut en principe gérer un nombre important de juridictions ainsi que des structures de coalition complexes, car nous montrons

[16]La terme 'grand' se réfère à la taille de la juridiction. Par la taille de la juridiction, il faut comprendre le volume des émissions réglementées dans la juridiction sous autarcie.

[17]Sections 2.4.3 et 2.5.1 fournissent d'autres cas particuliers de préférences de liaison relatives entre liaisons bilatérales et trilatérales.

[18]De façon formelle, une structure de coalitions est une partition de l'ensemble des juridictions.

que tout lien multilatéral peut être décomposé en ses liens bilatéraux internes. Ce résultat de décomposition nous permet de caractériser les gains aggrégés et juridictionnels de toute coalition de liaison comme une fonction (pondérée par la taille des jurisdictions) des gains aggrégés de tous les liens bilatéraux qui peuvent être formés au sein de cette coalition. En outre, nous montrons que le mécanisme de liaison est superadditif, c'est-à-dire que les gains aggrégés espérés d'une union des coalitions disjointes d'ETSs liés ne peuvent être inférieurs à la somme des gains espérés associés à chacune des coalitions séparées. En particulier, nous établissons une formule analytique pour ce gain économique en fonction des tailles de coalitions et des caractéristiques de chocs.

Une conséquence de la superadditivité est que le marché mondial est la structure de coalition socialement efficace. Quand des systèmes de transferts interjurisdictionnels ne sont pas envisageables, cela n'implique en aucun cas que le marché mondial est la coalition de liaison préférée du point de vue d'une juridiction. En outre, la superadditivité avec l'infaisabilité (supposée) de transferts implique que les préférences de liaison juridictionnelles ne s'accordent pas les unes aux autres. Cela pourrait être un facteur qui contribue au fait que l'on bserve peu de cas de liaisons en pratique.

Notre modèle nous permet également de caractériser la volatilité du prix des permis. Étant donné que les chocs juridictionnels de demande de permis sont corrélés, il n'y a aucune raison que la variabilité des prix liés diminue progressivement à mesure qu'augmente le nombre de juridictions participants à une coalition de liaison. Cependant, nous pouvons montrer que les juridictions très volatiles connaîtront toujours une volatilité réduite via une liaison par rapport à l'autarcie, car les chocs sont répartis sur un marché plus vaste et donc mieux amortis. À l'inverse, les juridictions ayant une faible volatilité en autarcie peuvent être confrontées à une augmentation de volatilité via une liaison, car les liens créent une exposition aux chocs qui se produisent à l'étranger. Cela est d'autant plus marqué lorsque ces juridictions sont relativement ptites car l'influence de plus grandes juridictions sur les résultat de la liaison sera relativement plus prononcée.

Enfin, nous proposons une application du modèle avec une portée plus orientée politique du changement climatique. Nous introduisons des coûts monétaires associés à la formation de coalitions de liaison comme moyen de rendre compte des frictions d'économie politique et donc d'apporter plus de réalisme à notre modèle. En effet, les rares cas pratiques de liaison qui se sont produits jusqu'à présent ont été effectués sur une base bilatérale entre (i) juridictions avec des ETSs avec des designs alignés et donc des coûts de liaison relativement faibles (par exemple, Californie et Québec); (ii) une petite juridiction qui souhaite adhérer à un système beaucoup plus vaste et qui supporte donc tous les coûts associés au lien (par exemple, l'Europe et la Norvège ou l'Europe et la Suisse). Nous prenons explicitement en compte cette observation en introduisant des coûts de liaison dans notre modèle et en envisageant divers accords de partage de ces coûts entre les juridictions partenaires.

