Smart Balancing of Electrical Power – Transparent Real-Time Market for Cost-Efficient Power Balancing

Dissertation by publication

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Executive Summary of publications

The European energy markets are crucial to facilitating the transition to renewable energies and eliminating greenhouse gas emissions on the continent. In a fossil fuel-free future, electricity supply and related system services must be built on volatile renewable energy sources (VRE), increasing storage facilities, and flexible consumption. As a contribution, this dissertation by publication summarises market theory, historical evidence, and simulation results about the market response (known as “passive” power balancing). A transparent real-time market in Germany is proposed: Smart Balancing is a set of measures that lead to (passive) market response. Smart Balancing reduces the demand and related costs for (active) power balancing. Smart Balancing aims to secure electricity supply and a more cost-efficient transition to VRE by cost-effectively balancing generation and load. The research was part of the project "Norddeutsche EnergieWende 4.0 (NEW 4.0[1])". Field data from project partners was obtained to improve the methods and develop a Smart Balancing model.

Smart Balancing Definition

Smart Balancing is a set of measures to minimize unnecessary activation of Frequency Restoration Reserves (FRR). Balance Responsible Parties (BRPs) optimize schedule deviations to offset other schedule deviations. Smart Balancing is a response to provide correct incentives in combination with public real-time information and should be designed to avoid reversing the sign of the Area Control Error (ACE).

Market theory and historical data

EU legislation has encouraged the integration of European balancing markets since 2017, as discussed in the first publication [1]. The steps are to harmonize products, and to develop international platforms for procuring and activating reserves. Nonetheless, different power balancing strategies remain, with the availability of real-time information being a key differentiation factor. The market design in the Netherlands and Belgium incentivizes deviations from the scheduled energy consumption and generation. Transparent real-time price signals create business cases for market parties (which are organized in BRPs). If their schedule deviation has the correct direction, it reduces the activation of FRR.

A case of “under-cover” balancing in Germany is presented in the second publication [2]. No official real-time signal is available in Germany, but BRPs can predict potential business cases based on the activation of FRR. The Netherlands and Belgium have transparent real-time information and profit from the reduced demand of FRR due to passive balancing. Another differentiation factor is combined imbalance pricing which is applied in the Netherlands to limit passive balancing and avoid reversing the sign of the ACE: Reversing the sign of the ACE leads to counter-activation of positive and negative FRR simultaneously within an ISP, because unnecessary FRR ramp down with delay while opposing FRR is already ramping up. The Dutch single imbalance pricing scheme changes to a dual imbalance pricing scheme in imbalance settlement periods (ISP) with counter-activation of positive and negative FRR. Combined

[1] Smart Balancing research was part of the project NEW 4.0 (North German Energiewende 4.0), which is partly funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

imbalance pricing limited the occurrence of counter-activation of FRR to 9.1 % of all ISPs, compared to 66.8 % in Belgium and 97.3 % in Germany.

The market liberalization in Ukraine in July 2019 was analyzed with data of FRR activation and prices to derive lessons learned in the third publication [3]. Market design changes were made in December 2019, March, April, May, and June 2020. The data illustrates temporary malfunctions and resulting FRR activation of up to 3 GW (30. of November 2019). Changing the imbalance pricing scheme reduced misplaced incentives and reduced the demand for FRR significantly.

Historical data from the Netherlands, Belgium, and Germany from 2016 to 2019 are analyzed in the fourth publication [4]. Over 7 GW of reserves were activated in Germany during the 12. of June 2019, caused by market response and a misplaced incentive. This incentive was caused by the combination of day-ahead balancing markets, intra-day “energy-only” markets, and limited imformation. The Netherlands and Belgium did not experience such situations and even generated financial income from neighbouring control blocks (e.g., Germany) via market response. Imbalance netting via the International Grid Control Cooperation (IGCC) occasionally led to revenues of several million € in the Netherlands and Belgium rather than costs like in Germany. The reason, the Netherlands and Belgium often have power imbalances reducing the activation of FRR in other countries via IGCC wich is revarded with an opportunity price.

Publications 1, 2, 3, and 4 show that market response (passive balancing) is an issue in all regarded countries. Dangerous situations in Germany and Ukraine with high imbalances of several GW were caused by market-oriented activities (of BRP). The Netherlands and Belgium profit from market response via transparent real-time signals resulting in cost-efficient power balancing.

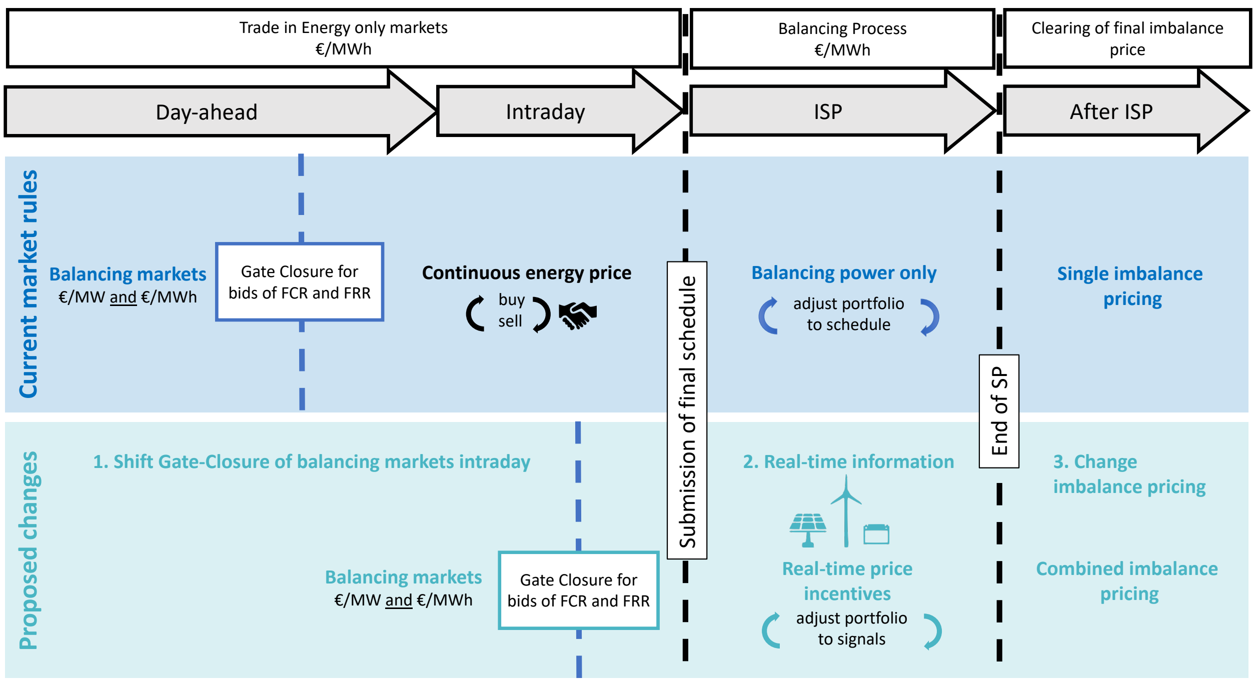
Simulation results

The development of the Smart Balancing model to showcase potential risks and benefits of market response in Germany is first introduced in the fifth publication based on field data from the industry and VRE owner [5]. The model is coded in Python, and its object-oriented structure simulates the behaviour of different BRPs. An estimation of the market response of all BRPs takes place via fuzzy logic, first introduced in the sixth publication [6]. All regarded scenarios with an example plant outage and transparent real-time information lead to a reduction of FRR demand. As next step, an ex-post simulation of 2019 with historical power imbalance and balancing energy prices in Germany is presented in the seventh publication [7]. The results quantify the potential cost savings of Smart Balancing. Most beneficial is the scenario with combined imbalance pricing and a cost reduction of 30 %, compared to a cost reduction of 17 % with single imbalance pricing.

Outlook for Smart Balancing

Historical data and simulation results support the hypothesis that the 3 measures: 1. correct timing of markets, 2. public real-time information for BRPs, and 3. combined imbalance pricing, facilitate Smart Balancing. Smart Balancing reduces the activation of FRR and thus leads to more cost-efficient power balancing. In the current German environment, this can be achieved by the following three proposed changes to the market rules.

1. Shift the Gate-Closure of balancing markets from day-ahead to a point close to real-time.
2. Introduce reliable real-time information about the system imbalance and imbalance price.
3. Change the current single imbalance pricing to combined imbalance pricing.



ISP: Imbalance Settlement Period
FCR: Frequency Containment Reserves
FRR: Frequency Restauration Reserves

The proposed measures would enable Smart Balancing. According to the presented findings, Smart Balancing can reduce the balancing demand in the European power system and thus reduce the balancing costs significantly. Consequently, publication 7 proposed a roadmap for Germany to introduce an adapted Smart Balancing approach, starting with a simple traffic light. In fact, the traffic light concept was implemented in Germany in September 2021 [8], five months after the publication of publication 7. The traffic light approach could in a next step be replaced by a fully transparent approach. In that case, the simulation results highly recommend replacing the single imbalance pricing by combined imbalance pricing. If implemented correctly, Smart Balancing in Germany could serve as a role model for other regions.

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The thousands of individuals who have coded for the Python, Git, and LaTeX projects for free. Due to their efforts, we can work with professional open-source software, use reliable version control, and generate typeset PDFs now.

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Glossary and abbreviations

Term	Abbrev.	Description
Area Control Error	ACE	The ACE is calculated by comparing measured, and scheduled power flows into and out of a control block. The ACE corresponds to the sum of all schedule deviations of all BRPs in the control block. FRR compensates the ACE to maintain the scheduled power interchange with neighbouring control blocks.
Ausgleichs-Energie-Preis	AEP	Imbalance price in Germany.
automatic Frequency Restauration Reserves	aFRR	Positive and negative aFRR is activated via an automatic feedback loop to compensate for the ACE.
Belgium	BEL	Belgium is a country with public real-time information and single imbalance pricing.
Balance Responsible Party	BRP	BRPs represent market parties. They agree on the generation and consumption of electricity on spot markets, which defines their schedule.
Balance Service Provider	BSP	Prequalified BRPs who offer reserve capacity via bids on balancing markets are BSPs.
Balancing markets		BSPs offer their prequalified reserves in auctions at balancing markets. The cheapest reserves are activated first via a MOL.
Combined imbalance pricing		The combined imbalance price in the NL allows limiting market response by allocating different incentives to BRPs with positive and negative schedule deviations in case of overcompensation of the ACE (counter-activation of positive and negative FRR).
Control Block		Countries organize their grid in control blocks. Each control block has a unique ACE, and only the frequency is synchronous with other control blocks.
Day-ahead market		The day-ahead market is an “energy-only market” with an auction mechanism to define the day-ahead energy price, which defines the temporary day-ahead schedule of BRP in 1-hour resolution.
Day-ahead price	da_{price}	Price for electrical energy at the day-ahead “energy-only” market.

Dual imbalance pricing		Dual imbalance pricing refers to two different prices for positive and negative schedule deviations. BRPs cannot profit, and the market response is not incentivized.
Energy		Electrical energy is electrical power over time. Energy is traded as a commodity at “energy-only” markets.
“Energy-only” markets		Day-ahead and intra-day markets to trade energy products. “Energy-only” refers to the absence of rules regarding the power characteristics during the ISP.
European Network of Transmission System Operators for Electricity	ENTSO-E	This organization represents all European transmission system operators (TSO)
Frequency Containment Reserves	FCR	FCR and inertia respond directly to the grid frequency and the ROCOF. They are not subject to real-time markets.
Frequency Restauration Reserves	FRR	FRR is the primary tool of power balancing. FRR “balances” the deviation between a control block's scheduled and measured power flows.
Germany	GER	Applies single imbalance pricing. No public real-time information
Imbalance netting		Imbalance netting applies if the imbalances of two control blocks have the opposite sign (netting of positive vs. negative imbalances). See section 2.6
Imbalance price		The imbalance price can be an incentive for market response because schedule deviations are settled with the imbalance price. Single imbalance pricing leads to a business case for BRPs.
Imbalance Settlement Period	ISP	Time unit (e.g. of 15 minutes) applies to the trade of energy products, for which the schedule is defined. The schedule deviation of BRP is calculated per ISP ex-post.
Intra-day market		The intra-day market is a (spot) “energy-only market” with continuous trade of 15 minutes energy products
manual Frequency Restauration Reserves	mFRR	Manual activated FRR (mFRR) deals with imbalances that last for a long time.
Marginal clearing		The most expensive FRR activated sets the price for all FRR within each ISP. Bids can be expected to be cheaper than with pay-as-bid clearing.

Market response		Market response refers to schedule deviations created intentionally in response to a business case. Market response requires a single imbalance price.
Merit-Order List	MOL	MOL of balancing energy bids starting with the lowest price for cost-efficient procurement and activation of FRR and FCR.
Netherlands	NL	The Netherlands is a country with public real-time information and combined imbalance pricing.
Passive balancing	PB	Found in the literature and a synonym for the market response.
Pay-as-bid clearing		All activated FRR receive the price indicated at the balancing market. Bids can be expected to be higher than with marginal clearing.
PICCASSO	PICASSO	European aFRR-Platform. The Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) is the implementation project of the ENTSO-E to establish the exchange of aFRR.
Power		Electrical power in the grid must be balanced in real-time. Any imbalance between generation and load causes activation of FCR.
Rate Of Change Of Frequency	ROCOF	The ROCOF describes the change of frequency over time and can indicate a plant outage before the frequency itself reaches a critical value.
Real-Time Market		The sub-title “Transparent Real-Time Market for Cost-Efficient Power Balancing” refers to the introduction of real-time price information. The real-time market response can be part of the balancing process.
Regulator		National regulators define the legal frame in a country where TSO, BRP, and BSP interact.
Residual load		Residual load is the sum of all load in a control block minus all VRE.
Schedule deviation		Schedules are made for each ISP based on predictions of load, VRE, and resulting trade at “energy-only” markets.
Single imbalance pricing		BRPs can make a profit, and the market response is incentivized. The sign of the price

		defines if a positive or a negative schedule deviation leads to profit.
Smart Balancing	SB	Definition in Section 3.1
Synchronous Zone		The Synchronous Zone of central Europe refers to the most extensive ENTSO-E grid with a synchronous frequency of 50 Hz.
Traffic light scenarios	TL2, TL5	Traffic light scenarios are considered in the Smart Balancing simulation. Only the sign of the ACE is published in case of high positive or high negative ACE.
Transmission System Operator	TSO	TSOs manage the physical constraints of their grid. TSOs organize the balancing markets and activate FRR according to the ACE of the control block.
Volatile Renewable Energy	VRE	Wind and solar power generation are based on volatile weather conditions.

1 Introduction

Power balancing occurs within national control blocks via system services organized by highly regulated companies. These Transmission System Operators (TSO) manage the physical constraints of their grid. The purpose of related legislation and agreements regarding power balancing is to deal with two physical constraints of electrical power: (A) frequency stability and (B) grid capacity.

A: Frequency Containment Reserves (FCR) and inertia stabilise the global European grid frequency to 50 Hz (also known as primary control). Decentral flexibility ramps up or down in the synchronous zone to balance generation and load.
B: Local flexibility, on the other hand, aims at solving bottlenecks of grid capacity.
C: Power balancing with Frequency Restoration Reserves (FRR) in a control block (also known as secondary and tertiary control) affects (A) the global frequency and (B) the local grid.

Both physical aspects of electrical power are managed separated from power balancing. First, the (A) frequency is the physical quantity that defines a synchronous zone. In addition to the frequency itself, the Rate Of Change Of Frequency (ROCOF) must be kept within limits. Therefore, frequency stability is obtained by combining FCR and system inertia [9]. Second, the (B) grid capacity is a local physical constraint. The maximum power flow through a transmission line must not be exceeded. If the maximum is reached, either curtailment can reduce the local power generation or (temporary) market splitting increases power consumption. Both measures can relieve the grid until the required capacity expansion is completed [10].

The (C) power balancing is based on the trade of electrical energy at “energy-only” markets. Market participants are called Balance Responsible Parties (BRP) because they are responsible for keeping the consumption and generation within the schedules. FRR are the main tool of power balancing. FRR “balance” the deviation between a control block's scheduled and measured power flows. FRR activation can be avoided in two neighbouring control blocks via imbalance netting, further described in section 2.6. Imbalance netting applies if the imbalances of two control blocks have the opposite sign (netting of positive vs. negative imbalances). Thanks to this recent development over the past decade, Smart Balancing can even reduce the activation of FRR in other control blocks via imbalance netting [11].

In addition to the standard system services (FCR and FRR) different power balancing strategies apply in Europe. Dutch (NL) and Belgian (BEL) TSOs count on a transparent real-time imbalance price allowing passive balancing: all BRPs are incentivized to balance generation and load. The German system pursues a strategy counting only on prequalified FRR without real-time incentive.

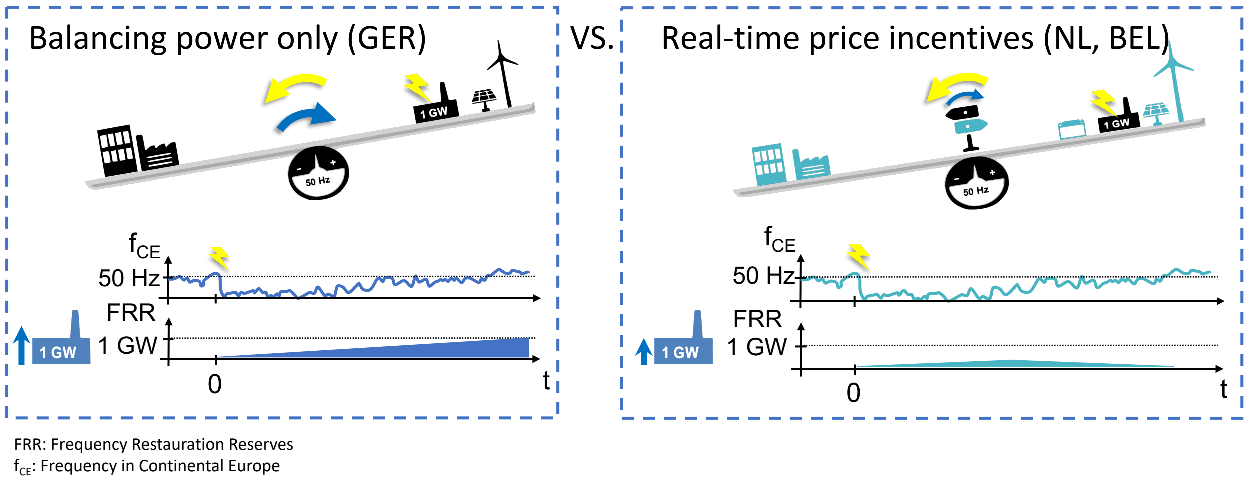


Figure 1: Balancing process in Germany (GER) vs. the Netherlands (NL) and Belgium (BEL). Illustration of strategies with fictional 1 GW plant outage

Figure 1 illustrates a fictive plant outage of 1 GW. According to the schedule deviation (imbalance = 1 GW), Germany activates 1 GW of FRR. The Netherlands and Belgium publish real-time price incentives, and other BRPs balance the control block. The FRR demand decreases. The fictitious case illustrates the advantages of real-time incentives, reason enough to investigate its introduction in Germany.

Section 2 presents the state of power balancing and market rules in the Netherlands, Belgium, and Germany. The discussion of literature leads to six hypotheses related to Smart Balancing. Section 3 introduces the Smart Balancing definition, summarizes hypotheses for possible market adaptations, and describes the proposed more cost-efficent solution for Germany. Section 4 presents the methods and results of the publications, which contain the scientific details of the dissertation. Methods and results include evidence of market response with examples from the Netherlands, Belgium, Ukraine, and Germany. Simulations with a focus on Germany result in the proposed solution. Finally, section 5 concludes on the outlook for Smart Balancing in Germany.

2 State of power balancing and market rules

This section introduces the state of power balancing and market rules: a relevant theory of power balancing, and the design of markets in the Netherlands, Belgium, and Germany. The literature presented in section 2.1 to section 2.6 leads to six hypotheses (complete list in Section 3).

Section 2.1 discusses existing literature about stochastic vs. deterministic causes for system imbalances, focusing on volatile renewable energy (VRE). Existing definitions of passive balancing are introduced in section 2.2. Imbalance pricing approaches are introduced in section 2.3. The German market set-up is discussed, focusing on evidence of passive balancing in section 2.4. Current market rules are outlined with a focus on Gate-Closure-Times in section 2.5. The concept of balancing blocks, focusing on imbalance netting, is discussed in section 2.6.

2.1 Stochastic vs. deterministic imbalances and Area Control Error (ACE)

Hirth and Ziegenhagen [12] provide a profound discussion of literature dealing with reasons for system imbalances. Imbalances are separated into stochastic and deterministic reasons. Deterministic imbalances are known as schedule leaps: Thermal and hydro power generation follow their schedules in (discrete) 1 hour or 15 minutes steps, which does not match the (concrete/continuous) physical demand (of the residual load). Stochastic imbalances are separated into sudden events and continuous forecast errors. Sudden events are unplanned outages of plants or grid interconnections. Forecast errors are wrong predictions of load or power generation from VRE. The EU legislation defines two classes of FRR to cope with imbalances: automatic activated FRR (aFRR) deal with any imbalance in the first place, and manual activated FRR (mFRR) deal with imbalances that last for a certain period [13],[14]. European grid codes do not provide a method for FRR dimension, but Maurer et al. present currently applied methods for estimating balancing demand to dimension FRR [15].

In day-to-day operation, the system imbalance is diverse. The area control error (ACE) is calculated as the central control variable by comparing scheduled power flows $P_{scheduled}$ and measured power flows $P_{measured}$ into or out of a control block [13]. The ACE represents the sum of all schedule deviations of BRPs in an area and is calculated by equation 1:

$$ACE = \sum P_{scheduled} - \sum P_{measured} = \sum schedule\ deviations \qquad (1)$$

In the subsequent step, FRR is activated to compensate for the ACE. First, the fast aFRR and, in long periods with high imbalance, slower mFRR. Three GW of FCR (primary control) are available in continental Europe, which measure and stabilize the grid frequency autonomously [13].

With this background and looking at the increasing share of VRE in Europe, balancing demand should have increased accordingly. In contrast to this common sense, Hirth and Ziegenhagen (2015) present empirical data from Germany indicating a negative correlation between capacity of VRE and balancing demand, which they named the "German Paradox" [12]. Partly, this was achieved by improved weather forecast techniques. Ocker and Ehrhart (2017) explain the "German Paradox" by improved cooperation of system operators and imbalance netting [16] (see section 2.6). Koch and Maskosa (2019) trace back a positive effect from improved intra-day trading [17] (see section 2.5). The "German Paradox" and related analysis lead to the first hypothesis.

Hypothesis 1: Increasing the capacity of VRE does not necessarily lead to higher balancing demand if the VRE expansion (an increase of stochastic imbalances) is overcompensated by market-related factors (reduction of deterministic imbalances).

2.2 Transparency as a design variable: Passive Balancing

The approach of passive balancing requires a degree of transparency about imbalance volumes and prices in real-time. As a result, BRPs provide passive balancing services (at no costs), and the activation of FRR by the TSO is reduced or even avoided. The Netherlands and Belgium publish real-time information to incentivize passive balancing. The Netherlands have published activated FRR and imbalance prices in nearly real-time since 2001 [18]. Belgium has published system imbalance in a 1-minute resolution since 2017 [19]. As of August 27th, 2019, Belgium followed the Dutch example, and real-time information was extended to the activated balancing energy and the corresponding imbalance prices.

The idea of passive balancing has been described in different sources:

- "In NL real-time feedback by the TSO on actual market balance position and imbalance price enables BRPs to act on opportunities to arbitrage between imbalance price and their own marginal production price resulting in a reduction of the system imbalance (the marginal price for control energy determines the actual balance energy price for this passive control)." Frank Nobel, 2016 [20, p. 102]
- "The imbalance price provides the incentive to BRPs to "passively" balance the system by purposely deviating from the schedule ("self-balancing")." Hirth and Ziegenhagen, 2015 [12, p. 1048]
- “BRPs can help the TSO keep the system balanced by intentionally incurring imbalanced positions in the opposite direction of the SI, which can be referred to as "passive balancing"." Brijs et al., 2017 [21, p. 45]

These descriptions point out that the imbalance price incentivizes BRPs to balance the ACE passively. Schedule deviations of BRPs cancel out, and the FRR demand decreases. The literature thus leads to the second hypothesis.

Hypothesis 2: Real-time information facilitates passive balancing. Passive balancing reduces the activation of FRR and improves the cost-efficiency of power balancing.

2.3 Single vs combined imbalance pricing

Section 3 suggests a definition of Smart Balancing, addressing the risk of reversing the sign of the ACE (leading to counter-activation of positive and negative FRR). Reversing the sign of the ACE leads to counter-activation of positive and negative FRR simultaneously within an Imbalance Settlement Period (ISP), because unnecessary FRR ramp down with delay while opposing FRR is already ramping up.The imbalance pricing scheme is of interest to evaluate this risk. Single imbalance pricing is the preferred option in Europe and is requested by the European commission in the “Electricity Balancing Guideline” (EBGL) [14]. The price sign (+ or -) defines if a positive or a negative schedule deviation leads to profit. Dual imbalance pricing refers to different prices (+ and -) for positive and negative schedule deviations without an incentive for passive balancing. Hence, all schedule deviations are penalized with dual pricing while there is a favorable direction leading to profit with single pricing. Baetens et al. (2020) discuss how Belgium introduced single imbalance pricing in 2012 [22]. Since 2020 a pure single imbalance price applies. Also, Germany applies a pure single imbalance price. Limiting market response and preventing reversing the sign of the ACE is difficult because a strong financial incentive for passive balancing exists.

Olmos et al. (2015) explain the difference between single vs. combined imbalance pricing in the project report Market4RES [23]. The Netherlands apply combined imbalance pricing: the imbalance price is a single price in any ISP without counter-activation of positive and negative FRR. If the ACE reverses its sign, leading to positive and negative FRR counter-activation within an ISP, the dual imbalance price applies. The combined pricing scheme allows limiting passive balancing by the optional changing to dual pricing in case of reversing the sign of the ACE. Therefore, the Dutch approach of combined pricing offers the most adequate incentives for BRPs with respect to system requirements [23, p. 82].

Hypothesis 3: Combined imbalance pricing is a correct incentive for BRPs and prevents reversing the sign of the ACE.

2.4 Passive balancing in Germany

The balancing strategy in Germany does not consider passive balancing. In fact, BRPs must guarantee to follow their schedule, as specified in the standard contract between system operator and market party [24]. On the other hand, comparing the market designs of Germany and the Netherlands shows a lot of similarities [25]. In the context of that contract, the single imbalance price is another "German paradox", which gives BRPs an incentive to deviate from the schedule and ignore their contractual obligation (see section 2.3). Koch (2019) presents a profitable trading strategy using the spread between intra-day price and German imbalance price, but this would increase the ACE in many cases [26]. Half of the time, the spread gave a misplaced incentive between 01.07.2017 to 30.06.2019. Eicke et al. (2020) show evidence of strategic schedule deviations in Germany; data from 12.07.2018 to 29.09.2019 indicates that BRPs in Germany apply passive balancing [27]. On average, the ACE was reduced by 20% by passive balancing during that period. Koch and Maskosa (2019) present similar positive effects of passive balancing in Germany and point out the limitation and delay of available information [17]. These studies indicate that BRPs use any available information to improve their strategy. In Germany, no official information is provided, and only the activation of FRR by the TSO can serve as an indicator for the current imbalance and imbalance price. These circumstances lead to the fourth hypothesis.

Hypothesis 4: Due to the lack of official information, the activation of mFRR is interpreted as a real-time signal leading to passive balancing in Germany.

2.5 Timing of "energy-only" and balancing markets

Koch and Maskosa provide a review article examining the "German paradox" focusing on intra-day trading. A sharp increase of 15-minute energy products between 2012 and 2017 indicates the shift from 1 hour to 15-minute portfolio management, which reduced deterministic imbalances at full hours [17]. Weibbach et al. evaluated the corresponding effect on frequency deviations which shows a significant deterministic behaviour resulting from the length of traded energy products [28].

On the other hand, excessive short-selling at intra-day markets led to events of extreme imbalances in Germany in June 2019. A Europe-wide black-out was likely, according to the report of the German TSOs [29]. The ACE in Germany reached values over 9.5 GW (12.06.2019), respectively over 6 GW (06.06.2019 and 25.06.2019). BRPs faced misplaced incentives, which can be explained by the timing of "energy-only" and balancing markets.

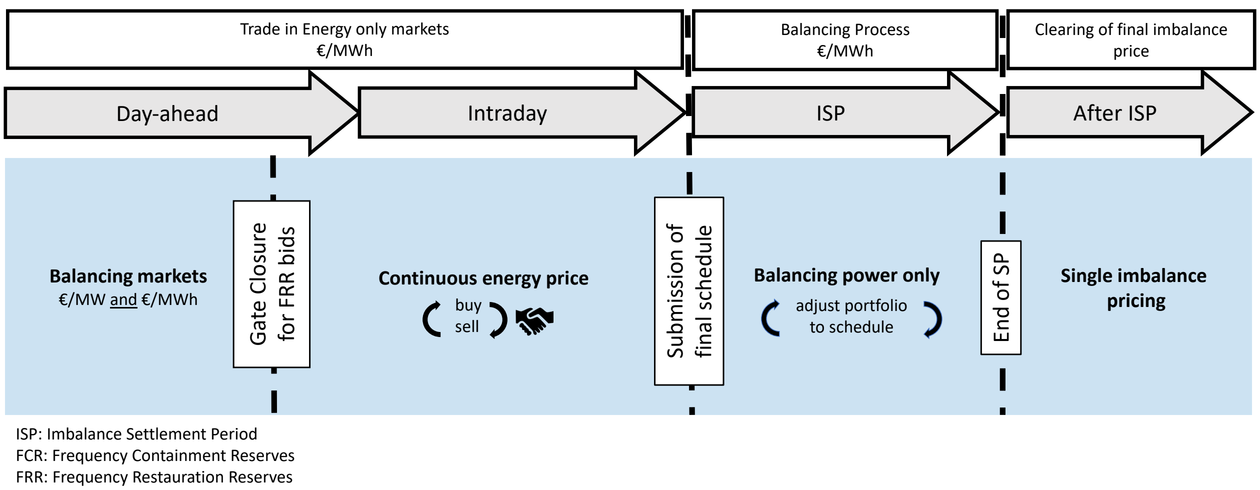


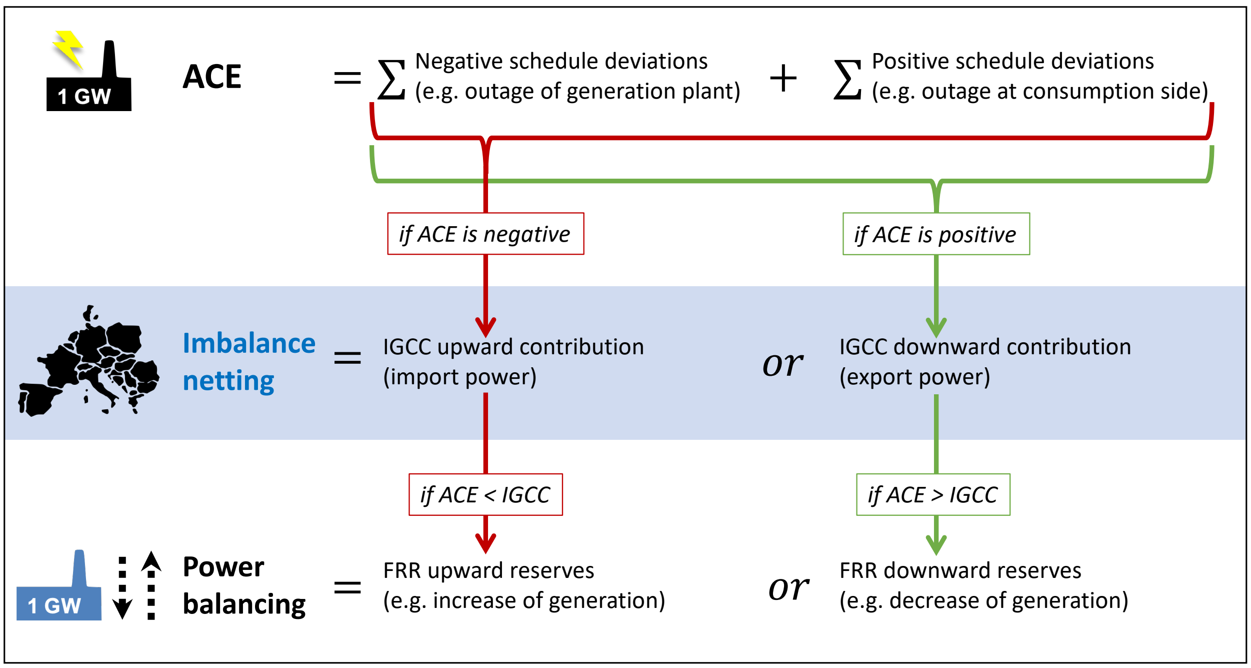
Figure 2: Current market rules in Germany

Figure 2 illustrates the timing. The first box over the timeline represents "energy-only" markets, which are the primary tool to plan the generation and load of electrical power. A day-ahead (D-1) auction with 1-hour products and continuous trade at intra-day markets with 15-minute products lead to final schedules of all BRPs. Changing the schedule is possible until 15 minutes before real-time (M-15) in Germany [24]. The boxes under the timeline are related to power balancing. BRPs offer prequalified reserves (FCR, aFRR, mFRR) at balancing markets in day-ahead (D-1) auctions. The schedule's deviation is cleared with the imbalance price (see section 2.3) for each 15-minute ISP. This price results from the costs at balancing markets and can be predicted by BRPs. The imbalance price and intra-day price difference are subject to passive balancing (section 2.2). The problem in June 2019 was a misplaced spread between intra-day price and the imbalance price. This misplaced incentive appeared because the prices at balancing markets were settled and published day-ahead. A moderate imbalance price could be expected while the intra-day price increased. The events in June lead to the fifth hypothesis.

Hypothesis 5: Wrong design of imbalance pricing and timing of markets can lead to misplaced incentives.

2.6 Imbalance netting

Ocker and Ehrhart (2017) describe the development of the German Grid Control Cooperation, which combined four German control areas into one single control block in 2010 [16]. This German grid control operates and four regional ACE are added to calculate one German ACE. This grid control implemented the concept of imbalance netting, leading to more schedule deviation, which cancels each other out. Imbalance netting reduces the activation of FRR in case of a positive and a negative ACE in neighboring areas. In the International Grid Control Cooperation (IGCC), imbalance netting works on the ENTSO-E level [11]. Figure 3 illustrates the interrelations. The schedule deviations of a control block cause the ACE in the first place. Power balancing now consists of two steps. First, the calculation of the imbalance netting contribution, and secondly the activation of FRR according to the remaining ACE.



ACE: Area Control Error = Sum of schedule deviations
IGCC: International Grid Control Cooperation = Reduction of ACE
FRR: Frequency Restauration Reserves = Compensation of Remaining ACE

Figure 3: Relation between schedule deviations, FRR, and imbalance netting - Input for observations and statistical tests

The netting process avoids FRR activation in two control blocks. The energy exchange is cleared with an opportunity price, reflecting the value of avoided FRR costs. In the case of the Netherlands and Belgium, imbalance netting contribution and applied opportunity price is part of the published real-time information. Combined with passive balancing, the opportunity price offers an additional business case and incentivizes BRPs to contribute to imbalance netting.

Hypothesis 6: Real-time information combined with imbalance netting gives Dutch and Belgium BRPs an advantage over German BRPs.

3 Smart Balancing: Definition, hypotheses, and proposed solution

The following definition of Smart Balancing gives guidance to develop a suitable market design for the German control block.

3.1 Definition of Smart Balancing

<u>Definition:</u> Smart Balancing is a set of measures to minimize unnecessary activation of FRR. BRPs optimize schedule deviations to offset other schedule deviations. Smart Balancing is a response to provide correct incentives in combination with public real-time information and should be designed to avoid reversing the sign of the ACE.

Besides the availability of real-time information, the definition of Smart Balancing addresses the unwanted reversing of the ACE from positive to negative values or the other way round. Passive balancing becomes Smart Balancing if BRPs are incentivized to reduce FRR activation without reversing of the ACE. As described in section 2.3: single imbalance pricing does not meet this requirement, but the Dutch approach of combined pricing offers such a correct incentive. With the International Grid Control Cooperation (IGCC), Smart Balancing can also reduce FRR demand in other control blocks via imbalance netting (see Figure 3).

3.2 Three measures for Smart Balancing in Germany

The hypotheses lead to three measures aiming to eliminate misplaced incentives and enable Smart Balancing. It creates a level playing field for Dutch, Belgium, and German BRPs via imbalance netting. Smart Balancing can be achieved in the current German market environment by three measures illustrated in Figure 4.

Measure 1: Shift the Gate-Closure of balancing markets to a point close to real-time.
Section 2.5 discusses a historical situation (20th of June 2019). That day a misplaced incentive occurred which led to an imbalance of 9.5 GW in Germany: A moderate imbalance price and the high intra-day price at energy-only markets made schedule deviations profitble. This situation was possible because the balancing market took place day-ahead. Such incentives can be avoided by shifting the Gate-Closure of balancing markets from day-ahead to a point close to real-time. By that, the balancing market will reflect information from the intra-day price at energy-only markets and the balancing process. The resulting imbalance price cannot lead to a misplaced incentive over long periods like in June 2019.

