Les Cahiers du GERAD ISSN: 0711–2440

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S. Debia,
P.-O. Pineau

G–2016–121

December 2016

GERAD HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
Montréal (Québec) Canada H3T 2A7

Tél. : 514 340-6053
Téléc. : 514 340-5665
info@gerad.ca
www.gerad.ca

An interconnection trading game: Market regimes and incentives to regulate

Sébastien Debia [a]
Pierre-Olivier Pineau [b]

[a] *GERAD & HEC Montréal, Montréal (Québec), Canada, H3T 2A7*

[b] *HEC Montréal, Montréal (Québec), Canada, H3T 2A7*

sebastien.debia@hec.ca
pierre-olivier.pineau@hec.ca

December 2016

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Abstract: Trade flows on High-Voltage Direct Current (HVDC) interconnections between two jurisdictions are frequently assessed as suboptimal, which can be explained in part by a light inter-jurisdictional regulation along with strong local regulation. More Specifically, transmission-right releasing rules, such as use-it-or-lose-it (UoL), require the enforcement of a consistent international regulatory framework. We ask whether it is beneficial for regulators, as local welfare maximizers, to cooperate in order to enforce such consistency. In the absence of releasing rules, we study the strategic withholding of physical transmission rights (PTRs). We model a two-settlement market and solve the model by backward induction. We show that any allocation of PTRs is associated to a specific market regime: competitive, monopolistic or duopolistic. We then show that, for extreme allocations of PTRs, regulators are not willing to cooperate in developing an international regulatory framework to enforce global optimality.

Keywords: HVDC interconnection, physical transmission rights, Cournot, withholding, regulation, unbundling

1 Introduction

The integration of power markets makes it possible to take advantage of complementary generation technologies or consumption patterns. It is well known, for example, that integrating two markets with different peaks reduces the need for generating capacity, since imports can be used as a substitute. Improving market integration naturally requires, additional capacity in the interconnection. In addition to facilitating exchange between markets, interconnections can also increase competition (Borenstein et al (2000)). However, alternate current (AC) networks are subject to loop-flows, which reduces the benefits of power exchanges (Cardell et al (1997); Neuhoff et al (2005)). High Voltage Direct Current (HVDC) interconnections prevent such loops and directly connect low-price zones to load pockets over long distances with controllable flows. Consequently, the number of HDVC interconnection projects has substantially increased in recent years. For example, in 2014, the European Union listed 30 HVDC initiatives as projects of common interest for security of supply (EC (2014)). In 2015, there were eight official merchant projects between Canada and the US (IEA (2015)). But trade on such lines has been persistently assessed as inefficient, which may be explained by various factors: imperfect coordination (Pineau and Lefebvre (2009); Turvey (2006); Meeus (2011)), incomplete information (Turvey (2006); Antweiler (2016)), market power, either through withholding strategies (Bunn and Zachmann (2010); Balaguer (2011)), or information asymmetry (Gebhardt and Höffler (2013)).

In this paper, we analyze the potential for strategic behavior in inter-jurisdictional merchant interconnections. The debate whether interconnection's investment should be merchant or regulated has been vivace in the past years. It could be grossly summarized as whether markets failures are more important than regulatory failures (see among others Joskow and Tirole (2005); Brunekreeft (2005); de Hautecloque and Rious (2011); Littlechild (2012); van Koten (2012); Boffa et al (2015)). Joskow (2010) suggests that these two approaches are imperfect substitutes, the pros and cons of each of them should be carefully weighted for each project. Hogan et al (2010) propose a two-part tariff based on Financial Transmission Rights to mix the two approaches: the fixed part being regulated and the variable part being based on nodal prices.

But the regulated model is hardly applicable for inter-jurisdictional interconnection projects. To be efficient, inter-jurisdictional trade indeed supposes the coordination of two regulated system operators. This point has been highlighted in IEA (2016) as a condition for further integration. On the one hand, this coordination can be seen as a harmonization of the market designs, which is more-or-less far from current realities. On the other hand, such a coordination suggests that the regulators at both ends of the line cooperate in order to enforce a competitive framework for inter-jurisdictional trade. Since a regulator's task is to maximize the welfare in its region, he is driven by local interests, which may be contradictory to a global cooperation. Hence, merchant projects would more likely appear to satisfy the need for inter-jurisdictional interconnection. It also suggests that each regulator may not be willing to cooperate in order to promote efficient trade, as it is consistent with a wealth transfer. Consequently, power trade at borders is often inefficient, especially between market and non-market areas Spees and Pfeifenberger (2012).

Hence, assuming those projects to be merchants, private owners recover their initial investment by selling transmission rights to traders, the value of which rights depends on the price spread between the two markets. Financial rights associated with implicit auctions are known to increase the competitiveness of trade between markets (Joskow and Tirole (2000); Ehrenmann and Neuhoff (2009)). These rights are purely financial: holders obtain the price differential times their number of rights, while the physical management is done by a regulated operator. However, such a design requires a high level of coordination between the two markets, which is generally not the case with inter-jurisdictional trade.[1] Thus, the approach of Hogan et al (2010) might not be applied. Alternatively, access can be provided through the sale of Physical Transmission Rights (PTRs), which allow holders to inject/retrieve power directly at one end of the line. As such, each agent actively participates in managing the line. Hence, holding a relatively large share of the PTRs *de facto*

[1] An implicit auction requires a relatively homogeneous market design at both ends of a line in order to efficiently assess the price differential (Hogan (1992)). By contrast, inter-jurisdictional trade often takes place between a regulated area and a market, for example between Quebec and the Northeastern US markets. But even trade among the Northeastern US markets is reported as suboptimal (see regional market reports). The Nortwestern Europe (NWE) market is a very specific case, and this multinational area may be considered a single jurisdiction. The European Commission enforces a regulatory framework, notably through the Third Energy Package. Consequently, there are institutions enforcing cooperation between regulators (ACER) and coordination between system operators (ENTSO-E) (de Hautecloque and Rious (2011)).

procures a dominant position (Joskow and Tirole (2000)). This dominant position on the interconnection is then used to reinforce local dominant positions of power marketers. We argue that this approach is not correct anymore. Indeed, the research has focused its effort on the local market power issue (see for example Wilson (2002); Wolak (2003); Cramton (2004); Hortaçsu and Puller (2008)), to the point where power markets are measured to be efficient, at least in the US (see regional market reports such as ISONE (2016); Patton et al (2016); PJM (2016)). Thus, designed rules are efficient in mitigating potential for existing dominant-positions abuses from a local perspective, in that, to a certain extent, firms cannot take advantage of their PTRs to *directly* mark-up their price. On the other hand, to assume that agents are price-takers on the interconnection is also, we argue, an incorrect approach because of the possible lack of coordination between the regulators at both ends of the interconnection, as exposed previously (see Doorman and Froystad (2013); Billette de Villemeur and Pineau (2016); Newberry et al (2016) for some recent examples of interconnections evaluation using a price-taker assumption).

