Local network operators in an integrated electricity market*

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Abstract

Electricity market integration can yield substantial gains from trade. But this requires that the system operators who control the local networks supply enough transfer capacity to the market. This paper identifies a trade-off between the local private sector benefits of increasing capacity and the congestion rent a system operator earns by reducing capacity. Efficient trade cannot be sustained in equilibrium. A forward market does not increase trade unless participation by system operators is mandatory. Minimum capacity requirements can improve the outcome, but face informational problems. However, a small change in market design can implement efficient trade.

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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. 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. The interconnector capacity must also be supplied to the market. In Europe, such decisions are made by the transmission system operators (TSOs) who own the national transmission networks and cross-border connections. These organizations often are national authorities.[3] 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.

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 later with data from the European electricity market. While capacity reductions can be imposed for innocuous reasons, such as transmission line failures, maintenance needs, and operational security measures, they can also result from system operators' withholding of capacity to achieve other objectives. These

[1] For instance, U.S. Department of Energy (2024) 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.

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

[3] However, some TSOs are publicly traded companies.

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.[4] 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."[5]

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.[6] 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 available 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 am equilibrium, then the algorithm clears the market by setting higher prices in import areas than in export areas.

Another standard feature of electricity markets is that consumers pay and producers

[4] European Union (2010) and European Union (2018), respectively.

[5] ACER (2019).

[6] The European market platform *Euphemia* uses a zonal design. Most countries constitute single bidding zones, but Denmark, Italy, Norway and Sweden have multiple bidding zones.

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 for each cross-border connection is set at the minimum of supplied capacity by the TSOs controlling the interconnector.[7] This "Leontief" property of the capacity allocation has important implications for market interaction.

Summary of the analysis We develop a two-country model. In each country there is a TSO that controls the national grid. There is scope for trade since the marginal cost of electricity production in autarky is lower in one country than the other. An interconnector between the national grids is in place. It is jointly owned by the two TSOs and has sufficient capacity to sustain efficient trade, which occurs at the point where marginal production costs are equalized across countries.

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. 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.

National TSOs serve as agents for their national governments and are to some extent likely to act in the interests of their principals. We assume that the objectives of the national TSOs are fully aligned with the respective national interests. Full alignment implies that we can focus on distortions caused by the decentralized decision making by TSOs, which to us appears as a more fundamental problem for realizing the benefits of market integration than national government-TSO agency problems. National welfare is represented by the unweighted sum of domestic consumer and producer surplus, plus government revenue—the congestion rent that the country's TSO receives from the market platform—as is standard in partial equilibrium analysis.

By the Leontief property of transfer capacity allocation, each TSO can reduce trade from a positive level, but it cannot increase trade beyond the other TSO's supply of capacity. A necessary and sufficient condition for an equilibrium 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

[7] The procedure is formally denoted "net transfer capacity allocation."

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. Trade restrictions hurt the private sector in both countries. In the exporting country, producers lose more from a price reduction than consumers gain. In the importing country, consumers suffer more from a price increase than producers benefit. Private sector concerns should induce both TSOs to supply full transfer capacity. However, TSOs face a trade-off because a capacity restriction creates a congestion rent for each of them. 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*.

As mentioned, some TSOs are privately-owned. We therefore generalize the results to a setting with profit-maximizing TSOs. The trade distortion is exacerbated since *the profit-maximizing TSO always supplies relatively less transmission capacity to the market*. This result is independent of the ownership share of the privately-owned TSO.

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 will for any strictly positive trade volume prefer 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 will be shown, 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 available 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 available 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 theoretical and empirical research has focused on the exercise of market power by producers in electricity markets.[8] Much less attention has been devoted to the efficiency properties of network capacity allocations. A strand of literature related to market integration analyzes efficiency gains of coordinating electricity supply, e.g. Oggioni et al. (2012); Oggioni and Smeers (2012, 2013); Kunz and Zerrahn (2015, 2016). Our paper differs from those contributions by focusing on the equilibrium supply of network capacity instead of treating it as exogenous.

Closest to our paper are Glachant and Pignon (2005); van Beesten and Hulshof (2023). Both papers use numerical representations of power grids to give examples of how TSOs can benefit from reducing cross-border capacity to relieve domestic congestion. We consider instead a qualitative framework and perform an equilibrium analysis which we extend in directions not previously considered. Related to our analysis of market design, Höffler 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.