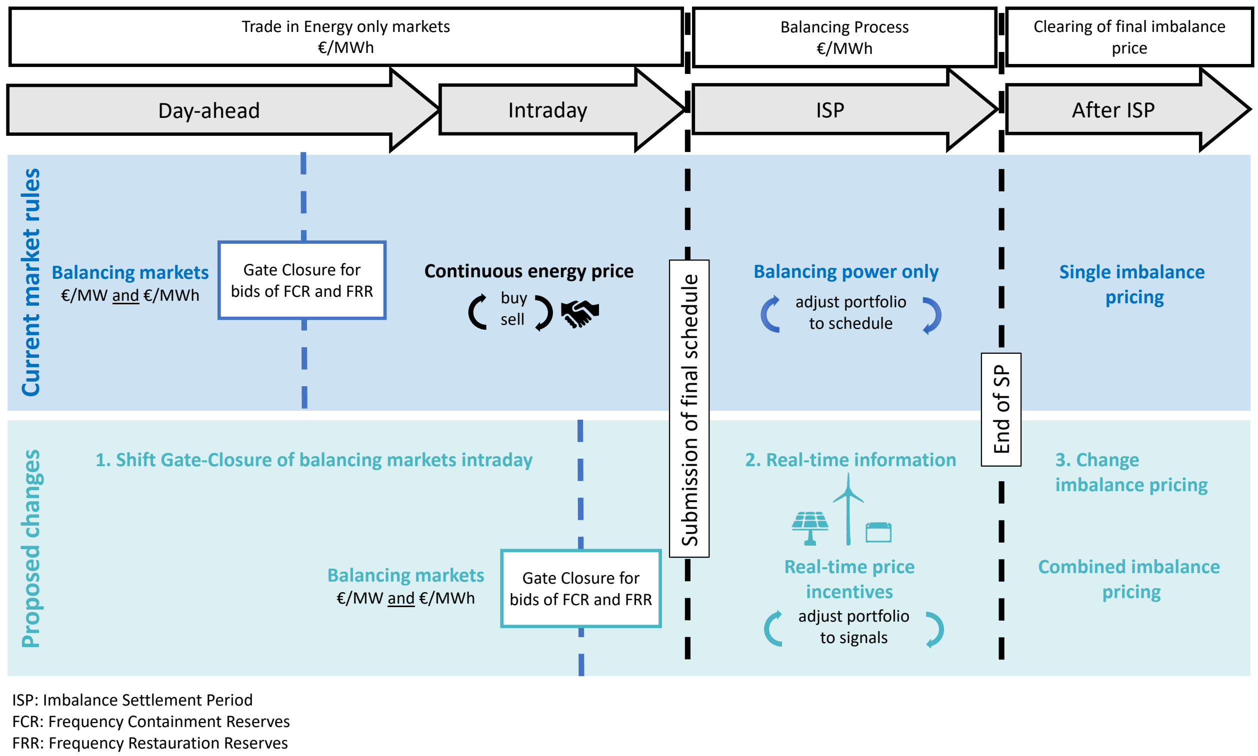


Figure 4: Current market rules and proposed set of three measures for Smart Balancing in Germany

Measure 2: Introduce real-time information about the system imbalance and imbalance price. Transparency on real-time information leads to market response (passive balancing), as explained in Section 2.2. BRPs can balance the German control block with accurate information rather than uncertain signals like the activation of mFRR and price information from the intra-day market.

Measure 3: The third measure can limit passive balancing by changing the current single imbalance pricing to combined imbalance pricing. Single vs. combined imbalance pricing is introduced in Section 2.3. Changing to combined imbalance pricing eliminates the incentive for overcompensation. The market design shown in Figure 5 thus meets the Smart Balancing definition.

3.3 Smart Balancing hypotheses

The literature in Section 2 led to six hypotheses. Table 1 indicates in which sections related literature is introduced, respectively, where the corresponding data analysis and simulation results can be found.

Hypothesis	Introduction	Data Analysis	Simulation Results
1. Increasing the capacity of VRE does not lead to higher balancing demand because the VRE expansion (an increase of stochastic imbalances) is overcompensated by market-related factors (reduction of deterministic imbalances).	Stochastic vs. deterministic imbalances in Section 2.1	Development of VRE capacity and balancing demand in Section 4.4.1	-
2. Real-time information facilitates passive balancing. Passive balancing reduces the activation of FRR and improves the cost-efficiency of power balancing.	Transparency as a design variable: Passive vs. Smart Balancing in Section 2.2	Market-response in NL, BEL, and Germany in Section 4.2 and 4.4.5, Introduction of real-time information in BEL in Section 4.4.2	Simulation of individual BRPs in Section 4.5, Market-response with fuzzy logic in Section 4.6, extrapolated market-response in Germany in Section 4.7
3. Due to the lack of official information, the activation of mFRR is interpreted as a real-time signal leading to passive balancing in Germany.	Passive balancing in Germany in Section 2.4	Evidence of market-response in Germany in Section 4.2 and 4.4.3	-
4. Wrong design of imbalance pricing and timing of markets can lead to misplaced incentives.	Timing of “energy-only” and balancing markets in Section 2.5	Misplaced incentives in Ukraine in Section 4.3 and Germany in Section 4.4.4	-
5. Combined imbalance pricing is a correct incentive for BRPs and prevents overcompensation.	Single vs. combined imbalance pricing in Section 2.3	Market-response and occurrence of FRR counter-activations in NL, BEL, and Germany in Section 4.2 and 4.4.5	Simulation of different imbalance pricing schemes in Section 4.6 and 4.7
6 Real-time information in combination with imbalance netting gives Dutch and Belgium BRPs an advantage over German BRPs.	Imbalance netting in Section 2.6	Costs and revenues from imbalance netting in NL, BEL, and Germany in Section 4.4.6	-

Table 1: Overview of Hypothesis - Introductions, corresponding Data Analysis and Simulation Results

4 Summary of publications: Market Theory, historical data, and simulations of market response for power balancing

The dissertation at hand consists of seven publications. Figure 5 illustrates the interrelations of the publications with hypotheses and the data availability via Digital Object Identifier (doi).

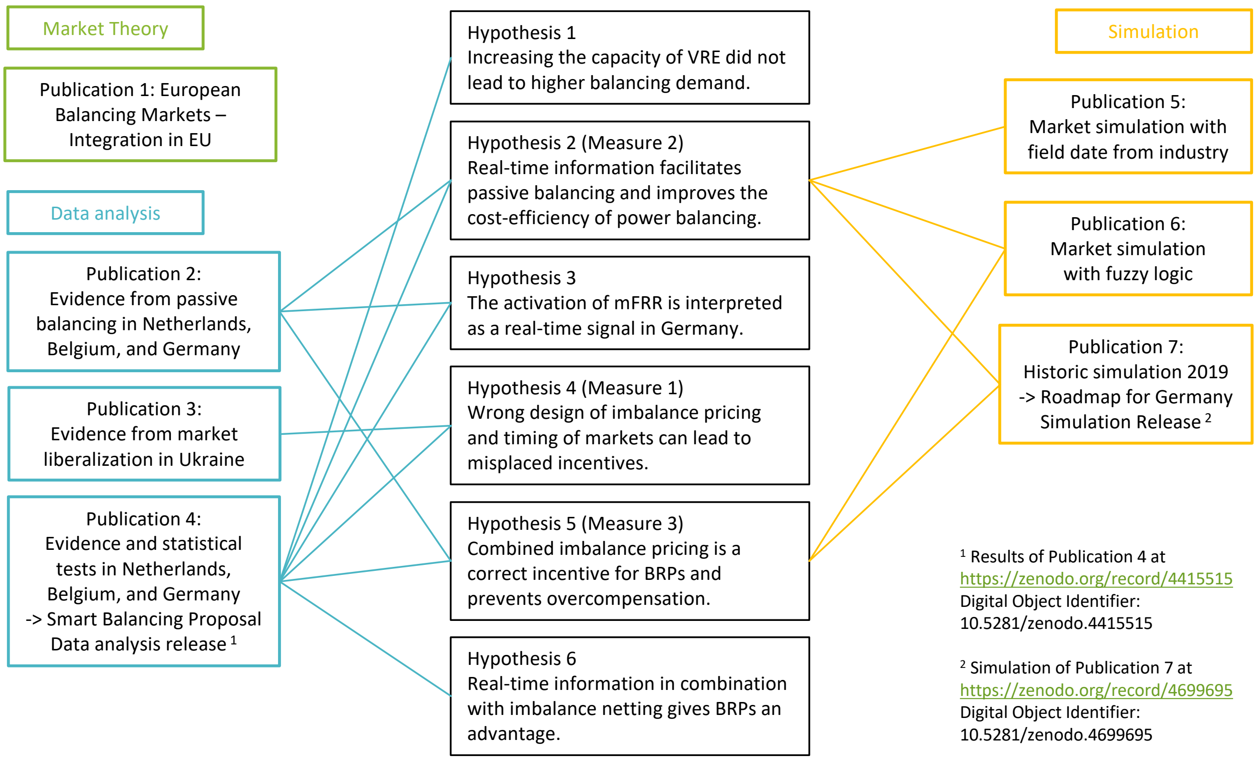


Figure 5: Relation of Publications with hypotheses and data availibilty via doi releases

Publication 1 in section 4.1 points out barriers for the European harmonization process. Publication 2 in section 4.2 showcases evidence of market response in the Netherlands, Belgium, and Germany. Publication 3 in section 4.3 showcases evidence of market response in Ukraine in 2019 and 2020, when the electricity market was first liberalized. Publication 4 in section 4.4 analysis the hypotheses with historic data. Publication 5 in Section 4.5 introduces the Smart Balancing model to estimate the potential benefit of market response from a small number of BRPs. Publication 6 in section 4.6 presents fuzzy logic as a method to estimate the behaviour of all BRPs in a country with single vs. combined imbalance pricing and results from a test environment. Publication 7 in section 4.7 presents different simulation scenarios in Germany with historical data and extrapolated market response via fuzzy logic.

4.1 Barriers to integration of power balancing markets in Europe – Publication 1

Heterogeneous legislation is in place in Europe because market rules developed historically, e.g., with national power generation and demand characteristics. The European markets shall be harmonized to facilitate an international market for balancing power, and the EU Commission partly directs the future design. On the other hand, national characteristics remain in place. Consequently, the first publication investigates current differences in European power balancing markets and an analysis of potential barriers for the harmonization of balancing markets took place. Current balancing market rules in Europe are compared to the predefined choices of the "EU commission regulation 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing" [14]. The regulation makes allowance for a step-by-step integration. It allows groups of TSOs to perform pilot projects. A barrier to fast integration is the diversity of balancing approaches in Europe. Potential harmful interrelations of all national characteristics with harmonized balancing procedures are complex to rule out. The European regulators counter this risk by involving all stakeholders and asking for industry proposals. The integration process is promising if it can involve all stakeholders.

Barriers to harmonizing balancing markets and products are the variety of applied balancing strategies. First, the differences in controller set-ups (e.g., signal and activation strategy) must be managed. Other than that, the predefined balancing energy market design (single imbalance pricing, marginal clearing of balancing energy, common merit order list, ISP of 15 minutes, and 1 MW power bid increments) are applied and functional in different countries [21], [30]. Nevertheless, the cost-efficiency of these design choices is part of scientific debates. The cost benefits of dual or combined imbalance pricing and "pay as bid" clearing is unclear [31]. The reduction of the ISP and minimum power bid to values under 15 minutes and 1 MW could cut costs further, according to a simulation of Burgholzer [31]. The issue of market response, respectively passive balancing, is not addressed in the EU regulation and is a significant barrier for a European level playing field for BRPs from different countries.

4.2 Market response in NL, BEL and Germany – Publication 2

Publication 2 puts the spotlight on historical evidence of market response in the Netherlands, Belgium, and Germany in 2017. Publication 2 highlights and evaluates different approaches to how market response is incentivized. Data from the three control blocks and the behaviour of BRPs are evaluated.

The Dutch TSO supports market response with information about power imbalance and costs. BRPs can evaluate their marginal costs for deviations from their schedule and compare it to the imbalance price. Additionally, the information about power imbalance indicates the risk of not being awarded in case of reversing the sign of the ACE when the dual imbalance price applies. Therefore, BRPs can take data-based decisions resulting in a system supporting market response which made mFRR in the Netherlands mainly redundant. An example of the effectiveness of passive balancing in the Dutch power system is elaborated by de Haan [32]. High transparency about power imbalance and costs combined with a penalization for reversing the sign of the ACE results in the best approach for an efficient market response. The low share of ISPs with counter-activation of positive and negative FRR (9.1 %) and the low ACE are the benchmarks that indicate the presence of controllable interaction between TSOs balancing efforts and market response without a nervous behaving system.

The Belgian TSO supported market response with information about power imbalance without prices in 2017. The sign and magnitude of the imbalance price can be derived from the available information, but the uncertainty about potential revenues limits the market response. Reversing the sign of the ACE is not penalized, risking overreaction due to market response. Belgium faced in 66.8 % of ISPs a counter-activation of positive and negative FRR.

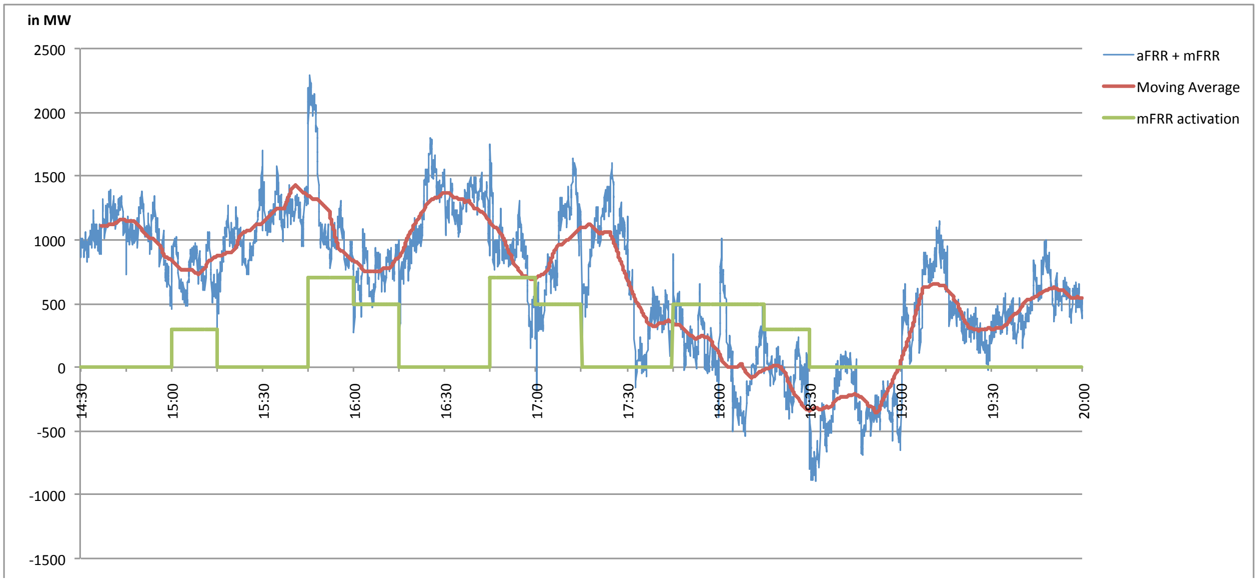


Figure 6: FRR demand and under-cover market response in Germany, 15.06.2017

Occasionally, some German BRPs respond to FRR activation, even though the German strategy does consider it. Figure 6 shows that the demand for reserves declines after activation of mFRR, which can be explained by market response. The call for mFRR activation is transmitted to the executing Balance Service Providers (BSPs) latest 7.5 minutes before the beginning of an ISP and in principle only known by the TSOs and the called BSPs [8]. Nevertheless, the presented evidence shows three cycles of an oscillation between mFRR activation of 300 to 700 MW and market response of roughly several hundreds of MWs in addition. The first call for mFRR activation took place between 14.45 and 14.52´30s for the ISP starting at 15 hrs. The demand for reserves starts declining during that time window. The same pattern can be observed before the ISPs starting at 15.45 and 17.45 hrs. The activation signal of mFRR leads to a financial incentive for schedule deviations. Some BRPs know it, and this particular example has led to a system supporting behaviour. Germany faced in 97.3 % of ISPs a counter-activation of positive and negative FRR.

Comparing the three countries shows that the ACE and resulting activation of FRR decline with a rising degree of transparency that allows market response real-time (passive balancing), subject to correct price incentives. This conclusion is based on the very similar power balancing approaches of the TSOs, differing mainly in the transparency about real-time system information. The high occurrence of counter-activations of positive and negative FRR in Belgium and Germany shows potential for improvement. Imperfect information occasionally leads to an overreaction of market response since a pure single price is applied, and balancing demand and market incentives are less coherent.

The Dutch approach seems to work best in this case, considering the low occurrence of counter-activations of FRR and, especially, the comparatively small ACE. Therefore, an additional mechanism to prevent overreaction of BRPs, like the Dutch approach of changing from single to dual price in case of FRR counter-activations, is advisable as a component for an efficient market response in real-time.

The presented evidence in Germany (Figure 6) shows some consequences of applying a single imbalance price for schedule deviation without full transparency of system and market information in real-time. The appliance of a single imbalance price is inherently the incentive for BRPs to have a system supporting schedule deviation to a certain degree. They can only react correctly in case of sufficient real-time information. This information consists of (expected) imbalance price as the incentive for market response. Most potential market responses remain inactive due to ambivalent information and financial risks. From the German observation, it is concluded that despite incomplete system information, single imbalance pricing still allows market response (passive balancing). However, the effectiveness and potential is limited. A clear mechanism to prevent reversing the sign of the ACE is currently also not provided.

Relevant design parameters are real-time information granularity and delay, pricing settlement (marginal vs. pay-as-bid imbalance clearing, single vs. combined pricing),and aFRR controller set-up (e.g., signal, full activation time, and activation strategy). The effectiveness of market response is strongly determined by the interaction of market design parameters and should be considered a package deal rather than a stand-alone option.

4.3 Liberalization and market response, evidence from Ukraine – Publication 3

The shift from regulated electricity monopolies towards liberal energy markets has taken place in EU countries since 1996. The legally-binding reason for the "unbundling" was the Directive 96/92/EC of the European Parliament and the Council of 19 December 1996 [33]. Market response is a consequence of liberal markets with price incentives. Publication 3 examines the recent case of liberalization in Ukraine, the initial market design, and its changes in December 2019, March, April, May, and June 2020. The effects on day-ahead market prices, imbalance prices, and activated balancing reserves are evaluated with data from July 2019 until April 2020.

Gencer et al. describe the liberalization in England and Wales, Germany, Belgium, Denmark, and Switzerland [34]. According to the analysis, energy markets evolve in three steps. The initial "Monopoly" is replaced by "Wholesale Competition": industry and generators trading at spot markets. Afterward, "Retail competition" allows all consumers to choose their energy supplier at free markets. The final stage of "Reregulation" adopts rules "to intervene to induce or prevent certain behaviours by market participants". Gencer et al. conclude that (i) many regulatory frameworks are lagging behind innovation in the market, (ii) the behavioural factors are as important as economics, and (iii) agile market frameworks should give a long-time perspective, but also pay attention to the feedback of stakeholders [34].

The liberalization of the electricity market in Ukraine in July 2019 led to unwanted behaviour of BRPs. The data illustrates temporary malfunctions. The different periods indicate that misplaced incentives of the initial market design led to situations of high power imbalances. In November 2019, the amount of activated downward reserves peaked. The misplaced incentive was a combination of low day-ahead market prices and fixed imbalance prices, as shown in Figure 7. The imbalance price exceeded the day-ahead market price in 500 out of 720 hours. BRPs could increase revenues by not selling energy day-ahead, but rather having schedule deviation.

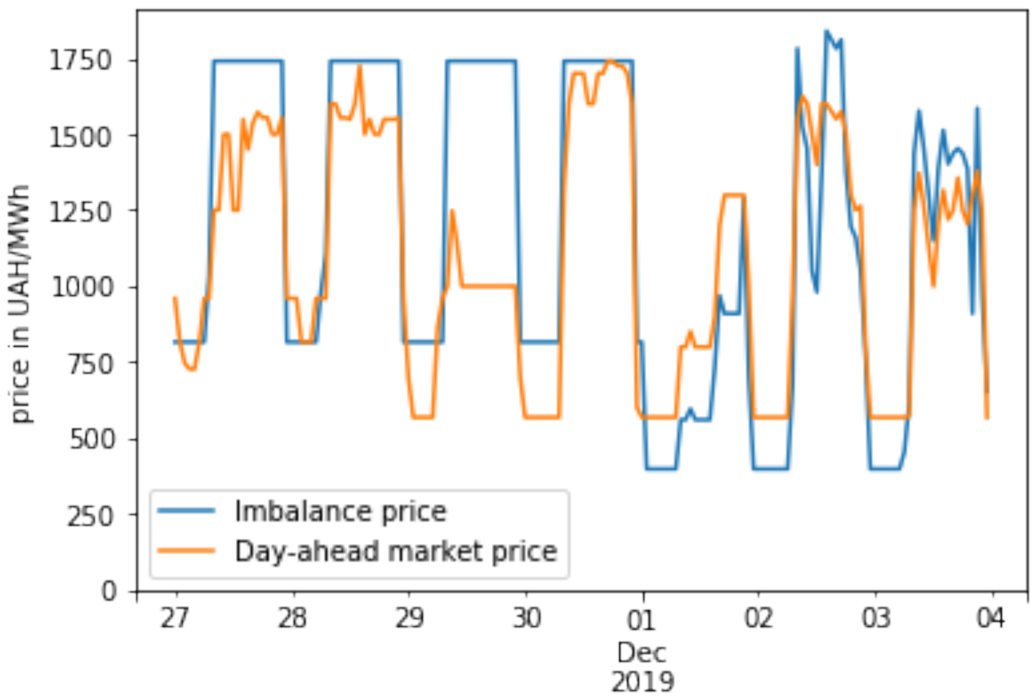


Figure 7: Imbalance price and Day-ahead market price in Ukraine from 27.11.2019 to 04.12.2019

The market design change of the calculation of the imbalance price caps by 1 December 2019 did eliminate the minimum imbalance price. The new approach avoided misplaced incentives in case of low day-ahead market prices, and an immediate reduction of the required balancing reserves was observed, as shown in Figure 8.

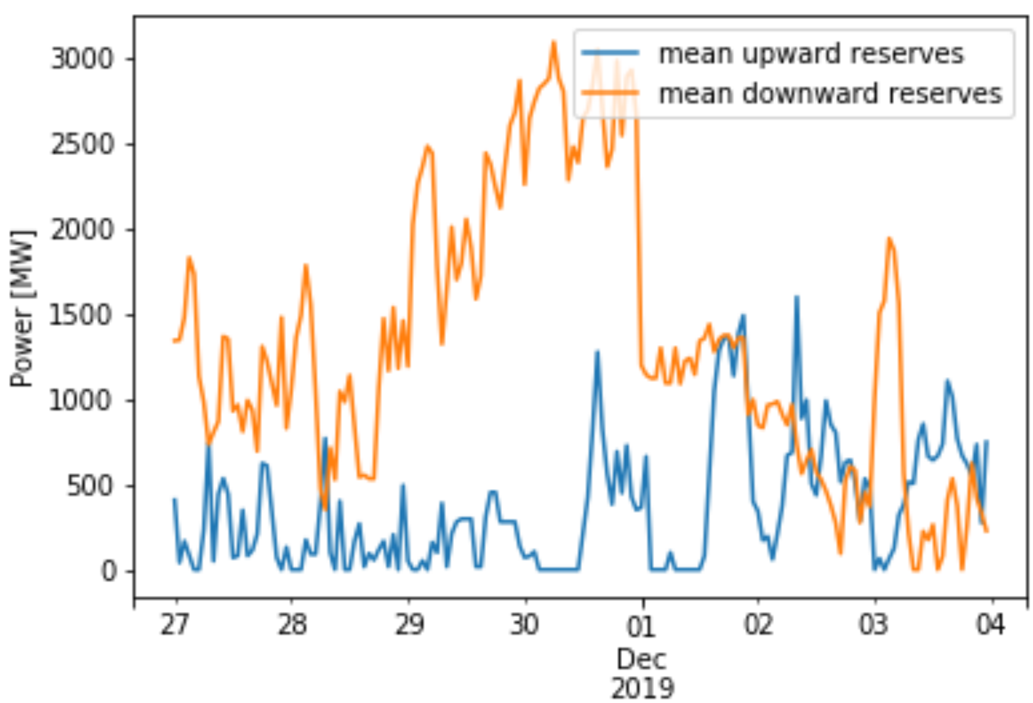


Figure 8: Activated reserves in Ukraine from 27.11.2019 to 04.12.2019

The governmental statement of starting an investigation on market manipulation in February 2020 came along with the most balanced month. The liberalization of the electricity market in Ukraine illustrated how misplaced incentives lead to unwanted market reactions. Initially, creating positive schedule deviations was more attractive than selling energy at the day-ahead market leading to high amounts of activated downward reserves in November 2019. Changing price caps and governmental warnings did stop this speculation of BRPs leading to minimum amounts of activated reserves in February 2020. Changing to dual imbalance pricing in March 2020 did not improve the situation further.

Changes in legislation should be transparent and implemented quickly to avoid temporary speculations. Changing the imbalance pricing scheme reduced misplaced incentives, but a transparent real-time market could lead to further improvements. The regulation should allow to adopt and give immediate feedback to the BRPs. In addition, elimination of price caps to allow higher prices for balancing reserves would give more substantial incentives to participate in balancing markets.

4.4 Analysis of historic Macro Data (DE, NL, BEL) – Publication 4

Publication 4 applied different data-based analysis and test approaches to evaluate the six hypotheses, first introduced in section 2. Applied historic data covers five years (2015 to 2019). The analysis is implemented in Python and can be obtained online [35].

The hypotheses are analysed by observations and statistical tests with empirical data from the three countries.

1. Observation: Development of VRE capacity and balancing demand
2. Observation: Events of high imbalances in June 2019 in Germany
3. Statistical test: Introduction of real-time information in Belgium
4. Statistical test: Market Response to mFRR activation in Germany
5. Observation: Occurrence of FRR counter-activations
6. Observation: Costs and revenues from imbalance netting

4.4.1 Observation: Development of VRE capacity and balancing demand

The suggested observation follows the argumentation of [12], [16], and [36]. Observing the installed capacity of VRE and balancing demand in Germany, the Netherlands, and Belgium allows considering if the "German paradox" is present in other countries.

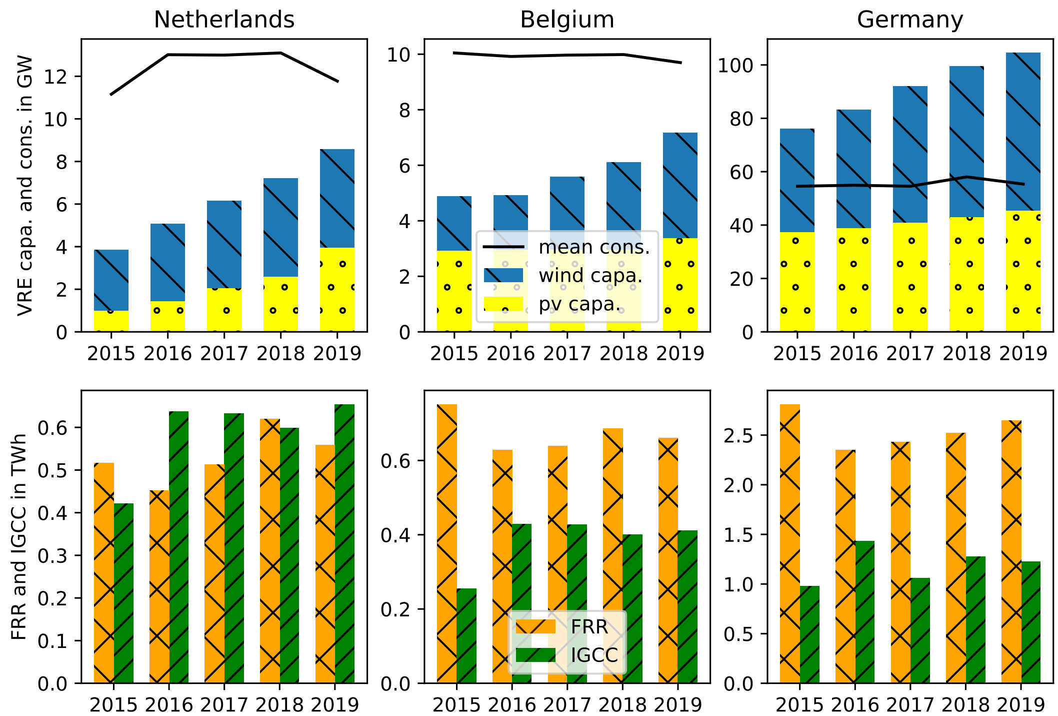


Figure 9: Top: Mean power consumption and installed capacity of VRE; Bottom: Activated Frequency Restoration Reserves (FRR) and imbalance netting via International Grid Control Cooperation (IGCC)

Figure 9 shows the installed capacity of VRE and mean consumption in GW in the upper row of plots. The balancing demand in TWh in the second row of plots consists of upward and downward FRR activation (including aFRR and mFRR) and upward and downward IGCC contribution.
The capacity of VRE increased, but the activation of FRR did not follow the same trend and remained relatively stable. Belgium and Germany activated less FRR in 2019 than in 2015. This is remarkable because the increase of VRE capacity compared to mean energy consumption from 49 % to 74 % (Belgium), respectively from 139 % to 189 % (Germany) is substantial. The Netherlands increased VRE capacity from 49 % to 70 % compared to mean energy consumption. They activated more FRR, but could decrease related costs by generating revenues from IGCC, shown in section 4.4.6.

These observations support the hypothesis that increasing capacity of VRE does not necessarily lead to higher balancing demand if negative effects are compensated by market-related factors (hypothesis 1).

4.4.2 Statistical test: Introduction of real-time information in Belgium

As described in section 2.2, Belgium first introduced real-time information in 2017 and changed to more transparency in 2019. The data is separated, and a t-test of independent samples [37, p. 19] is conducted with balancing demand and related costs. If the t-test indicates a statistically significant difference (p-value < 0.05) between the samples, the effect size is calculated using cohen's d [37, p. 66].

Belgium publishes their imbalance in real-time since 2017. The publication of the imbalance price was added at the end of August 2019. The information is now published in a 1-minute resolution together with the activated FRR [38]. In addition, the contribution to IGCC (in MW) and costs/revenues for imbalance netting (in €/MWh) is provided to the BRPs. The 5-year data from Belgium is separated in 3 datasets according to the different stages of real-time information.

The reduction of FRR volumes is significant in both comparisons. The costs for FRR increased when imbalance information was first introduced but decreased under the initial 2015/2016 level in the last three months with price information.

The imbalance netting volumes via IGCC increased significantly when real-time imbalance information was first introduced in 2017, but the slight increase of related costs was not significant. In the last three months of 2019, the imbalance netting volumes and related costs decreased significantly. As the negative costs prove, Belgium even generated revenues from imbalance netting during these three months.

The applied data covers only three months with real-time price publication. However, the applied statistical tests support the hypothesis that activation of FRR is reduced, and cost-efficiency can be improved by passive balancing. While the reduction of FRR could already be achieved by publishing information on the imbalance, improved cost-efficiency was only achieved when adding price information.

4.4.3 Statistical test: Market response to mFRR activation in Germany

The claim that BRPs in Germany react with passive balancing to the activation of mFRR in Publication 2 is tested with empirical 2015 to 2019 data [39]. The data is separated into comparable samples with an ACE in the same range (step size of 100 MW). The ACE difference to the following ISP is under consideration with and without mFRR activation. T-tests of independent samples are conducted [37, p. 19].

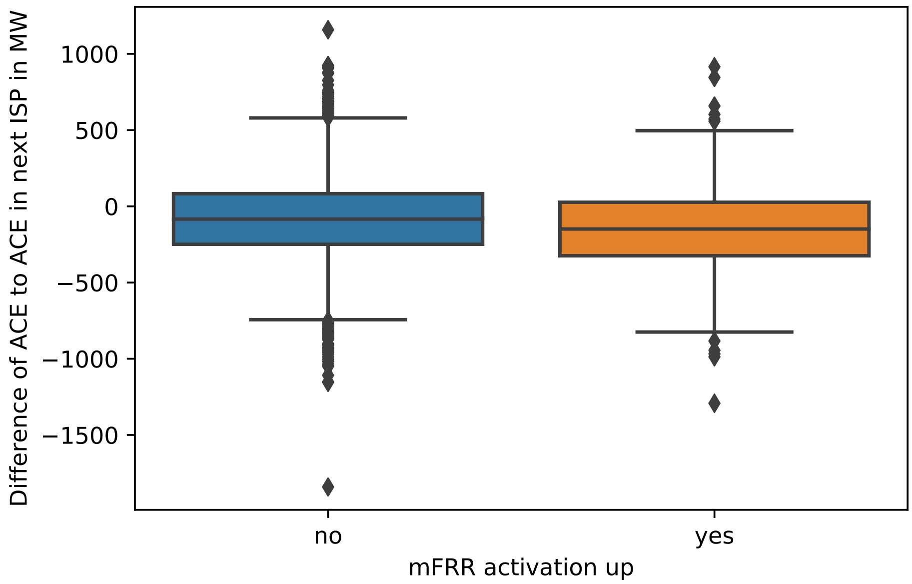


Figure 10: ISP with ACE over 0.6 GW and under 0.7 GW. ACE difference to next ISP no vs. yes mFRR activation, 2015 to 2019 data

For example, Figure 10 shows the imbalance range with ACE between 600 MW and 700 MW. The difference of the ACE to the ACE in the following ISP without (left) and with mFRR activation (right) illustrates the significant effect of mFRR activation. On average the ACE is reduced by 84 MW in all 5919 ISPs without mFRR activation. In contrast, the ACE is reduced by 157 MW in 379 ISPs with mFRR activation.

The results support the hypothesis that BRPs interpreted the activation of mFRR as a real-time signal which leads to passive balancing in Germany.

4.4.4 Observation: Events of high imbalances in June 2019 in Germany

Events in Germany in June 2019 are subject to a report of 50 Hertz et al [29]. Data obtained from ENTSO-E [39] show four days with critical imbalances (06.06., 12.06., 25.06., and 29.06.2019). The activated reserves and misplaced incentives in Germany during 12.06.2019 are analysed in this subsection. The day is particularly critical because of activated reserves (FRR and additional emergency reserves) of up to 7.5 GW at noon. The day-ahead auctions led to a moderate price of 51 €/MWh with scheduled power generation of 69.6 GW for the most critical period from 11 am to 12 am [40].

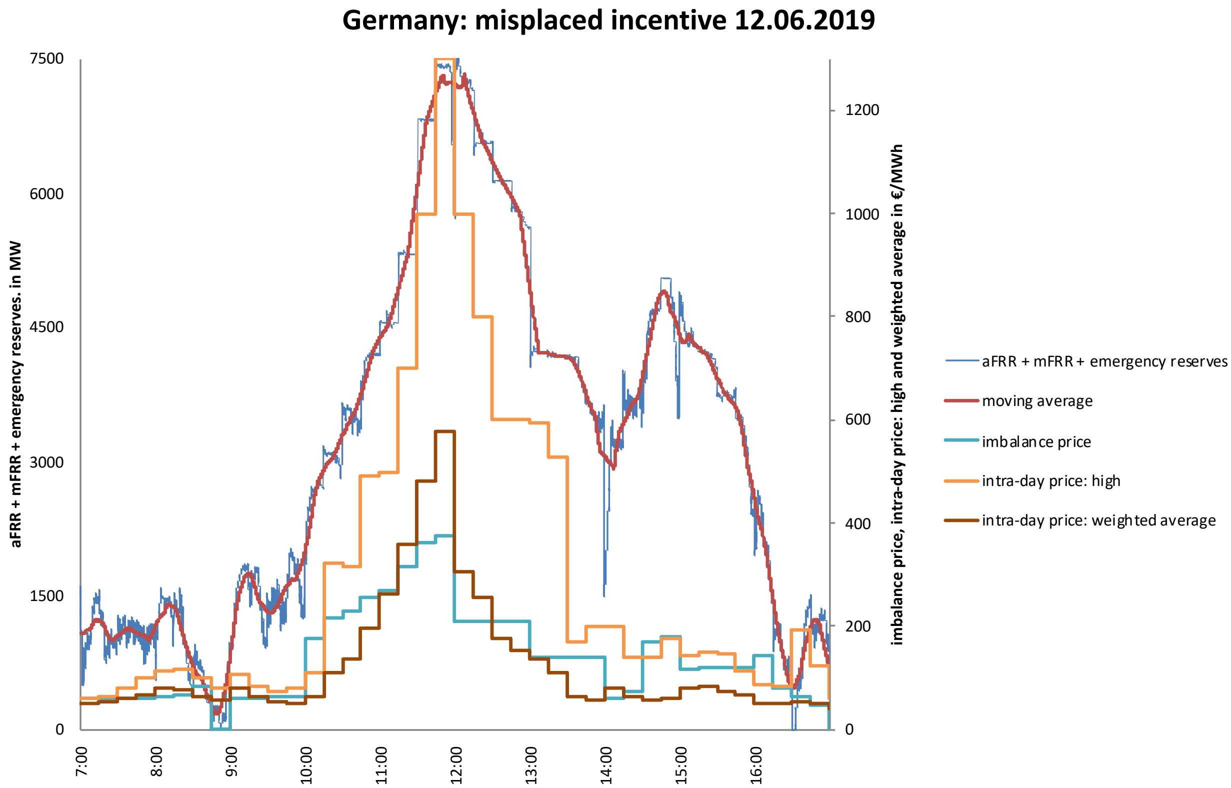


Figure 11: Activated reserves and imbalance price from ENTSO-E, and intra-day prices in Germany from epex, 12. of June

Figure 11 illustrates the development during the 12th of June 2019 between 7 am and 5 pm with activated reserves, the imbalance price, and the intra-day price (high and weighted average). The highest prices at the intra-day market exceeded the imbalance price most of the time. The weighted average price is calculated by considering the price of all trades weighted by the traded energy volume. During the peak of the imbalance event, even the weighted average price exceeded the imbalance price. 50 Hertz et al show that BRPs did "correct" their schedule by reselling energy volumes, even though the day-ahead schedule was accurate [29]. These short sales were the leading cause for the critical situation, but BRPs made revenues (spread between imbalance price and intra-day price). Also, wind forecast errors did occur that day, and less energy was generated than predicted [41]. BRPs were incentivized to stay with wrong schedules and pay the moderate imbalance price rather than correcting their schedule. Correcting a schedule means, in this case, paying a high intra-day price to buy back the energy not generated by wind turbines.

