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Strategic behavior of Virtual Power Plants (VPP) in EU balancing markets: exploring the impact of control

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Abstract

As electricity systems transition toward decarbonization, regulatory frameworks must adapt to the rise of Distributed Energy Resources (DERs) and their aggregation into Virtual Power Plants (VPPs). This paper examines how increased controllability from DERs within VPPs affects market participants' incentives to create imbalances. System imbalances—real-time mismatches between total generation and consumption—determine the need for corrective balancing actions and the associated settlement payments. Using a strategic bidding model adapted from prior literature and calibrated across five European markets (Germany, France, Spain, the Netherlands, and Denmark), we simulate VPP behavior under varying levels of portfolio controllability. Our findings suggest that while moderate control mitigates imbalances, excessive control exacerbates imbalances during periods of extreme market prices. These behaviors shift the source of VPP profits from unintentional imbalances to deliberate market arbitrage, challenging the regulatory assumption that imbalances are purely accidental. The results suggest that current imbalance settlement rules may need to be revised to address the strategic potential of increasingly controllable actors in future electricity systems.

1 Introduction

One of the central challenges for regulators in liberalized electricity systems is that competition can require that the regulation be adapted to new technologies, if the differences between them and existing ones are so substantial that they can inhibit the gain of efficiencies from the technological innovations or even more to prevent new inefficiencies arising from their interaction with current rules. A clear example of this challenge can be observed in the extensive body of literature that has examined the integration of wind and solar power over recent years (Bell & Gill, 2018; Inês et al., 2020; Joskow, 2022; Pérez-Arriaga et al., 2017).

This paper examines a similar type of regulatory challenge by investigating how Virtual Power Plants (VPPs) impact the functioning of balancing mechanisms in the European Union (EU). VPPs coordinate multiple Distributed Energy Resources (DERs)—such as electric vehicles (EVs), heat pumps, and other flexible assets—so that, collectively, they can meet the minimum size thresholds required for participation in energy markets (Ghavidel et al., 2016). When aggregated into VPPs, advanced DERs—such as EVs, home energy management systems, and heat pumps—exhibit two key characteristics that may present significant regulatory challenges. First, their sophisticated electronic and communication capabilities allow them to adjust generation or consumption across distributed locations almost instantaneously and at negligible cost (Pasetti et al., 2018). This operational flexibility may expand the strategic space of VPPs relative to centralized generators such as wind or gas plants.

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Second, the availability of these resources depends on the behavior of asset owners, who typically prioritize their own energy needs over supplying power or curtailing consumption to benefit the electricity system (Valentine et al., 2011). As a result, regulators might face difficulties in assessing the true capacity of VPPs without direct access to usage data or the algorithms VPPs employ to forecast their availability—unlike, for example, the more transparent data on wind forecasts or utilization rates used for thermal plants.

In alternating current (AC) electric systems, maintaining a constant balance between electricity supply and demand is essential, as even minor deviations can threaten grid stability. Balancing mechanisms (Just & Weber, 2015) refer to the institutional arrangements for managing electricity system imbalances in real-time, i.e., for eliminating deviations from the scheduled withdrawal/injection of energy by the actors connected to the network at the system level. Previous research on VPP integration has highlighted the need for regulatory changes to enable DER participation in providing balancing services, which implies that a VPP composed of DERs is paid for correcting the system imbalances; the focus has been on analyzing the minimum conditions and efficiency impacts of current market regulation which has been shown many times of being ill-suited to take the maximum advantage of VPP and DER technologies (Barbero et al., 2020; Borne et al., 2018; Schittekatte et al., 2021). In addition to this, to our knowledge, the VPP integration from the demand side of the balancing mechanism, which is mostly the regulatory framework that incentivizes each actor connected to the network to be responsible for any imbalance created in the system and encourages them to reduce the cost of system imbalance, has been overlooked from the VPP perspective.

Nevertheless, the main EU regulation on balancing mechanisms defines that each national regulatory authority should ensure that the transmission system operator (TSO), which is responsible for maintaining real-time balances of electricity systems, neither incurs economic gains nor suffers losses from the financial outcomes of balancing the system (ENTSO-E / ACER, 2020; European Commission, 2017). Thus, any positive or negative financial results from the procurement of balancing services must be neutralized and passed on to the network users, who are designated as balancing responsible parties (BRPs) and consider several types of market actors, such as generators, retailers, and potentially VPPs acting as both. The process of transferring balancing costs to the BRP is primarily divided into three main stages: allocating balancing responsibility across specified perimeters, observing deviations from the scheduled position of each perimeter, and matching aggregated imbalance levels with balancing supply. In the first stage, all assets of the systems are assigned to a perimeter in which a BRP takes responsibility for any deviations between the aggregate real-time physical position of the assets belonging to their perimeter and the one they contracted in the energy markets—typically closed from 15 minutes up to several hours or days before real-time operation. The TSO is responsible for the second stage: observing each BRP's perimeter deviation, referred to as private imbalances, and netting them all to assess the imbalance at the system scale, hereafter referred to as the system imbalance. In the third stage, the TSO activates assets previously contracted with Balancing Supply Providers (BSPs) to eliminate system imbalances and oversees the financial rewards or penalties of BRPs. Depending on the alignment between a BRP's private and system imbalances, the BRP may be penalized or remunerated with an imbalance price.

An important point of discussion among academics and regulators, who have focused on the balancing mechanisms from the perspective of the demand for balancing and thus from BRPs' incentives, has been if current regulation allows BRPs to strategically create imbalances to benefit from passive balancing payments or exploit market arbitrage opportunities from the spread between the imbalance price and the electricity price in short-term energy markets. One position, as described by Eicke et al. (2021) that is aligned with the current EU regulatory framework on balancing markets (ENTSO-E / ACER, 2020; European Commission, 2017), adopts a "linear" perspective. This view sees system imbalances as the outcome of stochastic forecasting errors or consumption variability, implying that there is too much uncertainty for a BRP to predict system imbalances and therefore balancing prices, thus reducing the incentives for deliberate strategic imbalances (Hirth & Ziegenhagen, 2015; Joos & Staffell, 2018; Ocker & Ehrhart, 2017). This line of thought proposes that strategic deviations are not a significant concern. In contrast, a second perspective is the "feedback-loop" or circular perspective, which suggests that system imbalances and market prices are not purely random, and are a consequence of strategic behaviors which acknowledge the full sequence of energy and balancing markets, and from which BRPs can increase profits by intentionally creating imbalances or creating scarcity in short-term energy markets to benefit of the imbalance-price spread (Just & Weber, 2015; Möller et al., 2011; Van Der Veen et al., 2012).

The challenge is that both positions have received some empirical support. For instance, Koch and Hirth (2019) and Joos and Staffell (2018) provide evidence in favor of the linear perspective by showing that the current balancing market design has reduced the frequency of balancing activations in Germany. This outcome is attributed to the efficient integration of intermittent renewable energy sources, particularly wind power. This phenomenon, where an increasing share of variable generation has not led to higher balancing needs, has been termed the German paradox (Ocker & Ehrhart, 2017). In contrast, studies supporting the feedback-loop perspective have emphasized the predictability of balancing prices and the potential for strategic behavior. For example, Bunn et al. (2020) and Lisi and Edoli (2018) demonstrate that balancing prices in the United Kingdom and Italy, respectively, exhibit patterns that can be anticipated. In the German context, Eicke et al. (2021) and Koch and Maskos (2020) show that incentives for strategic deviations do exist, suggesting that actors may respond to predictable market conditions in ways that current regulations may not fully anticipate.