De façon formelle, les coûts de liaison ont deux composantes: des coûts de mise en oeuvre qui sont plus élevés plus les juridictions concernées sont grandes, et des coûts de négociation qui sont plus élevés plus le nombre de participants est élevé. L'ampleur des coûts de liaison est donc endogène à la formation de la coalition de liaison. Cela reflète que (*i*) il est plus coûteux pour les grandes juridictions d'harmoniser leurs designs de marché pour une conformité avec le système lié; (*ii*) plus les parties assises à la table de négociation sont nombreuses, plus il est difficile de trouver un compromis (Keohane & Victor, 2016). Ces considérations ont donné lieu à des concepts tels que le minilatéralisme (Falkner, 2016) ou le polycentrisme (Ostrom, 2009; Dorsch & Flachsland, 2017).

En présence de coûts de liaison, des structures de coalition différentes du marché mondial peuvent générer des gains aggrégés plus élevés, nets des coûts. Il est à noter que de telles structures peuvent comporter certaines juridictions qui restent en autarcie (que nous désignons comme un lien incomplet) ainsi que des coalitions de liaison coexistantes (que nous désignons comme un lien polycentrique). Nous prenons la perspective d'un planificateur pour analyser de façon quantitative (*i*) la nature et les déterminants des structures de coalition efficaces en présence des coûts de liaison; (*ii* comment ces coûts peuvent être partagés entre les différents participants afin que ces structures constituent des améliorations de Pareto par rapport à l'autarcie complète. En particulier, nous trouvons des différences visibles dans les règles de partage des coûts pour répondre à ce critère. Dans un monde où les transferts de permis ou de liquidités peuvent avoir des obstacles d'économie politique notoires, ces différences ont des implications pour les initiatives politiques visant à orienter les juridictions vers des architectures de coalition efficaces, comme le Partnership for Market Readiness de la banque mondiale ou la Carbon Market Platform du G7.

Chapter 3: Intertemporal Abatement Decisions under Ambiguity Aversion

La plupart des systèmes d'échange de quotas d'émission offrent un certain degré de flexibilité intertemporelle par le biais du banking et du borrowing de permis.[19] Comme les firmes minimisent leurs coûts de conformité, la possibilité de stocker ou d'emprunter des permis

[19]En général, il existe des restrictions faibles ou nulles sur le banking. Le borrowing, en revanche, est souvent très limité ou tout simplement interdit, de peur que cela ne soit pas compatible avec la réalisation de l'objectif environnemental de long terme ou que les firmes couvertes évitent leurs obligations (Chevallier,

induit une condition d'arbitrage entre le prix du permis actuel et les prix futurs actualisés. En supposant un marché concurrentiel dans lequel les firmes ont un horizon temporel infini e une information parfaite, l'effort d'abattement total est réparti de manière coût efficiente dans le temps, c'est-à-dire que l'échange intertemporel implémente la solution de moindre coûts nets actualisés (Rubin, 1996; Cronshaw & Kruse, 1996; Kling & Rubin, 1997). Étant donné que les permis sont des commodités avec des coûts de stockage négligeables le prix du permis actuel devrait refléter la valeur actuelle nette du dernier permis utilisé dans le système et la chemin optimal de prix devrait augmenter au taux d'intérêt (Hotelling, 1931).

Cependant, les ETSs sont sujets à une incertitude importante. En effet, les ETSs ne sont pas des systèmes clos et sont influencés par des facteurs externes et des politiques agissants en dehors de leur périmètre. Par exemple, il est prouvé que les conditions macroéconomiques, la portée de politiques environnementales complémentaires et l'utilisation des crédits de compensation peuvent éroder le niveau de contrainte exercé par le cap (Chèze et al., 2016). Le chevauchement des politiques auxilliaires peut être fortuit comme dans l'EUETS ou intégré explicitement dans un système de régulation ouvert tel que dans l'ETS californien qui agit en conjonction avec un ensemble de mesures complémentaires et constitue un filet de sécurité assurant la réalisation de l'objectif étatique.[20] Comme ces facteurs sont par nature incertains, cela se traduit par une incertitude importante portant sur la demande permis, que Borenstein et al. (2016) estiment être «au moins aussi importante que l'incertitude quant à l'effet des mesures d'abattement». Il en découle que l'anticipation et la perception par les firmes couvertes de la contrainte du système dans le futur guideront leurs stratégies de réduction, de conformité et d'investissement dans le temps.

