

LOCAL NETWORK OPERATORS IN AN INTEGRATED ELECTRICITY MARKET*

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Abstract

Electricity market integration offers significant potential for gains from trade. However it requires that enough transfer capacity is supplied by the transmission system operators (TSOs) that manage local networks. The incentive for TSOs to allocate international interconnection capacity has long been a concern for competition authorities. For example, the European Commission has in several cases argued that withholding of interconnection capacity by TSOs may have represented abuse of dominant position.

This paper formally examines TSO incentives in a setting that captures salient features of the current European electricity market. It demonstrates that under the existing market design, TSOs have an incentive to withhold transmission capacity to increase congestion rents. By implication, it is impossible to implement full price equalization in equilibrium. The analysis then explores various market reforms aimed at mitigating exercise of TSO market power.

A minimum capacity requirement improves efficiency, but faces significant informational challenges that may render it impractical. Another possibility is to introduce a forward market, as advocated by the European Commission. Doing so requires no information, but only increases trade in equilibrium if forward market participation is mandatory for TSOs. We demonstrate how a small change to how congestion rents are distributed can implement efficient trade without imposing excessive informational burdens on regulators. Lastly, the paper cautions that TSOs might benefit from restricting domestic capacity allocations in order to manipulate spot prices even if regulation prevents exploitation of market power on international connections.

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1 Introduction

Trade in electricity can deliver substantial economic gains. Enabling lower-cost power production to replace higher-cost production in other countries or regions; realizing economies of scale by avoiding duplication of investment costs; intensifying competition among producers are some of the mechanisms (e.g., [Gonzales et al., 2023](#), and [Hausman, 2024](#)). Authorities worldwide seek to reap such benefits by integrating electricity networks both domestically and internationally. In Europe, national transmission networks have been integrated through extensive cross-border connections, and new interconnectors are under construction. The European Union (EU) has implemented a centralized market platform to facilitate trade of electricity across the pan-European internal market, and additional platforms for trading electricity closer to dispatch are under development. In North America, cross-border connections between Canada and the United States (U.S.) range from New England to the Pacific Northwest, and the U.S. trades electricity with Mexico, albeit on a smaller scale. There are also ambitions to better integrate domestic grids within the U.S. and Canada.¹ Similar integration processes are taking place in large parts of Asia.²

Physical interconnection of local grids is no guarantee that gains from trade are realized, however. Sufficient interconnector capacity must also be supplied to the market. In Europe, such decisions are effectively made by the transmission system operators (TSOs) who own the national transmission networks and cross-border connections. These organizations often are national authorities. In the U.S., transmission capacity is allocated by publicly-controlled independent or regional system operators. The intra-state transmission networks and the interconnectors are owned by private interests. There are reasons to be skeptical about operators' incentives to supply transfer capacity to the market.

The national or regional scope of system operators implies that they are more likely to promote narrow than system-wide interests. There are countless examples in other policy areas of how integration schemes have been undermined by local authorities using their influence to pursue national or regional objectives. There are thus a priori reasons to believe that TSOs might use transfer capacity allocations to achieve local objectives.

Indications from electricity markets also raise warning flags. One such signal is that actual allocated interconnector capacity sometimes falls substantially short of the nominal capacity. We illustrate this phenomenon with data from the Nord Pool power exchange.³ Table 1 shows the allocation of interconnector capacity to the spot (day-ahead) market

¹For instance, [U.S. Department of Energy \(2023\)](#) emphasizes the gains from expansion of inter-regional transmission capacity. [Federal Energy Regulatory Commission \(2024\)](#) recently released a report that, among other objectives, proposes to enhance the integration of U.S. regional electricity markets.

²See [Cornell \(2020\)](#) for an overview.

³Nord Pool is a nominated electricity market operator (NEMO) that serves market participants in the Nordic and Baltic countries in the European electricity market.

in each direction between bidding zones Denmark East and Germany (DK2-DE and DE-DK2), bidding zones Norway South and Germany (NO2-DE and DE-NO2), and bidding zones Sweden South and Germany (SE4-DE and DE-SE4) on sample data from 2021.⁴

Table 1: The percentage of hours with interconnector capacity restrictions in the Nord Pool day-ahead market in 2021, in terms of hours when (1) supplied capacity was smaller than nominal capacity, and (2) trade was constrained by supplied capacity below the nominal capacity

	DK2-DE	DE-DK2	NO2-DE	DE-NO2	SE4-DE	DE-SE4
(1) Sup. cap. < Nom. cap.	93	76	100	49	100	100
(2) Trade = Sup. cap. < Nom. cap.	66	39	80	12	28	77

The first row shows the percentage of all hours during 2021 for which the supplied capacity was below the nominal capacity. As we can see, capacity reductions were frequent on all those interconnectors. However, such reductions were a problem only insofar as they created bottlenecks that restricted trade. The second row of the table therefore reports the percentage of hours during 2021 when trade was constrained by capacities supplied at a level below the nominal capacity.⁵ Binding capacity restrictions were very common for most of these interconnectors during that year. Capacity reductions can be imposed for innocuous reasons, such as transmission line failures, maintenance needs, and operational security measures, but they can also result from system operators’ withholding of capacity to achieve other objectives. These shortfalls seem sufficiently frequent in Europe at least, to warrant a closer examination.

Even more incriminating, system operators have been caught with “smoking guns” on several occasions. The European Commission found in 2010 that the Swedish government-owned TSO had intentionally reduced export capacity from Sweden to Denmark. In a similar case from 2018, the Commission concluded that a German TSO had significantly limited import capacity from Denmark to Germany. The Commission concluded in both cases that the conduct has discriminated against foreign consumers and producers, and therefore could represent abuse of dominant position, in violation of EU competition rules.⁶ Indeed, this type of behavior has been sufficiently common that the EU Agency for the Cooperation of Energy Regulators (ACER) considers that “[o]ne of the main problems related to capacity calculation is the discrimination between electricity exchanges.”⁷

⁴The data is taken from nordpoolgroup.com/en/Market-data/1/nordic/table.

⁵By definition, such a restriction occurred between two interconnected bidding zones for a given trading hour during 2021 if and only if the transfer capacity on the interconnector was strictly below the nominal capacity and the prices differed between the two zones for that hour.

⁶European Union (2010) and European Union (2018), respectively.

⁷ACER (2019).

In sum, system operators can be suspected of pursuing objectives that are not fully in line with the objectives driving market integration, they have the means to at least partly achieve their own objectives, and there are actual instances where system operators have been found to use their market power to this effect.

This paper investigates system operators' incentives to exercise market power by withholding transmission capacity in an integrated market. The analysis builds on institutional features of the world's largest electricity market, the European market, which serves over half a billion people. The paper identifies trade-offs operators face when supplying cross-border capacity to the market and inefficiencies that result from market interaction. It also examines how regulation can implement more efficient outcomes. While the focus is on a European-style market, the findings should be of relevance for integrated electricity markets more generally.

Institutional features Spot markets for electricity differ from other commodity markets in important ways. One difference is that a centralized platform sets local area prices. Retailers and producers submit purchase bids and sales offers to the platform. A market algorithm clears supply and demand to maximize total surplus subject to the constraint that trade cannot exceed the network transfer capacity. The equilibrium price is the same in all areas if there is enough transfer capacity to sustain the volume of trade required to balance aggregate demand and aggregate supply at a uniform spot price. However, if transfer capacity is insufficient to implement such an equilibrium, then the algorithm clears the market by setting higher prices in import areas than in export areas.⁸

Another standard feature of electricity markets is that consumers pay and producers receive the local spot price of electricity. Consumer payments to the market platform therefore exceed the payments paid out to generation owners when area prices differ due to binding network constraints. The surplus is paid out to the owners of the congested transmission lines as a *congestion rent* in proportion to their ownership shares. This feature is known as an implicit auction of network capacity or market coupling.

A special feature of the European market is that network owners supply transfer capacity to the market. The capacity of an interconnector is commonly determined as the minimum of supplied capacity by the TSOs controlling the particular interconnector.⁹

⁸The European market platform *Euphemia* partitions the market into geographic bidding zones. Most countries constitute single bidding zones, but Denmark, Italy, Norway and Sweden have multiple bidding zones. In a nodal market design, which is employed in e.g. United States, every node in the electricity network can potentially have a unique price. In contrast, all nodes contained in a bidding zone have the same price in a zonal market. The two designs are equivalent if there is a free flow of electricity across all nodes contained in each bidding zone as is assumed in the model we present below.

⁹The procedure is denoted *net transfer capacity* allocation. Another method in the European spot market is *flow-based transfer capacity* allocation. The TSOs report their respective domestic network conditions to the market platform, which then calculates the transfer capacity and clears the market to

This “Leontief” property of the capacity allocation has important implications for market interaction. Intuitively, it places a ceiling on the capacity transfer that TSOs can allocate to the market, the height of which is determined by the TSO least interested in trade. Hence, the fact that TSOs at each end of an interconnector can unilaterally restrict the transfer capacity as they like, but cannot unilaterally undo restrictions imposed by other TSOs, provide a mechanism for trade to be downward distorted. In the decision to supply transmission capacity to the market, TSOs face a trade-off between the private sector gains from unconstrained trade and the congestion rent that arises as a consequence of constrained trade. We elaborate more on this trade-off below.

The formal setting We develop a two-country model in which there is scope for trade since the marginal cost of electricity production in autarky is lower in one country than the other. In each country there is a national grid. The two national grids are connected by a transmission line with sufficient capacity to sustain efficient trade, which occurs at the point where marginal production costs are equalized across countries.

In each country a government-owned TSO controls the national grid. The national TSOs jointly own the interconnector. Each TSO maximizes national welfare, as represented by the unweighted sum of domestic consumer and producer surplus, plus government revenue, as is standard in partial equilibrium analysis. This assumption allows us to focus on distortions caused by the national character of TSOs, while disregarding consequences of national government-TSO agency problems.

Market prices in the two countries are determined by a market platform, to which retailers and producers submit bids and offers and the TSOs supply cross-border transfer capacity. The transfer capacity on the interconnector is calculated as the minimum of the two capacities supplied by the TSOs, the Leontief property. We assume that retail bids reflect the marginal value of consumption and that supply offers reflect the marginal cost of production, so that any inefficiency stems from withholding of interconnector capacity by the TSOs. A congestion rent arises if the supplied transmission capacity restricts trade between the two countries. This congestion rent equals the difference between the import and the export price multiplied by the level of trade. It is split between the two TSOs according to their ownership share of the interconnector.

Findings By the Leontief property of transfer capacity allocation, each TSO can reduce trade from a positive level, but cannot increase trade beyond the other TSO’s supply of

maximize total surplus. [Tangerås \(2024\)](#) shows that the two methods yield identical trade in equilibrium in the context of the current model if TSOs are privately informed about domestic network conditions. Private information enables a TSO to implement its desired transfer capacity by manipulating the reported network condition. Net transfer and flow-based capacity allocations are strategically equivalent in this case.

capacity. A necessary and sufficient equilibrium condition is therefore that neither TSO can benefit from reducing trade. Hence, the market can sustain a continuum of equilibria, including autarky. But equilibria with more trade are shown to Pareto dominate those with less trade, so both TSOs want to implement an equilibrium that maximizes trade. By payoff dominance, we assume that TSOs can coordinate on such an equilibrium.