[8]The 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 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 national grids are joined via an *interconnector* that transmits electricity without any physical losses.

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 $y > 0$.[9] 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.[10] 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 Each national grid is owned by a national transmission system operator, TSO. TSO i also owns the share $\alpha_i \in (0, 1)$ of the interconnector. This interconnector has sufficient transfer capacity to sustain efficient trade, to be defined below. 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,

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

[9] An 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.

[10] Subscripts on functional operators denote partial derivatives.

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, $W_{zz} = -C^E_{xx} - C^I_{xx} < 0$, and therefore reaches its maximum under the trade volume $z^* > 0$ that equalizes the marginal production cost across the two countries,

$$C^E_x(y + z^*) \equiv C^I_x(y - z^*). \tag{2}$$

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 $C^E_x(y) < C^I_x(y)$. 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 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 assume that retailers in country (zone) i inelastically bid to purchase y for any price $p_i \leq v$. Flexible producers offer to sell at marginal cost up to the capacity limit $x^{\max}_i$. TSO E supplies export capacity $k_E \geq 0$ to the market platform, whereas TSO I supplies 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.[11]

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

[11] A less frequent method of deciding on transfer capacity 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 maximize total surplus. Tangerås (2024) establishes circumstances under which the two methods yield equivalent outcomes when TSOs are privately informed about domestic network conditions.

relationship must hold in country I:[12]

$$x_E - y = z = y - x_I. \tag{3}$$

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

$$p_i = P^i(y + \delta_i z) \equiv C^i_x(y + \delta_i z). \tag{4}$$

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 available 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, $P^E_x > 0$, which is offset by a corresponding decrease in production and a lower spot price in I, $P^I_x < 0$.

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

$$z = \min\{z^*; k\}, \tag{5}$$

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 vy 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 $(p_I - p_E)z$.[13]

[12]This 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.

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

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 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 3.4 by considering profit-maximizing TSOs.

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

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

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 distribution 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 by accounting for domestic congestion rent. 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 nonzero 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.*

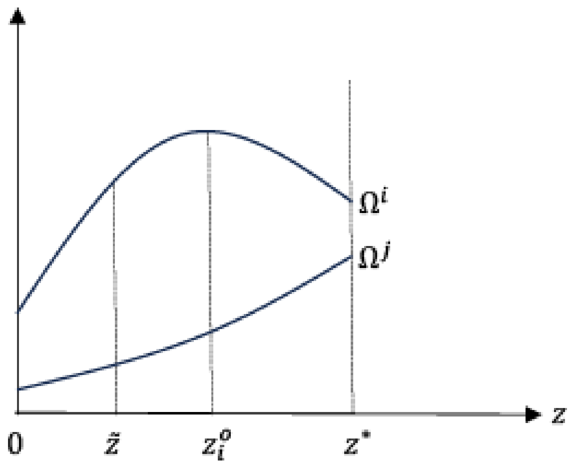

Figure 1: Equilibrium trade in the spot market

An unregulated internal market thus suffers from a fundamental market failure regarding allocation of cross-border transmission capacity to the market. 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.

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.

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

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

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) yields a continuum of equilibria, including autarky. We illustrate this phenomenon in Figure 1. For ease of exposition, we let both national welfare functions be strictly quasi-concave, although this is not needed for our results to go through. In the figure, $z_i^o \equiv \arg\max_z \Omega^i(z)$ identifies the transfer capacity TSO i would select if it had monopoly power over the interconnector. TSO j prefers maximal trade in $[0, z^*]$. It is impossible to sustain trade $z > z_i^o$ because TSO i could implement its most-preferred level of trade by reducing net transfer capacity to z_i^o through a capacity supply $k_i = z_i^o$. But all trade levels $z \in [0, z_i^o]$ can be sustained as equilibria when TSO objective functions are strictly quasi-concave. For instance, if $k_E = k_I = \tilde{z}$, then no TSO can unilaterally implement more trade than $\tilde{z}$, and each would lose by reducing trade below $\tilde{z}$.