The intra-day prices reflect new information on forecast errors of load and weather predictions. While this is the purpose of intra-day markets, the already defined maximum imbalance price can lead to a misplaced incentive for BRPs. The penalty for schedule deviations (the imbalance price) can be lower than the price at the intra-day market. If the balancing markets took place after Gate Closure of the intra-day market, the bids would reflect the latest information. The imbalance price would increase over the intra-day price in situations with high imbalances.

This evidence-based chain of arguments supports the hypothesis that changing the Gate-Closure-Time of balancing markets close to real-time avoids misplaced incentives.

4.4.5 Observation: Occurrence of FRR counter-activations

The occurrence of FRR activation with a focus on counter-activations in the Netherlands, Belgium, and Germany are analysed. Volumes smaller than 1 MW FRR activation are neglected in a second analysis to evaluate the occurrence of small counter-activations.

The FRR activation of each 15-minute ISP of the five years is analysed. The Netherlands faced 71 % of ISPs with positive or negative FRR activation and 22 % of ISPs with counter-activation of FRR. Belgium faced counter-activation of FRR in 70 % of ISPs, and Germany the figure even reached 100 % of all ISPs. The German value is odd and indicates that the data includes measured and not activated FRR volumes since there are ISPs with only positive ACE (e.g., June event). The numbers change when neglecting small amounts of FRR activation of 1 MW (FRR counter-activation in Germany over 1 MW is 91 % of all ISPs), but the overall picture remains the same. Only the Netherlands exhibited ISPs without any FRR activation (7 %), which can be traced back to ISPs where the ACE was completely netted via IGCC. In addition, a low share of ISPs with FRR counter-activation indicates that combined imbalance pricing works better with passive balancing.

These observations support the hypothesis that combined imbalance pricing is a correct incentive for BRPs and prevents reversing the sign of the ACE.

4.4.6 Observation: Costs and revenues from imbalance netting

The imbalance netting contribution and resulting costs, respectively revenues, are observed in the Netherlands, Belgium, and Germany.

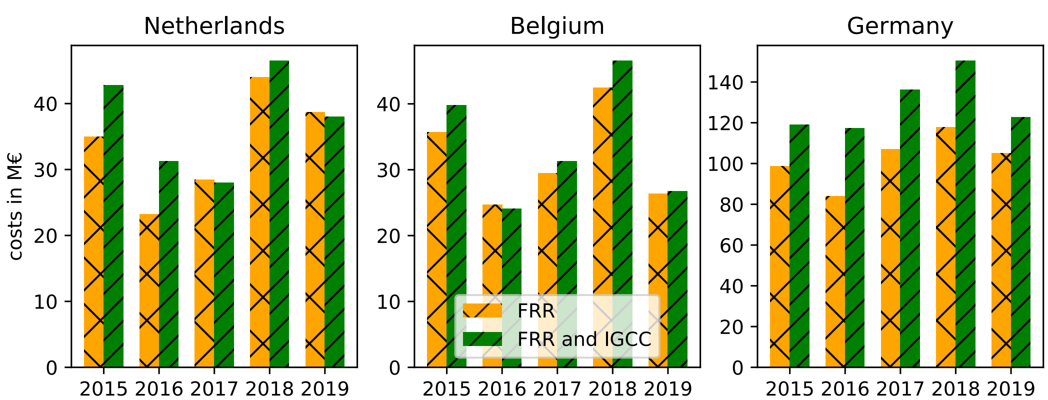


Figure 12: Costs for the balancing process, based on Frequency Restoration Reserves (FRR) volumes and prices from TenneT (2020), Elia (2020a) and 50Hertz et al. (2020); International Grid Control Cooperation (IGCC) volumes and prices: from 50Hertz et al. (2020)

Figure 12 illustrates costs and revenues in million euros (M€). Due to revenues from IGCC, the total costs for balancing (FRR and IGCC) can be smaller than the costs for FRR. The Netherlands generated revenues from IGCC in 2017 and 2019. Belgium generated revenues from IGCC in 2016. In addition, Belgium generated revenues in the last three months of 2019 after introducing real-time price information, as discussed in section 4.4.2.

These observations support the hypothesis that passive balancing with imbalance netting gives Dutch and Belgium BRPs an advantage over German BRPs.

Other than discussing costs and revenues from IGCC, it is challenging to compare the balancing performance of different countries. Due to differences in consumption and generation characteristics, any further comparison would require normalizing the data.

4.5 Simulation of four individual BRPs with historical data – Publication 5

In combination with historical data, a simulation can quantify the potential benefits of Smart Balancing in Germany. The Smart Balancing model was first presented in the fifth peer-reviewed publication, part of the dissertation. The first simulation applied historic data from 18. to 24. November 2019 in a 1-second resolution.

4.5.1 Environment for simulation of four BRPs

Field data from BRPs representing three industrial processes and one BRP representing VRE were obtained . The software is set up using object-oriented programming. Classes for all relevant grid structures, including the synchronous zone, control blocks, and BRPs, are defined to model the hierarchy of these structures within the synchronous zone. A balancing model is composed of objects for BRPs that are subordinated to objects modelling the control block, which are subordinate to an object modelling the synchronous zone. Following this approach, the hierarchy of objects reflects the hierarchy of the existing power system.

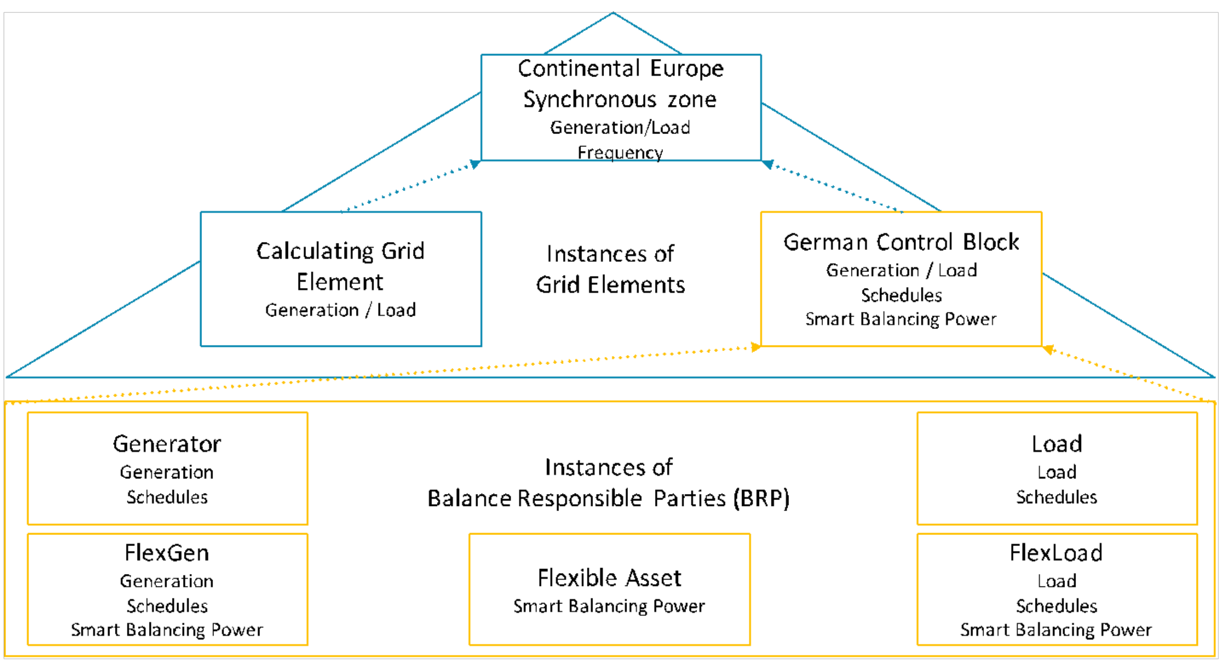
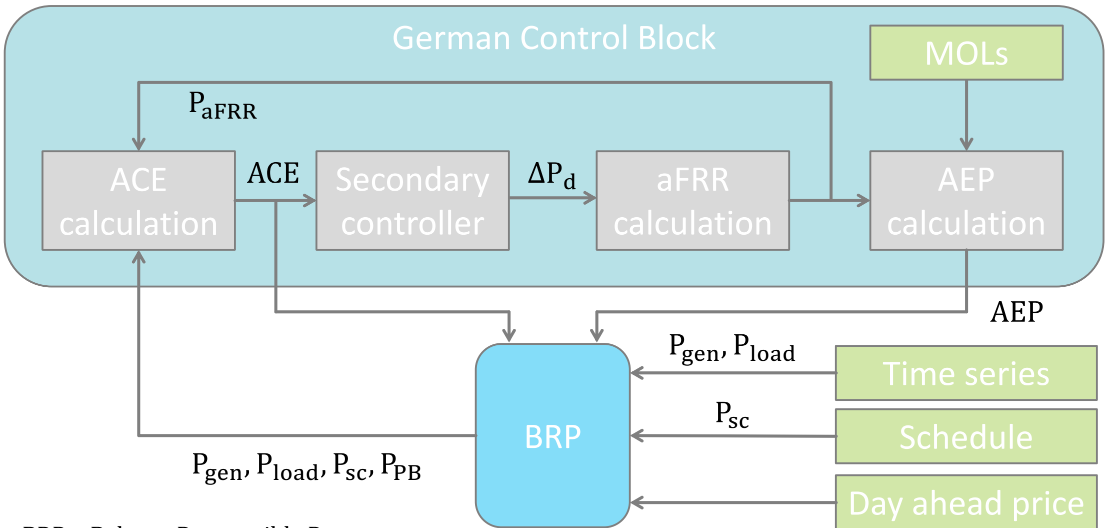


Figure 13: Smart Balancing model: Instances of Grid Elements in top triangle and Instances of BRP within the German Control Block (yellow) in bottom square. Instances show name of object type and most important properites

Figure 13 illustrates the object-oriented model structure. On top, instances of grid elements cover calculations on system frequency and activation of balancing energy according to the ENTSO-E grid code [13]. Objects within a control block are instances of BRPs. The simulation runs carried out covered the German control block. The rest of the European synchronous zone was assumed to have constant and balanced generation and load of 300 GW.



BRP - Balance Responsible Party
ACE – Area Control Error
ΔP_d - delayed power requested by secondary controller
P_{gen} - power generation of BRP
P_{load} - load of BRP
P_{sc} - scheduled power of BRP
P_{PB} - passive balancing of BRP
P_{aFRR} - automatic Frequency Restauration Reserves
MOLs – Merit Order Lists with bids for P_{aFRR}
AEP – imbalance price (Ausgleichs-Energie-Preis)

2

Figure 14: Flowchart of first version of Smart Balancing simulation in the German Control Block for calculation of individual passive balancing contribution from each BRP

Figure 14 illustrates the flowchart of the model. The ACE is defined in the control block class and is calculated as the sum of schedule deviations of all BRPs subordinated to the control block. In addition, the control block class is equipped with a discrete PI controller to model the activation of FRR. The output signal of balancing power is delayed by a parametrizable time constant to model the response time of the BSP. Further, the control block class contains Merit-Order-Lists (MOLs), containing the FRR sorted by price. The German FRR activation strategy and single imbalance pricing are implemented to calculate the imbalance price according to the simulated FRR activation and costs.

The mechanisms regarding market response are implemented in the BRP class. First, the currently available potentials to provide positive and negative power are calculated continuously according to the current power consumption and generation and their specific upper and lower limits. Each BRP object is provided with the ACE and price signals in real-time and the day-ahead price for each ISP. Using this information, BRPs can predict the financial outcome of their schedule deviation. Specific decision-making rules for the provision of market response are implemented for each BRP object. The activated power of a BRP object implies an alteration of their schedule deviation. As a result, the schedule deviation of the control block is altered, affecting the activation of FRR.

4.5.2 Results of simulation with four BRPs

In the simulation with passive balancing of four BRPs, the real-time imbalance price signal fluctuates between a maximum value of 620.51 €/MWh and a minimum value of -614.10 €/MWh. By that, the BRPs contribute to the power balancing in Germany significantly.

Over the whole week, both positive and negative FRR energy and related costs are reduced. The total activated positive aFRR energy is reduced by 287 MWh via reduction of industrial load. Due to the enormous potential for a negative market response of considered wind farms, negative aFRR is reduced by 883 MWh. The total FRR costs of the week are reduced by 57,354 € for the German control block. On the other hand, the four BRPs can optimize their imbalance costs significantly. The imbalance price and historical schedule deviations of the four BRPs amount to costs of 54,880 €. With market response the BRPs can lower their imbalance costs by 81.8 %. Three of the BRPs can even turn their imbalance costs into income.

The simulation supports the hypothesis that activation of FRR is reduced, and cost-efficiency can be improved by passive balancing.

4.6 Modelling market-response with fuzzy logic – Publication 6

In contrast to the Publication 5 with only four BRPs, the real potential of market response of all BRPs exceeds the ACE. Therefore, a limitation of market response, e.g., via fuzzy logic, is necessary. The concept of applying fuzzy logic to anticipate market behaviour was first presented in Publication 6.

4.6.1 Introduction to fuzzy logic

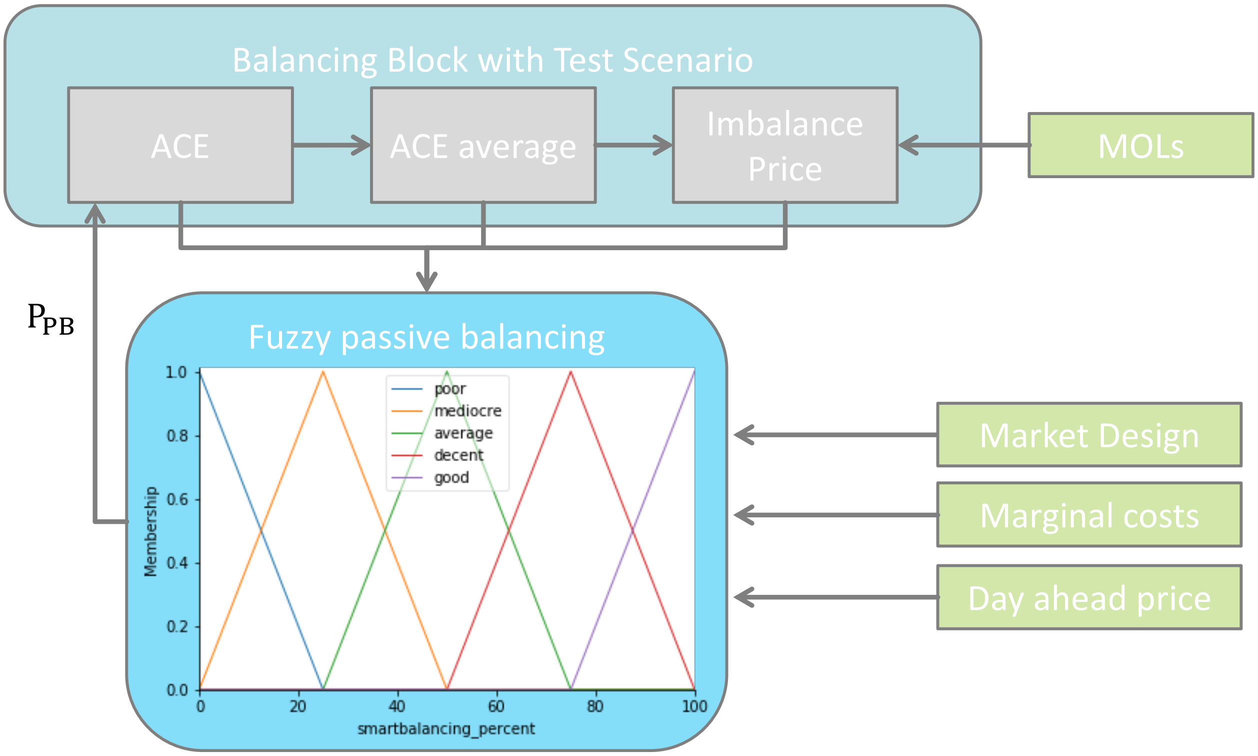
Fuzzy logic is introduced to optimize revenues for BRPs with minimal risk. Market response is simulated in market environments with marginal vs. pay-as-bid clearing mechanisms and single vs. combined imbalance pricing. Fuzzy logic classifies input data by membership functions and then relates them via rules. To set up a fuzzy controller, the relevant input data, including their minimum and maximum values and the classification of the data, are required. Suitable values are derived from historical data of the German energy market in 2019.

The fuzzy output is expressed as a percentage between zero and 100. The fuzzy output is defined by dividing its value range into five equally distributed gradations named poor, mediocre, average, decent, and good (see Figure 15)

4.6.2 Test scenario for fuzzy market response

Fuzzy logic shall optimize the financial advantage. Therefore, this section examines how individual participants would optimize their opportunities within different regulatory frameworks. Fuzzy logic optimizes market response by analysing financial opportunities and judging risks.

Passive balancing is determined by the economic flexibility potential, the potential income, and the risk of a changing imbalance price. BRPs calculate the economic flexibility potential, corresponding to the maximum possible response. The fuzzy logic determines the optimal response based on the potential income and considers the risk.



ACE – Area Control Error
P_{PB} - passive balancing
MOLs – Merit Order Lists

Figure 15: Environment of fuzzy logic for optimization of market response

Figure 15 illustrates the fuzzy environment used to simulate market response and real-time energy balancing. The steps to be executed by BRPs within the blue box are:

1. Calculate economic flexibility potential: All existing technical potential is ordered by marginal costs. The marginal costs, day-ahead, and imbalance price define the economic flexibility potential.
2. Identify optimal activation ratio: Market design, the potential income, and the power imbalance are used as input variables for the fuzzy logic since they define the potential financial benefit and risk of market response.
3. Market response: The economic potential is multiplied by the activation ratio. The resulting power is to be activated as market response. Flexible assets get that new set-point and ramp up or down according to their technical limitations.

The difficulty of risk assessment lies in anticipating the behaviour of other BRPs. Fuzzy logic is used to optimize market response based on limited knowledge about the current and future behaviour of other BRPs.

The average imbalance (ACE average) is used to predict the risk for single pricing. The imbalance price can change the sign. A positive imbalance over 15 minutes (upward reserves dominated) leads to a positive imbalance price (additional generation or reduced load is rewarded). A negative imbalance over 15 minutes (downward reserves dominated) leads to a negative imbalance price (additional load or reduced generation is rewarded).

With combined imbalance pricing, the imbalance (ACE) itself is used to predict the risk of changing to a dual imbalance pricing scheme.

4.6.3 Results of fuzzy logic in the test environment

The suitability of the fuzzy logic is evaluated within the different test scenarios. The scenarios consist of assumptions regarding the general market situation. Single pricing is compared with combined pricing, as applied in the Netherlands.

The ACE without market response is 1 GW in all scenarios. Further, three imaginary BRPs are instantiated, with 1 GW of technical flexibility each. The marginal costs of these BRPs differ, with 70, 90, and 110 EUR/MWh.

The balancing energy prices vary with the overall market situation. Therefore, a favourable MOL 1 and a more expensive MOL 2 are regarded to investigate its impact. Both MOLs include 1 GW reserves evenly distributed into ten bids of 100 MW. The lowest offer is 30 EUR/MWh in MOL 1 and MOL 2. MOL 1 includes bids up to 120 Euro/MWh. As a result, MOL 1 has an initial imbalance price of 75 EUR/MWh with pay-as-bid and 120 EUR/MWh with marginal clearing. Within the more expensive MOL 2 bids rise to 390 Euro/MWh. The initial imbalance price with pay-as-bid clearing is 210 EUR/MWh and 390 EUR/MWh with marginal clearing.

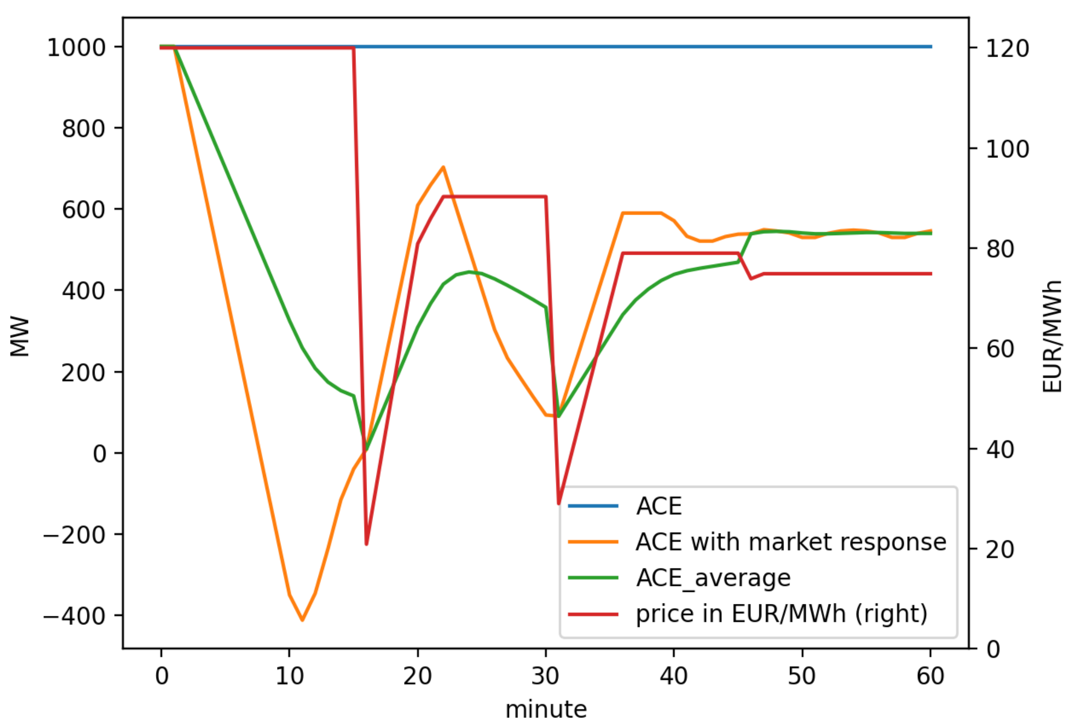


Figure 16: MOL 1: Marginal clearing, single pricing

Figure 16 illustrates market response with marginal clearing scheme and single imbalance pricing. The imbalance price is set to 120 EUR/MWh for 15 minutes. This price signal leads to an overreaction and a negative ACE of up to - 400 MW after 11 minutes. After 15 minutes, there is a drop in price and ACE. After 45 minutes, the price settles at 75 €/MWh at an ACE of 400 MW. Due to the single imbalance pricing, the BRPs consider the ACE average as a risk indicator of a changing sign of the imbalance price, which, in this case, cannot prevent an overreaction.

With a marginal clearing scheme and combined pricing, the imbalance price remains at 120 EUR/MWh for 15 minutes, but no overreaction occurs. After 5 minutes, the ACE oscillates between zero and less than 200 MW. BRPs consider the ACE as an indicator for the risk of a changing sign of the imbalance price and avoid an overreaction. With the new imbalance settlement period after 15 minutes, the price collapses from 120 €/MWh to just under 40 €/MWh, thus reducing the incentive for BRPs. The ACE rises to almost 700 MW. With the next imbalance settlement period, the price will settle at 65 €/MWh, corresponding to an ACE of 500 MW.
Pay-as-bid clearing results in a limited market response of 200 MW at the favourable MOL 1. The imbalance price decreases and limits market response since there is no economic flexibility potential as soon as the imbalance price falls under 70 EUR/MWh. There is no difference between single and combined pricing schemes since the economic potential is zero before the risk of a changing sign of the imbalance price appears.

The more expensive MOL 2 with a marginal clearing scheme leads to an overreaction and a negative ACE for both pricing schemes. The ACE reaches -600 MW with a single pricing scheme. The overreaction is limited with a combined pricing scheme, because the imbalance price is changed to dual pricing, and the ACE returns to 1000 MW.

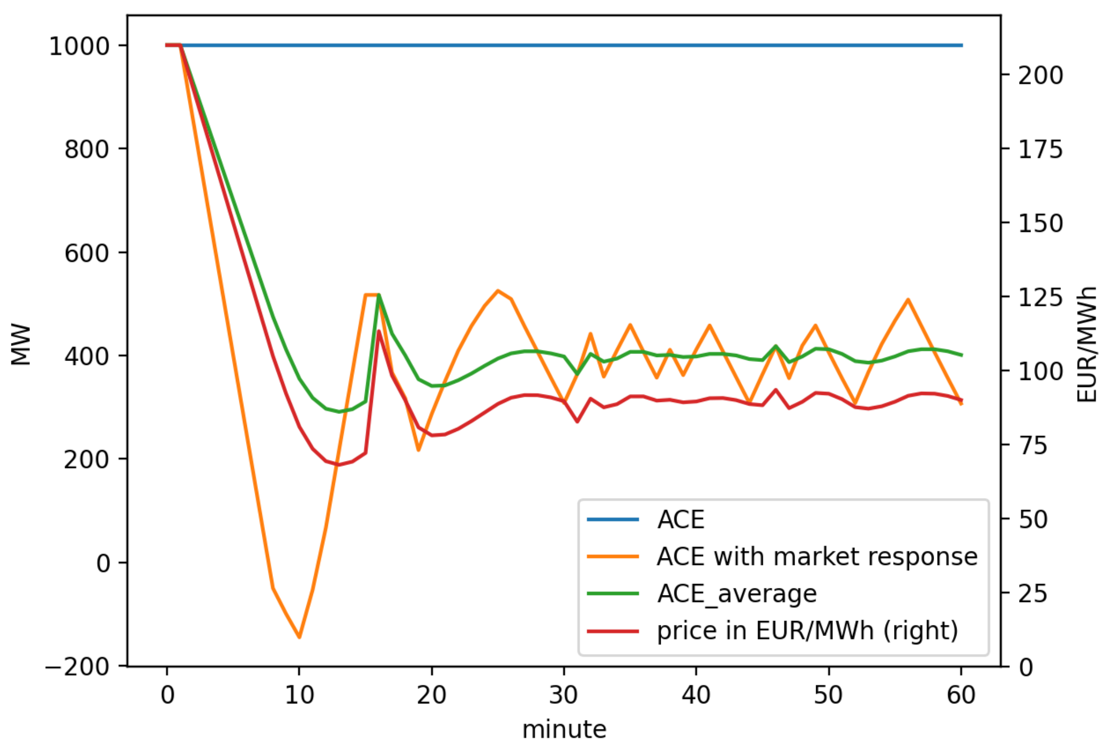


Figure 17. MOL 2: Pay-as-bid clearing, single pricing

Figure 17 illustrates market response with pay-as-bid clearing and single imbalance pricing. An overreaction occurs, but the ACE does not reach - 200 MW. Within 30 minutes, the imbalance price drops from 210 EUR/MWh to an almost stable value of around 90 EUR/MWh. The imbalance value has a similar pattern starting at 1 GW and stabilizing around 400 MW after 30 minutes.

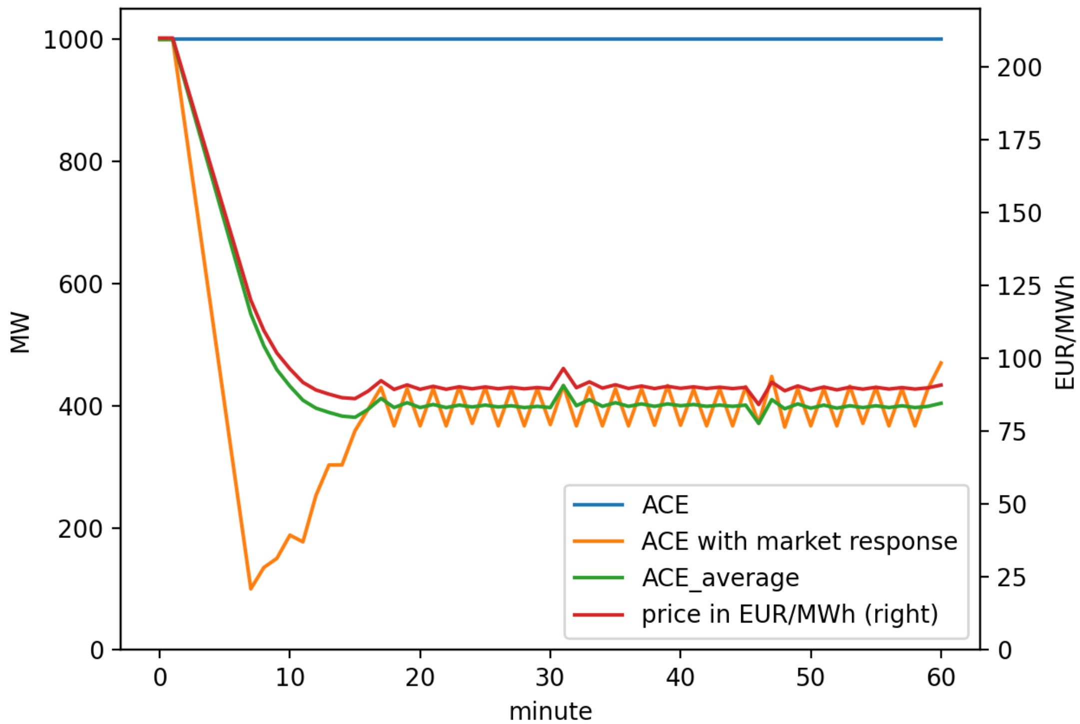


Figure 18: MOL 2: Pay-as-bid clearing, combined pricing

Figure 18 illustrates market response with pay-as-bid clearing and combined pricing. No overreaction takes place. The minimum ACE is 100 MW after about 8 minutes. After 15 minutes, it stabilizes around 400 MW with a range of about 50 MW. The imbalance price is 90 €/MWh.

The test scenarios show that fuzzy logic with the selected input variables can optimize market response for real-time energy balancing. From these first investigations, market response seems to be a promising tool for grid operators to balance the control block, especially with combined imbalance pricing.

The simulations support the hypothesis that activation of FRR is reduced, and cost-efficiency can be improved by passive balancing. The simulations further support the hypothesis that combined imbalance pricing is a correct incentive for BRPs and prevents overcompensation.

4.7 Simulation of extrapolated market-response with historical data – Publication 7

In combination with historical data, a simulation can estimate the potential benefits of Smart Balancing in Germany. The concepts from section 4.5 and section 4.6 are combined and applied to anticipate passive balancing of all BRPs in Germany. A simulation to extrapolate market-response with historical data of 2019 is introduced in the seventh publication. Balancing market simulation software is developed in Python and published online [42].

4.7.1 Smart Balancing model

Figure 13 already introduced the object-oriented model structure, because the first version of the model was applied in Publication 5.

Figure 19 shows the simulation flowchart. Relevant input data from csv files are read in the initial step. Afterward, the simulation starts with a one-minute resolution. Generation, load, and schedules are compared to calculate the ACE. Frequency and FCR activation are calculated based on a steady-state estimation, followed by aFRR activation. Smart balancing is calculated in the next step. The decision for mFRR activation is not based on local load-frequency control block agreements. mFRR is an optional response to critical situations, and the decision for its activation is made by the responsible Transmission System Operator (TSO) by evaluating the individual situation. mFRR is delivered in the next ISP and is included in the ACE calculation as a scheduled generation. Demand and costs of aFRR and mFRR are used to calculate the imbalance price according to the rules from 01.07.2020 [43]. Smart balancing results from the given market design and the related opportunities to generate revenues.

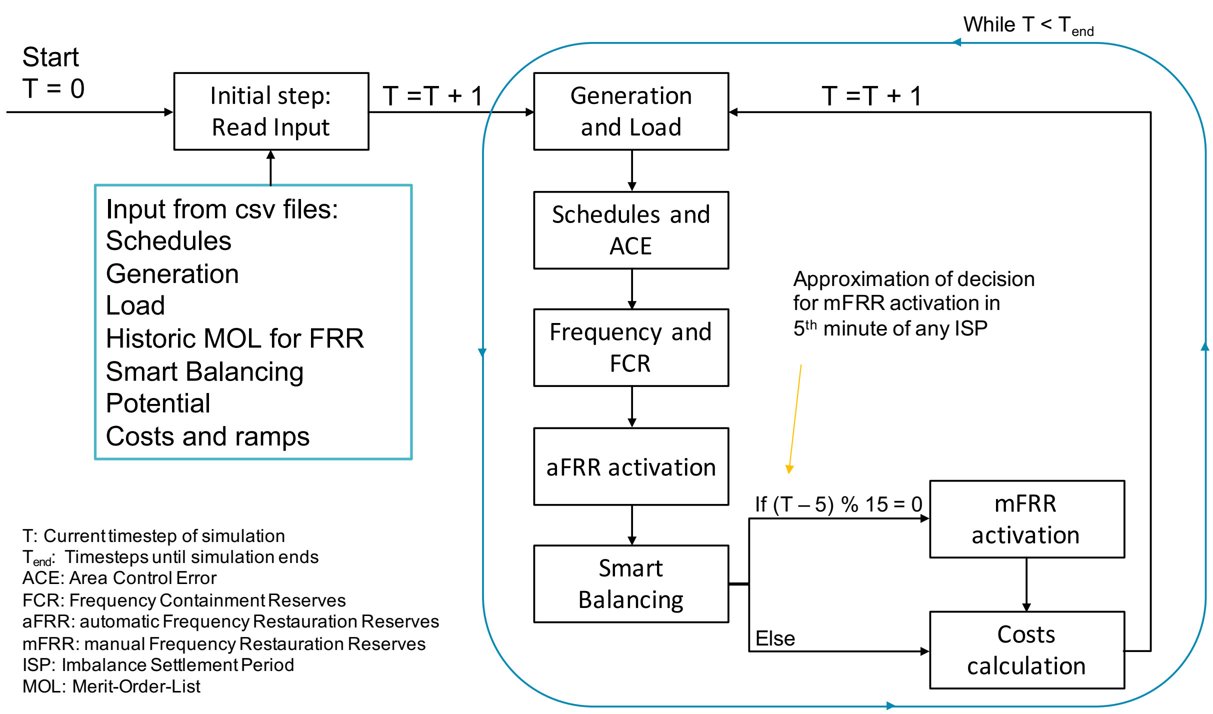


Figure 19: Flowchart of Smart Balancing simulation

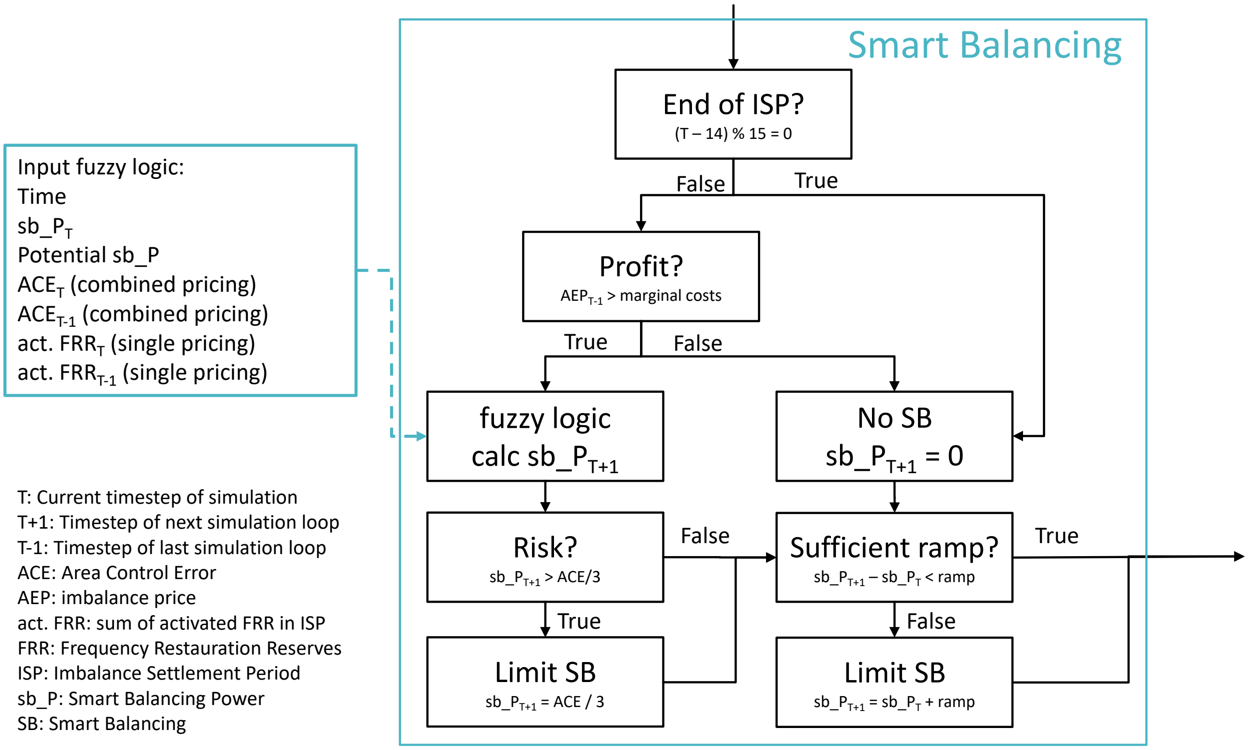


Figure 20: Flowchart with details of Smart Balancing calculation in the simulation

Figure 20 illustrates all steps around the fuzzy logic for calculating the respective Smart Balancing contribution for BRPs and assets with Smart Balancing potential. The net margin was derived from the imbalance price, which is the incentive for Smart Balancing and, therefore, mandatory to be considered. It quantifies the potential specific revenue and willingness to deviate from the BRP's schedule. The calculation logic differed for all simulated BRPs. The imbalance prices and the implemented marginal costs of BRPs led to individual net margin values.