For example, releasing rules, such as a Use-it-or-Lose-it (UoL) rule, theoretically correct the market-power failure by preventing potential PTR withholding through the promotion of free entry (Joskow and Tirole (2000)). But to implement them require a strong inter-jurisdictional regulatory framework (de Hautecloque and Rious (2011)). Furthermore, these rules can be circumvented if their definition lacks granularity. For example, the UoL rule is defined on a daily basis whereas the product is delivered on, e.g., a half-hourly basis (Bunn and Zachmann (2010)). The UoL rule also makes PTRs a very rigid instrument under uncertainty. An initial holder would thus run the risk of losing potentially valuable rights under this rule, in a context where uncertainty may cause dumping as an insurance strategy (Antweiler (2016)). Hence, the releasing provision of a PTR may be triggered just before gate closure. For example, US regulator FERC, decided to apply the UoL rule just before real-time in the case of the Neptune cable between PJM and Long Island (FERC (2003)). Unused rights are thus available from noon to five p.m. one day before start of service (PJM (2015)). Such a restricted operational window tends to reduce the effectiveness of the UoL rule. Finally, UoL would be void if not coupled with a must-offer provision for the line investor and initial holder of the rights. But, Brunekreeft and Newberry (2006) show that such a provision would largely impede merchant investment under uncertainty. In a context where investment is lacking, such a provision tends to be undesirable. Consequently, the extent to which HVDC interconnection is subject to imperfect arbitrage has been largely demonstrated empirically (see Pineau and Lefebvre (2009); Bunn and Zachmann (2010); Balaguer (2011); Meeus (2011); Gebhardt and Höffler (2013); Antweiler (2016)).

Taking all these elements into accounts, we try to answers the following questions:

1. Is there a local regulation that offers an alternative to releasing rules in making interconnection management more competitive?
2. Given an efficient local regulation, what impact does the allocation of PTRs have on the behavior of producer-traders on the interconnection?
3. Given an efficient local regulation, under what conditions the two local regulators would be willing to cooperate in order to enforce competitive behaviors of the producer-traders on the interconnection?

We answer these questions by developing a two-stage trading game, where the power trade is constrained by an HVDC interconnection with controllable flows. In the first stage, strategic producer-traders set their exports in order to maximize their profits in the local and foreign markets. Their action may be constrained by the number of PTRs they own, which is considered as given. To be consistent with our preliminary discussion, those PTRs are not subject to a releasing rule. In the second stage, each producer maximizes its profit on the local market. This model fundamentally has the same structure as the one in Joskow and Tirole (2000), in a non-commitment situation. We make two important modification to fit our model to realistic situations that are not covered in the literature. First, we modify the framework in Joskow and Tirole (2000) by making the local market subject to marginal-cost pricing. This is, by definition, an efficient regulation of local market power.[2] Second, we assume that the strategic producer-traders in the first stage

[2]In an auction setting, firms may not reveal their true marginal costs in their bids to the market operator (see, e.g., Cramton (2004); Hortaçsu and Puller (2008); Wolak (2003)). However, we ignore this possibility, and instead follow the observations from the market reports. Indeed, local market power represents such a credible threat since the California crisis that most U.S. power markets have designed rules to mitigate it. Consequently, prices and behaviors in those markets are highly monitored

are local price-takers. Indeed, anticipation of the price setting would result in dumping in order to raise the price locally (Debia and Zaccour (2016)). However, power in the interconnection could flow against the price differential during critical events. We consider that such situations, e.g., where a local producer exports even when the local price is higher than the foreign price, to be unacceptable from a regulatory point of view, since it would disadvantage local consumers, whose protection is one of the primary goals of efficient regulation. For example, the native-load-commitment provision requires utilities to commit to serving the local load at a predefined price before setting their exports (FERC (2012)). This type of regulation separates local from foreign incentives, which is what is modeled through our local price-taking assumption. This assumption can also be thought of as an unbundling regulation, without which a firm's operations department can communicate its supply function to its trading department. With the regulation, communication is limited to a threshold price below which a firm should import rather than export.

The contributions of this paper are the following. First, we show that, in our present framework, power always flows in the direction of the price differential, as an unbundled trader would lose the local incentive for dumping. To that extent, the unbundling of trade and production activities is efficient in mitigating anti-arbitrage behavior. Second, we extend the analysis not only to extreme allocations corresponding to monopoly situations, but also to any allocation of rights between the players and a competitive fringe of traders. Indeed, in the case where PTRs are initially sold through a discriminatory price auction, a result of Joskow and Tirole (2000) is that the players would randomize their strategy, which implies that any allocation may be finally distributed. Such a case has not been dealt with in the interconnection literature, even if it is a natural outcome of such auctions. We then characterize different market regimes as a function of PTR allocation, and of the size of the interconnection. Third, we demonstrate that, in our setting, and for relatively extreme rights allocation, the local regulators have no incentive to cooperate in order to promote free entry. However, for relatively homogeneous allocations, the equilibrium outcome is Pareto-dominated by the competitive one from the local welfare perspective. In these situations, both local markets would be better off cooperating.

The rest of the paper is organized as follows: In Section 2, we introduce the model and characterize the Cournot-Nash equilibrium. In Section 3, we show that these market regimes directly impact the local welfare, by doing comparative statics over the rights allocation. Section 4 briefly concludes.

2 PTRs and interconnection management

2.1 The model

Each player is a local monopolist at node i, which generates an amount of power y_i. A portion x_i is sold in the other node, and the rest $(y_i - x_i)$ is sold locally at marginal cost. The model has two stages. The first stage corresponds to the interconnection game. The players set their level of trading between the two nodes. They face a "make-or-pay" decision, such that the quantity traded may be positive or negative. A competitive fringe of traders is present. They are price-takers, such that they realize perfect arbitrage. The fringe and the players' actions are constrained by the quantity of PTRs they own. They maximize their profit against the price differential between the two nodes. The second stage corresponds to the local electricity market, in which physical production and consumption happen. We assume this stage to be regulated, such that each producer sells to local consumers at marginal cost.

These stages replicate most of the interconnection time frame, because exports to other jurisdictions are usually decided upon before local markets are. Figure 1 illustrates typical timing for the trading process between different power markets. Trading over the interconnections is usually decided upon before any bidding on spot markets occurs. A similar timeline can be seen in Gebhardt and Höffler (2013). The model is solved by backward induction: we solve the second stage and then the first. Thus, for all agents (players and competitive fringe) the decision variables of the second stage are expressed as implicit functions of the decision variables of the first stage.

and considered competitive (see regional market reports, e.g. ISONE (2016); Patton et al (2016); PJM (2016)). It is therefore consistent to consider a game where local production is subject to marginal-cost pricing, as this is the competitive benchmark in economics. We thus implicitly assume that regulation is locally efficient, and we focus on the management of the interconnection.

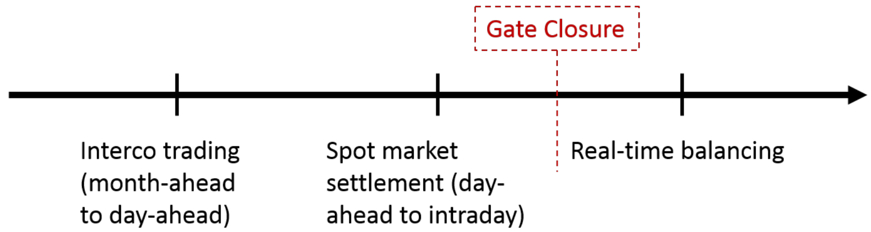

Figure 1: Model timeline.