Equilibria with maximal trade have features of potential significance for actual integration efforts. On the one hand, increased trade benefits the private sector in both countries. In the exporting country, producers gain more from an increase in the price of electricity than consumers lose. In the importing country, consumers gain more from a reduction in the price of electricity than producers lose. Private sector concerns should induce both TSOs to supply full transfer capacity. On the other hand, reduced trade increases congestion rent by enlarging the wedge between the price of electricity in the import and the export country. We show that the latter effect is so strong that one TSO has a strict incentive to reduce trade below the efficient level. Circumstances decide if it is the TSO in the importing or the exporting country that withholds capacity in equilibrium. The impossibility to sustain efficient trade in our model points to an inherent problem to achieve the full benefits of integration when system operators are decentralized.

The equilibrium in a market where network owners exercise market power is similar to the equilibrium in a market where producers exercise market power, but with important differences. A generation owner maximizes profit at the point where its Lerner index equals the inverse elasticity of residual demand. The relevant marginal cost in a TSO's Lerner index is the spot price in the exporting country as TSOs do not own generation capacity, but effectively buy electricity in the export country. For a profit-maximizing TSO, the Lerner index equals the sum of the inverse elasticity of residual demand in the import and the export country at optimum because trade affects prices in both countries.¹⁰ This aggregation effect increases the incentive to exercise market power compared to a generation owner. A mitigating effect arises for TSOs that maximize national welfare because they are concerned with the negative effects for the domestic private sector of reducing trade. This mitigating effect is proportional to the inverse elasticity of residual

¹⁰We consider also a setting with profit-maximizing TSOs because some TSOs are privately-owned. The association European Network of Transmission System Operators for Electricity (ENTSO-E) represents 40 TSOs from 36 countries across Europe. Members that are to some proportion privately-owned include Belgian Elia, Finnish Fingrid, French RTE, German EnBW, German 50Hz, Italian Terna, IPTO in Greece, Hungarian MAVIR, Lithuanian Litgrid, Creos Luxembourg, CGES in Montenegro, Portugues REN, Romanian Transelectrica, Spanish REE, Scottish Power Transmission, Scottish Hydro Electric Transmission, Swissgrid in Switzerland and Ukrenerg in Ukraine. See entsoe.eu/about/inside-entsoe/members/ for a list of European TSOs. There are also instances where a government-owned company from one country owns or controls a TSO in another country. For instance, German TenneT is fully-owned by the Dutch government, and Belgian Elia, which is partly owned by the Belgian government, controls German 50Hz, previously owned by Swedish state-owned Vattenfall.

demand in the home country and relatively more important when the TSO owns as smaller share of the interconnector.

Another empirically highly relevant aspect of TSO market power is that transmission constraints are not confined to cross-border connections. Many national and regional networks experience frequent internal congestion. Congestion rents on domestic networks do not have to be shared with other system operators. At the same time, such restrictions can have similar effects on trade with other networks as capacity restrictions on interconnectors. This raises the question if TSOs have incentives to use domestic transmission restrictions as a complement or substitute to restrictions on the interconnector. In an extension featuring a domestic transmission constraint in the exporting country, we show that the exporting country TSO for any strictly positive trade volume prefers to restrict domestic transmission capacity, unless the TSO fully owns the cross-border connection.

Policy implications Our analysis shows that electricity markets with decentralized system operators might feature insufficient trade. So how common is this in practice? As shown above, data from Northern Europe suggest that capacity restrictions are very frequent on international lines. Of course, this could have innocuous explanations. We therefore derive an econometric specification that makes it possible to distinguish between capacity reductions that occur for exogenous reasons, and those that result from market power by TSOs. This structural specification differs qualitatively from methods used to identify producer market power, and can be estimated on publicly available data.

A natural remedy for capacity withholding is a *minimal capacity allocation rule*. Such a rule is in place in the European market, where the EU requires at least 70 % of net capacity to be offered to the market. We show how such a rule increases welfare. Still, it can be difficult to implement in practice since operational security constraints may reduce the net transfer capacity in a way unobservable to outsiders.

Another alternative could be to introduce *forward markets*, since they have been shown to improve spot market performance elsewhere. We extend the model to include a forward market and examine whether such a market will be an effective remedy against exercise of TSO market power. While the forward market has certain beneficial features, TSOs will not participate in the market in equilibrium. Hence, mandatory forward trading by TSOs is required. The EU has taken steps in this direction by requiring TSOs to issue transmission rights. These have similar properties to forward contracts.

We finally show how efficient trade can be implemented as a unique equilibrium in our model through a *modification of the current EU market design*. It deviates from the EU design only with respect to how the congestion rent is split among the network owners. Under the modified rule, a TSO that exacerbates congestion by supplying strictly lower

capacity than the other TSO receives none of the congestion rent. This mechanism causes TSOs to internalize the full consequences of imposing a trade restriction.

Related literature A large body of research focuses on the exercise of market power by producers in electricity markets, mostly abstracting from network effects.¹¹ Some papers analyze how transmission constraints affect competition in the spot market from a theoretical (Blázquez de Paz, 2018) or empirical perspective (De Cannière, 2024). A strand of literature analyzes efficiency gains of coordinating electricity supply in competitive markets with network capacity constraints, e.g. Oggioni et al. (2012); Oggioni and Smeers (2012, 2013); Kunz and Zerrahn (2015, 2016). Our paper differs from the above contributions by focusing on the *endogenous* supply of network capacity.

Borenstein et al. (2000) show how producers in an import zone can induce congestion in the transmission network by withholding capacity from the spot market. This strategy can be profitable by insulating the local market from competition by producers located in surrounding bidding zones. Graf and Wolak (2022) demonstrate the relevance of this mechanism by establishing how endogenous network constraints can explain actual behavior by producers in the Italian spot market for electricity. Our paper emphasizes instead the behavior of network owners.

Closest to our paper are Glachant and Pignon (2005), van Beesten and Hulshof (2023), and Flachsbarth et al. (2024), which use numerical representations of power grids to show how TSOs can benefit from reducing cross-border capacity to relieve domestic congestion. We consider a qualitative framework and perform an equilibrium analysis which we extend in directions not previously considered. Related to our analysis of market design, Höfler and Wittmann (2007) identify an auction that reduces the incentive to withhold capacity when the owner of an interconnector sells access to it. Explicit auctions of transmission capacity have mostly been abandoned in Europe in favor of the design we consider where network owners receive congestion rent for the capacity they supply to the market.

2 The setting

Consider a setting in which two countries, E and I , trade electricity. We assume for the most part that the national grid in each country has sufficient capacity to handle all domestic electricity flows. The two national grids are joined via an *interconnector* that transmits electricity without any physical losses.

¹¹The basic theory was laid out by Klemperer and Meyer (1989) and von der Fehr and Harbord (1993). These frameworks have been extended in many directions. Classical empirical applications are Wolfram (1999) and Borenstein et al. (2002). See Reguant (2014) and Koichiro and Reguant (2016) for more recent contributions.

2.1 Market participants

There are three types of market participants.

Retailers In each country there is completely price inelastic demand for electricity as well as supply of intermittent renewable electricity production, such as solar and wind power. We refer to the difference as "retailer net demand," which we assume to be the same in both countries and equal to $y > 0$.¹² Retailers' gross welfare is v per consumed unit of electricity, which also is constant for ease of exposition.

Flexible producers Each country $i = E, I$ produces flexible electricity in amount x_i . Generation capacity $x_i^{\max}$ is sufficient to meet domestic net demand, $x_i^{\max} \geq y$. The cost of producing this power is represented by an increasing, strictly convex and twice continuously differentiable function $C^i(x_i)$. The marginal cost of production is smaller than the marginal value of consumption, $C_x^i(y) < v$, implying that economic rationing of consumption is inefficient.¹³ By an assumption that the marginal cost is lower in country E , $C_x^E(y) < C_x^I(y)$, country E will export electricity to country I .

TSOs The national grid in country i is owned by a national transmission system operator denoted TSO i . This TSO also owns a share $\alpha_i \in (0, 1)$ of an interconnector with sufficient transfer capacity to sustain efficient trade across the two countries. However, central to what follows, each TSO can restrict trade between the two national grids by imposing a capacity constraint on the interconnector.

2.2 Efficient trade

The joint welfare of the two countries,

$$W(z) \equiv 2vy - C^E(y + z) - C^I(y - z), \quad (1)$$

represents our benchmark for measuring the economic efficiency of market allocations as a function of trade $z \geq 0$ between the two countries. The welfare function is strictly concave, $W_{zz} = -C_{xx}^E - C_{xx}^I < 0$, and therefore reaches its maximum under the trade volume $z^* > 0$ that equalizes the marginal production cost across the two countries,

$$C_x^E(y + z^*) \equiv C_x^I(y - z^*). \quad (2)$$

¹²An earlier version assumed stochastic net demand in each country to capture the volatility of e.g. solar and wind power. Since uncertainty does not fundamentally change the incentives for risk-neutral TSOs to exercise market power, we here employ a significantly more transparent deterministic setting.

¹³Subscripts on functional operators denote partial derivatives.

With the efficient level of trade determined by (2), efficient production in country i equals $x_i^* \equiv y + \delta_i z^*$, where $\delta_E \equiv -\delta_I \equiv 1$. Absent trade, it would be necessary to serve local net demand entirely by local production, $x_i = y$, resulting in a globally inefficient marginal cost difference $C_x^E(y) < C_x^I(y)$. Given the strict concavity of the welfare function:

Observation 1 *Trade volumes closer to z^* strictly increase joint welfare, and unconstrained trade maximizes efficiency.*

2.3 The market platform

Retailers submit purchase bids, flexible producers submit sales offers, and TSOs supply available interconnector capacity to a market platform in a European-style zonal market for electricity. These actions are taken simultaneously and non-cooperatively.

Market bids and offers We let retailers in country (zone) i inelastically bid to purchase y at any price $p_i \leq v$. Flexible producers offer to sell at marginal cost up to the capacity limit $x_i^{\max}$. TSO E supplies available export capacity $k_E \geq 0$ to the market platform, and TSO I supplies available import capacity $k_I \geq 0$. The *net transfer capacity* k is calculated as the minimum of the two supplied capacities, $k \equiv \min \{k_E, k_I\}$; the "Leontief" property of capacity allocation. Trade z on the interconnector cannot exceed k .

Market-clearing prices The market platform sets prices in the two national markets (zones) based on the submitted bids, offers and the net transfer capacity. The market platform seeks to *maximize aggregate economic surplus* of the two countries, while ensuring the *physical balance* of the system. The electricity injected into the grid in country E must equal consumption in country E plus the exports to country I , and a symmetric relationship must hold in country I :¹⁴

$$x_E - y = z = y - x_I. \quad (3)$$

With competitive supply of flexible electricity, physical balance is achieved for an arbitrary trade volume $z \leq k$ through spot prices that satisfy

$$p_i = P^i(y + \delta_i z) \equiv C_x^i(y + \delta_i z). \quad (4)$$

¹⁴This might appear as a trivial market-clearing condition. However, physical balance of an electricity system is not achieved by an invisible hand. System operation is fundamental to prevent costly disruptions. A prominent example in the U.S. is the Northeast blackout of 2003. It started with a power plant in Ohio shutting down that spread through the system as transmission lines sequentially tripped offline. The ensuing outage affected some 10 million people in Ontario and 45 million people in eight U.S. states.

