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Market Equilibria in Cross-Border Balancing Platforms

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***Abstract*—The next phase of electricity markets integration in Europe will see the introduction of pan-European balancing platforms, MARI and PICASSO, for the trading of manual and automatic frequency restoration reserve. This paper provides an analytical framework for the study of pricing asymmetries between European member states in this context. The pricing asymmetries are due to balancing incentive components and consist of the unilateral introduction by a member state of either (i) an adder on the imbalance price and balancing price, (ii) an adder on the imbalance price solely, or (iii) the introduction of a real-time price for the trading of real-time balancing capacity. Our analytical framework allows us to characterize the optimal bidding strategy of flexible assets under the different designs and to derive the resulting equilibria. Our analysis demonstrates that adders without the trading of balancing capacity create inefficiencies by distorting the merit order and tend to be detrimental to the member state that introduces it.**

***Index Terms*—balancing market, cross-border balancing, frequency restoration reserve, real-time market for reserve.**

I. Introduction

A. The European Balancing Context

FOLLOWING in reverse of the appropriate order [1], the next phase of the European electricity market integration concerns balancing markets. These markets ensure the reliable operation of the grid by balancing, at all times, electricity generation with electricity consumption. European balancing markets coordinate interactions between three types of agents: (i) the *transmission system operator* or TSO, (ii) *balancing responsible parties* or BRPs, and (iii) *balancing service providers* or BSPs.

Balancing markets consist of energy auctions where TSOs restore system balance in response to real-time conditions. They cover the aggregated imbalance caused by BRPs' deviation from their forward position (*system imbalance*) by activating *balancing energy* from BSPs. BSPs are dispatched based on their *balancing energy bid*, a price-quantity pair that represents the limit price at which they are willing to be activated and the maximum quantity that they can deliver. BSPs' balancing energy is remunerated at the *balancing price*, which should be obtained through a "pay-as-cleared" following Article 30.1.a of the Electricity Balancing Guideline (EBGL). Instead, BRPs' imbalance is charged an *imbalance price* which is based, among other factors, on the activation cost of reserve [2]. In order to ensure sufficient balancing energy bids in real time, TSOs contract *balancing capacity* in the day ahead. In this 2-step process, the procurement cost of reserve capacity is passed on to consumers through the grid tariff, and the activation cost for balancing energy is borne by the BRPs that cause the imbalance.

The European integration of balancing markets will be accomplished through *balancing platforms*. These platforms are developed with the goal of centralizing balancing energy bids across Europe. Specifically, TSOs submit a demand for activation, and the platform select the offers that serve the demand of all TSOs at the cheapest cost. Even though the volumes involved in balancing markets are much lower than the ones traded in day-ahead and intraday markets, the design that determines price formation in balancing and imbalance settlement should not be overlooked as the expectation of the real-time prices generated by the balancing markets drives the wholesale electricity price in the day-ahead and other forward markets [3]. As Hogan has stated repeatedly: "The last (price generated) should be (designed) first" [1].

Regulatory discrepancies between European balancing markets remain present, and their potential influences on the operation of balancing platforms has not been fully assessed. One of these divergences concerns the existence of an incentivizing component for inducing BRPs to help balance the system, as is the case for instance in Belgium and the Netherlands. These components take the form of adders on the imbalance price, and aim at incentivizing BRPs to participate in the balancing process by penalizing (resp. rewarding) positions that hurt (resp. help) the system. Imbalances in the same (resp. opposite) direction as the SI are punished (resp. rewarded) with an increased imbalance price. The existence of adders reflects the TSOs' stance regarding *reactive balancing* (the self-activation of assets, in order to balance the system) [4].

The intention of introducing adders to the imbalance price is to keep the system imbalance stable and to prevent long-lasting imbalances by BRPs [5]. This imbalance pricing scheme holds BRPs accountable for their consumption of balancing capacity and one possible interpretation is that this acknowledges the real-time value of balancing capacity. Unfortunately, this design choice fails to efficiently back-propagate the value of balancing capacity to the day-ahead market [6]. The most adequate measure for this would be to co-optimize balancing energy and balancing capacity in real time, as is already the case in various US markets, such as [7]. Otherwise, its second best approximation, the introduction of a real-time market for reserve and the use of an adder on the energy price, which has been implemented in ERCOT [8], could be more realistically implemented in the immediate future.

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The argument for an increased participation of flexible demand, which is a necessary component of electric systems dominated by renewable generation, can also be invoked for supporting the introduction of adders [9]. Most importantly, energy adders can assist in compensating for the inability of electricity markets to price and remunerate reliability. Completely offsetting this market failure will require customers to specify their preferred reliability. Until then, administrative measures, such as *shortage pricing functions* through adders on the energy price which can approximate the co-optimization of reserve and energy, may be helpful in ensuring an adequate reliability level, since energy-only markets with dormant demand-side resources alone may face challenges in price discovery. This measure can improve the revenue profile of flexible assets and help overcome the reluctance of risk-averse investors to finance such assets due to their position at the end of the merit order, the high year-to-year volatility of energy prices, and the heavy reliance of these investments on infrequent high prices caused by shortages [10], [11].

B. Literature Review

This analysis is part of the balancing market design literature. Seminal work on coupled capacity and energy auctions includes [12], where the authors characterize with an analytical model the optimal bidding strategy and the necessary conditions for an equilibrium in early bid scoring systems with discriminatory settlement rules. Chao and Wilson establish through a backward analytical induction that uniform pricing for both energy and power can create incentives for truthful bidding [13]. Similar analytical methods have been employed in order to investigate the interplay between the wholesale market and the balancing market [14] and the switch from "pay-as-bid" to "pay-as-cleared" auctions [15]. Agent-based methods have also been used for analysing the impact of the imbalance pricing scheme on system cost [16], strategic bidding behaviors in joint or split balancing capacity and balancing energy markets [17], [18] and the back-propagation of real-time prices to day-ahead prices [6].