2.1.1 The lower-stage competitive equilibrium

The inverse demand function is assumed to be affine. This type of functional form is widely used in theoretical papers for simplicity of exposure. We represent the cost function as quadratic. Whereas the cost in the power system would be better represented with an increasing linear-by-part function, this form is not continuously derivable. Hence, a quadratic cost function is usually considered an acceptable approximation (see e.g. Antweiler (2016)). More precisely, let us assume the following functional forms for the cost and inverse demand functions, respectively:

$$C_i(y_i) = \frac{c_i}{2} y_i^2,\ c_i > 0, \qquad P_i(y_i, X_i) = a_i - b_i(y_i - X_i),\ a_i, b_i > 0,$$

where X_i,the total net exports of node i, is considered fixed at this stage. Given the marginal-cost-pricing architecture of the market, we obtain the generation as a function of the net exports X_i, that is,

$$\hat{y}_i(X_i) = \frac{a_i + b_i X_i}{b_i + c_i}, \tag{1}$$

and the price as

$$P_i(X_i) = \frac{c_i \left(a_i + b_i X_i\right)}{b_i + c_i}, \tag{2}$$

which is increasing in the net exports.

2.1.2 Unconstrained Nash equilibrium

Let assume, without loss of generality, that node 1 experiences a (weakly) lower price than node 2 in autarky, that is, $P_1(0) \leq P_2(0)$. Accordingly, we could define the export direction as being from node 1 to node 2, such that

$$X = X_1 = x_1 + x_2 + x_f = -X_2,$$

and the price differential as

$$\delta(X) = A - BX > 0, \quad \text{where } A = \frac{a_2 c_2}{b_2 + c_2} - \frac{a_1 c_1}{b_1 + c_1} \text{ and } B = \frac{b_1 c_1}{b_1 + c_1} + \frac{b_2 c_2}{b_2 + c_2} \tag{3}$$

In a preliminary step, we characterize the interior Nash equilibrium. At the first stage, the producer-traders maximize their profit considering the local price as a parameter p_i, that is, for the player at node 1:

$$\Pi_1(X) = \hat{y}_1(X) p_1 - C_i\left(\hat{y}_1(X)\right) + x_1(P_2(X) - p_1). \tag{4a}$$

And correspondingly, for the player at node 2,

$$\Pi_2(X) = \hat{y}_2(X) p_2 - C_i\left(\hat{y}_2(X)\right) + x_2(p_2 - P_1(X)). \tag{4b}$$

The interior Nash equilibrium without fringe is characterized as follows:

Result 1 *Assuming quadratic cost function, affine inverse demand function and absence of the competitive fringe the interior Nash equilibrium is characterized by, for $i = 1, 2$*

$$x_i^* = \frac{AD_i}{B^2 + D_1 D_2}, \tag{5a}$$

and the price differential as

$$\delta(X^*) = \frac{AD_1 D_2}{B^2 + D_1 D_2} \tag{5b}$$

where

$$D_i = \frac{b_i c_i}{b_i + c_i} > 0 \quad \text{such that } B = D_1 + D_2.$$

This equilibrium is unique.

Proof. See Appendix A.1. □

The strategy here consists in exporting such that there still exists a non-zero price differential, that is, the arbitrage is imperfect. However, the players never arbitrage against the price differential. Indeed, x_i has the same sign as A which is equal to the price differential in autarky. In order to link this result with the existing literature, we make the following remark:

Remark 1 *In a case where traders and producers within a firm are not unbundled, we get the following first-order condition:*

$$\frac{\partial \Pi_i}{\partial x_i} = \frac{\partial P_i(X_i)}{\partial x_i}(\hat{y}_i(X_i) - x_i) + \frac{\partial P_j(X_i)}{\partial x_i} x_i + P_j(X_i) - P_i(X_i) = 0.$$

The first term of this equation is positive, such that generator i has more incentive to export. To the extent that the local price $P_i(.)$ is more sensitive to exports than is the foreign price $P_j(.)$, and that exports represent a relatively small share of the production, a player is willing to dump its product. Such behavior is analyzed in Debia and Zaccour (2016), a companion paper, in a general setting of international trade. In the present case, by assuming local price-taking behavior from the strategic traders, this first term is removed, such that dumping is not a possible equilibrium strategy.

Because of the absence of dumping, adding a competitive fringe in an unconstrained setting comes down to a competitive equilibrium where strategic players are absent of the market.[3]

2.2 Constrained Nash equilibrium and market regimes

Let us now assume that each player owns an amount of PTRs $z_i \geq 0$, where $z_1 + z_2 + z_f = T$, T being the available transmission capacity. Given our definition of the arbitrage direction, and given that there is no dumping in this model, such a definition of rights is sufficient. Hereafter, the allocation $\mathbf{z} = \{z_1, z_2, z_f\}$, $\mathbf{z} \in \mathcal{V}$, is said to be in the arbitrage direction. Thus, the strategy set of each player is bounded. Provided that they arbitrage in the correct direction, for every other player's action, the feasible actions become

$$x_i^* = \max\left\{0, \min\left\{z_i, \frac{A - B(x_j^* + x_f^*)}{B + D_j}\right\}\right\} \tag{6}$$

where x_f^* is the optimal solution of the competitive fringe. Following from the previous subsection, it arises that, if the fringe experiences an interior solution, then the strategic players are absent from the market. Let us define T^* to be the volume of PTRs needed by the fringe to exercise perfect arbitrage. That is, T^* is defined such that

$$P_2(T^*) - P_1(T^*) = 0 \implies T^* = \frac{A}{B}. \tag{7}$$

[3] This result is obtained using the same method as for Result 1.

Because of these boundaries, the equilibrium becomes highly sensitive to the value of the parameters, and in particular to the access structure of the interconnection $\mathbf{z}$. For example, for a relatively low nonzero value of z_1, x_1 is bounded above. However, player 2 takes this constrained strategy of player i into account and can act as a monopolist on the residual demand of the interconnection market. By contrast, when x_i is interior, player k also plays à la Cournot. Hence the market outcome is characterized by different regime, in the spirit of the subgame in Kreps and Sheinkman (1983). The following proposition provides a characterization of the equilibrium strategies.

Proposition 1 *The equilibrium strategy x_i^* depends on the allocation $\mathbf{z}$ and is defined for any player i, with $j \neq i$:*

$$\begin{aligned}
\textit{Monopolistic: } x_i^* &= \frac{A - B(T - z_i)}{B + D_j} \iff \mathbf{z} \in S_i^M \\
\textit{Duopolistic: } x_i^* &= \frac{D_i(A - Bz_f)}{B^2 + D_i D_j} \iff \mathbf{z} \in S^D \\
\textit{Constrained: } x_i^* &= z_i \iff \mathbf{z} \in S_j^M \cup z_i \leq \sigma_i^M \\
\textit{Non-participating: } x_i^* &= 0 \iff z_f \geq T^*
\end{aligned}$$

where

$$\begin{aligned}
S_i^M &= \left\{\mathbf{z} \in \mathcal{V} \mid z_f < T^* \ \cap \ z_i > \sigma_i^M \ \cap \ z_j \leq \sigma_j^D, \ i \neq j\right\} \\
S^D &= \left\{\mathbf{z} \in \mathcal{V} \mid z_f < T^* \ \cap \ z_i > \sigma_i^D, \ i = 1, 2\right\}
\end{aligned}$$

and

$$\begin{aligned}
\sigma_i^M &= \max\left\{0, \frac{A - BT}{D_j}\right\} \\
\sigma_i^D &= \max\left\{0, \frac{D_i(A - B(T - z_j))}{D_j(B + D_j)}\right\}.
\end{aligned}$$

Proof. See Appendix A.2 □

This proposition characterizes the whole space of the players' strategy at the Nash equilibrium of the game. For $z_i > \sigma_i^D$, player i plays à la Cournot. For z_i below that threshold, the strategy is constrained. The other player takes this into account and acts as a monopolist over the residual demand. In other words, if $z_i \leq \sigma_i^D$, then player j considers player i to be part of the competitive fringe.