These prices ensure that generation owners in country E produce $x_E = y + z$, generation owners in country I produce $x_I = y - z$, and that the resulting trade levels are feasible given the net transmission capacity. In particular, these spot prices implement the physical balancing requirements in (3). An increase in trade requires additional production and thereby a higher price in E , $P_x^E > 0$, which is offset by a corresponding decrease in production and a lower spot price in I , $-P_x^I < 0$.

Expression (4) specifies zonal prices for arbitrary trade. To maximize the total economic surplus, the platform sets prices to implement trade z that minimizes the cost of serving demand. By the properties of the joint welfare function (1), and the conditions for economic efficiency in (2), a cost-minimizing trade flow z is characterized by

$$z = \min\{z^*; k\}, \quad (5)$$

thus accounting for the net transfer capacity k .

Country welfare The welfare of country i is the sum of three components. First, retailers derive utility $v_i y$ and pay $p_i y$ for their net consumption. Second, generation owners receive $p_i x_i$ and pay the cost $C^i(x_i)$ for their production. The third component is specific to electricity markets and arises because consumers pay and producers receive the domestic price of electricity. When a transmission constraint creates a price difference between countries, users pay more for their consumption than generation owners receive for supplying it. In line with EU regulation, the difference is split between the owners of the interconnector as a *congestion rent* in proportion to the ownership share (α_E, α_I) . In the present setting, the total congestion rent equals $(p_I - p_E)z$.¹⁵

3 Exercise of TSO market power

TSOs have market power in the spot market as they can affect prices by reducing the net transfer capacity of interconnectors. A central issue for market performance is the extent to which TSOs exercise this market power. We first discuss TSO objective functions, and then the implications for the market outcomes.

3.1 TSO objectives

Most of the TSOs in the European market are state-owned, regulated entities. As such, they are likely to take into consideration broader implications of their decisions than

¹⁵The aggregate rent corresponds to the sum of the net payments by the private sector in the two countries: $p_E y + p_I y - p_E x_E - p_I x_I = (p_I - p_E)z$.

just pure rents or profits, such as implications for domestic consumers and producers. To emphasize national ownership as the main mechanism behind our results rather than, say, a government-TSO agency problem, we will for the most part assume that TSOs maximize the welfare of their respective country. But this choice of TSO objective function is not essential to the results as we show in Section 3.3 by considering profit-maximizing TSOs.

Using the market-clearing price (4) and the condition $x_i = y_i + \delta_i z$ for physical balance, national welfare in country i ,

$$\begin{aligned}\Omega^i(z) \equiv & \quad vy - C^i(y + \delta_i z) + \delta_i P^i(y + \delta_i z)z \\ & + \alpha_i [P^I(y - z) - P^E(y + z)]z,\end{aligned}\tag{6}$$

can be written entirely as a function of trade z . In this expression, $vy - C^i(y + \delta_i z)$ captures the real component of national welfare, which is the utility of consumption minus the domestic production cost. The subsequent terms capture distributional effects of trade. The $\delta_i P^i(y + \delta_i z)$ term represents the net payment to the domestic private sector consisting of the retailers and generation owners in i . It is positive in the exporting country and negative in the importing country. The expression on the second row is TSO i 's congestion rent. Whether the system operator owns the interconnector does not matter, as long as it maximizes national welfare. In this case, our results extend to other network ownership structures than TSOs.

3.2 Incentives to exercise market power

When TSO i maximizes national welfare $\Omega^i(z)$ characterized in (6), it takes into account the net transfer capacity constraint $z = \min\{z^*, k\}$. Assume that TSO j has supplied sufficient capacity, $k_j \geq z^*$, to sustain efficient trade. The impact on TSO i of marginally relaxing a binding trade constraint $k_i = z < z^*$ is

$$\Omega_z^i(z) = P_x^i(x_i)z + \alpha_i \{p_I - p_E - [P_x^E(x_E) + P_x^I(x_I)]z\}.\tag{7}$$

Holding the domestic price fixed, a marginal increase in trade increases the revenue of producers in country E by p_E , but also raises their production cost by C_x^E . It decreases the revenue of producers in country I by p_I , but also reduces production cost by C_x^I . These quantity effects cancel out in both countries by the assumed competitive supply of generation capacity, $p_i = C_x^i$, $i = E, I$.

The higher export price associated with an increase in trade benefits domestic producers but hurts domestic consumers in E . The marginal producer benefit dominates the marginal consumer loss since the private sector in E is a net exporter in the spot market. In country I , the lower import price resulting from an increase in trade benefits domestic

consumers but hurts domestic producers. The marginal consumer benefit dominates the marginal producer loss since the private sector in I is a net importer in the spot market. Hence, the marginal price effect of an increase in trade is positive for the domestic sector in both countries. This is the first effect on the right-hand side of (7).

The increase in trade also affects congestion rent, as captured by the term in curly brackets in (7). Since the spot price in the importing country is higher than in the exporting country, a marginal expansion of the trade volume increases the congestion rent by $p_I - p_E$ for given prices. But a marginal increase in trade also reduces the price difference between the two countries by driving up the spot price in E and diminishing the spot price in I . Both price adjustments contribute to closing the price wedge, which reduces congestion rent. This is the second term inside the curly brackets.

It is of particular interest to examine whether TSOs have incentive and possibility to constrain trade below the efficient level. Evaluating marginal national welfare at z^* yields

$$\begin{aligned}\Omega_z^i(z^*) &= \{P_x^i(x_i^*) - \alpha_i[P_x^E(x_E^*) + P_x^I(x_I^*)]\}z^* \\ &= [\alpha_j P_x^i(x_i^*) - \alpha_i P_x^j(x_j^*)]z^*\end{aligned}\tag{8}$$

since prices in the two countries are identical under efficient trade. This expression is non-zero for all but one ownership configuration of the interconnector. The marginal benefit of reducing trade below z^* generally is strictly negative for one TSO and strictly positive for the other. This feature, combined with the Leontief property that enables TSOs to unilaterally reduce trade, has strong implications for efficiency:

Proposition 1 *One of the TSOs has a strict incentive to reduce trade below the efficient level for generic ownership distributions of the interconnector. Thus it is generally impossible to sustain an equilibrium with efficient trade.*

An unregulated internal market thus suffers from a fundamental inefficiency regarding the supply of cross-border transmission capacity. A further implication is that one TSO will be hurt by the other TSOs exercise of market power. Unlike in other markets, TSOs do not have a joint incentive to reduce trade.

Figure 1 illustrates the market outcome when the transmission capacity is set by one of the TSOs at a level z^M which is below the efficient trade z^* that equalizes prices at p^* in the two countries. In standard fashion, the upward sloping schedule is the export supply curve—that is, the exporting country’s supply less its domestic demand for any price—and the downward-sloping schedule is the correspondingly derived import demand for the other country. With trade restricted to z^M , the resulting local prices are p_E^M and p_I^M in the exporting and importing country, respectively. Consumers in the importing country pay a total of $p_I^M z^M$ for their imported electricity. Producers in the exporting country

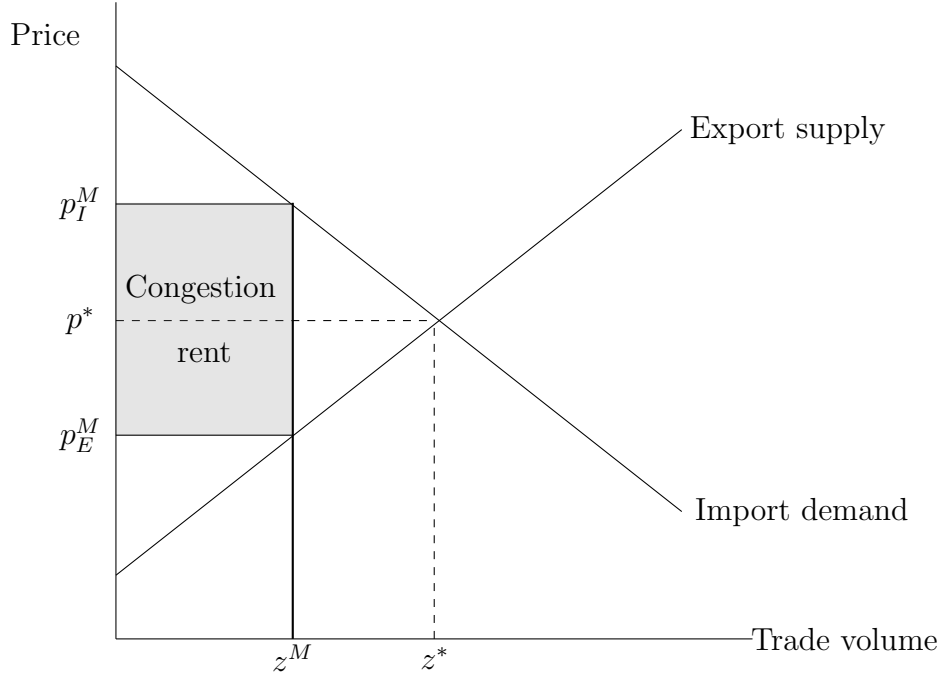


Figure 1: The electricity market with a binding transmission constraint z^M

receive a total of $p_E^M z^M$ for their exported electricity. The net difference $(p_I^M - p_E^M)z^M$, represented by the shaded area in the figure, represents the congestion rent which is split between the TSOs according to their ownership share of the interconnection.

The figure is based on an arbitrary level of the transmission capacity constraint z^M . We now turn to the central issue of what determines this level. For instance, will it be the TSO in the importing or the exporting country that imposes the more stringent capacity restriction, and which are the factors that determine this outcome?

3.3 How TSO market power distorts trade

The previous section showed that efficient trade generally cannot be an equilibrium. We now examine equilibrium properties of the spot market.

Multiple equilibria By the Leontief property of capacity allocations, trade $z \in [0, z^*]$ can be sustained as an equilibrium if and only if

$$\Omega^E(z') \leq \Omega^E(z) \text{ and } \Omega^I(z') \leq \Omega^I(z) \quad \forall z' \in [0, z]. \quad (9)$$

If $k_j = z$, then TSO i can only implement trade equal to or below z . Downward deviations are unprofitable if (9) is met. But if $\Omega^E(z') > \Omega^E(z)$ or $\Omega^I(z') > \Omega^I(z)$ for some $z' < z$, then one TSO can strictly increase national welfare by supplying capacity $z' < z$, thereby

reducing trade on the cross-border connection to z' .

Condition (9) implies that the game may exhibit multiple equilibria, including autarky (no trade). We illustrate this phenomenon in Figure 2 by displaying best-response functions for the two TSOs. The figure shows the export capacity k_E by TSO E on the horizontal axis and the import capacity k_I by TSO I on the vertical axis. $z_E^o \equiv \arg \max_z \Omega^E(z)$ represents the trade level that maximizes national welfare in the export country, and $z_I^o \equiv \arg \max_z \Omega^I(z)$ the corresponding level for the import country. In the figure, TSO I prefers more trade than TSO E .