While the evidence supporting the linear perspective has yielded important insights—particularly regarding the relationship between balancing markets and intermittent renewables (Hirth & Ziegenhagen, 2015)—its applicability to VPPs is limited. The controllability of the DERs differs significantly from that of wind generators, whose output is largely determined by uncontrollable weather conditions, and the degree of adjustments that can be made in real-time is more limited. In contrast, a VPP composed, for example, of bidirectional EVs could switch from charging to discharging within seconds, or even simultaneously charge some vehicles while discharging others. This high controllability could potentially expand the range of strategic actions available to BRPs, while at the same time making it very difficult for the regulator to monitor, if it were a consequence of a stochastic nature, as the "linear perspective" proposes. As a consequence of this, it becomes increasingly important for regulators who are planning to encourage the uptake of VPPs into energy markets to ask the following research question: *Does asset controllability challenge the efficiency of the current balancing market design in the EU?*

To answer the research question, we adapted the approach from previous research by Van Der Veen et al. (2012) on BRPs and balancing markets, formalizing control through a parameterization of a decision variable as a mix between a stochastic and deterministic variable, reflecting varying degrees of controllability over the portfolio of a VPP. Then, we characterize the two main types of strategic behavior that VPPs could implement that are negative from a system perspective: mainly, imbalances that exacerbate the system imbalance and remunerate the VPP, and imbalances that are costly for the VPP but are overall profitable for the VPP. We calibrate the model across five European markets: Germany, France, Spain, the Netherlands, and Denmark, which allows us to account for differences in market design and energy prices within the EU. For each country, we compare the incentives for creating imbalances according to varying degrees of controllability.

The results of the numeric calibration of our model reveal that increasing controllability consistently enhances the profitability of BRPs, primarily through more efficient participation in energy and retail markets. However, this rise in profits is accompanied by higher imbalance penalties, suggesting that greater controllability expands BRPs' strategic space rather than simply improving operational accuracy. Notably, controllability does not significantly increase the total volume of imbalances. Still, it alters their composition—leading BRPs to adopt shorter net positions and, in some cases, to benefit from system-adverse imbalances. More importantly, controllability strengthens incentives for market-arbitrage-driven imbalances, particularly during periods of high prices. Overall, our results suggest that controllability poses a challenge to the current balancing market framework because enhanced controllability introduces both efficiency gains and new strategic behaviors.

This paper makes three main contributions mainly to the literature on balancing markets and the regulation of VPPs in electricity systems, but it also has important implications for every other type of BRPs that have assets with high degree of controllability, such as stationary battery storages. First, we contribute empirically by providing quantitative evidence on how controllability affects the creation, direction, and profitability of imbalance across several European countries. Second, we show that greater controllability provides BRPs with economic incentives to increase profits by deliberately creating imbalances during periods of high energy prices, thereby potentially having a larger impact on energy markets. These results extend the findings of Just and Weber (2015) by providing additional evidence on how incentive distortions can arise not only from large price spreads between spot and imbalance markets but also under relatively small spreads. Furthermore, our results challenge the notion that a two-price imbalance system can effectively mitigate strategic behavior, as controllability appears to generate incentive problems across both one- and two-price designs. Finally, through our modeling framework and calibration, we bridge two dominant perspectives in the literature on balancing mechanisms. When controllability is low, imbalances primarily reflect stochastic fluctuations in consumption and generation—consistent with the linear perspective (Hirth & Ziegenhagen, 2015; Joos & Staffell, 2018; Ocker & Ehrhart, 2017). However, as controllability increases, VPPs act strategically and anticipate market conditions, aligning with the feedback-loop perspective (Just & Weber, 2015; Möller et al., 2011; Van Der Veen et al., 2012). Our framework, therefore, provides a unified way to reconcile both perspectives through the degree of controllability.

The paper is structured as follows: Section 2 presents our model. Section 3 details the calibration of the model and provides an overview of the regulatory frameworks in the countries analyzed. In Section 4, we discuss our contributions to the literature, the policy implications of our results, and limitations, as well as future avenues of research. Finally, in Section 5, we present our conclusions.

2 Methodology

This section formalizes the optimal behavior of a VPP aggregator through a model that builds on previous research relating to BRP (Van Der Veen et al., 2012), to which we add the particularities of parameterizing different levels of control, to analyze how controllability affects their incentives for strategic deviations. Then, we distinguish between different types of strategic deviations, which relate either to balancing market-only manipulations or to arbitrage incentives along the sequence of energy and balancing markets.

2.1 Model of aggregator

We begin by detailing our model of a VPP aggregator, which is also a BRP and participates in both day-ahead and intraday markets, before being rewarded or penalized by the TSO at the balancing stage. ompared to Van Der Veen et al., 2012, the main difference lies in the representation of the partial controllability of the VPP's assets.

2.1.1 BRP Framework

We consider a BRP that manages a portfolio of DERs and simultaneously acts as their electricity retailer through a VPP. he DERs may include EVs, heat pumps, rooftop photovoltaic (PV) systems, smart appliances, and other distributed or responsive assets.

For each Program Time Unit (PTU), denoted by the index t, which represents the smallest time interval in electricity markets according to the specific regulation of each country, the BRP, as part of its balancing responsibilities, communicates its expected consumption $\mathbb{E}[c_t]$ and expected generation $\mathbb{E}[s_t]$ to the system operator, who is responsible for maintaining the overall system balance.

To ensure internal balance within its portfolio, the BRP must communicate its schedule and decide on a net contracted market position q_t^c such that the following balancing condition is satisfied in expectation:

$$\mathbb{E}[I_t] = \mathbb{E}[s_t] - \mathbb{E}[c_t] + q_t^c \approx 0 \tag{1}$$

Where I_t is the real-time imbalance of the VPP and q_t^c denotes the net energy volume procured through wholesale electricity markets—specifically the day-ahead (DA) and intraday (ID) markets, which close approximately one day and 15 minutes before real-time, respectively. ote that the nullity of expected imbalances is not a constraint *per se* of the VPP's operations constraint, but is imposed through rewards and penalties paid to the TSO at the balancing stage and appearing in the VPP's objective function. pecifically, this nullity condition only reflects the ideal result of a balancing market from the TSO's perspective.

We subsequently divide the net contracted market position into positions taken in the day-ahead and intraday markets, and thus define:

$$q_t^c = q_t^{da} + q_t^{id}, \tag{2}$$

With q_t^{da} and q_t^{id} representing the contracted volumes (in MWh) on the DA and ID markets, respectively. he net-contracting capacity is constrained by the BRP's physical flexibility, characterized by the upward bidding capacity $\widehat{K}$ and the downward bidding capacity $\check{K}$, both approved by the system operator.

$$-\check{K} \leq q_t^{da} + q_t^{id} \leq \widehat{K}. \tag{3}$$

Under the 'linear' perspective (Eicke et al., 2021; Hirth & Ziegenhagen, 2015; Joos & Staffell, 2018; Ocker & Ehrhart, 2017), the BRP aims to neutralize expected deviations, such that the realized net imbalance is purely due to forecast errors. n this case, the real-time deviation in expectations is modeled as:

$$\mathbb{E}[I_t] = \mathbb{E}[\epsilon_t], \tag{4}$$

Where ϵ_t captures the aggregate forecast error in consumption and generation. his approach assumes that the BRP has no incentive to intentionally deviate from its contracted schedule.

