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National Transmission System Operators in an International Electricity Market

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Abstract

This paper develops a framework for analyzing the incentives of national transmission system operators (TSOs) to supply cross-border interconnection capacity in an international electricity market. Our results show that equilibrium transmission capacity is downward distorted, even in situations where full capacity utilization is inefficient. We derive a method for quantifying these distortions and propose a market design that uniquely implements efficient dispatch of electricity. In this design, the distribution of trade adjustment payments causes TSOs to internalize the full effect of network congestion. The design would improve, for instance, on the current European market design.
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Contents

1 Introduction **1**

2 Regulation of cross-border interconnections in the EU **5**

3 A model of an integrated electricity system **9**

4 First-best efficient dispatch **10**

5 The wholesale electricity market **11**
5.1 The day-ahead market 11
5.2 General properties of balancing markets 13

6 Efficiency of the day-ahead market **15**

7 Segmented balancing markets **17**

8 Fully integrated balancing market **23**

9 The EU balancing market **24**

10 A first-best efficient balancing market **31**

11 Discussion **33**

A Appendix **36**
A.1 Proof of Proposition 6 36

1 Introduction

A long-standing ambition of the European Union (EU) has been to create an internal market for electricity.[1] An integrated market enables member states to harvest gains from trade associated with exploitation of comparative advantage and increased competition. Market integration can also serve to increase the overall reliability of the electricity system by making each individual country less dependent on the availability of domestic generation capacity for supply security. This second aspect of market integration has become more important as many member states have increased the share of variable renewable energy such as solar and wind power, in an effort to reduce CO_2 emissions in electricity production.

Achieving the internal market has turned out to be challenging, even if many countries have undertaken substantial investment to expand network capacity. A fundamental obstacle to market integration has been the behavior of the national transmission system operators (TSOs) who own and operate the domestic transmission networks and cross-border connections. A common practice among TSOs for solving domestic supply constraints is to “move congestion to the border” by reducing exports. A second concern is TSO manipulation of prices through a strategy of withholding transmission capacity from the market. The Agency for the Cooperation of Energy Regulators (ACER) considers "discrimination between electricity exchanges within and between bidding-zones" as one of the main obstacles to electricity market integration in the EU (ACER, 2019).

Two examples illustrate this problem. In 2006, the European Commission received a complaint concerning the practice of the Swedish TSO, *Svenska Kraftnät* (SvK), of reducing export capacity from Sweden to Denmark through the Öresund interconnection. According to an assessment by the Commission, this behavior discriminated consumers in surrounding countries relative to consumers in Sweden (EU, 2010). In a similar case from 2018, the Commission concluded that the German TSO *TenneT* had significantly limited the import capacity on the interconnections between Germany and West Denmark. This behavior had discriminated users on the basis of their location in the network (EU, 2018). The Commission concluded in both cases that the conduct by the TSOs could represent an abuse of dominant position in violation of EU competition rules.[2]

The high degree of ownership concentration in electricity markets, the price insensitivity of demand, the structured auction format for wholesale electricity trade, and the availability of detailed and frequent market data, have generated a vast theoretical and empirical literature that examines market power by generation owners.[3] The purpose of this paper is to analyze a key aspect of market

[1] This objective was first formalized in Directive 96/92/EC (EC, 2019) which has been revised on several occasions. The most recent version is Directive 2019/944 (EU, 2019b).

[2] SvK accepted the assessment and took measures to reduce domestic congestion problems. TenneT agreed to increase the import capacities on the disputed connections.

[3] The basic theory was laid out by Wilson (1979), Klemperer and Meyer (1989), Green and Newbery (1992) and Von der Fehr and Harbord (1993). This framework has been generalized and extended in many directions, most recently by Holmberg and Philpott (2018), and Holmberg and Wolak (2018). Classical empirical contributions include Wolfram (1999), Borenstein et al. (2002), Wolak (2003), Sweeting (2007), Bushnell et al. (2008), Hortaçsu and Puller (2008),

performance that hardly has received any attention in the literature, namely *the incentives for TSOs to supply network capacity to the electricity market.* We frame our analysis in the context of cross-border interconnections in an international electricity market. Analysis of strategic behavior by TSOs calls for a different framework from that applied to power companies. TSOs are subject to particular network regulation, and they are often state-owned instead of privately owned companies. Hence, the *governance structure* differs between TSOs and power producers. Also, the *scope* of TSO operations differs from that of generators. Not only do they supply network capacity to the wholesale electricity market, each TSO is also responsible for maintaining the physical balance between consumption and production within its control area.[4] These differences in governance and scope imply that TSOs generally have different objectives and incentives to exercise market power than producers in the electricity market.

In Section 2, we present key legal provisions in the EU that apply to TSOs. These provisions explicitly prohibit quantitative restrictions aimed at resolving internal congestion problems or that are implemented with a purpose to affect market prices. However, the EU regulations also allow TSOs to impose restrictions on electricity flows if they are necessary to ensure the operational security of domestic electricity supply. By implication, TSOs have ample opportunity to pursue domestic objectives under the current regulation. In view of the TSOs' superior information about system conditions, the fundamental problem for regulatory authorities is how to distinguish between strategic restrictions and those that are required from a system point of view.

We formalize in Section 3 a two-country model of an interconnected electricity system. There is flexible and intermittent electricity production in both countries, and demand is constant. A transmission line that is jointly owned by the two national TSOs connects the two countries. The first-best efficient solution equalizes the marginal cost of flexible production across countries under the maintained assumption that the transmission network has sufficient capacity to sustain efficient dispatch in any state of the system; see Section 4.

Market interaction takes place in two stages, as described in Section 5. In the first stage, producers and consumers in both countries bid electricity into a common *day-ahead market* operated by a power exchange. The TSOs announce the maximal volume of electricity they are willing to trade in each direction. Consistent with actual market rules, the *day-ahead trading capacity* is calculated as the minimum of the announced export and import capacities. The day-ahead market is split into national price areas if trading capacity is insufficient to sustain full price equalization. In the second stage, flexible generation capacity participates in two *national balancing markets* operated by the TSOs. The purpose of the balancing markets is to enable redispatch of flexible generation to offset shocks to intermittent electricity generation. We assume that the TSOs maximize expected

Reguant (2014), Koichiro and Reguant (2016).

[4] A failure to do so may cause system disruptions and uncontrolled blackouts. A famous example is the Northeast blackout of 2003 that started with a power plant in Ohio shutting down. The failure 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.

national welfare. All other market participants behave non-strategically. These assumptions allow us to emphasize efficiency related to strategic interaction among TSOs, instead of distortions related to domestic governance problems or market performance in other dimensions.

Section 6 establishes fundamental efficiency properties of the day-ahead market. In particular, all distortions occur as a consequence of excessive withholding of capacity. It is impossible to sustain an inefficient equilibrium with too much trade because TSOs then can increase domestic welfare by a unilateral reduction in trading capacity. By implication, any equilibrium in the day-ahead market in which TSOs implement the maximal trading capacity is efficient. These results are derived from reduced-form welfare expressions and therefore hold for any balancing market design.

The rest of the analysis evaluates the efficiency properties of different types of balancing market designs. Section 7 considers the historically relevant benchmark of *segmented balancing markets.* The fundamental characteristic of this design is that the volume of international trade cleared in the day-ahead market represents a binding restriction on the cross-border exchange of electricity in the balancing market. Because trading capacities are set before the realization of intermittent electricity production, the constrained efficient solution equalizes the expected marginal cost of flexible production across the two countries. In particular, efficiency may dictate that some capacity is withheld from the day-ahead market. But the TSOs are concerned with maximizing expected national welfare rather than expected efficiency. Under a segmented balancing market design, national welfare equals gross consumer surplus plus export net revenue (or minus import net cost) in the day-ahead market minus expected domestic production cost. If a country exports electricity in the day-ahead market, then the optimal export capacity bid into the day-ahead market by the TSO in this country trades off a marginal increase in export net revenue against a marginal increase in the expected domestic production cost. For the TSO in the other country, the optimal import capacity bid into the day-ahead market trades off a marginal reduction in expected domestic production cost against a marginal increase in import net cost. TSO market power implies that they withhold too much capacity from the day-ahead market. This market power can materialize either as a quantitative restriction on export or on import capacity in equilibrium.

Section 8 considers the opposite polar extreme of a *fully integrated balancing market.* In this market design, all physically available transmission capacity can be used for short-term balancing of supply and demand in both countries, regardless of the volume of trade in the day-ahead market. The balancing market implements the first-best efficient outcome under the assumption that TSOs accept all cross-border exchange of electricity implied by efficient dispatch.

The segmented market is inefficient because the dispatch of electricity does not fully adapt to changes in system conditions. The fully integrated market is flawed by ignoring TSO incentives. In Section 9, we examine an intermediate type of market design, which captures core features of the current EU regime. It allows resdispatch across countries as system conditions change, but also incorporates equilibrium behavior by TSOs. A fundamental aspect of this design is that cross-border redispatch breaks the overall budget balance in the balancing market. The net payments to flexible generators now differ from the net payments from intermittent generators. The difference between the two payment streams represents a *trade adjustment payment*. Positive (negative) trade adjustment payments represent additional income (expenditure) for the TSOs. The current EU balancing market model specifies that trade adjustment payments should be equally split among TSOs. The EU market design increases the possibility for redispatch, but we show that cross-border redispatch will be inefficiently low if TSOs exercise market power. This result vindicates ACER's above-mentioned concern about the current balancing market design. The equilibrium conditions in the balancing market also allows us to derive a methodology for quantifying such distortions. Specifically, the price difference in the balancing market equals the (inverse of) the semi-elasticity of the trade adjustment payment. The data required to estimate this relationship can be collected from TSO balancing market operations.

We conclude the analysis by proposing in Section 10 a market design that implements first-best efficient dispatch as a unique equilibrium outcome. This design is similar to the EU design in prescribing an even split of trade adjustment payments if both TSOs bid the same capacities into the balancing market. However, any TSO that exacerbates a bottleneck by setting a lower capacity that the other TSO, receives none of the resulting trade adjustment payment if this payment is positive and must make the entire payment if it is negative. Carrying the full responsibility for any unilateral deviations causes TSOs to internalize the effect of excessive capacity reductions.

Section 11 draws policy implications, discusses limitations of the analysis and provides suggestions for model extensions. An Appendix contains the proof of a formal statement.

Related literature As mentioned above, the literature on TSO incentives in international markets is meagre. One line of research uses power grid models to calculate efficiency gains of coordinating electricity redispatch instead of solving these problems separately for each price area (e.g. Oggioni et al., 2012; Oggioni and Smeers, 2012, 2013; Kunz and Zerrahn 2015, 2016).[5] Translated into the context of our model, these papers essentially compare joint welfare in the segmented balancing market of Section 7 with the fully integrated balancing market of Section 8, treating the cross-border trading capacity in the day-ahead capacity as fixed and exogenous. Our paper differs from this literature by treating cross-border transmission capacity as *strategic*.

Glachant and Pignon (2005) are among the very few to consider the incentives of national TSOs to supply transmission capacity to the market. The authors build a power grid model of the integrated electricity market, and demonstrate by a numerical example how a TSO can earn congestion revenue and reduce redispatch cost by inducing congestion on a cross-border interconnection to relieve internal congestion. They conduct no systematic analysis. Höffler and Wittmann (2007)

[5] The models in these papers are deterministic. The demand for redispatch occurs because of transmission constraints within price areas that are neglected in the day-ahead market. Redispatch to solve internal congestion is commonly known as *counter-trading*. In our model, network capacity is sufficient within each price area to handle all allocations resulting from market clearing in the day-ahead market. Instead, redispatch arises because of the variability of intermittent production.

identify an auction design that reduces the incentive to withhold capacity when an owner auctions off access to a cross-border interconnection. Explicit auctions of transmission capacity have mostly been abandoned in Europe in favor of a market design where network owners instead receive congestion rent for the capacity they supply to the market.

2 Regulation of cross-border interconnections in the EU

Electricity markets are regulated at the EU level through a large number of legal instruments. In this section, we point to a few provisions that we see as being of immediate relevance to our analysis. We will distinguish between the general rules laid down in the *Treaty of the Function of the European Union* (TFEU, 2007), and sector-specific Directives and Regulations.

TFEU This directive is the basis for all EU regulation, and contains a number of general provisions that are fundamental to the Internal Market. Two sets of rules are of particular interest. The first set concerns the *prohibition of quantitative trade restrictions*:

> Quantitative restrictions on imports [exports], and all measures having equivalent effect shall be prohibited between Member States. (Article 34 [35])

These provisions are stated in very clear terms, but there are few prohibitions without exceptions:

> The provisions of Articles 34 and 35 shall not preclude prohibitions or restrictions on imports, exports or goods in transit justified on grounds of ... protection of industrial and commercial property..... (Article 36)

Even the exceptions come with qualifications:

> Such prohibitions or restrictions shall not, however, constitute a means of arbitrary discrimination or a disguised restriction on trade between Member States. (Article 36)

Hence, as is often the case, while the law seeks to strike down national measures that have negative externalities on other member states, it also recognizes that legitimate reasons can exist for countries to employ such measures. It leaves to the case law to draw the line between which quantitative restrictions are legal and which are not.

Articles 34-36 apply to measures by EU member states. Insofar as TSOs are considered undertakings, they are bound by TFEU rules regarding *competition*. Of particular relevance is the prohibition of abuse of dominance in Article 102, including:

> (a) directly or indirectly imposing unfair purchase or selling prices or other unfair trading conditions;

> (b) limiting production, [or] markets ... to the prejudice of consumers;
>
> (c) applying dissimilar conditions to equivalent transactions with other trading parties, thereby placing them at a competitive disadvantage...

The relevance of these rules to TSOs has already been demonstrated in practice with the intervention of the European Commission against SvK for trade restrictions on electricity between Sweden and Denmark and against TenneT for trade restrictions on electricity between Denmark and Germany.

