Cross-Border Exchange and Sharing of Generation Reserve Capacity

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ABSTRACT

This paper develops a stylized model of cross-border balancing. We distinguish three degrees of cooperation: autarky, reserves exchange and reserves sharing. The model shows that TSO cooperation reduces costs. The gains of cooperation increase with cost asymmetry and decrease with correlation of real-time imbalances. Based on actual market data of reserves procurement of positive and negative automatic frequency restoration reserves in Belgium, France, Germany, the Netherlands, Portugal and Spain, we estimate the procurement cost decrease of exchange to be €165 million per year without transmission constraints and €135 million per year with transmission constraints. The cost decrease of sharing is estimated to be €500 million per year. The model also shows that voluntary cross-border cooperation could be hard to achieve, as TSOs do not necessarily have correct incentives.

Keywords: Cross-border balancing, generation reserves, reserves procurement, multi-TSO interactions

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1. INTRODUCTION

Transmission System Operators (TSOs) are responsible for the security of their transmission system. They use upward and downward reserves to deal with imbalances, caused by unanticipated outages and forecast errors of demand and intermittent supply. Historically, each TSO procured and activated its reserves in its own zone. However—following cooperation in forward markets, the day-ahead market and the intraday market—some TSOs in Europe and the United States recently started cross-border cooperation of reserves procurement and activation.

The benefits of cross-border cooperation of balancing and reserves have already been studied in the literature. Most of the literature presents case study results. Vandezande et al. (2009) estimate that a Belgium-Netherlands balancing market would have decreased procurement and activation costs by 29–44% in 2008, depending on the availability of cross-border capacity. Likewise, Van den Bergh et al. (2017) estimate the benefits of cross-border activation of reserves to be around €25 million a year, of exchange to be €40 million a year and of sharing to be €50 million per year for a case study of the 2013 Central Western European (CWE) electricity system.[1] However, they find lower benefits of cooperation if transmission constraints are neglected during cross-border pro-

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curement. Farahmand et al. (2012) study the integration of the balancing and procurement markets of Northern Europe, Germany and the Netherlands. They estimate savings of approximately €204 million per year for exchange of balancing energy and €153 million per year for exchange of reserve capacity. This last number is in line with our estimation of €165 million per year for exchange between Belgium, France, Germany, the Netherlands, Portugal and Spain. Gebrekiros et al. (2013) find only a reduction of 2% of procurement costs in a small numerical illustration. van der Weijde and Hobbs (2011) quantify the inter-market benefits using a stylized 4-node network. They find that the benefits of coordinating balancing markets generally exceed unit commitment benefits. In a future with a 45% penetration of renewable generation, Mott MacDonald (2013) estimates operational cost savings of exchange and sharing of reserves on European scale in the order of €3 billion a year. They assume that the increased intermittent and unpredictable generation capacity results in increased volumes of imbalances. For exchange of balancing energy, the ACER Annual Monitoring (ACER, 2014) estimates the potential yearly benefits to be between €15 and €65 million per border in 2013, while Newbery et al. (2016) extrapolates these data to the EU-28 and finds yearly benefits of around €1.3 billion. The ACER Annual Monitoring does not quantify the benefits of exchange of reserve capacity, but notes that in the overall cost of balancing, in most European markets, the procurement of balancing capacity represents the largest proportion and important price differentials exist across countries (ACER, 2015).

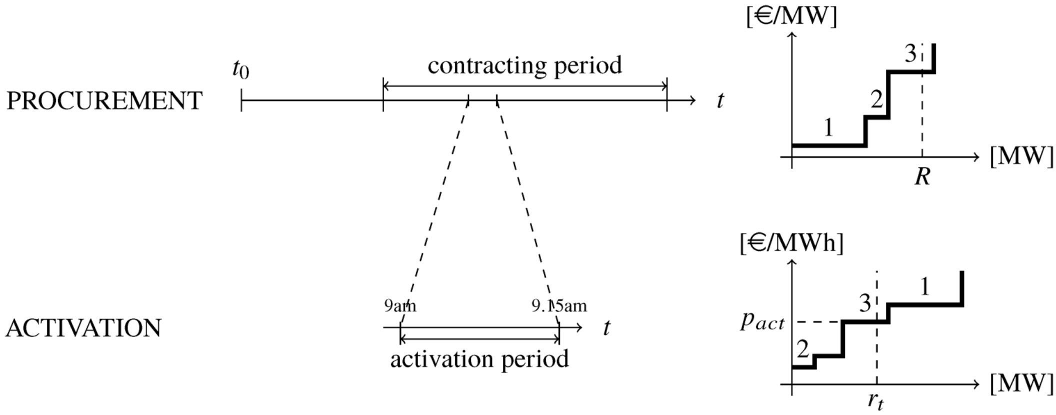
The case study approach in the literature means that there is still a lack of understanding, whether and to what extent TSO cross-border cooperation is economically efficient for each TSO zone and for the region as a whole. The contribution of this paper is to present a general model that analyses three degrees of TSO cooperation in reserves provision. First, we examine autarkic TSO reserve provision—a non-cooperative TSO equilibrium. Next we study the supply efficiency of reserves exchange, where a TSO can acquire reserve capacity in the adjacent TSO area. The last case investigates reserves sharing. Reserves sharing leads to both supply efficiency and dimensioning efficiency. We show that each step in the integration of zones results in progressively lower expected costs. We also present a numerical example in order to illustrate the three scenarios. In addition, to get an understanding of their order of magnitude, we estimate the possible cost decrease of cross-border procurement of generation reserves in Central West Europe (CWE) and Iberia, based on publicly available procurement data. Lastly, we show that the gains of cooperation are not equally distributed across TSOs. Some TSOs may even experience an increase of procurement costs, which makes voluntary cross-border cooperation harder to achieve. If supranational balancing guidelines, like (European Commission, 2017b), do not specify the details of inter-TSO agreements, there is room for bargaining.

The paper is organized as follows. The next section describes various concepts of electricity balancing, together with types and examples of cross-border balancing mechanisms. Section 3 introduces the model and analyses different degrees of cooperation of cross-border reserves procurement. In section 4, we estimate the possible cost decrease of cross-border procurement of generation reserves in CWE and Iberia. Next, section 5 studies the implementation of cross-border reserves procurement. Section 6 concludes.

2. ELECTRICITY BALANCING

Electricity balancing is the continuous process, in all time horizons, through which TSOs ensure that a sufficient amount of upward and downward reserves are available to deal with real-time imbalances between supply and demand in their electricity transmission system. Imbalances

Figure 1: Procurement of reserve capacity and activation of balancing energy



occur due to forecast errors of demand and renewable supply and unforeseen events such as line failures and generation outages. If imbalances between supply and demand persist for a certain period of time, the electricity system could collapse, leading to a blackout.

Most transmission systems consist of different interconnected networks, which are each governed by one TSO. Since system frequency is shared on all voltage levels of a synchronous area, due to the technical characteristics of electricity, power system reliability is considered to be a common good. That is, a non-excludable but rival good. This means that a MW of power can only be used once and that it is technologically difficult to prevent interconnected TSOs from using more than they provide. Underprovision of reserves in one TSO zone could thus lead to a widespread blackout throughout the synchronous area. Therefore, to prevent this 'Tragedy of the Commons', all TSOs in a synchronous area are obliged to provide reserves.

Figure 1 shows the two stages of electricity balancing: procurement and activation. First, to ensure that sufficient reserves are available for real-time balancing, TSOs procure or contract an amount of reserves—so-called reserve capacity or balancing capacity—in advance.[2] This reserve requirement, R, is stipulated by network codes and guidelines. To determine the least-cost procurement of reserve capacity to meet the reserve requirement, the TSO holds an open bidding process for each type of reserves[3] for a given future contracting period. Balancing service providers can submit reserve capacity bids, indicating the size [MW] and the price of the bid [€/MW/hour availability]. In the illustration of Figure 1, bid 1, bid 2 and part of bid 3 are accepted in the procurement phase to meet a reserve requirement R. Accepted bids are obliged to be available throughout the contracting period. Second, in each activation period[4] of the contracting period the TSO holds another open bid-

2. Even network operators with a real-time balancing spot market, like CAISO and Transpower, still procure some reserve capacity in advance. CAISO procures in the day-ahead market and hour-ahead market (Zhou et al., 2016), while Transpower holds a yearly tender for long-term contracts (Transpower, 2013). According to Transpower (2013), the procurement costs are €46.7 million per year.

3. In Europe, three main categories of reserves exist: (1) Frequency Containment Reserves (FCR), which is used for stabilizing the frequency after a disturbance; (2) Automatic and Manual Frequency Restoration Reserves (aFRR and mFRR), which bring the frequency back to its setpoint value; and (3) Reserve Replacement (RR), which replace the active reserves such that they are available to react to new disturbances (European Commission, 2017b). These three types are called primary, secondary and tertiary reserves in North America (Ela et al., 2011).

4. The activation period, also called settlement period, can be 15 minutes, 30 minutes or 1 hour depending on national market design characteristics. This should be standardized for cooperating TSO zones. According to Neuhoff and Richstein (2016), convergence to the largely used 15 minutes period is supported by most.

ding process where both the procured reserve capacity and available non-procured capacity submit balancing energy bids. Bids are accepted by financial merit order to meet the real-time imbalance or reserve need r_t of the system. Accepted positive bids increase their generation, while accepted negative bids decrease their generation. In return, they receive the activation price p_{act}. In the illustration of Figure 1, bid 2, part of bid 3 and an additional non-procured bid are accepted in the activation phase to meet the real-time imbalance r_t.[5,6]

Both generation and demand could voluntarily participate in balancing markets, i.e. in both procurement of reserve capacity and activation of balancing energy. However, if the upward reserve need is so large that available reserves are insufficient, the TSO will undertake controlled load-shedding as a last resort to avoid a blackout.