However, to explore the possibility of *strategic deviations*, we adopt the framework proposed by Van Der Veen et al. (2012), shifting the perspective from modeling deviations as passive outcomes of forecast errors to treating them as *active decisions*. We assume that the BRP receives forecasts of consumption and generation—possibly as the output of an external optimization procedure—and that its primary decision after the markets close is to select an upward real-time imbalance action x_t or downward real-time imbalance action y_t, representing a deliberate deviation from the contracted position q_t^c.

$$I(x_t, y_t)_t = \epsilon_t + x_t - y_t, \tag{5}$$

This formulation is justified in contexts where the BRP has the technical capability to control DERs (e.g., through power electronics) and the legal authority to exercise such control. nder these conditions, the imbalance strategy is constrained by both the position taken by the BRP in the energy markets and the BRP's physical flexibility, characterized by the upward bidding capacity $\widehat{K}$ and the downward bidding capacity $\check{K}$, as we have stated before. ne can determine the maximum allowable deviation in net injection—either upward (an increase in supply or a reduction in consumption) or downward (a reduction in supply or an increase in consumption).

The interval of feasible net-imbalance actions is therefore given by:

$$-(\check{K} + \widehat{K}) \leq x_t - y_t \leq (\check{K} + \widehat{K}). \tag{6}$$

In what follows, we introduce the concept of VPP control as a mechanism to capture how different degrees of controllability over DERs can influence the strategic incentives of the BRP.

2.1.2 Controllability

We introduce the concept of control as the ability of the BRP to strategically influence real-time dispatch or consumption by actively managing the consumption and production of its DERs. t models that while a BRP may aim to realize specific upward or downward imbalance y_t, the actual net consumption or production is influenced by uncertain and only partially controllable DER behavior. hus, we define the real-time energy position q_t^r as a convex combination of a forecast-based estimate and the intentional imbalance decision: $q_t^r = q_t^c + \beta.(x_t - y_t) + (1-\beta).\varepsilon_t$. Here, $\beta \in [0,1]$ represents the degree of control. value of $\beta = 1$ implies full control, while $\beta = 0$ implies no control over deviations. Hence, the VPP's imbalances are redefined to account for controlled imbalance decisions:

$$I(x_t, y_t)_t = (1-\beta)\cdot\varepsilon_t + \beta\cdot(x_t - y_t). \tag{7}$$

In the remainder, we consider that $\varepsilon_t \sim \mathcal{N}(0, \sigma^2)$ is a zero-mean normally distributed random variable capturing forecast errors or behavioral uncertainty in DER operation.

2.1.3 Objective Function

The VPP, acting as a BRP, seeks to maximize its expected profit over a planning horizon by coordinating its participation in electricity markets and managing the flexibility of its VPP. he total profit at each PTU, t, is composed of three main components:

1. *Wholesale market revenues:* These arise from the BRP's participation in the day-ahead and intraday electricity markets, where buying and selling quantities are scheduled ahead of delivery. ince market prices are not known during decision-making, the BRP is assumed to be risk-neutral and a price-taker, so it formulates its strategy based on its expected values. holesale market profits then take the form:
$$\pi_t^e(q^{da}, q^{id}) = p_t^{da}\cdot q_t^{da} + p_t^{id}\cdot q_t^{id}, \tag{8}$$
where q_t^{da} and q_t^{id} are the scheduled quantities traded in the day-ahead and intraday markets, respectively.

2. *Imbalance cost or gain:* These arise from deviations between scheduled and realized consumption or production. he settlement prices for balancing energy are stochastic, and their expected values are used in the profit function. mbalance net gains for the BRP write
$$\pi_t^{im}(x_t, y_t) = b_t^{up}\cdot\max\{0, I(x_t,y_t)_t\} - b_t^{down}\cdot\max\{0, -I(x_t,y_t)_t\}, \tag{9}$$
where positive and negative part or total imbalance $I(x_t, y_t)_t$ denote upward and downward imbalances of the BRP. The BRP incurs a cost for upward imbalances when actual demand exceeds contracted quantity, and may be penalized (or rewarded) for downward imbalances when actual supply exceeds the contracted value. he sign and structure of imbalance prices reflect the EU regulatory framework, which defines separate settlement prices for upward and downward deviations from the reference price.

3. *Retail revenues:* These capture the income from supplying electricity to distributed energy resources (DERs), such as electric vehicles (EVs). etail tariffs are assumed to be either regulated or contractual and thus known during the decision-making process. etail revenues are also affected by post-energy-markets controlled deviations, so that they write as
$$\pi_t^r(x_t, y_t) = r_t\cdot\left(c_t + (1-\beta)\epsilon_t + \beta(x_t - y_t)\right), \tag{10}$$
where r_t is the retail tariff paid per unit of electricity.

The BRP's profit maximization problem at a given time t is thus formulated as the Sum of wholesale revenue, the expected retail, and the imbalance net gains influenced by decisions

$$\max_{x_t, y_t, q^{da}, q^{id}} \ \pi_t^e(q_t^{da}, q_t^{id}) + \mathbb{E}_t\left[\pi_t^r(x_t(\omega), y_t(\omega)) + \pi_t^{im}(x_t(\omega), y_t(\omega))\right] \tag{11a}$$

$$-\check{K} \le q_t^{da} \le \widehat{K} \tag{11b}$$

$$-\check{K} \le q_t^{id} \le \widehat{K} \tag{11c}$$

$$-\check{K} \le q_t^{da} + q_t^{id} \le \widehat{K} \tag{11d}$$

$$\forall\omega, -(\check{K} + \widehat{K}) \le x_t(\omega) - y_t(\omega) \le (\check{K} + \widehat{K}), \tag{11e}$$

where the constraints ensure that all successive decisions of the VPP remain physically feasible regarding its injection and withdrawal capacities. ith this formulation, energy market decisions are not anticipatory of balancing market-clearing prices and decisions; therefore, the sequence between energy and the balancing markets is modeled.

2.2 Measuring Strategic Deviations

2.2.1 Types of strategic deviations

Strategic deviations occur when a BRP intentionally diverges from its contracted schedule q_t^c by selecting upward (x_t) or downward (y_t) real-time imbalance actions to increase its profits. However, not all deviations are equally consequential for system operation. n this subsection, we define two that are most important to study.

To provide an intuition, Figure 1 provides a schematic representation of the classification of imbalance situations. oth the BRP imbalance and the system imbalance can be classified as either long (production exceeds consumption) or short (consumption exceeds production). his yields four possible combinations in a 2×2 matrix. n quadrants (a) and (d), the BRP imbalance acts in a complementary way to the system imbalance (for example, if the system underestimates consumption and requires additional energy, a BRP that is overproducing alleviates the system stress). n contrast, quadrants (b) and (c) represent the unfavorable cases, in which the BRP's deviation amplifies the imbalance of the system.

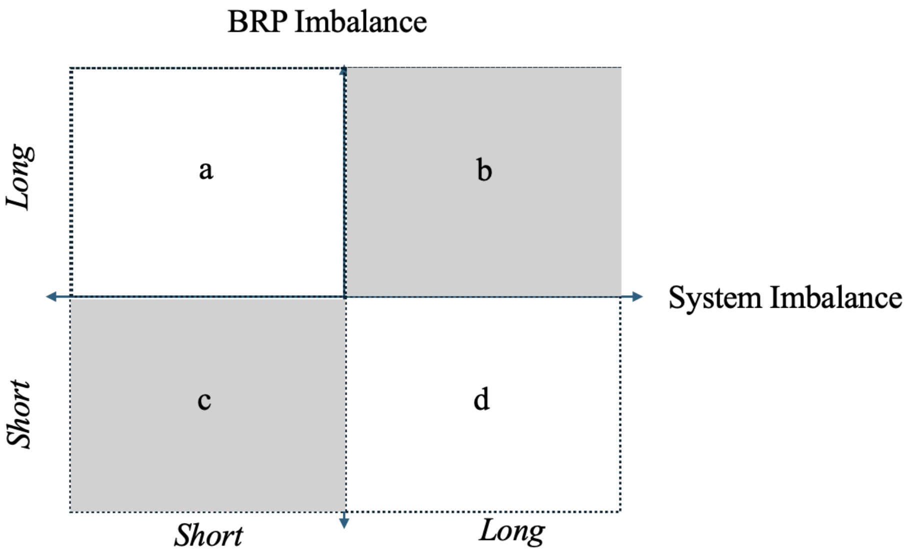

Figure 1: Favorable and unfavorable imbalances from the system perspective.