There also exists a broad literature on optimizing the strategy of different agents in balancing markets. Such litereture includes analyses of optimal trading strategies [19], [20], the minimization of portfolio imbalance [21], and the optimal activation of balancing energy by system operators [22]. Nevertheless, this line of work is tangent to our analysis, which is focused on the *design* of balancing markets.

The introduction of a real-time market for reserve links this discussion to the *scarcity pricing* literature based on *Operating Reserve Demand Curves* (ORDCs). The concept of scarcity pricing with ORDCs was formalized by Hogan in [9] and has since gained traction in the US, with ERCOT, PJM, ISO-NE, MISO, SPP and CAISO having implemented it [23]. [24] and [25] investigate the adaptation of the mechanism to European balancing markets. These works advocate for the introduction of a real-time market for reserve as a non-disruptive no-regret measure.

A similar analysis on the effect of uncoordinated regulation in spatially integrated electricity markets has been investigated by Bushnell in the context of carbon reduction policies [26]. The authors conclude that regulatory interventions can lead to a distortion of the merit order, which may in turn lead to inefficiencies.

C. Objective and Contributions

This work uses an analytical model to investigate how adders can be applied in a cross-border setting. Three designs are examined: (i) The *adder on BRPs* design, which is currently used in Belgium by ELIA, the Belgian TSO, where the adder is applied on the imbalance price [27], (ii) the *adder on BRPs and BSPs* design, suggested by the Dutch TSO TenneT, where an adder is applied on both the balancing and imbalance price [28], and (iii) the *Real-Time (RT) market for reserve* suggested by [6], [24], [25]. This design proposes to remunerate available but non-activated balancing capacity in addition to balancing energy. The coupling of the balancing capacity and balancing energy market uplifts the balancing and imbalance price by an adder equal to the balancing capacity price. The value of balancing capacity, the *reserve price*, is based on an ORDC which represents the probability of losing load given the current state of the system [29].

The paper completes and extends the model proposed in [6] in order to asses the back-propagation induced by different imbalance and balancing pricing schemes. Our modelling and theoretical contributions can be stated as follows: (i) we characterize an equilibrium for the "adder on BRPs design", which allows us to abandon the agent-based modeling method used in [6], (ii) we provide a novel analysis of a newly proposed pricing scheme, the "adder on BRPs and BSPs" design, and (iii) we apply our analysis to a cross-border setting. From a policy standpoint, our analysis shows the inability of both the "adder on BRPs" and the "adder on BRPs and BSPs" designs to support an optimal dispatch in a cross-border setting, in contrast to the "RT market for reserve" design which can achieve this objective.

The remainder of the paper is structured as follows. Section II goes on to describe the functioning of European balancing markets and balancing platforms, and introduces our notation and model. Sections III and IV characterize the optimal strategies of agents under the different designs analyzed in this work, as well as the resulting market equilibrium. Section V illustrates and compares the market equilibria in a two-zone setting. Section VI concludes.

II. European Balancing Market

This section presents a single-zone balancing market and then introduces balancing platforms for representing cross-zonal integration in balancing operations.

A. Single-Zone Balancing Market

The functioning of European balancing markets is outlined in the *Electricity Balancing Guideline* (EBGL) and described in a stylised manner hereunder.

TSOs are responsible for the operational security of the grid. They hold reservation auctions for ensuring an adequate level of available reserve capacity of different types in real-time. Balancing capacities can be differentiated according to their activation time. They include the following types of reserve. (i) *Frequency containment reserve* (FCR) is based on automatic control. (ii) *Automatic frequency restoration reserve* (aFRR) is also driven by automatic controllers, and strives to control the grid frequency. It has a full activation time of 5 to 7.5 minutes. (iii) *Manual frequency reserve* (mFRR) is activated manually by the controller in order to relieve aFRR. It has a full activation time of 15 minutes. (iv) *Replacement reserve* (RR) has a full activation time that ranges between 15 minutes and hours. The discussion in the paper is targeted at frequency restoration reserve, aFRR and mFRR, that are dispatched through energy balancing auctions. Any subsequent mention to balancing capacity and energy will respectively refer to the aFRR and mFRR capacity available for activation by the TSOs and to the aFRR and mFRR capacity dispatched by the TSOs. We assume a generic FRR product in the subsequent discussion.

BRPs are owners of portfolios that consist of residential, commercial and industrial load as well as generation assets. According to EBGL, they shall strive to be balanced or help the system to be balanced article (article 17.1 of EBGL) and they are financialy responsible for their imbalance (article 17.2 of EBGL). Their imbalance relative to their ex-ante position is charged at the *imbalance price*. For the sake of this analysis, BRPs can be considered as price-inelastic energy bids.

BSPs are flexibility providers participating in the balancing energy auctions. They belong to a BRP portfolio, and they include a wide range of assets, such as classical thermal units (CCGT, OCGT, ...), battery aggregations, and industrial and/or commercial demand response. BSPs can offer various reserves, depending on their characteristics and on the qualification criteria set by the TSO. BSPs can be considered as elastic suppliers of balancing energy in our context.

The term "balancing the market" refers to the process whereby a TSO activates balancing energy from BSPs, in order to cover the aggregation of the BRPs' inelastic imbalance. We proceed now with a description of the balancing process. We have voluntarily left aside the reserve procurement auctions, as their representation is not required in order to highlight the pricing asymmetries brought forth by adders.

Firstly, BSPs submit their balancing energy bids to a balancing energy auction which is organised by the TSO. The balancing energy auction is assumed to clear at a uniform price, following the pricing scheme of the European balancing platforms [30].

Secondly, the aggregation of the BRPs' inelastic imbalance is revealed. The TSO clears the balancing energy auction in order to balance the market and produces a *platform price*, λ_B. Given the available information, one can also compute a *scarcity component price*, λ_R. This represents the value of balancing capacity at the time of clearing. Balancing energy is remunerated at the balancing price, λ_{bal}, and BRPs' imbalances are charged at the imbalance settlement price, λ_{imb}.