The maximal equilibrium The Leontief property of capacity allocations leads to an equilibrium selection problem. However, in Figure 1 both TSOs prefer equilibria with more trade over those with less trade. Hence, equilibria that implement maximal trade Pareto dominate all other equilibria. In Figure 1, z_i^o represents the maximal trade than can be sustained in equilibrium. This example illustrates the following general property of the set of equilibria (formally verified in Appendix A):

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

In what follows we let $z^M > 0$ denote the maximal trade volume. 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 strictly 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, and we 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*

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

Equation (10) resembles the equilibrium condition $\frac{P(x)}{x} = P_x(x)$ for a monopolist producing at zero marginal cost, but with fundamental differences. The revenue of the TSO depends on the price difference between markets rather than the price level in a single market. Hence, the term on the left-hand side of (10). Because of this price difference, the incentive for a TSO to restrict trade is measured by the sum of the price slopes in the two countries, as seen by the first two expressions on the right-hand side of (10). Hence, price sensitivities aggregate across the two markets. The TSO accounts for the negative price effects on the domestic private sector of a reduction in trade by the assumption that the organization is state-owned. This effect, represented by the second term on the right-hand side of (10), reduces exercise of market power on the cross-border 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.

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. In the first case, TSO E exercises monopoly power by selling less electricity, whereas TSO I exploits monopsony power in the second case by purchasing less electricity. The nature of the market failure depends on the ownership shares and on the relative price sensitivities in the two countries. 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 interconnector or the marginal price effect on the domestic private sector is so weak, that it has a stronger incentive than TSO E to withhold transmission capacity. An export restriction applies if the inequality is reversed.[14]

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 will restrict 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.*

[14] The anecdotal evidence discussed in the introduction suggests that both can occur. In one competition case, the Swedish TSO was accused of limiting exports from Sweden, whereas the German TSO was accused of limiting imports into Germany in another case reviewed by the European Commission.

3.4 Private TSOs

We have assumed that TSOs maximize national social welfare. Yet, some European network owners are privately held companies.[15] Their objectives are likely to be profit-maximization, which 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.[16] We thus obtain:

Corollary 2 *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 them then wants to maximize the total congestion rent. They will then have a common interest in concealing exercise of market power.

3.5 Domestic transmission constraints

The analysis has so far focused on how TSO incentives to restrict cross-border transmission capacity can undermine market integration. But TSOs often control also transmission capacity for *domestic* transmission lines. To examine whether TSOs have similar incentives to withhold domestic transmission capacity, we generalize our benchmark model.

An extended model Let the electricity system in the exporting country be partitioned into two bidding zones, North (N) and South (S). 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.

[15] Elia Group is a publicly traded company that owns ETB (Belgian TSO) and 50Herz (German TSO). Another example is Terna (Italian TSO). See entsoe.eu/about/inside-entsoe/members/ for a list of European TSOs.

[16] If TSO i is a pure 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 $\alpha_i \to \infty$ in (10).

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:

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

Aggregating effects yield national welfare

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

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.[17]

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

[17] This extended model generalizes the model analyzed in the previous section. Set $S = E$ and $C^N(0) = 0$ to get $\Lambda^E(0, z) = \Omega^E(z)$.

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 $-\alpha_E P_x^S z$.

The only benefit for TSO E from reducing domestic transfer capacity results from driving up the export price. This marginal benefit is limited if the volume z of international trade is small or if the TSO owns a large share α_E of the interconnector. In this second case, TSO E internalizes most of the negative effect abroad of the price increase. TSO E has weak incentives to withhold domestic transmission capacity under those circumstances, yet allocation of domestic transmission capacity will be inefficient for any $z > 0$ and $\alpha_E < 1$. Let $H^*(z)$ be the allocation of 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 can thus conclude:

Proposition 3 *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.*

A direct implication of the proposition is that a TSO will implement a domestic capacity restriction even if it is unable to restrict international trade for instance due to regulation; see below. However, a marginal change in international trade has an ambiguous effect on the allocation of domestic transfer capacity. Let $H^E(z)$ solve the first-order condition $\Lambda_z^E(H^E, z) = 0$. The impact of z on the optimal h is then given by

$$H_z^E = \frac{1}{-\Lambda_{hh}^E}[\alpha_E P_x^S(x_S) - (1 - \alpha_E)P_{xx}^S(x_S)z]$$

where $\Lambda_{hh}^E < 0$ by the second-order condition. The sign of the numerator depends on the elasticity of the price slope P_x^S with respect to changes in output, the ownership distribution of the interconnector, and the trade volume. It is positive, for instance if TSO E owns a large share of the interconnector, in which case an increase in trade also has a positive impact on the allocation of domestic transmission capacity.