Building on the definition of unfavorable imbalances, we introduce a specific and potentially critical type of imbalance, which we formally term "Balancing-Driven Adverse Imbalance (BDAI)". This refers to imbalances for which the BRP receives remuneration for their creation, yet the imbalance is detrimental to the overall system.

The following provides a formal definition of this imbalance:

Definition 1 ()). *A BRP imbalance at time t constitutes an NRI if it simultaneously:*

1. *amplifies the existing system imbalance, and*
2. *yields a positive profit from the imbalance settlement.*

Formally, let $\pi_t^{im}(x_t, y_t)$ *denote the BRP's profit from imbalances at time* t*, and let* I_t^s *denote the system imbalance. Then, a deviation is an NRI if:*

$$NRI_t = \nVdash\Big(\pi_t^{im}(x_t, y_t) > 0 \ \wedge \ \big((x_t > 0 \ \wedge \ I_t^s < 0) \ \vee \ (y_t > 0 \ \wedge \ I_t^s > 0)\big)\Big), \tag{12}$$

where $\nVdash(\cdot)$ *is the indicator function.*

Second, is the case in which the imbalances result in the BRP paying a penalty while remaining profitable. n other words, these are the situations in which market arbitrage opportunities exist economically between intraday and balancing markets, making it profitable to pay a penalty whenever strategically creating an imbalance.

Definition 2 (Arbitrage-related imbalance penalties (ARIP))**.** *A BRP deviation at time* t *constitutes an ARIP if the following conditions hold:*

1. *The BRP incurs a negative profit from the imbalance settlement:* $\pi_t^{im}(x_t, y_t) < 0$*, but*
2. *The total expected profit, including wholesale and retail revenues, remains positive:*

$$\pi_t^{tot} = \pi_t^e(q_t^{da}, q_t^{id}) + \pi_t^r + \pi_t^{im}(x_t, y_t) > 0. \tag{13}$$

Thus, an imbalance is considered arbitrage-related when:

$$ARIP_t = \nVdash\Big(\pi_t^{im}(x_t, y_t) < 0 \ \wedge \ \pi_t^{tot} > 0\Big). \tag{14}$$

2.2.2 Indicators of strategic deviations

We propose three indicators to measure the relative impact of controllability on the incidence of (i) negative and remunerated imbalances, and (ii) arbitrage-related imbalance penalties.

To quantify the former, we introduce the *Unfavorable Passive Balancing (UPB)* indicator, which measures the share of the total imbalance volume (in MWh) corresponding to negative and remunerated imbalances. We use a volume-based indicator to capture both the likelihood and the material significance of imbalance events from a system perspective, Given that the cost of imbalances in balancing markets is proportional to the energy volume deviated from the scheduled position.

$$\text{UPB (\%)} = \frac{\sum_t \text{NRI}_t}{\sum_t |x_t - y_t|} \times 100, \tag{15}$$

where NRI_t denotes the volume of negative and remunerated imbalances at time t, and $x_t - y_t$ represents the net imbalance position.

The second indicator, the *Unfavorable Market Arbitrage Frequency (UMA-F)*, captures the frequency of imbalance penalties associated with market arbitrage opportunities. Because these effects are particularly relevant when market prices reach extreme levels, UMA-F focuses on imbalances occurring during periods when prices fall within selected tails of the price distribution.

$$\text{UMA-F (\%)} = \frac{\sum_{t \in F} \text{ARIP}_t}{\sum_t |x_t - y_t|} \times 100, \tag{16}$$

where t, and F denote the set of time t, in which p_t is the market price at, within a chosen price interval (e.g., the upper or lower 10% tails of the price distribution in energy markets).

3 Empirical Simulation of BRP Incentives Across Countries in Europe

3.1 Regulatory background of selected countries in Europe

The European balancing market is framed by two main regulatory pieces, the Guideline on Electricity Balancing Regulation (European Commission, 2017) and the Imbalance Settlement Harmonisation Methodology (ISH) (ENTSO-E / ACER, 2020). The former establishes a common framework for balancing market operations across the European Union. key provision of the regulation is that each national regulatory authority ensure that TSOs neither incur economic gains nor suffer losses from the financial outcomes of settlement processes. ny positive or negative financial results must therefore be neutralized and passed on to network users, ensuring the economic neutrality of balancing activities. he latter, ISH, was introduced in 2020 further to standardize the settlement of imbalances across EU Member States.

To perform the comparative analysis, the ideal setup would be to review most of the European balancing markets; however, much of the information necessary to estimate the incentives for strategic information, such as data on intraday auction results and continuous intraday data, remains private and is accessible only through the market operators. onsequently, the analysis focuses on Spain, where this data was publicly accessible, and four other countries for which we accessed their data through the EPEX Spot data service: France, Germany, the Netherlands, and Denmark.

Table 1 summarizes the main differences of the different regulatory frameworks for balancing markets, as reported in the last available balancing market report published by ENTSO-EU, the European association of TSOs (ENTSO-E, 2024). We have focused on summarizing the report for the selected countries by examining three key aspects of balancing market designs: the scope of the balancing perimeter, the methods of balancing procurement, and the characteristics of the imbalance price.

First, the scope of the balancing perimeter, in the case of Germany and Denmark, involves some particular considerations. or Germany, the balancing area covers the operation of Germany, together with Luxembourg, forming a common imbalance area. enmark, by contrast, is divided into two monitoring, bidding, and scheduling areas: DK1 (Western Denmark) and DK2 (Eastern Denmark). or the Netherlands, France, and Spain, the scope of the imbalance is the whole country.

Second, three important considerations for the design of a balancing market: (i) the dispatch model, (ii) the reserve dimensioning method, and (iii) the duration of the imbalance settlement period.

(i) The dispatch model determines how BRPs are responsible for their positions and how their imbalances are quantified. he ISH methodology (ENTSO-E / ACER, 2020) distinguishes between two primary models: self-dispatch and central dispatch. n the self-dispatch model, the BRP determines its own generation and consumption schedule, and its final position corresponds to the difference between its allocated energy and actual measured position. onversely, under the central dispatch model, the TSO issues dispatch instructions, and imbalances are calculated at the unit-dispatch level, meaning a BRP may hold several positions within a single imbalance area. Among the five countries analyzed, all—France, Germany, Spain, the Netherlands, and Denmark—apply the self-dispatch model.

(ii) The reserve dimensioning method specifies how and when balancing reserves are procured, influencing both system reliability and the shape of the balancing market's supply curve. rance applies a dynamic dimensioning approach, continuously adjusting required reserves throughout the day. ermany employs a probabilistic dynamic method for automatic and manual frequency restoration reserves (aFRR and mFRR), whereas Spain applies a dynamic approach only to aFRR. he Netherlands and Denmark do not explicitly report their dimensioning methods in public documentation, reflecting ongoing efforts at the European level to harmonize these methods.

(iii) The Duration of the imbalance settlement period (ISP) determines the temporal granularity at which imbalances are settled. armonization efforts led by ENTSO-E have progressively reduced the ISP to 15 minutes across Europe. s of 2025, all selected countries have transitioned to a 15-minute ISP, although France and Spain previously operated under longer durations (30 and 60 minutes, respectively) until the end of 2024.