Between the first and second step, BSPs, as part of a BRP's portfolio, can decide to perform reactive balancing and self-activate their assets. In this case, the activated energy is considered part of the BRP's imbalance and is charged at the imbalance price.

TABLE I
BALANCING AND IMBALANCE PRICES UNDER THE VARIOUS DESIGNS THAT ARE DEBATED IN EUROPEAN BALANCING MARKET DESIGN.

	λ_{bal}	λ_{imb}	Res. price
No adder	λ_B	λ_B	0
Adder on BRPs	λ_B	$\lambda_B + \lambda_R$	0
Adder on BSPs and BRPs	$\lambda_B + \lambda_R$	$\lambda_B + \lambda_R$	0
RT Market for resserve	$\lambda_B + \lambda_R$	$\lambda_B + \lambda_R$	λ_R

Both the balancing and imbalance price are constructed from the platform price. Future discussions about the implementation of scarcity pricing in European balancing markets also discuss the inclusion of scarcity components. This can generate different designs, as shown in Table I. The default design is the "no adder" policy, where the balancing and imbalance price are equal to the platform price. The "adder on BRPs" and "adder on BRPs and BSPs" designs respectively introduce an adder on the imbalance price and on the imbalance and balancing price. Finally, the "RT market for reserve" design has an adder on the imbalance and balancing price, and additionally trades balancing capacity in real-time. In this last design, the balancing capacity that has not been activated is entitled to the real-time reserve price, which is equal to an adder computed from an ORDC. More specifically, the "RT market for reserve" design proposes to introduce a market for *balancing capacity imbalance* which is equivalent to a market for balancing capacity that is conducted in real time.

B. Cross-Border Balancing Platforms

The transition from one zone to multiple zones will see the introduction of balancing platforms. These platforms aim at coordinating the dispatch of balancing energy from different zones and are called PICASSO (for aFRR) and MARI (for mFRR). Their objective is to cover the TSOs' demand, at least cost, by activating balancing energy from the BSPs of multiple zones. They have gone live in 2022 and are operating over Germany and the Czech Republic for MARI, with the addition of Austria for PICASSO. The other European TSOs are expected to join the platform in 2023 or 2024. MARI clears every 15 minutes and PICASSO clears every 4 seconds.[1]

TSOs connected to the platforms first receive the balancing bids from the BSPs. They filter these bids in order to suppress the ones that could create congestion and transmit the others to the platform. Afterwards, they send in real-time their demand for the activation of frequency restoration reserve to the platform. The platform clears a balancing energy auction and informs TSOs on which bids of their control area have been accepted. Finally, TSOs inform BSPs whose bids are accepted. TSOs will also be responsible for transferring the settlement between the BRPs and BSPs and the platform. This balancing

[1] MARI can clear more than one time per 15 minutes at TSOs' request.

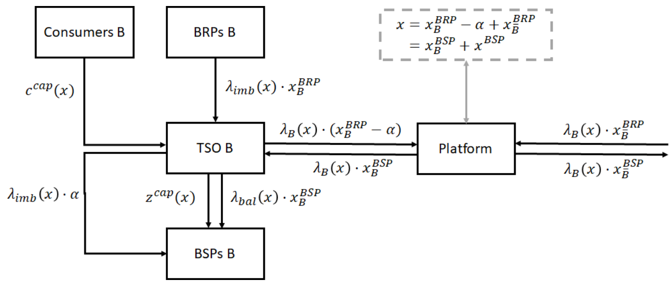

Fig. 1. Cash flow over multiple zone for a general European cross-border balancing market.

TABLE II
COST OF CAPACITY AND CAPACITY SETTLEMENT[2]

	$c^{cap}(x)$	$z^{cap}(x)$
No adder	0	0
Adder on BRPs	$-\lambda_R(x) \cdot (x_B^{BRP} - \alpha)$	0
Adder on BSPs and BRPs	$\lambda_R(x) \cdot (x_B^{BSP} - x_B^{BRP})$	0
RT Market for reserve	$\lambda_R(x) \cdot (P^{max} - x_B^{BRP})$	$\lambda_R(x) \cdot (P^{max} - x_B^{BSP})$

process and the cash flow between the different agents is represented graphically in Fig. 1 for the case of two zones: zone B and zone $\bar{B}$, where zone $\bar{B}$ corresponds to the rest of the system.

The demand for activation of balancing energy in zone i is denoted as x_i^{BRP} if there is no reactive balancing and as $x_i^{BRP} + \alpha$ in the case with reactive balancing. Note that the TSO cannot distinguish between the inelastic imbalance from BRPs and reactive balancing. The activated balancing energy in zone i is denoted as x_i^{BSP}. Settlements between the platform and the TSOs are charged at the platform price cleared by the balancing energy auction, but TSOs are free to unilaterally introduce adders, corresponding to the designs proposed in table I, for the settlements with the BRPs and BSPs.

These potential pricing asymmetries between the platform price and the balancing and imbalance price might result in a capacity cost component c^{cap} borne by all the consumers in the zone introducing the adder and socialized through the grid tariff. Outside of balancing settlement, BSPs are also entitled to a capacity settlement z^{cap} for their unused balancing capacity if their zone operates a "RT market for reserve". Both of these components are described for the different designs in Table II.

III. Characterization of Agents' Optimal Decisions

The objective of the analytical model is to characterize the optimal strategy for BSPs, as BRPs are assumed to be inelastic and do not behave strategically. We will first describe the profit function of a fringe BSP with P^+ MW of upward balancing capacity and marginal cost C €/MWh. We will then derive its optimal strategy. The notation and analysis presented here are an extension of the model presented in [6].