4 Mitigating exercise of TSO market power

The previous section showed how international integration of electricity markets can be undermined by TSO beggar-thy-neighbor behavior regarding allocation of international and domestic transmission 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 show how one can apply our findings to test empirically for exercise of TSO market power. Thereafter, we 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.

4.1 How to detect exercise of TSO market power

The model above suggests that TSOs have incentives and ability to artificially reduce transfer capacity on interconnectors. The following table illustrates that capacity restrictions are frequent in practice. It builds on data from the Nord Pool power exchange.[18] It shows allocation of interconnector capacity to the spot (day–ahead) 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). The sampl data are from 2021.

Table 1: **Capacity allocation in the Nord Pool day-ahead market 2021**

	DK2-DE	DE-DK2	NO2-DE	DE-NO2	SE-DE	DE-SE
Cap < Max cap:	93	76	100	49	100	100
0 < Flow = Cap Max cap:	66	39	80	12	28	77

Source: nordpoolgroup.com/en/Market-data1/#/nordic/table

The first row shows the share of all hours during 2021 for which the supplied capacity was below the nominal capacity. Capacity reductions were frequent on all interconnectors in the sample. However, such reductions were a problem only insofar as they created bottlenecks which restricted trade. The second row of the table therefore reports the share of hours during 2021 when trade was constrained by the supplied capacities at a level below the nominal capacity.[19] Binding capacity restrictions were very common for most of these interconnectors during that year.

In our model, all price differences in the spot market that result from capacity reductions are explained by exercise of TSO market power. For this conclusion to be valid based on the data presented in Table 1, it would have to be the case that the nominal

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

[19]By 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.

interconnector capacity always reflected the available capacity. In reality, domestic network constraints may limit the available 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.

Drawing on Proposition 2, it is possible to disentangle market power from exogenous capacity constraints, however, by estimating the following relationship:

$$\frac{p_I^M - p_E^M}{z^M} = \alpha + \beta[P_x^E(x_E^M) + P_x^I(x_I^M) - \min_{i=E,I} \frac{P_x^i(x_i^M)}{\alpha_i}] + \varepsilon$$

The dependent variable in this structural equation is the price difference in the spot market divided by the trade flow between the two bidding zones. The independent variable measures the incentive to exercise market power, and ε is an error term. An unbiased estimate of β would measure the extent to which TSOs exercise market power. In particular, price slopes have no systematic effects on price differences, and TSOs thus behave efficiently, if $\beta = 0$. Estimation of this structural equation only requires ownership data, and market information available through the power exchange.

4.2 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 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.

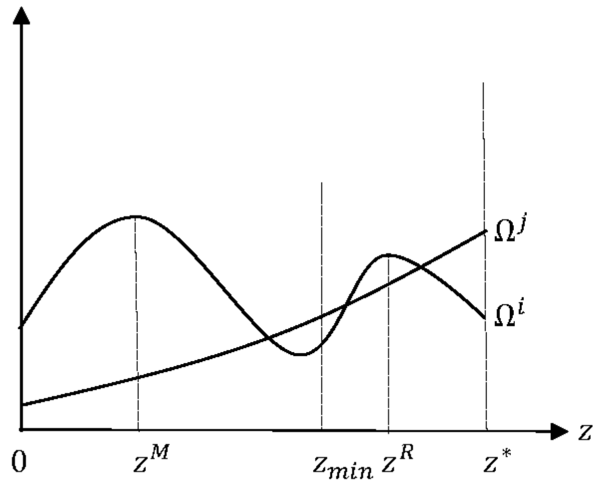

Figure 2: Maximal trade under minimal capacity regulation

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 $z_{\min}$. We illustrate this phenomenon in Figure 2. The unregulated maximal equilibrium is found at z^M. However, with z constrained to lie in $[z_{\min}, z^*]$, the maximal equilibrium is at $z^R > z_{\min}$. This illustrates that a regulation can be effective even if it does not bind in equilibrium.