The "End of ISP" box illustrates the test if the end of an ISP is reached. If T is equal to 14, the formula returns true and sets the Smart Balancing of the regarded BRP to zero ("No SB" box). The "Profit" box illustrates whether Smart Balancing would generate revenues. If the marginal costs are higher than the imbalance price, the Smart Balancing of the regarded BRP was set to zero ("No SB" box). The "fuzzy logic" box represents the fuzzy behaviour of BRPs. The time step, the current Smart Balancing contribution, and the technical potential were used as the input. In addition, the ACE or the activated FRR quantified the revenue potential. A high imbalance enabled a high Smart Balancing participation and set an upper limit since a market response larger than the occurring imbalance could change the sign of the imbalance price and therefore cause monetary losses. Counter-activation of FRR immediately changed the sign of the imbalance price in the case of combined pricing, and the ACE was used as the fuzzy input. In the case of pure single pricing, the sign only changed if the counter-activation was higher than the initially activated FRR over 15 min, and the sum of activated FRR was used as input. The "Risk" box illustrates whether the resulting behaviour would reduce the ACE by over a third of its value. The "Limit SB" box reduced the Smart Balancing accordingly if this was true. The limit was chosen to avoid fast response in case of high incentives. The "Sufficient ramp" box illustrates the last test if the resulting behaviour can be realized with the underlying technology. The “Limit SB” box reduced the Smart Balancing according to the technical limit if this was false.

Technology	Potential up/down (MW)	Marginal Costs up/down (Euro)
Aluminum electrolysis	281/-	$AEP - da_{price} > 100/-$
Cement raw mill	116/50	$AEP - da_{price} > 100/AEP < 10$
Cement mill	265/113	$AEP - da_{price} > 100/AEP < 10$
Amalgam chlorine electrolysis	114/72	$AEP - da_{price} > 100/AEP < 10$
Membrane chlorine electrolysis	359/227	$AEP - da_{price} > 100/AEP < 10$
Electric arc furnace (Steel)	753/-	$AEP - da_{price} > 250$
Polisher in paper production	207/46	$AEP - da_{price} > 100/AEP < 10$
Refiner in paper production	105/23	$AEP - da_{price} > 100/AEP < 10$
Solar and wind (Build 2017,2018)	-/dynamic	$-/AEP < -EEGbonus - 40$
Gas fired power plants	dynamic/dynamic)	$AEP > 50/AEP < 0$

Table 2: Assumption for profit optimization parameters of BRP based on the German imbalance price (Ausgleichs-Energie-Preis (AEP)) and the day-ahead auction price for electrical energy (da_{price})

The considered technologies with a (smart) balancing potential are shown in Table 2. Furthermore, their assumed flexibility potential and (smart) balancing logic are shown. Industrial processes represent the currently available flexibility from Demand Side Integration (DSI), based on an analysis [44]. It can be assumed that only the stated DSI technologies are able to contribute a market response without further investments. The potential is assumed to be static. Only certain VRE plants can respond to external signals and ramp-down power generation. Due to German legislation only generation plants installed in the years 2017 and 2018 that fall under the “Markt-Prämien-Modell” were considered because only they face an incentive for Smart Balancing. The potential downward balancing contribution is calculated dynamicly, based on the historic power generation from wind and solar. Finanlly, the potential upward and downward balancing contribution of gas fired power plants is calculated based on historic power generation.

4.7.2 Market Design scenarios

The scenarios analyse Smart Balancing and represent different combinations of market design parameters. The first scenario with historical data and no Smart Balancing served to validate the model. Ten other scenarios were simulated to answer the research question on which market design enabled efficient Smart Balancing.

Five investigated scenarios used historical data from the year 2019. In scenarios with historical data, market mechanisms and BRPs face the historic ACE and MOLs. 2019 includes events with high imbalances in June 2019 and showcases the advantage of Smart Balancing during these events. The considered data to (re-)build the historic ACE in a 1-min resolution were the aFRR in a 1-s resolution and the manual Frequency Restoration Reserves (mFRR) and the emergency reserves both in a 15-min resolution [39]. The total ACE would also include the German contribution to IGCC. However, this contribution was neglected since it did not lead to an activation of FRR and even reduced the demand for balancing energy in other control blocks [11].

The reference scenario of 2019 “1 no SB” served for calibration and validation in the attempt to model the German energy market as it is. The current situation in Germany can be defined as a “no active Smart Balancing”, “single pricing”, and “pay-as-bid clearing” scenario. The “2 TL2” and “3 TL 5” scenarios give limited information to BRPs with traffic light (TL) signals. TL2 simulates a market where BRPs face two possible signals (activation of over 80% / 100% of contracted FRR). TL5 simulates a market where BRPs face five possible signals (activation of over 60% / 80% / 100% 120% / 150% of contracted FRR). The “4 DE” and “5 NL” scenarios provide full information about activated FRR and the imbalance price to the BRPs. DE simulates a market with single imbalance pricing and NL simulates a market with combined imbalance pricing.

4.7.3 Results of Smart Balancing simulation with historical data

The total costs for balancing energy were reduced in all scenarios with Smart Balancing. Furthermore, the activation of mFRR was reduced in all cases; the aFRR activation, on the other hand, was not significantly reduced in the two traffic light scenarios.

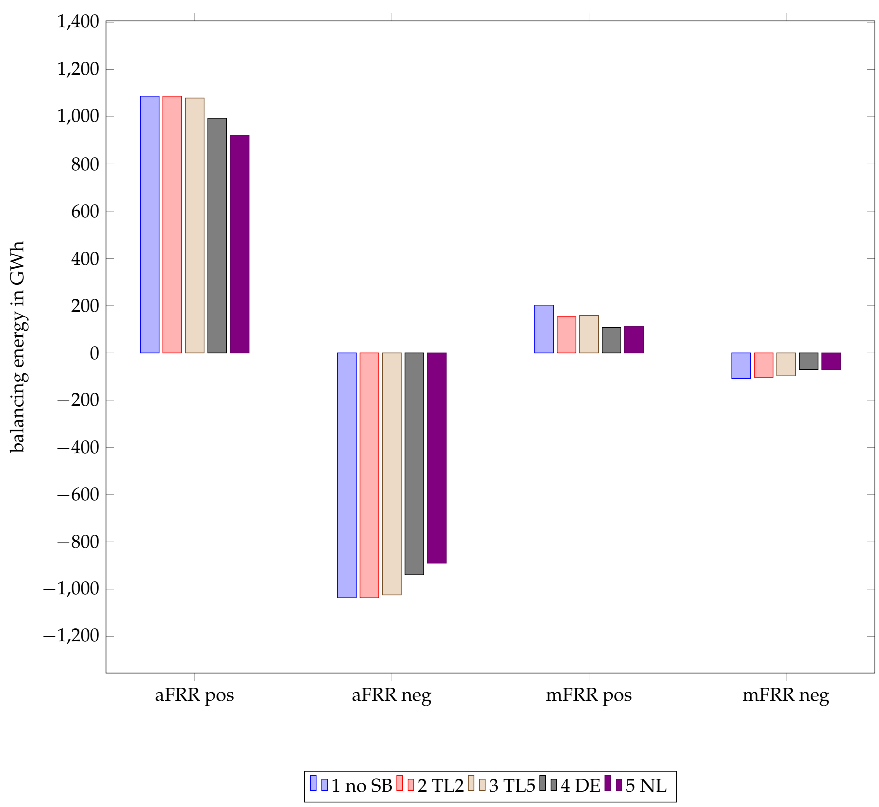


Figure 21: Smart Balancing simulation: demand of balancing energy in 2019

Figure 21 illustrates the cummulated demand for positive and negative aFRR and mFRR over the simulated year 2019 in GWh. The TL2 scenario results in a 25% reduction of positive mFRR and 5% reduction of negative mFRR. The TL5 scenario results in a 22% reduction of positive mFRR and 10% reduction of negative mFRR. The DE scenario results in 9% reduction of positive and negative

FRR, 47% of positive mFRR and 35% of negative mFRR. Finally, the NL scenario leads to 15% reduction of positive aFRR, 14% of negative aFRR, 45% of positive mFRR and 34% of negative mFRR. All scenarios support the hypothesis that Smart Balancing reduced the ACE and demand for balancing energy. The results show that the traffic light approaches mainly reduce the mFRR demand, while aFRR could only be reduced in scenarios with full transparency.

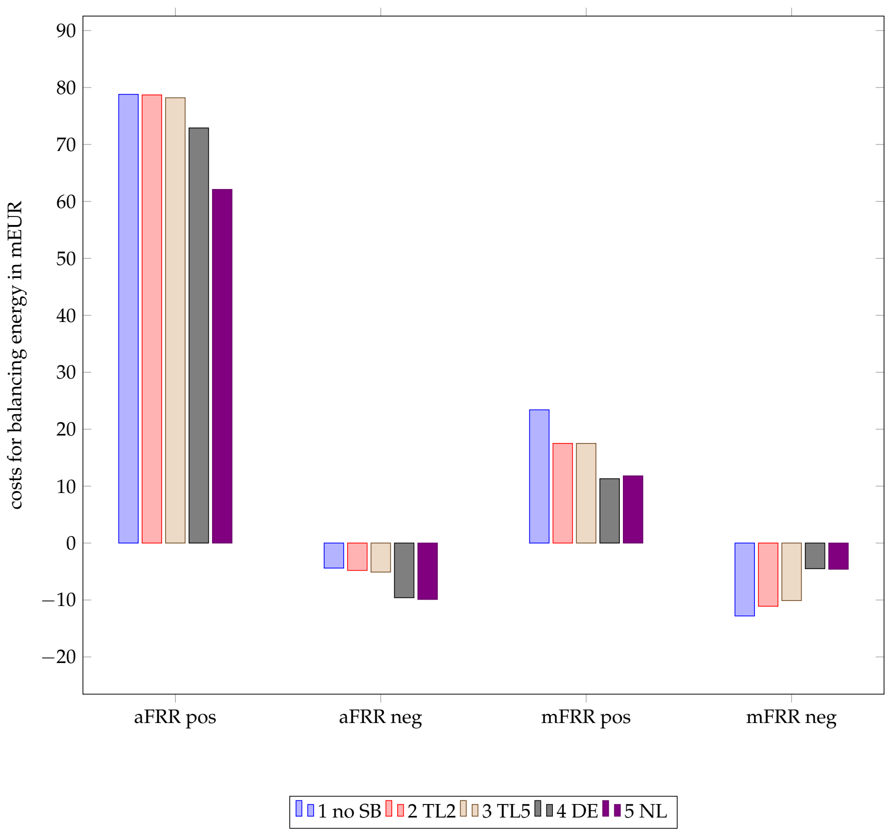


Figure 22: Smart Balancing simulation: costs for balancing energy in 2019

Figure 22 illustrates the total costs for positive and negative aFRR and mFRR over the simulated year 2019. Negative costs represent profit from the TSO perspective. The costs for positive aFRR and positive mFRR were reduced in all scenarios. The profits from activating negative aFRR was increased, but the profit from activating negative mFRR was reduced. In total both TL scenarios result in a 5% cost reduction, compared to a 17% cost reduction in the DE scenario and a 30% cost reduction in the NL scenario.

In all cases, the frequency standard deviation (std) was higher, and outliers (min, max) had a bigger distance to the set value of 50 Hz in scenarios with Smart Balancing. Therefore, the results indicated that Smart Balancing could negatively affect the quality of the frequency.

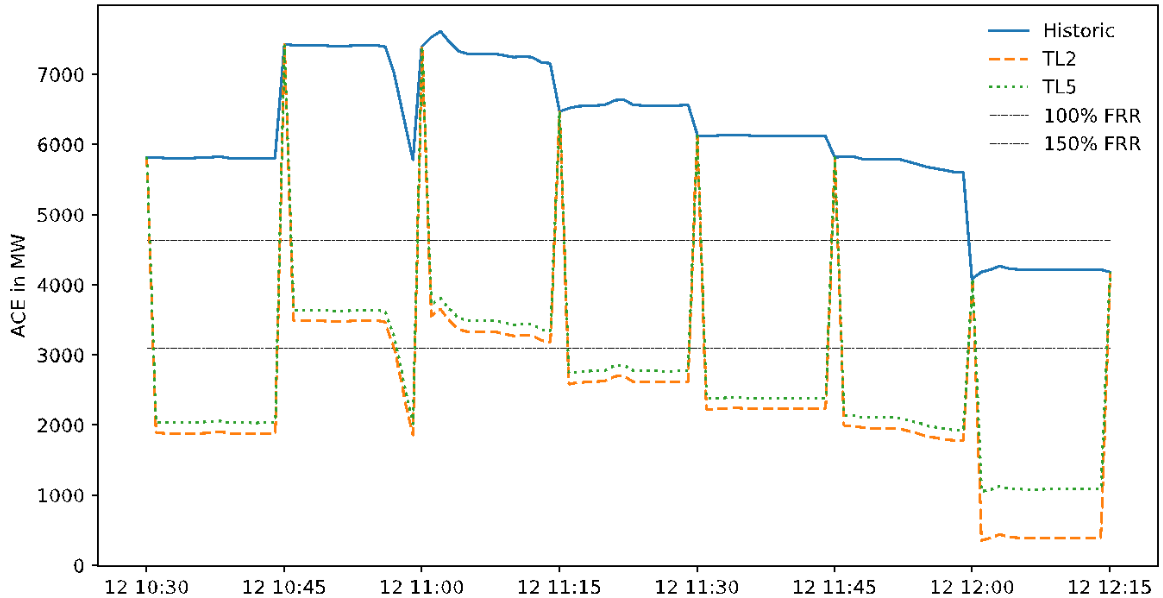


Figure 23: Historic imbalance event 12.06.2019 (Hist), traffic light scenarios (TL2 vs. TL5), and contracted automatic and manual Frequency Restauration Reserves (FRR)

The reason for the decrease in frequency quality while the demand for FRR is reduced is illustrated in Figure 23. The figure showcases the worst imbalance event of 2019 with activated reserves of over 7 GW and simulation results of the traffic light scenarios TL2 and TL5. The ACE and the demand for FRR could be reduced during each ISP, but going back to the schedule at the end of each ISP led to high-frequency deviations. Figure 23 also illustrates the difference between the two traffic light scenarios TL2 and TL5, in the case of high imbalance events. There was no further differentiation in the case of an ACE that was higher than 100 % of the contracted FRR. TL5, on the other hand, changed the signal at 12:00 from “over 150 %” to “over 120 %”, and a reduced Smart Balancing contribution was the result. The slightly higher Smart Balancing contribution with the TL2 approach before 12:00 can be traced back to the fuzzy logic, where fewer membership functions were defined in the TL2 scenario leading to higher output for “good Smart Balancing”.

5 Conclusion and outlook for Smart Balancing

The publications, part of this dissertation at hand, cover aspects of market theory, historic data analysis, and evaluated simulations considering field data of industrial consumption and VRE. The results support the six hypotheses, introduced in section 2. Further, they support the proposed market design changes to achieve Smart Balancing in Germany, as introduced in section 3.2.

The analysis shows that passive balancing is a cost-efficient tool to meet power balancing requirements. The combination with imbalance netting gives Dutch and Belgium BRPs an advantage over German BRPs. Observations of balancing events (publication 2) and statistical tests with data of historical balancing demand (publication 4) show that the German balancing strategy is undermined, and BRPs respond to available information with passive balancing. The historic passive balancing in Germany was not always beneficial, e.g. when misplaced incentives intensified German imbalance events in June 2019 (publication 4). Therefore, balancing markets should take place close to real-time. This new market timing, real-time information, and combined (single and dual) imbalance pricing give the most accurate Smart Balancing environment.

The simulations show how Smart Balancing could work in Germany. The impact of imbalance pricing (single vs. combined) is quantified in Publication 7. The results support the initial hypothesis that Smart Balancing reduces the demand for FRR activated via BSP products. In all considered scenarios, the demand for FRR and related costs could be reduced. Especially the reduction of mFRR balancing energy is a direct consequence of Smart Balancing. Large system imbalances that sustain for several ISPs are especially suitable for BRPs without taking too high risks that the system imbalance direction changes and the imbalance price results in a bill instead of an incentive.

Fuzzy logic is introduced as a possible approach for the decision-making process of BRPs. The implementation of the decision-making process of BRPs in the simulation provided the following observations. A fuzzy logic only leads to profit for BRPs if reversing the sign of the imbalance price is prevented by limiting the market response. In real operations, the introduction of Smart Balancing could in the beginning lead to reversing the sign of the imbalance price. Then BRPs would optimize their response by limiting it to necessary volumes. This can be compared to the tuning of fuzzy rules in the simulation. The observations made in the Netherlands in 2001 support this prediction [18].

Passive balancing is influenced by the ACE, the MOL of balancing energy bids, and the marginal costs for a market response of the BRPs. The scenarios examined show that market response for real-time energy balancing is strongly incentivized by single imbalance pricing. Passive balancing simulations with fuzzy logic (publication 6) identified that the most profitable market response with single imbalance pricing leads to reversing the sign of the ACE, which does not meet the Smart Balancing definition. The Dutch approach of switching to dual pricing in case of FRR counter-activation, referred to as combined pricing, meets the Smart Balancing definition and prevents reversing the sign of the ACE. Therefore, applying a combined imbalance pricing for schedule deviations is recommended in Germany as well. Thus, dual pricing applies if the German system is exposed to activation of positive and negative FRR within an ISP.

For a gradual implementation of Smart Balancing in Germany, the traffic light concept might be a serious concept to start (publication 7). Independently from the German imbalance price layout, this concept can support Germany during persistent imbalances exposed to the system. The first introduction could be chosen with Smart Balancing with a traffic light approach. In fact, the traffic light concept was implemented in Germany in September 2021, five months after the publication of publication 7 [8]. The traffic light approach could in a next step be replaced by a fully transparent approach. In that case, the simulation results highly recommend replacing the single imbalance pricing by combined imbalance pricing.

In contrast to the reduction of demand and costs for FRR, the simulation output indicates a negative effect of Smart Balancing on the frequency in the synchronous zone. The higher deviation, lower minimum, and higher maximum of the frequency result from the fast reaction, especially at the end of each ISP, when all BRPs return to their schedule. Even though such extreme behaviour is doubtful to be seen in actual operation, the Smart Balancing logic leads to this fast behaviour in response to the uncertain source of the ACE. The ACE also reflects scheduled energy exchanges with other control blocks and can, therefore, change at the beginning of an ISP.

Future research may focus first, on how Smart Balancing can work best with the emerging European platforms, e.g., IGCC and the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO). Secondly, the effect of changing the balancing energy pricing period (BEPP) in a future marginal clearing environment, including effects on the MOL, should be analysed with higher accuracy. Even though simulation-based research can lead to relevant findings, actual market behaviour can never be predicted without uncertainties. This uncertainty leads to the urgent need for field tests to generate profound knowledge about Smart Balancing and its value. Lastly, effects on grid capacity and demand for local flexibility are also of interest for future research because Smart Balancing is a response to activated FRR which is not considering limited grid capacity.

According to the presented findings, Smart Balancing would reduce the balancing demand in the European power system and thus reduce the balancing costs significantly. With accurate portfolio management and imbalance netting via the IGCC, this would further support the cost-efficient shift towards VRE without loss of grid reliability. If implemented correctly, Smart Balancing in Germany could serve as a role model for other regions.

6 References

Section 6.1 presents the list of peer-reviewed publications, part of the dissertation at hand, intending to obtain the title Doctor rerum politicarum (Dr. rer. pol). Section 6.2 lists two GIT releases with digital object identifier (doi) for full data availability. Section 6.3 presents further literature.

6.1 List of Publications with peer-review

[Publication 1] F. Röben, 'Comparison of European Power Balancing Markets - Barriers to Integration', in 2018 15th International Conference on the European Energy Market (EEM), Lodz, Jun. 2018, pp. 1–6. doi: 10.1109/EEM.2018.8469897.

[Publication 2] F. Röben and J. E. S. de Haan, 'Market Response for Real-Time Energy Balancing – Evidence From Three Countries', in 2019 16th International Conference on the European Energy Market (EEM), Ljubljana, Slovenia, Sep. 2019, pp. 1–5. doi: 10.1109/EEM.2019.8916553.

[Publication 3] N. Stuchynska and F. Röben, 'Liberalization of the Electricity Market in Ukraine in 2019 - Lessons Learned', in 2020 17th International Conference on the European Energy Market (EEM), Stockholm, Sweden, Sep. 2020, pp. 1–6. doi: 10.1109/EEM49802.2020.9221993.

[Publication 4] F. Röben, Smart Balancing of Electrical Power - Matching Market Rules with Balancing Requirements. Publication pending. Manuscript first submitted to Energy Policy in April 2020; Revision submitted in December 2020 and February 2022.

[Publication 5] J. Franz and F. Röben, 'Market Response for Real-Time Energy Balancing – Simulation using Field Test Data', in 2020 17th International Conference on the European Energy Market (EEM), Sweden, Sep. 2020, pp. 1–5. doi: 10.1109/EEM49802.2020.9221882.

[Publication 6] F. Röben and A. C. Meissner, 'Market Response for Real-Time Energy Balancing with Fuzzy Logic', in 2020 17th International Conference on the European Energy Market (EEM), Stockholm, Sweden, Sep. 2020, pp. 1–6. doi: 10.1109/EEM49802.2020.9221945.

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6.2 Script and software releases with Digital Object Identifier (doi)

[Publication 4] Data Analysis related to the manuscript "Smart Balancing of Electrical Power - Matching Market Rules with Balancing Requirements" at https://zenodo.org/record/4415515, Digital Object Identifier: 10.5281/zenodo.4415515

[Publication 7] Model and results related to the manuscript "Smart Balancing of Electrical Power in Germany: Fuzzy Logic Model to Simulate Market Response" at https://zenodo.org/record/4699695, Digital Object Identifier: 10.5281/zenodo.4699695

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Comparison of European power balancing markets – Barriers to integration

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***Abstract* — The European power balancing markets undergo disruptive changes due to the new European regulations. The commission regulation "establishing a guideline for electricity balancing" (GLEB) gives guidance to integrate markets in Europe. Intermediate harmonization of products for balancing services is scheduled already in 2018.**

The situation for concerned system operators, balance service providers and balance responsible parties in Europe will change. This paper presents an investigation of current differences in national power balancing markets and potential barriers for the integration. A systematic comparison of market designs and reserve controller set-ups with the predefined choices of the upcoming guideline took place. Identified barriers for the harmonization are differences in reserve controller set-ups and activation strategies. The task is to agree on common power balancing products, full activation time of all reserve types, prequalification requirements for service provider and rules for cross-border balancing.

***Index Terms* — EU winter package, European integration, Guideline for Electricity Balancing, NEW 4.0, Power Balancing Markets**

I. Introduction

This investigation is part of a broad research project on energy systems and markets. An alliance of regulators, industrial partners and universities work together on the transition to renewable energy sources in the project Norddeutsche Energiewende (NEW 4.0). The results of this paper will help developing models to answer identified research questions.

Motivation behind looking at balancing markets is security of electricity supply and cost efficiency. Mainly the latter is reason for the implementation of common markets.

Draft roadmaps for the integration of balancing markets are requested from all system operators latest by end 2019. Intermediate steps of harmonization are scheduled already in 2018 [1]. A profound understanding of the interrelations of market design parameter is crucial for the consultation process. The consideration of potential risks at an early stage is important.

Systematic literature review led to a dataset of applied balancing market designs and controller set-ups in Europe. The systematic review was followed by qualitative evaluation of the measures resulting from the commission regulation "establishing a guideline for electricity balancing" (GLEB).

Section II pictures the applied method. Section III presents the literature review and depicts the ongoing integration of balancing markets. In Section IV, the measures of harmonizing balancing markets are evaluated. Section V identifies barriers for the implementation of common European power balancing markets. Section VI concludes the main findings of this paper.

II. Method

The applied method starts with a literature review on the current situation and scheduled integration process. The following data analysis is focusing on technical and financial interrelations. The research question is:

What are barriers for the harmonization of balancing markets and products?

A. Literature review

At first, the current design of national balancing markets and the set-ups of reserve controller are listed and grouped.

The European Network of Transmission System Operators for Electricity (ENTSO-E) is in the scope. This organization represents all European transmission system operators (TSO). Balance responsible parties (BRP) agree on generation and consumption of electricity on spot markets. Prequalified BRP who offer reserve capacity via bids on balancing markets are balance service provider (BSP). National regulators define the legal frame in a country in which TSO, BRP and BSP interact.

NEW 4.0 "North-German transition towards renewable energy", several partners from industry and public institutions work on IT pilot schemes in the federal states Hamburg and Schleswig-Holstein. NEW 4.0 started in December 2016. See www.new4-0.de for details. *(sponsors)*

Data of the ENTSO-E members operating in the following countries is cumulated and considered:

Austria (AT); Belgium (BE); Bosnia and Herzegovina (BA); Croatia (HR); Czech Republic (CZ); Denmark (DK); Estonia (EE); Finland (FI); France (FR); Germany (DE); Greece (GR); Hungary (HU); Ireland (IE); Italy (IT); Latvia (LV); Lithuania (LT); the Netherlands (NL) Norway (NO); Poland (PL); Portugal (PT); Romania (RO); Serbia (RS); Slovak Republic (SK); Slovenia (SI); Spain (ES); Sweden (SE); Switzerland (CH); United Kingdom (UK)

A substantial design frame to describe balancing markets with 23 parameters exists in the literature [2]. A reduced design frame is used, but technical parameters of reserves are highlighted in comparison to the reference model.

B. European regulation

The identification of mandatory actions enacted by the GLEB takes place. The measures are put in the context of an incremental integration process. ENTSO-E proposals are considered.

C. Evaluating difficulty of measures

The scheduled actions are evaluated by their impact on EU member states with a systematic comparison, based on the difficulty of harmonization. The difficulty is rated in a systematic procedure. The procedure takes the number of applied design choices in Europe into account and evaluates the difficulty of reaching a common solution in a qualitative way.

III. REVIEW

In general, the TSOs organize the balancing process, coordinate the markets for balancing products and oversee cost settlement. BSP perform power balancing and the costs for this service are transferred to BRP. National regulators do not play an active role in power balancing, but define the market frame and aim at improving cost efficiency. Besides these relations, the design of markets, products and cost settlement varies among European countries.

A. Transmission System Operator (TSO)

Transmission system operator can be differentiated by their pro-active (DK, FR, UK) or reactive behavior (AT, BE, DE, NL) [4]. Passive balancing is a unique approach in the Dutch TSO. Publishing price signals for the BRP has the potential of cutting costs for balancing energy. Thus, a TSO limits reserve activation by providing BRPs with incentives to have an imbalance being in opposition to the system imbalance [5].

B. Classification of reserve types

The GLEB describes four reserve types: Frequency Containment Reserves (FCR), automatic Frequency Restoration Reserves (aFRR), manual Frequency Restoration Reserves (mFRR) and Replacement Reserves (RR). National balancing markets typically include three reserve types, which will be reassigned to the GLEB reserve types for the integration [1].

C. Gate Closure Time (GCT)

The GCT of markets is the point in time, when the submission or the update of bids is no longer permitted. The merit order list is finalized and the bidders are notified about the results of procurement in a next step. Not awarded reserve capacity bids can be offered on a different market, if the notification takes place before the GCT. Table I gives an overview about applied GCT und upcoming changes.

TABLE I. REVIEW ON GATE CLOSURE TIME (GCT)

Design variable	**Applied designs and evaluation of roadmap**		
	Examples [a]	***GLEB [b]***	***Pilot Projects [c,d]***
GCT of intra-day spot market	No intra-day market (Czech Republic, Serbia), 250 minutes (IT), 195 minutes (ES, PT) to 5 minutes (Belgium) [11]	max. 8 hours before real-time (b article 24.5 b)	
GCT of balancing market Capacity FCR	hours (Tschechien, Slovakei, HU, DK, Greece), day (DE, NL, CH, AT) to year (BEL, Irland) (a s. 10)		D-2 15.00 by 26.11.18 and D-1 8.00 by 27.11.2020 (c article 4)
GCT of balancing market aFRR Capacity	day (PG, ES, DE, CH, Finnland, Sweden, Greece) to year (NL, Croatia, Serbia) (a s. 31)	TSO proposal requested by 18.12.2018 (b article 21.1 & 21.3 h)	
GCT of balancing market mFRR Capacity	hour (DE, DK, Tschechien, Slovakei) to year (FR, NL, BEL, Finnland, Croatia etc.) s. 52 entso-e survey (a s. 52)	TSO proposal requested by 18.12.2018 (b article 20.1 & 20.3 h)	
GCT of balancing market RR Capacity	day (ES, GB, CH, Slovakei, HU) to year (Litauen, CR, Serbia) (a s. 76)	TSO proposal requested by 18.06.2018 (b article 19.1 & 19.3 h)	60 to 55 min before period (d article 7)

a. Entso-E survey: Survey on Ancillary services procurement, Balancing market design 2014 (January 2015) [6]; b. EU Commission regulation 2017 establishing a guideline on electricity balancing [1]
c. ENTSO-E Draft Proposal for common rules and processes for exchange and procurement of FCR (January 2018), applied by TSOs of AT, BL, CH, DE, DK, FR, NL [7]
d. ENTSO-E draft proposal for the implementation framework for the exchange of RR (February 2018) [8]

The GCT is crucial for volatile renewable energy sources, as the weather forecast error is reduced significantly over time. Therefore, trading of renewable power is more accurate, as closer the GCT is to the physical delivery.

D. Frequency Containment Reserves (FCR)

FCR is the most homogeneous reserve type. The awarded BSP follows a harmonized activation strategy, which is based on the system frequency. FCR starts within seconds after the frequency deviation exceeds 20 mHz as a joint action of all contracted BSPs in the synchronous area. The total FCR capacity is defined to be 3000 MW in the synchronous area, based on operational generation units and their reliability. Each TSO holds available a share of FCR, which is proportional to the share of energy consumption in the area. The full activation time (FAT) is 30 seconds in case of a frequency deviation of 200 mHz or more. As the reserves react directly to the frequency without central coordinating, all FCR within a synchronous area are activated in parallel [9].

While a common activation strategy is applied, the market design differs a lot. Products, procurement process and cost settlement vary among countries. Table II gives an overview about the applied designs.

Some countries apply a symmetric FCR product without clearing of energy costs. Therefore, only one FCR market exists and the bid consists of a power value and a capacity price. In this case it is assumed that positive and negative activation is equalized. Another approach is unsymmetrical products and applying an additional energy price. Thus, two markets exist (for positive and for negative FCR) and the bid consists of a power value, capacity price and energy price.

The cost settlement for capacity price is performed either pay as bid, with a marginal price or a regulated price. Countries applying the energy price use marginal pricing or a regulated price for the settlement. As all reserves are activated in parallel, all awarded capacity bids will lead to costs for energy.

TABLE II. REVIEW ON FREQUENCY CONTAINMENT RESERVES (FCR)

Design variable	**Applied designs and evaluation of roadmap**		
	Examples [a]	***GLEB*** [b]	***Pilot Project*** [c]
FCR Full Activation Time (FAT)	30 seconds (for 3000 MW, 15 seconds for 1500 MW) [9]		
Scoring rule for FCR Capacity		Activation optimisation function (b article 31)	Common Merit Order list by 01.07.2019 (c article 8, 11)
FCR capacity as symmetrical product	symmetric and not symmetric (GB, IE, BE, DK, HU, GR) (a s. 12)		Symmetric by 26.11.2018 (c article 5, 11)
FCR capacity product resolution in time	from year (IE, BE) to hour (DK, SE, NO, FI, CZ, SK, GR) (a s. 9)		24 h product by 26.11.2018 and 4 h product by 01.04.2020 (c article 5, 11)
FCR energy product resolution in time	30 min (FR, IE), hour (PL), week (DE) (a s. 20)		
FCR capacity product resolution in MW	1 MW (FR, BE, DE, DK, PL etc.) to 5 MW (NL, AT, TR) (a s. 8)		1 MW by 01.07.2019 (c article 4, 11)
FCR energy product resolution in MW	no minimum bid size (PG, DK, SI, BA) to 10 MW (GB) (a s. 19)		
FCR capacity settlement rule	pay as bid (DE, GB, NL, BE, CH, AT, CR, SK, HU, SE), marginal price (DK, GR, NO, FI) or regulated price (FR, IE, PL) (a s. 13)		Marginal price by 01.07.2019 (c article 8, 11)
FCR energy settlement rule	no energy bid at all (DE, NL, DK, CH, AT, PT, ES), pay as bid (GB), marginal pricing (PL, NO, SE, FI) or regulated price (FR, IT, SK) (a s. 23)	Separate price for positve and negative balancing energy (b article 46.2)	
FCR energy activation strategy	pro-rata, therefore all contracted reserves are "activated"		

a. Entso-E survey: Survey on Ancillary services procurement, Balancing market design 2014 (January 2015) [6] b. EU Commission regulation 2017 establishing a guideline on electricity balancing [1]
c. ENTSO-E Draft Proposal for common rules and processes for exchange and procurement of FCR (January 2018), applied by TSOs of AT, BL, CH, DE, DK, FR, NL [7]

E. automatic Frequency Restoration Reserves (aFRR)

After FCR, aFRR is the second fastest reserve type, but its activation is organized separately by each TSO. The control target is to deal with power deviations and to replace activated FCR. The power deviation is calculated by adding power generation (positive value), power consumption (negative value) and scheduled power exchange to other control areas (positive or negative). In an intermediate step, the measured frequency is used to calculate activated FCR (positive or negative). The FCR must be concerned, because it is part of the measured power flows. The calculated FCR of the TSO is added to the calculated power deviation. The result is called area control error (ACE), which than starts the activation of aFRR in corresponding size. A single controller per TSO performs this task. Maximum permissible FAT of aFRR is 15 minutes [9].

Besides these universal relations, the aFRR is procured in national balancing markets. The scoring, price and activation rules are crucial, looking at the BSP bidding strategies. Some countries contract BSP based on their capacity price, others on the energy price and a third group considers a combination of capacity and energy price. Pay as bid and marginal (single) prices are applied. [14]

The period, over which aFRR reserves are contracted vary from hours to weeks, the minimum size varies from no minimum to a minimum of 10 MW per bid. Symmetrical and unsymmetrical products exist. Different combinations of these settlement rules are applied [6].

From a technical perspective, also the aFRR controller work in different manners. Maximum permissible FAT of aFRR is 15 minutes, but a FAT of 5 to 15 minutes is applied. Some controllers send the ACE signal as continuous ramp with signals (at least every 10 seconds). Other controllers apply a stepwise activation and the BSP oversee the full activation of their aFRR within the FAT [10].

F. manuel Frequency Restoration Reserves (mFRR)

The mFRR are manually activated by the TSO to replace FCR and aFRR in case of a consistent power deviation. The product characteristics, product procurement process and settlement vary in a similar manner as aFRR [6].

G. Replacement Reserves (RR)

The fourth reserve type is RR, which is not used by all TSOs. RR is applied in 16 countries [11]. Table III gives an overview about the applied design of RR markets and a proposal for an integrated market (pilot project) of 10 TSOs performing RR.

TABLE III. REVIEW ON REPLACEMENT RESERVES (RR)

Design variable	**Applied designs and evaluation of roadmap**		
	Examples [a]	***GLEB*** [b]	***Pilot Project*** [c]
TSOs applying the Replacement Reserve Implementation Framework (RR IF)	16 countries in Europe use RR[d], 10 are RR IF members; BU, CH, ES, FR, GB, HU, IT PL, PT, and RO. Potential: CR, DK, HR,NW, FL and SW.		
RR Full Activation Time (FAT)		TSO proposal requested by 18.06.2018 (b article 19.1 & 19.3 i)	30 min (c article.9)
RR capacity product resolution in time	hours (ES, PL, SK, HU, RO) to year (FR, CR, RS, LT, LV) (a s. 75)	TSO proposal requested by 18.06.2018 (b article 19.1 & 19.3 i)	
RR energy product resolution in time	15 min (BE, IT) to hour (PT, ES, NL, CH, PL etc) (a s. 86)	TSO proposal requested by 18.06.2018 (b article 19.1 & 19.3 i)	min 15 minutes and max 60 minutes (c article 11)
RR capacity product resolution in MW	no minimum size (PT, CR) to min 10 MW (ES, LV) (a s. 74)	TSO proposal requested by 18.06.2018 (b article 19.1 & 19.3 i)	1 MW (c article 11)
RR capacity procurement scheme	mandatory offers (HU), Mandatory provision without reservation (PL, GR), bilateral market, organised market (FR, CH, SK, RO), hybrid (ES) (a s. 73)	Market with common merit order list (b acticle 19.2)	
RR energy activation strategy	mandatory offers (PL, HU, IT, PT), organised market (ES, NL, CH, CZ, SI, RO) (a s. 84)	Activation optimisation function (b acticle 19.2)	Optimisation algorithm (c article 8)
RR capacity settlement rule	Pay-as-bid (FR, GB, SK, HU), regulated price (PO, LT, RO, RS) or marginal price (ES, LT) (a s. 78)	Marginal price (b article 30.1 a)	cross-zonal marginal price (c article 13)

a. Entso-E survey: Survey on Ancillary services procurement, Balancing market design 2014 (January 2015) [6] b. EU Commission regulation 2017 establishing a guideline on electricity balancing [1] c. ENTSO-E draft proposal for the implementation framework for the exchange of RR (February 2018) [8] d. https://www.entsoe.eu/network_codes/eb/terre [11]

IV. MEASURES FOR INTEGRATION

The listed harmonization measures are an extract of the GLEB. Table I, Table II and Table III outline some harmonization process, enforced by the GLEB. The tables also put draft roadmaps of ENTSO-E members into the context. The planned European integration and identified measures are described hereafter.

A. Harmonisation of products

The main purpose of the GLEB is the establishment of common principles for the procurement and the settlement of FCR, aFRR, mFRR and RR (article 1). All TSOs shall develop proposals for aFRR, mFRR and RR standard products within two years. Therefore, by 18.12.2019 (article 25.2).

B. Harmonisation of GCT

The GCT of bids for at least one integrated scheduling process is defined to be no longer than eight hours before real-time. (article 24.5 b) The GCT of all balancing markets are set to be later in time. Thus, within eight hours before real time. (article 24.5)

C. Common merit order list and optimisation function

All TSOs shall submit the energy bids of BSP and a common merit order list is created based on the bids (article 29). The activation of FCR, aFRR, mFRR and RR is than executed by an optimization function (article 31). The consultation process is ongoing and all TSOs shall submit a proposal for classifying the activation purposes by 18.12.2018 (article 31.1).

D. "Free" energy bids

All BSP shall have the right to submit energy bids (article 16.5), entering into force by 18.12.2018 (article 65.2). Therefore, not awarded (no price for capacity is paid) BSP can submit energy bids in the capacity procurement process.