According to this strategy characterization, the interconnection market may follow four different regimes. A duopoly regime appears when both players own sufficient rights to withhold them and then act upward on the price. A monopoly regime for player i appears when it owns a relatively large quantity of rights and player j has too few to represent a credible threat. In this case, monopolist i maximizes his revenue against the residual demand curve. Finally, the market may also be competitive, in the sense that no withholding strategy appears, because the strategic players have insufficient rights ($x_i^* = z_i, \forall n$) or because there is a sufficiently high allocation to the competitive players ($z_f^* \geq T^*$ such that $x_i^* = 0$). In other words, there is a set of rights allocations S^P such that the equilibrium will be of perfect arbitrage.

Definition 1 *Let S^P be the set of perfect arbitrage equilibrium, that is*

$$S^P = \mathcal{V} \backslash \left\{S_i^M \cup S_j^M \cup S^D\right\} = \left\{\mathbf{z} \in \mathcal{V} \mid z_f \geq T^* \ \cup \ z_i \leq \sigma_i^D, \ i = 1, 2\right\}.$$

In this set, the allocation of rights to the strategic players may not be null. Indeed it is sufficient that their allocation be low enough that both players' actions are constrained. Figure 2 gives an example of how the strategy space defines the market-regime space. It is noteworthy that a larger interconnection capacity in the arbitrage direction T does not necessarily mean more opportunity for perfect arbitrage. The area where the

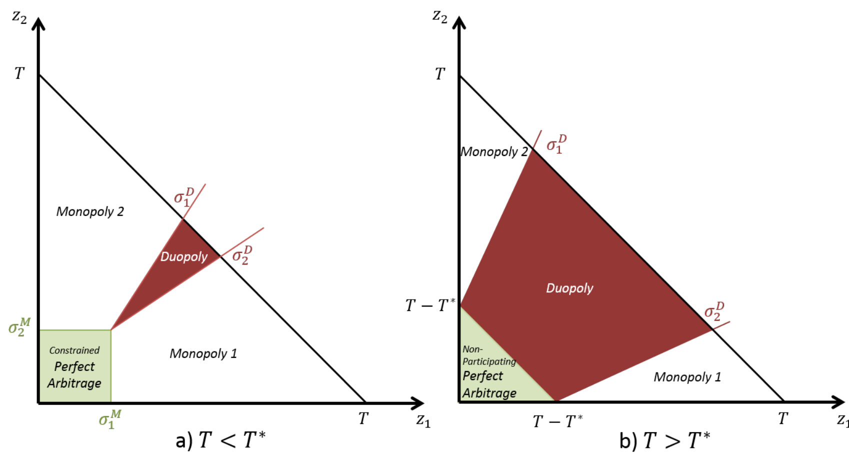

Figure 2: Market regime space.

interconnection market yields a competitive outcome decreases as T increases, up to the point $T = T^* = A/B$. At this point, only a full allocation to the fringe would yield a perfect arbitrage outcome. After this point, the area grows in T. For a relatively low value of T compared to the demand on the interconnection market, the price spread is high enough that it is not profitable to withhold many rights. Indeed, up to the point where T is sufficiently low compared to the demand, i.e.,

$$T \leq \frac{A}{B + D_j},$$

the only strategy that maximizes player i's profit is to use all the producer's rights, i.e., $x_i = z_i$. In this case, all the capacity T is used. Moreover, for

$$T > \frac{AB}{B^2 + D_i D_j},$$

a duopoly regime—where both players play an unconstrained strategy—exists. As T increases, this subset increases. This may be explained by a competitive effect. The market's output is larger in a duopoly than in a monopoly. In our framework, the market outcome is constrained by T, such that, as T increases, there is more room for competition. Consequently, σ_i^D decreases with T in terms of z_i for all i, and the array of rights allocation leading to a duopolistic market regime is extended.

2.3 Discussion

The existence of price-making behavior does not necessarily lead to the withholding of PTRs. Whether or not withholding by a strategic producer is an equilibrium strategy depends on three factors.

First, the relative fundamentals of each market, which are summarized by A, D_i, and D_j provide the primary incentives to the players. A represents the difference in reserve price between nodes 2 and 1, each weighted by the supply-quantity sensitivity. The higher is A, the higher the price spread and the greater the quantity supplied by a strategic exporter. D_i could be interpreted as the ability of player i to manipulate the price of market j. If D_i is high then strategic player i has an incentive to withhold its output in order to let the price at importing node j rise to a high level.

Second, the PTR allocation $\mathbf{z}$ defines the degree of competition in the interconnection market, ranging from perfect competition to monopoly. For relatively low values of the rights, the strategic generators play perfect arbitrage as a dominant strategy. Indeed, they define their strategy duopolistically or monopolistically depending on the allocation of the other players. For example, if z_i is large enough for player i to play Cournot–Nash, a withholding strategy emerges. But if z_j increases, z_i being constant, it impacts the threshold σ_i^D, such that $z_i < \sigma_i^D$. Player i would then play a constrained strategy, while player j plays a monopolistic strategy.

Third, the size of the interconnection T determines the size of the market. A large value of T (relatively to A) increases the zone of perfect arbitrage, but it also increases the expectation that the value of trade could be null. Hence, a large value of T is a necessary condition for a competitive interconnection market. However, it is not sufficient: if T is large, but no PTR is allocated to the competitive fringe of traders, then the market will be at best a duopoly.

In this configuration, withholding strategies are likely to appear when fundamental differences between the two markets are not very large relative to the interconnection capacity, i.e., when $T > T^*$. Hence, withholding would likely appear during periods when prices are relatively close between the two nodes. The next section provides further analysis of the strategies and their associated payoffs in terms of local welfare.

3 Regulators' interest in perfect arbitrage

Unbundling must be enforced by regulators at the local level, which may be easier to implement than inter-jurisdictional regulation. Assuming that the main achievement of the latter type of regulation is to enforce perfect arbitrage between nodes, then most of the rights allocations will result in a Pareto-dominated equilibrium for the perfect arbitrage solution. Hence, it is usually profitable for the system operators at the two nodes to coordinate, to prevent strategic behavior by their respective monopolists. However, if any player at a node owns a sufficient number of PTRs, then this equilibrium maximizes the local welfare at this node. Hence, the regulator may not be eager to cooperate in this case.

Since $x_i^*(\mathbf{z})$ is continuous despite the change in regimes, it follows that any function that is continuous in x_i is also continuous in $\mathbf{z}$ at equilibrium. Let the non-normalized local welfare function at node i be the sum of the local welfare and the power sold by local generators to the foreign market and the power sold by the local market to other traders. Let $\delta_i(\mathbf{z})$ be the non-normalized price differential $(P_j(.) - P_i(.))$.