A. Balancing and Imbalance Payoffs of Agents

The decision process under the "no adder", "adder on BRPs" and "adder on BRPs and BSPs" designs can be characterized as a 2-stage process. In the first stage, the agent submits a price-quantity bid (p, q) to the energy balancing auction and decides on their level of reactive balancing ai. Note that the sum of the level of reactive balancing and of the quantity bid must be lower than the total capacity of the agent. In the second stage, the demand for balancing energy, x, is equal to the negative of system imbalance. The TSO dispatches balancing energy through the balancing energy auction in order to balance it. This demand is assumed to be drawn from a known distribution with probability measure $\mu(x)$. The resulting price from the balancing energy auction, $\lambda_B(x)$, is a function of the random demand for balancing energy. It can be defined as the price offer of the most expensive accepted energy bid. An alternate definition would equal the platform price to the dual variable relative to the market clearing constraint of the economic dispatch solved by the system operator in order to balance the system.

The scarcity component, $\lambda_R(x)$, is obtained through an operating reserve demand curve. Scarcity pricing based on ORDC adders takes the leftover capacity in the system as an input, but leftover capacity can be equivalently reformulated as a function of the demand for balancing energy by assuming that the leftover capacity in the system is the total capacity in the system minus inelastic energy demand. The scarcity component is a non-decreasing function of demand.

The balancing payoff for a BSP, given a random demand for balancing energy, is characterized as the uniform balancing price multiplied by the quantity bid if the price bid is lower than the platform price, or 0 if the bid is not accepted.

$$z_B(p, q, x) = \begin{cases} \lambda_{bal}(x) \cdot q & \text{if } p \leq \lambda_B(x), \\ 0 & \text{else} \end{cases} \tag{1}$$

Note that bids are assumed to be either fully selected, if they are at-the-money or in-the-money, or not selected at all. The expectation of this payoff can be reformulated as follows, with the operator $\mathbb{E}_\mu$ being the expectation over the probability measure μ.

$$z_B(p, q) = \mathbb{E}_\mu[z_B(p, q, \cdot)] = \int_{\lambda_B(x) \geq p} \big((\lambda_{bal}(x) - C) \cdot q\big) d\mu(x) \tag{2}$$

The reactive-balancing payoff is found by first characterizing the level of reactive balancing performed by an agent. This is found by solving the following optimization problem.

[2]All $c^{cap}(x)$, except for the "no adder" one, should include a potential self-activation component α but they were dropped due to the level of self-activation at equilibrium being equal to 0 for the adder on BSPs and BRPs and the RT market for reserve. These results will be explicited in section IV.

$$\max_{ai} \quad (\mathbb{E}_\mu[\lambda_{imb}] - C) \cdot ai \tag{3}$$
$$s.t. \quad ai + q \leq P^+ \tag{4}$$
$$ai \geq 0 \tag{5}$$

If $C \geq \mathbb{E}_\mu[\lambda_{imb}]$, the optimal level of reactive balancing $ai^\star$ is 0, else $ai^\star$ is equal to the leftover capacity from the balancing energy auction. The reactive balancing payoff is then described as follows:

$$z_I(q) = \begin{cases} (\mathbb{E}_\mu[\lambda_{imb}] - C) \cdot (P^+ - q) & \text{if } C \leq \mathbb{E}_\mu[\lambda_{imb}], \\ 0 & \text{else.} \end{cases} \tag{6}$$

The optimal strategies for the "no adder", "adder on BRPs" and "adder on BRPs and BSPs" designs are then found by maximizing the sum of the balancing and of the reactive-balancing payoff.

A real-time market for balancing capacity results in the introduction of a new component in the payoffs. The unused balancing capacity of BSPs is now remunerated by the reserve price. As the balancing and imbalance prices are equal to the platform price plus the reserve component in the "RT market for reserve" design (see table I), the real-time payoff can be reformulated as follows for a random demand x, with $z_I(ai, x)$ being the reactive balancing payoff for self-activating ai MWh.

$$z_B(p, q, x) + z_I(ai, x) \tag{7}$$
$$= \begin{cases} (\lambda_B(x) + \lambda_R(x) - C) \cdot (q + ai) + \lambda_R(x) \cdot (P^+ - q - ai) \\ \qquad \text{if } \lambda_B(x) \leq p, \\ (\lambda_B(x) + \lambda_R(x) - C) \cdot ai + \lambda_R(x) \cdot (P^+ - ai) \\ \qquad \text{else,} \end{cases} \tag{8}$$
$$= \begin{cases} (\lambda_B(x) - C) \cdot (q + ai) + \lambda_R(x) \cdot P^+ & \text{if } \lambda_B(x) \leq p, \\ (\lambda_B(x) - C) \cdot ai + \lambda_R(x) \cdot P^+ & \text{else.} \end{cases} \tag{9}$$

This allows us to rewrite both the balancing and imbalance payoff as a function of the platform price.

$$z_I(q) = \begin{cases} (\mathbb{E}_\mu[\lambda_B] - C) \cdot (P^+ - q) & \text{if } C \leq \mathbb{E}_\mu[\lambda_B] \\ 0 & \text{else,} \end{cases} \tag{10}$$

$$z_B(p, q) = \int_{\lambda_B(x) \geq p} \big((\lambda_B(x) - C) \cdot q\big) d\mu(x) + \mathbb{E}_\mu[\lambda_R] \cdot P^+. \tag{11}$$

The objective of this reformulation is to isolate the scarcity component remuneration $\mathbb{E}_\mu[\lambda_R] \cdot P^+$ from the standard imbalance and balancing payoff, in order to highlight the correspondence between the payoffs of the "RT market for reserve" and "no adder" designs up to a constant.

The optimal bidding strategies for a BSP under the different designs are not modified by the transition to multiple zones. As long as the platform price and the reserve component price as a function of the aggregated demand for balancing energy over multiple zones and its probability measure are known, the profit functions presented earlier remain valid as do the optimal strategies presented hereunder.