2.1 Cross-border balancing

Under the impulse of increasing renewable energy integration, supranational legislation (European Commission, 2017a,b), and a general drive for more cost efficiency and reliability, some TSOs have started to coordinate electricity balancing between neighboring TSO zones. Often cited benefits of cross-border balancing include a more efficient use of electricity generation, including reduced renewable energy curtailment (Mott MacDonald, 2013); reduced reserve needs (NREL, 2011); a higher reliability level (Van den Bergh et al., 2017); internalization of external effects on neighboring TSOs (Tangerås, 2012); a standardization of the rules and products, which creates a level-playing field; and improved market liquidity, which increases competition[7] (Hobbs et al., 2005; Newbery et al., 2016). In the end, all these benefits decrease the cost of balancing. This paper focuses on the first two of the above-mentioned benefits:

(A) **Supply efficiency**: balancing services, both procurement of reserve capacity to meet reserve requirements and activation of balancing energy to meet real-time imbalances, are supplied by the cheapest balancing service providers. That is, if the market is enlarged, expensive balancing services in one part of the market can be substituted for cheaper ones in a different part of the market. The scope for supply efficiency depends on the difference of procurement and activation costs between cooperating TSO zones.

(B) **Dimensioning efficiency**: less procurement of reserve capacity is needed if a TSO in need of capacity can use idle reserve capacity of adjacent TSO zones.

Cross-border cooperation yields benefits both in procurement of reserve capacity and activation of balancing energy. Table 1 shows the different degrees of cooperation that are possible in procurement and in activation.

First, the three degrees of cooperation in procurement of reserve capacity are autarky, exchange and sharing. Reserves exchange makes it possible to procure part of the required level of reserves in adjacent TSO zones. These reserves are contractually obliged to be available for activation by the contracting TSO and they can only contribute to meeting this TSO's required level of reserves. Reserves exchange changes the geographical distribution of reserves. More reserves are

5. An alternative to merit order activation is pro rata activation. In that case all procured reserves are activated but in proportion to their relative procurement bid size.

6. In many TSO zones procurement and activation are more complex than presented here. For example, some TSOs co-optimize the market clearing of different types of reserves or assess the reserve capacity bid and the balancing energy bid jointly (50Hertz Transmission GmbH et al., 2014).

7. The level of concentration (CR3) in the market for reserve capacity is 100% in Belgium, France, Netherlands and Portugal, around 80% in Spain and 70% in Germany (ACER, 2015).

Table 1: Degrees of cooperation in cross-border balancing between TSO zones

PROCUREMENT of reserve capacity	ACTIVATION of balancing energy
To meet the reserve requirements resulting from reserve dimensioning	To meet real-time imbalances resulting from forecast errors and unforeseen events
Autarky: no cross-border cooperation **Exchange**: procure reserves in other zones **Sharing**: multiple zones take into account the same reserves	**Autarky**: no cross-border cooperation **Imbalance netting**: avoid counteracting activation **Exchange**: activate reserves in other zones

procured in cheap TSO zones and less in expensive TSO zones. Reserves exchange increases supply efficiency by decreasing the procurement costs.

Reserves sharing allows multiple TSOs to take into account the same reserves to meet their reserve requirements resulting from reserve dimensioning.[8] A TSO in need of balancing energy can use this shared capacity, if other TSOs do not. Reserves sharing leads to both supply efficiency and dimensioning efficiency.

Second, the three degrees of cooperation in activation of balancing energy are autarky, imbalance netting and exchange. Imbalance netting avoids counteracting activation of balancing energy in adjacent TSO zones. For example, activating upward reserves in response to a negative imbalance in one TSO zone, and separately activating downward reserves in response to a positive imbalance in another TSO zone, is inefficient since counteracting imbalances naturally net out on synchronous networks. A simple coordination of imbalances could avoid this inefficiency. Imbalance netting is a constrained version of exchange of balancing energy.

Exchange of balancing energy is a further degree of cooperation in activation of balancing energy. It implies that cooperating TSOs construct a common merit order of balancing energy bids and select the least-cost activation that meets the net imbalance of the joint TSO zone.[9] Imbalance netting and exchange of balancing energy increase supply efficiency by decreasing the activation costs.

Although in the remainder of this paper, we only study procurement of reserve capacity, it should be noted that activation is a prerequisite for implementing reserves sharing. It only makes sense to decrease the total amount of procured capacity if balancing energy is activated based on a common merit order and imbalances are netted out. Exchange of reserve capacity, however, is possible without cooperation in activation.

2.2 Examples of cross-border balancing

Balancing and reserve cooperation between TSOs is still in its infancy. However, a few examples of successful cooperation exist in Europe and in the United States.

In Europe, ENTSO-E is reviewing a number of pilot projects with the aim to test the feasibility of a multi-TSO cooperation on the cross border procurement of reserve capacity and activation of balancing energy. First, the International Grid Control Cooperation (IGCC) is a project of imbalance netting of frequency restoration reserves (FRR) to avoid counteracting activation of

8. In practice, reserves exchange and sharing is not limitless.Baldursson et al. (2016) summarize the limits on reserves exchange and sharing, as imposed by the EU guideline on electricity transmission system operation(European Commission, 2017a).

9. Other market arrangements, like BSP-TSO and an additional voluntary pool, are also possible (Doorman and Van der Veen, 2013).

balancing energy. The IGCC was launched in 2012 and currently consists of TSOs from Austria, Belgium, Czech Republic, Denmark, France, Germany, the Netherlands and Switzerland. Second, a part of this group of countries (Austria, Belgium, France, Germany, the Netherlands and Switzerland) also jointly procure frequency containment reserves (FCR) in a weekly auction. Third, the Trans-European Replacement Reserves Exchange (TERRE) is established between UK, France, Great Britain, Greece, Italy, Spain, Portugal and Switzerland. The project aims to jointly activate replacement reserves (ENTSO-E, Accessed: 1st of August 2016; Neuhoff and Richstein, 2016). A fourth example of TSO cooperation is the Regulating Power Market (RPM), which was established in 2002 between Denmark, Finland, Norway and Sweden. The RPM is a common merit order of manual frequency restoration reserves (mFRR) activation.

In the United States, a cross-border energy imbalance market (EIM) was established between CAISO and PacifiCorp in November 2014. As of 2017 the cross-border EIM consists of five network operators and public utilities in eight states.[10]

3. BENEFITS OF CROSS-BORDER RESERVES PROCUREMENT

In this section we derive analytical expressions for the optimal level of procured reserves and study the associated cost decreases. Each degree of cross-border cooperation is analyzed: autarky, reserves exchange and reserves sharing.[11]

3.1 Model

This model studies two TSO zones $i=1,2$ that can either not cooperate (autarky), exchange reserves or share reserves. The need for reserves in TSO zone i at a certain instant is denoted by a random variable r_i [MW]. This is the real-time imbalance between supply and demand due to a combination of forecast errors of demand and intermittent supply, and failures of generation capacity or transmission components. We denote the joint probability density function of the reserve needs by $f(r_1,r_2)$ and the marginal density functions of r_1 and r_2 by f_1 and f_2 respectively.[12] The TSO's variable of choice is R_i [MW], the quantity of reserves procured for its own zone i. The contracting period for the procurement of reserve capacity could be e.g. an hour, a week, a month, or a year. In the model we only focus on procurement of upward reserves. Negative reserve procurement is the mirror analysis and its equations are similarly interpreted.

In this paper we are interested in efficiency gains from exchange or sharing of reserve procurement, not efficient activation as such. Hence, the model does not take reserves activation into consideration and we therefore take marginal generation costs to be equal to zero. Costs of procuring R_i of reserve capacity in TSO zone i, however, are not zero and are given by $\gamma_i(R_i)$, with γ_i increasing, smooth and convex.

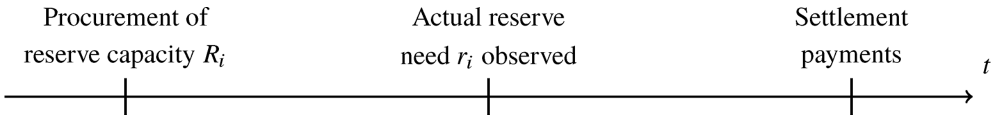
Figure 2 summarizes the order of events. First the TSO at each node i chooses how much reserve capacity R_i to procure. In case of exchange or sharing of reserves, the procurement may entail payments between TSOs. Next, in real time, the actual need for reserves r_i is observed in each

10. According to (CAISO, 2017), the benefits amounted to \$254.98 million between 2014Q4 and 2017Q3 and are expected to increase even more in the future with an increased share of renewable generation.

11. Transmission constraints are an important issue affecting power grids. In this section we assume, as a first approximation, that there is enough transmission capacity available to accommodate the flows arising from balancing. The effect of transmission constraints on reserves exchange is estimated in section 4.

12. The joint probability density function $f(r_1, r_2)$ will in general depend on the procurement interval and the time to real-time operation.

Figure 2: Order of events



node *i*. The procured reserves will be used to accommodate the reserve needs. In case local reserves are insufficient, TSOs will use exchanged or shared reserves, or, as a last resort, carry out load shedding. Last, settlement payments—if any—are made.

3.2 Optimal autarkic TSO reserve provision

We first consider the case where there is no trade or exchange of reserves between zones. We consider the first-best outcome where TSO *i* procures a quantity of reserves R_i such that expected social surplus in Zone *i* is maximized.[13] We assume the value of lost load (VoLL—measured in €/MWh) is fixed at v and that electricity demand D_i is price inelastic and also valued at v. Hence, for a given level of reserve needs r_i and procured reserves R_i social surplus is given by consumer surplus net of costs of interruptions (due to unserved demand) and costs of procuring reserves,

$$S_i = vD_i - v[r_i - R_i]^+ - \gamma_i(R_i). \tag{1}$$

The TSO selects R_i to maximize $E[S_i]$ with respect to R_i

$$\max_{R_i}\left\{vD_i - v\int_{R_i}^{\infty}[r_i - R_i]f_i(r_i)dr_i - \gamma_i(R_i)\right\} \tag{2}$$

Equivalently, since demand is inelastic, the TSO can minimize combined costs of interruptions and reserves, i.e.

$$\min_{R_i}\left\{v\int_{R_i}^{\infty}[r_i - R_i]f_i(r_i)dr_i + \gamma_i(R_i)\right\}. \tag{3}$$

This is the approach we shall use henceforth. Differentiating (3) we derive the following first-order condition for the optimal quantity of reserves R_i^a in autarky:

$$v\Pr\{r_i > R_i^a\} = \gamma_i'(R_i^a). \tag{4}$$

The condition (4) is very intuitive: reserves should be procured up to the point where the marginal cost of procurement (right-hand side) is equal to the marginal cost of interruptions (left-hand side). The left-hand side might be interpreted as VoLL times the loss of load probability (LoLP). The second-order condition for minimum is easily seen to be satisfied.