Turning to the imbalance price formation, four elements are particularly relevant under the European Electricity Balancing Regulation: the pricing approach and three optional price components—the scarcity, incentivising, and financial neutrality components. The pricing approach defines whether a single or dual price is used to settle imbalances. Under a single-pricing model, both long (excess generation) and short (generation shortage) positions are decided at the same price, promoting neutrality and market liquidity. Under a dual-pricing model, different prices apply depending on the direction of the imbalance, potentially discouraging deviations that worsen the system imbalance. France, Germany, and Denmark apply a single-pricing model, while Spain and the Netherlands maintain dual-pricing systems.

Regarding the optional price components, they reflect the discretion of national regulators. Germany includes a scarcity component, intended to reflect system stress during periods of limited reserve availability. France and Germany apply an incentivising component, designed to encourage BRPs to remain within operational limits. Finally, France uniquely incorporates a financial neutrality component, ensuring that TSOs remain revenue-neutral in terms of imbalance settlements.

Table 1: Balancing Market Design Features in Selected European Countries (2024 - 2025). Adapted from ENTSO-E (2024)

Feature	**France**	**Germany**	**Spain**	**Netherlands**	**Denmark**
Imbalance area	France	Germany and Luxembourg	Spain	Netherlands	DK1 (East) and DK2 (West)
Balancing procurement and activation					
Dispatch model	Self-dispatch	Self-dispatch	Self-dispatch	Self-dispatch	Self-dispatch
Reserve dimensioning	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
Duration of imbalance settlement period	30 min until 2024, 15 min onwards	15 min	1 hour until 2024, 15 min onwards	15 min	15 min
Imbalance price					
Type	Single	Single	Dual	Dual	Single
Considers scarcity component	No	Yes	No	Yes	No
Considers incentive component	Yes	Yes	No	No	No
Considers financial neutrality component	Yes	No	No	No	No

3.2 Data and model calibration

We simulate a BRP's bidding behavior in day-ahead and intraday markets under different levels of control. The model is implemented for 10 scenarios, incrementing the control parameter by 0.1 in each scenario.

The interval of feasible net-imbalance actions is given by $-(\check{K} + \widehat{K}) \leq x_t - y_t \leq (\check{K} + \widehat{K})$ where $\check{K}$ and $\widehat{K}$ represent minimum and maximum feasible adjustments, with 1 MW resolution, considering both consumption and production.

The time series of the market data spans from 2024 to July 15th, 2025. The total range of data is available only for France, Germany, and Spain. For the Netherlands and Denmark, data is only available for 2025. For comparability among different periods, and to control for year effects in energy prices, we divide the analysis by year series; thus, we have a total of nine time series, given that Denmark considers two imbalance zones, DK1 and DK2.

Table 2 summarizes the nine country-year series included in the analysis.

Table 2: Data sources for market prices and system imbalances.

Country	**Year**	**System balancing**	**Market Prices**
France	2024	ENTSO-E	EPEX SPOT
France	2025[1]	ENTSO-E	EPEX SPOT
Germany	2024	ENTSO-E	EPEX SPOT
Germany	2025[1]	ENTSO-E	EPEX SPOT
Spain	2024	ENTSO-E	OMIE
Spain	2025	ENTSO-E	OMIE
Netherlands	2025	ENTSO-E [2]	EPEX SPOT
Denmark (Western, DK1)	2025	ENTSO-E	EPEX SPOT
Denmark (Eastern, DK2)	2025[1]	ENTSO-E	EPEX SPOT

The expected energy market prices assume that the BRP is drawn from a forecasted normal distribution centered at the corresponding true data price and with a standard deviation of 10.

For the parameters c_t and s_t, we utilize the normalized unitary consumption and wind production data for each country, sourced from ENTSO-E, along with the scenarios defined in the previous sections. he expected value of these parameters is modeled as a realization of a centered normal distribution with a standard deviation of 0.05.

The optimal decision is computed as a mixed-integer linear program at each time step and is solved using the Gurobi solver.

3.3 Findings

We organize our findings into three parts. irst, we present general results regarding the impact of controllability on the overall BRP performance and overall portfolio position. econd and third, we analyze the two main types of strategic deviations that can be unfavorable for the system, (i) 'negative and remunerated imbalances' and (ii) 'arbitrage-related imbalance penalties' through the indicators that we defined in the previous section.

3.3.1 Controllability impact on profits and imbalances

The increasing control of assets by the BRPs corresponds to an overall rise in their potential profits. s illustrated in Figure 2, all year-series exhibit a positive, approximately linear trend linking controllability to profitability. owever, the relatively low $\mathbf{R^2}$ of the global fit—which considers the average behavior across all series—indicates substantial variability in how profit increases with controllability, likely reflecting differences in regulatory frameworks or market conditions. otably, the two German series (2024 and 2025) display the steepest slopes, with 2024 being particularly pronounced—almost twice the slope of 2025. he remaining series, except for Spain, which shows a markedly lower slope, generally exhibit increases of up to 400 k€ per 0.1 increment in controllability.

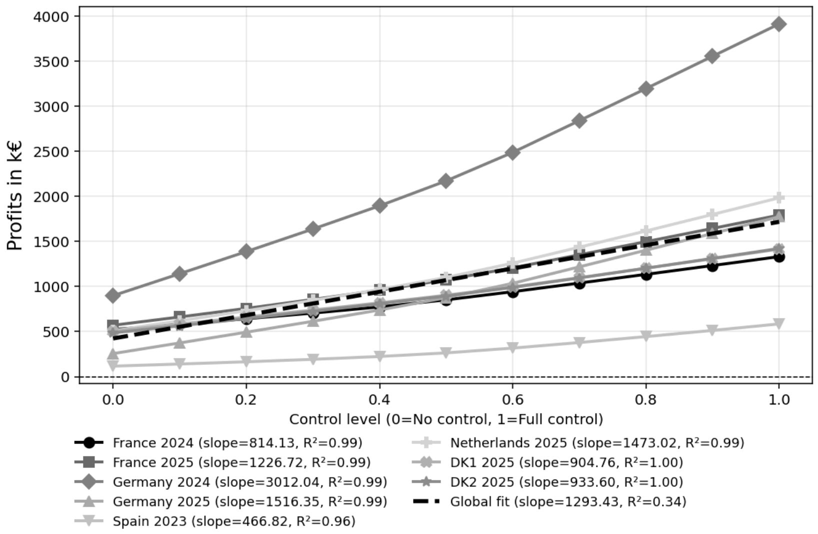

Figure 2: BRP total profits.

Surprisingly, despite the increase in profits, greater controllability also leads to higher penalties paid by BRPs to the TSO for their imbalances. Figure 3 shows that all series exhibit a negative and approximately linear relationship between the degree of control and total imbalance payments. More interestingly, it reveals a key aspect of controllability: it shifts the BRP's position from generating profits through imbalances when control is limited to incurring higher penalties as control improves. Furthermore, the series exhibit different degress of slope, where, Germany 2024 as in figure 2 is once again the series that displays the steepest slope. However, in this case, Germany 2025 follows the Netherlands 2025 series, while France 2024 presents the least steep slope. Such differences in slope might be

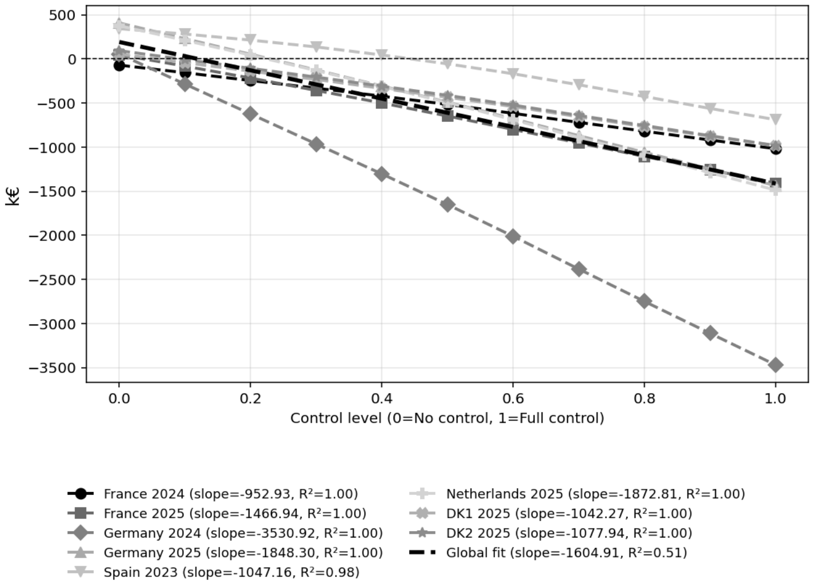

Figure 3: Penalties paid by the BRP from their imbalances.