Des chocs négatifs sur la demande de permis ont été courants dans la plupart des marchés de permis et, par conséquent, les prix des permis ont été inférieurs à ceux initialement prévus. Dans les conditions idéales de fonctionnement d'un marché de permis, les bas niveaux de prix ne devraient pas avoir de conséquence pour l'efficacité coût intertemporelle : un choc de demande positif (resp. négatif) déplacerait le chemin de prix optimal vers le haut (resp. vers le bas), mais sa pente serait préservée et le chemin resterait efficient. En d'autres termes, même si les coûts d'abattement étaient soumis à des chocs aléatoires, le plafond serait encore atteint au moins coût actualisé (Schennach, 2000; Salant, 2016).

Dans la pratique, cependant, il est difficile de déterminer si les prix bas sont attribuables à des chocs de demande externes ou à des imperfections de marché intrinsèques. Dans le

2012). Voir également PMR & ICAP (2016) et ICAP (2017) pour les exceptions et plus de détails, par exemple les holding limits en Californie ou le year-on-year borrowing implicite dans l'EUETS.

[20]Le chevauchement ne se limite pas à des politiques propres au changement climatique et aux politiques énergétiques. Par exemple, Schmalensee & Stavins (2013) soulignent l'impact de la déréglementation des chemins de fer sur le marchés de permis pour la régulatoion du SO_2 aux États-Unis.

contexte de l'EUETS, Hintermann et al. (2016) examinent la littérature empirique sur les déterminants du prix et concluent qu'«il existe une interaction complexe entre les émissions BAU, les quantités d'abattement et les prix des permis», c'est-à-dire que notre compréhension de ces déterminants est limitée Par exemple Koch et al. (2014) estiment que les fondamentaux du marché n'ont été responsable que de 10% de la variation du prix du permis. Quand de telles imperfections sont présentes, des prix bas peuvent avoir une incidence néfaste sur l'efficacité coût intertemporelle. Il est important de noter que l'interaction entre ces imperfections et les chocs exogènes nuirait à la formation des prix et au signal de prix à long terme transmis par le système.

Une analyse de la littérature indique que trois types d'imperfections sont au centre de l'attention, à savoir un horizon temporel limité, une actualisation excessive et l'incertitude règlementaire. Tout d'abord, si les agents ont des horizons de temps tronqués et que les permis sont relativement plus abondants aujourd'hui qu'ils ne le seront à l'avenir, les prix ne reflètent pas la rareté à long terme des permis et sont plus bas qu'ils ne devraient l'être (Ellerman et al., 2015). Deuxièmement, il se peut que les agents appliquent des taux d'actualisation plus élevés que le taux d'intérêt à leurs stratégies de banking parce qu'ils font face à des contraintes institutionnelles ou corporatives sur leur banking (Neuhoff et al., 2012; Schopp et al., 2015) ou à cause de l'aversion au risque (Kollenberg & Taschini, 2016).[21] Cela favoriserait une baisse des niveaux de banking et des prix de permis actuels, par rapport au chemin optimal. En outre, Bredin & Parsons (2016) ont trouvé que l'EUETS est en contango depuis 2008, c'est-à-dire que les prix des contrats à terme ont été supérieurs aux prix de cost and carry avec des convenience yilds negatifs significatifs.