Definition 2 *The local welfare function at node i is*

$$W_i(.) = \int_0^{\hat{y}_i(\mathbf{z})-X_i(\mathbf{z})} P_i(\xi_i)\ \mathrm{d}\xi_i - C_i(\hat{y}_i(\mathbf{z})) + X_i(\mathbf{z})P_i(\mathbf{z}) + x_i(\mathbf{z})\left[P_j(\mathbf{z}) - P_i(\mathbf{z})\right].$$

After normalization of the functions (as previously, we assume that node 1 is the exporting node), the local welfare function at equilibrium can be given within a constant for any i:[4]

$$W_i^* = \frac{1}{2}\left[\frac{a_i^2}{b_i+c_i} + D_i\left[X^*(\mathbf{z})\right]^2\right] + x_i^*(\mathbf{z})\delta^*(\mathbf{z}).$$

The first term, which is a monotone convex-increasing function of X, represents the welfare from local production and consumption. The second term is the additional value earned on the interconnection market.

We compare the local welfare at equilibrium with the same function, assuming that inter-jurisdictional regulation enforces perfect arbitrage. In this case, strategic traders become price-takers regardless of the allocation of rights. Let X^P and δ^P be the value of total exports and price differential in the competitive situation. The normalized local welfare in the latter case is

$$W_i^P = \frac{1}{2}\left[\frac{a_i^2}{b_i+c_i} + D_i\left[X^P\right]^2\right] + z_i\delta^P,$$

where[5]

$$X^P = \min\{T; T^*\} \implies \delta^P = \max\{A - BT; 0\}.$$

[4] At equilibrium $x_i^*(\mathbf{z})$ and $\delta^*(\mathbf{z})$ have the same sign for all $\mathbf{z}$, and $X^*(\mathbf{z})$ is squared, so the corresponding terms are always positive.

[5] Since X^P and δ^P are constant, $W_i^P(\mathbf{z})$ is linear in $\mathbf{z}$ and constant if $\delta^P = 0$.

Definition 3 *Let $F_i(\mathbf{z})$ be the local-welfare-difference function at node i, such that*

$$F_i(\mathbf{z}) = W_i^* - W_i^P = \frac{D_i}{2}\left[[X^*(\mathbf{z})]^2 - \left[X^P\right]^2\right] + x_i^*(\mathbf{z})\delta^*(\mathbf{z}) - z_i\delta^P.$$

The function F_i compares local welfare at node i with and without inter-jurisdictional regulation. A negative function F_i means that the regulator at node i would be better off with this type of regulation. Hence, it would be willing to cooperate with the regulator at the other node in order to enforce competition. Figure 3 shows $F_i(\mathbf{z})$ as an example where $T > T^*$.

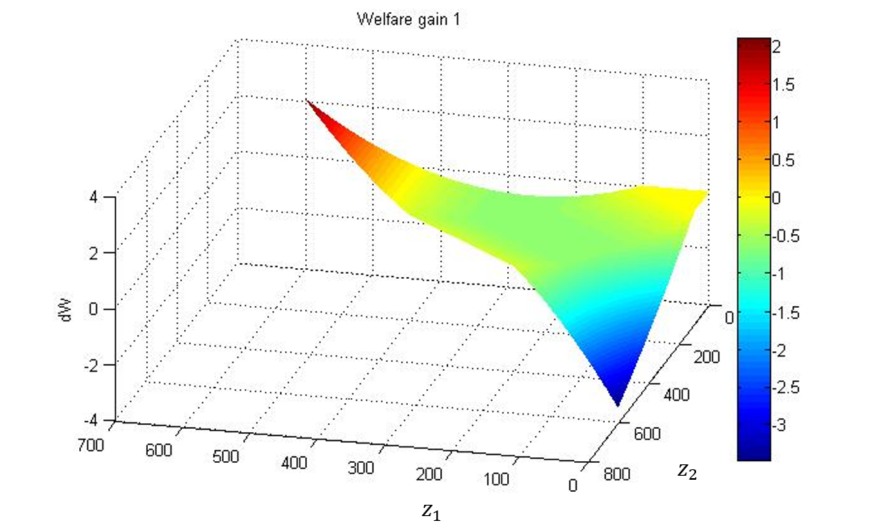

Figure 3: Local welfare: Equilibrium vs. perfect arbitrage.

The interconnection market has four regimes. Each triggers different player strategies, and consequently, different payoffs. From this example, we see that F_i is not monotonic in z_i when player i acts as a monopolist or a duopolist. Under these regimes, the local welfare is characterized by a global minimum and local maxima.

First, let us prove that x_i is continuous in $\mathbf{z}$ for all i. This property will be used to prove subsequent results.

Lemma 1 *$x_i(\mathbf{z})$ is continuous in z_k, $k = 1, 2, f$.*

Proof. See Appendix A.3. □

Proposition 2 *Let F_i be the local-welfare-difference function at node i, $i = 1, 2$, and $\mathbf{z}$ be the allocation of PTRs.*

(i) $F_i = 0$ for any $\mathbf{z} \in S^P$.
(ii) $F_i < 0$ for any $\mathbf{z} \in S^D$.
(iii) $F_i < 0$ for any $\mathbf{z} \in S_j^M$.
(iv) If $\mathbf{z} \in S_i^M$, there exists a threshold $\tilde{z}_i$ such that $F_i < 0$ for every $z_i < \tilde{z}_i$, where

$$\tilde{z}_i > T - \frac{AD_j}{B^2 + D_iD_j}.$$

Proof. See Appendix A.4. □

If the equilibrium is perfectly arbitraged, then F_i is obviously null. Moreover, if the market is in the monopoly j regime, then the local welfare at node i at equilibrium is strictly dominated by the perfect arbitrage solution. However, even if node i's generator is in its own monopolistic regime, there exists an allocation of PTRs in this subset such that the equilibrium strategy is strictly dominated by the perfect arbitrage solution. This result seems quite counterintuitive. For $z_i = T$, the value of W_i^* corresponds to the maximum of the local welfare by construction, since at this point, marginal utility and marginal cost equate at node i, which in turn equates the marginal revenue perceived by the monopolist at node j. However, there always exists a threshold in S_i^M such that $F_i < 0$. The intuition for this result should be put in conjunction with the observation that $F_i < 0$ for any allocation $\mathbf{z}$ in the duopoly regime S^D. As the system operator enforces unbundling, each player doesn't see the variations in the local price when setting its strategy. Hence, the players are missing a piece of information about the impact of the others' strategy on their profit. The extent to which they can internalize the others' strategy, which is already imperfect in a usual Cournot game, is thus even more limited. The deadweight losses at node i resulting from these externalities increase with the allocation to player j. The firms' profits decrease to the point where consumers' relative losses w.r.t. the competitive case outweigh the producers' extra profits.

This characterization in terms of local welfare implies that a large set of allocations leads to a Pareto-dominated equilibrium from a local welfare point of view.