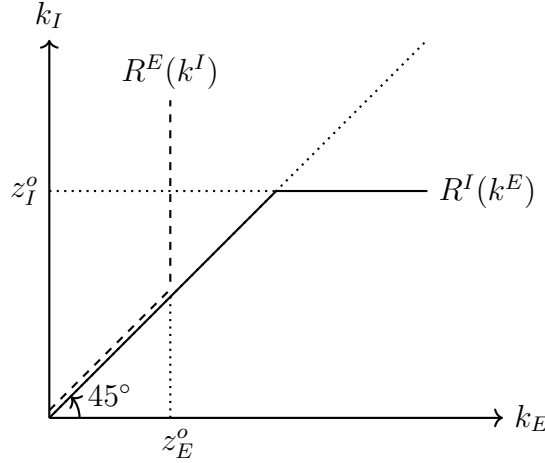


Figure 2: TSO best-reply functions illustrating the multiplicity of equilibria

For any capacity supply $k_E \geq z_I^o$ by TSO E , TSO I maximizes country I national welfare by setting the import capacity $k_I = z_I^o$, thus implementing its most preferred trade z_I^o . If $k_E < z_I^o$, then TSO I cannot implement its most-preferred trade because of the export restriction imposed by the other TSO. However, if national welfare is quasi-concave in trade, TSO I will prefer to maximize imports subject to TSO E 's export restriction. In this case, it is optimal to match TSO E 's capacity supply by setting $k_I = k_E$. The solid line in the figure shows an optimal capacity allocation $R^I(k^E)$ for TSO I as a function of the capacity allocation k_E by TSO E . The dashed line displays a best-reply function $R^E(k^I)$ for TSO E depending on the capacity k_I supplied by TSO I , assuming that national welfare in country E is quasi-concave in trade. It is impossible to sustain trade $z > \min\{z_E^o, z_I^o\}$ because one TSO could implement its most-preferred trade by reducing net transfer capacity otherwise. All trade equal to or below z_E^o can be sustained in equilibrium if TSO objective functions are quasi-concave. If both TSOs supply the same capacity $k_E = k_I = z \in [0, z_E^o]$, then neither of them can unilaterally implement more trade than z , and each would lose by reducing trade below z .

Selecting the maximal equilibrium The Leontief property of capacity allocations leads to an equilibrium selection problem. However, among the potential equilibria, both TSOs prefer those with more trade over those with less. Hence, equilibria that implement maximal trade Pareto dominate all other equilibria.¹⁶ In the above figure, $z_E^o < z_I^o$ represents the maximal trade than can be sustained in equilibrium. The following general property of the set of equilibria is formally verified in Appendix A.1:

Lemma 1 *Equilibria with more trade Pareto-dominate those with less trade. There exists a maximal equilibrium with strictly positive trade.*

Positive trade can be sustained in equilibrium because both TSOs prefer some trade over autarky,

$$\Omega_z^i(0) = \alpha_i[P^I(y) - P^E(y)] > 0.$$

Starting at zero, only the marginal gain from trade associated with exporting low-cost electricity to the import country matters. All marginal price effects vanish.

Interactions are very frequent in electricity markets, so it seems reasonable to assume that TSOs can coordinate sufficiently to implement an equilibrium with maximal trade. This outcome seems particularly plausible if TSO objective functions are quasi-concave. It is then a weakly dominating strategy for each TSO to supply capacity equal to its most-preferred trade in $[0, z^*]$. We will from now on assume that TSOs implement an equilibrium with maximal trade z^M , and characterize it in the generic case when $z^M < z^*$.

Features of the maximal equilibrium In maximal equilibrium, flexible production in country i equals $x_i^M \equiv y + \delta_i z^M$, and the corresponding spot price is $p_i^M \equiv P^i(x_i^M)$. By necessity, $\Omega_z^E(z^M) \geq 0$ and $\Omega_z^I(z^M) \geq 0$ because one of the TSOs would reduce trade by a downward deviation from z^M otherwise. One of the first-order conditions must hold with equality since TSOs could implement an equilibrium with more trade than z^M if the marginal national welfare expressions were both strictly positive evaluated at z^M . The first-order condition $\Omega_z^i(z^M) = 0$ yields the following characterization:

Proposition 2 *An equilibrium with maximal trade is characterized by*

$$\frac{p_I^M - p_E^M}{z^M} = P_x^E(x_E^M) + P_x^I(x_I^M) - \min_{i=E,I} \frac{P_x^i(x_i^M)}{\alpha_i}. \quad (10)$$

¹⁶Equilibrium selection based on Pareto-dominance is sometimes problematic despite its intuitive appeal. However, the most common weaknesses of this selection concept do not arise in our simple setting. The maximal equilibrium is the unique Pareto-dominant allocation so the criterion has full bite. The common incompleteness of the ordering of equilibria based on the Pareto criterion is not an issue. There is no scope for strategic manipulation of preferences in our full information setting, and there is no status quo-dependency.

The equilibrium condition in a market where network owners exercise market power is similar to the equilibrium condition in a market where producers exercise market power, but with important differences. A generation owner in the import country maximizes profit when its Lerner index equals the inverse elasticity of residual demand,

$$\frac{p_I - mc}{p_I} = |P_x^I| \frac{x}{p_I},$$

where mc measures the generation owner's marginal production cost. We can rewrite (10) in a similar manner as

$$\frac{p_I^M - p_E^M}{p_I^M} = P_x^I \frac{z^M}{p_I^M} + P_x^E \frac{z^M}{p_I^M} - \frac{1}{\alpha_i} P_x^i \frac{z^M}{p_I^M}. \quad (11)$$

The TSO does not own any production, but buys electricity from producers in the export country to sell it in the import country. Its relevant marginal cost is therefore the price of electricity in the export country. The first term on the right-hand side of TSO i 's optimality condition (11) measures the inverse elasticity of residual demand. However, the TSO also exercises buyer power by accounting for how trade increases the price of electricity in the export market. The second term on the right-hand side of (11) measures the inverse elasticity of supply. Price sensitivities aggregate across the two markets, which tends to increase exercise of market power. By the assumption of national welfare maximization, the TSO accounts for the beneficial price effect on the domestic private sector of an increase in trade. This effect, represented by the third term on the right-hand side of (11), reduces exercise of market power on the interconnector. Joint ownership implies that each TSO only receives a part of the congestion rent resulting from a trade restriction. The private sector effects are relatively less important to TSO i when its ownership share α_i of the interconnector is larger, which tends to reduce trade and drive up price differences between the two markets.

In our setting, all price differences in the spot market result from TSO exercise of market power. In reality, domestic network constraints may limit the interconnector capacity for operational security reasons. TSOs have private information about these constraints through their superior knowledge of domestic operating conditions. The challenge for competition authorities is the impossibility of distinguishing between efficient and inefficient capacity allocation simply by observation of nominal capacity restrictions.

By drawing on Proposition 2, competition authorities might be able to econometrically disentangle whether price differences are caused by exercise of market power or exogenous capacity constraints. Equation (10) establishes a structural relationship between the price difference in the spot market as the dependent variable on the left-hand side, and the incentive to exercise market power as the independent variable on the right-hand

side. An unbiased estimate of this relationship would measure the extent to which TSOs exercise market power. In particular, TSOs would be found to behave efficiently if there was no statistically significant relationship between the price elasticity of demand and the price differences between bidding zones. Estimation would require ownership data and market information held by the power exchange, both of which should be readily available to competition authorities. Identification issues still apply, of course. For instance, it is necessary to plausibly control for exogenous changes in system conditions that affect the demand slopes as well as price differences, since actual available transmission capacity is not directly observable. We leave resolution of such endogeneity problems for future empirical applications of the theory.

Which TSO will restrict trade? A reduction in trade can be in the shape of an export restriction imposed by the TSO in country E or an import restriction imposed by the TSO in country I . By inspection of (10), trade is limited by an import constraint if

$$\frac{P_x^I(x_I^M)}{P_x^E(x_E^M)} < \frac{\alpha_I}{\alpha_E}.$$

TSO I either owns such a large share of the interconnector or the marginal price effect on the domestic private sector is so weak that it has more to gain than TSO E from withholding transmission capacity. An export restriction applies if the inequality is reversed.¹⁷

Whether trade is restricted by the TSO in the exporting or importing country depends in general on the interaction between ownership shares of the cross-border interconnector, and the sensitivity of local prices to changes in trade. But we can identify two polar cases:

Corollary 1 *The TSO in country i restricts trade if its ownership share is close to one, or if the price elasticity in market i is very small ($P_x^i(x_i^M)$ close to 0), regardless of whether country i is exporting or importing.*

Ownership of the interconnector The benefit of exploiting market power depends on the TSO's ownership share of the interconnector; see equation (7). This leads to the question of how interconnector ownership affects trade and thereby efficiency. Let $z_i^o(\alpha_i)$ be the level of trade that maximizes national welfare in country i . Equilibrium trade is then characterized by $z^M = \min\{z_E^o(\alpha_E); z_I^o(\alpha_I)\}$ if the national welfare functions are strictly quasi-concave.

¹⁷The anecdotal evidence discussed in the introduction suggests that both forms of restrictions have occurred. There have also been competition cases involving both forms: The European Commission found in 2010 that the Swedish TSO limited exports from Sweden to Denmark, and it found in 2018 that the German TSO TenneT restricted imports into Germany from Denmark.

Consider a very skewed distribution in which TSO E earns most of the congestion rent. With α_E close to 1, TSO E has strong incentives to increase congestion rent by reducing trade. TSO I has weak incentives to exercise market power and prefers maximal trade, $z_I^o(\alpha_I) = z^*$. Hence, the export constraint is binding in equilibrium, $z^M = z_E^o(\alpha_E)$. A marginal reduction in TSO E 's ownership share then increases trade and efficiency by

$$-\frac{dz_E^o}{d\alpha_E} = \frac{-P_x^E}{\alpha_E \Omega_{zz}^E} > 0.$$

However, there is a limit to how much TSO E 's ownership share can be reduced before efficiency starts to fall. The corresponding increase in TSO I 's ownership share increases the incentive to withhold import capacity. In interior optimum ($z_I^o > 0$),

$$\frac{dz_I^o}{d\alpha_I} = \frac{P_x^I}{\alpha_I \Omega_{zz}^I} < 0.$$

Increasing α_I eventually causes the import restriction to bind, after which a further increase in α_I reduces trade as $z^M = z_I^o(\alpha_I)$. We conclude that:

Corollary 2 *Joint ownership of the interconnector is efficient in the sense that there exists a distribution $\alpha_E > 0$ and $\alpha_I > 0$ such that equilibrium trade is higher than what is the case under single ownership, $\alpha_E = 1$ or $\alpha_I = 1$.*

Private TSOs We have assumed that TSOs maximize national social welfare since most European TSOs are government-owned. But a significant number of European network owners are privately held companies, at least in part. Profit maximization seems a more natural assumption in such instances, and is equivalent to maximization of congestion rent in our setting. It is straightforward to infer from (7) that a TSO solely interested in congestion rent has a stronger incentive to exercise market power than a TSO concerned with national welfare maximization.¹⁸ We thus obtain:

Corollary 3 *If one of the TSOs is a profit-maximizing company, then this TSO will constrain trade in equilibrium. The equilibrium transfer capacity is independent of the distribution of ownership.*

Market performance will thus be even more problematic when one of the TSOs is privately owned. If both are privately owned, an additional problem arises from a regulatory perspective. Whereas the TSOs have partly conflicting interests when they are both publicly-owned, their interests will be perfectly aligned if both are private, since each of

¹⁸If TSO i is a profit-maximizer, then $\Omega_z^i = \frac{\alpha_i}{\alpha_j}(\Omega_z^j - P_x^j) < 0$ for $\Omega_z^j = 0$ implies that TSO i restricts capacity in maximal equilibrium. Equilibrium trade is characterized by letting $\alpha_i \rightarrow \infty$ in (10).

them then wants to maximize the total congestion rent. They will then have a common interest in concealing exercise of market power.