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 available transfer capacity. Furthermore, full allocation need not be efficient even if the available capacity was public knowledge. The extension of the model in Section 3.5 to include a domestic transmission line, illustrates this point. If a decrease in international trade increases unregulated domestic transfer capacity, $-H_z^E(z^*) > 0$, then full allocation of interconnection capacity to implement z^* is suboptimal.

4.3 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. 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 Betrand 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).

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

TSO objectives The extended objective function of TSO i equals

$$\begin{aligned}\tilde{\Omega}^i(z, \bar{\mathbf{p}}, \bar{\mathbf{z}}) \equiv\ & \delta_i[\bar{p}_i - P^i(x_i)]\gamma_i \bar{z} + \delta_j[\bar{p}_j - P^j(x_j)](1-\gamma_j)\bar{z} \\ & + [\bar{p}_I - \bar{p}_E - P^I(x_I) + P^E(x_E)]\bar{z}_i \\ & + \Omega^i(z)\end{aligned} \tag{11}$$

under the assumption that each TSO takes full account of the domestic private sector surplus in the forward market.[21] 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 (11) 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 (11) captures the TSO welfare from the spot market as defined in eq. (6).

To emphasize forward versus spot market decisions, we rewrite (11) as

$$\tilde{\Omega}^i(z, \bar{\mathbf{p}}, \bar{\mathbf{z}}) \equiv \delta_i \bar{p}_i \gamma_i \bar{z} + \delta_j \bar{p}_j (1-\gamma_j)\bar{z} + (\bar{p}_I - \bar{p}_E)\bar{z}_i + \hat{\Omega}^i(z, \bar{\mathbf{z}}). \tag{12}$$

The first three terms on the right-hand side of (12) capture the transactions in the forward market; the monetary value of these transactions only depend of forward prices.

$$\hat{\Omega}^i(z, \bar{\mathbf{z}}) \equiv \Omega^i(z) - [P^I(x_I) - P^E(x_E)]\bar{z}_i - \delta_i P^i(x_i)\gamma_i \bar{z} - \delta_j P^j(x_j)(1-\gamma_j)\bar{z} \tag{13}$$

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

$$\hat{\Omega}^i_z(z, \bar{\mathbf{z}}) = \Omega^i_z(z) + [P^I_x(x_I) + P^E_x(x_E)]\bar{z}_i - [P^i_x(x_i)\gamma_i + P^j_x(x_j)(1-\gamma_j)]\bar{z} \tag{14}$$

[21] Recall that $\delta_E \equiv -\delta_I \equiv 1$.

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 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 (14). 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, $Z^i(\bar{\mathbf{z}}) \in (0, z^*)$,

$$\hat{\Omega}^i_{z\bar{z}_i} = (1-\gamma_i)P^i_x(x_i) + \gamma_j P^j_x(x_j) \geq 0 \tag{15}$$

implies $Z^i_{\bar{z}_i} \geq 0$ with strict inequality if $\gamma_i < 1$ or $\gamma_j > 0$. Moreover,

$$\hat{\Omega}^i_{z\bar{z}_j} = -\gamma_i P^i_x(x_i) - (1-\gamma_j)P^j_x(x_j) \leq 0 \tag{16}$$

implies $Z^i_{\bar{z}_j} \leq 0$ 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 (15) and (16) 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 *An increase in the volume contracted in the forward market by TSO i increases trade in the spot market if TSO i constrains trade in equilibrium (i.e. $Z^i(\bar{\mathbf{z}}) < Z^j(\bar{\mathbf{z}})$), but reduces trade otherwise (when $Z^j(\bar{\mathbf{z}}) \leq Z^i(\bar{\mathbf{z}})$).*

This feature differs fundamentally from the standard Allaz-Vila model, in which forward contracting improves competition in the spot market 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 in equilibrium: $\bar{P}^E(\bar{\mathbf{z}}) = P^E(y_E + Z(\bar{\mathbf{z}}))$ 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

$$\bar{\Omega}^i_{\bar{z}_i}(\bar{\mathbf{z}}) \equiv \hat{\Omega}^i_z Z_{\bar{z}_i} + \tilde{\Omega}^i_{\bar{z}_i} + \tilde{\Omega}^i_{\bar{p}_i} \bar{P}^i_{\bar{z}_i} + \tilde{\Omega}^i_{\bar{p}_j} \bar{P}^j_{\bar{z}_i}$$