Troisièmement, les risques règlementaires associés aux éventuels ajustements du plafond, qu'ils soient à la hausse ou à la baisse, pèsent sur la formation des prix.[22] Salant (2016) développe un modèle théorique dans lequel l'incertitude règlementaire affecte la formation des prix même lorsque les agents sont rationnels.[23,24] Koch et al. (2016) fournissent un appui

[21] Au niveau d'une firme, le banking à au taux sans risque est limité aux stratégies de couverture. Au-delà, des primes peuvent être appliquées car les opérations de banking sont considérées comme spéculatives. Au niveau institutionnel, le banking peut être limité par des holding limits. En cas d'aversion au risque, les primes de risque peuvent aussi être associées au banking des firmes.

[22] Les exemples sont nombreux. La hausse des prix au début de 2016 dans l'ETS de Nouvelle-Zélande est attribuable à l'annonce que la règle de conformité '2 tonnes pour 1 permis' sera supprimée. De même, la pression à la baisse sur les prix au sein des pilotes chinois résulte de l'incertitude règlementaire quant à la transition vers un marché national, notamment en ce qui concerne la valeur des permis des pilotes sur le marché national. Les prix du RGGI ont augmenté lorsque un réduction de 45% du plafond a été discutée, mais avant qu'elle ne soit réellement adoptée et mise en oeuvre.

[23] Salant (2016) s'appuie sur son analyse du 'peso problem' et du prix de l'or dans les années 70 qui n'était pas en accord avec à l'hypothèse d'agents rationnels et neutres au risque (Salant & Henderson, 1978).

[24] Le fait que les interventions règlementaires discrétionnaires distordent l'optimalité intertemporelle des décisions des agents en raison de leur anticipation des actions réglementaires renvoie au débat 'rules versus discretion' qui remonte à la contribution séminale de Kydland & Prescott (1977). Voir Helm et al. (2003),

empirique à ce modèle théorique puisqu'ils établissent que l'EUETS est très sensibles aux événements politiques et aux effets d'annonce. C'est-à-dire que non seulement le niveau de plafond annoncé aura de l'influence sur la formation des prix, mais aussi la spéculation sur l'engagement des autorités associé à cette annonce peut entraîner des variations de prix. Cela suggère qu'il est très difficile de se couvrir contre les risques règlementaires.[25] En outre, notez que les bas niveaux de prix ont suscité des interventions réglementaires à court terme (par exemple, une gestion de l'offre ex post) ainsi que des réformes de design structurelle (par exemple, sous forme de réserves de permis indexées à des prix ou des quantités) dans tous les ETS existants, qui vient amplifier le niveau perçu d'incertitude règlementaire.

Face à l'incertitude règlementaire, les firmes couvertes par un ETS manquent de confiance et/ou d'informations sûres pour assigner correctement une mesure de probabilité décrivant de manière unique la nature stochastique de leurs problèmes décisionnels. Cela correspond à une situation caractérisée par de l'ambiguïté.[26] En revanche, le risque se rapporte à des situations où ces distributions sont parfaitement connues et uniques. Ce chapitre examine les décisions d'abattement intertemporelles d'une firme considérée neutre au risque mais averse à l'ambiguïté afin de prendre en compte la prévalence de l'incertitude règlementaire. La neutralité à l'ambiguïté constitue notre scénario de référence naturel dans lequel le flux d'abattement optimal coincide avec la solution de minimisation des coûts nets actualisés en expérance (Schennach, 2000).

Nous considérons que la firme est couverte par un ETS à deux périodes: l'ETS démarre au début de la date 1 et se termine à la fin de la date 2. Nous supposons que l'entreprise est déjà en conformité à la date 1, mais, en prévision de la contrainte imposée en date 2, elle peut encore abattre des unités supplémentaires et banquer les permis correspondants jusqu'à la date 2. À la date 1, cependant, le prix de marché de date 2 et la demande de permis de l'entreprise sont ambigus ex ante et exogènes à la firme. Cela reflète que l'incertitude règlementaire (*i*) influence directement la formation des prix (Salant, 2016); (*ii*) affecte également la demande de permis de la firme, par exemple à cause de chevauchements de politiques directs ou indirects (Borenstein et al., 2016). On pourrait s'attendre à une incertitude règlementaire sur la dotation initiale en permis reçue par la firme. Cependant,

Brunner et al. (2012) et Jakob & Brunner (2014) pour une application de ce débat dans le contexte de la politique sur le changement climatique.