Nevertheless, the increase in penalties is not mainly driven by significant changes in the total level of imbalances, as controllability does not seem to increase total imbalances. Figure 3 shows the brute imbalances, as the sum of the absolute value of long and short imbalances, where the slope is quite marginal, and in many cases, such as Germany, Spain, Netherlands, DK1, and DK2, suggests a low correlation with controllability. Only Germany in 2024 remains the exception, with a relatively low impact from controllability compared to previous analyses, but with a significantly higher impact than the rest.

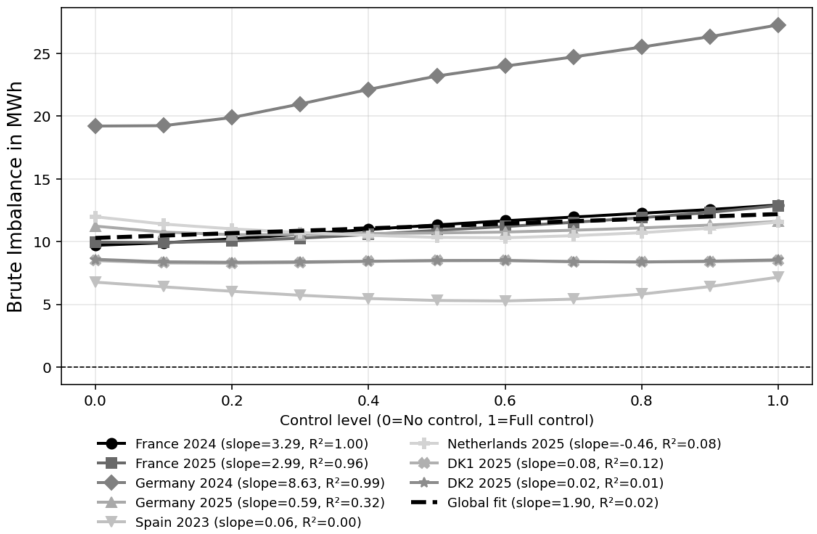

Figure 4: Sum of upward and downward imbalances.

The puzzling situation, in which controllability increases BRP total profits, despite the increasing cost of penalties from imbalances, can be explained by the increase in profits resulting from the arbitrage of BRP participation in energy and retail markets. Figure 5 shows a positive and linear correlation between control level and energy and retail profits for all time series. Similar to previous cases, the impact is more significant in Germany 2024 than in other cases; however, the difference in Germany 2025 is not particularly substantial.

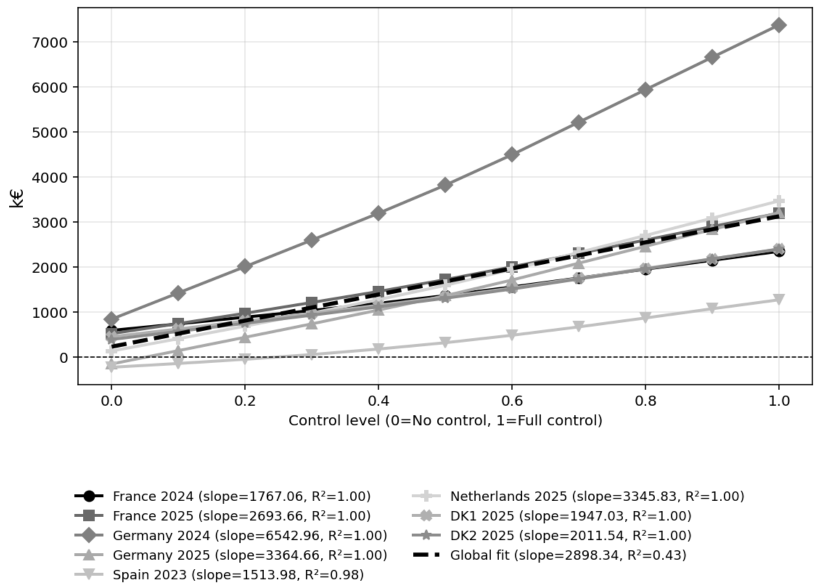

Figure 5: BRP profits from energy and retail markets .

Figure 6 shows that for all the time series, except DK 1, the net position is negative with full controllability. For Germany 2024, the slope is the highest, again showing that some particular aspects of Germany 2024 might be driving the results to have more potential for profitability in changing the net position. All series exhibit a negative and strong correlation between the degree of controllability and the change in net imbalances, indicating that controllability incentivizes BRPs to take shorter positions more frequently, and that low controllability, in contrast, leads to longer positions. or all the time series, with the exception of DK 1, the net position is negative with full controllability. or Germany 2024, the slope is the highest, again indicating that some particular aspects of Germany 2024 may be driving the results, suggesting more potential for profitability in changing the net position.

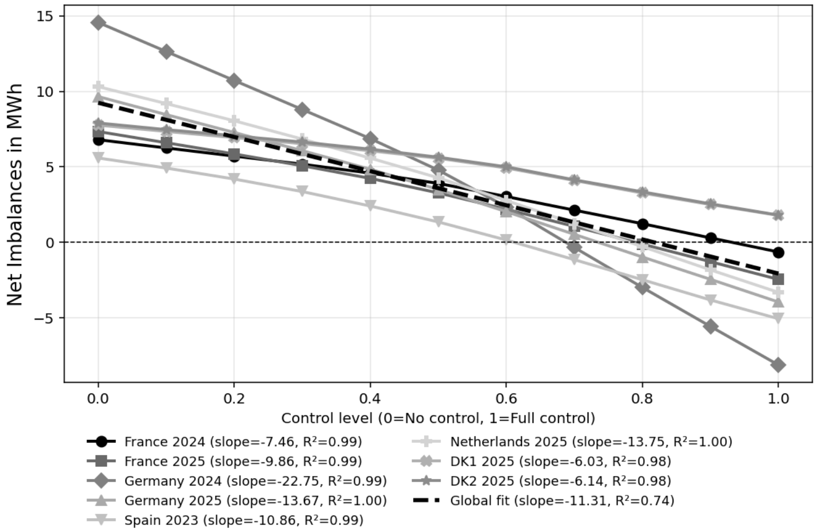

Figure 6: Net imbalance position by country and year.

3.3.2 Controllability impact on the share of negative and remunerated imbalances

Figure 7 shows that controllability does not appear to have a mostly negative but not that significant impact on the share of negative imbalances for most series, except DK1, where the slope is positive and highly correlated. he results also highlight interesting within-country differences in the share of negative imbalances. n particular, DK1 and DK2 exhibit opposite behaviors: DK2 shows the highest proportion of negative imbalances—above 70% with the highest decrease in slope after Spain, whereas DK1 displays the lowest share but the steepest decline among all series. hese contrasting results may be explained by the geographical and structural separation between Denmark's western and eastern bidding zones. he east zone (DK2) is more interconnected with the Nordic synchronous area, while the zone of the west (DK1) is coupled with continental Europe, leading to distinct system dynamics and balancing conditions. he remaining countries exhibit broadly similar behaviors, with both German series (2024 and 2025) displaying relatively high shares, similar to those of the Netherlands, in contrast to Spain.