4 Mitigating TSO exercise of market power

The previous section showed how integration of electricity markets can be undermined by TSO beggar-thy-neighbor behavior in the supply of interconnector capacity. Such incentives not only exist for profit-maximizing TSOs, but also for TSOs that maximize national welfare. This section discusses possibilities to mitigate such behavior through regulation. We first discuss the current EU regulation which imposes a minimal capacity allocation threshold. We then consider an alternative EU regulation which forces TSOs to participate in the forward market and the consequences thereof. Finally, we show how a change in market design regarding allocation of congestion rent can implement efficient trade in the spot market.¹⁹ The section also contains a brief discussion of domestic transmission constraints.

4.1 Minimal capacity allocation

As shown above, a fundamental problem facing international integration of electricity markets is the incentive for TSOs to withhold transmission capacity. Article 16 of EU Regulation 2019/943 ([European Union, 2019](#)) explicitly requires TSOs to internalize external effects:

When taking operational measures to ensure that its transmission system remains in the normal state, the transmission system operator shall take into account the effect of those measures on neighbouring control areas.

The regulation specifies a sufficient condition for compliance:

For borders using a coordinated net transmission capacity approach, the minimum capacity shall be 70 % of the transmission capacity respecting operational

¹⁹It might appear as if the inefficiency identified in the previous section could most directly be resolved by letting the two TSOs negotiate over the trade volume. They would implement efficient trade because this is the solution that maximizes total welfare. This outcome would have to be sustained through side payments by the incentive incompatibility of efficient trade established in Proposition 1. The side payment would have to change frequently since the incentives to deviate would vary from one dispatch period to the next. Efficient negotiated outcomes would be even more complicated to implement in a market with multiple interconnected national networks. There is no reason to believe that bilateral negotiations between TSOs would yield an efficient outcome in such a setting, due to the externalities across bargaining processes. Multilateral negotiations involving all TSOs and all trade flows could yield an efficient outcome in theory. Yet it is hard to see how such a negotiation would be feasible in practice, given the number of TSOs involved, the complexity of their interrelationships, and the rapidly changing market conditions. Hence, we explore more plausible remedies to inefficient trade than unlimited negotiations.

security limits.

This type of rule has straightforward welfare benefits in our model. Let $z_{\min}$ be a mandatory minimal capacity allocation on the interconnector. This regulation either has no effect ($z^M \geq z_{\min}$), or forces TSOs to increase capacity compared to the unregulated equilibrium ($z^M < z_{\min}$), thereby strictly increasing joint welfare.

If TSO objective functions are strictly quasi-concave, then the unique regulated equilibrium is found at $z_{\min}$ because there will always be one TSOs that wants to minimize trade subject to the regulation. But more generally, the minimal capacity regulation can implement equilibria with trade above $z_{\min}$.

Observation 2 *A minimal allocation rule increases efficiency, and may increase trade above the minimal threshold.*

A 100 % minimal allocation rule would be efficient in the present context by implementing maximal trade, but would be difficult to implement in practice. Operational security concerns make it infeasible to supply the full nominal capacity in all circumstances, and private information about system conditions makes it difficult for outsiders to observe actual transfer capacity. Furthermore, full allocation of available capacity need not even be efficient. The extension of the model in Section 4.4 below to include domestic transmission bottlenecks, illustrates this point. If a decrease in international trade increases unregulated domestic transfer capacity, then full allocation of interconnection capacity is suboptimal. This interdependence between domestic and international capacity allocation points to a reason why current EU regulation might be inefficient by only applying to international transfer capacity.

4.2 Forward contracting

We argued above that private information makes it difficult to implement an efficient minimal capacity allocation rule. It is therefore of interest to identify other types of regulation that can increase efficiency. It is well-known that forward contracting can reduce the incentive of producers to exercise market power; see [Wolak \(2000\)](#) for an application to electricity markets. Pro-competitive forward contracting can arise endogenously, as first shown by [Allaz and Vila \(1993\)](#). A natural question from a theory point of view is therefore whether forward contracts can mitigate TSO market power and to investigate the incentives of network owners to provide such forward contracts.

Implications of forward contracting are also of interest from a practical perspective. EU Regulation 2019/943 ([European Union, 2019](#)) requires TSOs to issue so-called transmission rights, or introduce equivalent measures, to enable market participants to hedge

price risks across bidding zones. Many European TSOs issue transmission rights, which operate similarly to forward contracts. As a first in the EU, the Swedish TSO auctions forward contracts since 2023. It is not obvious whether TSO participation in the financial market is a response to regulation, but our analysis suggests this might be the case.

An extended model To examine whether forward contracting can mitigate TSO exercise of market power in the spot market, we complement the benchmark model with a financial forward market in which the TSOs can trade forward contracts before interacting in the spot market. TSO i purchases forward contracts for the amount $\bar{z}_i \geq 0$ of electricity where the underlying asset is electricity produced in country E .²⁰ We refer to this as a “forward export contract” because the spot price p_E in the export country represents the reference price of that contract. TSO i simultaneously sells forward contracts for the same amount $\bar{z}_i$ of electricity where the underlying asset is electricity produced in country I . This second type of contract is denoted a “forward import contract” since its reference price equals p_I .²¹ Both TSOs trade forward contracts at identical forward prices $\bar{\mathbf{p}} \equiv (\bar{p}_i, \bar{p}_j)$. Let $\bar{z} \equiv \bar{z}_E + \bar{z}_I$ be the total amount of forward contracts sold for each of the two underlying assets; these amounts are the same since each TSO purchases and sells the same volume of each of the two assets. Also, let $\bar{\mathbf{z}} \equiv (\bar{z}_i, \bar{z}_j)$ be the pair of forward trade positions taken by the two TSOs.

TSO i ’s direct utility from trades in the forward market depends on the volumes traded in the forward market by domestic producers and consumers, as in the spot market. Let $\gamma_E \in [0, 1]$ be the share of forward export contracts sold by the private sector in country E . The remaining $1 - \gamma_E$ share is sold by the private sector in I . Similarly, the private sector in country I purchases a share $\gamma_I \in [0, 1]$ of forward import contracts. The remaining $1 - \gamma_I$ share is purchased by the private sector in E . These shares will be indeterminate in equilibrium because Bertrand competition drives forward premia to zero. Hence, the private sector is in equilibrium indifferent between participating in the forward market or not. However, the subgame-perfect equilibrium will not depend fundamentally on (γ_E, γ_I) .

TSO objectives The extended objective function of TSO i is

$$\begin{aligned} \tilde{\Omega}^i(z, \bar{\mathbf{p}}, \bar{\mathbf{z}}) &\equiv \delta_i[\bar{p}_i - P^i(x_i)]\gamma_i\bar{z} + \delta_j[\bar{p}_j - P^j(x_j)](1 - \gamma_j)\bar{z} \\ &\quad + [\bar{p}_I - \bar{p}_E - P^I(x_I) + P^E(x_E)]\bar{z}_i \\ &\quad + \Omega^i(z) \end{aligned} \tag{12}$$

²⁰Variables and functions pertaining to the forward market are indicated with bars.

²¹By assumption, we rule out the possibility of contract positions where a TSO sells export forward contracts and buys import forward contracts, that is, where $\bar{z}_E < 0$ or $\bar{z}_I < 0$. Such a non-negativity constraint is applied, for instance, by the Swedish TSO in its auctions of forward contracts.

under the assumption that each TSO takes full account of the domestic private sector surplus in the forward market.²² The first term on the right-hand side represents the profit of the domestic private sector from trading forward contracts with a reference price equal to the domestic spot price, and the second term is that sector's profit of trading forward contracts with a reference price equal to the foreign spot price. Specifically, the private sector in E sells forward export contracts for the amount $\gamma_E \bar{z}$ of electricity. These transactions are weakly profitable if $\bar{p}^E \geq P^E(x_E)$, but unprofitable otherwise. The private sector in E also purchases forward import contracts for the amount $(1 - \gamma_I) \bar{z}$ of electricity. It weakly benefits from these contracts if $\bar{p}^I \leq P^I(x_I)$, but loses otherwise. Such price differences have the same implications for the private sector in I .

The second row of (12) represents TSO i 's forward congestion profit. The TSO purchases contracts in country E for the export volume $\bar{z}_i$, and sells contracts for the corresponding volume in country I . This yields a profit if and only if the forward price difference $\bar{p}_I - \bar{p}_E$ is larger than the spot price difference $P^I(x_I) - P^E(x_E)$. The third row of (12) captures the TSO welfare from the spot market as defined in eq. (6).

To emphasize forward versus spot market decisions, we rewrite (12) as

$$\tilde{\Omega}^i(z, \bar{\mathbf{p}}, \bar{\mathbf{z}}) \equiv \delta_i \bar{p}_i \gamma_i \bar{z} + \delta_j \bar{p}_j (1 - \gamma_j) \bar{z} + (\bar{p}_I - \bar{p}_E) \bar{z}_i + \hat{\Omega}^i(z, \bar{\mathbf{z}}). \quad (13)$$

The first three terms on the right-hand side of (13) capture the transactions in the forward market; the monetary value of these transactions only depend of forward prices.

$$\hat{\Omega}^i(z, \bar{\mathbf{z}}) \equiv \Omega^i(z) - [P^I(x_I) - P^E(x_E)] \bar{z}_i - \delta_i P^i(x_i) \gamma_i \bar{z} - \delta_j P^j(x_j) (1 - \gamma_j) \bar{z} \quad (14)$$

shows how TSO i 's objective function in the spot market is affected by the volumes traded in the forward market. To simplify, we assume that $\hat{\Omega}^i(z, \bar{\mathbf{z}})$ is strictly quasi-concave in z .