[25]Selon Hintermann et al. (2016), les prix positifs en Phase II de l'EUETS indiquent du banking de la part des firmes car elles s'attendent à une contrainte d'émission serrée dans le futur et «en raison de leur connaissance d'une incertitude règlementaire».

[26]Par exemple, Hoffmann et al. (2008) définissent l'incertitude règlementaire comme «l'incapacité perçue par un individu à prédire l'état futur de son environnement règlementaire» où Hoffmann et al. utilisent délibérément le terme 'incertitude' au sens de Knight (Knight, 1921).

nous choisissons de maintenir l'allocation des permis comme paramètre dans le modèle pour pouvoir mesurer son influence sur les décisions d'abattement intertemporelles.[27] En effet, nous montrons que la neutralité de l'allocation ne tient pas sous aversion à l'ambiguïté.[28]

L'ambiguïté est résolue au début de la date 2.[29] Nous résolvons le programme intertemporel de minimisation des coûts de l'entreprise par induction à rebours et nous comparons le niveau optimal d'abattment de date 1 sous aversion à l'ambiguïté par rapport à la neutralité à l'ambiguïté. Nous utilisons le théorème de représentation sous ambiguïté dîte 'smooth' à la Klibanoff et al. (2005) (KMM) dans lequel la firme est confrontée à différents scénarios possibles du cadre réglementaire futur (c'est-à-dire à des mesures de probabilité objectives pour le prix des permis et les prévisions de demande) et a des croyances subjectives sur cet ensemble de scénarios.[30] Les attitudes à l'égard de l'ambiguïté proviennent de la relaxation de la linéarité entre les loteries objectives et subjectives et l'aversion à l'ambiguïté correspond à l'aversion (additionnelle vis à vis de l'aversion au risque) associée à l'incertitude quant aux probabilités. Cela conduit la firme à favoriser les flux d'abattement qui réduisent le niveau d'ambiguïté.

L'aversion à l'ambiguïté distord l'efficience coût intertemporelle et flux d'abattement d'équilibre associé. Avant d'examiner l'effet joint d'une ambiguïté sur le prix et d'une ambiguité sur la demande en permis de la firme, nous considérons chaque source d'ambiguïté isolément. Cela nous permet de séparer deux effets induits par l'aversion à l'ambiguïté. Tout d'abord, avec une ambiguïté purement portée sur la demande de la firme, et du point de vue de la firme neutre au risque, le marchés de permis peut être assimilé à un régime de taxation environnementale où le taux de taxe est fixé au prix du permis espéré. L'aversion à l'ambiguïté induit un décalage vers le haut (resp. vers le bas) du facteur d'escompte effectif de la firme lorsque celle-ci présente une aversion à l' ambiguïté absolue décroissante (resp. croissante) que l'on note DAAA (resp. IAAA). Par conséquent, du surabattement précoce se produit par rapport à la situation de référence sous DAAA, que nous définissons comme prudence envers ambiguïté dans la lignée de Berger (2014) et de Gierlinger & Gollier (2017). Nous notons que l'augmentation (resp. la diminution) du taux d'escompte induite

[27]En fin de compte, c'est l'effort brut d'abattement de la firme (émissions baseline moins allocation) qui est influencé par l'incertitude règlementaire, ce que nous avons déjà en supposant la baseline ambiguë.

[28]L'allocation de permis n'est pas neutre dès qu'une des hypothèses soutenant la solution d'équilibre de marché de Montgomery (1972) et Krupnick et al. (1983) est relachée. Le lecteur peut se référer à Hahn & Stavins (2011) pour une revue de littérature à ce propos.