Corollary 1 *There exists a set $\mathcal{V}^{\mathcal{D}} \subset \mathcal{V}$ such that, for any $\mathbf{z} \in \mathcal{V}^{\mathcal{D}}$, the equilibrium is strictly Pareto-dominated by the perfect arbitrage solution from the local welfare perspective, that is,*

$$\mathcal{V}^{\mathcal{D}} = \{\mathbf{z} \in \mathcal{V} \mid F_i(\mathbf{z}) < 0,\ i = 1,2\} = \left\{\mathbf{z} \in \mathcal{V} \backslash S^P \mid z_i < \tilde{z}_i,\ i = 1,2\right\}.$$

This implies $S^D \subset \mathcal{V}^{\mathcal{D}}$ and $S_i^M \cap \mathcal{V}^{\mathcal{D}} \neq \{\varnothing\}$, $i = 1,2$.

Proof. See Appendix A.5. □

Thus, any equilibrium in this region is Pareto-dominated by the competitive situation. In other words, if the rights are allocated relatively homogeneously among the players, then each node would be better off to cooperate. These cases correspond to situations of sub-perfect-competition where the deadweight losses are relatively evenly distributed between the two nodes. Figure 4 illustrates Corollary 1 for a case where $T < T^*$.

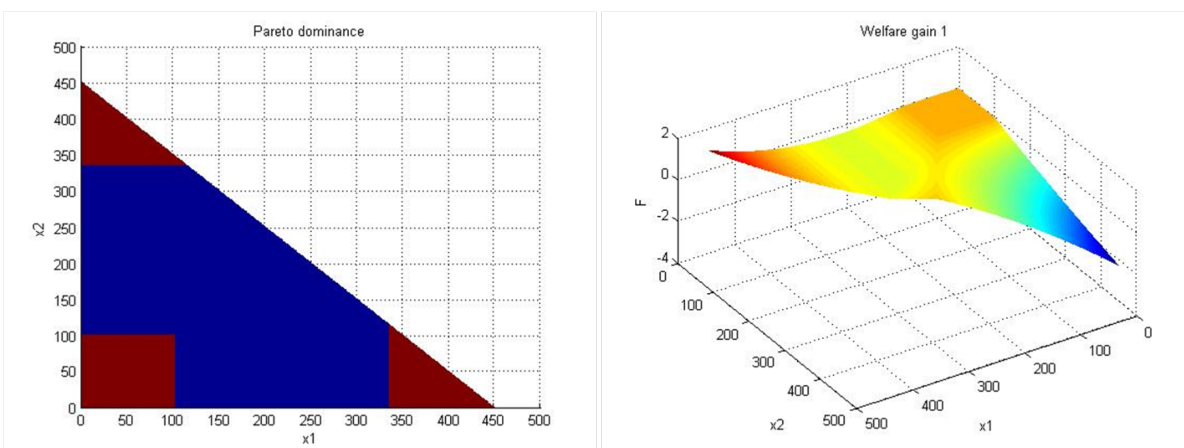

Figure 4: Local welfare: Pareto dominance.

The right-hand graph shows the associated F_1, and the left-hand graph shows the corresponding set $\mathcal{V}^{\mathcal{D}}$, in blue. Comparing Figure 4 and the corresponding case in Figure 2 (the left-hand graph, which assumes the same parameter value), we can see that $\mathcal{V}^{\mathcal{D}}$ include a significant share of the sets S_i^M and S_j^M.

This result is of prime importance in a context where the system operator is not gamed. The goal of regulation is to maximize welfare, but in most cases, this is not achieved. By emphasizing the service of local consumption at a minimal cost, and thereby enforcing regulation at a local level, the regulated market operator fails to compare the exporter's marginal willingness to pay and its consumers' marginal willingness to receive in exchange for this export. This is implicitly because the physical market operator is a quantity-taker of the interconnection game's outcome, provided that the local monopolist does not game it. Therefore, the market operator cannot arbitrage efficiently. We could view this effect as a non-internalized market externality.

To conclude this section, a local regulator may not wish to implement an efficient cross-border regulation if it has already enforced unbundling between trading and production activities. This is especially true if its local player owns a significant share of the PTRs. Indeed, by unbundling its local player, the regulator is ensured that the strategic trader will not dump its product in a foreign country, in order to raise the local price. That is, the local firm makes extra profit on exports without jeopardizing the local welfare at its node. However, such a case only happens for relatively extreme distributions of PTRs. For most PTR allocation, a node would be better off with a competitive situation. To that extent, the local player being a dominant player on the interconnection is not sufficient to ensure higher local welfare.

4 Conclusion

We model a power-trading game between two markets linked by a finite HVDC interconnection with controllable flows. The strategic trading parametrizes an implicit physical power market. Our assumption of locally regulated markets is in line with the regulatory framework in the U.S., where markets are strongly monitored. Our assumption of local price-taking behavior of producer-traders is consistent with situation where a native load commitment provision applies. In the absence of such native load commitment, the local price-taking assumption is interpretable as functionnal unbundling, a situation where communication is restricted between producers and traders within a generation company. Without unbundling, Debia and Zaccour (2016) have shown in a more general international-trade model that trading may create inefficiencies caused by players' willingness to dump their product in the foreign market. We show that such behavior may be mitigated by unbundling. In this sense, to generalize unbundling between trade and production, not only to utilities but to all producer-traders, is desirable.

Under this regulation, and in the absence of a releasing rule such as UoL, we show that trade always goes in the same direction as the price spread, but that the withholding of rights exists under relatively weak conditions. We demonstrate different market regimes depending on PTR allocations. For most allocations, the equilibrium outcome is dominated by the competitive one from a local welfare point of view. Hence, the local regulators would be better off to cooperate in order to enforce competitive behavior by their local producers on the interconnection market for these allocations, provided that the cost of international regulation is low enough. On the other hand, each regulator would increase its wealth if its local producer owned an amount of rights greater than a certain threshold. To that extent, they are not willing to cooperate, and an releasing rules may not be enforced.

Such an unbundling regulation can have negative effects which are not modeled here. For example, in a world with uncertainty and where agents are risk averse, one of the main goal of trading is to hedge the production on the financial markets. An unbundling regulation would make this type of behavior less efficient.

This work could be extended by adding a third stage where rights are auctioned. This would allow an examination of what are the most credible allocations of rights in this setting. With enforcement of local regulation and without the UoL rule, one could expect different results than those in Joskow and Tirole (2000). Another interesting extension, which could be done in conjunction with the previous one, would be to develop a meta-game between the regulators. This would allow further analyses of the regulators' incentive to cooperate in order to enforce perfect arbitrage on the interconnection.