13. In reality, network codes and guidelines stipulate the quantity of reserves each TSO zone is required to procure. For example, European Commission (2017a) requires that the reserve capacity on FRR or a combination of reserve capacity on FRR and RR is sufficient to cover the imbalance for at least 99% of the time. Such an exogenous requirement is also standard in reliability management of the day-ahead market, where the N-1 reliability criterion is used instead of balancing the costs of reliability and interruptions (Ovaere and Proost, 2016). If the reserve requirements of network codes diverge from this first-best optimum (e.g. due to imperfect information or socio-political constraints), costs are higher than in the first-best.

3.3 Reserves exchange

We now turn to the case of reserves exchange, which makes it possible to procure part of the required level of reserves in adjacent TSO zones. In this section we assume that sufficient transmission capacity is available to accommodate the flows arising from use of reserve capacity in adjacent TSO zones and thus neglect any limits transmission capacity constraints would place on reserves exchange.[14] That is, there is only load-shedding if $r_i > R_i$, irrespective of where the reserve capacity is procured. We assume that procurement costs are not symmetrical so there is a motive for reserves exchange.

This sections shows that exchange of reserves only leads to supply efficiency, not dimensioning efficiency. We study two variants of reserves exchange. First, that the required level of reserves in each TSO zone is the same as in autarky (regulated reserve levels); and second, that it is adjusted in accordance with procurement prices of reserves exchange (locally optimal reserve levels).

3.3.1 Regulated reserves levels

In accordance with the EU guideline on electricity transmission system operation (European Commission, 2017a) we assume, that the required level of reserves in each TSO zone is the same as in autarky, i.e. R_i^a.

In the first-best solution for this setting the two TSOs jointly minimize total costs of procurement, subject to the constraint on reserves. That is, the cheapest reserve capacity in the two TSO zones is procured first. This amounts to the following constrained cost minimization

$$\min_{R_1,R_2} \{\gamma_1(R_1)+\gamma_2(R_2)\} \text{ s.t. } R_1 + R_2 = R_1^a + R_2^a \tag{5}$$

where R_i denotes the combined quantity of reserves procured in Zone i by the two TSOs. The side constraint states that the overall quantity of reserves procured has to equal the sum of the required reserve levels in the two zones. The solution to this minimization problem indicates that overall costs are lowest when the marginal cost of reserve procurement is equal in the two TSO zones.

$$\begin{cases} \gamma_1'(R_1) = \gamma_2'(R_2) \\ R_1 + R_2 = R_1^a + R_2^a. \end{cases} \tag{6}$$

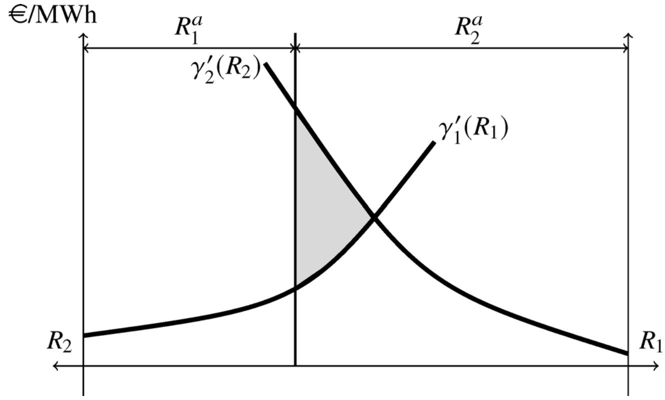
Figure 3 shows this cost minimization graphically. The axis runs from left to right for TSO zone 1 and from right to left for TSO zone 2. The upward sloping lines are the marginal procurement costs in Zone 1 and 2. Clearly, if costs are symmetrical in the two zones, then there is no reason to exchange reserves and the optimal solution is for each TSO to procure reserves within his own zone. If costs are asymmetrical, then there is a rationale for exchange. The gray area in the figure represents the reduction of procurement costs under the optimal procurement of reserves as compared to the costs in autarky where exchange is not possible and each zone supplies its own required reserves.

3.3.2 Locally optimal reserves levels

The regulatory reserve levels in our model were set so as to match marginal costs of interruptions and reserves, however after opening up for exchange the resulting outcome is no longer an

14. The effect of transmission constraints on reserves exchange is estimated in section 4.

Figure 3: Cost minimization under reserves exchange between two TSO zones



optimum: marginal interruption costs no longer match marginal costs of procuring reserves; it will be tempting to lower required reserves in the cheaper zone, where marginal procurement costs have risen, and raise them in the more expensive zone, where they have fallen. Therefore we analyze another scenario where TSOs are allowed to adjust their reserves levels in accordance with prices.[15]

We begin by considering the first-best solution for the present setting. This involves finding the jointly optimal reserve levels, viz. solving

$$\min_{R_1,R_2,R_1^e,R_1^e \ s.t.\ R_1+R_2=R_1^e+R_2^e} \left\{ \sum_{i=1}^{2} v \int_{R_i^e}^{\infty} [r_i - R_i^e] f_i(r_i) dr_i + \sum_{i=1}^{2} \gamma_i(R_i) \right\} \tag{7}$$

where R_j is the amount of reserves procured in Zone j (as before) and R_i^e is the amount of reserves procured by TSO i. The optimal solution in this case is determined by the condition that all marginal costs be equal, both across zones and cost types.[16]

3.4 Reserves sharing

Reserves sharing allows multiple TSOs to draw on the same reserves resources to meet their required level of reserves when it comes to operation. While exchange of reserves leads only to supply efficiency, reserves sharing leads to both supply efficiency and dimensioning efficiency. As before, we assume that transmission capacity is sufficient to always accommodate the flows arising from use of reserve capacity in adjacent TSO zones. That is, there is only load-shedding if $r_1 + r_2 > R_1 + R_2$.

In our model, reserves sharing amounts to maximizing the surplus of both zones jointly. Since we take demand to be inelastic, this is tantamount to minimizing expected costs of interruptions and procurement:

15. This would seem likely to be the tendency over the longer run.

16. For simplification we have assumed the VoLL (v) to be identical across zones. In some adjacent markets, e.g. in the EU, estimations of VoLL differ (Ovaere et al., 2016). Different VoLL can easily be taken into account, but would slightly complicate the analysis without significantly changing results. Specifically, the condition that marginal costs of interruption is the same across zones would continue to hold, but the expression for it would change: (Here an expression where v is replaced by v_1 in the first MC and by v_2 in the second MC.) In particular, the LoLP would be higher in the zone with the lower VoLL and vice versa

$$\min_{R_1^s, R_2^s} \left\{ v \int_0^\infty \int_{R_1^s + R_2^s}^\infty [r_1 + r_2 - R_1^s - R_2^s] f(r_1, r_2) dr_1 dr_2 - \gamma_1(R_1^s) - \gamma_2(R_2^s) \right\} \quad (8)$$

The optimal reserve capacities when reserves sharing is allowed, R_1^s and R_2^s, are determined from respectively differentiating (8):[17]

$$v \Pr\{r_1 + r_2 > R_1^s + R_2^s\} = \gamma_1'(R_1^s) = \gamma_2'(R_1^s) \quad (9)$$

The first-order conditions imply that marginal costs of reserves procurement are equal to VoLL times the loss of load probability in the two zones together. Clearly, this implies that marginal costs of procurement are equal at the optimal levels of procurement, $\gamma_1'(R_1^s) = \gamma_2'(R_2^s)$. Hence, the costs of reserves procurement are minimized as in reserves exchange, but for different levels of reserves and, hence, also reliability.

3.5 Efficiency of different degrees of cooperation

To compare the efficiency of the different degrees of cooperation, we need to compute the total costs c^j for each degree of cooperation $j \in \{a, e, l, s\}$. It leads to the following proposition.

Proposition 1 *Each step in the integration of zones results in progressively lower expected costs, i.e.* $c^a \geq c^e \geq c^l \geq c^s$.

The proof is presented in Appendix A.

Moving from autarky to exchange with regulated reserve levels leads to lower procurement costs but leaves interruption costs unchanged, because the reliability level is held fixed. Exchange with locally optimal reserve levels increases procurement costs but less than the decreases of interruption costs. A thing to notice is also that moving from autarky to locally optimal exchange has an ambiguous effect on procurement costs because the cost increase of a higher reliability level can exceed the cost decrease of reserves exchange. The cost decrease depends on the cost asymmetry between procurement costs in both TSO zones. Last, reserves sharing leads to an even higher reliability level and thus interruption costs decrease. As before, its effect on procurement costs is ambiguous and depends on the correlation of reserve needs in TSO zones.

3.6 Numerical illustration and comparative statics

The benefits of cross-border exchange and sharing of reserve capacity depend on two parameters: the difference in procurement cost in both TSO zones (g_1 and g_2) and the correlation of reserve needs between TSO zones (ξ=corr(r_1,r_2)). Supply efficiency increases if procurement costs are more asymmetric and dimensioning efficiency increases if reserve needs are less correlated. Figure 4 plots the sum of interruption costs and procurement costs with reserves exchange and sharing, relative to the costs in autarky, and shows that the benefits of exchange increase with cost asymmetry (g_1 / g_2) and that the benefits of sharing increase with decreasing reserve need correlation ξ. The probability density functions of reserve needs are jointly normal with correlation ξ, each with a mean of 0 MW and a variance of 100 MW: N(0,100). The cost of reserve procurement in Zone i is $\gamma_i(R_i) = g_i R_i^2$, with $g_1 = g_2 = 1$ at $g_1 / g_2 = 1$. The VoLL is 10,000 €/MWh.