Figure 8 shows that controllability exhibits a negative and linear relationship with the share of negative imbalances that are remunerated to the BRP. his suggests that higher controllability discourages situations in which BRPs profit from system-adverse imbalances, reducing the incentives to deliberately create negative imbalances to exploit balancing opportunities. he figure also highlights substantial cross-country differences, consistent with those observed in Figure 7, with Denmark once again standing out as an extreme case. pecifically, DK1 shows almost no likelihood (close to 0%) of BRPs being remunerated for negative imbalances, while Spain 2023, DK2, and Germany 2025 exhibit the steepest slopes—indicating the sharpest reductions in remunerated negative imbalances as controllability increases.

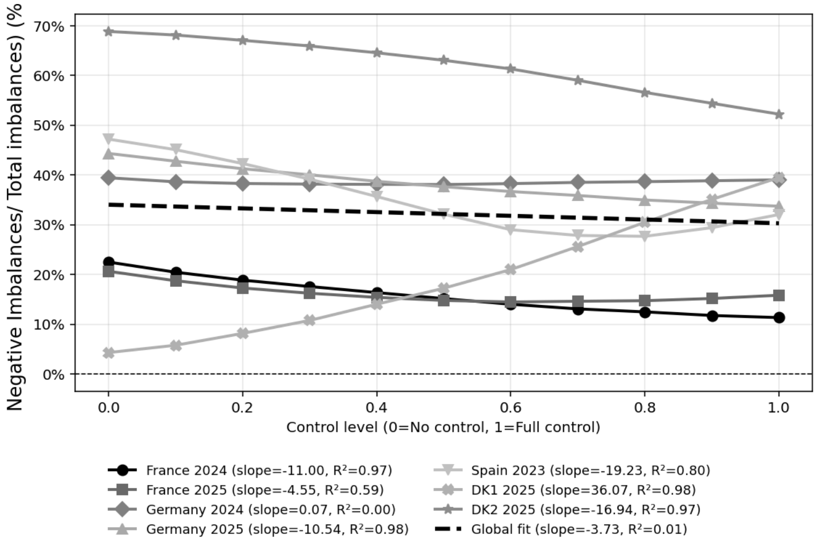

Figure 7: Percentage of BRP imbalances adverse to system balance.

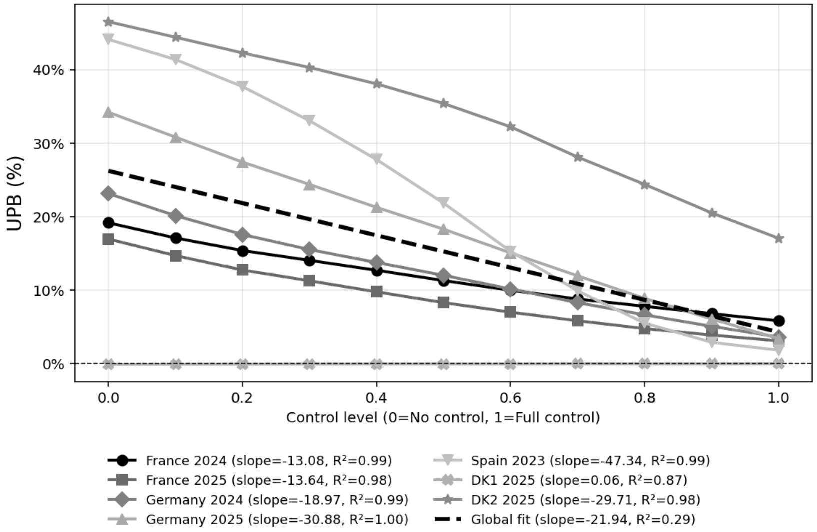

Figure 8: Percentage of remunerated BRP imbalances adverse to system balance.

3.3.3 Controllability impact on arbitrage-related imbalance penalties

Overall results show that controllability has a positive and linear relationship with the share of imbalances that the aggregator commits to gain advantage of arbitrage in market opportunities. Which suggests that the higher the degree of controllability, the greater the incentives for the BRP to incur a penalty from imbalances, to take advantage of market arbitrage opportunities. Figure 9 shows the results for the whole distribution of prices, where the highest impact can be observed in DK1, Spain, Germany 2024 and 2025 in that order; and that France in particuar have almost half of the impact. This pattern reflects the BRP's willingness to accept a penalty for imbalances when total profits remain positive.

Furthermore, Figures 10 and 11 show that market-arbitrage incentives decrease during periods of low market prices (below the 10th percentile) and increase during periods of high prices (above the 90th percentile) as controllability rises. In countries such as France, Germany, and Spain, the slope increases by up to 2% per decimal increase in controllability—a magnitude that can be substantial

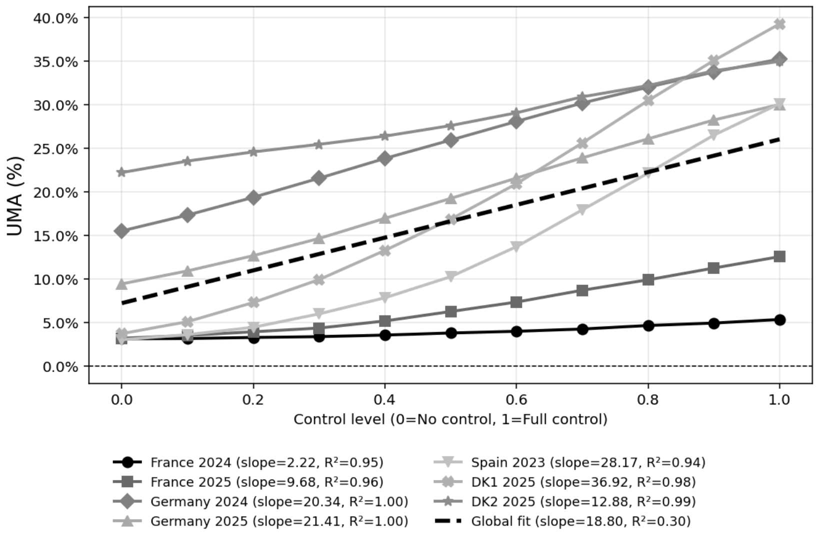

Figure 9: Percentage of BRP-penalty imbalances used for market arbitrage.

during scarcity events. This suggests that balancing prices in these periods may not be sufficiently high to reflect the system's scarcity value fully.

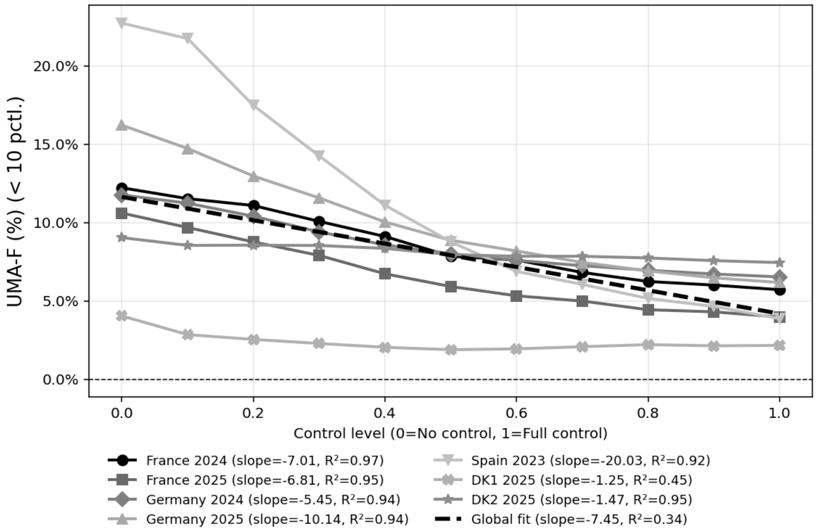

Figure 10: Percentage of remunerated BRP imbalances adverse to system balance.