A Proofs

A.1 Proof of Result 1

Proof. Trivially, the value at equilibrium is given by calculating the first order condition (FOC) which is, after aggregating the parameters,

$$\frac{\partial \Pi_i}{\partial x_i} = A - Bx_j - (B + D_j)x_i = 0, \quad \forall i.$$

We get the closed-form solution from there. From the second derivative, it comes that

$$\frac{\partial^2 \Pi_i}{\partial x_i^2} = -(B + D_j) < 0, \qquad \frac{\partial^2 \Pi_i}{\partial x_i \partial x_j} = -B < 0.$$

Thus, the equilibrium is unique. We get the price differential by replacing the value accordingly. □

A.2 Proof of Proposition 1

Proof. For $z_f \geq T^*$, we have $P_2(x_f^*) - P_1(x_f^*) = 0$ and consequently $x_i = 0$ for any i. We therefore focus on the case where $z_f < T^*$, such that $x_f^* = z_f$. Given this, each player always exercises a strictly positive export. Using Equation (6), the strategy is thus the best response

$$x_i(x_j^*) = \min \left\{ z_i, \frac{A - B(x_j^* + z_f)}{B + D_j} \right\}$$

In this case, the closed-form strategy for player i, when the two players have an interior solution, is

$$x_i^* = \frac{D_i(A - Bz_f)}{B^2 + D_i D_j}. \tag{8a}$$

If $x_j^* > z_j$, then player i is a monopolist and equates his marginal cost to the marginal revenue received from the interconnection market's residual demand. Replacing x_j^* and x_f^* in (6) by z_j and z_f, respectively, and since $z_j + z_f = T - z_i$, we finally end up with

$$x_i^* = \frac{A - B(T - z_i)}{B + D_j}. \tag{8b}$$

For x_j to be strictly greater than z_j, it must be the case that

$$z_j < \frac{D_j(A - Bz_f)}{B^2 + D_i D_j}. \tag{8c}$$

Replacing z_f by $T - z_i - z_j$ in (8c), we obtain a necessary condition for the two players to play an interior equilibrium. That is, it is necessary that

$$z_j > \sigma_j^D = \frac{D_j\left(A - B\left(T - z_i\right)\right)}{D_i\left(B + D_i\right)}, \qquad i = 1, 2, j \neq i, \tag{8d}$$

which naturally leads to the definition of S^D. If $z_j \leq \sigma_j^D$, player i acts as a monopolist if he has a sufficient amount of z_i. That is, using Equation (8b),

$$z_i \geq \sigma_i^M = \frac{A - BT}{D_j}. \tag{8e}$$

Comparing the two thresholds σ_i^M and σ_i^D, we obtain

$$\sigma_i^M \geq \sigma_i^D \iff z_j \leq \sigma_j^D.$$

These two elements lead to the definition of S_i^M. □

A.3 Proof of Lemma 1

Proof. According to Definition 3, $F_i(X)$ is continuous in X, which in turn is continuous in x_i for every i. It is thus sufficient to show continuity of $x_i(\mathbf{z})$ in $\mathbf{z}$ for every i. Within each strategy regime defined in Proposition 1, the function $x_i(\mathbf{z})$ is continuous in $\mathbf{z}$. Thus, we must check continuity at the limit of each transition point. From the interior (monopolistic or duopolistic) solutions to the constrained solution, the function is, by definition of the thresholds σ_i^D and σ_i^M, continuous in z_i. Continuity at the transition point between the monopolistic and duopolistic strategies remains to be checked. We have

$$\begin{aligned}
\mathbf{z} \in S_i^M &\iff z_i > \sigma_i^M \text{ and } z_i \le \sigma_j^D \\
\mathbf{z} \in S^D &\iff z_i > \sigma_i^D \text{ and } z_i > \sigma_j^D \\
z_i = \sigma_j^D &\iff \sigma_i^M = \sigma_i^D.
\end{aligned}$$

Since S^D is an open set in the space $(z_i; z_j)$, we show that x_i^D (x_i^* iff $\mathbf{z} \in S^D$) converges to x_i^M (x_i^* iff $\mathbf{z} \in S_i^M$) as z_i tends to σ_j^D. This is sufficient since at this point $z_i > \sigma_i^M \iff z_i > \sigma_i^D$, and S_i^M is bounded in the space $(z_i; z_j)$. We calculate

$$\lim_{z_i = \sigma_j^D} x_i^D = \frac{D_j(A - B(T - z_i - \sigma_j^D))}{B^2 + D_i D_j}.$$

Replacing σ_j^D by its mathematical expression, the required equality is found: $\lim_{z_i=\sigma_m^D} x_i^D = x_i^M \ \forall n$. Hence $x_i(\mathbf{z})$ is continuous in $\mathbf{z}$, $i = 1, 2, f$. In turn $X(\mathbf{z})$ is the sum of all x_i, which sum preserves continuity. This implies that $F_i X(\mathbf{z})$ is continuous in $\mathbf{z}$. □

A.4 Proof of Prop 2

Proof. Following Definition 3, F_i has the following gradient:

$$\triangledown_{F_i} = \triangledown_{X^*} D_i X^*(\mathbf{z}) + \triangledown_{x_i^*} \delta^*(\mathbf{z}) + \triangledown_{\delta^*} x_i^*(\mathbf{z}) - \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \delta^P, \tag{9}$$

(i) $\mathbf{z} \in S^P \implies F_i = 0$. Trivial since by definition $X^P = X^*$.

(ii) $\mathbf{z} \in S^D \implies F_i < 0$.

Implicit variables are functions of z_f only, that is,

$$\mathbf{x}^* = \begin{bmatrix} \frac{D_i(A - B z_f)}{B^2 + D_i D_j} \\ \frac{D_j(A - B z_f)}{B^2 + D_i D_j} \\ z_f \end{bmatrix}, \ X^* = \frac{AB + D_i D_j z_f}{B^2 + D_i D_j}, \ \delta^* = \frac{D_i D_j (A - B z_f)}{B^2 + D_i D_j}. \tag{10a}$$

The derivative for each function w.r.t. z_f are

$$\frac{\partial x_i^*}{\partial z_f} = \frac{-B D_i}{B^2 + D_i D_j}, \qquad \frac{\partial X^*}{\partial z_f} = \frac{D_i D_j}{B^2 + D_i D_j}, \qquad \frac{\partial \delta^*}{\partial z_f} = \frac{-B D_i D_j}{B^2 + D_i D_j}. \tag{10b}$$

Consider first $\tilde{F}_i = F_i + z_i \delta^P$. $\tilde{F}_i$ is a function of z_f only. We have

$$\frac{\partial \tilde{F}_i}{\partial z_f} = \frac{D_i^2 D_j}{(B^2 + D_i D_j)^2} \left(-AB + z_f (D_i D_j + 2B^2) \right).$$

The second derivative is strictly positive, such that $\tilde{F}_i$ is strictly convex in z_f, and the optimum is a minimum. Setting the first derivative to zero, we obtain

$$\underline{z_f} = \frac{AB}{D_i D_j + 2B^2} > 0.$$

Hence, there is a local maximum of $\tilde{F}_i$ on the border of S^D where $z_f = 0$, such that $T = z_i + z_j$. Since $\tilde{F}_i$ is an affine projection of F_i, this is also true for F_i.

For any given $z_f = a$, an increase in z_j corresponds to a reduction of same order in z_i. The gradient of $F_i|_{z_f=a}$ with respect to z_i, z_j, for all a such that $\{z_i, z_j, a\} \in S^D$, is

$$\nabla_{F_i} = \begin{bmatrix} -\delta^P \\ \delta^P \end{bmatrix},$$

such that $F_i|_{z_f=a,\ z_i \to \sigma_i^D} \geq F_i|_{z_f=a,\ z_j = \to \sigma_j^D}$.