With regard to implementation of the internal market for electricity, the TFEU stipulates shared competence between the Union and EU member states. The TFEU also specifies that the Union is obliged to foster integration of trans-European energy networks:

> ... the Union shall contribute to the establishment and development of trans-European networks in the areas of ... energy infrastructures... (Article 170)
>
> ...Union policy on energy shall aim, in a spirit of solidarity between Member States, to ... promote the interconnection of energy networks. (Article 194)

But the TFEU also requests member states–which typically are the owners of the TSOs—to contribute to the integration process:

> Member States shall, in liaison with the Commission, coordinate among themselves the policies pursued at national level which may have a significant impact on the achievement of the objectives referred to in Article 170. (Article 171)

Directives and Regulations The first EU measure directly aimed at electricity production and transmission was a 1996 Directive on common rules for the internal market in electricity. A series of directives and Commission regulations have since been introduced, many of which have implications for TSO operations. Among the acts currently in force, Regulation 2015/1222 (EU, 2015) establishes guidelines for capacity allocation and congestion management for day-ahead and intra-day markets. Rules for electricity balancing are laid down in Regulation 2017/2195 (EU, 2017). The regulatory framework was recently updated through the adoption of the "Clean Energy for all Europeans Package". This package contains a number of legal acts aimed at facilitating a clean energy transition, including Regulation 2019/943 (EU, 2019a) and Directive 2019/944 (EU, 2019b) on the internal market for electricity. These acts specify a broad range of relevant measures.

Like earlier legal acts, Regulation 2019/943 emphasizes the *need for more trade in electricity*. For instance, the preamble to the regulation states:

> More market integration and the change towards a more volatile electricity production requires increased efforts .... to use the opportunities of cross-border electricity trade. (Recital 8)

The Regulation sees a particular need for integration to emanate from the shift toward renewable energy production:

> Efficient decarbonisation of the electricity system via market integration requires systematically abolishing barriers to cross-border trade to overcome market fragmentation and to allow Union energy customers to fully benefit from the advantages of integrated electricity markets and competition. (Recital 32)

Regulation 2019/943 specifies a number of requirements for the integration of electricity markets. Among these is the need for *full non-discriminatory use of transmission capacity.* For instance:

> Day-ahead .... markets shall ... ensure operational security while allowing for maximum use of transmission capacity; ... make no distinction between trades made within a bidding zone and across bidding zones. (Article 7)

Importantly, the Regulation imposes restrictions on the ability of TSOs to pursue nationally defined objectives. For instance, it *prohibits TSOs from seeking to affect market prices*:

> Transmission system operators shall not take any measures for the purpose of changing wholesale prices. (Article 10)

The Directive also requests TSOs to *internalize external effects* of their decisions:

> 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 neighboring control areas... (Article 16)

TSOs are *not permitted to reduce cross-zonal capacity to resolve internal congestion problems*:

> Transmission system operators shall not limit the volume of interconnection capacity to be made available to market participants as a means of solving congestion inside their own bidding zone or as a means of managing flows resulting from transactions internal to bidding zones. (Article 16)

But the Directive also specifies sufficient conditions for compliance:

> (a) for borders using a coordinated net transmission capacity approach, the minimum capacity shall be 70 % of the transmission capacity respecting operational security limits after deduction of contingencies...;
>
> (b) for borders using a flow-based approach, the minimum capacity shall be a margin set in the capacity calculation process as available for flows induced by cross-zonal exchange. The margin shall be 70 % of the capacity respecting operational security limits of internal and cross-zonal critical network elements, taking into account contingencies. (Article 16)

Finally, Directive 2019/944 requests each member state to designate a single regulatory authority at national level (Article 57). Among its duties is to ensure:

> ... that transmission system operators make available interconnector capacities to the utmost extent pursuant to Article 16 of Regulation (EU) 2019/943. (Article 59)

Trade agreements While the EU regulates member states and their national TSOs, the EU regulation is in turn constrained by international agreements to which the EU is a party.[6] In particular, the EU has signed *trade agreements* that address domestic regulations, and thereby also the electricity market. There is considerable legal debate regarding the pecking order between these international agreements, and international law more generally, on the one hand, and EU law on the other hand. Without taking a stand on this complicated legal issue, we here just make a few remarks regarding the constraints that trade agreement can potentially impose.

The World Trade Organization (WTO) agreement is by far the largest trade agreement in terms of membership. For the purpose of the WTO agreement, electricity is a good, and is as such covered by its broad range of rules for trade in goods, including the general rules in the GATT, and specialized rules in e.g. the Agreement on Technical Barriers to Trade. For instance, as part of the GATT, the EU has made commitments on the maximal import tariffs it can levy on imports of electricity from third countries. A deeply rooted notion in WTO law with potential relevance for the regulation of TSOs, is the prohibition of quantitative restrictions on trade. But as in the case of the TFEU, the WTO agreements also include various exceptions for measures that are deemed "necessary" to achieve certain legitimate policy objectives, provided they do not constitute "disguised protection", etc.. These rules are clearly relevant to any EU measure that affects trade with other WTO members. But they formally apply also to trade between EU member states.

Another agreement of particular interest to electricity is the Energy Charter Treaty (ECT). This is a combined trade and investment agreement with approximately 50 members, including most EU countries and the EU itself. The agreement only applies to the energy sector. It encompasses the GATT rules, but goes further in certain regards. For instance, it includes rules regarding competition. ECT formally applies between EU members states. But the Commission and most member states are currently seeking to limit its applicability in this regard. ECT provisions regarding investment protection have often been used by non-EU investors against EU member states concerning investments in electricity generation. But there are also examples of intra-EU disputes, such as the ongoing investment dispute between the Swedish electricity producer Vattenfall and Germany regarding the decommissioning of nuclear power. If ECT continues to apply to intra-EU matters, it could be relevant for intra-EU electricity trade, including the operations of TSOs.

[6] See e.g. Plaza (2013) for an analysis of international law aspects of international power transmission.

Implications The legal framework is complex. But for the purpose of the present paper, certain aspects stand out regarding the role of TSOs in the EU:

- There is a very clear ambition to increase intra-EU trade in electricity;
- TSOs are not allowed to restrict quantities to affect prices or export congestion problems to other member states.
- TSOs are allowed to impose measures that are necessary to fulfil the central task of ensuring the operational security stability of their respective national grids.

3 A model of an integrated electricity system

There are two countries, A and B, each of which has a representative consumer with deterministic and completely inelastic demand for $D_i > 0$, $i = A, B$, megawatthours (MWh) electricity. Consumer i obtains utility v_i per MWh electricity consumed.

There are two production technologies in each country. Flexible generation in country i dispatches x_i MWh electricity by way of a continuous, increasing, strictly convex and twice continuously differentiable cost function $C^i(x_i)$. We denote the marginal cost of flexible production by $C^i_x(x_i)$ (subscripts on functional operators denote partial derivatives throughout), and assume that $C^i(0) = C^i_x(0) = 0$.[7] One can think of flexible generation capacity as gas-fired electric power. We assume that these cost functions are asymmetric.

Each country also has inflexible generation that dispatches y_i MWh electricity using a renewable energy source. This output is stochastic and distributed according to the continuous cumulative distribution function $F^i(y_i)$ on $Y^i \equiv [0, y_i^{\max}]$. Intermittent production has zero marginal cost. Using tildes to identify expectations, the expected intermittent electricity production is

$$\tilde{y}_i \equiv \int_0^{y_i^{\max}} y_i dF^i(y_i).$$

Denote by $F(\mathbf{y})$ the joint cumulative distribution of intermittent production $\mathbf{y} \equiv (y_A, y_B)$ on $\mathbf{Y} \equiv Y^A \times Y^B$. One can think of intermittent production as wind or solar power. We let $y_i^{\max} < D_i$, so that some flexible generation is always required to clear consumption and production. Each country has sufficient flexible generation capacity to meet domestic demand, regardless of intermittent production. Let $C^i_x(D_i) < v_i$, so that curtailment of consumption is inefficient.

We assume that the transmission network connecting producers and consumers within each country does not have any internal capacity constraints, since the focus of the paper is on international aspects of electricity supply. The two national grids are connected via a cross-border

[7] We assume that the marginal cost of flexible production is weakly convex, $C^i_{xxx}(x_i) \geq 0$, for some complementary analysis.

interconnection with sufficient transfer capacity in both directions to sustain efficient dispatch of electricity in any state of the system. Each national grid is owned and maintained by a national TSO. Each of the two TSOs owns half of the international interconnection.

We take country A to be the *natural exporter,* in the sense that the marginal cost of supplying the expected residual demand $D_A - \tilde{y}_A$ in country A is smaller than the marginal cost of supplying the expected residual demand $D_B - \tilde{y}_B$ in country B: $C_x^A(D_A - \tilde{y}_A) < C_x^B(D_B - \tilde{y}_B)$.

4 First-best efficient dispatch

Joint welfare across the two countries equals

$$v^A D^A + v^B D^B - C^A(D^A - y_A + t) - C^B(D^B - y_B - t)$$

as a function of the exchange t of electricity from country A to B.

The transmission grid has unconstrained capacity, so the first-best efficient exchange $T^*(\mathbf{y})$ equalizes the marginal flexible production cost across the two countries:

$$C_x^A(D_A - y_A + T^*(\mathbf{y})) \equiv C_x^B(D_B - y_B - T^*(\mathbf{y})). \tag{1}$$

The corresponding first-best efficient dispatch of flexible generation capacity is

$$X^{i*}(\mathbf{y}) \equiv D_i - y_i + \delta_i T^*(\mathbf{y}),\ i = A, B, \tag{2}$$

where δ_A and δ_B are two indicator functions with the properties $\delta_A \equiv -\delta_B \equiv 1$. We can also define the first-best efficient joint expected welfare:

$$\tilde{w}^* \equiv \sum_{i=A,B} [v_i D_i - \int_{\mathbf{y}\in\mathbf{Y}} C^i(X^{i*}(\mathbf{y}))dF(\mathbf{y})]. \tag{3}$$

An increase in intermittent production in A [B] increases [reduces] the flow of electricity from A to B at the first-best efficient dispatch:

$$T^*_{y_i}(\mathbf{y}) = \frac{\delta_i C^i_{xx}(X^{i*}(\mathbf{y}))}{C^A_{xx}(X^{A*}(\mathbf{y})) + C^B_x(X^{B*}(\mathbf{y}))}. \tag{4}$$

The efficient exchange of electricity can go in either direction depending on $\mathbf{y}$. Country A exports electricity to B under efficient dispatch, i.e. $T^*(\mathbf{y}) > 0$, if $C_x^A(D_A - y_A) < C_x^B(D_B - y_B)$. Otherwise, the efficient flow is from B to A. In particular, $\bar{t}^* \equiv T^*(\tilde{\mathbf{y}}) > 0$ when renewable electricity production is exactly equal to the expected output in both countries, $\tilde{\mathbf{y}} \equiv (\tilde{y}_A, \tilde{y}_B)$.

Observation 1 *First-best efficient dispatch can yield exchange of electricity in either direction,* *even if country A is the natural exporter from an ex ante perspective.*

5 The wholesale electricity market

Retailers purchase electricity on behalf of consumers, and producers supply their generation in a wholesale electricity market. The two TSOs also supply transmission capacity to this market. The wholesale market consists of an international day-ahead market and two balancing markets, one in each country. The fundamental difference is that the day-ahead market clears before and the balancing markets after the resolution of uncertainty $\mathbf{y}$. The day-ahead market is run by a power exchange, whereas each national balancing market is run by the respective TSO. There are several reasons why electricity markets feature trade in a day-ahead market. One of them is to facilitate the operation of inflexible dispatchable base-load generation capacity such as nuclear power. We simply assume the existence of a day-ahead market. The purpose of a balancing market is to enable TSOs to redispatch electricity so as to achieve the balance between production, consumption and cross-border electricity exchange that is fundamental to system operation. Events unfold as follows:

1. Market participants submit simultaneous and independent bids to the day-ahead market.
2. The day-ahead market mechanism sets prices that clear the market.
3. Intermittent production $\mathbf{y}$ is realized.
4. Market participants submit simultaneous and independent bids to the balancing markets.
5. The balancing market mechanisms set prices that clear the markets.
6. Production and consumption take place.

5.1 The day-ahead market

All market participants behave non-strategically, except possibly the two TSOs. A representative retailer submits a price-independent bid for the demand D_i, inflexible producers offer the expected output $\tilde{y}_i$ at zero price, and flexible production is bid in at marginal cost $C_x^i(\cdot)$ in the day-ahead market. Consistent with standard day-ahead market designs, each TSO submits import and export capacity bids on the international interconnection at zero price. Specifically, $\bar{k}_i \geq 0$ ($\underline{\bar{k}}_i \geq 0$) is the pair of capacity bids submitted to the day-ahead market by TSO i for electricity trade from A to B (B to A). Also consistent with standard day-ahead market designs, the *commercial trading capacities* are set at the minimum of the offered capacities in each direction:

$$\bar{k} \equiv \min\{\bar{k}_A; \bar{k}_B\},\ \underline{\bar{k}} \equiv \min\{\underline{\bar{k}}_A; \underline{\bar{k}}_B\}.$$

The feasible electricity trade from A to B in the day-ahead market is contained in the interval $[-\underline{\bar{k}}, \bar{k}]$, where $\bar{k} \geq 0$ is the export capacity from A to B, and $\underline{\bar{k}} \geq 0$ is the export capacity from B to A in the day-ahead market. Bars on variables and functions indicate that we are at the day-ahead stage of the interaction.

Day-ahead prices and allocations The *system day-ahead price* $\bar{p}^*$ is the uniform price that clears the integrated day-ahead market:

$$\bar{p}^* \equiv C_x^A(\bar{x}_A^*) \equiv C_x^B(\bar{x}_B^*),\, \bar{x}^* + \tilde{y} \equiv D,$$

where $D \equiv D_A + D_B$ is the aggregate demand across the two countries, $\tilde{y} \equiv \tilde{y}_A + \tilde{y}_B$ is the corresponding aggregate expected intermittent electricity production, $\bar{x}_i^*$ is the contracted day-head volume of the flexible generator in country i at the system price p^*, and $\bar{x}^* \equiv \bar{x}_A^* + \bar{x}_B^*$ is the total amount of flexible generation sold in the day-ahead market at the system price. By definition, $\bar{k}^* > 0$ is the *minimum transmission capacity required to sustain international trade in the day-ahead market at the system price.* Hence, the system price $\bar{p}^*$ is the equilibrium price in the day-ahead market in both countries if $\bar{k} \geq \bar{k}^*$.