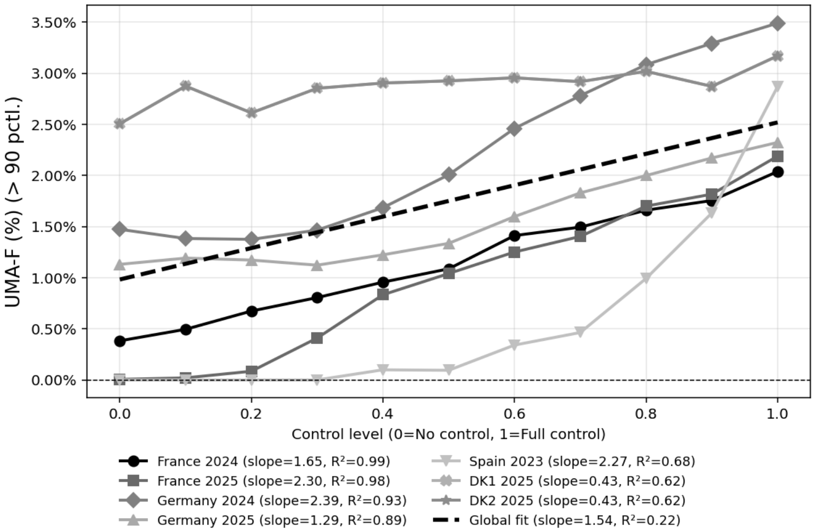

Figure 11: Percentage of remunerated BRP imbalances adverse to system balance.

4 Discussions

Previous research analyzing the potential strategic deviations of BRPs in balancing markets has been divided between two main perspectives. The first, known as the feedback-loop perspective, argues that under current regulation, BRPs have incentives to behave strategically by creating imbalances to benefit from passive balancing payments or to exploit arbitrage opportunities arising from the spread between imbalance and energy prices (Just & Weber, 2015; Möller et al., 2011; Van Der Veen et al., 2012). The second, or linear perspective, contends that imbalances mainly result from stochastic forecasting errors or consumption variability, rather than intentional strategic behavior (Hirth & Ziegenhagen, 2015; Joos & Staffell, 2018; Ocker & Ehrhart, 2017).

Our first contribution is to show that, under the current EU regulatory framework, controllability over DERs can substantially increase the incentives for strategic behavior that may negatively affect system efficiency. Specifically, greater controllability gives VPPs clear economic incentives to increase profits through the deliberate creation of imbalances (Figures 2 and 3). Moreover, controllability changes the composition of imbalances: as shown in Figure 6, higher controllability leads VPPs to systematically adopt shorter positions, although it does not significantly increase the total imbalance volume (Figure 4). Finally, controllability enables VPPs to exploit arbitrage opportunities between short-term energy prices and imbalance prices, particularly during periods of high prices or scarcity (Figure 11). Hence, the most significant impact of controllability may not lie within the balancing mechanism itself, but in how it reshapes the interaction between energy and balancing markets.

Our second contribution is to extend the work of Just and Weber (2015) by providing additional evidence of how large price spreads between spot and imbalance markets can create incentive distortions. More importantly, our results show that controllability can generate similar distortions even when this spread is small—contrary to the expectation that narrowing the spread would eliminate such behavior. Furthermore, our findings contrast with the suggestion that a two-price imbalance system could reduce strategic deviations. In our analysis, the effects of controllability persist across both one- and two-price systems, suggesting that the problem is structural rather than dependent on a specific pricing mechanism.

Finally, our third contribution is methodological. Through our modeling framework and its calibration, we demonstrate that both main perspectives in the literature can be reconciled by adjusting the degree of controllability. When controllability is low, imbalances primarily reflect stochastic fluctuations in consumption and generation, consistent with the linear perspective (Hirth & Ziegenhagen, 2015; Joos & Staffell, 2018; Ocker & Ehrhart, 2017). Conversely, when controllability is high, VPPs can act strategically and anticipate market conditions, consistent with the feedback-loop perspective (Just & Weber, 2015; Möller et al., 2011; Van Der Veen et al., 2012).

5 Conclusions

This paper examined how the controllability of DERs within VPPs affects the efficiency and stability of European balancing markets. Motivated by the growing regulatory challenge of integrating highly controllable technologies into liberalized electricity systems, we explored whether increasing asset controllability undermines the assumptions underpinning the current EU balancing market design. Using a calibrated model inspired by Van Der Veen et al. (2012), we formalized controllability as a parameter capturing the degree to which VPPs can deterministically influence their aggregate portfolio position. We applied this model to five European markets—Germany, France, Spain, the Netherlands, and Denmark.

Our results indicate that controllability can have a significant impact on VPP behavior. First, higher controllability consistently increases the profitability of Balancing Responsible Parties (BRPs), primarily through enhanced opportunities for energy market arbitrage. Importantly, these gains do not arise from improved operational efficiency or reduced imbalances, but from strategic positioning across both energy and balancing markets. Second, controllability alters the composition of imbalances: as it increases, BRPs tend to systematically adopt shorter positions, although the total imbalance volume remains largely unchanged. Third, controllability amplifies incentives for imbalance-related arbitrage, particularly during periods of high energy prices, when spreads between spot and imbalance prices are most pronounced. Collectively, these findings suggest that greater controllability expands the strategic space available to BRPs, potentially challenging the neutrality and efficiency objectives of existing balancing mechanisms.

From a regulatory perspective, these results reveal an emerging paradox. While controllability enhances operational flexibility and can improve the technical reliability of balancing, it simultaneously opens new opportunities for strategic behavior that may stress the energy markets during times of scarcity. Thus, the regulatory challenge is not merely to enable DER participation in balancing markets, but to ensure that increasing controllability does not have negative impacts in other markets (ENTSO-E / ACER, 2020; European Commission, 2017).

Our findings also contribute to the broader academic debate on the origins of imbalances and the behavioral dynamics of BRPs. Specifically, we show that the degree of controllability can reconcile two previously competing perspectives in the literature. Under low controllability, imbalances behave as stochastic forecasting errors—consistent with the linear perspective (Hirth & Ziegenhagen, 2015; Joos & Staffell, 2018; Ocker & Ehrhart, 2017). However, as controllability increases, imbalances become increasingly strategic, confirming the feedback-loop perspective (Just & Weber, 2015; Möller et al., 2011; Van Der Veen et al., 2012). This finding bridges the gap between both interpretations by demonstrating that the dominant mechanism depends on the controllability of the underlying assets. Moreover, this paper extends the work of Just and Weber (2015) by showing that incentive distortions can persist even with a two-price imbalance system in the presence of highly controllable assets.

Finally, the implications of this research extend beyond VPPs to all types of BRPs managing highly controllable assets, including stationary batteries and industrial demand-response portfolios. Nevertheless, this study has important limitations: it does not explore in detail the potential design adjustments or regulatory interventions needed to align incentives under high controllability. Future research should therefore focus on developing and evaluating market designs that preserve efficiency while minimizing the incentives for strategic imbalances. In this context, controllability should be viewed as a crucial dimension that shapes market behavior and regulatory performance.

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