17. As in the case of exchange, different VoLL can easily be taken into account, see footnote 16 above.

Figure 4: Relative cost of reserves exchange and reserves sharing, as a function of the cost asymmetry (g_1 / g_2) and the reserve needs correlation (ξ)

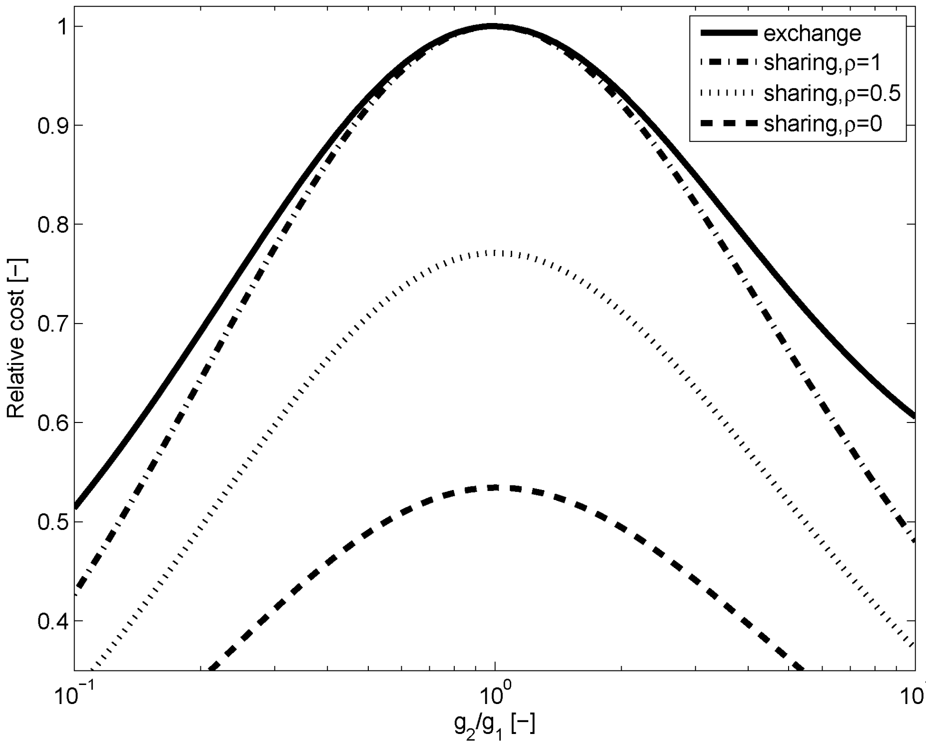


Figure 4 illustrates several issues. First, when the two TSO zones have identical procurement costs, no cost arbitrage is possible and exchange of reserve does not yield any cost reduction. However, reserves sharing leads to a lower reserve need and thus a lower cost. Second, when the cost of reserve procurement differs between TSO zones, reserves exchange does yield a cost reduction. For example, when the cost of reserve procurement is higher in TSO zone 1, TSO 1 procures part of its reserve obligation with reserve capacity providers in TSO zone 2. Third, the cost reduction decreases when the reserve needs in the two TSO zones are more correlated. When the reserve needs are fully correlated, reserves sharing yields almost no additional cost reduction compared to reserves exchange.

Figure 4 also illustrates that the cost reduction increases when reserve procurement costs become more asymmetric and reserve needs are less correlated. With low cost asymmetry and low correlation, reserves sharing yields the major part of the cost reduction, while with high cost asymmetry and a high correlation, reserves exchange yields the major part of the cost reduction. With symmetric costs and high correlation, cross-border cooperation in reserves yields very little cost reduction.

In addition to cost asymmetry and the reserve needs correlation, three other parameters influence relative costs of reserves exchange and sharing: VoLL (v), procurement costs, and the relative size of the TSO zones. Table 2 compares the relative cost of a base case ($g_1 = 2, g_2 = 1$) with a case with higher VoLL, a case with higher procurement costs, and a case where countries differ in size. First, the relative gains of cooperation increase with increasing VoLL, since both the gains

Table 2: Sensitivity of costs, relative to the costs in autarky [%]

	BASE	$v=10v_{base}$	$g_i=10g_{i,base}$	$\sigma_1=6\sigma_{base}$
Autarky	100	100	100	100
Exchange	93.2	92	95.5	96.7
Sharing $\xi=1$	92.2	91.2	94.0	96.1
Sharing $\xi=0.5$	71.2	69.9	73.9	85.4
Sharing $\xi=0$	49.4	48.0	52.4	74.6

of decreased interruption costs and decreased procurement costs are higher.[18] Second, higher procurement costs decrease the relative gains of cooperation. Third, if the TSO zones differ in size[19] the relative gains of cooperation decrease. As before, relative costs of reserves sharing decrease with decreasing reserve need correlation ξ.

4. ESTIMATION OF THE PROCUREMENT COST DECREASE OF CROSS-BORDER PROCUREMENT

While the previous section presented a small numerical illustration to show the effect of reserve needs correlation and of asymmetry of procurement costs, this section estimates the possible cost decrease of cross-border procurement of automatic frequency restoration reserves (aFRR)[20] between Belgium, France, Germany, the Netherlands, Portugal and Spain. As discussed in section 2.2, Belgium, France, Germany and the Netherlands have already implemented imbalance netting and jointly procure frequency containment reserves (FCR) in a weekly auction. However, they do not yet jointly procure aFRR. This section shows that the gains of exchanging and sharing aFRR are substantial. Our estimation differs from earlier studies (see section 1), because it is not based on simulation but based on actual market data. To our knowledge, the only exception is Vandezande et al. (2009) who estimate the cost decrease of a Belgium-Netherlands cross-border balancing market in 2008. Our study, however, estimates the cost decrease of cross-border exchange and sharing of aFRR for 2015–2016 in different subsets of Central West Europe (CWE) and Iberia.[21]

4.1 Data

We use price and quantity data of aFRR procurement in Belgium, France, Germany,[22] the Netherlands, Portugal and Spain.[23] For each considered country i and for each time instant t, these consist of a price p_{it} [€/MWh] and procured capacity R_{it} [MW]. Detailed analysis of these data can be found in Appendix B.

18. Note that decreasing the cost coefficients g_i leads to exactly the same relative costs, as can be seen from (4) and (9), but to absolute costs that are an order of magnitude lower.

19. The relationship between the size of a TSO zone and its reserve need standard deviation σ is not linear because larger countries already internalize their imbalance variability. If the correlation of reserve needs between regions of a TSO zone 1 is ξ_1 and this zone is 2^n times larger than an adjacent TSO zone 2, then $\sigma_1=(\sqrt{2(1+\xi)})^n\sigma_2$. If $\xi_1=0.65$, $\sigma_1=6\ \sigma_2$.

20. aFRR is used to bring the frequency back to its setpoint value in case of imbalances.

21. German TSOs already exchange aFRR capacity since December 1th 2007.

22. German data also contain Luxembourg.

23. The data are publicly available on the ENTSO-E Transparency Platform since the end of 2014. To supplement and check the data, we have also used websites of the TSOs in the six countries. For example, German data of marginal prices comes from www.regelleistung.net, the platform for cooperation between the four German TSOs.

Figure 5: Marginal price of aFRR in Belgium, France, Germany, the Netherlands and Spain (01.01.2015–31.12.2016)

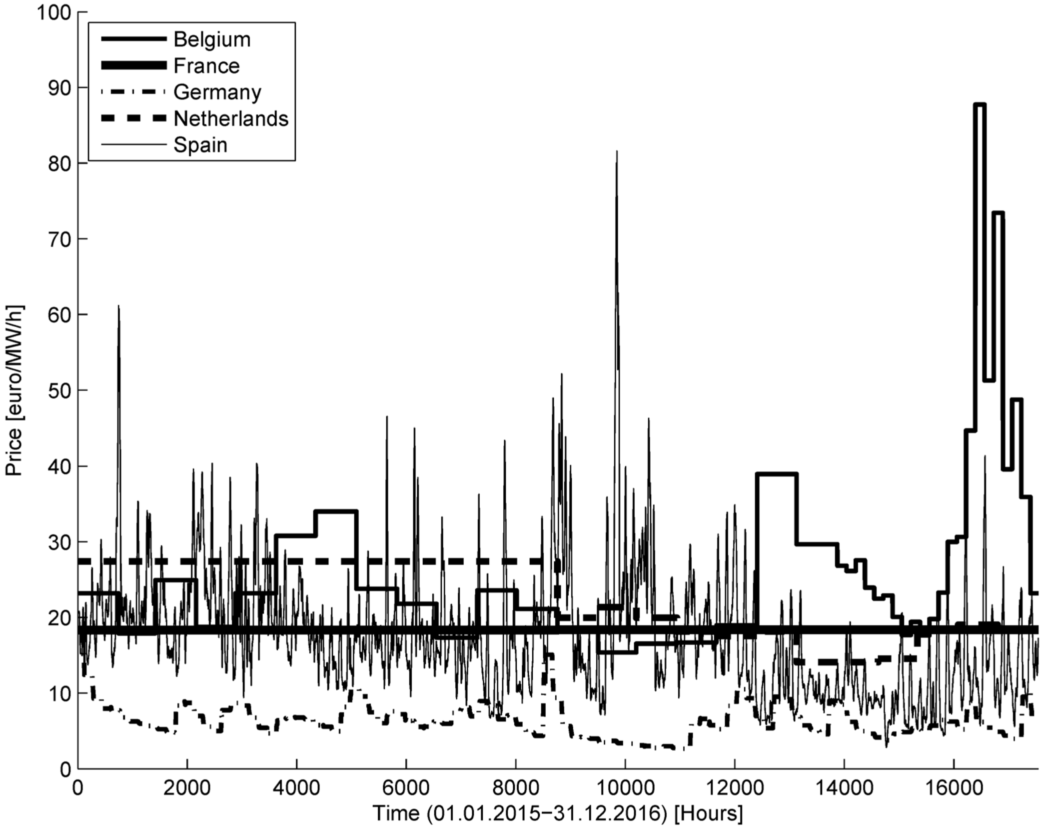


Figure 5 shows the marginal prices of aFRR in Belgium, France, Germany, the Netherlands and Spain for all hours from 01.01.2015 to 31.12.2016.[24] As the hourly data of Germany and Spain is volatile, we report their 24-hour moving average. The price of the yearly auction in France is almost the same throughout the assessed period, while the prices in the Netherlands are constant and above French prices in 2015 but decrease in 2016, after moving to monthly auctions. Belgium, which went from monthly to weekly auctions after August 2016, saw a price spike at the end of 2016. This figure also shows that, except for Germany, price lines cross constantly. As a result, no single country is the most expensive at all times. In Germany, prices are almost consistently lower than in the other five countries.