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, $\hat{\Omega}^i_z Z^i_{\bar{z}_i} = 0$. 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,

$$\bar{\Omega}^i_{\bar{z}_i} = \{[\gamma_i P^i_x + (1-\gamma_j) P^j_x]\bar{z} - [P^I_x + P^E_x]\bar{z}_i\} Z_{\bar{z}_i}$$

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

$$\bar{\Omega}^j_{\bar{z}_j} = \{\hat{\Omega}^j_z + [\gamma_j P^j_x + (1-\gamma_i) P^i_x]\bar{z} - [P^I_x + P^E_x]\bar{z}_j\} Z_{\bar{z}_j} = \Omega^j_z Z_{\bar{z}_j}, \tag{17}$$

For this TSO, only the strategic incentive $\Omega^j_z > 0$ 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 effect is opposite to what occurs in the standard Allaz-Vila model, in which the purpose for producers of trading in the forward market is to reduce competition, by reducing competitors' outputs. The purpose here is to increase trade, and thus indirectly to reduce the distortion that results from the non-cooperative supply of network capacity.

Forward market equilibrium An equilibrium $\bar{\mathbf{z}}^F = (\bar{z}^F_E, \bar{z}^F_I)$ in the forward market is characterized by $\bar{z}^F_E = \arg\max_{\bar{z}_E \geq 0} \bar{\Omega}^E(\bar{z}_E, \bar{z}^F_I)$, with a similar optimality condition for $\bar{z}^F_I$. 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 B:

Proposition 4 *Zero trade of forward contracts represents a subgame-perfect equilibrium ($\bar{z}^F_E = \bar{z}^F_I = 0$). This equilibrium is unique if $\gamma_E \in (0,1)$, $\gamma_I \in (0,1)$ and $q^o_E \neq q^o_I$ all hold.*

The assumptions regarding γ_E and γ_I ensure that marginal changes in the forward positions $\bar{\mathbf{z}}$ strictly affect interior trade $Z(\bar{\mathbf{z}})$ 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.

4.4 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

$$L(k) \equiv [P^I(y - \min\{z^*, k\}) - P^E(y + \min\{z^*, k\})] \min\{z^*, k\}, \tag{18}$$

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

$$L^i(k_i, k_j) \equiv \begin{cases} \alpha_i L(k) & \text{if } k_i = k_j, \\ -\psi(k_i) & \text{if } k_i < k_j. \end{cases} \tag{19}$$

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, $L^j(k_j, k_i) = L(k) - L^i(k_i, k_j)$.

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.

The sharing rule (19) provides strong incentives for the two TSOs to coordinate capacity supply. A concern is that such coordination might enable TSOs to sustain less efficient outcomes as well, for instance an equilibrium without trade.[22] The penalty function $\psi(\cdot)$ is designed precisely to avoid autarky. We prove the following result in Appendix C:

Proposition 5 *Consider a market design with congestion rent shared according to (19).*
(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 (19), the authority just needs to observe the individual supply of capacity and the congestion rent L, both of which are readily 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 (19) 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.

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

[22]The proposed sharing rule could facilitate collusion in an infinitely repeated game. However, the trade that maximizes the two TSOs joint surplus is the efficient volume of trade. In our setting, collusion on the jointly surplus-maximizing trade would therefore be efficient.

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 system operators in electricity markets.

This paper analyzes incentives in a decentralized European-style electricity market. It shows that pursuit of national objectives will cause transmission system operators (TSOs) to restrict transfer capacity below the level required for efficient trade. But the paper also points to institutional modifications that can mitigate exercise of TSO market power. Still, it leaves many interesting questions for future research:

(1) The present model features two countries. A setting with three or more 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 price-takers in the spot market in the present model. How would market power of retailers and generation owners affect performance and the realized gains from integration?