[29]Le learning est parfait et exogène à la firme car celle-ci peut facilement observer le prix de marché et sa propre demande à la date 2 et ne peut influencer l'étendue de son learning par ses actions de date 1.

[30]Typiquement, on peut considérer que ces scénarios objectifs sont fournis par des groupes d'experts, par exemple BNEF, Energ Aspects, ICIS-Tschach, Point Carbon, divers fora académiques ou groupes de réflexion, etc.

par DAAA (resp. IAAA) peut créer une pression à la baisse sur les prix des permis futurs (resp.présents).[31]

Deuxièmement, dans une situation d'ambiguïté de prix pure, l'aversion à l'ambiguïté induit un autre effet par lequel la firme distord ses croyances subjectives de façon pessimiste en mettant plus de poids sur les scénarios qui lui sont dommageables. Intuitivement, lorsque la firme s'attend à être courte (resp. longue), elle accorde plus d'importance aux scénarios où les prix élevés (resp. bas) sont relativement plus probables. Cela augmente (resp. diminue) son estimation du prix futur par rapport au scénario de référence et, en conséquence, augmente (resp. diminue) son incitation à l'abattement précoce. Par rapport à la situation de référence, la firme averse à l'ambiguïté ne fonde pas seulement ses décisions d'abattement présentes sur le prix futur espéré, mais aussi sur sa future position sur le marché. Cela dépend en définitive de l'allocation initale des permis, et nous pouvons identifier les seuils d'allocation en-dessous (resp. en-dessus) desquels le pessimisme conduit la firme au surbattement (resp. sousabattement) précoce de façon inconditionnelle.

Troisièmement, quand les deux sources d'ambiguïtés sont prises en compte simultanément, nous montrons qu'il y a une incitation au surabattement précoce lorsque les conditions pour un surabattement précoce sous pure ambiguïté de prix sont obtenues et qu'en outre, les scénarios à prix élevé coïncident avec les scénarios où la demande en permis de la firme est élevée. Nous considérons ensuite un continuum de firmes identiques sauf en terms d'allocation de permis. Le prix du marché est alors déterminé de manière endogène par l'ambiguïté aggrégée sur les émissions baseline de l'ensemble des firmes couvertes. Cela nous permet d'affiner la condition de seuil sur l'allocation des permis et nous montrons que le pessimisme génère un surabattement précoce sous une allocation de permis symétrique. Cela peut être un facteur comportemental qui contribue à la formation d'une bank de permis dans les ETS existants qui vient s'ajouter à d'autres facteurs physiques, comme par exemple la récession économique, l'utilisation de de crédits de compensation, les politiques auxiliaires (Newell et al., 2013; de Perthuis & Trotignon, 2014; Tvinnereim, 2014; Chèze et al., 2016).

Les deux effets induits par l'aversion à l'ambiguïté peuvent être alignés ou opposés. Leurs directions et ampleurs respectives dépendent à la fois du degré d'aversion à l'ambiguïté et de l'allocation de permis. Une augmentation du degré d'aversion à l'ambiguïté augmente toujours la magnitude de la distorsion pessimiste dans le sens d'une détérioration du monotone likelihood ratio (Gollier, 2011) et nous montrons qu'elle peut augmenter celle de la prudence envers l'ambiguïté uniquement lorsque la prudence envers l'ambiguïté n'est

[31]Dans notre modèle, l'hypothèse d'une actualisation excessive que l'on trouve dans la littérature pour expliquer les prix bas actuels coïncide avec de l''imprudence envers l'ambiguïté'.