The commercial trading capacities are insufficient to sustain the trade flows required to implement the system price if $\bar{k} < \bar{k}^*$. The day-ahead market is then divided into two separate *price areas* with local market clearing. The market-clearing area prices are characterized by:

$$\bar{Q}^A(\bar{k}) \equiv C_x^A(D_A - \tilde{y}_A + \bar{k}) < C_x^B(D_B - \tilde{y}_B - \bar{k}) \equiv \bar{Q}^B(\bar{k}),\, \bar{k} < \bar{k}^*. \tag{5}$$

The day-ahead market prices can then be summarized as

$$\bar{P}^i(\bar{k}) \equiv \begin{cases} \bar{p}^* & \text{for} \quad \bar{k} \geq \bar{k}^* \\ \bar{Q}^i(\bar{k}) & \text{for} \quad \bar{k} < \bar{k}^* \end{cases}, \tag{6}$$

as functions of the export capacity $\bar{k}$ from A to B in the day-ahead market. The bids $(\underline{\bar{k}}_A, \underline{\bar{k}}_B)$ that concern trade from B to A are irrelevant for the day-ahead market, since country A is the natural exporter. The day-ahead prices are marginally independent also of $(\bar{k}_A, \bar{k}_B)$ for all $\bar{k} > \bar{k}^*$. However, if the export constraint is binding in the day-ahead market, an increase in the export capacity $\bar{k}$ increases the day-ahead price in A, and reduces the day-ahead price in country B:

$$\bar{P}_{\bar{k}}^A(\bar{k}) = C_{xx}^A(D_A - \tilde{y}_A + \bar{k}) > 0,\, \bar{P}_{\bar{k}}^B(\bar{k}) = -C_{xx}^B(D_B - \tilde{y}_B - \bar{k}) < 0,\, \bar{k} < \bar{k}^*. \tag{7}$$

The flexible generation capacity contracted in day-ahead market equals

$$\bar{X}^A(\bar{k}) \equiv D_A - \tilde{y}_A + \bar{T}(\bar{k}),\, \bar{X}^B(\bar{k}) \equiv D_B - \tilde{y}_B - \bar{T}(\bar{k}), \tag{8}$$

where $\bar{T}(\bar{k}) \equiv \min\{\bar{k}; \bar{k}^*\}$ is the amount of electricity traded between the two countries in the day-ahead market.

Congestion revenue Producers in country A are paid $\bar{P}^A(\bar{k})$ for the electricity $\bar{T}(\bar{k})$ they export to country B, and retailers in country B pay $\bar{P}^B(\bar{k})$ for that same electricity. A trade surplus arises in the day-ahead market if the network is congested, so that $\bar{k} < \bar{k}^*$, because retailers then pay more on average for the electricity they purchase in the day-ahead market than what producers receive for supplying electricity to the day-ahead market. The difference

$$[\bar{P}^B(\bar{k}) - \bar{P}^A(\bar{k})]\bar{T}(\bar{k}) \geq 0 \tag{9}$$

represents a *congestion revenue*. In standard day-ahead market designs, this congestion revenue is collected by the owner(s) of the congested interconnection, the two national TSOs in our model. Each TSO earns 50% of the congestion revenue by the assumption that ownership is equally split between the two. Notice that the congestion revenue is zero if the network is uncongested in the sense of $\bar{T}(\bar{k}) = \bar{k}^*$, because then electricity is sold at the system price in both price areas.

We treat the above day-ahead market design as given throughout.

5.2 General properties of balancing markets

Intermittent output $\mathbf{y}$ typically diverges from the scheduled production $\tilde{\mathbf{y}}$ bid into the day-ahead market. It is then the responsibility of the TSOs to restore the balance between consumption and production through the balancing markets. Participation in this market requires that the generation capacity is dispatchable and has sufficient flexibility to ramp production up and down at short notice. In our model, it is only flexible producers in the two countries that have this capacity. This section describes fundamental characteristics of such balancing markets.

Flexible producers in i receive the day-ahead revenue $\bar{P}^i(\bar{k})\bar{X}^i(\bar{k})$. However, intermittent production $\mathbf{y}$ can be so low that flexible generation in i must increase above $\bar{X}^i(\bar{k})$ to clear consumption and production. TSO i purchases such *up-regulation* by offering a balancing price $p_i > \bar{P}^i(k)$ on any incremental output above $\bar{X}^i(k)$. The problem for flexible producers in the balancing market is

$$\max_{x_i} \; \bar{P}^i(\bar{k})\bar{X}^i(\bar{k}) + p_i[x_i - \bar{X}^i(\bar{k})] - C^i(x_i),$$

which has solution $p_i = C^i_x(x_i)$. Flexible generation i produces $x_i > \bar{X}^i(\bar{k})$ by virtue of $p_i > \bar{P}^i(\bar{k})$.

Intermittent production can in other situations be so high that flexible generation in country i must be reduced below $\bar{X}^i(\bar{k})$ to avoid curtailment of production. TSO i then sells *down-regulation* at price $p_i < \bar{P}^i(\bar{k})$. The flexible producer still receives $\bar{P}^i(\bar{k})\bar{X}^i(\bar{k})$ as contracted in the day-ahead market, but is now able to purchase output in the balancing market instead of supplying that electricity itself. Hence, the flexible producer can save on production costs by purchasing electricity in the balancing market. Specifically, the producer faces the problem how to choose the revised volume x_i that minimizes its production costs:

$$\max_{x_i} \bar{P}^i(\bar{k})\bar{X}^i(\bar{k}) - C^i(x_i) - p_i[\bar{X}^i(\bar{k}) - x_i],$$

This problem also has solution $p_i = C^i_x(x_i)$, and flexible generation is $x_i < \bar{X}^i(\bar{k})$ by $p_i < \bar{P}^i(\bar{k})$.

Two fundamental challenges of national balancing markets We have not yet discussed how TSOs determine the amount of redispatch they trade through the balancing market. In fact, independent operation of national balancing markets can cause serious disruptions to an integrated electricity system. Let TSO A trade z_A MWh electricity in its national balancing market, where $z_A > 0$ under up-regulation and $z_A < 0$ under down-regulation. Flexible producer A then injects a total amount of $x_A = \bar{X}^A(\bar{k}) + z_A$ MWh electricity into the grid. Domestic consumption amounts to D_A and intermittent electricity production to y_A, so excess production in country A equals

$$x_A + y_A - D_A = y_A - \tilde{y}_A + \bar{T}(\bar{k}) + z_A.$$

TSO B trades z_B MWh electricity in its national balancing market, which generates excess consumption in country B equal to

$$D_B - x_B - y_B = \tilde{y}_B - y_B + \bar{T}(\bar{k}) - z_B.$$

The cross-border exchange implied by (z_A, z_B) is *infeasible* if excess consumption in country B differs from excess production in country A, so that $z \neq \tilde{y} - y$, where $z \equiv z_A + z_B$ measures total redispatch in the two balancing markets. Such physical imbalances cause frequency disturbances and may even lead to blackouts if they become too large.

Challenge 1 *The integrated electricity system risks disruption unless aggregate redispatch equals the aggregate need for regulation:* $z = \tilde{y} - y$.

Assume that trade (z_A, z_B) in the balancing markets is such that the system in fact is in aggregate balance. But physical balance does not imply that balancing markets are efficient. The dispatch of electricity is inefficient if the marginal cost of flexible production differs across the two countries, $C^A_x(x_A) \neq C^B_x(x_B)$. By way of the analysis in Section 4, such inefficiency occurs if either $x_A \neq D_A - y_A + T^*(\mathbf{y})$ or $x_B \neq D_B - y_B - T^*(\mathbf{y})$. Consequently,

Challenge 2 *The dispatch of electricity in the integrated electricity system is inefficient unless redispatch in each balancing market corrects both for unscheduled changes in domestic renewable electricity production and unscheduled modifications to cross-border electricity exchange:*

$$z_i = z_i^* \equiv \tilde{y}_i - y_i + \delta_i(T^*(\mathbf{y}) - \bar{T}(\bar{k})),\ i = A, B. \tag{10}$$

The first-best efficient dispatch of electricity implies that the overall system is in balance, $z_A^* + z_B^* = \tilde{y} - y$, but national TSOs may lack incentives to implement this outcome. Decentralized decision-making can cause market integration to collapse even if the physical transmission capacity does not constrain feasible dispatch. Suppose $T^*(\mathbf{y}) > 0$, but TSO A trades $z_A = \tilde{y}_A - y_A - \bar{T}(\bar{k})$ in the day-ahead market instead of z_A^* as dictated by efficiency. By implication, flexible production equals $x_A = D_A - y_A$ instead of the required $D_A - y_A + T^*(\mathbf{y})$. TSO A achieves a domestic balance between production and consumption at reduced domestic system cost by effectively eliminating all electricity exchange with country B. To maintain the balance in the domestic electricity system, TSO B must increase domestic production by $T^*(\mathbf{y})$ to compensate for the loss of electricity transmission from abroad. The practice of curtailing export in order to reduce domestic system costs is known as *moving congestion to the border.* If TSOs could behave in this manner without facing any associated costs, then no TSO would have any incentive to dispatch domestic electricity for use abroad. An important aspect of creating an efficient international balancing market is to mitigate TSO incentives to move congestion to the border.

6 Efficiency of the day-ahead market

Generally, the export capacity $\bar{k}$ in the day-ahead market will affect dispatch and prices in the balancing market and therefore overall efficiency. Those effects will depend on the specific design of the balancing market. However, we can derive conditional efficiency results on the basis of expressions in reduced form even without specifying anything about balancing markets.

In the following sections, we will identify different balancing market designs by superscripts on functionals and variables. Let $\tilde{W}^{iM}(\bar{k})$ be the reduced-form expected welfare in country $i = A, B$ under some (balancing) market design M. We will for the most part assume that the national TSOs act non-cooperatively by maximizing national welfare.

Lemma 1 *Assume that the national TSO in each country $i = A, B$ chooses $(\bar{k}_i, \underline{\bar{k}}_i)$ to maximize expected domestic welfare $\tilde{W}^{iM}(\bar{k})$ under market design M.*
(i) Market design M features an equilibrium $(\bar{k}_A^M, \underline{\bar{k}}_A^M)$ and $(\bar{k}_B^M, \underline{\bar{k}}_B^M)$ in the day-ahead market.
(ii) Export capacity $\bar{k}^M$ from A to B can be sustained as an equilibrium under market design M if and only if $\tilde{W}^{AM}(\bar{k}) \leq \tilde{W}^{AM}(\bar{k}^M)$ and $\tilde{W}^{BM}(\bar{k}) \leq \tilde{W}^{VM}(\bar{k}^M)$ for all $\bar{k} \leq [0, \bar{k}^M]$.
(iii) Equilibria with more trade in the day-ahead market Pareto dominate those with less trade for any market design M.

Proof: We establish Item (i) by way of an example: If $\bar{k}_j^M = \underline{\bar{k}}_j^M = 0$, $j = A, B$, then $\tilde{W}^{iM}(\bar{k}) = \tilde{W}^{iM}(0)$, $i \neq j$, for all $(\bar{k}_i, \underline{\bar{k}}_i)$. Hence, $\bar{k}_i^M = \underline{\bar{k}}_i^M = 0$ represents a best-response to $\bar{k}_j^M = \underline{\bar{k}}_j^M = 0$.

Sufficiency of (ii): Let $(\bar{k}_A^M, \underline{\bar{k}}_A^M) = (\bar{k}_B^M, \underline{\bar{k}}_B^M) = (\bar{k}^M, 0)$. The expected equilibrium welfare of TSO i then equals $\tilde{W}^{iM}(\bar{k}^M)$. We only need to check for deviations $\bar{k}_i \neq \bar{k}^M$ since the expected national welfare of TSO i is independent of $\underline{\bar{k}}_i^M$. A unilateral deviation $\bar{k}_i > \bar{k}^M$ is weakly unprofitable since $\tilde{W}^{iM}(\bar{k}_i) = \tilde{W}^{iM}(\bar{k}^M)$ for all $\bar{k}_i > \bar{k}^M$ by $\bar{k} = \min\{\bar{k}_i, \bar{k}^M\}$. If $\bar{k}^M > 0$, then a unilateral deviation $\bar{k}_i \in [0, \bar{k}^M)$ is also weakly unprofitable since $\tilde{W}^{iM}(\bar{k}_i) \leq \tilde{W}^{iM}(\bar{k}^M)$ for all $\bar{k}_i < \bar{k}^M$ by assumption.

Necessity of (ii): If $\bar{k}^M > 0$ and either $\tilde{W}^{AM}(\bar{k}) > \tilde{W}^{AM}(\bar{k}^M)$ or $\tilde{W}^{BM}(\bar{k}) > \tilde{W}^{VM}(\bar{k}^M)$ for some $\bar{k} \in [0, \bar{k}^M)$, then at least one TSO i can deviate to $\bar{k}_i = \bar{k}$ and strictly increase national welfare.

Item (iii): Compare two equilibria, and assume that $\bar{T}(\bar{k}^M) > \bar{T}(\hat{k}^M)$. By implication, $\bar{k}^M > \hat{k}^M$. From (ii), we deduce that $\bar{k}^M$ can be sustained as an equilibrium only if $\tilde{W}^{AM}(\bar{k}^M) \geq \tilde{W}^{AM}(\hat{k}^M)$ and $\tilde{W}^{BM}(\bar{k}^M) \geq \tilde{W}^{BM}(\hat{k}^M)$. Hence, the equilibrium with more trade in the day-ahead market Pareto dominates the one with less trade.■

An equilibrium always exists, and there can be a continuum of equilibria. By the Leontief property of how trading capacities are determined in the day-ahead market, a TSO cannot unilaterally increase transmission capacity above the level of the other TSO. Hence, a necessary and sufficient condition for existence of an equilibrium is that downward deviations are unprofitable. The implemented equilibrium may entail very little trade. In particular, the no-trade equilibrium can always be sustained in any market design M.

Despite the potentially large set of equilibria, Lemma 1 demonstrates that they can all be Pareto ranked in order of increasing equilibrium trade in the day-ahead market. It would then be natural to assume that the two TSOs coordinate on the equilibrium with maximal trade if such an equilibrium exists, although our welfare results do not rely on equilibrium selection.