E. Cost settlement

The common imbalance settlement period is defined to be 15 minutes, implemented latest by 18.12.2019 (article 53). BRP pay the price for their imbalance and a single price shall be applied, but dual price is possible (article 55.3 c). TSO proposals of harmonization roadmaps are requested by 18.12.2018 (article 52.2 c).

While processes are harmonized and markets integrated, the imbalance price stays heterogeneous (article 55.3). Thus, it is still calculated separately in control areas and settled by the TSOs.

V. EVALUATION OF BARRIERS

Barrier for the harmonization of balancing markets and products is the variety of applied balancing strategies.

First, the differences in controller set-ups (e.g. signal and activation strategy) should be considered. If a technical issue prevents the integration, the deadline for implementation could be scheduled accordingly late. IT-Security is crucial to guarantee security of supply and should be designed accordingly.

The indicated balancing energy market design choices (single price, common merit order list, settlement period of 15 minutes and 1 MW power bid) are internationally applied and functional [3, 12]. Nevertheless, the cost efficiency of these design choices is part of scientific debates.

The cost benefits compared to dual price (or a combination of single and dual) and "pay as bid" pricing is unclear, according to the literature [13]. The reduction of the settlement period and minimum power bid to values under 15 minutes and 1 MW could cut costs further, according to the literature [13]. Thus, the interrelations of activation strategy, clearing and settlement should be examined in greater detail. In this context, the FAT of reserves should be considered. Also, passive balancing of BRP could cut costs for balancing. The interrelation of FAT and passive balancing should be investigated.

The different balancing approaches were developed to cope with individual power generation portfolios of each region. Therefore, other barriers to integration of the power balancing markets might exist.

VI. CONCLUSION

The GLEB implies the harmonization of all tradable power balancing products, of the FAT of all reserve types, of the prequalification requirements for service provider and common rules for cross-border balancing. Proposals and roadmaps for the integration are requested from all TSOs latest by December 2019. The GLEB makes allowance for a step-by-step integration. It allows groups of TSOs to perform pilot projects (e.g. FCR and RR markets, see Table II and Table III).

Barrier for a fast integration is the diversity of balancing approaches. Potential harmful interrelations of all national characteristics with harmonized balancing procedures are difficult to rule out. The European regulators counter this risk by involving all stakeholders and ask for proposals from the industry.

To enable "free bids" (see chapter IV.D) is a new approach that bears the chance of increasing market competition. It may complicate collusive behavior on markets, according to the literature [14].

The targets of the GLEB are ambitious, but the harmonization is accompanied by the operating industry. The process is promising, if it can involve all stakeholder.

The identified research questions for future investigations: How does the market set up (interrelations of activation strategy, clearing and settlement) interact with the full activation time? How does passive balancing influence power balancing?

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Market response for real-time energy balancing – Evidence from three countries

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***Abstract* — This paper highlights and evaluates different approaches how market response is incentivized by local balancing market design to support real-time balancing of electrical energy within an ongoing imbalance settlement period, also known as "passive balancing". Data from the control blocks of the Netherlands, Belgium and Germany are analyzed and the behavior of market parties is evaluated.**

Even though the three countries pursue similar power balancing strategies for the activation of balancing reserves and cost allocation, the incentives for market parties to support transmission system operators in balancing the control block differs. The highest degree of supported market response is found in the Dutch system with real-time publication of imbalance prices, followed by the Belgian system publishing only activated reserves. The German balancing market design does not explicitly incentivize market response for energy balancing in real-time.

***Index Terms* — Passive Balancing, Power Balancing Market Design, EU Regulation**

I. Introduction

The tendency that optimizing dispatch of electric power moves closer to real-time is founded in the transition to fluctuating renewable energies and resulting demand for schedule adaptations. Gate Closure Time (GCT) of intra-day and balancing markets moves closer to the imbalance settlement period (ISP), as an obvious indicator of this development. For some European balancing markets, real-time balancing becomes ever more an interactive task between Transmission System Operators (TSOs) and balance responsible parties (BRPs), where balancing energy prices are supposed to reflect scarcity in real-time to incentivize system supporting behavior by all BRPs besides only activating explicit qualified balancing service providers (BSPs).

The comparison is motivated by the commission regulation, which established a "guideline on electricity balancing" (EBGL) to set the course for harmonized European balancing markets. Amongst other claims, the EBGL aims "to provide incentives for market participants to contribute to solving the system scarcities for which they are responsible" and "efficient balancing rules should be developed" accordingly (EBGL Article (3), [1]). This work aims to research which design parameters are effective to let market participants contribute to solve system scarcities within an ongoing ISP. Therefore this paper is organized as follows. Section II describes the applied analysis method. Section III compares national approaches of how real-time energy balancing and market response is dealt with. In Section IV, results of the data analysis are presented. Section V identifies key market design parameters for efficient market response. Section VI concludes main findings of this paper.

II. Method

The applied method starts with a qualitative comparison of national balancing markets and to which extent market response is incentivized to support the balancing process. The performance of the different approaches is evaluated in a second step by analyzing historical data of the Area Control Error (ACE) and activation of balancing energy from Frequency Restoration Reserves. Goal is to investigate benefits and risks of market response to support real-time energy balancing for TSOs.

A. *Comparison of national balancing markets*

The balancing market design of the countries The Netherlands (NL), Belgium (BE), and Germany (DE) is compared and evaluated. Investigated design parameters are (i) real-time information, granularity and delay, (ii) settlement of TSO-BSP (metered vs. requested) and (iii) settlement of TSO-BRP (single vs. dual imbalance price).

B. *Evaluation of data*

Public data from the year 2017 is evaluated. In order to benchmark performance of the different approaches, the mean values (μ) and standard deviation (σ) of ACE and activated balancing energy from automatic Frequency Restoration Reserves (aFRR) and manual Frequency Restoration Reserves (mFRR) are compared. Results are scaled according to local

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electrical energy consumption. Additionally, occurrence of ISPs with activation of both upward and downward balancing energy within one ISP, so-called “counter-activations”, is evaluated.

III. Balancing and Market Response

Conventionally, the balancing process is described in two separate steps. (A.) BRPs plan their dispatch according to trades and submit their schedules to the TSOs. The schedules have a granularity of 15 minutes, corresponding to the length of an ISP. (B.) By default, this leads to power deviations between load and generation in real-time. The TSOs perform physical power balancing to counterbalance these deviations (MW). Furthermore, energy deviations (MWh) of BRPs over an ISP are also compensated by the responsible TSO. (C.) Market response for real-time energy balancing describes the interaction of these two steps. Table 1 gives an overview of relevant parameters in the three control blocks.

A. Energy balancing and schedules

Sell and buy orders define the price for electrical energy at different electricity markets (futures, day-ahead, intra-day). BRPs are financially responsible for any energy deviation between submitted schedule and actual dispatch for each ISP. Any deviation is settled and results in an imbalance price. Since all three countries apply in general a single imbalance pricing mechanism, BRPs deviating in the system supporting direction will receive the imbalance price. Germany applies a pure single imbalance price. Belgium applies a dual imbalance price, but the difference in imbalance price between the short position and long position is negligible which means that BRPs with system supporting imbalance can be rewarded. The Netherlands apply in general a single imbalance pricing mechanism, but in case of counter-activations a dual imbalance pricing mechanism is applied, to control and limit market response.

B. Power balancing

The TSOs in the Netherlands, Belgium and Germany pursue similar balancing strategies and use mainly aFRR from a merit order list to counterbalance power imbalances. Activation of balancing reserves leads to costs, channeled to BRPs via the imbalance price. The Netherlands and Germany apply merit order activation of reserves, while Belgium applies pro rata activation. In the Netherlands all called BSPs are rewarded based on request with a marginal price, and the imbalance price is equal to that marginal price (price based). Germany and Belgium apply pay-as-bid for activated reserves resulting in an average price for imbalances (volume based) that is deviated from all costs and available ex post. German BSPs are settled based on measured values.

C. Market response for real-time energy balancing

BRPs can use their assets to support the balancing process the moment it creates a beneficial deviation from their schedule as a consequence of the single imbalance price. By supporting balancing, BRPs can minimize risk and costs and/or maximize revenues, if system information like activated reserves and/or imbalance price is available.

The Netherlands apply the most transparent balancing process. Activated reserves and the imbalance price of the Dutch control block are published real-time with a resolution of one minute and a delay of two to four minutes within each ongoing ISP. Thus, market participants can adjust their dispatch according to this real-time incentive and consequently help balancing the control block. Belgium publishes only activated reserves in real-time, also with a one-minute resolution and delay. The imbalance price is published every 15 minutes at the end of the ISP. German regulation does not foresee active market response in real-time and schedule deviations are not explicitly incentivized. Therefore no real-time information is published.

D. Potential implications of active market response

Besides pure balancing advantages, it must be noted that an active real-time market response also includes some potential implications. These are the necessity of effective price signals based on the prices of balancing energy bids. Furthermore, a strong internal network is required in order to facilitate different flows induced by deviating dispatch. Thirdly, real-time market response remains a voluntary action and TSOs cannot rely on this support likewise from explicit activated BSPs.

TABLE I. Comparison of design parameter in NL, BE and DE.

Design parameter	**Country**		
	The Netherlands	***Belgium***	***Germany***
(i) Real-time information for market response[a,b]	Activated reserves and marginal price in 1 min resolution, delay of 2 - 4 min	Activated reserves in 1 min resolution, delay of 2 - 4 min	No public real-time information
(ii) TSO-BSP settlement and activation of aFRR[c]	Marginal price, merit order activation Full activation time: 15 min	Pay-as-bid, pro-rata activation Full activation time: 7.5 min	Pay-as-bid, merit order activation Full activation time: 5 min
(iii) TSO-BRP and imbalance price settlement[d]	Mainly single and occasionally dual imbalance price Marginal Control Energy Price	Dual imbalance price (differences neglibible) Average Control Energy Price	Single imbalance price Average Control Energy Price

a. https://www.tennet.org/english/operational_management/System_data_relating_implementation/system_balance_information/BalansDeltawithPrices.aspx#PanelTabTable [2]

b. https://www.elia.be/en/grid-data/balancing/current-system-imbalance [3] c. E-Bridge 2016, p.11 [4] d. WGAS Survey 2018, p. 122 [5]

IV. DATA ANALYSIS

Table II shows the results of the data analysis. Consumption of electrical energy in the three counties was used to scale the ACE, activated aFRR and activated mFRR accordingly. The μ of the scaled ACE in the Netherlands and Belgium are in a similar range between 2 to 3 MWh imbalance per GWh consumption, while Germany faced μ of 1.6 MWh imbalance per GWh consumption. The σ of 3.3 MWh per GWh consumption shows that the Dutch system was in general the most concentrated around a balanced position, followed by Germany with σ of 6.9 MWh per GWh consumption and Belgium with σ of 15.7 MWh per GWh consumption..

TABLE II. DATA ANALYSIS OF THE BALANCING PERFORMANCE IN 2017

Data from 2017[a,b]	**Control Block of**		
	The Netherlands	***Belgium***	***Germany***
Energy consumption	115.4 TWh in total μ = 3 293 MWh per ISP	84.8 TWh in total μ = 2 408 MWh per ISP	538.7 TWh in total μ = 15 373 MWh per ISP
Area Control Error (ACE)	μ = 9.5 MWh per ISP σ = 10.9 MWh per ISP	μ = 5.8 MWh per ISP σ = 37.9 MWh per ISP	μ = 24.9 MWh per ISP σ = 106.3 MWh per ISP
ACE scaled to local energy consumption	μ = 2.88 MWh per GWh cons. σ = 3.31 MWh per GWh cons.	μ = 2.41 MWh per GWh cons. σ = 15.73 MWh per GWh cons.	μ = 1.62 MWh per GWh cons. σ = 6.91 MWh per GWh cons.
Counter-activations of aFRR upward and downward	Occurrence in 9.1 % of all ISPs	Occurrence in 66.8 % of all ISPs	Occurrence in 97.3 % of all ISPs
Activation of aFRR upward or downward	Occurrence in 71.4 % of all ISPs	Occurrence in 29.2 % of all ISPs	Occurrence in 2.7 % of all ISPs
No activation of aFRR	Occurrence in 19.5 % of all ISPs	Occurrence in 4.0 % of all ISPs	Occurrence in 0.0 % of all ISPs
Activated aFRR upward	μ = 5.9 MWh per ISP σ = 13.0 MWh per ISP	μ = 11.6 MWh per ISP σ = 13.3 MWh per ISP	μ = 107.5 MWh per ISP σ = 183.6 MWh per ISP
Activated aFRR upward scaled to local energy consumption	μ = 1.79 MWh per GWh cons. σ = 3.95 MWh per GWh cons.	μ = 4.82 MWh per GWh cons. σ = 5.52 MWh per GWh cons.	μ = 6.99 MWh per GWh cons. σ = 11.94 MWh per GWh cons.
Activated aFRR downward	μ = 7.6 MWh per ISP σ = 13.9 MWh per ISP	μ = 15.0 MWh per ISP σ = 15.0 MWh per ISP	μ = 100.7 MWh per ISP σ = 177.4 MWh per ISP
Activated aFRR downward scaled to local energy consumption	μ = 2.31 MWh per GWh cons. σ = 4.22 MWh per GWh cons.	μ = 6.23 MWh per GWh cons. σ = 6.23 MWh per GWh cons.	μ = 6.55 MWh per GWh cons. σ = 11.54 MWh per GWh cons.
Activated mFRR upward	μ = 0.0 MWh per ISP σ = 0.7 MWh per ISP	μ = 2.6 MWh per ISP σ = 12.2 MWh per ISP	μ = 15.3 MWh per ISP σ = 92.9 MWh per ISP
Activated mFRR upward scaled to local energy consumption	μ = 0.00 MWh per GWh cons. σ = 0.21 MWh per GWh cons.	μ = 1.08 MWh per GWh cons. σ = 5.07 MWh per GWh cons.	μ = 1.00 MWh per GWh cons. σ = 6.04 MWh per GWh cons.
Activated mFRR downward	μ = 0.0 MWh per ISP σ = 0.3 MWh per ISP	μ = 2.0 MWh per ISP σ = 9.6 MWh per ISP	μ = 8.1 MWh per ISP σ = 69.0 MWh per ISP
Activated mFRR downward scaled to local energy consumption	μ = 0.01 MWh per GWh cons. σ = 0.09 MWh per GWh cons.	μ = 0.91 MWh per GWh cons. σ = 3.99 MWh per GWh cons.	μ = 0.53 MWh per GWh cons. σ = 4.49 MWh per GWh cons.

a. ENTSO-E Statistical Factsheet 2017 [6] b.Data from ENTSO-E Transparency platform, https://transparency.entsoe.eu/ [7]

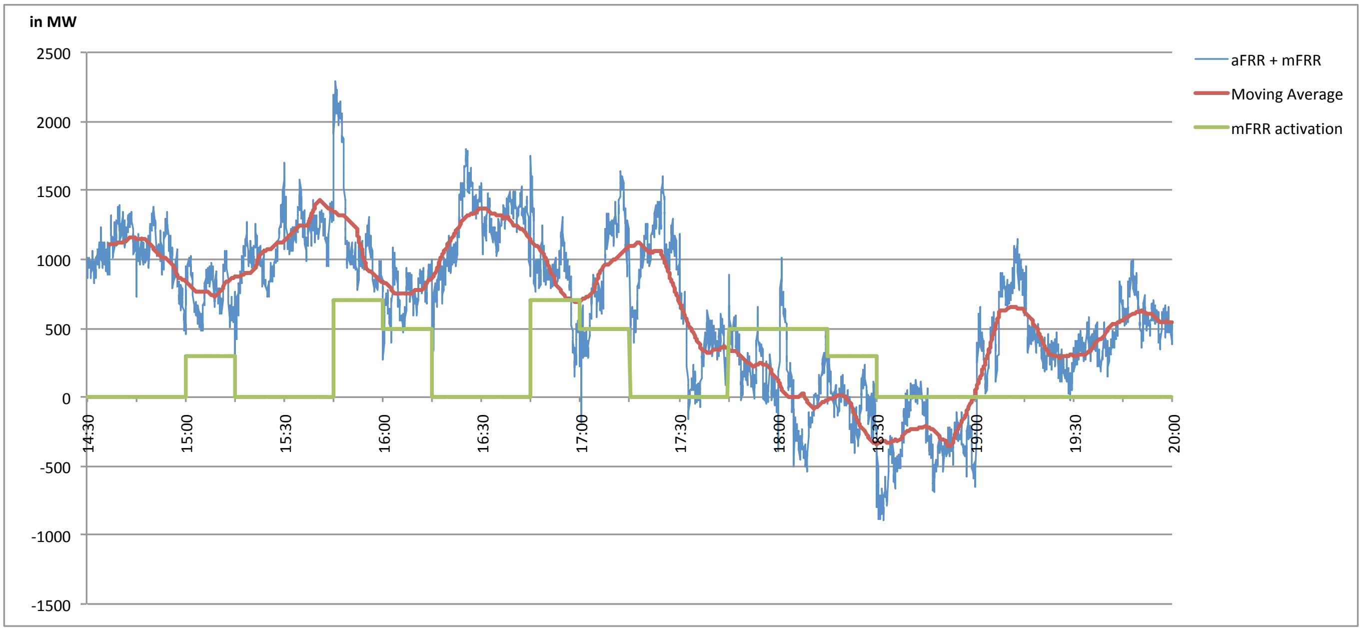

FIGURE I. EVIDENCE OF MARKET RESPONSE TO ACTIVATION OF MFRR IN GERMANY, DATA FROM TENNET TSO GMBH.

Consistent with the ACE, also the scaled activation of all reserve types is comparatively small in the Netherlands. Germany was confronted with the highest scaled activation of aFRR upward and downward, followed by Belgium. Remarkable is the activation of mFRR in the Netherlands, which is close to zero. The low demand for mFRR in the Netherlands indicates a well functioning market response, as the system imbalance is real-time compensated by market response reducing need for high volumes of reserves. Thus, solving system scarcity with schedule deviations seems to be beneficial for the BRPs in the Netherlands and makes mFRR only a tool for scarce system needs. This occurrence is a strong indication that market response is apparently a cost-effective market-based measure for balancing market designs to support real-time power balancing.

The scaled μ of activated mFRR upward and downward in Belgium is slightly higher than in Germany, but the σ is higher in Germany. Apparently, the missing price component in Belgium leads to less effective market response than in the Netherlands, as the comparatively high demand for mFRR indicates. Inquiry at market parties confirms this observation.

Occasionally, some German BRPs respond to system scarcity, even though the German system does not foresee it. Figure I shows that the demand for reserves declines after activation of mFRR which can be explained by market response. The call for mFRR activation is transmitted to the executing BSPs latest 7.5 minutes before the beginning of an ISP and in principle only known by the TSOs and the called BSPs [8]. Nevertheless, the presented evidence shows three cycles of an oscillation between mFRR activation of 300 to 700 MW and market response of roughly several hundreds of MWs in addition. The first call for mFRR activation is submitted between 14.45 and 14.52´30s for the ISP starting at 15 hrs. The demand for reserves starts declining during that time window. The same pattern can be observed before the ISPs starting at 15.45 and 17.45 hrs. The activation signal of mFRR leads to a financial incentive for dispatch deviations and is known by some market parties and in this particular example has led to a system supporting behavior.

Where the Dutch system experiences counter-activations in only 9.1 % of all ISPs and 66.8 % of all ISPs in Belgium, Germany experienced this in 97.3 % of all ISPs. Nevertheless, for the German case, these results are somehow misleading, since the aFRR balancing energy activation in the counter direction quite often relates to very small volumes. Table III shows how the share of ISPs with counter-activations in Germany decreases when neglecting a rising amount of aFRR balancing energy activation.

TABLE III. COUNTER-ACTIVATIONS IN GERMANY.

Data from 2017[a]	Neglect aFRR activation of					
	1 MWh	***2 MWh***	***3 MWh***	***4 MWh***	***5 MWh***	***10 MWh***
ISPs with counter-activations	83 %	68 %	56 %	49 %	43 %	26 %

a. Data from ENTSO-E Transparency platform, https://transparency.entsoe.eu/ [7]

The high share of ISPs with rather small aFRR counter-activation in Germany results mainly from German BSPs with aFRR delivery without TSO aFRR activation request, and settlement based on measured values (with tolerance band) instead of request settlement. In this case, the small amount of aFRR activation does not relate to a physical need of balancing energy and should be disregarded when analyzing German data of balancing energy activation from aFRR and counter-activation influencing real-time price incentives.

In addition, the Netherlands experienced 19.5 % of all ISPs without aFRR activation at all. This circumstance occurred in 4.0 % of all ISPs in Belgium and in 0.0 % of all ISPs in Germany. This occurrence is only possible because of the International Grid Control Cooperation (IGCC) that performs imbalance netting between the control blocks of Austria, Belgium, Switzerland, Czech Republic, Germany, Denmark, France and the Netherlands [9]. IGCC is an optimization system for the avoidance of counter-activation of aFRR between countries, respecting available cross-zonal capacity.

V. Efficient market response for energy balancing

The Dutch TSO supports market response with information about power scarcity and costs. BRPs can evaluate their marginal costs for deviations from dispatch and compare it to the imbalance price. Additionally, the information about energy scarcity indicates the risk of not being awarded in case of a counter-activation when the dual imbalance price applies. Therefore, BRPs can take data-based decisions resulting in a system supporting market response which made mFRR mainly redundant. An example of the effectiveness of passive balancing in the Dutch power system is elaborated in [10]. High transparency about energy scarcity and costs in combination with a penalization for overreaction results to be the best approach for efficient market response. The low share of ISPs with counter-activation and the low scaled ACE are the benchmarks that indicate the presence of controllable interaction between TSOs balancing efforts and market response without a nervous behaving system.

The Belgian TSO supports market response with information about energy scarcity without prices. Counter-activations are not penalized which might lead to overreaction due to market response. The sign and magnitude of the imbalance price can be derived from the available information, but the market response is limited by the uncertainty about potential revenues.

From the German observation in this work it is concluded that incomplete system information still contributes to participation of market response (passive balancing) due to single imbalance pricing, however the effectiveness and potential is limited. A clear mechanism to prevent overreaction is currently also not provided.

VI. Conclusion

The comparison of the three countries shows evidence that the ACE open loop and resulting activation of Frequency Restoration Reserves decline with a rising degree of transparency that allows market response real-time (passive balancing), subject to correct price incentives. This conclusion is based on the very similar power balancing approaches of the TSOs differing mainly in the transparency about real-time system information. The high occurrence of counter-activations in Belgium and Germany shows potential for improvement. Imperfect information occasionally leads to overreaction of market response, since a pure single price is applied and physics and market incentives are less coherent.

The Dutch approach seems to work best in this case, considering the low occurrence of counter-activations of aFRR upward and downward and, especially, the comparatively small deviation of the scaled ACE. Therefore, an additional mechanism to prevent overreaction of market participants, like the Dutch approach of changing from single to dual price in case of counter-activations, is advisable as a component for an efficient market response in real-time.

The presented evidence in Germany (Figure I) shows some consequences of applying a single imbalance price for schedule deviation without full transparency of system and market information real-time. The appliance of a single imbalance price is inherently the incentive for BRPs to have to a certain degree a system supporting schedule deviation, but they can only react correctly in case of sufficient real-time information. This information consists of (expected) imbalance price as the motivation for market response and TSO's activated reserves as risk management for market response. The majority of potential market response remains inactive due to ambivalent information and financial risks.

These results should be considered when developing common European balancing rules by power balancing TSOs aiming to use the potential of real-time market flexibility in addition to pre-qualified BSPs only. However, it must be noted that networks must be able to facilitate changes in dispatch and balancing energy prices must be correct in order to set efficient incentives. As described, identified design parameters are real-time information granularity and delay, pricing settlement (marginal imbalance pricing, single and dual), aFRR controller set-up, and full activation time of reserves. The effectiveness of market response is strongly determined by the interaction of these design parameters and should be considered as a package deal rather than stand-alone options.

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Liberalization of the Electricity Market in Ukraine in 2019 - Lessons Learned

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***Abstract*—The liberalization of the electricity market in Ukraine in July 2019 led to unexpected behavior of the market. The initial market design and its changes in December 2019, March, April, May and June 2020 are discussed. The effects on day-ahead market prices, imbalance prices and activated balancing reserves are evaluated with data from July 2019 until April 2020. The data illustrates temporary malfunctions. Changing the imbalance pricing scheme reduced misplaced incentives. In future, more transparency could lead to further improvements. The regulation should allow to quickly adopt and give immediate feedback to the market participants. In addition, allowing higher prices for balancing reserves would give stronger incentives to participate in balancing markets.**

***Index Terms*—Ukraine Electricity Market, Power Balancing, Liberalization**

I. Introduction

The government of Ukraine adopted the law "On Electricity Market" in April 2017 [1]. This law paved the way for the introduction of a liberal electricity market in July 2019. Historically, Ukraine had focused on power exchange with Russia and Belarus. The liberal electricity market is the first step towards coupling with other European markets. The purpose of the liberal market is to ensure transparent and competitive pricing. This shall optimize the energy balance and improve economic, energy, and environmental security. Competitive mechanisms for market participants shall encourage the industry to modernization [2].

The liberalization aims for more competition and more efficiency, but it goes along with more complex mechanisms and legislation. Market participants are organized in Balance Responsible Parties (BRPs). The day-ahead market (DAM) is their main tool for creating schedules and dispatching power generation and load. BRPs shall track their real-time power generation and consumption and stick to the schedule. In addition, BRPs can offer upward and downward reserves at balancing markets. These reserves are activated in case of any imbalance between generation and load in real-time. The costs for the balancing process are allocated to the BRPs with schedule deviations via an imbalance pricing mechanism.

This growing number of market opportunities creates complex interrelations. The design of electricity spot markets, balancing markets and the imbalance pricing mechanism can include misplaced incentives for BRPs. The interaction of these market opportunities is crucial for system stability. Correct incentives lead to efficient electricity markets and a balanced power system. Misplaced incentives can lead to an imbalance between generation and load, as it was seen in Germany in June 2019 [3]. This work aims to research which lessons can be learned from the liberalization of the electricity market in Ukraine since July 2019.

Section II outlines the analysis method. Section III describes the initial market design in Ukraine in July 2019 and relevant changes over time. Section IV presents the applied data and the effects of market design changes. In section V, the findings are discussed and put into context. Section VI concludes main findings of this paper and presents an outlook.

II. Methodology

The method covers a review of the market design, followed by a data analysis. This study aims to identify the key market design parameter for a cost-efficient power system. The initial market design in July 2019 is compared to the market design changes in November 2019, March, April, May and June 2020. Data of DAM prices, the imbalance prices, prices for balancing reserves and the amount of activated balancing power is used to analyze the effects of the market design changes. The intraday market is not considered. Data over a ten-month period from July 2019 until the end of April 2020 is applied. Data of the integrated power system of Ukraine is evaluated. The zone of Burshtyn, which is in synchronous operation with central Europe, is not considered.

III. Electricity market of Ukraine

The law "On Electricity Market" of April 2017 was adopted several times to change the market design [1]. This section describes the changes with regard to the DAM, power balancing markets and imbalance pricing.

A. Initial market design in July 2019

Prices at the DAM are limited since the first implementation. Different price caps apply during the night, from 23:00 until

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08:00, and during the day, from 8:00 until 23:00. Prices at the power balancing market and the imbalance price for schedule deviations are regulated, too. The price caps are set to be maximum 115% of DAM price cap and minimum 85% of DAM price cap. BRPs with power plants are obligated to offer all available flexibility at power balancing markets with prices in this range. Single imbalance pricing applied in the first place, which was changed later on. The imbalance price is the weighted average price of upwards and downwards balancing energy. The imbalance price is maximum 115% of DAM price cap in case of an positive imbalance (upward reserves dominated) and minimum 85% of DAM price cap in case of negative imbalance (downward reserves dominated). Table I shows the price caps in Ukrainian hryvnia (UAH) per MWh, as implemented in July 2019. The clearing process takes more than a month. This means BRPs pay or receive the imbalance price 4-6 weeks after the considered time period. In contrast, the DAM price has to be paid or is received in advance.

TABLE I
PRICE CAPS FOR DAY-AHEAD MARKET, BALANCING MARKET AND SINGLE IMBALANCE PRICING FROM JULY TO NOVEMBER 2019

	Day hours	**Night hours**
Day-ahead market (max)	2048.23 $\frac{\text{UAH}}{\text{MWh}}$	959.12 $\frac{\text{UAH}}{\text{MWh}}$
Upward reserves (max)	2355.46 $\frac{\text{UAH}}{\text{MWh}}$	1102.98 $\frac{\text{UAH}}{\text{MWh}}$
Downward reserves (min)	1740.99 $\frac{\text{UAH}}{\text{MWh}}$	815.25 $\frac{\text{UAH}}{\text{MWh}}$
Imbalance price (max)	2355.46 $\frac{\text{UAH}}{\text{MWh}}$	1102.98 $\frac{\text{UAH}}{\text{MWh}}$
Imbalance price (min)	1740.99 $\frac{\text{UAH}}{\text{MWh}}$	815.25 $\frac{\text{UAH}}{\text{MWh}}$

B. Changes in December 2019

The government of Ukraine changed the legislation framework with regard to the price caps. The new pricing mechanism came into effect by the 1 of December 2019. The actual DAM price is considered and not the DAM price cap. That means the fixed price range at the power balancing market was changed to a dynamic range. The maximum price for upward reserves is limited to 115% of DAM price and bids for downward reserves have a minimum of 85% of DAM price. The maximum single imbalance price is set to 115% of the DAM price in case of a positive imbalance (upward reserves dominated) and the minimum imbalance price is at least 70% of DAM price in case of negative imbalance (downward reserves dominated). Table II shows the new dynamic price caps.

TABLE II
PRICE CAPS FOR BALANCING RESERVES AND SINGLE IMBALANCE PRICING FROM DECEMBER 2019 TO FEBRUARY 2020

	Day hours	**Night hours**
Upward reserves (max)	DA Price + 15%	DA Price + 15%
Downward reserves (min)	DA Price - 30%	DA Price - 30%
Imbalance price (max)	DA Price + 15%	DA Price + 15%
Imbalance price (min)	DA Price - 30%	DA Price - 30%

C. Changes in March 2020

The government of Ukraine changed the legislation framework with effects on DAM, power balancing markets and imbalance pricing. The new mechanisms came into effect by the 1 of March 2020.

1) Day and night hours: In accordance to new changes of the Market rules for day-ahead market and intra-day market the 8th hour was moved from off-peak hours to peak hours. As a result, the highest price between 7.00 and 8.00 at the DAM increased from 959.12 $\frac{\text{UAH}}{\text{MWh}}$ to 2048.23 $\frac{\text{UAH}}{\text{MWh}}$.

2) Power balancing market: The power balancing market price was set back to be maximum 115% of DAM price cap for upward reserves. The minimum power balancing market price was set to be 55% of the actual DAM price for downward reserves. Table II shows the new price caps.

TABLE III
PRICE LIMITS FOR POWER BALANCING MARKETS FROM MARCH 2020 TO APRIL/MAY 2020

	Day hours	**Night hours**
Upward reserves (max)	2355.46 $\frac{\text{UAH}}{\text{MWh}}$	1102.98 $\frac{\text{UAH}}{\text{MWh}}$
Downward reserves (min)	DA Price - 45%	DA Price - 45%

3) Dual imbalance pricing: The imbalance pricing scheme changed from single pricing to dual pricing. The clearing result for each BRP is now calculated according to Fig. 1. The formula results in different prices for positive schedule deviations (more generation or less consumption than scheduled) and negative schedule deviations (less generation or more consumption than scheduled).

D. Changes in April/May/June 2020

Since 8. of April the maximum price for upward reserves was set to be 105% (not 115%) of DAM price cap. Since 27. of May the minimum price for downward reserves is 65% (not 55%) of the DAM price. Since the 10. of June the minimum price for downward reserves was changed again to be 80% (not 65%) of the DAM price. Table IV shows the new price caps.

TABLE IV
PRICE CAPS FOR POWER BALANCING MARKETS SINCE 08. OF APRIL (MAX) AND BETWEEN 27 OF MAY TO 9 OF JUNE (MIN)

	Day hours	**Night hours**
Upward reserves (max) since 08.04.	2150.64 $\frac{\text{UAH}}{\text{MWh}}$	1007.08 $\frac{\text{UAH}}{\text{MWh}}$
Downward reserves (min) since 27.05.	DA Price - 35%	DA Price - 35%
Downward reserves (min) since 10.06.	DA Price - 20%	DA Price - 20%

E. Summery of market changes

Fig. 2 illustrates all the described changes of the market design at hand.

$$CR_{b,t} = \begin{cases} SD_{b.t} * min(DA_t, IP_t) * (1 - K^{im}) & \text{if } SD_{b,t} > 0 \\ SD_{b.t} * max(DA_t, IP_t) * (1 + K^{im}) & \text{if } SD_{b,t} < 0 \\ 0 & \text{if } SD_{b,t} = 0 \end{cases}$$

With
$CR_{b,t}$ - clearing result (debit, if positive or credit, if negative) of BRP b in time period t
$SD_{b,t}$ - schedule deviation of BRP b in time period t
DA_t - Day-ahead market price in period t
K^{im} - coefficient of imbalance price
IP_t - imbalance price in time period t

Fig. 1. Dual imbalance pricing: calculation since 1 of March 2020

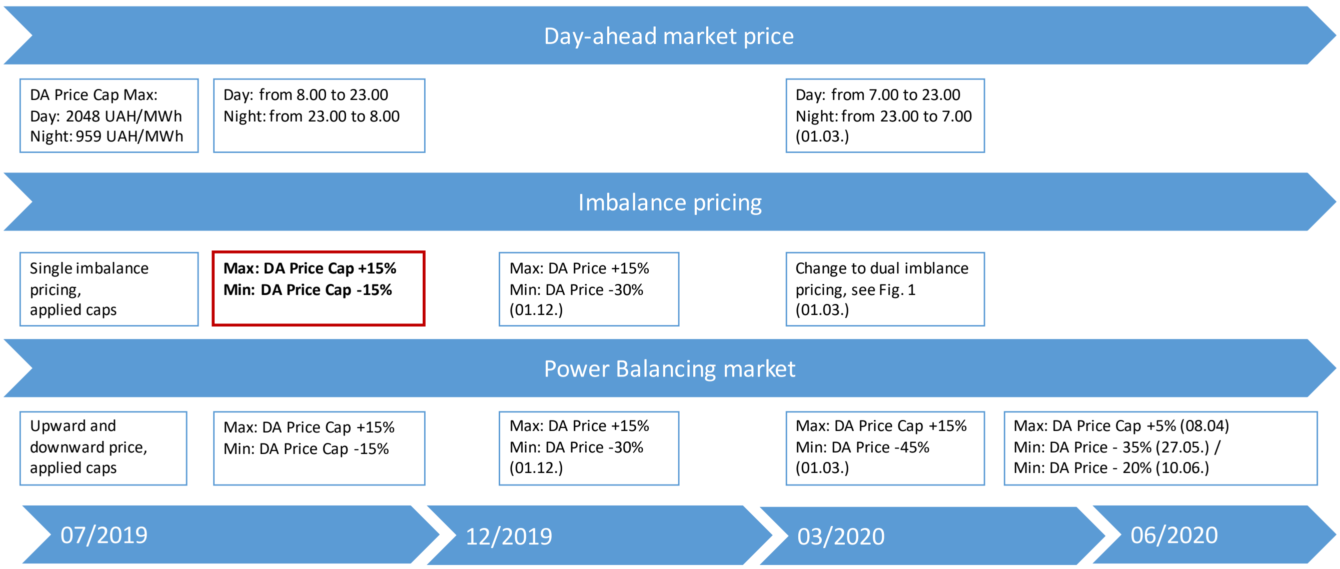

Fig. 2. Market changes over time in Ukraine

IV. Data analysis

The applied data include DAM prices, the imbalance prices, prices for balancing reserves and the amount of activated balancing power in Ukraine from July 2019 until April 2020. The data is available in 1 hour resolution [10].

Fig. 3 illustrates the mean activated upward and downward reserves per month. The mean activated downward reserves peaked and were 10 times higher than activated upward reserves in November 2019.

Fig. 4 illustrates the costs and revenues for the activation of reserves. Again, November is remarkable. BRPs offering downward reserves actually lost money, because the price for downward reserves was higher than the DAM price.

A. Effects of design change in December 2019

November had 500 hours (of 720 hours) where the imbalance price was higher than the DAM price. BRPs could maximize revenues by not selling energy at the DAM but rather creating an upward imbalance. The data indicates, that this financial incentive led to unwanted behavior. Energy was fed into the grid which was not scheduled and, thus, led to the activation of downward reserves.