B. Optimal Balancing Market Bid

The strategy for characterizing the optimal behaviour under the different design is an extension of [6] to accomodate the "adder on BRPs and BSPs design". Only the statement and a brief intuition of the results are provided here. The complete proofs are available in the electronic supplement. These proofs consider fringe agents reacting to an exogenous platform price. The platform price is also assumed to be strictly monotonic increasing. Section IV shows that the strict increasing monotonicity assumption holds at equilibrium.

Proposition 1 (Bidding Strategy – No Adder)**.** *The optimal strategy for a fringe agent under a "no adder" design is to bid truthfully in the balancing auction.*

Bidding more or less than the marginal cost in the balancing energy auction will result in a lower balancing payoff for an agent, as the agent can respectively lose some potential payoff (in the case of overbidding) or be unprofitable (in the case of underbidding). One can then conclude that it is optimal for every agent to bid its full capacity in the balancing auction since the payoff of the balancing auction will be (i) equal to the payoff from self-activation whenever the agent is in the money in the balancing auction, and (ii) is higher than the payoff of self-activating whenever the agent is out of the money.

Proposition 2 (Bidding Strategy – Adder on BRPs)**.** *The optimal strategy for a fringe agent under "an adder on BRPs" design is to bid truthfully in the balancing market if*

$$C \geq \mathbb{E}_\mu[\lambda_B + \lambda_R] - \int_{\lambda_B(x) \geq C} (\lambda_B(x) - C) d\mu(x),$$

else to perform reactive balancing with its full capacity.

The pricing asymmetry of this design can incentivize BSPs to self-activate when they have a low marginal cost. If a BSP is very likely to be activated, the little it would lose when the imbalance price is not sufficient to cover its cost can be compensated by the additional payoff of the imbalance settlement, compared to the balancing energy auction, due to the scarcity component in the former.

In order to analyze the next design, we define $(\lambda_B + \lambda_R)^{-1}$ as the inverse function of the sum of the platform price and the scarcity component under the adder on BRPs and BSPs design. This sum is equal to both the balancing and imbalance price (see Table I). The expression $(\lambda_B + \lambda_R)^{-1}(p)$ is then the level of demand for balancing energy such that the balancing price p is attained. Note that $\lambda_B + \lambda_R$ has a well-defined inverse everywhere because the platform price is strictly monotonic increasing and the reserve component is non-decreasing.

Proposition 3 (Bidding Strategy – Adder on BRPs and BSPs)**.** *The optimal strategy for a fringe agent under an "adder on*

BRPs and BSPs" design is to bid its full capacity in the balancing energy market at price

$$\lambda_B((\lambda_B + \lambda_R)^{-1}(C)).$$

BSPs should internalize the value of the adder in their balancing energy bid so as to ensure always being activated when the balancing price is higher than or equal to their marginal cost. This corresponds to bidding the platform price $\lambda_B(x')$ for x' such that

$$(\lambda_B + \lambda_R)(x') = C.$$

Proposition 4 (Bidding Strategy – RT Market for Reserve)**.** *The optimal strategy for a fringe agent under a RT market for reserve design is to bid truthfully in the balancing energy market.*

The profit function of the "RT market for reserve design" is equal to the one of the "no adder" design up to a constant $\mathbb{E}_\mu[\lambda_B] \cdot P^+$, independent of the agent's strategy.

IV. Market Equilibrium

This section commences by characterizing the Nash equilibria resulting from the optimal strategy outlined earlier in a single zone. We then extend the analysis to multiple zones and we discuss the ensuing inefficiencies.

The result presented here assumes a truthful merit order curve $MC(x)$, which is strictly monotonic increasing, as well as a nominal balancing capacity P^{max} which is greater than the upper bound of the distribution of the random demand for balancing energy.

A. Single-zone

Proposition 5 (Equilibrium – "No Adder" and "RT market for reserve")**.** *The Nash equilibrium generated by fringe agents under the "no adder" and "RT market for reserve" design are characterized by all agents participating truthfully in the balancing energy auction and the following platform price:*

$$\lambda_B(x) = MC(x).$$

Proof. The agents' optimal strategies consisting of bidding truthfully are independent between agents. This behavior, coupled with the balancing energy auction selecting bids in increasing price order, results in the platform price following the merit order and being strictly monotone increasing. The strict monotonicity confirms the validity of propositions 1 and 4. □

We now define $\lambda_B(x, \alpha)$ as the platform price for energy demand x, a total of α MWh of reactive balancing from the cheapest BSPs with upward balancing capacity, and with other BSPs bidding truthfully. The platform price in this situation is characterized as follows.

$$\lambda_B(x,\alpha) = \begin{cases} MC(x-\alpha) & \text{if } x \leq \alpha, \\ MC(x) & \text{else} \end{cases} \tag{12}$$

If $x \leq \alpha$, $x - \alpha$ MWh of downward balancing capacity has to be activated in order to balance the excessive self-activation by the agents, resulting in $\lambda_B(x,\alpha) = MC(x-\alpha)$. If $x > \alpha$, there is no price distortion and $\lambda_B(x,\alpha) = MC(x)$.

In a single-zone setting, the reserve component is not impacted by the level of reactive balancing, due to the presence of downward balancing capacity. To see this, note that if the level of reactive balancing is greater than the demand for balancing energy, then the potential curtailment of downward balancing capacity that was dispatched to cover the excessive reactive balancing can be assimilated as upward balancing energy. In case of an increased demand for balancing energy, reducing the level of the dispatched downward balancing capacity will help reduce the imbalance and not impact the level of upward balancing capacity.

The opportunity cost of participating in the balancing auction given a level α of self-balancing from the cheapest agents with upward balancing capacity for an agent with marginal cost C is characterized as follows:

$$\begin{aligned} z(\alpha, C) =& (\mathbb{E}_\mu[\lambda_B(\cdot,\alpha) + \lambda_R(\cdot)] - C) \\ & - \int_{\lambda_B(x,\alpha)\geq C} (\lambda_B(x,\alpha) - C) d\mu(x). \end{aligned} \tag{13}$$

If $z(\alpha, C) < 0$, an agent with marginal cost C should bid truthfully in the balancing auction for a level α of reactive balancing. If $z(\alpha, C) > 0$, the agent should self-activate its capacity.