Define the joint expected welfare under market design M by $\tilde{W}^M(\bar{k}) \equiv \tilde{W}^{AM}(\bar{k}) + \tilde{W}^{BM}(\bar{k})$. Denote the joint maximal welfare by $\tilde{w}^M$ if $\tilde{W}^M(\bar{k})$ attains a global maximum. Let $\bar{k}_{eff}^M \in [0, \bar{k}^*]$ be the minimal trading capacity from A to B that implements $\tilde{w}^M$.[8]

Proposition 1 *Assume that the joint expected welfare function $\tilde{W}^M(\bar{k})$ under market design M attains a global maximum contained in $[0, \bar{k}^*]$.*
(i) Equilibrium trade in the day-ahead market is efficient conditional on market design M if the TSOs fully exploit the capacity of the transmission network ($\bar{T}(\bar{k}^M) = \bar{k}^*$ implies $\tilde{W}^M(\bar{k}^M) = \tilde{w}^M$).
(ii) Equilibrium trade in the day-ahead market is inefficiently low conditional on market design M if the equilibrium does not maximize joint welfare ($\tilde{W}^M(\bar{k}^M) < \tilde{w}^M$ implies $\bar{T}(\bar{k}^M) < \bar{T}(\bar{k}_{eff}^M)$).

Proof: Item (i): If $\bar{T}(\bar{k}^M) = \bar{k}^*$, then $\bar{k}^M \geq \bar{k}^*$. By Lemma 1, $\tilde{W}^{AM}(\bar{k}^M) \geq \tilde{W}^{AM}(\bar{k})$ and $\tilde{W}^{BM}(\bar{k}^M) \geq \tilde{W}^{BM}(\bar{k})$ for all $\bar{k} \in [0, \bar{k}^*]$. Hence, $\tilde{W}^M(\bar{k}^M) \geq \tilde{W}^M(\bar{k})$ for all $\bar{k} \in [0, \bar{k}^*]$. Therefore, $\bar{k}^M = \bar{k}^*$ maximizes $\tilde{W}^M(\bar{k})$ over $\bar{k} \in [0, \bar{k}^*]$.

Item (ii): We´know from the previous item that $\tilde{W}^M(\bar{k}^M) = \tilde{w}^M$ if $\bar{T}(\bar{k}^M) = \bar{k}^*$. Hence, $\tilde{W}^M(\bar{k}^M) < \tilde{w}^M$ only if $\bar{T}(\bar{k}^M) < \bar{k}^*$, in which case also $\bar{k}^M < \bar{k}^*$. Then $\tilde{W}^{AM}(\bar{k}^M) \geq \tilde{W}^{AM}(\bar{k})$ and $\tilde{W}^{BM}(\bar{k}^M) \geq$

[8] $\tilde{W}^M(\bar{k})$ attains a global maximum in $[0, \bar{k}^*]$ if $\tilde{W}^{AM}(\bar{k})$ and $\tilde{W}^{BM}(\bar{k})$ are both continuous on $[0, \bar{k}^*]$ and both national welfare functions also satisfy $\tilde{W}^{AM}(\bar{k}) = \tilde{W}^{AM}(\bar{k}^*)$ and $\tilde{W}^{BM}(\bar{k}) = \tilde{W}^{BM}(\bar{k}^*)$ for all $\bar{k} \geq \bar{k}^*$.

$\tilde{W}^{BM}(\bar{k})$ for all $\bar{k} \in [0, \bar{k}^M]$. By implication, $\tilde{W}^M(\bar{k}) \leq \tilde{W}^M(\bar{k}^M)$ for all $\bar{k} \in [0, \bar{k}^M]$. Since $\tilde{w}^M > \tilde{W}^M(\bar{k}^M)$ by assumption, it must necessarily be the case that $\bar{k}^M_{eff} > \bar{k}^M$.■

Proposition 1 establishes that equilibrium trade is either efficient or inefficiently low under any market design M, despite the possibility that the jointly efficient volume of trade can be lower than $\bar{k}^*$. To see why there cannot be excess trade in equilibrium, assume for the sake of the argument that the export constraint from A to B is binding in equilibrium: $\bar{k}^M_A \leq \bar{k}^M_B$. Suppose trade is excessive in equilibrium $\bar{k}^M_{eff} < \bar{k}^M$. TSO A then effectively imposes a negative externality on TSO B by maintaining trade at $\bar{k}^M$ instead of $\bar{k}^M_{eff}$.[9] However, TSO B can offset any such negative externality by a unilateral reduction of import capacity to $\bar{k}_B = \bar{k}^M_{eff}$, which makes it impossible to sustain an inefficient equilibrium with excessive trade.[10]

The above results only depend on the design of the day-ahead market. Hence, a competition authority does not need to know anything about the balancing market to conclude that TSOs have behaved efficiently if they have bid all their capacity into the day-ahead market. In fact, this result holds regardless of any strategic behavior of other participants in the day-ahead market. The only concern is that TSOs may withhold too much capacity from the day-ahead market.

The above reduced-form analysis does not contain sufficient structure to allow us to draw conclusions about whether the equilibrium is distorted conditional on M for $\bar{k}^M < \bar{k}^*$, nor about how market design affects TSO incentives to withhold capacity from the day-ahead market. It is also not possible to compare efficiency across different balancing market designs. To perform such analysis, one must study balancing markets in detail.

7 Segmented balancing markets

We consider first the historically relevant benchmark of *segmented balancing markets*. The fundamental characteristic of this design is that the volume $\bar{T}(\bar{k})$ of trade between A and B cleared in the day-ahead market represents a binding restriction on the exchange of electricity in the balancing market. As a consequence, each TSO can only use adjustments to flexible domestic production to correct domestic imbalances, but not engage in cross-border redispatch.

Dispatch and prices in the balancing market Each TSO i trades $z_i = \tilde{y}_i - y_i$ in its respective balancing market to correct imbalances in domestic renewable electricity generation. These

[9] $\tilde{W}^{BM}(\bar{k}^M_{eff}) - \tilde{W}^{BM}(\bar{k}^M) = \tilde{W}^{AM}(\bar{k}^M) - \tilde{W}^{AM}(\bar{k}^M_{eff}) + \tilde{w}^M - \tilde{W}^M(\bar{k}^M) > 0$ by individual rationality of $\bar{k}^M_A = \bar{k}^M$, $\tilde{W}^{AM}(\bar{k}^M) \geq \tilde{W}^{AM}(\bar{k}^M_{eff})$, and the assumed inefficiency of $\bar{k}^M$, $\tilde{w}^M > \tilde{W}^M(\bar{k}^M)$.

[10] This logic mirrors an argument for why excess export subsidization is impossible, as long as the importing country can impose a countervailing import duty to offset any export subsidy. With such a duty the import country can restore the no-subsidy allocation if it so wishes, and collect tax revenue in the process. Hence, the only possible distortion from a joint welfare point of view that can be sustained in equilibrium, is too little subsidization.

interventions ensure that the amount

$$X^{iS}(\bar{k}, y_i) \equiv D_i - y_i + \delta_i \bar{T}(\bar{k}),\ i = A, B,$$

of flexible electricity dispatch in country i is in physical balance with domestic consumption and the cross-border exchange of electricity contracted in the day-ahead market, where superscript S denotes a segmented market design. The corresponding balancing price in country $i = A, B$ that implements $X^{iS}(k, y_i)$ is given by

$$P^{iS}(\bar{k}, y_i) \equiv C^i_x(D_i - y_i + \delta_i \bar{T}(\bar{k})).$$

The role of TSO i in the segmented balancing market is essentially to reallocate production between the owners of renewable and flexible generation if $y_i \neq \tilde{y}_i$. In case of up-regulation of flexible production, $z_i > 0$, the owners of renewable generation make the required balancing payment $P^{iS}(\bar{k}, y_i)z_i = P^{iS}(\bar{k}, y_i)(\tilde{y}_i - y_i)$ because they fail to achieve their production target. In the opposite case of down-regulation of flexible production, $z_i < 0$, the owners of renewable generation receive the balancing payment $-P^{iS}(\bar{k}, y_i)z_i = P^{iS}(\bar{k}, y_i)(y_i - \tilde{y}_i)$ made by the owners of flexible generation capacity as compensation for reducing flexible production.

The main advantage of the segmented market design is that the system will be in physical balance even absent any coordination of dispatch across the two countries: $z = \tilde{y} - y$. Hence, a segmented market ensures a reliable electricity supply. The major downside is that the segmented balancing market is inefficient relative to the first-best benchmark since $T^*(\mathbf{y}) \neq \bar{T}(\bar{k})$ for almost all $\mathbf{y}$. Hence, allocations in the segmented balancing market can be at most constrained efficient.

National welfare The ex-post welfare in country i is given by

$$\begin{aligned}
&v_i D_i - \bar{P}^i(\bar{k}) D_i \\
&+\bar{P}^i(\bar{k})\tilde{y}_i + P^{iS}(\bar{k}, y_i)(y_i - \tilde{y}_i) \\
&+\bar{P}^i(\bar{k})\bar{X}^i(\bar{k}) + P^{iS}(\bar{k}, y_i)[X^{iS}(\bar{k}, y_i) - \bar{X}^i(\bar{k})] - C^i(X^{iS}(\bar{k}, y_i)) \\
&+\frac{1}{2}[\bar{P}^B(\bar{k}) - \bar{P}^A(\bar{k})]\bar{T}(\bar{k})
\end{aligned}$$

The first row of the above expression represents the sum of consumer and retailer surplus because the retailer pays the domestic day-ahead price for the electricity purchased in the wholesale market. The sum of the terms on the second row captures the total revenue of intermittent electricity production. The sum of the terms on the third row is the total operating profit of flexible generation. The final term represents TSO i's congestion revenue.

We can rewrite the expression for ex-post welfare in country i as

$$W^{iS}(\bar{k}, y_i) \equiv v_i D_i + \delta_i \bar{R}(\bar{k}) - C^i(D_i - y_i + \delta_i \bar{T}(\bar{k})). \tag{11}$$

The term $\bar{R}(\bar{k})$ will play a central role in the analysis to follow. $\bar{R}^A(\bar{k}) \equiv \bar{R}(\bar{k})$ represents country A's *net export revenue* in the day-ahead market, as given by the gross revenue of selling $\bar{T}(\bar{k})$ MWh electricity in country B at $\bar{P}^B(\bar{k})$ per MWh, minus the rental cost of utilizing the cross-border interconnection, which is equal to half of the congestion rent:

$$\begin{aligned}\bar{R}(\bar{k}) &\equiv \bar{P}^B(\bar{k})\bar{T}(\bar{k}) - \frac{1}{2}[\bar{P}^B(\bar{k}) - \bar{P}^A(\bar{k})]\bar{T}(\bar{k}) \\ &= \frac{1}{2}[\bar{P}^A(\bar{k}) + \bar{P}^B(\bar{k})]\bar{T}(\bar{k}).\end{aligned} \tag{12}$$

Equivalently, since there are only two countries, $\bar{R}^B(\bar{k}) \equiv -\bar{R}(\bar{k})$ represents country B's *net import cost* measured by the cost of purchasing $\bar{T}(\bar{k})$ electricity in the international market at unit cost $\bar{P}^B(\bar{k})$, plus the rent from TSO B's ownership share in the cross-border interconnection.[11]

By taking expectations over renewable output y_i, we obtain the expected national welfare in country i under the segmented balancing market design:

$$\tilde{W}^{iS}(\bar{k}) \equiv v_i D_i + \delta_i \bar{R}(\bar{k}) - \int_0^{y_i^{\max}} C^i(D_i - y_i + \delta_i \bar{T}(\bar{k}))dF^i(y_i). \tag{13}$$

Efficient day-ahead transmission capacity The jointly efficient trade in the day-ahead market maximizes

$$\tilde{W}^S(\bar{k}) \equiv \tilde{W}^{AS}(\bar{k}) + \tilde{W}^{BS}(\bar{k}) = \sum_{i=A,B}[v_i D_i - \int_0^{y_i^{\max}} C^i(D_i - y_i + \delta_i \bar{T}(\bar{k}))dF(y_i)]$$

if balancing markets are segmented. The net export revenue $\bar{R}(\bar{k})$ is just a transfer of rent from B to A and therefore vanishes in the aggregate. Starting at $\bar{k} < \bar{k}^*$, an increase in trade increases the expected cost of balancing consumption and production in the export country and reduces it in the import country. By way of perfect competition in the balancing market, these marginal costs and benefits are measured by the expected balancing prices, so that

$$\tilde{W}^S_{\bar{k}}(\bar{k}) = -\tilde{P}^{AS}(\bar{k}) + \tilde{P}^{BS}(\bar{k}),$$

[11] The net export revenue $\bar{\mathcal{R}}(\bar{k}, \alpha)$ depends on TSO A's ownership share $\alpha \in [0, 1]$ of the interconnection as follows: $\bar{\mathcal{R}}(\bar{k}, \alpha) \equiv [(1 - \alpha)\bar{P}^A(\bar{k}) + \alpha\bar{P}^B(\bar{k})]\bar{T}(\bar{k})$. However, the benchmark $\bar{\mathcal{R}}(\bar{k}, \frac{1}{2}) \equiv \bar{R}(\bar{k})$ is realistic. For instance, it was long a legal requirement in Sweden that SvK must have an ownership share of at least 50% in all cross-border interconnections to and from Sweden. If such legislation would apply uniformly to all countries, then $\alpha = \frac{1}{2}$.

where

$$\tilde{P}^{iS}(\bar{k}) \equiv \int_0^{y_i^{\max}} P^{iS}(\bar{k}, y_i)dF^i(y_i) = \int_0^{y_i^{\max}} C_x^i(D_i - y_i + \delta_i\bar{T}(\bar{k}))dF^i(y_i) \tag{14}$$

is the expected balancing price in country i in the segmented balancing market. The following result is straightforward:

Proposition 2 *The efficient amount of trade under the segmented market design is characterized by*

$$[\tilde{P}^{BS}(\bar{t}^S_{eff}) - \tilde{P}^{AS}(\bar{t}^S_{eff})][\bar{t}^S_{eff} - \bar{k}^*] \equiv 0. \tag{15}$$

if $\bar{t}^S_{eff} > 0$.