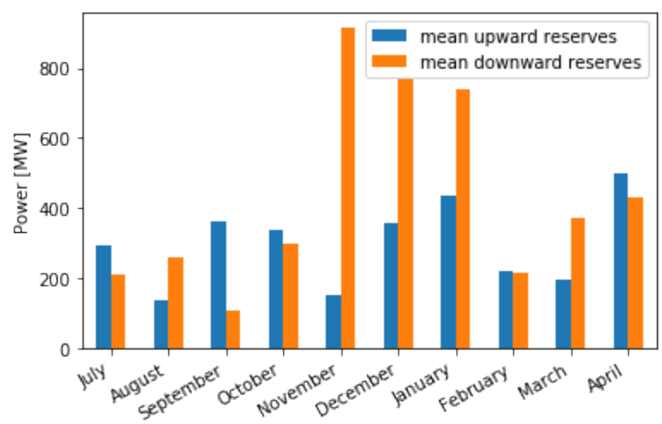

Fig. 3. Mean of activated reserves - July 2019 to April 2020

The government of Ukraine changed the legislation framework and the approach of how to calculate the price caps of the balancing market and the imbalance price by the 1 of December. Fig. 5 illustrates the imbalance price and the DAM price from 27.11.2019 until 03.12.2019. Fig. 6 illustrates

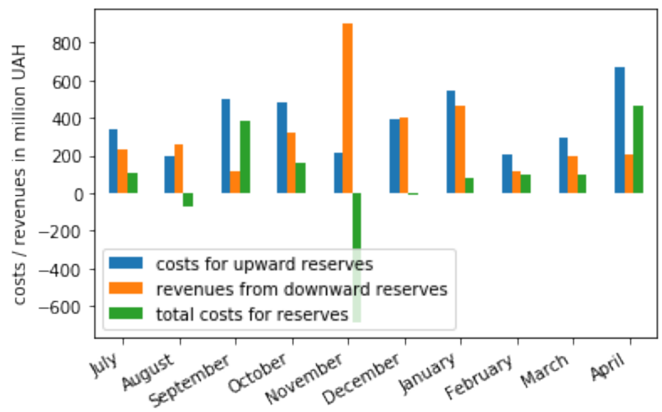

Fig. 4. Costs / revenues for activated reserves per month - July 2019 to April 2020

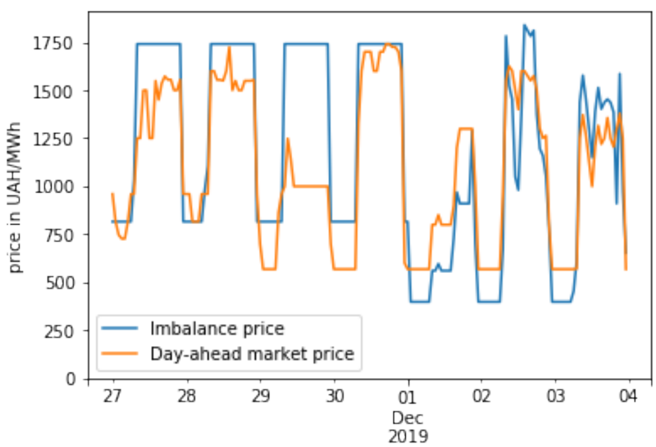

Fig. 5. Imbalance price and DAM price from 27.11.19 to 03.12.19

the prices for upward and downward reserves per hour from 27.11.2019 until 03.12.2019. Due to the market design change, the imbalance price and the price for downward balancing reserves can reach values under 1741 $\frac{\text{UAH}}{\text{MWh}}$. Fig. 7 illustrates the mean of activated upward and downward reserves per hour from 27.11.2019 until 03.12.2019. In December 2019 and January 2020, the system was in a more balanced situation. Nevertheless, the activation of downward reserves was still higher than the activation of upward reserves, as shown in Fig. 3. Fig. 8 illustrates the hourly distribution of activated downward reserves in December 2019 and January 2020, which peaked especially in night hours during these two months. The government stated to investigate the manipulation of DAM and balancing markets in February 2020. This statement reduced the activation of reserves very effectively.

B. Effects of design change in March 2020

As shown in Fig. 3 and Fig. 4, the differences between February and March are less extreme. The new market design allows higher prices for balancing reserves. The immediate effects are a shift back to higher prices for reserves, which can

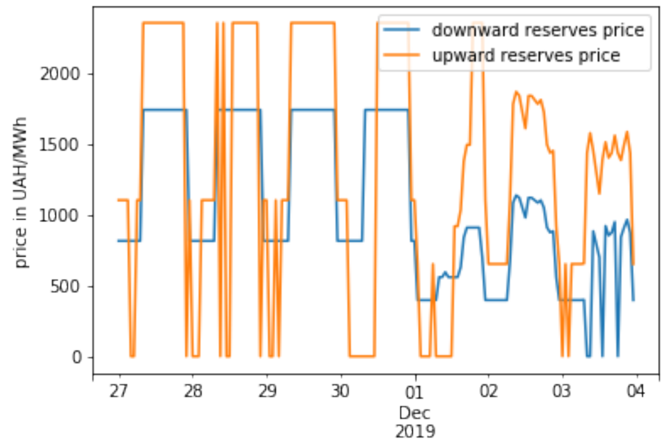

Fig. 6. Price for reserves from 27.11.19 to 03.12.19

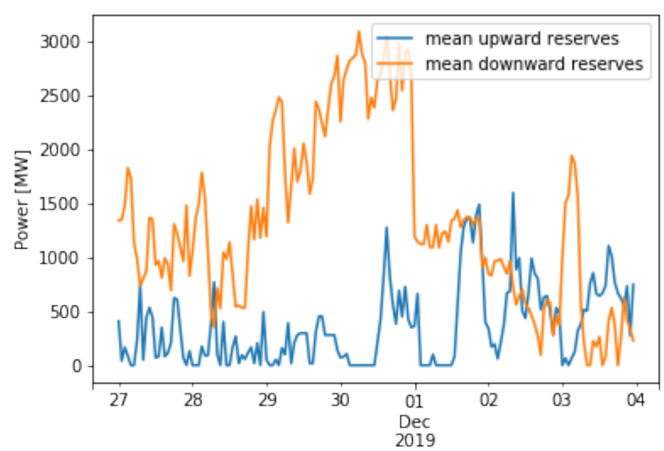

Fig. 7. Activated reserves from 27.11.19 to 03.12.19

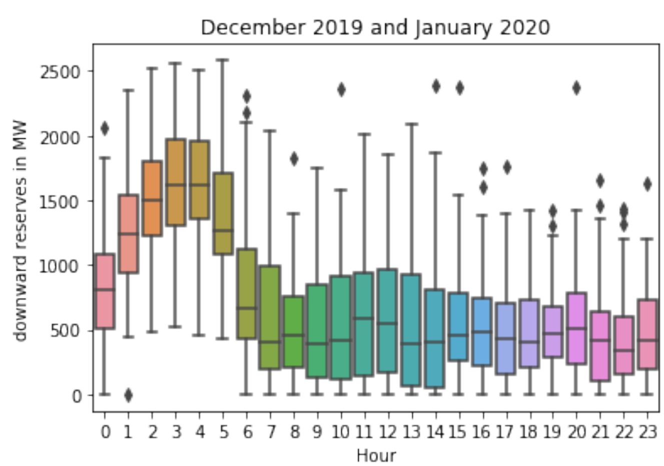

Fig. 8. Hourly distribution of downward reserves in December 2019 and January 2020

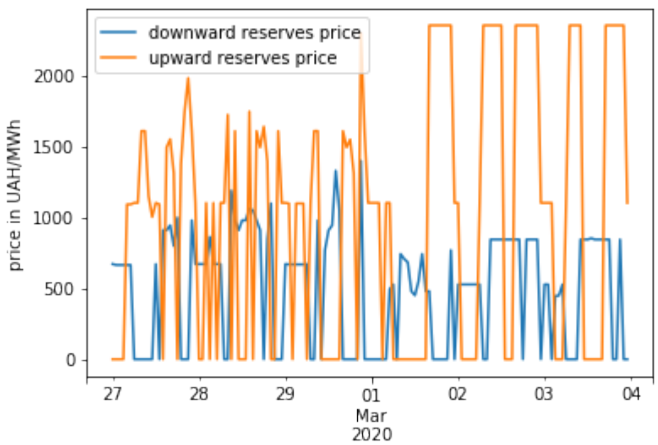

Fig. 9. Price for reserves from 27.02.20 to 04.03.20

be seen in Fig. 9. The activation of reserves increased in March and in April. Dual imbalance pricing leads to penalties for all schedule deviations, also for those who reduce the required balancing reserves.

C. Effects of design change in April, May and June 2020

The potential income from balancing reserves are reduced, in contrast to the market design changes in March 2020. The available data does not allow to evaluate the effects of design changes in April, May and June 2020.

V. Discussion

The different time periods are short and statistical evidence cannot be provided. Nevertheless, the data indicates that misplaced incentives of the initial market design led to situations of physical energy scarcity. In November 2019, the amount of activated downward reserves peaked. The misplaced incentive was a combination of low DAM prices and fixed imbalance prices, which exceeded the DAM price in 500 out of 720 hours. The market design change of how to calculate the imbalance price caps by 1 December 2019 did eliminate the minimum imbalance price. The new approach avoids misplaced incentives in case of low DAM prices. The governmental statement of starting an investigation on market manipulation in February 2020 came along with the most balanced month. Changing to dual imbalance pricing in March 2020 did not improve the situation further.

A. Lessons learned in other countries

The market liberalization in other countries is put into context. This leads to an outlook of how the market design in Ukraine might develop in the nearby future. The shift from regulated electricity monopolists towards liberal energy markets takes place in European countries since 1996. Reason of the "unbundling" was the Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 [4].

Gencer et. al. (2020) describe the liberalization in England and Wales, Germany, Belgium, Denmark and Switzerland. According to the analysis, energy markets evolve in three steps. The initial "Monopoly" is replaced by "Wholesale Competition": industry and generators start trading at spot markets. Afterwards, "Retail competition" allows all consumers to choose their energy supplier at free markets. The final stage of "Reregulation" adopts rules "to intervene to induce or prevent certain behaviours by market participants". Gencer et. al. (2020) conclude that (i) many regulatory frameworks lagging behind innovation in the market, (ii) the behavioral factors are as important as economics and (iii) agile market frameworks should give a long time perspective, but also pay attention to feedback of stakeholders. [5]

B. Harmonization of markets

Ukraine aims to develop energy markets in convergence with EU guidelines, as stated in Article 338 (d) of the Association Agreement [6]. The EU electricity balancing guideline (EBGL) gives guidance for the process of harmonization in Europe [8]. As of today, European energy markets are diverse and details of common rules are still under consultation [7].

According to Article 53, the imbalance settlement period shall be 15 minutes. Ukraine applies 1 hour. The imbalance pricing scheme shall be single pricing, as stated in Article 52 (2). Ukraine applies dual pricing since March 2020. Clearing of power balancing markets shall be marginal, defined in Article 30 (1). Ukraine applies marginal clearing. [8] [1]

C. Integration of power systems

Besides the market harmonization, Ukraine aims for synchronous operation of its two zones. In addition to the zone of Burshtyn, also the integrated power system of Ukraine shall operate within the Central European zone. As a first step, Ukraine plans to run the integrated power system of Ukraine in island mode in 2022. The grid operator and balancing service provider are preparing for this test period. [9] Ukraine could benefit from its position between Russia and central Europe. Enabling power balancing between different zones becomes more important with increasing amounts of renewable energy generation.

VI. Conclusion and outlook

The liberalization of the electricity market in Ukraine illustrated how misplaced incentives lead to unwanted market reactions. Initially, creating positive schedule deviations was more attractive than selling energy at the DAM leading to high amounts of activated downward reserves in November 2019. Changing price caps and governmental statements did stop this speculation of BRPs leading to minimum amount of activated reserves in February 2020. Dual imbalance pricing was introduced in March 2020, but no further improvements could be seen. Lessons learned in other countries can help to evaluate behavioral factors. In the future, regulation should allow to change the pricing schemes again, if the market behavior makes it necessary. The elimination of price caps in balancing markets could lead to an increase of competition and innovation. Changes of legislation should be made transparent and with fast implementation to avoid temporary speculations.

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Smart Balancing of Electrical Power – Matching Market Rules with Balancing Requirements ⋆

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ABSTRACT

Different power balancing strategies apply in Europe. The German system pursues a strategy counting only on "active balancing" via prequalified reserves. Dutch and Belgian systems count on real-time transparency allowing additional "passive balancing": all market parties are incentivized to balance generation and load. This article discusses current market rules and proposes a Smart Balancing strategy. Applied data covers a five-year time period (2015 to 2019). Statistical tests suggest that the German strategy is undermined, and passive balancing is present. The analysis show that passive balancing is a cost-efficient tool to meet power balancing requirements. Due to the combination with imbalance netting, it gives Dutch and Belgium market parties an advantage over German market parties. The findings lead to policy implications. In the German system, real-time information would improve the cost-efficiency of power balancing. Another implication results from misplaced incentives which intensified German imbalance events in June 2019. Balancing markets should take place close to real-time. This new market timing together with real-time information and combined (single and dual) imbalance pricing gives the most accurate incentives for Smart Balancing.

1. Introduction

In electrical systems it is crucial to always ensure the equilibrium between generation and load by power balancing. With growing size of an electrical system this task becomes easier and the reliability of power supply increases. For that reason, the European electrical grid evolved from independent island systems (cities) to national balancing blocks (countries), finally connected to international synchronous grids (continental Europe). In a next step, liberalization, harmonization and integration of energy markets facilitated international trade with economic benefits. The objective of current efforts is harmonization and integration of balancing markets (Commission, 2017). This article aims to contribute to the discussion about the role of passive balancing in future European balancing markets.

Germany does not provide official real-time information and relies only on prequalified reserves. The Dutch and Belgian balancing strategies count on market response for power balancing, also known as passive balancing. For that purpose, real-time information about activated balancing reserves and the current imbalance price are available (Elia, 2020b; TenneT, 2019a). All market parties are incentivized to "passively" balance generation and load in addition to "active balancing" via prequalified reserves (see Figure 2).

Existing literature about market rules and power balancing is discussed in section 2. Section 3 provides a definition

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of Smart Balancing and the methodology is described. Section 4 introduces the analyzed data covering a five-year period from 2015 to 2019 of the Netherlands, Belgium, and Germany. Section 5 presents case studies and statistical tests. Section 6 discusses the results and thus evaluates the considered balancing strategies. Policy implications are developed and an approach for the future European energy market is outlined. Section 7 concludes on the implications for policy.

2. Market rules and power balancing

Each of the following six literature subsections lead to a Smart Balancing observation regarding market rules.

2.1. Stochastic vs. deterministic imbalances and Area Control Error (ACE)

A profound discussion of system imbalances is provided by Hirth and Ziegenhagen (2015). Imbalances are separated into stochastic and deterministic reasons. Deterministic imbalances are known as schedule leaps: Thermal and hydro power generation follow their schedules in discrete 1 hour or 15 minutes steps, which does not match the physical demand and generation from volatile renewable energy sources wind and solar (VRE). Stochastic imbalances are separated into sudden events and continuous forecast errors. Sudden events are unplanned outages of plants or grid interconnections. Forecast errors are wrong predictions of load or generation of VRE. Maurer et al. (2009) present currently applied methods for estimating balancing demand and the approaches to dimension aFRR and mFRR. Load and VRE forecast errors are assumed to be normally distributed.

When it comes to real operation, the reasons for the system imbalance are diverse. The area control error (ACE) of a national balancing block is calculated by comparing scheduled power flows ($P_{\text{scheduled}}$) and measured power flows (P_{measured}) into or out of a country (ENTSO-E, 2009). The ACE of each balancing block is calculated by equation 1.

$$ACE = \sum P_{\text{scheduled}} - \sum P_{\text{measured}} \tag{1}$$

In a next step Frequency Restauration Reserves (FRR) are activated to compensate the ACE. FRR are distinguished between fast automatic activated FRR (aFRR) and, in long periods with high imbalance, slow manually activated FRR (mFRR). Three GW of Frequency Containment Reserves (FCR) are available in continental Europe, which measure and stabilize the grid frequency autonomously (ENTSO-E, 2009).

With this background and looking at the increasing share of VRE in Europe, balancing demand should have increase accordingly. In contrast to this common sense, Hirth and Ziegenhagen (2015) present empirical data from Germany indicating a negative correlation between capacity of VRE and balancing demand ("German Paradox"). Partly, this was achieved by improved weather forecast techniques. Ocker and Ehrhart (2017) explain the decrease of balancing

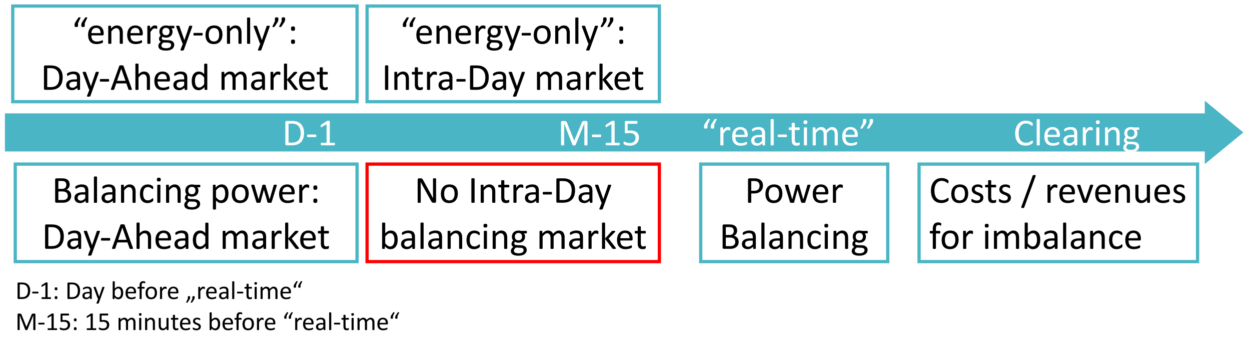

Figure 1: Timing of "energy-only" markets, balancing markets, and imbalance clearing

demand by improved cooperation and imbalance netting (see section 2.6). Koch and Hirth (2019) trace back a positive effect from improved intra-day trading (see section 2.2).

Observation 1: Increasing capacity of VRE does not necessarily lead to higher balancing demand if the market design is improved.

2.2. Timing of "energy-only" and balancing markets

Koch and Hirth (2019) provided a review article examining the "German paradox" with a focus on intra-day trading. A sharp increase of 15 minute trading between 2012 and 2017 indicate the shift from 1 hour to 15 minute portfolio management, which reduced deterministic imbalances. Weibbach et al. (2018) evaluated the corresponding effect on deterministic frequency deviations.

On the other hand, excessive short selling at intra-day markets led to events of high imbalances in June 2019 which could have ended in a Europe wide black-out. According to the report of 50Hertz et al. (2019), the ACE in Germany reached values over 9.5 GW (12.06.2019), respectively over 6 GW (06.06.2019 and 25.06.2019). Market parties faced wrong incentives, which can be explained by the timing of "energy-only" and balancing markets.

Figure 1 illustrates the timing. The box over the timeline represents energy-only markets, which are the main tool to plan the generation and load of electrical power. A day-ahead (D-1) auction with 1 hour products and continuous trade at intra-day markets with 15 minute products lead to final schedules of all market parties. Changing the schedule is possible until 15 minutes before real-time (M-15) in Germany (Bundesnetzagentur, 2011). The boxes under the timeline are related to power balancing. Market parties offer their prequalified FRR in day-ahead (D-1) auctions at balancing markets. Deviations from the schedule are cleared with the imbalance price (see section 2.5) for each 15 minute Imbalance Settlement Period (ISP). The ISP is a time unit (e.g. of 15 minutes) and applies to the trade of energy products, for which the schedule is defined. The schedule deviation is calculated per ISP ex-post. The imbalance price results from the costs for FRR and can be predicted by market parties. The spread between imbalance price and intra-

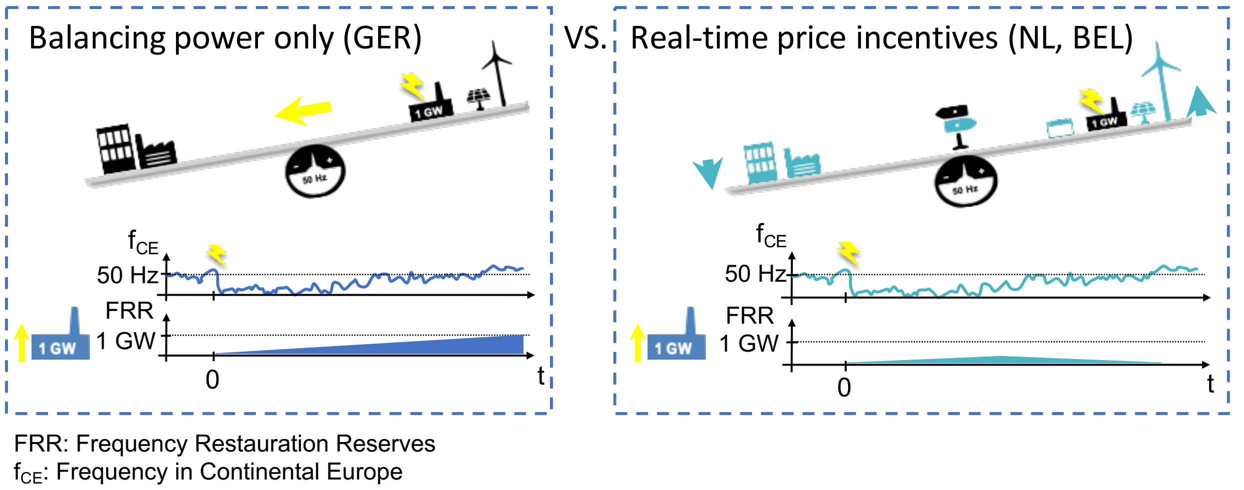

Figure 2: Balancing process in Germany (GER) vs. the Netherlands (NL) and Belgium (BEL). Illustration of strategies with fictional 1 GW plant outage

day price is an additional market opportunity which can incentive passive balancing (see section 2.3). The problem in June 2019 was a misplaced spread between intra-day price and the imbalance price. This misplaced incentive appeared, because the prices at balancing markets were settled and published day-ahead. A moderate imbalance price could be expected, while the intra-day price increased. If balancing markets would take place close to real-time (intra-day, red box in Figure 1), the bids for balancing power, and thus the resulting imbalance price, would reflect the latest information.

Observation 2: Day-ahead balancing markets in combination with intra-day "energy-only" markets can create misplaced incentives.

2.3. Passive balancing

The Netherlands and Belgium publish real-time information and therefore create incentives for passive balancing as a supplement to the active balancing via activation of FRR by the system operator. The notion of passivity is only specific from the perspective of system operators, because the market parties decide based on available information if their generation or consumption is changed. The Netherlands publish activated FRR together with the imbalance price close to real-time since 2001 (Beune and Nobel, 2001). Elia (2019) in Belgium publish system imbalance in 1 minute resolution since 2017. As from August, 27th, 2019, Belgium followed the Dutch example and real-time information was extended by the activated balancing energy and the corresponding imbalance prices. Figure 2 illustrates a fictive plant outage of 1 GW in the two systems. Germany activates 1 GW of FRR, according to the ACE. The Netherlands and Belgium publish real-time price incentives and other market parties "passively" balance the control block. The FRR demand decreases.

The idea of passive balancing has been described in different sources. The authors use the abbreviations Balance Responsible Parties (BRPs) for market parties, the Netherlands (NL), transmission system operator (TSO) and System Imbalance (SI) for the ACE:

- "In NL real-time feedback by the TSO on actual market balance position and imbalance price enables BRPs to act on opportunities to arbitrage between imbalance price and their own marginal production price resulting in a reduction of the system imbalance (the marginal price for control energy determines the actual balance energy price for this passive control)." (Nobel, 2016, p.102).
- "The imbalance price provides the incentive to BRPs to "passively" balance the system by purposely deviating from the schedule ("self-balancing")."(Hirth and Ziegenhagen, 2015, p.1048)
- BRPs can help the TSO keep the system balanced by intentionally incurring imbalanced positions in the opposite direction of the SI, which can be referred to as "passive balancing"." (Brijs et al., 2017, p.45).

These descriptions point out that market parties are incentivized by the imbalance price to passively balance the ACE of the control block. Schedule deviations of market parties cancel out and the balancing demand decreases.

Observation 3: Real-time information facilitate passive balancing. Passive balancing reduce the activation of FRR and improve cost-efficiency of power balancing.

2.4. Passive balancing in Germany

The balancing strategy in Germany does not foresee passive balancing. In fact, market parties must guarantee to follow their schedule, as specified in the standard contract between system operator and market party (Bundesnetzagentur, 2011). In the context of that contract, the single imbalance price is another "German paradox" (see section 2.5), which gives market parties an incentive to deviate from the schedule and ignore their contractual obligation. Koch (2021) presents a profitable trading strategy for the German market using the spread between intra-day price and imbalance price, but this would increase the ACE in a lot of cases. The spread gave a misplaced incentive half of the time in the period between 01.07.2017 to 30.06.2019. Eicke et al. (2021) lists literature which deals with strategic schedule deviations in Germany (strategies and evidence). Data from 12.07.2018 to 29.09.2019 indicates that market parties in Germany apply passive balancing. On average, the ACE is reduced by 20% by passive balancing. Koch and Maskos (2020) present similar positive effects of passive balancing in Germany, but also point out the limitation and delay of available information. A previous case study suggests a correlation between activation of mFRR and passive balancing, as a result from the deficit of official information (Röben and de Haan, 2019).

Observation 4: Due to the lack of official information, the activation of mFRR is interpreted as a real-time signal leading to passive balancing in Germany.

2.5. Single vs. dual vs. combined imbalance pricing

Single imbalance pricing is the preferred option in Europe and requested by the Electricity Balancing Guideline (EBGL) (Commission, 2017). The sign of the price defines if a positive or a negative schedule deviation leads to profit. Dual imbalance pricing refers to different prices for positive and negative schedule deviations without an incentive for passive balancing. Hence, all schedule deviations are penalized with dual pricing while there is a favorable direction leading to profit with single pricing.

Olmos et al. (2015) explain the difference between single vs. dual vs. combined imbalance pricing in the project report Market4RES. The Netherlands apply combined imbalance pricing: the imbalance price is a single price in any ISP without counter-activation of FRR. If the ACE reverses its sign, leading to positive and negative FRR counter-activation within an ISP, the dual imbalance price applies. The combined pricing scheme allows limiting passive balancing to the single price by the optional changing to dual pricing in case of reversing the sign of the ACE. Therefore, the Dutch approach of combined pricing offers the most adequate incentives for market parties with respect to system requirements (Olmos et al., 2015, p.82). Baetens et al. (2020) discuss how Belgium introduced single imbalance pricing with correction factor in 2012. The difference between the two prices increased with increasing ACE. FRR counter-activation did not influence the two prices. The correction factor was used until the end of 2019 and since 2020 a pure single imbalance price applies. Germany applies a pure single imbalance price. Limiting market response is more difficult, because a strong financial incentive for passive balancing exists. Passive balancing simulations with fuzzy logic identified that the most profitable market response with single imbalance pricing leads to reversing the sign of the ACE (Röben and Meissner, 2020). Section 3.1 suggests a definition of Smart Balancing, addressing the risk of reversing the sign of the ACE to avoid counter-activation of FRR.

Observation 5: Combined imbalance pricing is a correct incentive for market parties and prevents reversing the sign of the ACE.

2.6. Imbalance netting

Ocker and Ehrhart (2017) describe the development of the German Grid Control Cooperation which combined four German control areas to one single control block. This grid control operates since 2010 and four regional ACE are added to calculate one German ACE. The overall ACE is the sum with automatic netting of negative schedule deviations offsetting positive schedule deviations. This is the concept of imbalance netting, leading to more schedule deviation which offset each other out. In the International Grid Control Cooperation (IGCC), imbalance netting now works on ENTSO-E (2016) level. The schedule deviations of a control block cause the ACE in the first place. Power balancing now consists of two steps. First, calculate the imbalance netting contribution, secondly activation of FRR according to the remaining ACE.

The netting process avoids FRR activation in two control blocks. The energy exchange is cleared with an opportunity price, which reflects the value of avoided FRR costs. In case of the Netherlands and Belgium, imbalance netting contribution and applied opportunity price is part of the published real-time information. In combination with passive balancing, the opportunity price offers an additional business case and can incentive market parties to contribute to imbalance netting. This business case is missing in Germany, where no information is published.

Observation 6: Real-time information in combination with imbalance netting gives Dutch and Belgium market parties an advantage over German market parties.

3. Methodology

The observations amount to stating that providing information close to real-time with the correct signals is better than the absent of information. This section suggests a definition of Smart Balancing (3.1) and lists the related observations (3.2), derived in section 2. The methodology to analyze the observations are described.

3.1. Definition of Smart Balancing

Based on the descriptions of passive balancing in section 2.3, the following definition of Smart Balancing is proposed. The concept of passive balancing is expanded.

Definition:

Smart Balancing is a set of measures to minimize unnecessary activation of FRR. Market parties optimize schedule deviations to offset other schedule deviations. Smart Balancing is a response to provide correct incentives in combination with public real-time information and should be designed to avoid reversing the sign of the ACE.

Besides availability of real-time information, the definition of Smart Balancing addresses the risk of counter-activation of FRR. Passive balancing becomes Smart Balancing, if market parties are incentivized to reduce FRR activation without reversing the sign of the ACE. As described in section 2.3: single imbalance pricing does not meet this requirement, but the Dutch approach of combined pricing offers such a correct incentive. With IGCC, Smart Balancing can also reduce FRR demand in other control blocks.

3.2. Smart Balancing observations and methodology

The discussed literature in section 2 lead to the following six Smart Balancing observations:

1. Increasing capacity of VRE does not necessarily lead to higher balancing demand if the market design is improved.
2. Day-ahead balancing markets in combination with intra-day "energy-only" markets can create misplaced incentives.

3. Real-time information facilitate passive balancing. Passive balancing reduce the activation of FRR and improve cost-efficiency of power balancing.
4. Due to the lack of official information, the activation of mFRR is interpreted as a real-time signal leading to passive balancing in Germany.
5. Combined imbalance pricing is a correct incentive for market parties and prevents reversing the sign of the ACE.
6. Real-time information in combination with imbalance netting gives Dutch and Belgium market parties an advantage over German market parties.

Observations 1 and 2 are analyzed by case studies. For observation 3 and 4, applied data is separated and t-tests of independent samples (Cohen, 1988, p.19) are conducted with balancing demand and related costs. If a t test indicates a statistical significant difference (p-value < 0.05) between the samples, the effect size is calculated using cohen's d (Cohen, 1988, p.66). Observation 5 and 6 are analyzed by case studies.

The analysis are set up with python scripts, e.g. the t tests with the function ttest_ind from the library scipy.stats or manual calculation of conhent́s d. The scripts including all results presented in section 5 are available online via a GIT repository with digital object identifier (Röben, 2021).

4. Availability of applied data

This section gives a brief introduction to the applied data. All time series have a resolution of 15 minutes and cover a five-year period from 2015 to 2019. Activated volumes and related costs of FRR (including automatic and manually activated reserves) from the Netherlands, Belgium, and Germany are obtained from TenneT (2020), Elia (2020a) and 50Hertz et al. (2020). The IGCC contribution of each country is provided by 50Hertz et al. (2020). The data include upward and downward values of their power and price components. Power values are given in average power over 15 minutes in MW. Price values are given in €/MWh. Resulting costs, respectively revenues, are calculated for each 15 minutes period in €. Section 5.1 discusses installed capacity of VRE (solar, wind on- and offshore). The values are obtained from ENTSO-E (2020).

Figure 3 shows the mean power consumption μ in GW for comparison. The values are derived from the 15-min average power consumption (calculate mean), obtained from ENTSO-E (2020). Figure 4 visualizes activated balancing power from 50Hertz et al. (2020) and intra-day prices from epexspot (2019).

5. Results

The observations from section 3.2 are analyzed.

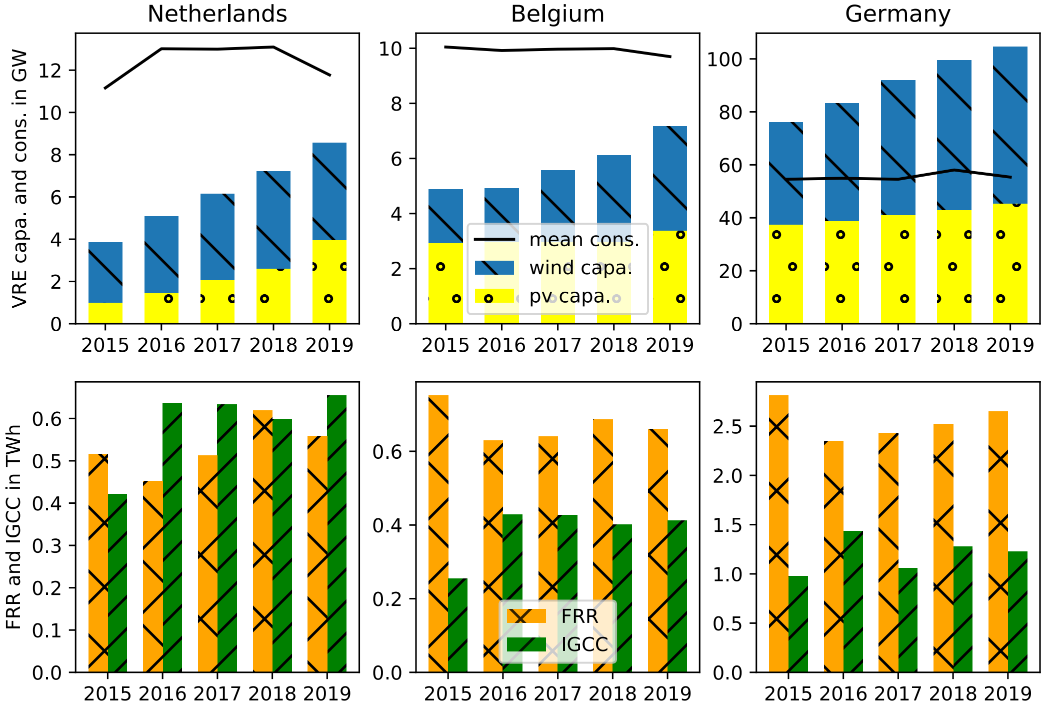

Figure 3: Mean power consumption and installed capacity of VRE from ENTSO-E (2020), Frequency Restoration Reserves (FRR) volumes from TenneT (2020), Elia (2020a) and 50Hertz et al. (2020), International Grid Control Cooperation (IGCC) volumes from 50Hertz et al. (2020).

5.1. Development of VRE and balancing demand

The suggested observation follows the argumentation of Hirth and Ziegenhagen (2015), Ocker and Ehrhart (2017) and Koch and Hirth (2019). Observing the installed capacity of VRE and balancing demand not only in Germany, but also in the Netherlands and Belgium allows to consider, if the "German paradox" is present in other countries.

Figure 3 shows the installed capacity of VRE and mean consumption in GW in the upper row of plots. The balancing demand in TWh in the second row of plots consists of upward and downward FRR activation (including automatic and manually activated reserves) and upward and downward IGCC contribution. These annual net values consist of the absolute upward and downward activation, positive values do not offset negative values.

The capacity of VRE increased, but the activation of FRR did not follow the same trend and remained rather stable. Belgium and Germany activated less FRR in 2019 than in 2015. This is remarkable, because the increase of VRE capacity compared to mean energy consumption from 49% to 74% (Belgium), respectively from 139% to 189% (Germany) is substantial. The Netherlands increased VRE capacity from 49% to 70% compared to mean energy consumption. They activated more FRR, but could decrease related costs by generating revenues from IGCC (see

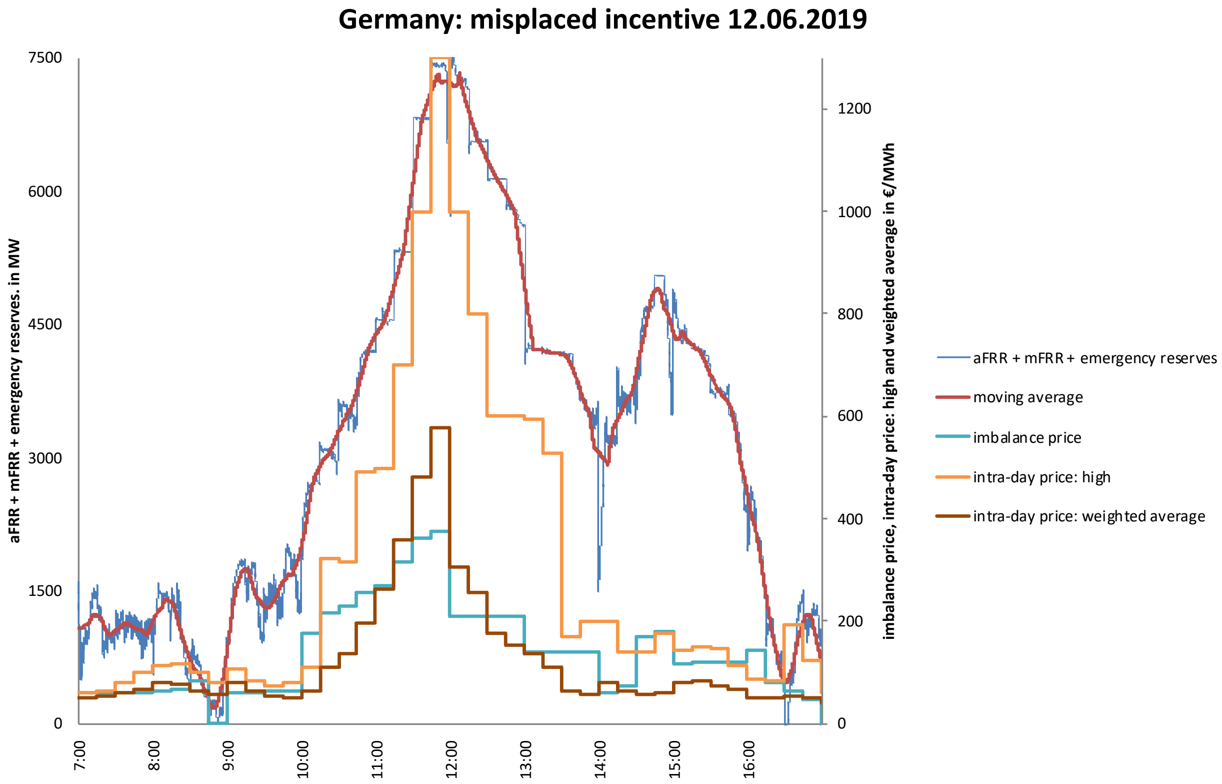

Figure 4: Activated reserves and imbalance price from 50Hertz et al. (2020), and intra-day prices from epexspot (2019) in Germany, 12. of June

section 5.6).

These observations show that increasing capacity of VRE does not lead to higher balancing demand, because negative effects are compensated by market related factors (section 2.1).

5.2. Critical imbalances in Germany in June 2019

Severe situations took place in Germany in June 2019, as described in section 2.2. With regard to the report of 50Hertz et al. (2019), prices from the intra-day market and the imbalance price are compared. The resulting price spread (misplaced incentive) and the ACE are observed.