Table 3 presents the correlation coefficients between imbalances in the six considered countries. These values are statistically different from zero at the 0.0001% level, except for the correlation between Netherlands and France, Portugal and Spain. As none of these country-pairs has a high positive correlation, significant efficiency gains of reserves sharing are possible.

A last piece of data are day-ahead energy prices in the six considered countries from 01.01.2015 to 31.12.2016. Table 4 shows the percentage of hours that the price difference on the six borders in the day-ahead energy market is (i) equal to zero or above respectively zero, one and

24. Portuguese prices are not shown because they are close to the prices in Spain. Prices in Portugal and Spain have correlation coefficient of 0.7 for 2015–2016.

Table 3: Correlation coefficients between imbalances in the six considered countries (aFRR)

	Belgium	France	Germany	Netherlands	Portugal	Spain
Belgium	1					
France	0.068	1				
Germany	–0.122	–0.035	1			
Netherlands	–0.160	–0.005	0.094	1		
Portugal	–0.026	–0.08	0.029	0.006	1	
Spain	–0.038	–0.051	0.060	0.005	–0.019	1

Table 4: The percentage of hours that the price difference on the six borders in the day-ahead energy market is (i) equal to zero or above zero, one and three €/MWh and (ii) has the same sign as the price difference in the reserves procurement market.

	$\Delta p_{DA}=0$	$\Delta p_{DA}\geq 0$	$\Delta p_{DA}\geq 1$	$\Delta p_{DA}\geq 3$
Belgium-Netherlands	43.8	23.3	8.5	1.7
Germany-Netherlands	36.7	57.5	22.9	2.6
Belgium-France	45.4	36.6	10.9	1.7
France-Germany	34.2	32.5	10.0	0.5
France-Spain	22.2	26.6	15.9	1.9
Spain-Portugal	94.5	3.6	0.4	0

three €/MWh and (ii) has the same sign as the price difference in the reserves procurement market. The first column shows that only on the SP-PT border, prices converged almost always. On the other borders, prices converged between 45% (BE-FR) and 22% (FR-SP) of the time, but the next three columns show that if the price difference in the reserves procurement market and the energy market have the same sign, the price difference is limited and almost always below 3 €/MWh. The energy prices are used to approximate transmission constraints, as explained in the next section.

4.2 Methodology

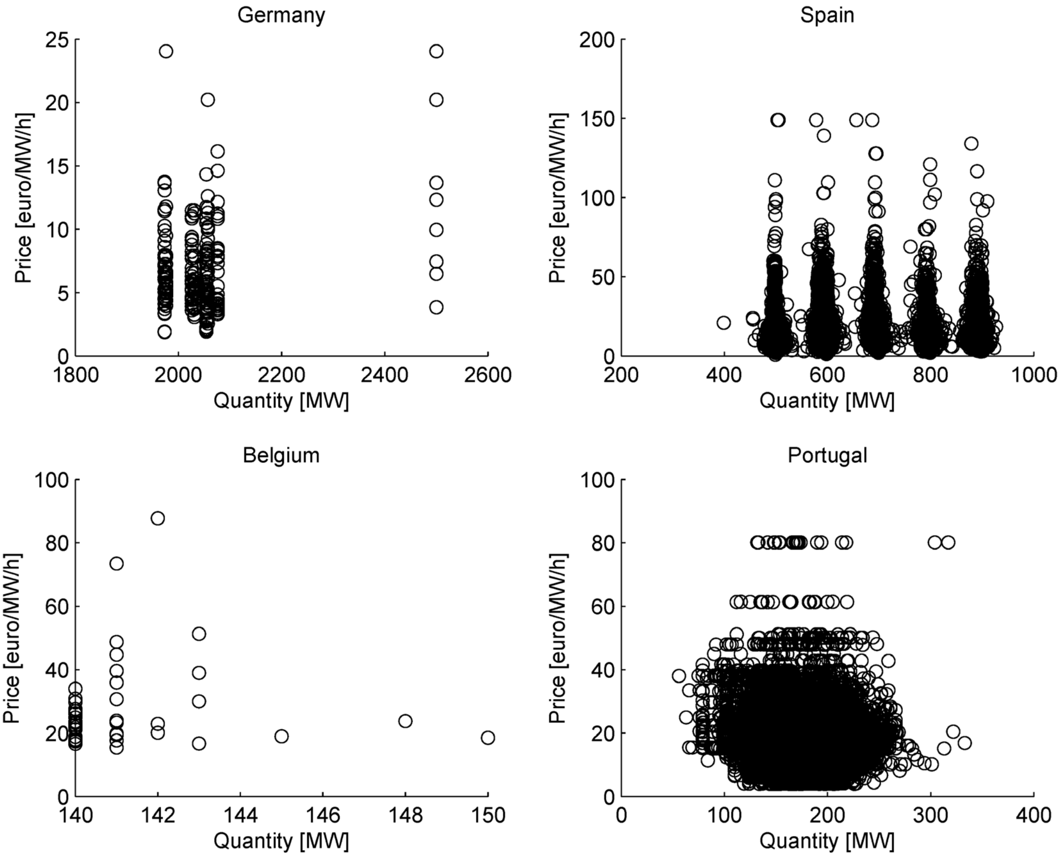
First, we need to make an assumption on the functional form of the supply curves of generation reserves. Our only available information is the price-quantity pair for each of the 17544 hours for each country. Figure 6 plots these points for Germany, Spain, Belgium and Portugal. These plots clearly show that the supply curve is not constant throughout the period. Therefore, as there is only one price-quantity pair for each hour, we assume that for each considered country i and for each hour t the supply curve is linear between the origin and (R_{it}, p_{it}):

$$b_{it} = \frac{p_{it}}{R_{it}} \tag{10}$$

Second, in our dataset some countries report the average price while others the marginal price. As we assume supply to be linear, marginal prices are assumed to be twice the average price.

Third, transmission constraints can limit cross-border cooperation. For the estimation of the procurement cost decrease due to reserves exchange, transmission constraints are taken into account by imposing that, if the trade flow in the energy market and the reserves procurement market are in the same direction, cross-border trade is only possible if the price difference in the reserves

Figure 6: Scatterplot of procurement price and quantity for Germany, Spain, Belgium and Portugal (01.01.2015–31.12.2016)



market is above the price difference in the energy market. That is, we equate the marginal benefit of trade in energy and reserves. This approach neglects the effect of reserves on the energy market, but this approximation does not significantly alter the results, as the reserves market is small compared to the energy market.

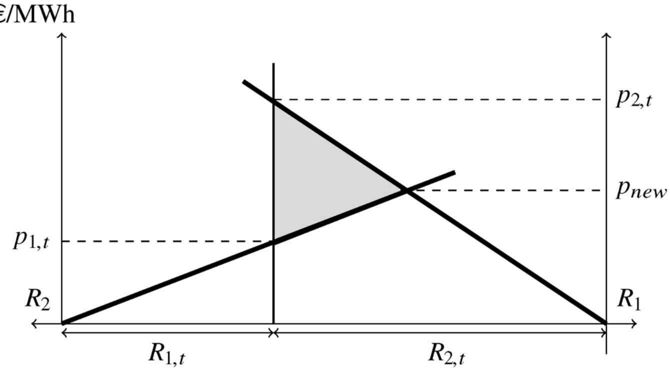
In addition to transmission constraints, we assess institutional constraints on cross-border trade. The European Commission (2017a) imposes that minimally 50% of required aFRR should be in the own country (exchange) and that required aFRR capacity cannot decrease more than 30%, compared to the autarkic level (sharing) (Baldursson et al., 2016). For reserves sharing, only the institutional limits are assessed. As sharing requires that sufficient transmission capacity is available between cooperating countries,[25] transmission constraints can not be assessed.

4.2.1 Reserves exchange

The procurement cost decrease of reserve capacity exchange can be calculated using equation (6) in the case of two countries. Figure 7 shows their supply curves and the cost decrease is represented by the gray area. Generalizing this to exchange of generation reserve capacity between n countries, the common marginal price of procurement p_{new} for each hour t is:

25. The left-hand side of equation (10) implies that the marginal procurement prices are equal.

Figure 7: The procurement cost decrease of reserves exchange between two countries



$$p_{new} = \frac{\prod_{i=1}^{n} b_i}{\sum_{i=1}^{n} \prod_{j \neq i}^{n} b_j} \sum_{i=1}^{n} R_i \qquad with \qquad b_i = \frac{p_i}{R_i} \tag{11}$$

As the supply slopes are assumed to be linear, the decrease of procurement costs ΔPC due to cross-border exchange of generation reserve capacity for each hour t is:

$$\Delta PC = 0.5\left(\sum_{i=1}^{n} R_i p_i - p_{new} \sum_{i=1}^{n} R_i \right) \tag{12}$$

where p_i and q_i are the actual price and procured quantity in country i, and p_{new} is the price determined by the common merit order and the total procured quantity of the n countries that are exchanging reserves.