The expected marginal cost of flexible production in country A can be so small compared to production in country B, $\tilde{P}^{AS}(\bar{k}^*) \leq \tilde{P}^{BS}(\bar{k}^*)$, that it is efficient from an ex ante point of view to export as much as possible from A to B in the day-ahead market in order to minimize the expected cost of maintaining system balance. However, Proposition 2 has another policy implication:

Corollary 1 *Under the segmented balancing market design, it can be jointly efficient to constrain trade by withholding transmission capacity from the day-ahead market.*

The present setting thus differs sharply from those in standard trade models, where trade restrictions typically are unambiguously welfare reducing. If $\tilde{P}^{AS}(k^*) > \tilde{P}^{BS}(k^*)$, then country A exports so much electricity to country B under full market integration that the expected marginal cost of balancing the market is higher in the export country than the import country. The efficient policy response is then to reduce trade in the day-ahead market. In interior optimum, the efficient day-ahead capacity is set in such a manner as to equate the expected short-term prices in the two countries. This efficiency condition is very similar to (1), except transmission capacity is set prior to the realization of intermittent production, so marginal production costs are equalized in *expectation*. In principle, it could also be efficient to set export capacity from A to B to zero. Zero trade is efficient if and only if $\tilde{P}^{AS}(0) \geq \tilde{P}^{BS}(0)$.

Equilibrium day-ahead transmission capacity Let us now turn to the incentives facing the TSOs. Recall the assumption that TSOs bid capacity into the day-ahead market to maximize expected domestic welfare. Suppose TSO A could unilaterally decide $\bar{k}$ to maximize domestic welfare $\tilde{W}^{AS}(\bar{k})$ defined in (13). For $\bar{k} < \bar{k}^*$, the marginal expected domestic welfare equals

$$\tilde{W}^{AS}_{\bar{k}}(\bar{k}) = \bar{R}_{\bar{k}}(\bar{k}) - \tilde{P}^{AS}(\bar{k}), \tag{16}$$

where the first term represents the marginal net export revenue in the day-ahead market:

$$\bar{R}_{\bar{k}}(\bar{k}) = \frac{1}{2}[\bar{P}^A(\bar{k}) + \bar{P}^B(\bar{k}) + (\bar{P}^A_{\bar{k}}(\bar{k}) + \bar{P}^B_{\bar{k}}(\bar{k}))\bar{k}] \tag{17}$$

In its decision whether to increase trade in the day-ahead market, TSO A weighs the marginal effect on net export revenue against the increase in expected domestic balancing costs.

A typical feature of models of international trade is that a country with market power in international markets has an incentive to reduce trade in order to manipulate world market prices in its own favour. For instance, an exporting country might prefer to hold back exports to increase the export price, or an importing country might levy an import tariff in order to push down prices paid to foreign producers. These incentives exist in particular when domestic firms are perfectly competitive, and thus are unable to exploit market power themselves. The government then acts as a form of national cartel on behalf of domestic producers through trade policy interventions. A similar type of mechanism is at play in the present context. Although we have assumed that producers are price takers, *the ability of TSOs to restrict trade by holding back transmission capacity effectively gives them market power.* This is one of the fundamental problems with the market design investigated here.

The incentive for TSO A to hold back trade is captured in expression (17) by the price effect $\bar{P}^B_{\bar{k}}(\bar{k}) < 0$, which yields a marginal benefit of withholding capacity $\bar{k}$ to increase the price in market B. However, matters are more complicated than in a standard trade model, because of the marginal congestion revenue. A smaller export volume increases the congestion revenue by reducing the price in market A, since $\bar{P}^A_{\bar{k}}(\bar{k}) > 0$. If TSO A received the full congestion revenue, then this marginal effect would cancel out against the corresponding marginal revenue loss for producers in A. But joint ownership of cross-border transmission implies that some of the increase in congestion revenue is transferred to TSO B. A price reduction in market A therefore reduces the net export revenue in country A, all else equal. Hence, the incentive for TSO A to hold back on transmission capacity in the day-ahead market to increase its export price, is mitigated in the present setting by joint ownership of the cross-border interconnection.

The equilibrium trade between A and B in the day-ahead market depends not only on TSO A's optimal export capacity in the day-ahead market, but also on TSO B's optimal import capacity. For TSO B, more trade implies *lower* expected balancing costs, but may also increase the cost of imported electricity in the day-ahead market. Lemma 1 establishes that the segmented balancing market can sustain a continuum of equilibria in the day-ahead market, one of which is the zero trade equilibrium. However, both TSOs prefer equilibria with more trade over those with less. The frequency with which TSOs interact in the wholesale electricity market suggests that they could be able to coordinate on the equilibrium that maximizes trade. Denote this equilibrium transmission capacity by $\bar{k}^S$, and the associated equilibrium trade by $\bar{t}^S \equiv \bar{T}(\bar{k}^S)$.

Proposition 3 *If the segmented market can sustain positive trade in equilibrium ($\bar{t}^S > 0$), then:*

$$\bar{P}^B_{\bar{k}}(\bar{t}^S) \geq \bar{R}_{\bar{k}}(\bar{t}^S) \geq \bar{P}^A_{\bar{k}}(\bar{t}^S). \tag{18}$$

Both inequalities are strict only if $\bar{t}^S = \bar{k}^*$. Equilibrium trade is inefficiently low ($\bar{t}^S < \bar{t}^S_{eff}$) in *interior equilibrium ($0 < \bar{t}^S < \bar{k}^*$), except in the knife-edge case, $\bar{P}^A_{\bar{k}}(\bar{t}^S) = \bar{P}^B_{\bar{k}}(\bar{t}^S)$.*

Proof: $\tilde{W}^{AS}_{\bar{k}}(\bar{t}^S) \geq 0$ and $\tilde{W}^{BS}_{\bar{k}}(\bar{t}^S) \geq 0$ both hold in equilibrium because one of the TSOs has a strict incentive to reduce trade below $\bar{t}^S$ if $\tilde{W}^{AS}_{\bar{k}}(\bar{t}^S) < 0$ or $\tilde{W}^{BS}_{\bar{k}}(\bar{t}^S) < 0$. The two weak inequalities are equivalent to (18). Assume that $\bar{t}^S \in (0, \bar{k}^*)$, and suppose both inequalities in (18) are strict. In that case, $\tilde{W}^{AS}_{\bar{k}}(\bar{t}^S) > 0$ and $\tilde{W}^{BS}_{\bar{k}}(\bar{t}^S) > 0$ both hold, which implies that it would be possible to implement an equilibrium with strictly more trade than $\bar{t}^S$, which is a contradiction. Assume that $0 < \bar{t}^S < \bar{k}^*$ and $\bar{P}^A_{\bar{k}}(\bar{t}^S) \neq \bar{P}^B_{\bar{k}}(\bar{t}^S)$. $\tilde{W}^S_{\bar{k}}(\bar{t}^S) \neq 0$ in this case, so $\bar{t}^S_{eff} \neq \bar{t}^S$ and $\tilde{W}^S(\bar{t}^S) < \tilde{w}^S$ by strict concavity of $\tilde{W}^S(\bar{k})$. Then, $\bar{t}^S_{eff} > \bar{t}^S$ by Proposition 1. Hence, $\bar{t}^S_{eff} = \bar{t}^S$ in interior equilibrium $\bar{t}^S \in (0, \bar{k}^*)$ only if $\bar{P}^A_{\bar{k}}(\bar{t}^S) = \bar{P}^B_{\bar{k}}(\bar{t}^S)$.■

Marginal changes in transmission capacity in the day-ahead market creates externalities abroad that national welfare maximizing TSOs neglect. If TSO A's offer of export capacity from A to B is binding, $\bar{k}^S_A < \bar{k}^S_B$, and $\bar{k}^S_A < \bar{k}^*$, then an increase in $\bar{k}_A$ would reduce the expected cost of balancing demand and supply in country B, but might also increase B's cost of importing electricity in the day-ahead market. Proposition 3 shows that the first effect dominates the second when evaluated at $\bar{k}^S$, thus creating a positive net externality on country B. By implication, an interior equilibrium $0 < \bar{k}^S < \bar{k}^*$ is direct evidence that TSOs exercise market power by withholding capacity in the day-ahead market in a segmented market.

It is possible that TSO A has *no* incentive to restrict trade. In this case, the value of net export revenue dominates the marginal expected balancing cost at full capacity utilization of the interconnection: $\bar{R}_k(\bar{k}^*) \geq \bar{P}^A_{\bar{k}}(\bar{k}^*)$. More surprising is perhaps the opposite possibility. In particular, $\tilde{W}^{AS}_{\bar{k}}(0) \leq 0$ if and only if

$$\frac{1}{2}[\bar{P}^B(0) - \bar{P}^A(0)] \leq \tilde{P}^{AS}(0, y_A) - \bar{P}^A(0).$$

In this case, the marginal increase in net export revenue in the day-ahead market is insufficient to cover TSO A's associated increase in expected balancing costs. The right-hand side of the above expression is strictly positive by Jensen's inequality if the marginal flexible production cost is strictly convex, $C^A_{xxx} > 0$. Then the inequality holds if the day-ahead prices in the two countries are sufficiently similar in autarky, $\bar{k} = 0$, so that $\bar{P}^B(0) - \bar{P}^A(0)$ is sufficiently close to zero. A policy relevant implication is that a TSO maximizing national welfare might have an incentive to exercise market power by choking off all trade in the day-ahead market.[12]

[12] For instance, the Norwegian TSO, Statnett, pursued this strategy on several occasions in the winter of 2009/10 when they set export to southern Sweden to zero in order to minimize the domestic cost of maintaining system balance. However, this policy was not necessarily inefficient since it could also have been the case that $\bar{k}^S_{eff} = 0$.

8 Fully integrated balancing market

Integration of national electricity markets in the EU is driven by a belief that such integration will benefit member states in general. To shed some light on possible implications of integration, we consider the polar extreme case of a *fully integrated balancing market.* Under this design, all physically available transmission capacity can be used for short-term balancing of supply and demand in both countries, regardless of the transmission capacity bids in the day-ahead market. The fundamental characteristic of this design is that the exchange of electricity between A and B is set at the efficient level $T^*(\mathbf{y})$.

Dispatch and prices in the balancing market Each TSO i trades z_i^* in its respective balancing market under efficient exchange; see (10). These allocations ensure that the electricity system is in physical balance and that flexible producers in both countries dispatch the first-best efficient output $X^{i*}(\mathbf{y})$; see (2). Since the cross-border connection is unconstrained, electricity is sold in both markets at the *system balancing price*

$$P^*(\mathbf{y}) \equiv C_x^A(D_A - y_A + T^*(\mathbf{y})) = C_x^B(D_B - y_B - T^*(\mathbf{y})). \tag{19}$$

Unlike in the segmented balancing market design, the payments to and from renewable producers in country i need not balance against the payments to and from the flexible producers because of cross-border redispatch: $z_i^* \neq \tilde{y}_i - y_i$. However, total balancing payments still add up:

$$P^*(\mathbf{y})[X^{A*}(\mathbf{y}) - \bar{X}^A(\bar{k}) + y_A - \tilde{y}_A] + P^*(\mathbf{y})[X^{B*}(\mathbf{y}) - \bar{X}^B(\bar{k}) + y_B - \tilde{y}_B] = 0.$$

National welfare It is straightforward to verify that expected national welfare in country i can be written as

$$\tilde{W}^{iI}(\bar{k}) \equiv v_i D_i + \delta_i \bar{R}(\bar{k}) + \int_{\mathbf{y}\in\mathbf{Y}} \{P^*(\mathbf{y})[\bar{X}^{i*}(\mathbf{y}) - \bar{X}^i(\bar{k}) + y_i - \tilde{y}_i] - C^i(\bar{X}^{i*}(\mathbf{y}))\} dF(\mathbf{y}), \tag{20}$$

where superscript I indicates a fully integrated balancing market. Unlike in the expression (13) for expected national welfare in a segmented balancing market, the domestic compensation payments between the owners of flexible and intermittent generation capacity do not generally cancel out.

Efficient day-ahead transmission capacity Summing up the joint expected welfare across the two countries yields joint expected welfare $\tilde{W}^{AI}(\bar{k}) + \tilde{W}^{BI}(\bar{k}) \equiv \tilde{W}^I(\bar{k}) = \tilde{w}^*$. The fully integrated balancing market implements the first-best efficient outcome regardless of the allocation $\bar{k}$ of transmission capacity in the day-ahead market because all initial allocations can be offset in the balancing market.

Equilibrium day-ahead transmission capacity Although the day-ahead market does not affect allocations in the fully integrated balancing market, this does not mean that day-ahead bids are irrelevant to the individual TSOs. For $k < k^*$, TSO A still faces a trade-off between the potential benefit of increasing net export revenue in the day-ahead market against the increased cost of balancing production and consumption. However, the two TSOs now play a zero-sum game in the day-ahead market since joint welfare is independent of $\bar{k}$. Consequently, the incentives facing TSO B are the opposite of those facing TSO A:

$$\tilde{W}_{\bar{k}}^{AI}(\bar{k}) \ = \bar{R}_{\bar{k}}(\bar{k}) - \int_{\mathbf{y}\in Y} P^*(\mathbf{y})dF(\mathbf{y}) = -\tilde{W}_{\bar{k}}^{BI}(\bar{k}).$$

In particular, any interior local maximum of TSO A is an interior local minimum of TSO B, and vice versa. The only robust equilibrium then features $\bar{k}_A^I = \bar{k}_B^I = 0$. We conclude:

Proposition 4 *The only robust equilibrium features no trade in the day-ahead market under the fully integrated balancing market design ($\bar{k}^I = 0$). This market design nevertheless implements the first-best efficient outcome.*

9 The EU balancing market

The segmented balancing market design yields reliable electricity supply, but is generally inefficient because the cross-border exchange of electricity does not adapt to changes in system conditions. The fully integrated market design is both reliable and yields efficient dispatch of electricity, but assumes that TSOs simply implement all electricity dispatch implied by the system balancing price. We now consider a more general model in which the day-ahead capacity does not represent a binding restriction on the cross-border exchange of electricity in the balancing market, but where TSO incentives in the balancing market are also accounted for.

The balancing market does not necessarily implement balanced budget payments if the exchange of electricity across countries differs from the amount scheduled in the day-ahead market. The TSOs can either be net recipients or net payers of those *trade adjustment payments* that arise because of budget imbalance. The magnitudes of these payments depend on the price differentials in the balancing market and whether cross-border redispatch is positive or negative. An important determinant of efficiency is how trade adjustment payments are distributed across the owners of cross-border interconnections. The rule laid down in the current EU regulations, and the one we investigate in this section, prescribes that such payments should be *shared equally* among owners.