Proposition 6 (Equilibrium – Adder on BRPs)**.** *If $z(\alpha, MC(\alpha))$ is continuous, there exists a unique Nash equilibrium generated by fringe agents under the "adder on BRPs" design characterized by an equilibrium level of reactive balancing, α^*, such that $0 \leq \alpha^* \leq P^{max}$, and with other BSPs bidding truthfully. This optimal level of reactive balancing is equal to (i) 0 if $z(0, MC(0)) < 0$, (ii) P^{max} if $z(P^{max}, MC(P^{max})) > 0$ or (iii) α^* characterized by the identity*

$$z(\alpha^*, MC(\alpha^*)) = 0. \tag{14}$$

This equilibrium level of reactive balancing generates platform prices equal to $\lambda_B(x, \alpha^*)$.

The existence of an equilibrium relies on the continuity of z. The stability of α^* is derived analytically. Stability in this context refers to a level of reactive balancing for which no agent has an incentive to deviate from their decision. BSPs after α^* on the merit order prefer to participate in the balancing auction and agents before α^* prefer resorting to reactive balancing. The uniqueness of the equilibrium results from the monotonicity of z. The complete proof can be found in the electronic supplement.

Note that assuming a positive distribution for the demand for balancing energy results in z being continuous. Under this assumption, the probability of a particular demand is infinitesimal. Discrete random demand can generate a price indeterminacy if the level of reactive balancing is equal to the imbalance. This breaks the continuity of z and an example of a system without a pure-strategy equilibrium can be found in the appendix.

Proposition 7 (Equilibrium – Adder on BRPs and BSPs)**.** *If $MC(x)-\lambda_R(x)$ is strictly monotonic increasing, there exists a*

TABLE III
OFFER CURVES UNDER DIFFERENT DESIGNS.

Design in zone i	$B_i(x)$
No adder	$MC_i(x)$
Adder on BRPs and BSPs	$MC_i(x) - \lambda_{R,i}(x)$
Adder on BRPs	$\begin{cases} MC_i(x-\alpha_i) & \text{if } x \leq \alpha_i \\ MC_i(x) & \text{else} \end{cases}$
RT market for reserve	$MC_i(x)$

Nash equilibrium generated by fringe agents under an "adder on BRPs and BSPs" design. It is characterized by all agents participating in the balancing energy auction and internalizing the value of the adder in their balancing energy bid. The produced platform price is described as follows:

$$\lambda_B(x) = MC(x) - \lambda_R(x).$$

Proof. The agents' optimal strategy is to bid at their marginal cost minus the scarcity component.This bidding behavior, coupled with the balancing energy auction selecting bids in increasing price order, results in the platform price following the merit order minus the scarcity component and being strictly monotonic increasing. The strict monotonicity confirms the validity of proposition 3. □

If $MC(x) - \lambda_R(x)$ is not strictly monotonic increasing, the optimal strategy derived in proposition 3 could modify the order of activation.

In terms of efficiency, the "no adder", "adder on BRPs and BSPs" and "RT market for reserve" designs support the optimal dispatch for a single zone, as they do not modify the order of activation specified by the truthful merit order. The "adder on BRPs" design increases the cost by inducing the dispatch of assets out of the merit order.

B. Multiple Zones

The characterization of an equilibrium in a setting with multiple zones requires introducing an aggregation operator $\cup$ for the aggregation of offer curves from different zones. Given $B_i(q)$, the offer curve in zone i, the aggregated offer curve, $B(q)$, can be obtained through the aggregation operator, as follows.

$$B(q) = \cup_i B_i(q) = \{\pi : B_i(q_i) = \pi \text{ for all } i \text{ and } \sum_i q_i = q\}. \tag{15}$$

The optimal strategies derived in section III remain valid in a multi-zone setting, and are used in order to characterize offer curves under different designs, as shown in Table III. $\lambda_{R,i}$ is the reserve demand curve in zone i and α_i is the optimal level of self-activation in zone i.

For the "adder on BRPs" design, the opportunity cost function has to be modified in order to account for multiple zones. The assumption regarding the scarcity component not being impacted by the level of self-activation needs to be revisited. Excessive self-activation in a multi-zone setting is covered by activating downward balancing capacity from all zones. This reduces the total level of available upward balancing capacity in the zone with self-dispatched assets. This means that we need to characterize the scarcity component as a function of both the level of aggregated demand for balancing energy over all zones, as well as the level of self-activation in the zone with the "adder on BRPs", $\lambda_R(x, \alpha)$, and to update the opportunity cost of self-activation, as follows.

$$\begin{aligned} z(\alpha, C) = {} & (\mathbb{E}_\mu[\lambda_B(\cdot, \alpha) + \lambda_R(\cdot, \alpha)] - C) \\ & - \int_{\lambda_B(x,\alpha) \geq C} (\lambda_B(x, \alpha) - C) d\mu(x), \end{aligned} \tag{16}$$

This modifies the condition for an equilibrium level of self-activation and might lead to multiple equilibria if $z(\alpha, MC(\alpha))$ is not strictly monotonic decreasing in α.

Two conclusions can be drawn from the aggregation of the offer curves presented in table III. First, only the introduction of a "RT market for reserve" does not affect the optimal dispatch induced by the aggregation of the truthful merit order curves. Both the "adder on RBPs and BSPs" and the "adder on BSPs" modify the bidding incentives in the zone implementing it and result in a suboptimal aggregated offer curve. Second, the suboptimal aggregated offer curves generate lower platform prices than the one generated by the aggregation of the truthful merit-order curves.

V. ILLUSTRATION ON A STYLIZED EXAMPLE

The examples presented in this section assume a maximum level of upward balancing capacity P^{max}, and a BSP merit order curve $MC(x)$ which is a function of the level of demand for balancing energy, x. The demand is drawn from a known distribution with probability measure μ. The scarcity component λ_R is obtained from an operating reserve demand curve defined as a function of the level of demand for balancing energy in the system.