To incorporate transmission constraints between the six European countries, we reformulate the Matpower tool (Zimmerman et al., 2011) such that it minimizes the cost of the linear supply curves subject to the additional constraints on price differences between countries.

4.2.2 Reserves sharing

The gains from sharing of generation reserve capacity between n countries are calculated using the following expression:

$$v \Pr\left\{ \sum_{i=1}^{n} r_i > \sum_{i=1}^{n} R_i^s \right\} = p_{new} \tag{13}$$

where p_{new} is calculated from (11) and the value of lost load (VoLL) v is assumed to be 10,000 €/MWh.[26] It shows that the total reserve capacity of n reserve-sharing countries is optimal when the marginal expected interruption cost (left-hand side) equals the marginal cost of reserves (right-hand side). The country in which these reserves are procured depends on the countries' individual supply curves.

26. This expression is the n-country generalization of first order conditions obtained in Section 3.4.

The cumulative distribution function of aggregate imbalances in n countries is estimated based on the imbalance data r_{it} of 2015–2016. We see in the data that the probability distribution function of imbalances is a symmetrical bell-shaped curve with mean slightly above zero and fatter tails than the normal distribution.[27]

Again, we estimate the equation for each hour separately, which means that the total procured reserve capacity differs every hour, depending on p_{new}.[28] The higher this price, the lower the procured reserve capacity.

The decrease of procurement costs from cross-border sharing of generation reserve capacity is also calculated using equation (12). However, as we can not make statements about the optimality of actual aFRR capacity that is currently procured in each of the six countries,[29] we will calculate the cost decrease relative to optimal autarkic reserves procurement, i.e. according to equation (4).

As noted before, European Commission (2017a, art. 157.(2)(h)) requires that the sum of procured aFRR, mFRR and RR should be sufficient to cover 99% of all imbalances. As we only study aFRR, but still need to link procured capacity to system imbalances to calculate the gains of aFRR sharing, the imbalance data are scaled by the ratio of average procured reserve capacity (R_{av}) and the required reserve capacity to cover 99% of all imbalances ($r^+_{99\%}$). This means that for all countries, except for Germany, the imbalance data are scaled down.

4.3 Results

4.3.1 Cost decrease due to reserves exchange

Table 5 presents the estimated decrease of procurement costs [million € per year] due to exchange of positive aFRR between different sets of countries. Note that we do not focus on the cost of activation and do not estimate the change of interruption costs (see section 3.6). The first three columns present results for 2015, while the last three columns present results for 2016. For 2015, we estimate a procurement cost decrease of two-country reserves exchange of less than €1 million (Belgium-France and Belgium-Netherlands) up to €19 million (France-Germany). Gains are higher for 2016, except for Germany-Netherlands, as Dutch prices decreased in 2016. Evidently, the gains increase when more countries are cooperating. For three-country reserves exchange, the procurement cost decrease is estimated to be less than €4 million (Belgium-France-Netherlands) up to €16–26 million (Belgium-Germany-Netherlands). The gains due to exchange between Belgium, France and Netherlands are limited because their procurement costs are similar. But, when these countries exchange reserves with Germany, where costs are low, significant gains are possible. If all CWE countries exchange reserves, the estimated benefits are around €40 million per year. If all six countries exchange reserves, they are above €60 million per year. The effect of the institutional constraint on estimated gains is limited to a few million €. The transmission constraints, however, have a significant effect on estimated gains, especially if the price difference in the energy market is large and in the same direction as the price difference in the reserves market, like the GE-NL border.

27. In reality, obviously, it is estimated based on historical data, but since only little imbalance data prior to 2015 is available on the ENTSO-E Transparency Platform, we use the complete 2015–2016 imbalance data for our 2015–2016 estimation. This should not greatly influence our estimation results.

28. To simplify the procurement auction in reality, TSOs might choose $\sum_{i=1}^{n} R_i^s$ for a longer period, which decreases the possible gain.

29. As the optimal trade off minimizes the sum of procurement and interruption costs, procurement costs can both increase or decrease when moving from the currently procured aFRR capacity to the optimal quantity with sharing.

Table 5: Efficiency gains [M€] from exchange of aFRR for different sets of countries

	2015			2016		
[M€]	(1)	(2)	(3)	(1)	(2)	(3)
Belgium-France	0.88	0.88	0.63	2.89	2.77	2.53
Belgium-Netherlands	0.70	0.70	0.67	2.73	2.68	2.44
Belgium-Germany	7.13	6.36	3.81	10.59	9.01	6.53
France-Germany	18.94	17.88	11.61	24.37	22.20	14.56
France-Spain	6.68	6.64	5.66	9.74	9.55	8.62
Germany-Netherlands	19.44	17.23	13.29	6.46	5.77	3.63
Portugal-Spain	1.61	1.60	1.60	1.88	1.85	1.84
France-Portugal-Spain	7.63	7.59	6.84	11.19	11.01	10.25
Belgium-France-Netherlands	3.58	3.58	1.76	3.24	3.10	2.25
Belgium-Germany-Netherlands	26.05	23.29	17.87	16.80	14.64	9.60
Belgium-France-Germany-Netherlands	42.40	39.65	30.08	39.42	36.04	26.91
Belgium-France-Germany-... Netherlands-Portugal-Spain	67.80	64.3	52.90	63.06	58.01	48.15

(1) No constraints.
(2) No transmission constraints but institutional constraint that minimally 50% of required aFRR should be in the own country.
(3) Transmission constraints and institutional constraint.

Transmission constraints lead to 30% lower efficiency gains in CWE and 23% lower gains if the six countries cooperate.

A similar estimation is also done for negative reserves. It leads to an additional €75 million per year in CWE and €100 million per year when all six countries exchange aFRR.[30] This is larger than the gain for positive aFRR because the price of German negative reserves is somewhat lower than of positive reserves. Without transmission constraints, the total gain of aFRR exchange is therefore around €115 million per year in the CWE area and around €165 million per year if all six countries cooperate (summing gains of positive (Table 5) and negative reserves). With transmission constraints, the total gain is respectively around €85 million and €135 million per year.

4.3.2 Cost decrease due to reserves sharing

Table 6 presents the estimated decrease of procurement costs [million € per year] due to sharing of positive aFRR between different sets of countries. As proven in section 3, these are larger than the gains of exchange if the imbalance correlation is smaller than one. Table 6 shows that the gains of sharing are a multiple of the gains of exchange. The reason is that the imbalance correlations are close to zero. For example, the procurement cost decrease for Belgium-France, Belgium-Netherlands and Portugal-Spain are low for exchange but considerably for sharing, because their marginal costs are similar but their imbalances have a low correlation. The estimated gains of two-country reserves sharing are €22 million (Belgium-Germany) up to €75 million (France-Germany), while the estimated gains of reserves exchange between the six countries exceeds €200 million per year. The third and fifth column show that the constraints on reserves sharing have little effect on the estimated gains. Lastly, as noted before, the gains are estimated relative to procurement costs in case of optimal reserves procurement in autarky, i.e. according to equation (4). As the procured reserve

30. Respectively €55 million and €85 million with transmission constraints.

Table 6: Cost decrease [M€/year] due to sharing of aFRR for different sets of countries

	2015		2016	
[M€/year]	(1)	(2)	(1)	(2)
Belgium-France	23.85	23.82	25.55	25.50
Belgium-Netherlands	28.51	28.51	24.18	24.18
Belgium-Germany	21.90	21.90	21.95	21.95
France-Germany	74.72	74.72	71.16	71.16
France-Spain	67.02	66.96	72.82	72.19
Germany-Netherlands	47.47	47.47	21.55	21.55
Portugal-Spain	49.36	48.36	42.41	41.68
France-Portugal-Spain	108.56	103.15	101.44	95.88
Belgium-France-Netherlands	73.29	72.97	54.99	54.68
Belgium-Germany-Netherlands	69.37	69.37	43.25	43.25
Belgium-France-Germany-Netherlands	142.83	142.83	114.48	114.48
Belgium-France-Germany-... Netherlands-Portugal-Spain	249.27	248.68	205.74	205.35

(1) No constraints.
(2) No transmission constraints but institutional constraint that required aFRR capacity cannot decrease more than 30%.

Table 7: Sensitivity of procurement cost decrease [M€/year] to value of lost load *v*

year	$v=5{,}000$	$v=10{,}000$	$v=20{,}000$
2015	200.60	249.27	307.6
2016	165.85	205.74	251.27

capacity is not necessarily optimal in our data, the change of procurement costs from sharing will be different when compared to current procurement costs.

A similar estimation is also done for negative reserves. It leads to an additional yearly gain of €198 million (2016) to €225 million (2015) in CWE and €300 million (2016) to €350 million (2015) when all six countries share aFRR. As a result, the total estimated gain of positive and negative aFRR sharing is around €310 to €370 million per year in CWE and €500 to €600 million per year when all six countries share aFRR. This is lower than the €3 billion estimated by Mott MacDonald (2013), but they (i) assess the whole of Europe, (ii) assume higher imbalances in 2030, and (iii) use a simulation model.

The estimated gains of sharing depend on VoLL. A higher VoLL leads to a higher optimal reliability level and thus higher procurement costs. As a result, possible gains of sharing also increase. Table 7 shows that the procurement cost decrease changes with around €50 million per year if VoLL is two times smaller or bigger.

4.3.3 Discussion

As shown earlier in the numerical illustration of section 3.6, most of the procurement cost decrease is due to sharing, if marginal costs are similar and imbalances are not much correlated. However, when marginal costs differ substantially, as between Germany and its neighbors, exchange already leads to sizable gains.

A limitation of our estimation is that we assume an unlimited linear supply curve between the price-quantity pair and the origin. However, the Spanish TSO makes the hourly supply curves of aFRR publicly available.[31] These show that a linear curve through the origin is a good approximation of the actual supply curve up to a certain level of reserves. In a random sample of hours (3am and 7pm every 10th day of all 24 months of 2015–2016), we have estimated this value to be on average 183% of procured capacity. Beyond this value, the supply curve is convex. As a robustness check we have imposed this limit in our numerical analysis, but the results do not change much. However, as the convex part at times starts well below 183% of procured capacity, assuming an unlimited linear supply curve leads to a slight overestimation of the possible gains of reserves exchange.