(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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Appendices

A 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 $\Omega^i_z(0) = \alpha_i[P^I(y) - P^E(y)] > 0$, $i = E, I$, 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. 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.■

B Proof of Proposition 4

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

$$\bar{\Omega}^E(\bar{\mathbf{z}}) = \Omega^E(Z(\bar{\mathbf{z}})),\ \bar{\Omega}^I(\bar{\mathbf{z}}) = \Omega^I(Z(\bar{\mathbf{z}})) \tag{A.20}$$

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 (A.20). 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 (17), we know that $\bar{\Omega}^j_{\bar{z}_j} = \Omega^j_z Z_{\bar{z}_j}$. By the assumed strict quasi-concavity of $\Omega^j(z)$, $\Omega^j_z(Z(0,\bar{z}_j)) \geq 0$ since $Z^i(0,\bar{z}_j) \leq Z^i(0,0) = z_i^F \leq z_j^F = Z^j(0,0) = z_j^o = \arg\max_z \Omega^j(z)$. Since $Z_{\bar{z}_j} = Z^i_{\bar{z}_j} \leq 0$, we obtain $\bar{\Omega}^j_{\bar{z}_j} \leq 0$ 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 $z_E^o \neq z_I^o$. The proof is in six steps.

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

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

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

$$\hat{\Omega}^i_z(0,\bar{z}_i,\bar{z}_j^F) = [\gamma_j P^j_x(y_j) + (1-\gamma_i)P^i_x(y_i)]\bar{z}_i - [\gamma_i P^i_x(y_i) + (1-\gamma_j)P^j_x(y_j)]\bar{z}_j^F + \Omega^i_z(0)$$

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

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

which contradicts the assumption that $\bar{z}^F_i$ is a best-reply to $\bar{z}^F_j$.

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

$$\hat{\Omega}^l_z(z, 0, \bar{z}^F_h) = -[\gamma_l P^l_x + (1 - \gamma_h)P^h_x]\bar{z}^F_h + \Omega^l_z(z) \leq \Omega^l_z(z),$$

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

$$\bar{\Omega}^l(\bar{b}_l, \bar{z}^F_h) = \Omega^l(z^o_l) > \Omega^l(z^*) = \bar{\Omega}^l(\bar{\mathbf{z}}^F),$$

which contradicts the assumption that $\bar{z}^F_l$ is a best-reply to $\bar{z}^F_h$.

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

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

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

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

Step (iv): Assume that $z^F \in (0, z^*)$, and suppose $\bar{z}^F_j > 0 = \bar{z}^F_i$. If $z^F_i < z^F_j$, then $\bar{\Omega}^j_{\bar{z}_j}(\bar{\mathbf{z}}^F) = \Omega^j_z(z^F_i)Z^i_{\bar{z}_j}(\bar{\mathbf{z}}^F) < 0$. If $z^F_i = z^F_j$, then TSO j can implement trade z^o_j by deviating to $\bar{z}_j = 0$. This deviation yields $\bar{\Omega}^j(0, \bar{z}^F_i) > \bar{\Omega}^j(\bar{\mathbf{z}}^F)$ by the same argument as in Step (iii). These results contradict $\bar{z}^F_j > 0$ being a best-reply to $\bar{z}^F_i = 0$.

Step (v): Assume that $z^F \in (0, z^*)$, and suppose $\bar{z}^F_i > 0$, $\bar{z}^F_j > 0$ and $z^F \neq z^o_j$. Then

$$\bar{\Omega}^i_{\bar{z}_i}(\bar{\mathbf{z}}^F)Z_{\bar{z}_j} + \bar{\Omega}^j_{\bar{z}_j}(\bar{\mathbf{z}}^F)Z_{\bar{z}_i} = \Omega^j_z(z^F)Z_{\bar{z}_i}Z_{\bar{z}_j} \neq 0.$$

This equilibrium cannot exist because either $\bar{\Omega}^E_{\bar{z}_E}(\bar{\mathbf{z}}^F) \neq 0$ or $\bar{\Omega}^I_{\bar{z}_I}(\bar{\mathbf{z}}^F) \neq 0$, 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

$$\bar{\Omega}^i_{\bar{z}_i}(\bar{\mathbf{z}}^F) = \Omega^i_z(z_j^o) Z_{\bar{z}_i} \neq 0$$

where $\Omega^i_z(z_j^o) \neq 0$ 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.■

C Proof of Proposition 5

Consider a balancing market design as analyzed in Section 3, except TSO i's congestion rent is defined by (19). National welfare in country i then equals

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

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

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

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 $k_i < z^*$,

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

The inequality holds because $\psi(k_i) \geq 0$ and $R^i_z(z) = P^i_x(y + \delta_i z) z > 0$ 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

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

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

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

The net benefit

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

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 $i = I$.■