Data obtained from 50Hertz et al. (2020) show that there were even four days with critical imbalances (06.06., 12.06., 25.06., and 29.06.2019). The activated reserves and misplaced incentives in Germany during the 12.06.2019 are analyzed in this subsection. The day is particularly critical because of activated reserves (FRR and additional emergency reserves) of up to 7.5 GW at noon. The day-ahead auctions led to a moderate price of 51 €/MWh with scheduled power generation of 69.6 GW for the most critical period from 11 am to 12 am (ENTSO-E, 2020).

Figure 4 illustrates the development during the 12th of June 2019 between 7 am and 5 pm with activated reserves, the imbalance price and the intra-day price (high and weighted average). The highest prices at the intra-day market exceeded the imbalance price most of the time. The weighted average price is calculated by considering the price of all trades weighted by the traded energy volume. During the peak of the imbalance event, even the weighted average price exceeded the imbalance price. 50Hertz et al. (2019) show that market parties did "correct" their schedule by reselling energy volumes, even though the day-ahead schedule was accurate. These short sales were the main cause for the critical situation, but market parties made revenues (spread between imbalance price and intra-day price). Also wind forecast errors did occur that day (TenneT, 2019b), but market parties were incentivized to pay the moderate imbalance price rather than correcting their schedule paying a high intra-day price.

The intra-day prices reflect new information on forecast errors of load and weather predictions. While this is the purpose of intra-day markets, the already defined maximum imbalance price then can lead to a misplaced incentive for market parties. The penalty for schedule deviations (which is the imbalance price) can be lower than the price at the intra-day market. If the balancing markets would take place after Gate Closure of the intra-day market, the bids would reflect the latest information. The imbalance price would increase over the intra-day price in situations with energy scarcity.

This chain of arguments supports the approach of introducing intra-day balancing markets close to real-time to avoid misplaced incentives (section 2.2).

5.3. Implications of real-time information in Belgium

As described in section 2.3, Belgium introduced real-time information in 2017 and 2019. Belgium publish their imbalance in real-time since 2017. The publication of the imbalance price was added at the end of August 2019. The information is now published in a 1-minute resolution together with the activated FRR (Elia, 2020b). In addition, the contribution to IGCC (in MW) and costs/revenues for imbalance netting (in €/MWh) is provided to the market parties. The 5 year data from Belgium is separated in 3 datasets according to the different stages of real-time information.

Table 1 shows the mean values of power balancing demand (average power over 15 minutes) and resulting costs (in € per15 minutes) of the 3 datasets. Table 2 shows the results of statistical tests comparing the first vs. second time period and second vs. third time period. The reduction of FRR volumes is significant in both comparisons and Cohen's d implies a very small effect. The costs for FRR increased when imbalance information was available, but decreased under the initial 2015/2016 level in the last three month with price information. Increase and reduction of costs for FRR are significant with a small effect.

The imbalance netting volumes via IGCC increased with a small effect without an significant increase of related costs when real-time imbalance information was first introduced in 2017. In the last three month with price information the imbalance netting volumes and related costs both deceased with a very small effect. Belgium even generated revenues from imbalance netting during these three month, as the negative costs for imbalance netting prove.

Table 1
Mean FRR activation, Imbalance netting, and costs in Belgium, 2015 to 2019 (Elia, 2020b)

Mean values per ISP	01.01.2015 to 31.12.2016	01.01.2017 to 26.08.2019	27.08.2019 to 31.12.2019
$\text{FRR}_{\text{(upward and downward)}}$	78.6 MW	75.8 MW	74.1 MW
Costs for FRR	859.8 €	973.2 €	644.4 €
$\text{Imbalance netting}_{\text{(import and export)}}$	38.9 MW	47.6 MW	44.1 MW
Costs for Imbalance netting	50.5 €	69.6 €	-18.1 €
counter-activation of FRR	68.4%	71.4%	72.7%

Table 2
Analysis: t test and cohen's d of FRR activation, Imbalance netting, and costs in Belgium, 2015 to 2019 (Elia, 2020b)

Comparison of Datasets	2015/16 vs. $2017/18/19_{\text{Jan-Aug}}$		$2017/18/19_{\text{Jan-Aug}}$ vs. $2019_{\text{Aug-Dez}}$	
	t test	Cohen's d	t test	Cohen's d
$\text{FRR}_{\text{(upward and downward)}}$	0.00	very small (0.04)	0.01	very small (0.02)
Costs for FRR	0.00	very small (0.05)	0.00	very small (0.14)
$\text{Imbalance netting}_{\text{(import and export)}}$	0.00	small (0.23)	0.00	very small (0.09)
Costs for Imbalance netting	0.21	-	0.00	very small (0.04)

While FRR demand decreased with both levels of real-time information, the imbalance netting contribution first increased before it decreased again. Related costs, on the other hand, first increased for FRR and than decreased with real-time price information. Costs for imbalance netting first remained at the same level (increase was not significant) and decreased significantly to be revenues with real-time price information.

The applied data covers only three month with real-time price publication, but the applied statistical tests show that activation of FRR is reduced and cost-efficiency can be improved (section 2.3). While the reduction of FRR could already be achieved by publishing information on the imbalance, improved cost-efficiency was only achieved when adding price information.

5.4. Passive balancing in Germany

The claim that market parties in Germany react with passive balancing to the activation of mFRR (Röben and de Haan, 2019) is tested with empirical data. The data is separated into comparable samples with an ACE in the same range (step size of 100 MW). The ACE difference to the next ISP (ΔACE) is under consideration with and without mFRR activation. T-tests of independent samples are conducted (Cohen, 1988, p.19). If the t test indicates a statistical significant difference (p-value < 0.05), the effect size is calculated using cohen's d (Cohen, 1988, p.66).

Table 3 shows the considered data sets with more than 300 ISPs with and without mFRR activation and results of statistical tests. Imbalance ranges which have one of the two datasets with less than 300 ISPs are not considered. The relevant balancing ranges with negative ACE between -900 MW and -1.1 GW and positive ACE between 1.2 GW and

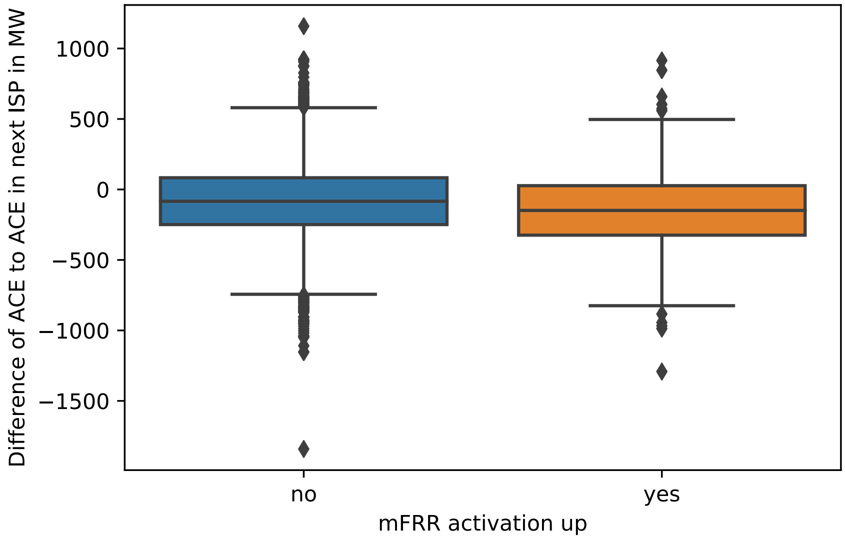

Figure 5: ISP with positive ACE over 0.6 GW and under 0.7 GW. ACE difference to next ISP without vs. with mFRR activation, 2015 to 2019 data from 50Hertz et al. (2020)

1.3 GW have no statistical significant difference in ΔACE to the next ISP. On the other hand, the relevant imbalance ranges with positive ACE between 600 MW and 1.2 GW have a significant difference in ΔACE to the next ISP with very small to small effect size. In these data sets, the mean ΔACE is negative and thus the ACE is reduced. In ISPs with mFRR activation, this trend is (significantly) more favorable and the ACE reduction is higher.

Table 3
Market response to mFRR activation in Germany, 2015 to 2019 (50Hertz et al., 2020)

Imbalance range	ISP count (with/no mFRR)	ΔACE (with/no mFRR)	t-test	Cohen's d
1.3 GW < ACE < 1.2 GW	592 / 302	-175.4 / -166.0 MW	0.70	-
1.2 GW < ACE < 1.1 GW	709 / 602	-179.2 / -137.3 MW	0.01	very small (0.13)
1.1 GW < ACE < 1.0 GW	717 / 1070	155.3 / -124.4 MW	0.04	very small (0.10)
1.0 GW < ACE < 0.9 GW	716 / 1861	-165.7 / -121.5 MW	0.00	very small (0.15)
0.9 GW < ACE < 0.8 GW	665 / 2848	-184.2 / -117.4 MW	0.00	small (0.23)
0.8 GW < ACE < 0.7 GW	495 / 4296	-147.8 / -98.3 MW	0.00	very small (0.17)
0.7 GW < ACE < 0.6 GW	379 / 5919	-157.3 / -83.7 MW	0.00	small (0.28)
-0.9 GW > ACE > -1.0 GW	336 / 746	158.3 / 197.5 MW	0.12	-
-1.0 GW > ACE > -1.1 GW	316 / 478	208.9 / 222.5 MW	0.63	-

Therefore, these statistical tests indicate that the ACE tends to move in a favorable direction in case of positive ACE between 600 MW and 1.2 GW and upward mFRR activation. As an example, Figure 5 shows the imbalance range with positive ACE between 600 MW and 700 MW. The ΔACE to the next ISP without (left) and with mFRR activation (right) illustrate the big variance of ΔACE to the next ISP. The mean ΔACE is negative and thus the ACE is reduced in both datasets, but the mean ACE reduction is higher with mFRR activation. The effect is statistical significant, but small.

The results show that market parties interpreted the activation of mFRR as a real-time signal which leads to passive balancing in Germany (section 2.4).

5.5. Combined imbalance pricing and counter-activation of FRR

The occurrence of FRR activation with a focus on counter-activations in the Netherlands, Belgium and Germany are analyzed. A counter-activation is defined as an ISP with activation of positive and negative FRR, what indicates that the sign of the ACE was reversed. FRR volumes smaller 1 MW are neglected in a second analysis to evaluate the occurrence of small counter-activations.

The FRR activation of each 15 minute ISP of the five year time period is shown in Table 4. The Netherlands faced 71% of ISPs with positive or negative FRR activation and 22% of ISPs with counter-activation of FRR. Belgium faced counter-activation of FRR in 70% and Germany even in 100% of all ISPs. The German number is odd and indicates that the data includes measured and not activated FRR volumes, since there are ISPs with only positive ACE (e.g. June event in Figure 4). The numbers change when neglecting small amounts of FRR activation of 1 MW. The occurrence of FRR counter-activation in Germany decreases to 91% of all ISPs, but the overall picture remains the same. Only the Netherlands faced ISPs without any FRR activation (7%), what can be traced back to ISPs where the ACE was completely netted via IGCC. In addition, low share of ISPs with FRR counter-activation indicates that combined imbalance pricing works better with passive balancing. In Belgium, the occurrence of FRR counter-activation did increase slightly with the introduction of real-time information, as shown in the last row in Table 1.

Table 4
ISPs - relative share no FRR, FRR activation and FRR counter-activation, 2015 to 2019 balancing volumes from TenneT (2020), Elia (2020a) and 50Hertz et al. (2020)

Country	Netherlands	Belgium	Germany
ISPs no FRR	7%	0%	0%
ISPs FRR activation up or down	71%	30%	0%
ISPs FRR counter-activation	22%	70%	100%
ISPs no FRR over 1 MW	12%	0%	0%
ISPs FRR activation up or down over 1 MW	75%	49%	9%
ISPs FRR counter-activation over 1 MW	13%	51%	91%

These observations show that the Dutch approach of combined imbalance pricing is a correct incentive for market parties and prevents reversing the sign of the ACE and FRR counter-activation (section 2.5).

5.6. Costs and revenues from imbalance netting

The imbalance netting contribution and resulting costs, respectively revenues, are observed in the Netherlands, Belgium and Germany. Figure 6 illustrates costs and revenues in million Euro (M€). Due to revenues from IGCC, the total costs for balancing (FRR and IGCC) can be smaller than the costs for FRR. The Netherlands generated revenues

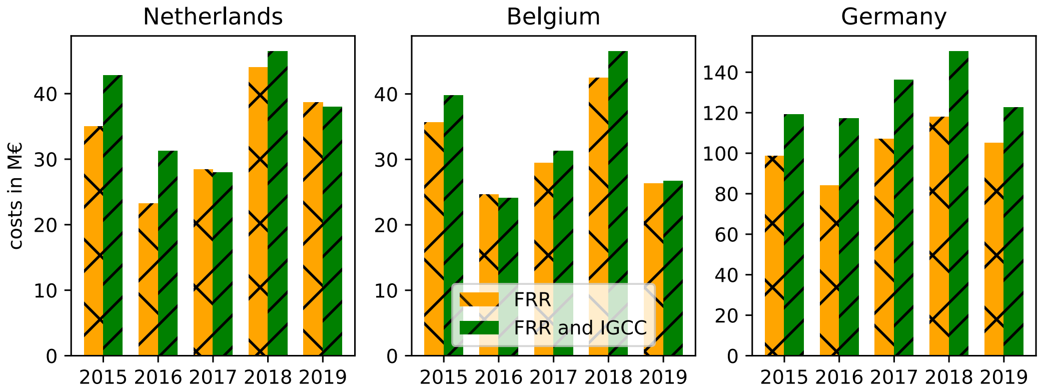

Figure 6: Costs for the balancing process, based on Frequency Restoration Reserves (FRR) volumes and prices: from TenneT (2020), Elia (2020a) and 50Hertz et al. (2020); International Grid Control Cooperation (IGCC) volumes and prices: from 50Hertz et al. (2020).

from IGCC in 2017 and 2019. Belgium generated revenues from IGCC in 2016. In addition, Belgium generated revenues in the last three month of 2019 after the introduction of real-time price information, as discussed in section 5.3 and shown in Table 1.

Passive balancing is an additional market opportunity. The signals provided in the Netherlands and Belgium include IGCC information and thus costs for FRR activation in other control blocks such as Germany. While German market parties are obligated to stick to their schedule, Dutch and Belgium market parties might generate revenues by contributing to power balancing in Germany via IGCC. This observation show that passive balancing in combination with imbalance netting gives Dutch and Belgium market parties an advantage over German market parties (section 2.6).

Other than discussing costs and revenues from IGCC, it is difficult to compare balancing performance of different countries. Due to differences in consumption and generation characteristics, any further comparison requires a method to normalize the data.

6. Discussion

This section discusses the results and thus evaluates the balancing strategies of the considered countries (the Netherlands, Belgium, and Germany) with a focus on passive balancing. The results support all six Smart Balancing observations, introduced in section 2. Policy implications are developed and an approach for the future European energy market is outlined.

6.1. Current market rules

Installation of VRE capacity does not go along with increasing balancing demand, as shown in section 5.1. Market related improvements of intra-day portfolio management in 15 minute resolution and imbalance netting via IGCC must

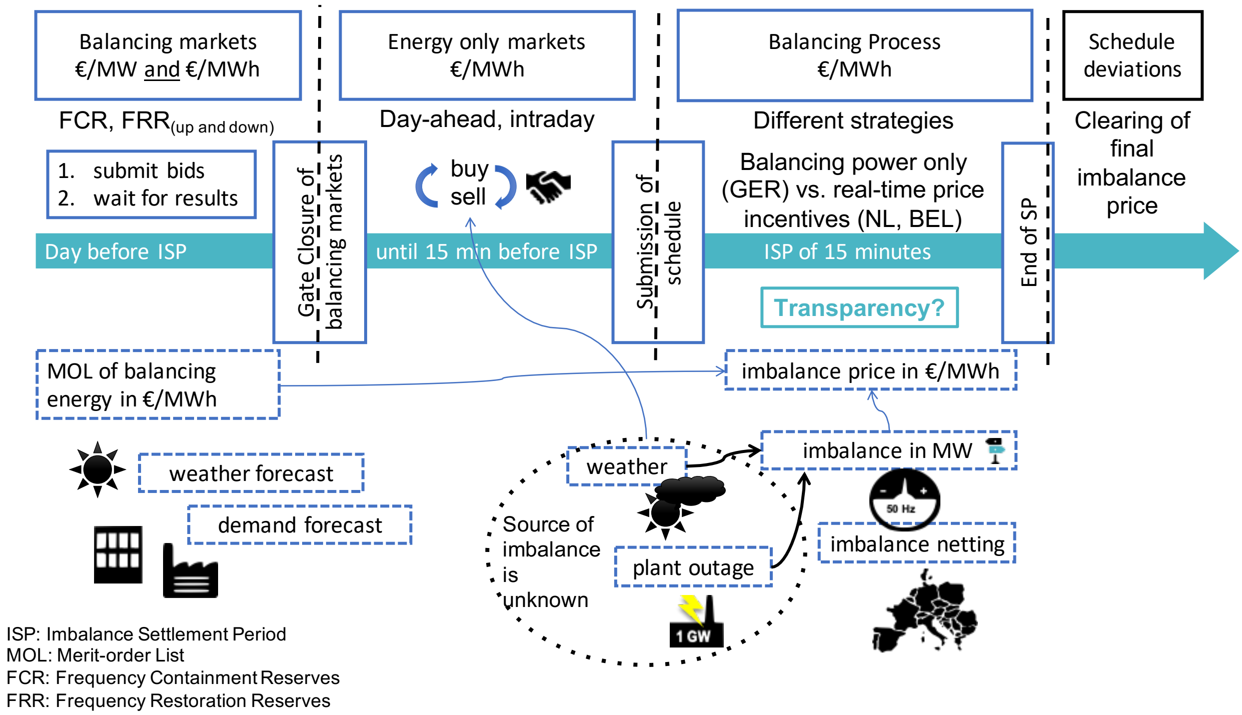

Figure 7: Current market rules in the Netherlands (NL), Belgium (BEL), and Germany (GER)

have compensated any negative effect. Figure7 illustrates the current market rules on a timeline, which facilitated this remarkable development.

Even though the current market design allowed to integrate high shares of VRE, misplaced incentives did occur in June 2019. The high spread between the intra-day market price and imbalance price made system threatening behavior profitable. Market parties were incentivized to sell energy without the capacity to deliver (short sales of energy).

These events require rethinking the timing schemes of current market rules. Incentivized short sales of energy must be avoided. The correction of forecast errors at intra-day markets must be rewarded. The European Commission mandates the answer in the EBGL, Article 24.2: "Balancing energy gate closure times shall: (a) be as close as possible to real-time; (b) not be before the intraday cross-zonal gate closure time; (c) ensure sufficient time for the necessary balancing process" (Commission, 2017, p. 312/28). By adjusting the timing schemes accordingly, reliable flexibility would be available in short term intra-day markets. Wrong scheduling could still lead to high prices at the intra-day market, but the balancing energy bids at balancing markets are submitted afterwards. The imbalance price would, therefore, increase over the market price in case of a (short) system imbalance because only expansive reserves remain for the balancing market. Short sales at the intra-day market are not incentivized.

6.2. Smart Balancing of electrical power

The introduction of real-time information in Belgium in 2017 and end of August 2019 shows that no unexpected market (over-) reactions took place. Section 5.3 shows how power balancing demand decreased and the cost-efficiency was improved. The Belgian case suggests that the practice of publishing not only the imbalance but also the imbalance price is the more efficient approach for passive balancing.

The German balancing market design does not include transparent incentives for market parties other than keeping to their submitted schedule. The German strategy is to minimize imbalances by promoting good scheduling (accurate load and generation prediction). Information on imbalance volumes and prices is only published ex-post. But the German strategy is undermined and the single imbalance price leads to temporary market response, as discussed in section 2.4 and confirmed by the analysis in section 5.4.

The analysis of FRR counter-activation in section 5.5 imply that the Dutch strategy of combined imbalance pricing can avoid reversing the sign of the ACE. Only the Netherlands have a low occurrence of FRR counter-activation. FRR counter-activation occurred in only 22% of all ISPs, compared to 70% in Belgium and 100% in Germany, which than leads to dual pricing and market parties are not rewarded for their balancing contribution. This Dutch approach of combined imbalance pricing limits passive balancing to the necessary.

Passive balancing in the Netherlands and Belgium is incentivized by real-time information. Section 5.6 shows the low costs, respectively revenues, for imbalance netting contribution compared to moderate costs in Germany. Transparency about the imbalance netting contribution in combination with the imbalance price leads to cross-zonal passive balancing. Therefore, passive balancing in the Netherlands and Belgium helps to balance neighboring control blocks (such as Germany) and improve the cost-efficiency on both sides.

6.3. Previous research on passive balancing

The results imply that transparency improves the cost-efficiency of power balancing. The introduction of transparency in Germany could, therefore, improve power balancing. Findings in previous research came to similar results.

- (Hirth and Ziegenhagen, 2015, p.1048) state: "Fostering passive balancing could be an alternative (indeed, a very good substitute) to the introduction of energy- only balancing markets."
- (Brijs et al., 2017, p.49) conclude: "as passive balancing can serve a valuable social purpose and improve the valorization of flexibility, incentivizing design changes should be considered for the French and German balancing markets."

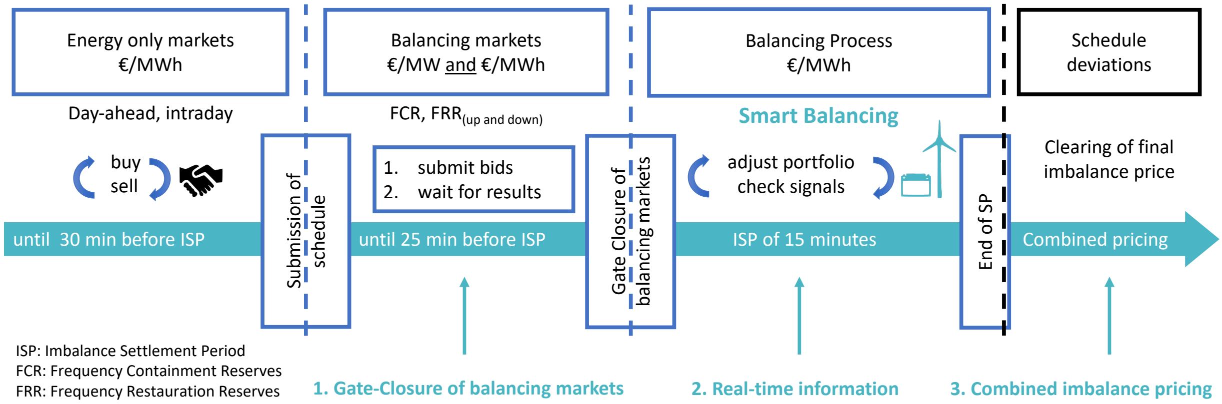

Figure 8: Three market changes for Smart Balancing in future European markets (Proposal)

6.4. Future European Market

The results lead to policy implications. First, intra-day balancing markets should take place close to real-time. The timing scheme shall ensure that the FRR and resulting imbalance price can exceeds the "energy-only" market price in case of high ACE. Market parties will rather close high imbalance positions at the "energy-only" market, than paying an even higher imbalance price. Short sales do not lead to profit and the orders will therefore be executed.

Second, public real-time information about FRR activation, costs, and imbalance netting via IGCC should be introduced. Third, the Dutch balancing strategy is the best fit for the proposed definition of Smart Balancing (section 3.1): The approach of combined imbalance pricing should be adopted.

Figure 8 illustrates the future European market after the proposed changes. For the first implementation, an intraday cross-zonal gate closure time of 30 minutes and bids at balancing markets until 25 minutes before the ISP is recommended. This should ensure sufficient time for the balancing process and secondary measures to cope with grid capacity issues. During the ISP in real-time, Smart Balancing is applied and the demand for FRR is reduced.

6.5. Limitations and Future Research

The presented observational analysis approaches and statistical tests do not take into account two aspects of electrical power. Potential limitations of grid capacity and interrelations with the system frequency are not considered.

The grid capacity is a local physical constraint. The maximum power flow through a transmission line must not be exceeded. If the maximum is reached, either curtailment can reduce the local power generation or (temporary) market splitting increases power consumption. Both measures can relieve the grid until the required capacity expansion is completed (Håberg et al., 2019).

The frequency is the physical quantity which defines a synchronous zone. In addition to the frequency itself, the rate of change of frequency (ROCOF) must be limited. Frequency stability is therefore obtained by the combination of FCR and system inertia within predefined boundaries (Dreidy et al., 2017).

Potential interrelations of Smart Balancing and these two grid issues might be of interest for future research. Even though the practicability on a national level could be shown, further elaboration on how Smart Balancing can be organized in harmonized European markets with cross-zonal activation of FRR (via optimization function) is required. Modeling different market design parameters with a focus on worst-case scenarios and balancing performance would help to identify interrelations with other balancing mechanisms.

An ISP of 15 minutes is the common energy product resolution in Europe, harmonized by Article 53 of the EBGL (Commission, 2017, p. 312/45). In the future, changing to a shorter ISP of e.g. 10 or 5 minutes could be beneficial as it reduces deterministic imbalances. A shorter ISP may limit this energy vs. power conflict. On the other hand, market parties have less time to be balanced in their portfolio, requiring more quality and flexibility. Liquidity might be kept within the portfolio. The optimal ISP length should be part of future research.

From the perspective of market parties, further research on business cases and marketing strategies for flexible assets is required. Asset owners face changing legislation and growing opportunities, but also more competition at the future European balancing markets.

7. Conclusion and Policy Implications

This article discussed current market rules and developed a Smart Balancing strategy for efficient power balancing. Current concepts of passive balancing are controversial, because market rules are not consistent with balancing requirements.

The analysis of misplaced incentives in June 2019 in Germany lead to policy implications regarding timing schemes. Balancing markets take place day-ahead and the imbalance price can, therefore, not reflect forecast errors (weather or demand). The intra-day market price can increased over the imbalance price. In that case, the correction of forecast errors at the intra-day market is more expensive than paying the imbalance price. Selling energy without delivery (short sales) lead to revenues. The following proposal goes along with Article 24.2 of the EBGL (Commission, 2017, p. 312/28) and would avoid such incentives.

- Netherlands, Belgium, and Germany: Timing of balancing markets (day-ahead) and energy-only markets (intra-day) can lead to misplaced incentives (e.g. during the events in June 2019).

- Proposal: Gate-closure-Time of balancing markets (intra-day) after energy-only markets and as close as possible to the start of an ISP.

After solving this timing related problem, the Dutch balancing strategy offers the best fit for the proposed definition of Smart Balancing: Combined imbalance pricing and imbalance netting via IGCC in combination with public real-time information.

Market parties generate revenues with schedule deviations which reduce the demand for power balancing. Combined imbalance pricing is able to limit reversing the sign of the ACE by allocating separate prices to market parties with positive and negative schedule deviations, if necessary. Remarkable is the combination of passive balancing with imbalance netting via IGCC, which creates an additional business case. Market parties in the Netherlands and Belgium can make profit by supporting power balancing in other countries, e.g. in Germany.

Germany, on the other hand, has inconsistent market rules: The balancing strategy does not allow schedule deviations and real-time information is missing, but passive balancing is rewarded by a single imbalance price. Market parties respond to uncertain information, like the activation of expensive mFRR. There is no option to limit or control their behavior in the current German system. Combined imbalance pricing was identified as useful tool. Belgium and Germany could reduce FRR counter-activation by adopting this approach.

The power balancing strategies in Belgium and Germany should, therefore, converge towards the strategy in the Netherlands. The following proposals are recommended for national policymakers to allow passive balancing which meets the Smart Balancing definition.

- Germany: Single imbalance pricing incentivized passive balancing, which is not allowed (paradox). Lacking transparency and incomplete information lead to unpredictable behavior of market parties.
- Belgium: Single imbalance pricing incentivized passive balancing, but this often leads to reversing the sign of the ACE.
- Proposal: Real-time information for market parties and combined imbalance pricing to limit reversing the sign of the ACE.

According to the presented findings, Smart Balancing would reduce the balancing demand in the European power system. Together with accurate portfolio management and imbalance netting this would further support the cost-efficient shift towards renewable energy sources without loss of reliability. If implemented correctly, it could serve as role model for other regions.

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A. Appendix

A.1. List of abbreviations

ACE - Area Control Error

aFRR - FRR with automatic activation

BEL - Belgium

BMWi - German Federal Ministry for Economic Affairs and Energy

BRP - Balance Responsible Party

D-1 - Day-ahead

EBGL - Electricity Balancing Guideline

ENTSO-E - European Network of Transmission System Operators for Electricity

f_{CE} - Frequency in Continental Europe

FCR - Frequency Containment Reserves

FRR - Frequency Restoration Reserves

GER - Germany

IGCC - International Grid Control Cooperation

ISP - Imbalance Settlement Period

M-15 - 15 minutes before real-time

mFRR - FRR with manual activation

NEW 4.0 - North German Energy Transition 4.0 (research project)

NL - Netherlands

$P_{measured}$ - measured power flows into or out of a control block

$P_{scheduled}$ - scheduled power flows into or out of a control block

ROCOF - Rate of change of frequency

SI - System Imbalance

TSO - Transmission System Operator

VRE - Volatile Renewable Energy sources (wind and solar)

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Market Response for Real-Time Energy Balancing: Simulation using Field Test Data

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***Abstract*—Maintaining the balance between load and generation is crucial to power system stability. Automatic Frequency Restoration Reserves (aFRR) are activated to cope with any imbalance occurring in each Control Area (CA). Other than that, European countries pursue different balancing strategies. Incentivizing market response for real-time energy balancing is a promising balancing strategy, which is applied in the Netherlands and Belgium and is referred to as Passive Balancing (PB). Advantages are reduced demand and costs for aFRR and additional business cases for Balance Responsible Parties (BRPs). The system imbalance and the imbalance price are published close to real-time, enabling BRPs to support the balancing process by optimizing their consumed and generated power. This study addresses the implementation of PB in Germany by simulating the contribution of four real BRPs using measured field test data and object oriented programming.**

***Index Terms*—Load management, Power Market, Market Opportunities, Power System Simulation**

I. Introduction

The balance between load and generation in a power system is to be kept at any time. The purpose of automatic Frequency Restoration Reserves (aFRR) is the elimination of unscheduled power flows between Control Areas (CAs) in the synchronous grid of Continental Europe [1]. The activation of aFRR is the responsibility of each CA, which are to fully compensate their imbalance with aFRR within 15 minutes at the latest [2]. Each CA is divided up into Balance Responsible Parties (BRPs). Each BRP trades the amount of energy they plan to generate and consume within each Imbalance Settlement Period (ISP) beforehand at the day-ahead and intraday markets. By that, a schedule is defined for the BRP and the respective ISP. During grid operation, certain schedule deviations occur due to e.g. load noise or forecast errors. The sum of schedule deviations of all BRPs of a CA defines the Area Control Error (ACE), i.e. the total imbalance of the CA and which is to be compensated by aFRR.

The CA of Germany coordinates the activation of balancing power of certain aFRR providers, which are paid for their service following the pay-as-bid principle [3]. The costs for aFRR are allocated to the BRPs according to their respective schedule deviation [4]. Depending on the arithmetic sign of the deviation and the aFRR costs, this can imply costs or income for a BRP, indicating, if their deviation worked to the advantage of the total ACE or not. In principle, BRPs have a financial incentive to deviate from their schedule, as long as it implies a reduction of the ACE. In real-time operation, a BRP generally has no means of predicting, if their schedule deviation will lead to costs or income, since the publication of aFRR costs takes place after the end of an ISP.

The idea of Passive Balancing (PB) is to provide BRPs with certain information during an ISP enabling them to estimate the financial consequences of their current schedule deviation. By that, each BRP can actively decide to resolve, to keep, or even cause a deviation according to the implied financial incentive. This effectively enables BRPs to reduce the aFRR demand and costs for the CA while their own imbalance costs are optimized [5]. Studies show that certain BRPs in Germany already actively manipulate their schedule deviations to generate profit [6], although they are legally prohibited to do so [7]. On the one hand, this implies a non-transparent and unequal market for BRPs. On the other hand, the situation can lead to significant disincentives for BRPs and escalating imbalances and aFRR costs due to non-transparency [6]. In addition, the pay-as-bid pricing in balancing energy markets has been discussed controversially [8]. It has been shown to favor a certain bidding behaviour that results in escalating prices and collusion in the German CA [3]. The concept of PB has already been implemented into the energy markets of Belgium and the Netherlands. The transparent real-time markets feature minimized use of aFRR energy as well as low and steady aFRR costs [9].

This study addresses the potential implementation of PB in the German CA. In the context of the research project *Norddeutsche Energiewende 4.0* (NEW 4.0) a field test was conducted in November 2019, testing a number of progressive ancillary services in grid operation. Four BRPs, that participate in the project, indicated their interest in providing PB during the field test. Due to technical limitations, no real-time information could be provided as a decision making

This study was conducted within the project NEW 4.0 (Northern German Energy Transition 4.0) which is partly funded by the German Federal Ministry for Economic Affairs and Energy (BMWI). *(sponsors)*

basis for the BRPs. Their real-time market response is simulated in retrospect and presented in this study. The impact of the four BRPs on the total aFRR demand and costs of the German CA are simulated, while showing the financial consequences for each BRP, if they provided PB during the field test.

An introduction to the basic guidelines for aFRR and their cost calculation method for the German energy market are described in sections II-A and II-B, whereupon the simulation setup is presented in section II-C. An initial simulation to verify the model is described in section III. The actual implementation of PB into the model is shown in section IV. The simulation results are presented in section V, before section VI discusses the results and possible applications of PB.

II. Method and Modelling

The modelling and simulation approach is described in this section. The principles of aFRR, which the model is based on are outlined in section II-A, followed by the specific aFRR cost calculation procedure of the German CA in II-B. The object-oriented modelling approach then is described in section II-C.

A. Secondary Controller in a Control Area

The ACE of a CA is the sum of all schedule deviations of its BRPs and hence equals the sum of all unscheduled load flows across the borders of the CA [2]. In a CA with n BRPs the ACE thereby is defined as

$$G = \sum_{i=1}^{n} P_{sc,i} - \sum_{i=1}^{n} P_{gen,i} - \sum_{i=1}^{n} P_{load,i} + K_r \Delta f, \tag{1}$$

with the scheduled, generated, and consumed active power of the i-th BRP $P_{sc,i}$, $P_{gen,i}$ and $P_{load,i}$, the frequency deviation Δf, and the frequency characteristic K_r of the CA [2]. The ACE signal is processed close to real-time and is the input of the Secondary Controller (SC) of the CA. The SC is a Proportional Integral (PI) controller, in which the correction variable

$$\Delta P_d = \beta G - \frac{1}{T_r} \int G \mathrm{d}t, \tag{2}$$

is the output of the SC, while the parameters β and T_r are the proportional gain and the integration time factor of the SC, respectively [2]. The signal ΔP_d is used to trigger power plants which activate the required aFRR power within the CA. In order to minimize aFRR costs, CAs use two separate Merit Order Lists (MOLs) for positive and negative balancing power, respectively [10].

B. Control Area of Germany

The German power system is subdivided in four CAs. Since 2010, the four CAs have been coordinating the activation of aFRR, effectively forming a single CA in terms of aFRR [11]. The reimbursement of aFRR uses pay-as-bid pricing, meaning that for each ISP of 15 minutes, each aFRR provider is reimbursed according to the amount of balancing energy they provided and the exact price claimed in the MOL. Summing up the amounts of aFRR energy and costs of m providers, total amounts of positive and negative aFRR energy and costs can be assigned to each ISP. The imbalance price (*Ausgleichsenergiepreis*–AEP) per ISP is calculated using (3):

$$AEP = \frac{\sum_{j=1}^{m} C_j}{\sum_{j=1}^{m} E_{pos,j} - \sum_{j=1}^{m} E_{neg,j}}, \tag{3}$$

in which C_j are the costs of provider j, and $E_{pos,j}$ and $E_{neg,j}$ are the amounts of positive and negative balancing energy, provider j activated [4]. Due to a singularity in (3) for equal total amounts of positive and negative energy, the AEP escalates in respective cases. For this reason, the AEP is capped by the highest price of a single aFRR provider active in the ISP. Beyond that, the AEP follows four additional steps, each applicable in certain situations, but which are not applied in the simulations of this study. In general, the AEP can be positive or negative at the end of an ISP. It is multiplied by the schedule deviations of each BRP, resulting in costs or income for the BRP, depending on the arithmetic sign of both the AEP and their schedule deviation.

C. Simulation Environment

Balancing market simulation software is developed in Python and used in this study. The software is set-up using object-oriented programming. Classes for all relevant grid structures including the synchronous zone, CAs, and BRPs are defined to model the hierarchy of these structures within the synchronous zone. A grid model is composed of objects for BRPs that are subordinated to objects modelling the CAs, which in turn are subordinates to an object modelling the synchronous zone. Following this approach, the hierarchy of objects reflects the hierarchy of the actual power system. A schematic illustrating the data and signal flow of the simulation environment and the interaction of the CA and BRP classes is shown in figure 1.

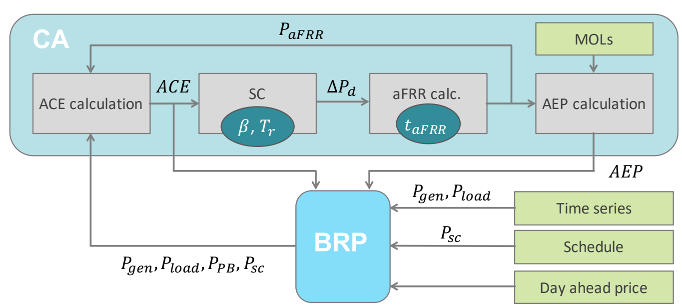

Fig. 1. Schematic data and signal flow of the simulation environment

Time series for the actual and scheduled power generation and consumption of each BRP are to be set-up to serve as input data for the simulation and the basis for the calculation of schedule deviations and activation of aFRR. The ACE is defined in the CA class and is calculated as the sum of schedule deviations of all BRPs, that are subordinated to the CA according to (1). In addition, the CA class is equipped with a discrete PI controller to model the SC and which can be parametrised according to (2). Using a first-in-first-out queue, the output signal of the SC is delayed by a parametrisable time constant, to model the response time t_{aFRR}, aFRR providers take to actually activate the balancing power P_{aFRR} according to the requested power ΔP_d. Further, the CA class contains MOLs and methods calculating the aFRR costs as described in section (II-B). The principles of aFRR activation and cost calculation are intrinsic to the grid model due to the hierarchy of objects.