Van den Bergh et al. (2017) estimate the gains of reserves exchange and sharing in the CWE area to be respectively €40 and €50 million per year (before transmission constraints are taken into account), while this paper estimates these to be respectively around €115 and above €310 million per year for aFRR. The difference in magnitude could be due to their use of data on installed generation capacity to estimate the reserve and energy supply curve, while our study uses actual data on market prices and quantities.[32] Our data captures potential market power issues, which can be substantial according to ACER (2015, p.207), while a cost-minimization model does not. In addition, they only focus on imbalances stemming from wind and solar forecast errors, while our study uses actual data on system imbalances. This could explain why our study finds much larger gains for sharing than their study.

5. IMPLEMENTATION OF CROSS-BORDER RESERVES PROCUREMENT

Whenever TSOs start exchanging and sharing reserves, there are gains and distributional effects. This section first analyses the distribution of the benefits of cooperation and secondly, what institutions improve the incentive for cooperation.

We consider first the autarkic TSO case, where each TSO can implement a market mechanism to minimize the procurement costs of the reserves required. Next we discuss the distributional effects of reserves exchange via a uniform-price auction. These effects can be negative for one of the parties so that compensation mechanisms need to be put in place to guarantee cooperation. We develop a Nash bargaining game to study the compensation necessary for TSOs to agree on exchange of reserves.

5.1 Optimal autarkic TSO reserve provision

In a market-based system the TSO does no have direct control of the available reserves which have to be procured by some market mechanism. Here we assume a uniform-price auction with the resulting price p_i.[33] The TSO now determines the level of reserves R_i that minimizes the cost of procurement and the cost of interruptions:

$$\min_{R_i}\left\{v\int_{R_i}^{\infty}[r_i - R_i]f_i(r_i)dr_i + p_i^a R_i\right\}, \tag{14}$$

which results in the first-order condition for the optimal level of reserves.

31. https://www.esios.ree.es

32. Future research could combine engineering simulation studies with economic analysis and market data. Price and quantity data can improve the estimation of reserve and energy supply curves based on installed generation capacity.

33. Some TSO zones use pay-as-bid clearing but this is considered to be less preferable (Neuhoff and Richstein, 2016).

$$v \Pr\{r_i > R_i\} = p_i^a. \tag{15}$$

Generation firms supply the reserves. We assume they do not exercise market power and take prices as given, so generators will bid up to the point where marginal procurement costs equal the reserves price, i.e. where

$$\gamma_i'(R_i) = p_i^a. \tag{16}$$

The market equilibrium is determined by (15) and (16).[34]

5.2 Reserves exchange

5.2.1 Regulated reserves levels without inter-TSO compensation

Now suppose we are in a more realistic setting where, instead of a joint minimization of costs, each TSO minimizes its own costs, subject to the constraint that regulatory reserve levels must be met. As in the autarkic setting, we assume reserves in each TSO zone are procured by a uniform-price auction and, moreover, that these auctions are run simultaneously. Since exchange is unfettered, prices and marginal procurement costs will be equal in the two zones, i.e.

$$p^e = \gamma_1'(R_1) = \gamma_2'(R_2), \tag{17}$$

where p^e denotes the price of reserves in exchange, common to the two zones. Comparing (17) to (6), since each TSO will procure the level of reserves required by regulation, it is clear that the market solution achieves the cost-minimizing outcome.

5.2.2 Inter-TSO transfers to guarantee cooperation

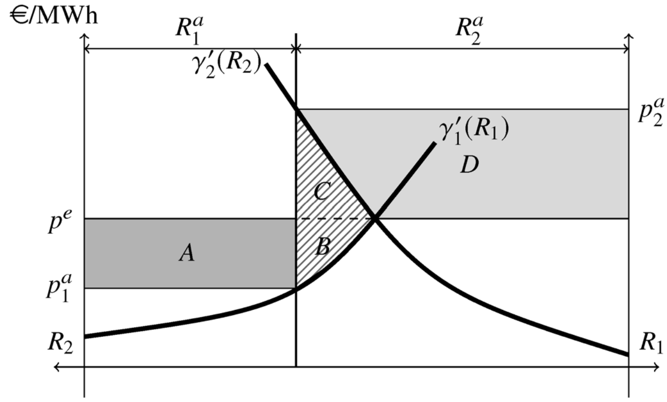
In a transition from autarky to exchange, the reserves price will rise in the cheap zone where marginal procurement costs are lower in autarky than in exchange, and fall in the expensive zone where these costs are higher. Hence, the TSO in the cheap zone will not have an incentive to participate in joint procurement auctions without compensation. Figure 8 shows this situation, with Zone 1 being the cheaper and Zone 2 the more expensive. The financial gain of TSO 2 corresponds to area C+D, whereas the loss of TSO 1 corresponds to area A. TSO 1 can compensate TSO 2 for his loss and retain some surplus provided $C + D > A$.

If the cross-border reserves procurement is organized via a uniform-price auction, we need transfers between the TSOs to guarantee cooperation. We will analyze the situation where there are lump-sum transfers.[35] In principle, there are infinitely many solutions to the bargaining game between the two TSOs, as long as a bargaining solution is feasible. Here we use the approach of the Nash bargaining game (Nash, 1953; Binmore et al., 1986) and assume that the autarkic solution is the fallback for both TSOs. Assuming consumers are compensated for interruptions, total costs for TSO i in autarky are $C_i^a = p_i^a R_i^a + L_i$, where $L_i = v\int_{R_i}^{\infty}[r_i - R_i^a] f_i(r_i) dr_i$ are expected interruption

34. Clearly, equation (4) follows from these two conditions so the market equilibrium coincides with the first-best level of reserves in autarky. In a market implementation the resulting reserves price is p_i^a.

35. Another possibility is a distortionary tax on import or export. However, such a tax would reduce the gains from trade.

Figure 8: Cost minimization under reserves exchange between two TSO zones. Area A indicates the procurement cost increase of TSO 1; area C+D indicates the procurement cost decrease of TSO 2.



costs.[36] We denote the lump-sum side payment from TSO 2 to TSO 1 by x. Similar to (Kolstad, 2005), the side payment can be interpreted as a measure of difficulty to make an agreement.

With exchange the TSOs have the following costs: $C_1^e = p^e R_1^a + L_1 + x$, $C_2^e = p^e R_2^a + L_2 - x$. Assuming equal bargaining power of the two TSOs the Nash product is given by

$$N = [(p_1^a - p^e)R_1^a + x][(p_2^a - p^e)R_2^a - x] \tag{18}$$

The first-order condition for maximum with respect to x, defining the transfer, is equal to $0.5(A+C+D)$. The drop in costs for TSO i, going from autarky to exchange with bargaining and side payment is seen to be

$$C_i^a - C_i^e = \frac{1}{2}[((p_2^a - p^e)R_2^a - (p^e - p_1^a)R_1^a)] \tag{19}$$

The right-hand side of (19) is half the net financial surplus resulting from reserves exchange (C + D – A). If one TSO has a stronger bargaining position than the other this result would not be reached. In this case the stronger TSO would gain more of the surplus. The basic result that a positive financial surplus is necessary for a bargaining solution to be feasible would, however, clearly still hold.

The analysis above assumes that a TSO only cares about its procurement costs. In reality, however, a TSO is also concerned about social welfare in its zone, in part because increased costs of reserves procurement are charged to consumers through network tariffs, and therefore do not affect TSO profits. Including this welfare concern into the TSO utility function increases the willingness to cooperate. Suppose that a TSO has a preference $\alpha \in [0,1]$ for social welfare (SW) and $(1-\alpha)$ for a decrease of procurement costs (PC). It favors cooperation if:

$$\Delta U_i = \alpha \Delta SW_i - (1-\alpha)\Delta PC_i \geq 0 \tag{20}$$

With a lump sum transfer y the TSOs have the following changes of utility:

$$\Delta U_1 = \alpha \Delta SW_1 + (1-\alpha)(p_1^a - p^e)R_1^a + y \tag{21}$$

36. Since required reserve levels are the same as in autarky it is in fact irrelevant whether consumers receive compensation. This is no longer the case when reserve levels are allowed to adjust to changed marginal reserve procurement costs.

$$\Delta U_2 = \alpha \Delta SW_2 + (1-\alpha)(p_2^a - p^e)R_2^a - y \tag{22}$$

where ΔSW_1 equals area B and ΔSW_2 equals area C in Figure 8. Assuming equal bargaining power of the two TSOs the Nash product is given by

$$N = [\alpha \Delta SW_1 + (1-\alpha)(p_1^a - p^e)R_1^a + y][\alpha \Delta SW_2 + (1-\alpha)(p_2^a - p^e)R_2^a - y] \tag{23}$$

and the first-order condition for maximum with respect to y turns out to be

$$y^* = (1-\alpha)x^* + \alpha \frac{\Delta SW_2 - \Delta SW_1}{2} \tag{24}$$

That is, if a TSO also cares about social welfare in its zone, the lump sum transfer is lower, which is an indication that voluntary cooperation is easier(Kolstad, 2005).

Proposition 2 *If a TSO, in addition to procurement costs, also cares about social welfare in its zone, the lump sum transfer needed for cooperation is lower: If* $\alpha > 0$, $y^* < x^*$.

The proof is presented in Appendix C.

Thus, in regions without an obligation to cooperate, cost-reducing cross-border cooperation will only materialize if all TSOs reap the benefits of cooperation. This can be ensured with side payments, which can be both the explicit value of our analysis (as in the inter-TSO compensation mechanism) or more implicitly (e.g. distortionary import tariffs or transaction costs to join the cross-border cooperation platform); see further discussion in the Conclusions.