pas trop forte par rapport à l'aversion à ambiguïté . Par conséquent, un degré plus élevé d'aversion à l'ambiguïté ne garantie pas nécessairement un ajustement plus important de la quantité d'abattement précoce (en termes absolus). Avec un exemple paramétrique, nous montrons numériquement que l'abattement précoce diminue avec l'allocation de permis et que l'ampleur de la distorsion pessimiste est généralement supérieure à celle du changement du facteur d'actualisation. Cela montre que sous aversion à l'ambiguïté, le surabattement précoce est plus important sous un mécanisme d'enchère que sous allocation gratuite. Cela suggère également que la distorsion de l'efficacité intertemporelle est plus marquée dans un marché de permis que dans un régime de taxe. Enfin, nous montrons que les contrats forwards ne peuvent pas restaurer l'efficacité intertemporelle: ils ont le potentiel d'atténuer partiellement le pessimisme, mais le changement du taux d'actualisation persiste de façon inconditionnelle.

* * *

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Résumé

Les systèmes d'échange de quotas d'émission (SEQEs) sont un instrument de régulation environnementale important et ont un rôle clef à jouer dans la réduction des émissions de gaz à effet de serre pour l'atténuation du changement climatique. Cette thèse a une double orientation : les liaisons spatiales entre SEQEs et les échanges intertemporels au sein d'un SEQE.

Les liaisons entre SEQEs peuvent aider à établir un futur cadre de politique climatique mondiale coût-efficient. Cependant, ces liaisons sont difficiles à mettre en place et peu nombreuses à ce jour. Premièrement, à l'aide d'un modèle simple et unifié et en se basant sur des expériences réelles de SEQEs, nous comparons différentes restrictions à l'échange comme éléments facilitant une transition vers le libre échange de quotas. Deuxièmement, nous construisons un modèle qui décrit et caractérise analytiquement les effets et gains associés à des liaisons multilatérales sous incertitude. Ensuite, le modèle est calibré sur émissions historiques de différentes juridictions pour illustrer les déterminants des préférences de liaison.

Les SEQEs sont sujets à une forte incertitude, notamment de type règlementaire, ce qui peut affaiblir le signal-prix de long terme et nuire à l'efficience-coût dynamique. La prévalence d'une telle incertitude peut être assimilée à une situation d'ambiguïté. Afin de prendre en compte son influence, nous supposons les entités couvertes par un SEQE averses à l'ambiguïté, puis analysons leurs décisions intertemporelles et les distorsions induites sur le fonctionnement du système. Nous rapprochons enfin l'éclairage apporté par ces résultats des observations faites sur le fonctionnement des SEQEs existants.

Mots Clés

Échange de quotas d'émission, Politique climatique, Liaisons inter-systèmes, Échange intertemporel de quotas, Restrictions à l'échange de quotas, Incertitude, Ambiguïté.

Abstract

Emissions Trading Systems (ETSs) are an important instrument in regulating pollution and have a key role to play in reducing greenhouse gas emissions to mitigate climate change. This dissertation has a twin focus: Spatial linkages between ETSs at a point in time and intertemporal trading within an ETS.

Linkages between ETSs are crucial for the cost-effectiveness of the future climate policy architecture. Complete linkages, however, are difficult to agree and to date, few and far between. Here, our contribution is twofold. First, using a simple and unified model and drawing on experiences with real-world ETSs, we compare alternative permit trading restrictions as transitional and facilitative mechanisms toward unrestricted bilateral linkages. Second, we develop a model able to describe and analytically characterize the effects and gains from multilateral linkages under uncertainty. The model is then calibrated to historical emissions of real-world jurisdictions to illustrate the determinants of linkage preferences.

ETSs are subject to considerable uncertainty, especially of a regulatory nature, which can disrupt dynamic cost-effectiveness and undermine the long-term price signal. The prevalence of such uncertainty can be assimilated to a situation of ambiguity. Here, our contribution is to introduce ambiguity aversion on the part of regulated entities to account for the influence of such uncertainty, analyze their intertemporal decisions, and discuss how the induced distortions in market functioning can help explain observations from existing ETSs.

Keywords

Emissions trading, Climate change policy, Inter-system linkage, Intertemporal emissions trading, Permit trade restrictions, Uncertainty, Ambiguity.