TSO incentives in the spot market TSO i maximizes $\hat{\Omega}^i(z, \bar{\mathbf{z}})$ subject to $z = \min\{z^*, k\}$. The TSO's marginal utility from an increase in trade z equals

$$\hat{\Omega}_z^i(z, \bar{\mathbf{z}}) = \Omega_z^i(z) + [P_x^I(x_I) + P_x^E(x_E)] \bar{z}_i - [P_x^i(x_i) \gamma_i + P_x^j(x_j) (1 - \gamma_j)] \bar{z} \quad (15)$$

The first term on the right-hand side represents the marginal effect absent forward contracting; see (7) for a characterization. The remaining two terms stem from transactions in the forward market. The second term captures how an increase in trade reduces the price difference in the spot market, and thereby increases TSO i 's forward congestion profit. This thus reflects the standard pro-competitive effect of forward contracting. However, the higher spot price in the export country and the lower spot price in the import country

²²Recall that $\delta_E \equiv -\delta_I \equiv 1$.

reduce the profit of the forward export contracts sold, and the forward import contracts purchased, by the domestic private industry. The marginal forward market losses of the private industry reduce the incentive to supply network capacity into the spot market, as represented by the third term on the right-hand side of (15). Hence, forward contracts $\bar{\mathbf{z}}$ have pro- as well as anti-competitive effects on TSO incentives in the spot market.

We denote by $Z^i(\bar{\mathbf{z}})$ the spot market trade volume that maximizes TSO i welfare as a function of the forward positions $\bar{\mathbf{z}}$. In an interior optimum, $Z^i(\bar{\mathbf{z}}) \in (0, z^*)$, the weakly positive cross-partial derivative

$$\hat{\Omega}_{z\bar{z}_i}^i = (1 - \gamma_i)P_x^i(x_i) + \gamma_j P_x^j(x_j) \geq 0 \quad (16)$$

of TSO i 's objective function implies $Z_{\bar{z}_i}^i \geq 0$ with strict inequality if $\gamma_i < 1$ or $\gamma_j > 0$. The weakly negative cross-partial derivative

$$\hat{\Omega}_{z\bar{z}_j}^i = -\gamma_i P_x^i(x_i) - (1 - \gamma_j)P_x^j(x_j) \leq 0 \quad (17)$$

implies $Z_{\bar{z}_j}^i \leq 0$ with strict inequality if $\gamma_i > 0$ or $\gamma_j < 1$. Let TSO i supply its dominating capacity $Z^i(\bar{\mathbf{z}})$ to the spot market. The opposite signs of expressions (16) and (17) have straightforward implications for trade $Z(\bar{\mathbf{z}}) = \min\{Z^E(\bar{\mathbf{z}}); Z^I(\bar{\mathbf{z}})\}$ in the spot market:

Lemma 2 *A marginal increase in the volume contracted in the forward market by TSO E increases trade in the spot market if TSO E constrains trade in equilibrium (i.e. $Z^E(\bar{\mathbf{z}}) < Z^I(\bar{\mathbf{z}})$), but reduces trade otherwise (when $Z^E(\bar{\mathbf{z}}) \leq Z^I(\bar{\mathbf{z}})$). A symmetric result holds for TSO I .*

This feature differs fundamentally from the standard Allaz-Vila model, in which additional forward contracting improves spot market efficiency regardless of which producer has sold more forward contracts. The implications of forward contracting for market performance therefore depends fundamentally on the individual incentives for TSOs to participate in the forward market. This is the issue we turn to next.

TSO incentives in the forward market Since market participants have perfect foresight, and there is no uncertainty, forward prices must equal spot prices along the equilibrium path: $\bar{P}^E(\bar{\mathbf{z}}) = P^E(y_E + Z(\bar{\mathbf{z}}))$ and $\bar{P}^I(\bar{\mathbf{z}}) = P^I(y_I - Z(\bar{\mathbf{z}}))$. We can then define the TSO i reduced form objective function

$$\bar{\Omega}^i(\bar{\mathbf{z}}) \equiv \tilde{\Omega}^i(Z(\bar{\mathbf{z}}), \bar{P}^i(\bar{\mathbf{z}}), \bar{P}^j(\bar{\mathbf{z}}), \bar{\mathbf{z}}).$$

Consider the marginal incentive to contract more trade in the forward market

$$\bar{\Omega}_{\bar{z}_i}^i(\bar{\mathbf{z}}) \equiv \hat{\Omega}_z^i Z_{\bar{z}_i} + \tilde{\Omega}_{\bar{z}_i}^i + \tilde{\Omega}_{\bar{p}_i}^i \bar{P}_{\bar{z}_i}^i + \tilde{\Omega}_{\bar{p}_j}^i \bar{P}_{\bar{z}_i}^j$$

if TSO i restricts trade in the spot market. The first term on the right-hand side measures an indirect effect operating through trade in the spot market. This indirect effect is of second-order importance for TSO i , $\hat{\Omega}_z^i Z_{\bar{z}_i}^i = 0$. The second term, which is the direct effect of an increased volume of trade in the forward market, is also zero because forward prices are equal to the spot prices. The only relevant implication for TSO i of a marginal change in its forward market contracting volume $\bar{z}_i$ is the impact on forward market prices, captured by the last two terms in the above expression. Hence,

$$\bar{\Omega}_{\bar{z}_i}^i = \{[\gamma_i P_x^i + (1 - \gamma_j) P_x^j] \bar{z} - [P_x^I + P_x^E] \bar{z}_i\} Z_{\bar{z}_i}$$

The situation is different for TSO j which does not constrain trade in the spot market:

$$\bar{\Omega}_{\bar{z}_j}^j = \{\hat{\Omega}_z^j + [\gamma_j P_x^j + (1 - \gamma_i) P_x^i] \bar{z} - [P_x^I + P_x^E] \bar{z}_j\} Z_{\bar{z}_j} = \Omega_z^j Z_{\bar{z}_j}, \quad (18)$$

For this TSO, only the strategic incentive $\Omega_z^j > 0$ for forward contracting matters, since all forward price effects cancel against the spot price effects.

Observation 3 *A TSO that does not constrain trade in the spot market has an incentive to trade in the forward market to increase the other TSO's supply of capacity to the spot market.*

This strategic incentive is opposite to what occurs in the standard Allaz-Vila model where each producer trades more in the forward market to induce the competitor to supply less output to the market. The producers are caught in a Prisoner's dilemma which drives them to oversupply forward contracts (from an industry perspective), and thereby increase spot market competition. The purpose of forward contracting in the present context is to increase trade, and thus indirectly reduce the distortion that results from insufficient supply of network capacity.

Forward market equilibrium An equilibrium $\bar{\mathbf{z}}^F = (\bar{z}_E^F, \bar{z}_I^F)$ in the forward market is characterized by $\bar{z}_E^F = \arg \max_{\bar{z}_E \geq 0} \bar{\Omega}^E(\bar{z}_E, \bar{z}_I^F)$, with a similar optimality condition for $\bar{z}_I^F$. Network owners have weak incentives to trade forward contracts. TSO i only cares about the forward price effects by its de facto exercise of monopoly power in the spot market. Forward prices tend to go in the wrong direction if TSO i trades more forward contracts. TSO j takes the indirect effect of TSO i 's market power in the spot market into account.

However, an increase in $\bar{z}_j$ reduces TSO i 's incentive to trade in the spot market. The proof of the following result is in Appendix A.2:

Proposition 3 *Zero trade of forward contracts represents a subgame-perfect equilibrium ($\bar{z}_E^F = \bar{z}_I^F = 0$). This equilibrium is unique if $\gamma_E \in (0, 1)$, $\gamma_I \in (0, 1)$ and $q_E^o \neq q_I^o$ all hold.*

The assumptions regarding γ_E and γ_I ensure that marginal changes in the forward positions $\bar{z}$ strictly affect interior trade $Z(\bar{z})$ in the spot market. The assumptions regarding q_E^o and q_I^o rule out degenerate special cases, and are met for almost any ownership configuration $\alpha_E = 1 - \alpha_I$.

Policy implications The finding that TSOs lack incentive to trade in the forward market seems to have direct relevance for several features of the European electricity market. First, it is consistent with the limited interests in such markets that most European TSOs have shown. Second, the finding helps explain why the EU has seen it necessary to resort to regulation to induce TSOs to trade forward contracts. Third, it shows that regulation could be warranted even if speculators already provide sufficient hedging opportunities. Forward contracts traded by speculators do not affect competition in the spot market, but contracts traded by TSOs do. Finally, the analysis also suggests that asymmetries between TSOs are important because forward contracting theoretically can have negative consequences for spot market efficiency by Lemma 2.

4.3 Efficient spot market design

The EU has sought to improve the efficiency of European electricity market through a range of regulatory measures that aim at increasing cross-border trade. Yet, authorities remain concerned about the sufficiency of these policies. [ACER \(2019\)](#) argues that an ideal regulation should adhere to a "polluter pays principle" by which TSOs bear the full cost of any distortions they cause, but there is no suggestion how to implement this principle. Using the framework developed above, we here propose a modified market design that can be interpreted as such a "polluter pays" mechanism for TSOs.

The crucial difference between our proposal and the current market design lies in the treatment of the congestion rent

$$L(\min\{z^*, k\}) \equiv [P^I(y - \min\{z^*, k\}) - P^E(y + \min\{z^*, k\})] \min\{z^*, k\}, \quad (19)$$

where $k = \min\{k_E, k_I\}$. A fundamental property of the EU design is a fixed split of this rent. Our mechanism prescribes that same split when TSOs supply the same capacity,

but a drastically different split otherwise. Specifically, TSO i receives the congestion rent

$$L^i(k_i, k_j, z^*) \equiv \begin{cases} \alpha_i L(\min\{z^*, k\}) & \text{if } k_i = k_j, \\ -\psi(k_i) & \text{if } k_i < k_j. \end{cases} \quad (20)$$

By this design, any TSO that unilaterally imposes a transmission constraint receives no congestion rent, but instead pays a small penalty $\psi(k_i) > 0$ if $k_i = 0$ and no penalty otherwise. By a balanced-budget assumption, $L^j(k_j, k_i, z^*) = L(\min\{z^*, k\}) - L^i(k_i, k_j, z^*)$.

The intuition for why the above scheme would work is straightforward. A reduction in trade has negative consequences for the domestic private sector; see (7). The only reason for a national TSO to restrict trade would be to increase congestion rent. Under the modified design considered here, any reduction in the supply of transfer capacity by TSO i to $k_i < k_j$ causes TSO i to lose its whole share of the congestion rent and may also trigger a small penalty. Therefore, efficient trade can be sustained in equilibrium.

Sharing rule (20) provides strong incentives for the two TSOs to coordinate capacity supply. A concern is that such coordination might enable TSOs to sustain even inefficient outcomes, for instance an equilibrium without trade. The penalty function $\psi(\cdot)$ is designed precisely to avoid autarky. We prove the following result in Appendix A.3:

Proposition 4 *Consider a market design with congestion rent shared according to (20).*

- (i) *There exists an equilibrium in this market that implements efficient trade z^* .*
- (ii) *All equilibria implement efficient trade.*

The above market design solves the inefficiencies associated with decentralized capacity choices by the TSOs. Many other designs can sustain efficient trade in equilibrium. One of them is simply to impose a heavy fine on any TSO that deviates from efficient trade. For such a mechanism to be feasible, the responsible authority must know the volume of efficient trade. Our mechanism only requires that TSOs have this information. To implement (20), the authority just needs to observe the individual supply of capacity and the realized congestion rent L , both of which are available from the power exchange.