5.2.3 Locally optimal reserves levels

In the case of locally optimal reserve levels, not only costs of reserves, but also expected consumer interruption costs will change. Hence, the feasibility of a bargaining solution and side payments will be affected. Basic insights, however, remain the same as in the previous case.

5.3 Reserves sharing

As in the case of reserves exchange there are, in general, distributional consequences of reserves sharing that may make one zone better off and the other worse off, both as regards procurement costs and expected interruptions.[37] Similar to reserves exchange, incentive compatibility of sharing requires a minimal side payment from the zone that gains the most to the one that is worse off and a bargaining outcome can be predicted using the Nash bargaining solution. If there is sufficiently low correlation in reserve needs between the two zones, it is, however, possible that the gains from lower interruption costs due to integration outweigh any rise in reserves procurement costs. An extreme example of this is when the two zones have perfectly negatively correlated reserve needs. In this case reserve sharing eliminates any needs for reserve procurement! This is, however, unlikely to be the case in real situations.

37. With reserves sharing, assigning procurement costs to TSOs is ambiguous since the decrease depends on the correlation of reserve needs between the TSO zones. In addition, expected interruption costs in each TSO zone depend on how interruptions are shared. For example, if interruptions are shared in equal proportions, the distribution of expected interruption cost is different than if the reserves-providing TSO has priority over the reserves-receiving TSO.

6. CONCLUSIONS

This paper compares three degrees of TSO cooperation in generation reserves provision: autarky, reserves exchange and reserves sharing. We derive analytically the optimal procurement of reserves in each of the three cases and show that costs decrease with cooperation. The benefits of reserves exchange and reserves sharing depend on cost asymmetry and correlation of real-time imbalance variability between cooperating TSO zones. That is, when TSO zones have highly asymmetric reserve procurement costs but highly correlated reserve needs, reserves exchange already yields a high cost reduction. When TSO zones have fairly equal reserve procurement costs but a low degree of reserve needs correlation, reserves sharing is needed to reap the full benefits of TSO reserves cooperation.

Based on actual 2015–2016 market data of reserves procurement of positive and negative automatic frequency restoration reserves in Belgium, France, Germany, the Netherlands, Portugal and Spain, we estimate the efficiency gains of exchange and sharing for different subsets of these countries. Cross-border cooperation in these six countries leads to around €165 million per year for exchange and around €500 million per year for sharing. In the CWE area, the gains are respectively around €117 million and €310 million per year. Incorporating transmission constraints, the gains of reserves exchange decrease to respectively €135 million and €85 million per year.

Our analysis shows that cross-border reserves cooperation has distributional impacts on TSOs; some TSOs may even experience an increase of procurement costs. This can be a factor hindering cooperation of TSOs on cross-border reserves procurement and balancing and thus prevent potential efficiency gains from being realized.[38] In general, the extent of the disincentives created by such distributional impacts will depend on the market mechanisms in place in different areas as well as on the weight TSOs place on social welfare, rather than their own costs; cooperation will be easier when TSOs place a weight on social welfare in their zone. This underscores the importance of careful design of regulation and mechanisms for trade, as well as for redistribution of efficiency gains. We illustrate, in the context of a particular market mechanism (uniform price auctions), how side payments can be used to induce cooperation. Full analysis of these issues is beyond the scope of this paper, but is, however, an important area for further research.

In this paper we focused on the changes of procurement and interruption costs generated by more efficient supply. The true benefits of cross-border cooperation can be higher than presented in our model because of improved market liquidity, internalization of external effects, and increased market access through standardization of rules and products. In addition, TSOs that are first to cooperate can define the rules and standards of cooperation and have therefore lower transaction and compliance costs.

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38. This is perhaps illustrated by the elimination of an obligation to cooperate on reserves procurement, initially included in the proposed Electricity Balancing Guideline (ENTSO-E, 2014), but now dropped in the recently adopted EU Regulation (European Commission, 2017b).

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APPENDIX A: PROOF OF PROPOSITION 1

Proof: Recall that for each degree of cooperation $j \in \{a,e,l,s\}$, R_i^j is the optimal amount of reserves procured in Zone i and c^j is the sum of procurement costs and interruption costs in both TSO zones. By contrast, R_i is the amount of reserves procured by TSO i. Equation (25) is the sum of procurement costs and interruption costs with autarky. This minimization determines R_1^a and R_2^a. Adding an additional variable R_1^e leads to equal interruption costs and weakly lower procurement costs in equation (26). The inequality is strict if $R_1^e \neq R_1^a$ and $R_2^e \neq R_2^a$. Adding even more variables to allow a trade off between procurement costs and interruption costs causes equation (27) to be weakly lower than equation (26). Again the inequality is strict if $R_1^e \neq R_1^a$ and $R_2^e \neq R_2^a$. To proof the last inequality, notice that equation (27) equals equation (28) if the correlation of reserve needs is one. If the correlation is lower than one, both procurement costs and interruption costs decrease.

$$c^a = \min_{R_1^a, R_2^a} \{vE[r_1 - R_1^a]^+ + vE[r_2 - R_2^a]^+ + \gamma_1(R_1^a) + \gamma_2(R_2^a)\} \tag{25}$$

$$\geq c^e = \min_{R_1^e} \{vE[r_1 - R_1^a]^+ + vE[r_2 - R_2^a]^+ + \gamma_1(R_1^e) + \gamma_2(R_1^a + R_2^a - R_1^e)\} \tag{26}$$

$$\geq c^l = \min_{R_1^l, R_1, R_2} \{vE[r_1 - R_1]^+ + vE[r_2 - R_2]^+ + \gamma_1(R_1^l) + \gamma_2(R_1 + R_2 - R_1^l)\} \tag{27}$$

$$\text{with } R_1 + R_2 = R_1^l + R_2^l$$

$$\geq c^s = \min_{R_1^s, R_2^s} \{vE[r_1 + r_2 - R_1^s - R_2^s]^+ + \gamma_1(R_1^s) + \gamma_2(R_2^s)\} \tag{28}$$

□

APPENDIX B: PRICE, QUANTITY AND IMBALANCE DATA

The contracting period goes from hourly (Portugal and Spain) to yearly (France). In Belgium, France and the Netherlands, only the average price of reserve procurement is reported, while Germany, Portugal and Spain report the marginal price of the procurement auction. The price and quantity data are complemented with imbalance data r_{it} [MWh], which has a granularity between 15 minutes and 1 hour. Table 8 summarizes the imbalance and procurement data in the considered European countries. The complete dataset consists of 105,264 values of r, p and R. That is, 731 days of 24 hours for 6 countries.

Table 9 presents summary statistics of the procurement and imbalance data. For both 2015 and 2016, this table reports the minimum, maximum and average procurement price and procured quantity. For example, the first row shows that in 2015 in Belgium the marginal price of procurement[39] is between 17.3 €/MWh and 34 €/MWh, with an average of 23.4 €/MWh. The procured aFRR capacity is between 140 MW and 148 MW, with an average of 141 MW. Germany procures by far the largest amount of aFRR capacity, while Belgium, the Netherlands and Portugal procure

39. See section 4.2 that deals with the calculation methodology.

Table 8: Summary of available imbalance and procurement data in considered European countries (Source: ENTSO-E Transparency Platform)

	r_t	R_t	Since	Price
Belgium	15'	weekly	01.08.2016	average
		monthly	01.01.2015	average
France	30'	yearly	01.01.2015	average
Germany	15'	weekly	27.06.2011	marginal
Netherlands	15'	monthly	01.01.2016	average
		yearly	01.01.2015	average
Portugal	60'	hourly	13.12.2014	marginal
Spain	60'	hourly	12.12.2014	marginal

Table 9: Summary of aFRR procurement data in considered European countries (Source: ENTSO-E Transparency Platform)

[€/MW/h] and [MW]	Year	p_{min}	p_{max}	p_{av}	R_{min}	R_{max}	R_{av}	$r^+_{99\%}$
Belgium	2015	17.3	34	23.4	140	148	141	432
	2016	15.4	87.7	26.8	140	150	142	456
France	2015	18.3	18.3	18.3	500	1177	647	2352
	2016	18.4	18.4	18.4	500	1100	639	2718
Germany	2015	2.58	24	7.2	2026	2500	2070	1739
	2016	1.88	24	5.6	1973	2500	2014	1541
Netherlands	2015	27.4	27.4	27.4	300	300	300	992
	2016	14.1	21.3	17.8	170	170	170	896
Portugal	2015	5	61.4	20.5	66	322	171	697
	2016	4	80.1	16.6	56	333	173	860
Spain	2015	2.1	121	19.6	467	913	685	3846
	2016	0.76	200	15.6	399	927	682	2447

the smallest amount of aFFR capacity. Average prices are lowest in Germany and highest in the Netherlands (2015) and Belgium (2016). The last column reports the positive imbalance value r^+ [MW] that is not exceeded in 99% of hours with positive imbalance.[40] In European countries, the total reserve capacity of aFRR, mFRR and RR should be sufficient to cover this 99% limit (European Commission, 2017a, art. 157.(2)(h)). Comparison of the two last columns shows that Germany satisfies this requirement with aFRR only, while the other five countries do not. Section 4.2 explains how we deal with this in our estimation.

APPENDIX C: PROOF OF PROPOSITION 2

Proof: If $\alpha > 0$, $y^* < x^* \Leftrightarrow \frac{\Delta SW_2 - \Delta SW_1}{2} < x^*$, where $\frac{\Delta SW_2 - \Delta SW_1}{2} = 0.5(C - B)$ and $x^* = 0.5[((p_2^a - p^e)R_2^a - (p_1^a - p^e)R_1^a)] = 0.5(D + C + A)$. Therefore $y^* < x^* \Leftrightarrow A + B + D > 0$. Since areas A, B and D are positive, $y^* < x^*$. □

40. For reference, the hourly 2016 peak demand and average demand [GW] in the six countries are: France (81.2/53.4), Germany (57/48), Spain (40.1/28.5), Netherlands (19.7/13), Belgium (13.6/9.9) and Portugal (8.1/5.6) (Source: ENTSO-E Transparency Platform).

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