Market mechanism adjustments As we discussed in Section 5, one of the fundamental challenges of the balancing market is to maintain the balance between production and consumption in the integrated system, $z = \tilde{y} - y$. To ensure reliable electricity supply, we augment the model depicted in Section 5 with an intermediary step between 3 and 4. The two TSOs agree on the amount of cross-border electricity exchange in the balancing market after the realization of $\mathbf{y}$, but before trading in the balancing market occurs.

The trading capacity on the cross-border connection is determined in a similar manner as in the day-ahead market. Each TSO reports a capacity constraint $k_i \geq 0$ ($\underline{k}_i \geq 0$) on the electricity exchange from A to B (B to A). The trading capacities in the balancing market are set at the minimum of the offered capacities in each direction:

$$k \equiv \min\{k_A; k_B\},\ \underline{k} \equiv \min\{\underline{k}_A; \underline{k}_B\}.$$

Based on these capacity constraints, the cross-border exchange of electricity from A to B becomes:

$$T(k, \underline{k}, \mathbf{y}) \equiv \begin{cases} k & \text{if } T^*(\mathbf{y}) > k \\ T^*(\mathbf{y}) & \text{if } T^*(\mathbf{y}) \in [-\bar{\underline{k}}, k] \\ -\underline{k} & \text{if } T^*(\mathbf{y}) < -\underline{k} \end{cases} \tag{21}$$

Dispatch and prices in the balancing market TSO i trades

$$z_i = \tilde{y}_i - y_i + \delta_i(T(k, \underline{k}, \mathbf{y}) - \bar{T}(\bar{k}))$$

MWh flexible redispatch in the national balancing market to ensure balance between domestic production, consumption and cross-border electricity exchange. The corresponding dispatch of flexible electricity in country i becomes

$$X^i(k, \underline{k}, \mathbf{y}) \equiv D_i - y_i + \delta_i T(k, \underline{k}, \mathbf{y}), \tag{22}$$

all of which is traded at the balancing price

$$P^i(k, \underline{k}, \mathbf{y}) \equiv C_x^i(D_i - y_i + \delta_i T(k, \underline{k}, \mathbf{y})). \tag{23}$$

The designs in the two previous sections are special cases of this more general model, with $T(k, \underline{k}, \mathbf{y}) \equiv \bar{T}(\bar{k})$ in the segmented market and $T(k, \underline{k}, \mathbf{y}) \equiv T^*(\mathbf{y})$ in the fully integrated market. Unlike those two designs, the balancing market here does not necessarily yield balanced budget payments. Renewable producers make the aggregate payment

$$P^A(k, \underline{k}, \mathbf{y})(\tilde{y}_A - y_A) + P^B(k, \underline{k}, \mathbf{y})(\tilde{y}_B - y_B)$$

to the TSOs, whereas flexible producers receive

$$P^A(k, \underline{k}, \mathbf{y})(X^A(k, \underline{k}, \mathbf{y}) - \bar{X}^A(\bar{k})) + P^B(k, \underline{k}, \mathbf{y})(X^B(k, \underline{k}, \mathbf{y}) - \bar{X}^B(\bar{k}))$$

from the TSOs. The difference

$$L(k,\underline{k},\bar{k},\mathbf{y}) \equiv [P^B(k,\underline{k},\mathbf{y}) - P^A(k,\underline{k},\mathbf{y})][T(k,\underline{k},\mathbf{y}) - \bar{T}(\bar{k})] \gtreqless 0, \tag{24}$$

represents the *aggregate trade adjustment payment* from producers to the TSOs. This payment is defined as the price difference in the balancing market multiplied by the cross-border redispatch of electricity. The TSOs receive a trade adjustment payment if the balancing price is larger in country B than A, and an adjustment of the electricity system increases exports from A to B. Producers receive trade adjustment payments if $L(k,\underline{k},\bar{k},\mathbf{y}) < 0$. The reason why adjustment payments have not turned up in our analysis until now is because cross-border redispatch is zero, $T(k,\underline{k},\mathbf{y}) \equiv \bar{T}(\bar{k})$, when markets are segmented, and price differences are zero, $P^A(k,\underline{k},\mathbf{y}) = P^B(k,\underline{k},\mathbf{y}) = P^*(\mathbf{y})$, when markets are fully integrated.

National welfare The ex-post welfare in country i is given by

$$\begin{aligned}
&v_i D_i - \bar{P}^i(\bar{k})D_i \\
&+\bar{P}^i(\bar{k})\tilde{y}_i + P^i(k,\underline{k},\mathbf{y})(y_i - \tilde{y}_i) \\
&+\bar{P}^i(\bar{k})\bar{X}^i(\bar{k}) + P^i(k,\underline{k},\mathbf{y})[X^i(k,\underline{k},\mathbf{y}) - \bar{X}^i(\bar{k})] - C^i(X^i(k,\underline{k},\mathbf{y})) \\
&+\frac{1}{2}[\bar{P}^B(\bar{k}) - \bar{P}^A(\bar{k})]\bar{T}(\bar{k}) + \frac{1}{2}L(k,\underline{k},\bar{k},\mathbf{y}).
\end{aligned}$$

The fundamental difference between this expression and the previous welfare expressions is TSO i's share of the trade adjustment payment that appears on the final row. We can rewrite the expression for ex-post welfare in country i as

$$W^{iU}(k,\underline{k},\bar{k},\mathbf{y}) \equiv v_i D_i + \delta_i[\bar{R}(\bar{k}) + R(k,\underline{k},\bar{k},\mathbf{y})] - C^i(D_i - y_i + \delta_i T(k,\underline{k},\mathbf{y})), \tag{25}$$

where superscript U identifies the EU market design. In this expression,

$$R(k,\underline{k},\bar{k},\mathbf{y}) \equiv \frac{1}{2}[P^A(k,\underline{k},\mathbf{y}) + P^B(k,\underline{k},\mathbf{y})][T(k,\underline{k},\mathbf{y}) - \bar{T}(\bar{k})] \tag{26}$$

characterizes country A's net export revenue in the balancing market. This is the sum of the revenue from the balancing market exports of flexible and intermittent generation, and from (the possibly negative) trade adjustment payment.

Equilibrium cross-border exchange of electricity Consider first the case where $T^*(\mathbf{y}) > 0$, so that country A a exports electricity to B in the balancing market. Assume for the sake of the argument that $k_j \geq T^*(\mathbf{y})$, so that k_i determines the exchange of electricity between A and B. Any choice $k_i \geq T^*(\mathbf{y})$ implements first-best efficient dispatch. For $k_i < T^*(\mathbf{y})$, the marginal net benefit to TSO i of increasing trade in the balancing market equals

$$W_k^{iU}(k_i, \underline{k}, \bar{k}, \mathbf{y}) = \frac{1}{2}[P^B(k_i, \underline{k}, \mathbf{y}) - P^A(k_i, \underline{k}, \mathbf{y})] + \frac{\delta_i}{2}[P_k^A(k_i, \underline{k}, \mathbf{y}) + P_k^B(k_i, \underline{k}, \mathbf{y})][k_i - \bar{T}(\bar{k})].$$

The first marginal effect is the direct trade benefit of selling electricity in the high price instead of the low price area. The second effect measures the impact of market power operating through the price effects on TSO i's net export revenue in the balancing market. This market power effect is ambiguous in general. Evaluated at $k_i = T^*(\mathbf{y})$, the price effect vanishes, leaving only the market power effect:

$$W_k^{iU}(T^*(\mathbf{y}), \underline{k}, \bar{k}, \mathbf{y}) = \frac{\delta_i}{2}[C_{xx}^A(X^{A*}(\mathbf{y})) - C_{xx}^B(X^{B*}(\mathbf{y}))][T^*(\mathbf{y}) - \bar{T}(\bar{k})].$$

The right-hand side is different from zero for almost all $\mathbf{y}$, so either TSO A or TSO B has a strict incentive to reduce the flow of electricity below $T^*(\mathbf{y})$. By implication, the efficient exchange $T^*(\mathbf{y}) > 0$ of electricity cannot be sustained as an equilibrium. It is straightforward to verify that the same result also holds for $T^*(\mathbf{y}) < 0$.

By the Leontief technology applied for determining $(k, \underline{k})$, the balancing market has the same qualitative properties as the day-ahead market analyzed in Section 6. The model can sustain a continuum of equilibria, one of which is the no-trade equilibrium. One can also Pareto rank equilibria in these sense that both TSOs prefer equilibria with relatively more trade. We assume that TSOs coordinate on the equilibrium with maximal trade. We label this equilibrium capacity k^U if $T^*(\mathbf{y}) > 0$ and $\underline{k}^U$ if $T^*(\mathbf{y}) < 0$.

Proposition 5 *The equilibrium capacities $(k^U, \underline{k}^U)$ that sustain maximal trade are characterized by*

$$P^B(k^U, \underline{k}^U, \mathbf{y}) - P^A(k^U, \underline{k}^U, \mathbf{y}) = |[P_k^A(k^U, \underline{k}^U, \mathbf{y}) + P_k^B(k^U, \underline{k}^U, \mathbf{y})][\bar{T}(\bar{k}) - k^U]| \tag{27}$$

if efficient trade is from A to B ($T^*(\mathbf{y}) > 0$), and by

$$P^A(k^U, \underline{k}^U, \mathbf{y}) - P^B(k^U, \underline{k}^U, \mathbf{y}) = |[P_{\underline{k}_i}^A(k^U, \underline{k}^U, \mathbf{y}) + P_{\underline{k}_i}^B(k^U, \underline{k}^U, \mathbf{y})][\bar{T}(\bar{k}) + \underline{k}^U]| \tag{28}$$

if efficient trade is from B to A ($T^*(\mathbf{y}) < 0$) under the EU balancing market design. The cross-border exchange of electricity is almost always below the first-best efficient level ($|T(k^U, \underline{k}^U, \mathbf{y})| < |T^*(\mathbf{y})|$ for almost all $\mathbf{y}$).

Proof: We only establish the equilibrium conditions. Assume that $T^*(\mathbf{y}) > 0$. $W_k^{AU} \geq 0$ and $W_k^{BU} \geq 0$ both hold in equilibrium because one of the TSOs has a strict incentive to deviate to $k_i < k^U$ if $W_k^{AU} < 0$ or $W_k^{BU} < 0$. Also, it cannot be the case that both $W_k^{AU} > 0$ and $W_k^{BU} > 0$ in the equilibrium with maximal trade, because it would then be possible to sustain an equilibrium with even more trade. Hence, either $W_k^{AU} = 0$ or $W_k^{BU} = 0$ in the equilibrium with maximal trade.

Solving the first-order condition produces (27). We can solve for (28) in a similar manner.■

The dispatch of electricity is generically inefficient under the EU balancing market design. In fact, our model predicts that all price differences in the balancing market will be the result of TSOs exercising market power by reducing cross-border exchange of electricity. This strong result arises because of our assumption that the transmission network is unconstrained and therefore can sustain trade at the system balancing price in all states of the world. In reality, there can be exogenous capacity constraints that render price equalization in the balancing market impossible even at efficient dispatch. The challenge for competition authorities and other market monitors is that they cannot tell the difference between efficient and inefficient dispatch merely by observing trade flows.

Proposition 5 shows how one can disentangle market power from exogenous capacity constraints by estimation of the following relationship:

$$\Delta P = \alpha + \beta\Omega + \varepsilon \tag{29}$$

The dependent variable $\Delta P \equiv |P^A - P^B|$ is the absolute value of the price difference in the balancing market. The independent variable Ω measures the (inverse) semi-elasticity of net export revenue in the balancing market. It is defined as the right-hand side of (27) if trade in the balancing market goes in the same direction as trade in the day-ahead market, and by the right-hand side of (28) under trade reversal, i.e. when trade in the day-ahead and the balancing market go in opposite directions. An unbiased estimate of β measures the extent to which TSOs exercise market power. In particular, $\beta = 0$ if TSOs behave efficiently. Price elasticities then have no systematic effects on price differences in the balancing market.

The balancing market prices often are publicly available, and so is the equilibrium trade $\bar{T}(\bar{k})$ in the day-ahead market. The fundamental informational challenge to estimating (29) above is that the price effects P_k^A and P_k^B in the balancing market can be private information of the TSOs. The trading capacities $(k^U, \underline{k}^U)$ can also be unavailable to outside observes, for instance if they are implicit. Nevertheless, competition authorities should be able to obtain this information, which will enable them to perform empirical analysis of TSO market power.

Equilibrium day-ahead transmission capacity The expected national welfare of country i is

$$\tilde{W}^{iU}(\bar{k}) \equiv v_i D_i + \delta_i \bar{R}(\bar{k}) + \int_{\mathbf{y}\in\mathbf{Y}} [\delta_i R(k^U, \underline{k}^U, \bar{k}, \mathbf{y}) - C^i(D_i - y_i + \delta_i T(k^U, \underline{k}^U, \mathbf{y}))] dF(\mathbf{y})$$

under the EU balancing market design. We can partition $\mathbf{Y}$ into a subset $\mathbf{Y}^{AB} \equiv \{\mathbf{y} \in \mathbf{Y} : T^*(\mathbf{y}) > 0\}$ of intermittent production $\mathbf{y}$ for which the first-best efficient flow of electricity is from A to B, and we denote its complement by $\mathbf{Y}^{BA} \equiv \{\mathbf{y} \in \mathbf{Y} : T^*(\mathbf{y}) \leq 0\}$.