This section presents three examples: (i) a single-zone example without information on the level of demand for balancing energy in the system, (ii) a single-zone example with information on the level of demand for balancing energy and (iii) a multiple-zone example with information on the level of demand for balancing energy.

A. Example 1: Single Zone without Information on the Demand for Balancing Energy

In this example, we assume that the demand is uniformly distributed between -100 and 100 and that the merit order curve is described as follows:

$$MC(x) = x/2 + 60. \tag{17}$$

The scarcity price component is defined as

$$\lambda_R(x) = \begin{cases} 0 & \text{if } x \leq 0, \\ x/6 & \text{else,} \end{cases} \tag{18}$$

which can be equivalently formulated as a function of the leftover capacity in the system, $\lambda_R^r(r)$, assuming a maximum level of balancing capacity in the system P^{max}, equal to 200 MW in our case.

$$\lambda_R^r(r) = \lambda_R(P^{max} - r) = \begin{cases} (P^{max} - r)/6 & \text{if } r \leq P^{max}, \\ 0 & \text{else.} \end{cases} \tag{19}$$

TABLE IV
EXAMPLE 1

	No adder	Adder on BRPs and BSPs	Adder on BRPs	RT market for reserve
$\mathbb{E}_{\mu}[\lambda_B]$ (€/MWh)	60.00	55.83	60.00	60.00
$\mathbb{E}_{\mu}[\lambda_R]$ (€/MWh)	0.00	4.17	4.17	4.17
α (MWh)	0.00	0.00	0.00	0.00
Activation cost (€)	833.38	833.38	833.38	833.38

All BSPs (i) bid truthfully under the no-adder and RT market for reserve design, thus $\lambda_B(x) = MC(x)$ (see proposition 5); (ii) bid at their marginal cost minus the level of the adder at their position on the merit order under the adder on BRPs and BSPs design, thus $\lambda_B(x) = MC(x) - \lambda_R(x)$ (prop. 7); (iii) bid in the balancing energy auction at their marginal cost under the adder on BRPs design, thus $\lambda_B(x) = MC(x)$ (prop. 6). No BSP does reactive balancing, as the opportunity cost of the cheapest generator when no asset is self-activating is negative If participating in the balancing auction is more profitable for the cheapest generator then this is also the case for every generator.

Table IV presents the expected platform price, the expected scarcity component, the level of self-activation, and the cost of reserve activation under the four designs. The four designs result in the same activation cost as the merit order is not distorted.

B. Example 2: Single Zone with Information on the Demand for Balancing Energy

In this example, BSPs have some information on the level of demand that the system will be exposed to, and are specifically aware of the sign of the required balancing activation. Specifically, we assume a draw with a probability 0.5 of having a negative demand that is distributed uniformly between -100 MW and 0 MW and a probability 0.5 of having a positive demand that is distributed uniformly between 0 MW and 100 MW.

All the parameters are identical to the previous example. The BSPs' strategy under the "no-adder," "adders on BRPs and BSPs" and "RT market for reserve" designs are not modified by the introduction of information on the imbalance, but there is an impact on the "adder on BRPs" design. The optimal level of reactive balancing in the "adder on BRPs" design is (i) 0 MW if the system imbalance is in the interval $[-100, 0]$ MW, and (ii) 33.33 MW if the system imbalance is in the interval $[0, 100]$ MW. The optimal level of reactive balancing is found by resolving the identity of Eq. (14) for α, the level of self-activation. In the first interval, no generator self-balances, as $z(\alpha, MC(\alpha)) \leq 0$ for all α. For the second interval, $\alpha = 33.33$ MW does satisfy the identity. This process is illustrated graphically in Fig. 2 by splitting the opportunity cost between the balancing auction and reactive balancing component.

The platform prices for the four designs are presented in Fig. 3 as a function of the level of demand for balancing energy. Agents bid truthfully under the "no adder" and "RT market for reserve" designs, and they internalize the reserve adder under the "adder on BRPs and BSPs" design. Some

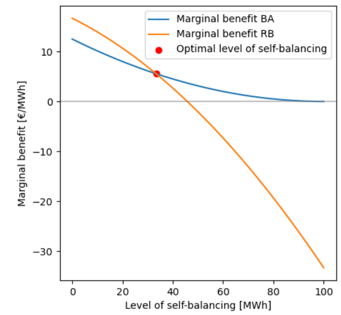

Fig. 2. Comparison of marginal benefit of reactive balancing and balancing auction for the frontier agent in the case of example 2.

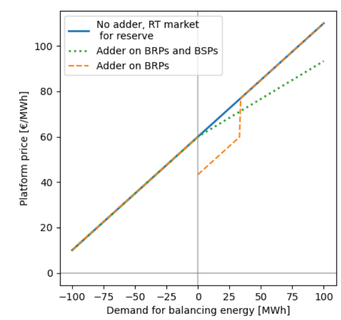

Fig. 3. Offer curve in example 2.

of the BSPs decide to do reactive balancing if they know that the demand will be between 0 MW and 100 MW. This self-activation results in a translation of the merit order curve for negative balancing activation up to the level of reactive balancing.

The metrics concerning both intervals are presented in the first two columns of Table V. Columns 3 and 4 compare the result for the "adder on BRPs" design with and without self-activation. The reactive balancing results in an inefficient dispatch that increases the total activation cost of the system. It also decreases the platform price, which is beneficial to the BRPs.

C. Example 3 – Multiple Zones with Information on the Demand for Balancing Energy

We now refer to the system mentioned in examples 1 and 2 as zone B, and connect it to a new zone with an unlimited interconnector capacity between the two zones. The system in

TABLE V
EXAMPLE 2 – COMPARISON ON THE LEVEL OF INFORMATION ON THE DEMAND FOR BALANCING ENERGY FOR THE "ADDER ON BRPS" DESIGN.