Transmission restrictions may of course also occur for reasons beyond the direct control of the TSOs. If such an exogenous event affects transmission capacity asymmetrically, the sharing rule in (20) will punish the affected party. For instance, assume that the maximal export capacity from E to I happens to be smaller than the import capacity of I : $k_E^{\max} < k_I^{\max}$. TSO E will in this instance be punished for an event beyond its control. However, the expected cost should be near zero if failures occur randomly and with equal probability in both countries.

The proposed sharing rule could facilitate collusion in an infinitely repeated game by aligning TSO preferences. As the efficient level of trade maximizes TSO joint surplus in

our setting, collusion would here be efficient. Pairwise collusion would likely be inefficient in a multi-country setting with more than two TSOs or if TSOs were privately owned. Addressing collusion requires substantial model development and analysis which is outside the scope of this paper and left for future research.

4.4 Implications of domestic transmission constraints

The analysis has so far focused on how competition authorities can detect and mitigate TSOs undermining of market integration through restrictions on cross-border transmission capacity. Even if the authorities manage to solve this problem, they still need to be wary about TSO exercise of market power through other means. We illustrate this challenge by showing how TSOs in certain situations might have incentives to withhold *domestic* transmission capacity, when unable to affect the trade volume through other means.

Let the electricity system in the exporting country be partitioned into two bidding zones, North (N) and South (S).²³ The importing country I is interconnected with S , but not with N . Flexible generation x_N is produced at cost $C^N(x_N)$ in N and $C^S(x_S)$ in S . All consumption in E takes place in S , so all production in N is transmitted to S . By implication, S in part serves as a transit zone for electricity produced in N and consumed in I . Transmission capacity between N and S is sufficient to sustain full price equalization in E for any amount of export z from S to I . Contrary to the case of cross-border transmission capacity, TSO E unilaterally decides supply h of the domestic transmission capacity to the market, and it collects the entire domestic congestion rent.

Production in N equals $x_N = h$ by the assumption that all domestic consumption in E takes place in S . Production in S is given by $x_S = y + z - h$. Perfect competition in the spot market implies that the price in bidding zone N is defined by $p_N = P^N(h) \equiv C_x^N(h)$, in bidding zone S by $p_S = P^S(y + z - h) \equiv C_x^S(y + z - h)$, and in the importing country by $p_I = P^I(y - z) \equiv C_x^I(y - z)$.

Exporting country welfare The private sector surplus in country E is the sum of consumer surplus in S , and producer surplus in N and S :

$$(v - p_S)y + p_N h - C^N(h) + p_S(y + z - h) - C^S(y + z - h)$$

Congestion rents arise from capacity constraints on the domestic line, which is fully owned by TSO E , and on the partially owned interconnector:

$$(p_S - p_N)h + \alpha_E(p_I - p_S)z$$

²³This setting captures features of the electricity grids in the Nordic market.

Aggregating effects yield national welfare

$$\begin{aligned}\Lambda^E(h, z) \equiv & \quad vy - C^N(h) - C^S(y + z - h) \\ & + P^S(y + z - h)z + \alpha_E[P^I(y - z) - P^S(y + z - h)]z.\end{aligned}$$

in country E . Compared to $\Omega^E(z)$ as defined in (6), national welfare now depends on the production volume in each of the two bidding zones in E . The export price p_S is now a function also of the domestic transmission constraint h .²⁴

TSO E incentives TSO E maximizes $\Lambda^E(h, z)$ over the capacity h on the domestic line and the transfer capacity z on the interconnector subject to $z = \min\{z^*, k\}$. The consequences of a marginal reduction in the domestic transmission capacity h for arbitrary cross-border trade z equals

$$-\Lambda_h^E(h, z) = -[P^S(y + z - h) - P^N(h)] + (1 - \alpha_E)P_x^S(y + z - h)z.$$

Tightening a domestic transmission constraint implies that more expensive generation in S replaces cheaper generation in N to cover demand in S . This marginal loss is captured by the negative of the price difference between S and N , mirroring the difference in marginal production costs. A tighter domestic transmission constraint increases the price in S to the net benefit of the domestic sector in E , as captured by the term $P_x^S z$. A higher export price has the drawback for TSO E of reducing congestion rent by decreasing the price wedge between the two countries; as captured by the term $-\alpha_E P_x^S z$.

TSO E benefits from reducing domestic transfer capacity since it drives up the export price. The benefit is smaller if trade is smaller. It will also be small if the TSO owns a large share α_E of the interconnector, since TSO E then internalizes most of the negative effect abroad of the price increase. But domestic transmission capacity will be inefficient for any $z > 0$ and $\alpha_E < 1$. Let $H^*(z)$ be the domestic network capacity that leads to full price equalization in E given trade z ; $P^N(H^*) \equiv P^S(y + z - H^*)$. By implication

$$-\Lambda_h^E(H^*(z), z) = (1 - \alpha_E)P_x^S(y + z - H^*(z))z > 0$$

for $z > 0$ and $\alpha_E < 1$. We conclude that the exporting country TSO will for a given strictly positive trade volume withhold domestic transmission capacity, unless the TSO fully owns the cross-border connection. Hence:

Observation 4 *TSO E might benefit from implementing domestic capacity restrictions*

²⁴The present model generalizes the model analyzed in the previous section: set $S = E$ and $C^N(0) = 0$ to get $\Lambda^E(0, z) = \Omega^E(z)$.

in order to drive up the export price, if unable to restrict international trade, for instance due to regulation.

5 Concluding remarks

Many economies seek to integrate electricity markets to reap the benefits of electricity trade. For such efforts to fully succeed, system operators must supply sufficient network capacity to achieve efficient trade. There are reasons to be concerned about national system operators' incentives in this regard. Yet, hardly any research has examined exercise of market power by transmission system operators (TSOs) in electricity markets. We consider such incentives in a European-style electricity market.

The analysis reveals the general impossibility of achieving an efficient equilibrium because TSOs have incentives to reduce trade to increase congestion rent. The equilibrium condition is a modified Lerner condition that depends on the elasticities of demand in both countries. This condition can in principle be structurally estimated to quantify TSO market power. The paper discusses the implications for efficiency of minimal capacity restrictions and forward contracting. We show how a change in the allocation of congestion rent can restore efficiency.

Many interesting issues are left for future research:

- (1) The present model features two countries. A setting with multiple countries in a meshed network raises separate issues, including loop flows and new opportunities for strategic interaction between TSOs. How efficient is supply of network capacity in a multi-country market?
- (2) Retailers and producers are assumed to be price-takers in the spot market in the present model, to highlight TSO incentives to capture congestion rents. However, these firms often have considerable market power. How would TSO incentives, and the realized gains from trade, be affected by financial or by physical withholding by retailers and generation owners?
- (3) Countries have sufficient capacity to meet demand in our model. Relaxing this assumption would make it possible to analyze issues related to reliability and security of supply. What are the consequences of TSO behavior for reliability?
- (4) Our model assumes complete information. Accounting for private information about system conditions would shed light on the problems faced by authorities in the assessment of TSO market performance.

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Appendix

A.1 Proof of Lemma 1

Pareto dominance of equilibria with more trade follows directly from the equilibrium conditions. Compare two equilibria with trade z respective $z' < z$. From (9), z can be sustained as an equilibrium only if $\Omega^E(z) \geq \Omega^E(z')$ and $\Omega^I(z) \geq \Omega^I(z')$.

Our next result shows that equilibria with positive trade exist. Observe that $\Omega_z^i(0) = \alpha_i[P^I(y) - P^E(y)] > 0$, $i = E, I$, implies that there exists $z_i > 0$ such that $\Omega^i(z') < \Omega^i(z_i)$ for all $z' \in [0, z_i]$. Then $z = \min\{z_E, z_I\} > 0$ fulfills (9).

To establish existence of an equilibrium with maximal trade, it is sufficient to show that the set Γ of trade levels that can be sustained as an equilibrium is closed. Since Γ is a subset of the interval $[0, z^*]$, Γ is compact and therefore contains both a minimal and a maximal element which we define as z^M . To show that Γ is closed, it is sufficient to show that the complementary set $\bar{\Gamma}$, containing all trade levels that cannot be sustained as an equilibrium, is open. This is trivially true if $\bar{\Gamma} = \emptyset$. For every $z \in \bar{\Gamma} \neq \emptyset$, $\Omega^i(z') > \Omega^i(z)$ for some $z' < z$ and $i \in E, I$ by (9). Continuity of the national welfare functions then implies $\Omega^i(z') > \Omega^i(t)$ for all t in an interval around z . Hence, $z \in \bar{\Gamma}$ implies that all t in an interval around z are also contained in $\bar{\Gamma}$, which proves that $\bar{\Gamma}$ is open. ■

A.2 Proof of Proposition 3

Let $\bar{\mathbf{z}}^F = (\bar{z}_i^F, \bar{z}_j^F)$ be the forward positions taken by the two TSOs in subgame-perfect equilibrium. Denote by $z_E^F = Z^E(\bar{\mathbf{z}}^F)$ TSO E 's and $z_I^F = Z^I(\bar{\mathbf{z}}^F)$ TSO I 's most-preferred trade in equilibrium given forward positions $\bar{\mathbf{z}}^F$. Assume without loss of generality that TSO i prefers weakly less trade in equilibrium than TSO j , $z_i^F \leq z_j^F$, so that equilibrium trade in the spot market equals $z^F = z_i^F$.

We will repeatedly use that

$$\bar{\Omega}^E(\bar{\mathbf{z}}) = \Omega^E(Z(\bar{\mathbf{z}})), \quad \bar{\Omega}^I(\bar{\mathbf{z}}) = \Omega^I(Z(\bar{\mathbf{z}})) \quad (.21)$$

for arbitrary $\bar{\mathbf{z}}$ since the forward prices are identical to the spot prices.

Existence If $\bar{z}_j = 0$, then TSO i has no unilateral incentive to choose $\bar{z}_i > 0$:

$$\bar{\Omega}^i(\bar{z}_i, 0) = \Omega^i(Z(\bar{z}_i, 0)) \leq \Omega^i(Z^i(0, 0)) = \bar{\Omega}^i(0, 0).$$

The inequality follows from $Z^i(0, 0) = z_i^0 = \arg \max_z \Omega^i(z)$, and the equalities are from (.21). Let $\bar{z}_i = 0$ and consider $\bar{z}_j > 0$ by TSO j . Monotonicity implies $Z^i(0, \bar{z}_j) \leq z_i^F \leq z_j^F \leq Z^j(\bar{z}_j, 0)$ and therefore $Z(0, \bar{z}_j) = Z^i(0, \bar{z}_j)$ for all $\bar{z}_j > 0$. From (18), we know that $\bar{\Omega}_{\bar{z}_j}^j = \Omega_z^j Z_{\bar{z}_j}$. By the assumed strict quasi-concavity of $\Omega^j(z)$, $\Omega_z^j(Z(0, \bar{z}_j)) \geq 0$ since $Z^i(0, \bar{z}_j) \leq Z^i(0, 0) = z_i^F \leq z_j^F = Z^j(0, 0) = z_j^0 = \arg \max_z \Omega^j(z)$. Since $Z_{\bar{z}_j} = Z_{\bar{z}_j}^i \leq 0$, we obtain $\bar{\Omega}_{\bar{z}_j}^j \leq 0$ for all $\bar{z}_j > 0$. Hence, $\bar{z}_j = 0$ represents a best-reply to $\bar{z}_i = 0$.