The marginal effect of an increase in export capacity $\bar{k} < \bar{k}^*$ has the following impact on TSO i:

$$\begin{aligned} \tilde{W}_{\bar{k}}^{iU}(\bar{k}) &= \delta_i[\bar{R}_{\bar{k}}(\bar{k}) - \frac{1}{2}(\tilde{P}^{AU}(\bar{k}) + \tilde{P}^{BU}(\bar{k}))] \\ &+ \int_{\mathbf{y}\in\mathbf{Y}^{AB}} \Psi^{iU}(\bar{k},\mathbf{y})[P^B(k^U,\underline{k}^U,\mathbf{y}) - P^A(k^U,\underline{k}^U,\mathbf{y})]k_{\bar{k}}^U dF(\mathbf{y}) \\ &+ \int_{\mathbf{y}\in\mathbf{Y}^{BA}} \Psi^{iU}(\bar{k},\mathbf{y})[P^A(k^U,\underline{k}^U,\mathbf{y}) - P^B(k^U,\underline{k}^U,\mathbf{y})]\underline{k}_{\bar{k}}^U dF(\mathbf{y}) \end{aligned}$$

An increase in export capacity has marginal impact $\bar{R}_{\bar{k}}(\bar{k})$ on the net export revenue in the day-ahead market and reduces the net export revenue (or increases the net export expenditure) in the balancing market by $R_{\bar{k}} = -\frac{1}{2}(P^A + P^B)$, see (26). Taking expectations, the direct effect on the net export revenue in the balancing market is equal to the average expected balancing price, where

$$\tilde{P}^{iU}(\bar{k}) \equiv \int_{\mathbf{y}\in\mathbf{Y}} P^i(k^U,\underline{k}^U,\mathbf{y})dF(\mathbf{y}),\ i = A, B$$

is the expected balancing price in country i given the cross-border exchange of electricity $(k^U, \underline{k}^U)$ in the balancing market.

Since TSOs behave strategically in the balancing market, an increase in $\bar{k}$ may also affect expected national welfare through the equilibrium transmission capacities in the balancing market. Rows two and three in the above expression identify the strategic effects. Here, $\Psi^{iU}(\bar{k},\mathbf{y})$ is an indicator function that takes the value 0 if $\mathbf{y} \in \mathbf{Y}^{AB}$ and $W_k^{iU}(k^U,\underline{k}^U,\bar{k},\mathbf{y}) = 0$ or if $\mathbf{y} \in \mathbf{Y}^{BA}$ and $W_{\underline{k}}^{iU}(k^U,\underline{k}^U,\bar{k},\mathbf{y}) = 0$. For such realizations of $\mathbf{y}$, the capacities $(k_i^U,\underline{k}_i^U)$ submitted by TSO i are binding in the balancing market, and so the indirect effect is of second-order importance to TSO i. The indicator function $\Psi^{iU}(\bar{k},\mathbf{y})$ takes the value 1 for all other realizations of $\mathbf{y}$, meaning that the capacities $(k_j^U,\underline{k}_j^U)$ submitted by TSO j are binding. The indirect effect then has a first-order impact on the national welfare in country i. By way of

$$k_{\bar{k}}^U[\bar{k} - k^U] = \frac{P^B(k^U,\underline{k}^U,\mathbf{y}) - P^A(k^U,\underline{k}^U,\mathbf{y})}{2W_{kk}^{iU}(k^U,\underline{k}^U,\bar{k},\mathbf{y})} < 0,\ T^*(\mathbf{y}) > 0$$

and

$$\underline{k}_{\bar{k}}^U[\bar{k} + \underline{k}^U] = \frac{P^A(k^U,\underline{k}^U,\mathbf{y}) - P^B(k^U,\underline{k}^U,\mathbf{y})}{2W_{\underline{k}\underline{k}}^{jU}(k^U,\underline{k}^U,\bar{k},\mathbf{y})} < 0,\ T^*(\mathbf{y}) < 0,$$

the strategic effect tends to reduce the value of bidding capacity into the day-ahead market. Exceptions occur when intermittent production in country A is so large relative to intermittent production in country B ($T^*(\mathbf{y}) > \bar{k}$) that the cross-border redispatch is positive ($k^U > \bar{k}$). Hence, the strategic effect is ambiguous in general. Yet, Proposition 1 establishes that the equilibrium $\bar{k}^U$ in the day-ahead market either is efficient or downward distorted compared to the efficient capacity $\bar{k}_{eff}^U$.

Comparison of balancing market designs Comparing the efficiency of the EU balancing market design with the segmented balancing market design yields

$$\tilde{W}^U(\bar{k}^U) - \tilde{W}^S(\bar{k}^S) = \underbrace{\tilde{W}^U(\bar{k}^S) - \tilde{W}^S(\bar{k}^S)}_{\text{Direct effect}} + \underbrace{\tilde{W}^U(\bar{k}^U) - \tilde{W}^U(\bar{k}^S)}_{\text{Incentive effect}}.$$

The direct effect of switching to the EU balancing market can be written as

$$\begin{aligned}\tilde{W}^U(\bar{k}^S) - \tilde{W}^S(\bar{k}^S) \;&=\; \int_{\mathbf{y}\in\mathbf{Y}^{AB}} \int_{\bar{k}^S}^{k^U} [P^B(k, \underline{k}^U, \mathbf{y}) - P^A(k, \underline{k}^U, \mathbf{y})] dk dF(\mathbf{y}) \\ &\quad + \int_{\mathbf{y}\in\mathbf{Y}^{BA}} \int_{-\underline{k}^U}^{\bar{k}^S} [P^A(k^U, \underline{k}, \mathbf{y}) - P^B(k^U, \underline{k}, \mathbf{y})] d\underline{k} dF(\mathbf{y}).\end{aligned}$$

Fixing the capacity bid into the day-ahead market at $\bar{k}^S$, the EU balancing market design is unambiguously better than the segmented balancing market design for all realizations of intermittent electricity production $\mathbf{y} \in \mathbf{Y}^{BA}$ because the associated flexibility of cross-border redispatch better allows TSOs to adapt to the change in system conditions: $T^*(\mathbf{y}) < -\underline{k}^U < \bar{k}^S$. This market design is better also for all realizations $\mathbf{y} \in \mathbf{Y}^{AB}$ such that $k^U > \bar{k}^S$. However, there are also realizations $\mathbf{y} \in \mathbf{Y}^{AB}$ such that $\bar{k}^S$ is closer than k^U to $T^*(\mathbf{y})$ because of strategic behavior in the balancing market. Hence, the direct effect can be positive or negative.

The incentive effect has a first-order impact on expected welfare because the balancing market design affects equilibrium trade in the day-ahead market. Because of strategic withholding, $\bar{k}^U \leq \bar{k}^U_{eff}$, one would expect the incentive effect to be positive if the EU balancing market design drives up trade in the day-ahead market, $\bar{k}^U > \bar{k}^S$. A comparison of TSO i's marginal incentives

$$\begin{aligned}\tilde{W}^{iU}_{\bar{k}}(\bar{k}) - \tilde{W}^{iS}_{\bar{k}}(\bar{k}) \;&=\; \delta_i[\tilde{P}^{iS}(\bar{k}) - \frac{1}{2}(\tilde{P}^{AU}(\bar{k}) + \tilde{P}^{BU}(\bar{k}))] \\ &\quad + \int_{\mathbf{y}\in\mathbf{Y}^{AB}} \Psi^{iU}(\bar{k}, \mathbf{y})[P^B(k^U, \underline{k}^U, \mathbf{y}) - P^A(k^U, \underline{k}^U, \mathbf{y})] k^U_{\bar{k}} dF(\mathbf{y}) \\ &\quad + \int_{\mathbf{y}\in\mathbf{Y}^{BA}} \Psi^{iU}(\bar{k}, \mathbf{y})[P^A(k^U, \underline{k}^U, \mathbf{y}) - P^B(k^U, \underline{k}^U, \mathbf{y})] \underline{k}^U_{\bar{k}} dF(\mathbf{y})\end{aligned}$$

to supply capacity to the day-ahead market reveals that even this effect can be positive or negative. On the one hand, the expected marginal production cost can be lower under the EU balancing market design. On the other hand, the strategic effect may reduce $\bar{k}^U$ below $\bar{k}^S$. We can therefore only conclude the following:

Observation 2 *Joint expected welfare can be higher or lower in the EU balancing market design compared to the segmented market, depending on the circumstances.*

Which market design is better, is likely to depend on the distribution of intermittent production. If this distribution is symmetric so that trade in both directions is equally likely, then the flexibility associated with the EU market design can be so valuable that both equilibrium trade in the day-ahead market is larger and the expected efficiency of dispatch is higher than under the segmented market design.

10 A first-best efficient balancing market

Many of the regulations that have been introduced by the EU in recent years aim at improving efficiency by increasing the cross-border exchange of electricity. Yet, authorities such as the Agency for the Cooperation of Energy Regulators (ACER), remain concerned about the current balancing market design. ACER worries in particular about the incentive for TSOs to pass the costs of their actions onto neighboring countries. The analysis in the previous section suggests that these concerns are valid. Our results demonstrate that TSOs have excessive incentives to limit trade in the balancing market. ACER proposes that the ideal regulation should adhere to a "polluter pays principle" by which TSOs bear the full cost of the consequences of their actions. However, ACER does not suggest any balancing market design for implementing this principle.

We propose a market design that can be interpreted as a "polluter pays" mechanism. In this design, TSO incentives are affected by how the transmission capacities they bid into the balancing market influence the distribution of trade adjustment payments between the owners of the relevant cross-border interconnection. A fundamental property of the EU design is an even split of trade adjustment payments. Our mechanism prescribes even split under symmetric capacity choices, but not otherwise. Specifically, TSO i receives the trade adjustment payment

$$L^i(k_i, k_j, \underline{k}_i, \underline{k}_j, \bar{k}, \mathbf{y}) \equiv \begin{cases} \min\{L(k, \underline{k}, \bar{k}, \mathbf{y}); 0\} - \varepsilon(k) & \text{if } k_i < k_j,\ T^*(\mathbf{y}) > 0 \\ \frac{1}{2}L(k, \underline{k}, \bar{k}, \mathbf{y}) & \text{if } k_i = k_j,\ T^*(\mathbf{y}) > 0 \end{cases} \tag{30}$$

if efficient trade in the balancing market is in the same direction as trade in the day-ahead market. In (30), the share of the aggregate imbalance payment L that accrues to TSO i, depends on its capacity bid k_i for electricity exchange from A to B relative to the capacity offer k_j by the other TSO. By unilaterally restricting capacity, $k_i < k_j$, TSO i must account for the entire trade adjustment payment if this is negative, $L < 0$, but receives nothing of the rent if the aggregate payment is positive, $L > 0$. The other TSO is residual claimant to the aggregate transfer payment by budget balance, $L^A + L^B = L$. The corresponding trade adjustment payment is

$$L^i(k_i, k_j, \underline{k}_i, \underline{k}_j, \bar{k}, \mathbf{y}) \equiv \begin{cases} 0 & \text{if } \underline{k}_i < \underline{k}_j,\ T^*(\mathbf{y}) \leq 0 \\ \frac{1}{2}L(k, \underline{k}, \bar{k}, \mathbf{y}) & \text{if } \underline{k}_i = \underline{k}_j,\ T^*(\mathbf{y}) \leq 0 \end{cases} \tag{31}$$

under trade reversal. In this case, TSO i receives nothing of the trade adjustment payment $L \geq 0$ if it unilaterally restricts trade from B to A in the balancing market.

It seems straightforward why the above scheme would work. Any reduction in the capacity bid from $k_i = k_j$ to $k_i < k_j$ either causes TSO i to lose its half of the trade adjustment payment or forces the TSO to pay the entire deficit instead of only half of it. However, this intuition does not paint the full picture. If $\underline{k}_j = T^*(\mathbf{y}) < 0$, then a reduction in $\underline{k}_i$ below $\underline{k}_j$ has no effect on TSO i's transfer payment because it is zero in any case. But even if a downward deviation should generate a deficit resulting from a trade adjustment payment, there are other effects that the TSO must take into account that can work in the opposite direction of the transfer payment. To illustrate this second point, observe that the welfare of TSO i can be written as

$$W^{iE}(k_i, k_j, \underline{k}_i, \underline{k}_j, \bar{k}, \mathbf{y}) \equiv v_i D_i + \delta^i \bar{R}(\bar{k}) + \Pi^i(\underline{k}, k, \bar{k}, \mathbf{y}) + L^i(k_i, k_j, \underline{k}_i, \underline{k}_j, \bar{k}, \mathbf{y}), \quad (32)$$

where superscript E signifies an efficient market design. The term

$$\Pi^i(k, \underline{k}, \bar{k}, \mathbf{y}) \equiv P^i(k, \underline{k}, \mathbf{y})[X^i(k, \underline{k}, \mathbf{y}) - \bar{X}^i(\bar{k}) + y_i - \tilde{y}_i] - C^i(X^i(k, \underline{k}, \mathbf{y})) \quad (33)$$

represents the operating profit of flexible and intermittent generation in the balancing market. It is the joint effect on the operating profit and the trade adjustment payment that determines whether TSO i has an incentive to restrict trade below the efficient level $T^*(\mathbf{y})$.

Even if the trade adjustment payment (30) and (31) can sustain an efficient equilibrium, one might worry that these trigger strategies also enable TSOs to implement less competitive equilibria. A specific concern is that TSOs can uphold the same level of trade $\bar{T}(\bar{k})$ as in the day-ahead market. In (30), the incremental penalty $\varepsilon(\bar{T}(\bar{k})) > 0$ if $\bar{T}(\bar{k}) < T^*(\mathbf{y})$ and $\varepsilon(k) = 0$ otherwise, is designed with the exact purpose to break such an equilibrium. We prove the following result in the Appendix:

Proposition 6 *Consider a balancing market design in which trade adjustment payments are settled according to (30) and (31).*
(i) There exists an equilibrium in the balancing market that implements the first-best efficient dispatch $(X^{A*}(\mathbf{y}), X^{B*}(\mathbf{y}))$ *for any day-ahead capacity* $\bar{k}$ *and system condition* $\mathbf{y}$.
(ii) All equilibria in the balancing market implement efficient dispatch, regardless of the day-ahead capacity $\bar{k}$ *and system condition* $\mathbf{y}$.

The above market design solves the inefficiencies associated with decentralized capacity choices by the TSO in the balancing market. There are many other designs that can sustain first-best efficient dispatch as an equilibrium. One of them is simply to impose a heavy fine on any TSO that deviates from efficient dispatch. The feasibility of such a mechanism obviously requires that the efficient dispatch is observable to the responsible authority. The mechanism in this section only builds on the assumption that the TSOs have this information. Implementation of (30) and (31) merely requires that the responsible authority can observe the capacity bids $(k_A, \underline{k}_A)$, $(k_B, \underline{k}_B)$, the day-ahead trade $\bar{T}(\bar{k})$, and the actual trade adjustment payment L. The payment L can be calculated as the difference between the payments made by market participants to the TSOs minus the compensation by TSOs to participants in the two balancing markets. The day-ahead trade is available from the power exchange. The capacity bids in the balancing markets can be verified by making the balancing market itself depend on such explicitly bids, similar to the day-ahead market.