Information level	Some			None
Imbalance interval	[-100.0]	[0.100]	[-100.100]	[-100.100]
$\mathbb{E}_{\mu}[\lambda_B]$ (€/MWh)	35.00	79.42	57.21	60.00
$\mathbb{E}_{\mu}[\lambda_R]$ (€/MWh)	0.00	8.33	4.17	4.17
α (MWh)	0.00	33.33	16.67	0.00
Activation cost (€)	-2166.63	3925.99	879.68	833.38

TABLE VI
EXAMPLE 3 – EXPECTED PRICES (€/MWH)

	No adder	Adder on BRPs and BSPs	Adder on BRPs	RT market for reserve
Platform price	60.00	59.07	58.37	60.00
Scarcity component	0.00	4.64	8.72	3.40
Balancing price (zone B)	60.00	63.71	58.37	63.40
Imbalance price (zone B)	60.00	63.71	67.08	63.40

this new zone, called zone D, is four times larger than the one in zone B, resulting in a less steep merit order curve (see Eq. (20)).

$$MC_D(x) = x/8 + 60 \tag{20}$$

The example is intended to mimic, in a highly stylized setting, the interaction between Belgium and Germany, hence the initials of the zones. We limit the exposition to the 2-zone case with zone D implementing a “no adder” policy in order to outline the effect of the pricing asymmetry between the zones, since this has also dominated the policy discussion thus far [31].

The demand in zone D is distributed as in example 2, except for the distributions being uniform between 0 MW and 400 MW, and -400 MW and 0 MW. The combination of the probability distributions in zone B and zone D results in a equiprobable four-branch probability tree with distribution $\mathcal{U}[0,100] + \mathcal{U}[0,400]$ MW, $\mathcal{U}[0,100] + \mathcal{U}[-400,0]$ MW, $\mathcal{U}[-100,0]+\mathcal{U}[0,400]$ MW, and $\mathcal{U}[-100,0]+\mathcal{U}[-400,0]$ MW.

The equilibrium prices are presented in Table VI and Fig. 4 compares the surplus distribution with respect to the “no adder” benchmark. They are based on the aggregated offer curves that are generated from the optimal BSP bids in zone B and D. The aggregated curve is constructed with Eq. (15) and are described in section IV of the electronic supplement. Consumer surplus refers to the cost of serving the inelastic BRP imbalance plus the capacity cost borne by all the consumers of zone B or D.

The platform prices from the “adder on BRPs and BSPs” and the “adder on BRPs” design are lower than the ones in the designs that induce truthful bidding, due to the lower offer curve in zone B. These altered offer curves result in an over-dispatch of the assets in zone B, and in an increased level of adders compared to the “RT market for reserve” design. The self-activation of assets for the “adder on BRPs” design generates particularly high imbalance prices in zone B.

Three adverse effects resulting from the “adder on BRPs and BSPs” and the “adder on BRPs” designs can be observed. First, the induced out-of-merit activations lead to an increased activation cost and an inefficient dispatch which could potentially go against the guidelines outlined in article 3(m) of the Clean Energy Package [32].

Second, these designs give rise to cross-zonal distributive effects between consumers. The cost of decreasing the platform price is borne by the consumers in zone B, either

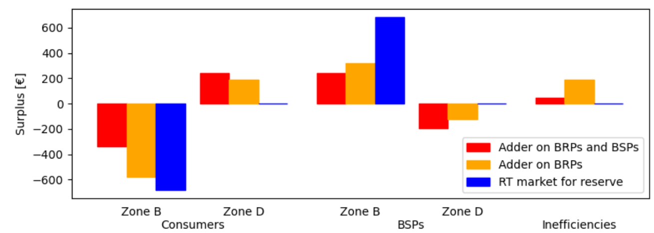

Fig. 4. Differences in surplus compared to the ”no-adder” benchmark (€).

through an increased imbalance price or through the capacity cost. This suggests that the consumers in the zone with the adder subsidize the consumption of the consumers in the zone without the adder.

Third, these designs result in discrimination between BSPs from different zones. At similar marginal costs, BSPs in zone B are more likely to be activated than BSPs in zone D due to the increased balancing price or the possibility of resorting to reactive balancing. This leads to an increased surplus for BSPs in zone B compared to the “no-adder” benchmark and an opposite effect for zone D.

Only the “RT market for reserve” manages to introduce adders without inducing inefficiencies. In addition, this design only influences the surplus distribution between BRPs and BSPs in zone B and does not generate cross-zonal distributional effects.

The complete characterization of the equilibrium prices and surplus for each branch of the probability tree and for both zones can be found in the electronic supplement.

VI. CONCLUSION

This paper investigates the unilateral application of a balance-incentivizing component, or adder, in a cross-border setting. An analytical model is used in order to characterize the optimal strategies of flexibility providers under three different designs: the “adder on BRPs” design where the adder is applied to the imbalance price, the “adder on BRPs and BSPs” design where the adder is applied to the balancing and imbalance price and the ”‘RT market for reserve” design that sees the introduction of a balancing capacity market. Market equilibria are derived based on these optimal strategies, extended to the cross-border setting, and illustrated on a two-zone example.

Adders, either on the imbalance price or on the balancing and imbalance price, without a RT market for reserve, induce out-of-merit dispatch and increase the activation cost that is required for balancing the system. In a cross-border setting, this increased cost is borne by the consumers in the zone with the adder, as they face higher balancing and imbalance prices, whereas consumers in other zones enjoy lower prices. The introduction of a RT market for reserve restores the truthful bidding incentives and ensures that the increased consumer cost in a zone, due to the adder, is fully distributed back to the flexibility supplier in that zone.

In future work, we are interested in extending the analysis to equilibria for multiple products (aFRR and mFRR) on cross-border balancing platforms. An alternative direction of future work would apply the present methodology for investigating cross-zonal distributional effects between the Iberic peninsula and mainland Europe in the context of the ongoing European gas crisis.

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