Uniqueness Assume that $\gamma_E \in (0, 1)$, $\gamma_I \in (0, 1)$ and $z_E^0 \neq z_I^0$. The proof is in six steps.

Step (i): $z^F > 0$. Suppose, on the contrary, that $z^F = 0$. By

$$\hat{\Omega}_z^E(0, \bar{\mathbf{z}}) + \hat{\Omega}_z^I(0, \bar{\mathbf{z}}) = P^I(y_I) - P^E(y_E) > 0,$$

either $Z^E(\bar{\mathbf{z}}) > 0$ or $Z^I(\bar{\mathbf{z}}) > 0$ for arbitrary forward portfolio $\bar{\mathbf{z}}$. In particular, $z^F = 0$ implies $z_i^F = 0 < z_j^F$. TSO i 's marginal objective function

$$\hat{\Omega}_z^i(0, \bar{z}_i, \bar{z}_j^F) = [\gamma_j P_x^j(y_j) + (1 - \gamma_i) P_x^i(y_i)] \bar{z}_i - [\gamma_i P_x^i(y_i) + (1 - \gamma_j) P_x^j(y_j)] \bar{z}_j^F + \Omega_z^i(0)$$

is linearly increasing in $\bar{z}_i$. By the assumption that $\hat{\Omega}_z^i(0, \bar{\mathbf{z}}^F) \leq 0$, $\hat{\Omega}_z^i(0, \bar{a}_i, \bar{z}_j^F) = 0$ for some $\bar{a}_i \geq \bar{z}_i^F$. Trade in the spot market equals $Z^i(\bar{z}_i, \bar{z}_j^F) = 0$ for all $\bar{z}_i \leq \bar{a}_i$. For $\bar{z}_i$ strictly above but sufficiently close to $\bar{a}_i$, $0 < Z^i(\bar{z}_i, \bar{z}_j^F) < Z^j(\bar{z}_j^F, \bar{z}_i)$ by $Z^i(\bar{a}_i, \bar{z}_j^F) = 0 < Z^j(\bar{z}_j^F, \bar{a}_i)$ and continuity. Seeing as $\Omega_z^i(0) = \alpha_i [P^I(y_I) - P^E(y_E)] > 0$, there exists $\bar{z}_i > \bar{a}_i \geq \bar{z}_i^F$ such that

$$\bar{\Omega}^i(\bar{z}_i, \bar{z}_j^F) = \Omega^i(Z^i(\bar{z}_i, \bar{z}_j^F)) > \Omega^i(0) = \bar{\Omega}^i(\bar{\mathbf{z}}^F),$$

which contradicts the assumption that $\bar{z}_i^F$ is a best-reply to $\bar{z}_j^F$.

Step (ii): $z^F < z^*$. Suppose, on the contrary, that $z^* = z_E^F = z_I^F$. By the assumptions of the proposition, $z_l^o < z^*$ for some $l = E, I$. Since

$$\hat{\Omega}_z^l(z, 0, \bar{z}_h^F) = -[\gamma_l P_x^l + (1 - \gamma_h) P_x^h] \bar{z}_h^F + \Omega_z^l(z) \leq \Omega_z^l(z),$$

$Z^l(0, \bar{z}_h^F) \leq z_l^o$. As $Z^l(\bar{\mathbf{z}}^F) = z^* > z_l^o$ by assumption, continuity of spot market trade implies $Z^l(\bar{b}_l, \bar{z}_h^F) = z_l^o$ for some $\bar{b}_l \in [0, z_l^F)$. Evaluated at this forward position

$$\bar{\Omega}^l(\bar{b}_l, \bar{z}_h^F) = \Omega^l(z_l^o) > \Omega^l(z^*) = \bar{\Omega}^l(\bar{\mathbf{z}}^F),$$

which contradicts the assumption that $\bar{z}_l^F$ is a best-reply to $\bar{z}_h^F$.

Steps (i) and (ii) imply $z^F \in (0, z^*)$ in any subgame-perfect equilibrium. The remaining four steps verify that $\bar{z}_E^F = \bar{z}_I^F = 0$ is the only equilibrium candidate if $z^F \in (0, z^*)$.

Step (iii): Assume that $z^F \in (0, z^*)$, and suppose $\bar{z}_i^F > 0 = \bar{z}_j^F$. Then

$$\bar{\Omega}^i(0, \bar{z}_j^F) = \Omega^i(Z^i(0, 0)) > \Omega^i(z_i^F) = \bar{\Omega}^i(\bar{\mathbf{z}}^F),$$

which contradicts the assumption that $\bar{z}_i^F > 0$ is a best-reply to $\bar{z}_j^F = 0$. The strict inequality follows from $z_i^o = Z^i(0, 0) < Z^i(\bar{z}_i^F, 0) = z_i^F = z^F$ by monotonicity of $Z^i(\mathbf{z})$.

Step (iv): Assume that $z^F \in (0, z^*)$, and suppose $\bar{z}_j^F > 0 = \bar{z}_i^F$. If $z_i^F < z_j^F$, then $\bar{\Omega}_{\bar{z}_j}^j(\bar{\mathbf{z}}^F) = \Omega_{\bar{z}_j}^j(z_i^F) Z_{\bar{z}_j}^i(\bar{\mathbf{z}}^F) < 0$. If $z_i^F = z_j^F$, then TSO j can implement trade z_j^o by deviating to $\bar{z}_j = 0$. This deviation yields $\bar{\Omega}^j(0, \bar{z}_i^F) > \bar{\Omega}^j(\bar{\mathbf{z}}^F)$ by the same argument as in Step (iii). These results contradict $\bar{z}_j^F > 0$ being a best-reply to $\bar{z}_i^F = 0$.

Step (v): Assume that $z^F \in (0, z^*)$, and suppose $\bar{z}_i^F > 0$, $\bar{z}_j^F > 0$ and $z^F \neq z_j^o$. Then

$$\bar{\Omega}_{\bar{z}_i}^i(\bar{\mathbf{z}}^F) Z_{\bar{z}_j} + \bar{\Omega}_{\bar{z}_j}^j(\bar{\mathbf{z}}^F) Z_{\bar{z}_i} = \Omega_z^j(z^F) Z_{\bar{z}_i} Z_{\bar{z}_j} \neq 0.$$

This equilibrium cannot exist because either $\bar{\Omega}_{\bar{z}_E}^E(\bar{\mathbf{z}}^F) \neq 0$ or $\bar{\Omega}_{\bar{z}_I}^I(\bar{\mathbf{z}}^F) \neq 0$, thus violating the first-order condition of at least one TSO.

Step (vi): Assume that $z^F \in (0, z^*)$, and suppose $\bar{z}_i^F > 0$, $\bar{z}_j^F > 0$ and $z^F = z_j^o$. Then

$$\bar{\Omega}_{\bar{z}_i}^i(\bar{\mathbf{z}}^F) = \Omega_z^i(z_j^o) Z_{\bar{z}_i} \neq 0$$

where $\Omega_z^i(z_j^o) \neq 0$ by the assumption that $z_E^o \neq z_I^o$.

These results leave $\bar{z}_E^F = \bar{z}_I^F = 0$ as the only equilibrium candidate under the assumptions of the proposition. ■

A.3 Proof of Proposition 4

Consider a balancing market design as analyzed in Section 3, except TSO i 's congestion rent is defined by (20). National welfare in country i then equals

$$\Omega^{ie}(k_i, k_j, z^*) \equiv vy - C^i(y + \delta_i \min\{z^*; k\}) + \delta_i P^i(y + \delta_i \min\{z^*; k\}) \min\{z^*; k\} + L^i(k_i, k_j, z^*)$$

Superscript "e" here refers to the (proposed) efficient balancing market design. Let (k_E^e, k_I^e) be a pair of equilibrium capacities, and define $k^e = \min\{k_E^e, k_I^e\}$.

Existence of an equilibrium with efficient trade We verify that TSO i cannot strictly profit from setting $k_i \neq z^*$ if TSO j supplies its interconnector capacity efficiently to the balancing market, $k_j = z^*$. Define

$$R^i(z) \equiv \delta_i P^i(y + \delta_i z)z - C^i(y + \delta_i z).$$

With this definition, $\Omega^{ie}(k_i, z^*, z^*) = vy + R^i(z^*)$ for all $k_i \geq z^*$ whereas

$$\Omega^{ie}(k_i, z^*, z^*) = vy + R^i(k_i) - \psi(k_i) \quad \forall k_i < z^*.$$

An upward deviation by TSO i to $k_i > z^*$ does not affect trade nor prices and therefore cannot be strictly profitable. For all deviations $k_i < z^*$,

$$\Omega^{ie}(z^*, z^*, z^*) - \Omega^{ie}(k_i, z^*, z^*) = \int_{k_i}^{z^*} R_z^i(z) dz + \psi(k_i) \geq 0.$$

The inequality holds because $\psi(k_i) \geq 0$ and $R_z^i(z) = P_x^i(y + \delta_i z)z > 0$ for all $z > 0$. Hence, $k_i = z^*$ is a best-response to $k_j = z^*$.

All equilibria feature efficient trade The proof is by contradiction. Suppose there exists an equilibrium such that $k^e < z^*$. There are two sub-cases. In the first, $k_i^e = k^e < k_j^e$. The expected national welfare in country i equals

$$\Omega^{ie}(k_i^e, k_j^e) = vy + R^i(k_i^e) - \psi(k_i^e)$$

in this proposed equilibrium. The expected national welfare in country i under the alternative strategy $k_i = k_j^e$ equals

$$\Omega^{ie}(k_j^e, k_j^e) = vy + R^i(k_j^e) + \alpha_i L(k_j^e)$$

The net benefit

$$\Omega^{ie}(k_j^e, k_j^e) - \Omega^{ie}(k_i^e, k_j^e) = \int_{k_i^e}^{k_j^e} R_z^i(z) dz + \alpha_i L(k_j^e) + \psi(k_i^e)$$

of the deviation is strictly positive. Intuitively, TSO i can increase its private sector surplus, congestion rent and avoid the incremental penalty by choosing the same capacity as the other TSO.

In the second sub-case, $k_i^e = k_j^e = k^e$. The expected value of TSO i equals

$$\Omega^{ie}(k^e, k^e) = vy + R^i(k^e) + \alpha_i L(k^e)$$

in the proposed equilibrium. An upward deviation to $k_i > k^e$ yields

$$\Omega^{ie}(k_i, k^e) = vy + R^i(k^e) + L(k^e) + \psi(k^e)$$

The net benefit

$$\Omega^{ie}(k_i, k^e) - \Omega^{ie}(k^e, k^e) = (1 - \alpha_i)L(k^e) + \psi(k^e)$$

of this deviation is strictly positive because $L(k) > 0$ for all $k > 0$, $\psi(0) > 0$ and $\alpha_i < 1$ either for $i = E$ or $i = I$. ■