In particular, $F_i|_{z_f=0,\ z_i\to\sigma_i^D}$ is a local maximum of a convex function. Calculating F_i at this point, that is, for

$$z_i = \sigma_i^D = \frac{AD_i}{B^2 + D_i D_j} = x_i^*,$$

F_i is equal to

$$F_i|_{z_f=0,\ z_i\to\sigma_i^D} = \frac{D_i}{2}\left[\left(\frac{AB}{B^2 + D_i D_j}\right)^2 - \left(X^P\right)^2\right] + \frac{AD_i}{B^2 + D_i D_j}\left(\frac{AD_i D_j}{B^2 + D_i D_j} - \delta^P\right).$$

Replacing δ^P by $A - BX^P$, $F_i(.)$, we finally obtain

$$F_i|_{z_f=0,\ z_i\to\sigma_i^D} = \frac{-D_i}{2}\left(X^P - X^*\right)^2 < 0. \tag{10c}$$

This implies that $F_i|_{z_f=\underline{z_f}} < 0$, such that $\lim_{\mathbf{z}\to S^P} = 0^-$, $\mathbf{z} \in S^D$, S^D. Hence, the maxima on every bound of S^D are negative, such that $F_i < 0 \forall \mathbf{z} \in S^D$.

(iii) $\mathbf{z} \in S_j^M \implies F_i < 0$.

First, note that for $z_i = 0$, we see, by comparing X^* and X^P, that $F_i(\mathbf{z}) < 0$. The values of individual exports, total exports and price differentials (in the arbitrage direction) in this regime are

$$\mathbf{x}^* = \begin{bmatrix} z_i \\ \frac{A - B(T - z_j)}{B + D_i} \\ z_f \end{bmatrix},\ X^* = \frac{A + D_i(T - z_j)}{B + D_i},\ \delta^* = \frac{D_i\left(A - B(T - z_j)\right)}{B + D_i}. \tag{11a}$$

Notice that z_f is the residual part of z_i and z_j. A two-dimensional representation of $F_i(\mathbf{z})$ is sufficient to describe the value space of the function, namely, in z_i and z_j. This is equivalent to assuming that every addition to (removal from) z_i or z_j is removed from (added to) z_f. Accordingly, the gradients for each function of $\mathbf{z}$ are

$$\nabla_{x_i^*} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \qquad \nabla_{X^*} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}\frac{-D_i}{B + D_i}, \qquad \nabla_{\delta^*} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}\frac{BD_i}{B + D_i}. \tag{11b}$$

Hence, we have

$$\nabla_{F_i} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}\left(\frac{D_i}{B + D_i}\right)\left(-D_i X^* + Bz_i\right) + \begin{bmatrix} 1 \\ 0 \end{bmatrix}\left(\delta^* - \delta^P\right). \tag{11c}$$

If $z_i = T - z_j$, we have

$$-D_i X^* + Bz_i \leq 0 \implies z_i \leq \frac{D_i}{B}X^* \implies z_i \leq \frac{D_i}{B}\frac{A + D_i z_i}{B + D_i} \implies z_i \leq \frac{AB}{D_i^2}$$
$$z_i \leq \sigma_i^D \implies z_i \leq \frac{D_i(A - Bz_i)}{D_j(B + D_i)} \implies z_i \leq \frac{AD_i}{B^2 + D_i D_j}.$$

From this, we conclude that

$$z_i \leq \sigma_i^D \implies -D_i X^* + Bz_i \leq 0, \quad \forall\, \mathbf{z} \in S_j^M, \tag{11d}$$

and thus that any F_i is monotonically decreasing in z_j for any $\mathbf{z} \in S_j^M$. By continuity, $\lim_{z_j \to \sigma_j^M} F_i = 0^-$ since $\mathbf{z} \to S^P$. For the other bound S_j^M, that is, for

$$z_i = \sigma_i^D = \frac{D_i(A - Bz_f)}{B^2 + D_i D_j},$$

we've seen in part (ii) that $F_i < 0$. Hence, for any allocation $\mathbf{z} \in S_j^M$, $F_i(\mathbf{z}) < 0$.

(iv) $\mathbf{z} \in S_i^M \implies \exists\ \tilde{z}_i \in S_i^M$ such that $F_i|_{z_i < \tilde{z}_i} < 0$.

In this regime, the individual and total exports and the price differential are

$$\mathbf{x}^* = \begin{bmatrix} \frac{A - B(T - z_i)}{B + D_j} \\ z_j \\ z_f \end{bmatrix}, \ X^* = \frac{A + D_j(T - z_i)}{B + D_j}, \ \delta^* = \frac{D_j(A - B(T - z_i))}{B + D_j}. \tag{12a}$$

Hence, F_i is a function of z_i only. The first and second derivatives are

$$\frac{\partial F_i}{\partial z_i} = \frac{D_j}{B + D_j}\left[A - (T - z_i)(B + D_i)\right] - \delta^P \tag{12b}$$

$$\frac{\partial^2 F_i}{\partial z_i^2} = \frac{D_j(B + D_i)}{B + D_j} > 0 \tag{12c}$$

Hence F_i is strictly convex in z_i, such that there exists a global minimum $\underline{z_i}$:

$$\underline{z_i} = \begin{cases} \text{if } T < T^*, \text{ then } \frac{AB - T(B^2 - D_i D_j)}{D_j(B + D_i)} < T \text{ if } T > \frac{A}{B + D_j} \\ \text{if } T \geq T^*, \text{ then } T - \frac{A}{B + D_i} < T, \end{cases}$$

where $T > \frac{A}{B + D_j}$ is a necessary condition for S_i^M to exist (see Proposition 1). Below a threshold $\tilde{z}_i$ the value function F_i is always negative. To show this, we calculate the value function at each bound of S_i^M and the associated gradient. For the upper bound $z_i = T$,

$$F_i|_{z_i = T} = \left(\frac{A}{B + D_j}\right)^2 \left(\frac{D_i}{2} + D_j\right) - X^P \left(A - BX^P + \frac{D_i}{2} X^P\right) > 0$$

if $T > \frac{A}{B + D_j}$, which is a necessary condition for S_i^M to exist. Since $\underline{z_i} < T$ and F_i is strictly convex, F_i decreases with a reduction in z_i.

In part (ii) of the proof, we saw that $F_i|_{z_j = \sigma_j^D} \leq F_i|_{z_i = \sigma_i^D} < 0$. In particular, the greatest value of z_i on this border is for $z_f = 0$. Hence,

$$\tilde{z}_i > T - \frac{AD_j}{B^2 + D_i D_j}.$$

By strict convexity and continuity, we finally have that $\lim_{\mathbf{z} \to S^P} F_i = 0^-$, $\mathbf{z} \in S_i^M$. Hence, the threshold $\tilde{z}_i$ exists in S_i^M and is unique, such that $F_i|_{z_i < \tilde{z}_i} < 0$, $\mathbf{z} \in S_i^M$.

□

A.5 Proof of Corollary 1

Proof. Using Lemma 1, continuity of $x_i(\mathbf{z})$ implies that $F_i(\mathbf{z})$ is continous in $\mathcal{V}$. Following Proposition 2, both F_i and F_j are negative for $\mathbf{z} \in S^D$, and thus, the equilibrium is always Pareto-dominated from a local welfare viewpoint in this set. When $\mathbf{z} \in S_i^M$, $F_j < 0$, and for $z_i < \tilde{z}_i$, $F_i < 0$ also, these allocations correspond to Pareto-dominated equilibria. The same situation, but reversed, occurs when $\mathbf{z} \in S_j^M$. From there, the definition of $\mathcal{V}^{\mathcal{D}}$ comes naturally. □

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