11 Discussion

Electricity networks are becoming increasingly interconnected across jurisdictions in Europe and elsewhere. Anecdotal evidence suggests that withholding of network capacity by TSOs constitutes a barrier to efficient use of the integrated electricity system. Yet, hardly any research has been done on TSO incentives to make transmission capacity available to the market. To remedy this lacuna, we have developed a model of strategic interaction between two national TSOs that jointly own a cross-border interconnection between their respective national grids. Each TSO is assigned the dual role of enabling international trade by supplying interconnection capacity to the day-ahead market, and to ensure security of supply by maintaining the balance between domestic production, consumption and cross-border exchange of electrical power.

A main policy conclusion from the analysis is that a standard market design similar to the one applied in the EU generally yields incentives to exercise market power by limiting international trade of electricity. We show that a modification of the current design could be sufficient to implement the first-best efficient outcome, also in the presence of strategic TSOs. Central to this market design is to appropriately define sharing rules for the trade adjustment payments that arise from cross-border redispatch. Our analysis leaves important questions unanswered, however:

(1) What are the implications of domestic bottlenecks for efficiency? Our model assumes that domestic networks are unconstrained, but internal network constraints are common in practice. Such constraints may lead to costly counter-trading if they occur within designated price areas. But they are endogenous insofar as they depend on the transmission capacities announced by the national TSOs, for instance under flow-based congestion management. An interesting issue is whether TSOs have incentives to use even domestic transmission capacity for strategic purposes.

(2) How efficient is allocation of transmission capacity in a multi-country market? Our model assumes that there are only two countries. A more realistic setting with three or more countries in a meshed network will yield opportunity for strategic interaction that potentially has important consequences for TSO market power and efficiency.

(3) How does regulation and ownership structure affect incentives to supply transmission capacity? We assume that TSOs maximize national welfare. The specific regulations that govern TSOs, for instance revenue cap or cost-plus, will affect the extent to which TSOs internalize the domestic effects of their actions. Related, some cross-border interconnections are privately owned, either because one of the TSOs is a private company, or because they are merchant transmission lines. A detailed analysis might yield insights concerning the link between governance and efficiency.

(4) How does strategic behavior affect performance? In our model, consumers and producers are non-strategic in the sense that retailers bid demand and intermittent producers their expected output inelastically into the day-ahead market, whereas flexible producers bid their marginal cost. But even market participants that treat prices as exogenous face a choice whether to participate in the day-ahead or the balancing market. Allowing such portfolio selection would create a stronger link between the day-ahead and expected balancing market prices. A related issue with implications for efficiency is the interplay between TSO and generator market power.

(5) How important is the day-ahead market for efficiency? Our model assumes that all dispatchable generation is flexible. The only implication of the day-ahead market is through the effect on TSO behavior. In reality, much of the dispatchable generation capacity has insufficient flexibility to participate in the balancing market. Introducing such capacity would provide for a more realistic description of interaction in the day-ahead market.

(6) What are the consequences of TSO behavior for reliability? In our model, countries have sufficient capacity to meet demand in all system conditions. Relaxing this assumption would make it possible to analyze issues related to reliability and security of supply.

(7) How does private information affect outcomes? Our model assumes complete information. Explicitly accounting for private information about system conditions would shed light on the problems faced by authorities in the assessment of TSO market performance.

Addressing these and other pertinent questions will contribute to broadening our understanding of the challenges involved in achieving efficient integration of electricity markets.

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A Appendix

A.1 Proof of Proposition 6

Existence Assume that $(k_j, \underline{k}_j) = (T^*(\mathbf{y}), 0)$ for all $T^*(\mathbf{y}) > 0$ and that $(k_j, \underline{k}_j) = (0, T^*(\mathbf{y}))$ for all $T^*(\mathbf{y}) \leq 0$. By expression (24), $L(k, \underline{k}, \bar{k}, \mathbf{y}) < 0$ if $T^*(\mathbf{y}) > 0$, $\bar{T}(\bar{k}) > 0$, and $k < \min\{T^*(\mathbf{y}); \bar{T}(\bar{k})\}$. Instead, $L(k, \underline{k}, \bar{k}, \mathbf{y}) \geq 0$ for all $k \geq \bar{T}(\bar{k})$ and $T^*(\mathbf{y}) > 0$. Hence, (30) implies

$$L^i(k_i, T^*(\mathbf{y}), \underline{k}_i, 0, \bar{k}, \mathbf{y}) = \begin{cases} L(k_i, 0, \bar{k}, \mathbf{y}) & \forall k_i \in [0, \min\{T^*(\mathbf{y}); \bar{T}(\bar{k})\}),\ \underline{k}_i \geq 0,\ \bar{T}(\bar{k}) > 0,\ T^*(\mathbf{y}) > 0 \\ -\varepsilon(k) & \forall k_i \geq \bar{T}(\bar{k}),\ \underline{k}_i \geq 0,\ T^*(\mathbf{y}) > 0 \end{cases}$$

On the basis of these trade adjustment payments, we can derive the national welfare function of country i

$$\begin{aligned} W^{iE}(k_i, T^*(\mathbf{y}), \underline{k}_i, 0, \bar{k}, \mathbf{y}) &= v_i D_i + \delta_i \bar{R}(\bar{k}) + \Pi^i(k_i, 0, \bar{k}, \mathbf{y}) \\ &\quad - [P^B(k_i, 0, \mathbf{y}) - P^A(k_i, 0, \mathbf{y})][\bar{T}(\bar{k}) - k_i] \end{aligned} \tag{A.1}$$

for all $k_i \in [0, \min\{T^*(\mathbf{y}); \bar{T}(\bar{k})\})$, $\underline{k}_i \geq 0$, $\bar{T}(\bar{k}) > 0$, $T^*(\mathbf{y}) > 0$, and

$$W^{iE}(k_i, T^*(\mathbf{y}), \underline{k}_i, 0, \bar{k}, \mathbf{y}) = v_i D_i + \delta_i \bar{R}(\bar{k}) + \Pi^i(k_i, 0, \bar{k}, \mathbf{y}) - \varepsilon(k) \tag{A.2}$$

for all $k_i \geq \bar{T}(\bar{k})$, $\underline{k}_i \geq 0$, $T^*(\mathbf{y}) > 0$. Using (31), we also get

$$W^{iE}(k_i, 0, \underline{k}_i, T^*(\mathbf{y}), \bar{k}, \mathbf{y}) = v_i D_i + \delta_i \bar{R}(\bar{k}) + \Pi^i(0, \underline{k}_i, \bar{k}, \mathbf{y}) \tag{A.3}$$

for all $k_i \geq 0$, $\underline{k}_i \geq 0$, $T^*(\mathbf{y}) \leq 0$. We proceed by establishing existence in subcases.

Assume that $0 \leq \bar{T}(\bar{k}) < T^*(\mathbf{y})$. Differentiation of (A.1) yields

$$W^{iE}_{k_i}(k_i, T^*(\mathbf{y}), \underline{k}_i, 0, \bar{k}, \mathbf{y}) = P^B(k_i, 0, \mathbf{y}) - P^A(k_i, 0, \mathbf{y}) + C^j_{xx}(X^j(k_i, 0, \mathbf{y}))[\bar{T}(\bar{k}) - k_i] > 0 \tag{A.4}$$

for all $k_i \in (0, \bar{T}(\bar{k}))$ if $\bar{T}(\bar{k}) > 0$. Differentiation of (A.2) yields

$$W^{iE}_{k_i}(k_i, T^*(\mathbf{y}), \underline{k}_i, 0, \bar{k}, \mathbf{y}) = C^i_{xx}(X^i(k_i, 0, \mathbf{y}))[k_i - \bar{T}(\bar{k})] > 0 \tag{A.5}$$

for all $k_i \in (\bar{T}(\bar{k}), T^*(\mathbf{y}))$. Since national welfare drops discontinuously at $k_i = \bar{T}(\bar{k})$, TSO i strictly prefers $k_i \neq \bar{T}(\bar{k})$. Monotonicity of W^{iE} and continuity for all $k_i \neq \bar{T}(\bar{k})$ imply that $k_i = T^*(\mathbf{y})$ is an optimal capacity choice. Since the welfare function of TSO i is independent of $\underline{k}_i$ for all $T^*(\mathbf{y}) > 0$, $(k_i, \underline{k}_i) = (T^*(\mathbf{y}), 0)$ represents a best-response to $(k_j, \underline{k}_j) = (T^*(\mathbf{y}), 0)$.

Assume that $0 < T^*(\mathbf{y}) \leq \bar{T}(\bar{k})$. Differentiation of (A.1) yields $W^{iE}(k_i, T^*(\mathbf{y}), \underline{k}_i, 0, \bar{k}, \mathbf{y}) > 0$ for all $k_i \in (0, T^*(\mathbf{y}))$, by (A.4). Hence, $(k_i, \underline{k}_i) = (T^*(\mathbf{y}), 0)$ represents a best-response to $(k_j, \underline{k}_j) = (T^*(\mathbf{y}), 0)$.

Assume that $T^*(\mathbf{y}) < 0$. Differentiation of (A.3) yields

$$W^{iE}_{\underline{k}_i}(k_i, 0, \underline{k}_i, T^*(\mathbf{y}), \bar{k}, \mathbf{y}) = C^i_{xx}(X^i(0, \underline{k}, \mathbf{y}))[\underline{k}_i + \bar{T}(\bar{k})] > 0$$

for all $\underline{k}_i \in (0, T^*(\mathbf{y}))$. Since TSO i's welfare function is independent of k_i for $T^*(\mathbf{y}) < 0$, $(k_i, \underline{k}_i) = (0, T^*(\mathbf{y}))$ represents a best-response to $(k_j, \underline{k}_j) = (0, T^*(\mathbf{y}))$.

Finally, national welfare in country i is independent of $(k_i, \underline{k}_i)$ if $k_j = \underline{k}_j = T^*(\mathbf{y}) = 0$. In this case, $k_i = \underline{k}_i = 0$ trivially represents an optimal capacity choice by TSO i.

Uniqueness of efficient trade Let $(k^E_A, \underline{k}^E_A)$ and $(k^E_B, \underline{k}^E_B)$ be an equilibrium. The corresponding equilibrium transmission capacities are $k^E \equiv \min\{k^E_A, k^E_B\}$ and $\underline{k}^E \equiv \min\{\underline{k}^E_A; \underline{k}^E_B\}$. Let $t^E(\bar{k}, \mathbf{y}) \equiv T(k^E, \underline{k}^E, \bar{k}, \mathbf{y})$ be the cross-border exchange of electricity from A to B in equilibrium. If $T^*(\mathbf{y}) = 0$, then $t^E(\bar{k}, \mathbf{y}) = T^*(\mathbf{y})$ is implied directly by (21). Assume that $T^*(\mathbf{y}) > 0$, and suppose $t^E(\bar{k}, \mathbf{y}) <$

$T^*(\mathbf{y})$. By implication, $t^E(\bar{k},\mathbf{y}) = k^E$. Consider first the possibility that $k_i^E{<}k_j^E$. In this case,

$$\begin{aligned} W^{iE}(k_i^E, k_j^E, \underline{k}_i^E, \underline{k}_j^E, \bar{k}, \mathbf{y}) \quad &= v_i D_i + \delta_i \bar{R}(\bar{k}) + \Pi^i(k_i^E, \underline{k}^E, \bar{k}, \mathbf{y}) \\ &-[P^B(k_i^E, \underline{k}^E, \mathbf{y}) - P^A(k_i^E, \underline{k}^E, \mathbf{y})][\bar{T}(\bar{k}) - k_i^E] \end{aligned}$$

if $k_i^E < \bar{T}(\bar{k})$ and

$$W^{iE}(k_i^E, k_j^E, \underline{k}_i^E, \underline{k}_j^E, \bar{k}, \mathbf{y}) = v_i D_i + \delta_i \bar{R}(\bar{k}) + \Pi^i(k_i^E, \underline{k}^E, \bar{k}, \mathbf{y})$$

if $k_i^E > \bar{T}(\bar{k})$. If $k_i^E = \bar{T}(\bar{k})$, then TSO i suffers an incremental cost $\varepsilon(\bar{T}(\bar{k})) > 0$. Either way, TSO i can strictly increase national welfare by a marginal increase in k_i above k_i^E by expressions qualitatively similar to (A.4) and (A.5), which contradicts the presumed optimality of k_i^E. Hence, $t^E(\bar{k},\mathbf{y}) < T^*(\mathbf{y})$ for $T^*(\mathbf{y}) > 0$ implies $k_A^E{=}k_B^E = k^E$. Consider a deviation by TSO i to $k_i > k_i^E = k_j^E = k^E$. The expected national welfare of this strategy is

$$W^{iE}(k_i, k^E, \underline{k}_i^E, \underline{k}_j^E, \bar{k}, \mathbf{y}) = v_i D_i + \delta_i \bar{R}(\bar{k}) + \Pi^i(k^E, \underline{k}^E, \bar{k}, \mathbf{y}) + \max\{L(k^E, \underline{k}^E, \bar{k}, \mathbf{y}); 0\} + \varepsilon(k^E)$$

The net benefit of the deviation is:

$$W^{iE}(k_i, k^E, \underline{k}_i^E, \underline{k}_j^E, \bar{k}, \mathbf{y}) - W^{iE}(k^E, k^E, \underline{k}_i^E, \underline{k}_j^E, \bar{k}, \mathbf{y}) = \frac{1}{2}|L(k^E, \underline{k}^E, \bar{k}, \mathbf{y})| + \varepsilon(k^E).$$

The right-hand side of this expression is strictly positive if $k^E = \bar{T}(\bar{k})$ by $\varepsilon(\bar{T}(\bar{k})) > 0$ and strictly positive if $k^E \neq \bar{T}(\bar{k})$ by $L(k^E, \underline{k}^E, \bar{k}, \mathbf{y}) \neq 0$. This contradicts the assumed optimality of $k_A^E{=}k_B^E = k^E < T^*(\mathbf{y})$. This leaves $t^E(\bar{k},\mathbf{y}) = T^*(\mathbf{y})$ as the only possibility for $T^*(\mathbf{y}) > 0$. The proof that $t^E(\bar{k},\mathbf{y}) = T^*(\mathbf{y})$ for $T^*(\mathbf{y}) < 0$ is analogous, so we simply omit it.■