The PB mechanisms are implemented in the BRP class. First, the currently available potentials to provide positive and negative PB power are calculated continuously according to the current power consumption P_{load} and power generation P_{gen} and their specific upper and lower power limits. Each BRP object is provided with the ACE and AEP signals in real-time and the day-ahead price for each ISP. Using this information, BRPs can predict the financial outcome of their schedule deviation. Specific decision making rules for the provision of PB are implemented for each BRP object, which reacts by providing Passive Balancing power P_{PB}, according to the current potentials and decision making variables. The activated PB power of a BRP object implies an alteration of their schedule deviation. As a result, the schedule deviation of the CA is altered, affecting the activation of aFRR.

III. Model Verification

Before simulating the PB provision of the participating BRPs, a model verification is presented in this section. To verify the model and to create comparison data for the following simulation, the field test is simulated without PB. The field test conducted in the NEW 4.0 project started on November 18th 2019 at 00:00 and ended November 24th at 23:59. The aim of the model verification is to simulate aFRR provision and costs during this week and to compare the results with historic data. For that purpose, only one BRP object without potential PB provision is implemented in the CA of Germany. The historic ACE [12] of the field test week is implemented as the power generation P_{gen} of the BRP object, while its schedule is set to zero. By that, the time series represent the ACE of the CA in the model. The SC parameters β and T_r are set according to grid code requirements [13]. The response time t_{aFRR} is set to the minimum requirement of $30\,\mathrm{s}$ for aFRR [2]. Furthermore, the historic MOLs of the field test week are provided [14] and updated every 4 hours for a realistic calculation of the AEP. Table I shows the correlation factors between simulated aFRR power and aFRR costs with historic time series [15]. The historic and simulated AEP are shown for an exemplary day of the simulation in figure 2.

TABLE I
Correlation between simulated and historic time series

aFRR direction	aFRR power	aFRR costs
Positive	0.987	0.982
Negative	0.993	0.926

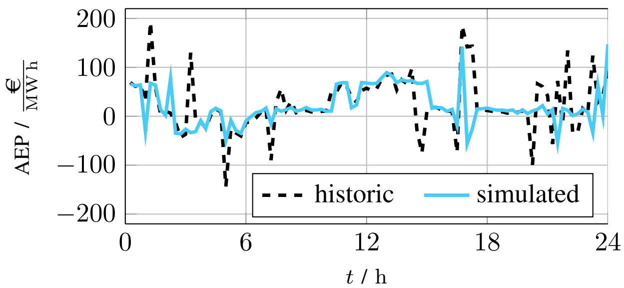

Fig. 2. Historic and simulated AEP for an exemplary day

The simulated and historic aFRR time series have a strong correlation. the AEP calculation in the model is less accurate, as a correlation factor of 0.525 indicates. Possible reasons are the simplified calculation method for the AEP, as described in section II-B and the fact that imbalance netting mechanisms are neglected in the simulation. In general, the historic data shows a more fluctuating AEP and higher extrema. The average positive historic AEP equals $59.42\,€/\mathrm{MWh}$ for the field test, while the average negative AEP is $-40.05\,€/\mathrm{MWh}$. The average simulated values amount to $52.29\,€/\mathrm{MWh}$ and $-32.89\,€/\mathrm{MWh}$. Further, it can be noted that occasionally the simulated AEP has the opposite sign of the historic AEP, which is related to the singularity in (3). Nevertheless, the accuracy of the model is considered sufficient to evaluate market response for real-time energy balancing with the field test simulation.

IV. Field Test Simulation

Four BRPs participating the NEW 4.0 project provided data enabling the implementation of their PB potentials and decision making processes into BRP objects. The BRP models are added to the grid model, as described in section III, to simulate their PB provision during the field test week. The provided data and deducted implementation of the BRPs is described in section IV-A. A description of the field test simulation, that was executed is given in section IV-B.

A. Implementation of Field Test Participants

The provided data contains the consumed and generated power of the four BRPs in high time resolution as well as the schedules for all ISPs of the field test week. Further, certain potentials for adjusting their loads and generators as well as possible ramp rates were communicated.

Three of the BRPs operate large-scale industrial loads in production, which can increase or decrease their consumed power to a certain degree without disturbing the production process. The BRPs have potentials to provide positive or negative PB power accordingly. The fourth BRP operates several wind farms with a combined rated power above $2500\,\mathrm{MW}$. The turbines can decrease their power output down to $10\,\%$ of their power rating and provide negative PB power accordingly. Both the loads and wind turbines can change their operating point quickly resulting in fast activation of the PB potentials.

TABLE II
COMBINED PB POTENTIALS FOR THE FIELD TEST

PB direction	Max. PB power	Max. ramp rate
Positive	80.0 MW	80.1 MW s^{-1}
Negative	−2517.6 MW	−249.4 MW s^{-1}

The combined PB potentials and ramp rates of the four BRPs are shown in table II.

Regarding the decision making process, the four BRPs gave detailed information. For the actual provision of PB they would have to consider a large number of variables including commodity prices and their order situation. For this reason, certain assumptions and simplifications were made for the simulation, presumably resulting in a certain tendency to overestimate the current PB potentials. The implemented decision making is limited to the real-time ACE and AEP signals as well as the day ahead price. Accordingly, some BRP objects simply activate PB power, as soon as the AEP exceeds certain thresholds. Others consider both the AEP and the day ahead price to estimate the financial outcome of PB provision. However, all BRPs limit their total PB power to the magnitude of the ACE at any time, as they could otherwise solely overcompensate the total imbalance of the CA, which would be an unreasonable behaviour under any circumstance.

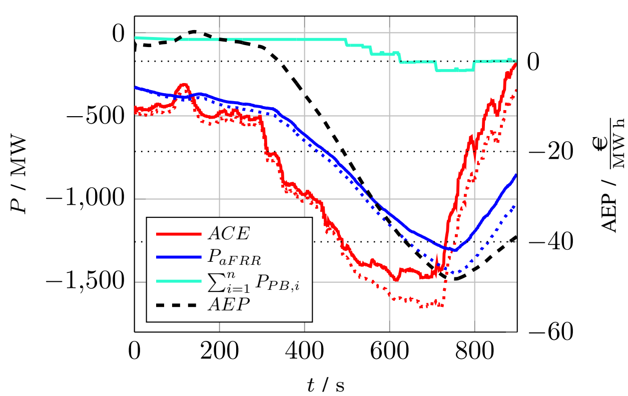

Fig. 3. Activation of PB over one ISP

B. Execution of Field Test Simulation

The same week described in section III is simulated again using the same simulation input for the CA including the historical data of the ACE and parametrisation of the SC. For this simulation, five additional BRP objects are added to the grid model, four of which represent the BRPs participating in the field test. Time series for the scheduled, consumed and generated power are added to these BRP objects to simulate their schedule deviations, as they actually occurred during the field test. These additional schedule deviations imply a certain alternation of the total power balance and ACE of the CA in the simulation. In order to compensate this effect, a fictional fifth BRP is added, that precisely mirrors the combined load, generation, and schedules of the other four BRPs. Accordingly, the sum of consumed power of the four BRPs at any given time step appears as the generated power of the fictional BRP, while the sum of scheduled generated power appears as a schedule for consumed power in the fifth BRP and so forth. This way, the actual schedule deviations of the four BRPs during the field test do not alter the total power balance and schedule deviation of the CA as simulated in the verification simulation, which can therefore be used as a point of reference. The time series for scheduled, consumed and generated power of the four participating BRPs are also used to dynamically calculate their PB potentials for each time step. According to the PB potentials and the price signals, the four BRPs provide PB, as described in section II-C. By activating PB power and thereby modifying their schedule deviations, the four BRPs alter the total deviation of the CA and contribute to power balancing.

V. SIMULATION RESULTS

In the simulation, the real-time AEP signal fluctuates between a maximum value of 620.51 €/MWh and a minimum value of −614.10 €/MWh, inducing the activation of certain amounts of PB in all four BRPs. By that, the BRPs contribute to the power balancing of the CA significantly. As outlined in section IV-A, the simulated PB potentials are expected to be greater than the potentials in reality. On the other hand, the simulated AEP shows a steadier behaviour as the historic data, as shown in section III. The result of the latter being a more moderate use of mentioned PB potentials. To illustrate the mechanics at hand, figure 3 shows the simulation results for the ACE, the balancing power of aFRR and PB, and the AEP signal for an exemplary ISP. The dotted graphs show the respective results of the model verification simulation, in which no PB was applied.

During the initial 300 s of the ISP, the simulated AEP signal fluctuates around approximately 18 €/MWh, inducing an incentive for PB provision for certain BRPs, which respond by activating around −38 MW of negative balancing power. This leads to a reduction of the absolute schedule deviation of the CA, as the ACE graphs indicate, and which results in a reduction of aFRR power. Around $t = 500$ s the AEP signal drops below −20 €/MWh, which induces further activation of negative PB power, until a maximum of −227.87 MW is provided at $t = 711$ s. Over the whole ISP, the four BRPs provide −23.66 MW h of balancing energy, by which the activated negative aFRR energy is reduced by 15.78 MW h. The implied imbalance costs drop by 27.2 % to 7381.74 €.

Over the whole week, both positive and negative aFRR energy and costs are reduced. A summary and comparison of the simulation results is given in table III. By applying PB, the total activated positive aFRR energy is reduced by 287 MW h. Due to the large potentials for negative PB, the amount of negative aFRR is reduced by 883 MW h. The total aFRR costs of the week are reduced by 57 354 € for the German CA. On the other hand, the four BRPs can optimize their imbalance costs significantly. Using the simulated AEP for each ISP the imbalance costs of the four BRPs amount to 54 880 € for the week. Calculating their imbalance costs using historic AEP

TABLE III
SIMULATION RESULTS COMPARED TO THE REFERENCE SIMULATION

	without PB	with PB	Rel. change
Pos. aFRR energy	16.2 GW h	15.9 GW h	−1.77 %
Neg. aFRR energy	−19.4 GW h	−18.5 GW h	−4.56 %
Pos. aFRR costs	1.342 M€	1.299 M€	−3.19 %
Neg. aFRR costs	−0.217 M€	−0.231 M€	−6.74 %
Pos. PB power	–	387.7 MW h	–
Neg. PB power	–	−983.7 MW h	–
total AEP costs	54 880 €	9968 €	−81.84 %

data and the simulated schedule deviations results in 73 951 €. By manipulating their schedule deviations, the BRPs can lower the simulated imbalance costs by 81.84 %. Three of the BRPs can even turn their imbalance costs into income.

However, looking at certain ISPs, in which the AEP signal particularly fluctuates, shows that the PB mechanisms, as they are applied, can lead to decisions, that result in higher imbalance costs for single BRPs at the end of the ISP. The response of a single BRP during an exemplary ISP is shown in figure 4.

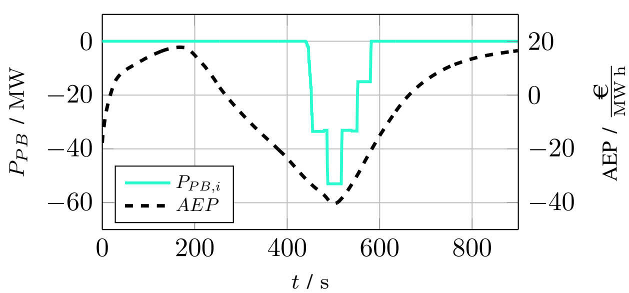

Fig. 4. Activation of PB of a single BRP

During this ISP, the AEP signal fluctuates between a maximum of 17.78 €/MWh and a minimum value of −40.31 €/MWh, crossing the zero line three times. From $t = 441$ s to $t = 582$ s the signal induces the activation of negative PB power for the BRP, which provides a total of −1.228 MW h of balancing energy until the end of the ISP. The AEP converges towards the final value of 16.51 €/MWh at the end of the ISP. Thereby, the additional schedule deviation of −1.228 MW h leads to additional imbalance costs of 20.28 € for the BRP for this particular ISP. Analogous ISPs, in which a fluctuating AEP signal leads to adverse provision of PB for single BRPs, can be observed frequently in the field test simulation results. Overall, ISPs, in which BRPs can in fact optimize their imbalance costs, prevail. Hence, providing PB leads to lower imbalance costs for each of the four participating BRP over the course of the week.

VI. CONCLUSION AND OUTLOOK

This study addresses the implementation of PB in the German CA by simulating the real-time market response of four BRPs during a field test. Using detailed information and data provided by the BRPs, their potential provision of balancing power during the field test was simulated. The results indicate, that both the German CA and the BRPs could benefit from the implementation of PB in Germany. The amounts of positive and negative aFRR energy as well the aFRR costs could be lowered, while new business cases for the BRPs arise, enabling them to purposefully use their schedule deviations to minimize imbalance costs or even actively generate income.

However, the simple decision making rules based on the continuously calculated AEP signal can lead to adverse behaviour of BRPs and to an increase of their imbalance costs for certain ISPs. As the simulation results show, the risk of adverse behaviour is particularly high for ISPs, in which the AEP signal fluctuates particularly. Especially due to a singularity in the calculation method of the AEP, its behaviour is highly unstable in certain situations and especially in the beginning of an ISP. A possible implication being that in a PB market using the AEP signal as simulated, BRPs should interpret the signal as a prediction and be careful with manipulating their schedule deviations unless the signal is stable and unambiguous. A second implied solution being, that the AEP signal itself can be improved to be more reliable by e.g. applying low pass or moving average filters or be replaced altogether for a more stable PB response. These approaches are subject to future studies.

In grander scope, this study points out the complex imbalance price calculation method to be a problematic characteristic of the German energy balancing market. In a context of other studies regarding the obligation for BRPs to keep their schedule or the pay-as-bid pricing for aFRR, this study further indicates that reforming the existing German energy balancing market is expedient. Changes including a transparent imbalance price and the implementation of PB can lead to improved system stability, steadier prices and lowered costs for balancing energy.

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Market Response for Real-Time Energy Balancing with Fuzzy Logic

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***Abstract*—Market response for real-time energy balancing is a promising tool for power balancing: Smart Balancing. Transparency about the balance and imbalance price in the control area incentivizes market response. Market participants benefit from real-time business cases in addition to energy and balancing products. Fuzzy logic is introduced to optimize revenues for market participants with minimal risk. Market response (with fuzzy logic) is simulated with marginal vs. pay-as-bid clearing mechanisms and single vs. dual imbalance pricing. Single imbalance pricing can lead to overcompensation. This requires an additional rule to meet the Smart Balancing definition. Smart Balancing is present with a combination of single and dual pricing.**

***Index Terms*—Power Balancing, Real-Time Market, Passive Balancing, Fuzzy Logic**

I. Introduction

Maintaining the balance between power generation and load in a control area is a system requirement. Power balancing aims for a stable system frequency and prevents unscheduled power flows between neighboring control areas. Power balancing is organized by grid operators who organize balancing markets and control the contracted units. Market response is an additional tool to cope with imbalances in a control area by creating an additional business case for market participants. The area control error (ACE) and the imbalance price are published close to real-time. This information enables market participants to optimize their generation and consumption in real-time to support the balancing process. Market response is aiming to reduce the imbalance within a control area and generate profit via the imbalance price. This leads to reduced demand for Frequency Restoration Reserves (FRR) and saves costs.

The concept of market response for real-time energy balancing is widely discussed in the literature [1], [2], [3]. For example as "Smart Balancing" which is defined as "a set of measures to avoid the activation of FRR by market parties who create schedule deviations. Smart Balancing is incentivized by correct imbalance pricing in combination with public real-time information. Correct pricing does not incentivize overcompensation." [4]

Smart Balancing is currently incentivized by public real-time information in the Netherlands and Belgium. However, this approach involves uncertainty for the grid operators, as they predict network conditions based on scheduled power flows. Before such a concept can be implemented in other countries, its effects must be assessed. For this purpose, it is important to identify potential market participants and to predict their behavior.

This study presents fuzzy logic as possible approach for the decision-making process of market participants with regard to the Smart Balancing definition and the German energy market. The imbalance price as existing incentive and the area control error as indicator for the risk of a changing imbalance price are investigated as input parameters. The clearing schemes marginal and pay-as-bid clearing as well as the pricing schemes single and combined single and dual pricing were analyzed. For that reason, fuzzy logic as a method to optimize financial benefits at minimized risks is introduced and a suitable set-up is presented.

The following research questions are addressed: What kind of information is used and needed by market participants to optimize their portfolio in real-time? Is fuzzy logic a suitable tool to predict and optimize market responds? Which fuzzy logic set-up optimizes financial benefits at minimized risks and what are relevant tuning parameters? The analysis is organized in three-steps:

1) Analysis of relevant input data, considering market design options pricing and clearing scheme. (Section II)
2) Introduction of fuzzy logic as method for decision making. Definition of the fuzzy logic set up to optimize financial benefits at minimized risks for market participants. (Section III)
3) Simulation of test scenarios to evaluate fuzzy logic based market response under varying conditions. (Section IV)

II. Energy markets and Smart Balancing

In the first place, power generation and load is dispatched at energy markets; prices are determined and schedules are created. All market participants shall keep to their schedule. In real-time, summing up all (positive AND negative) schedule deviations results to the (positive OR negative) ACE which

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is compensated by FRR. Thus, the ACE can be reduced by additional schedule deviations in the correct direction. Market participants can achieve financial benefits, if the imbalance price exceeds their marginal costs. Potential financial benefits are, thus, determined by the imbalance price. The risk is, that excessive real-time market response could result in overcompensation of the ACE and change the imbalance price.

Market response is a combination of technical and financial optimization. This section compares different market design options and its influence on the decision-making process. A previous study identified six relevant design parameters for market response: Imbalance settlement period, publication of data, full activation time of reserves, balancing service pricing mechanism, activation strategy and imbalance pricing mechanism [5].

The imbalance settlement period is assumed to be 15 minutes in the following discussion, as defined in the EU regulation [6]. The full activation time of reserves and the activation strategy are not considered and shall be subject to future research. Considered market design options are (A) transparency, (B) single vs. dual imbalance pricing and (C) marginal vs. pay-as-bid clearing scheme. Furthermore, (D) the potential decision-making process is discussed.

A. Design option - transparency

Smart Balancing is achieved by correct imbalance pricing in combination with public real-time information. From historical data can be seen, that financial opportunities of the imbalance price (between -324 EUR/MWh and 2130 EUR/MWh) did exceed the financial opportunities at the day-ahead market (between -90 EUR/MWh and 122 EUR/MWh) [7], which shows the already existing incentive for market response. Provided information shall, therefore, include the ACE in MW and the imbalance price in EUR/MWh.

B. Design option - single vs. dual imbalance pricing

Market response is a reaction to the imbalance price. The ACE is only considered, because it indicates the risk of a changing imbalance price. In the regarded countries there are two common imbalance pricing mechanisms, single and dual pricing. Single pricing means that the costs of all balancing energy activated within the imbalance settlement period are added up to one price, regardless of their sign. This results in three scenarios for a balancing group: In the case of schedule adherence, the price has no relevance, in the case of a deviation with the imbalance of the control area, costs are incurred, and in the case of a system-related deviation, a compensation is paid. With dual pricing, one price each for positive and negative balancing energy is applied. This means that each deviation is paid for and the option of remuneration is no longer applicable. The Dutch use a combined approach, hereinafter referred to as combined pricing. They consider whether or not there was a change in the sign of the activated balancing energy within the imbalance settlement period. In periods without a change of sign, the single price is applied and systemic deviations are rewarded. In periods with sign change, the dual price is applied and all deviations are penalized.

C. Design option - marginal vs. pay-as-bid clearing scheme

The risk of a changing imbalance price depends on the market mechanism and clearing process. They can significantly determine the behavior of market participants and their influence on the overall system. It is therefore important to take these mechanisms into account in the decision-making process. The clearing schemes under consideration are marginal pricing and pay-as-bid. Both clearing schemes use merit order lists (MOL) to calculate the imbalance price. Marginal pricing means that the price for the most expensive activated reserve determines the price for all reserves. With pay-as-bid, the bid of each reserve is taken into account.

D. Decision-making of market participants

The decision-making process to participate in Smart Balancing depends on (i) the flexibility potential, (ii) the potential income and (iii) the associated risk.

(i) In real-time, the technical flexibility potential of a market participant is of physical nature. It is asset-specific and must be determined individually for each asset of the market participant. It depends on the overall system state (positive or negative imbalance) and the available flexibility. Available flexibility is calculated taking the operational state of each asset into account. The features maximum possible ramp, maximum full load hours and, if applicable state of charge define the technical potential. The economic flexibility potential describes that part of the technical potential of which marginal costs are covered by the imbalance price in real time. It would therefore generate profit.

(ii) The day-ahead market price (represents the benchmark price for power) and the imbalance price (represents the real-time price for power) are of interest for the economical potential. The market response of any market participant results from a variety of factors, such as the spread between day-ahead price and imbalance price and the deviation between real-time and scheduled consumption and generation.

(iii) In case of single imbalance pricing or a combination of single and dual imbalance pricing, the risk of a changing sign of the imbalance price is of mayor interest, as well. The next section introduces fuzzy logic to control market response, which considers this risk parameter in competition to the financial incentive.

III. Fuzzy logic

The decision-making of market participants is anticipated to optimize market response. Fuzzy logic shall optimize the financial advantage. Therefore, this section examines how individual participants would optimize their opportunities within different regulatory frameworks. Fuzzy logic optimizes market response by analyzing financial opportunities and judging risks. Relevant inputs for the fuzzy logic are described. The membership functions and the associated rules are defined and the framework in which fuzzy is embedded to represent the decision-making process is explained.

A. Fuzzy environment

Market response to real-time information is determined by (i) the economic flexibility potential, (ii) the potential income and (iii) the risk of changing imbalance price as described in Section III. Market participants calculate (i) the economic flexibility potential, which corresponds to the maximum possible response. The fuzzy logic determines the optimal response based on (ii) the potential income and takes (iii) the risk into account. Flexible assets get that new set-point and ramp up or down according to technical limitations.

Fig. 1 illustrates the fuzzy environment, which is used to optimize market response for real-time energy balancing. The steps to be executed by market participants are:

1) Calculate economic flexibility potential: All existing technical potential is ordered by marginal costs. The marginal costs, the day-ahead price and the imbalance price define the economic flexibility potential.
2) Identify optimal activation ratio: Market-design, the potential income and the power imbalance are used as input variables for the fuzzy logic, since they define the potential financial benefit and risk of market response.
3) Market response: The economic potential is multiplied by the activation ratio. The resulting power is to be activated as market response. In the present simulation the ramp of the technology is considered.

B. Input - potential income

The fuzzy logic is called with the potential income as input variable. Marginal costs have to be identified by the market participant first, to be compared to the imbalance price. Data should include all available flexibility and its marginal costs. The day-ahead market price is the benchmark price at the current period. It can influence the economic potential in different manners.

$$Income = ImbalancePrice - Costs \tag{1}$$

C. Input - risk indicator

The difficulty of risk assessment lies in anticipating the behavior of other market participants. Fuzzy logic is used to optimize and predict the relative Smart Balancing contribution based on limited knowledge about the current and future behavior of other market participants.

1) Risk with single pricing: For single pricing, the average $ACE_{average}$ is used to predict the risk that the single price change the sign. A positive imbalance over 15 minutes (upward reserves dominated) leads to a positive imbalance price (additional generation and reduced load is rewarded). A negative imbalance over 15 minutes (downward reserves dominated) leads to a negative imbalance price (additional load and reduced generation is rewarded).

$$ACE_{average} = \frac{\int ACE}{t} \tag{2}$$

2) Risk with combined pricing: As described in Section III, a combination of single and dual imbalance pricing is another market design option. In this case, the ACE itself is used to predict the risk of changing to a dual imbalance pricing scheme. This would involve a changing sign for the applied imbalance price.

D. Introduction of membership functions

Fuzzy logic classifies input data by membership functions and then relates them via rules. To set up a fuzzy controller, the relevant input data, including their minimum and maximum values and the distribution of the data, are required. Suitable values are derived from historical data of the German energy market in 2019, summarized in table 1. Fig. 2 illustrates the membership functions of ACE and $ACE_{average}$, used as risk indicators of a changing sign of the imbalance price.

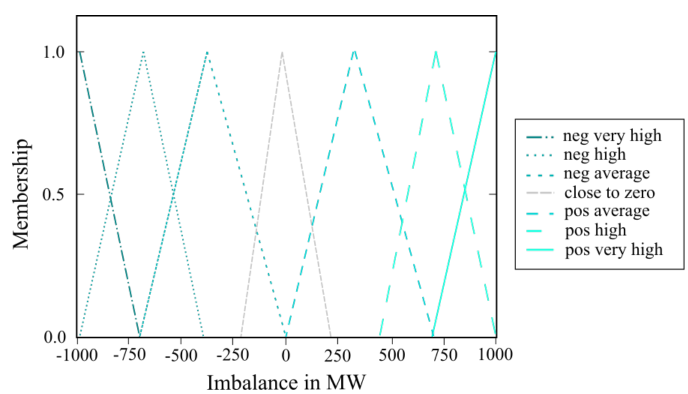

Fig. 2. Membership functions of input variable imbalance in MW

Membership functions are also assigned for the net margin as further input. Values between zero and 100 EUR/MWh are

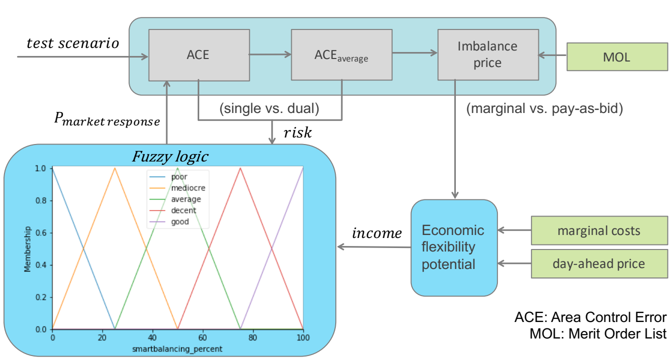

Fig. 1. Environment of fuzzy logic for optimization of market response

TABLE I
FINANCIAL OPPORTUNITIES IN GERMANY 2019, DATA FROM [7]

2019	Day-Ahead Market	Imbalance Price	ACE
Average	37.7 EUR/MWh	39.2 EUR/MWh	117.4 MW
St. deviation	15.5 EUR/MWh	51.1 EUR/MWh	106.3 MW
Min	-90.0 EUR/MWh	-323.9 EUR/MWh	0.0 MW
Max	121.5 EUR/MWh	2130.0 EUR/MWh	1600.0 MW

assumed as relevant net margin. The fuzzy output is expressed as a percentage between zero and 100. The membership functions of netmargin and fuzzy output are defined by dividing their value range into five equally distributed gradations named poor, mediocre, average, decent and good.

E. Introduction of fuzzy rules

Besides the input data and their classification in membership functions, knowledge of the relationship between the parameters is required. The following rules are used in the test scenario to relate the inputs to the output.

1) If the ACE / $ACE_{average}$ is neg very high OR pos very high, then smartbalancing will be good
2) If the ACE / $ACE_{average}$ is neg high OR pos high, then smartbalancing will be average
3) If the ACE / $ACE_{average}$ is neg low OR pos low, then smartbalancing will be mediocre
4) If the ACE / $ACE_{average}$ is close to zero, then smartbalancing will be poor
5) If the netmargin is poor, smartbalancing will be poor
6) If the netmargin is mediocre, smartbalancing will be mediocre
7) If the netmargin is average, smartbalancing will be average
8) If the netmargin is decent, smartbalancing will be decent
9) If the netmargin is good, smartbalancing will be good

IV. Simulation of test scenarios

The suitability of the fuzzy logic is evaluated within different test scenarios. The scenarios consist of assumptions regarding the general market situation the three scenario parameters balancing energy prices, clearing scheme and pricing scheme.

A. Scenario definition

The ACE without market response is 1 GW in all scenarios. All scenarios include three imaginary market participants with 1 GW of technical flexibility each. The marginal costs of these market participants differ with 70, 90 and 110 EUR/MWh.

1) Regarded balancing energy prices: The balancing energy prices vary with the overall market situation. Therefore a favorable and a more expensive MOL are regarded to investigate it's impact on the control. Both MOLs includes 1 GW reserves evenly distributed into 10 bids of 100 MW. The lowest offer is 30 EUR/MWh. The less expensive MOL 1, includes bids up to 120 Euro/MWh, resulting in an initial imbalance price of 75 EUR/MWh with pay-as-bid and 120 EUR/MWh with marginal clearing. Within the more expensive MOL 2 bids rise up to 390 Euro/MWh. The initial imbalance price with pay-as-bid clearing is 210 EUR/MWh and 390 EUR/MWh with marginal clearing.

2) Regarded clearing and pricing schemes: As clearing schemes marginal clearing and pay-as-bid clearing are investigated. For pricing single pricing is compared with combined pricing, as applied in the Netherlands.

B. Results

The results show the effects of the chosen scenario parameters.

1) Results for MOL 1: Fig. 3 illustrates market response with marginal clearing scheme and single imbalance pricing. The imbalance price remains at 120 EUR/MWh for 15 minutes. This leads to an overreaction and a negative ACE of up to - 400 MW. Every 15 minutes there is a drop in price and ACE. After 45 minutes the price settles at 75 /MWh at an ACE of 400 MW. Due to the single imbalance pricing the market participants consider the $ACE_{average}$ as risk indicator of a changing sign of the imbalance price, which, in this case can not prevent an overreaction.

With marginal clearing scheme and combined pricing the imbalance price remains at 120 EUR/MWh for 15 minutes, but no overreaction occurs. After 5 minutes the ACE oscillates between zero and less than 200 MW. The market participants consider the ACE as indicator for the risk of a chancing sign of the imbalance price. This avoids an overreaction. With the new imbalance settlement period after 15 minutes, the price collapses from 120 /MWh to just under 40 /MWh, thus reducing the incentive for market participants. The ACE rises to almost 700 MW. With the next imbalance settlement period, the price will settle at 65 /MWh, which corresponds to an ACE of 500 MW. The imbalance could be halved within two periods.

Pay-as-bid clearing results in limited market response of 200 MW at a favorable MOL. The imbalance price decreases and limits market response, since there is no economic flexibility potential as soon as the imbalance price falls under 70 EUR/MWh. There is no difference between single and combined pricing scheme, since the economic potential is zero before the risk of a changing sign of the imbalance price appears.

2) Results for MOL 2: Regarding the more expensive MOL marginal clearing scheme leads to an overreaction and a

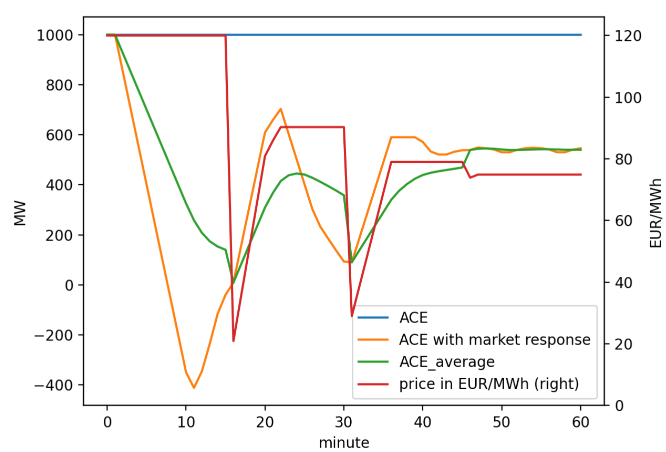

Fig. 3. MOL 1: Marginal clearing, single pricing

negative ACE for both pricing schemes. The ACE reaches -600 MW with single pricing scheme. The overreaction is limited with combined pricing scheme. The imbalance price is set to zero and the ACE returns to 1000 MW.

Fig. 4 illustrates market response with pay-as-bid clearing and single imbalance pricing. An overreaction takes place, but the ACE does not reach - 200 MW. Within 30 minutes the imbalance price drops from 210 EUR/MWh to an almost stable value around 90 EUR/MWh. The imbalance value has a similar pattern starting at 1 GW and stabilizing around 400 MW after 30 minutes.

Fig. 5 illustrates market response with pay-as-bid clearing and combined pricing. No overreaction takes place. The minimum ACE is 100 MW after about 8 minutes. After 15 minutes it stabilizes around 400 MW with a range of about 50 MW. The imbalance price is 90 /MWh.

3) Discussion of the results: With fuzzy logic it is possible to achieve a stable price and ACE state in all presented scenarios. This is reached within a maximum of three imbalance pricing periods (Fig 3). Single pricing causes greater fluctuations in ACE and price than combined pricing. The settling time is also lower with combined pricing with a minimum of 15 min in the case of an expensive MOL at pay-as-bid clearing with combined pricing (Fig 5).

The simulations show that the ACE seems to be a promising input variable in case of combined pricing. It leads to the observed fast and stable approximation to the equilibrium of price and ACE determined by MOL and marginal costs of market participants.

The range of the MOL might be another important parameter to tune the fuzzy logic. In combination with the clearing scheme it influences the incentive. Therefore, both parameters should be considered in fuzzy tuning to avoid overreactions. Limited market responds depends on the marginal costs of market participants and can not be solved by fuzzy tuning.

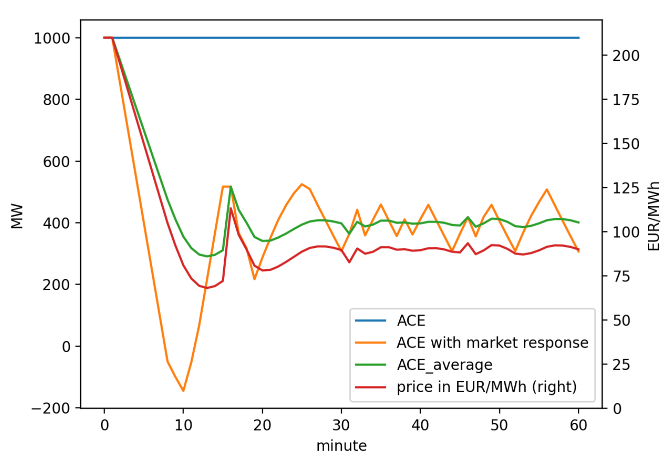

Fig. 4. MOL 2: Pay-as-bid clearing, single pricing

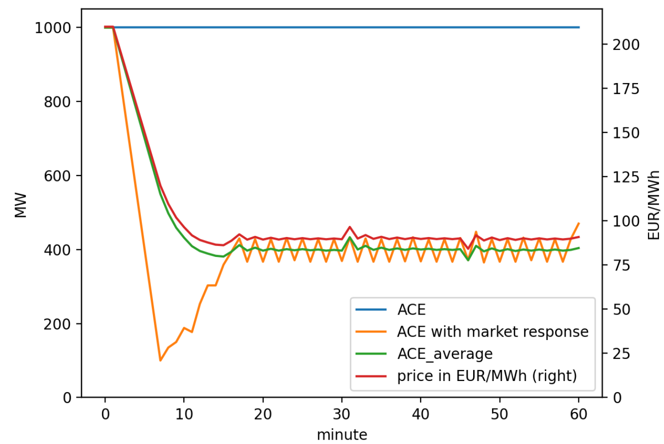

Fig. 5. MOL 2: Pay-as-bid clearing, combined pricing

V. Summary and Outlook

This study presents fuzzy logic as possible approach for the decision-making process of market participants with regard to the Smart Balancing definition. The imbalance price as existing incentive and the area control error as indicator for the risk of a changing imbalance price are investigated as input parameters. The clearing schemes marginal and pay-as-bid clearing as well as the pricing schemes single and combined pricing were analyzed. Different scenarios consisting of the applied imbalance pricing mechanism, the clearing scheme and the associated MOL are investigated.

The economic flexibility potential and with it the market responds results from the deviation of the control area, the MOL and the marginal cost distribution of the market participants. The scenarios examined show that market response for real-time energy balancing is strongly incentivized by single imbalance pricing. This can lead to overcompensation and requires an additional rule to meet the Smart Balancing definition. The Dutch approach of switching to dual pricing in case of overcompensation, referred to as combined pricing, meets the Smart Balancing definition and prevents unwanted overreactions in three out of four cases. The combination of marginal clearing and high balancing energy bids does lead to an overreaction at combined pricing. The level of the balancing energy bids proved to be a critical safety factor as it determines the financial incentive. A fuzzy tuning adapted to this is to be investigated.

The test scenarios show that a fuzzy logic with the selected input variables can serve to optimize market response for real-time energy balancing. From this first investigations it seems to be a promising tool for grid operators to balance the control area in case of incentivized market response. Future research should focus on identifying the overall flexibility potential and related marginal costs in Germany. A more precise impact assessment on optimal fuzzy tuning and market-design-options can be done with that information.

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Smart Balancing of Electrical Power in Germany: Fuzzy Logic Model to Simulate Market Response

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Abstract: Recent EU legislation enforces the integration of European balancing markets, with harmonized products and international platforms for the procurement and activation of reserves; nonetheless, different power balancing strategies remain. The Netherlands and Belgium encourage market participants to support balancing the control block by publishing real-time information. This article refers to such concepts as smart balancing, and a market simulation tool was developed to assess the relevant market parameters for effective smart balancing. This shall contribute to the true integration of real-time balancing energy markets. The scope of the assessment of relevant market parameters was Germany, and the results showed that a pricing scheme had less impact on the results, as currently is understood by European TSOs and regulators. Moreover, the accuracy and frequency of real-time publication indicate the effectiveness of smart balancing and the associated reduction of the activation of balancing energy and associated costs. Consequently, this article proposed a road map for Germany to introduce an adapted smart balancing approach, starting with a simple traffic light.

Keywords: energy market design; smart balancing; passive balancing

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1. Introduction

The tendency that the dispatch of electrical energy moves closer to real time is driven by opportunities for financial optimization of intra-day markets. As a consequence, power balancing becomes an ever-more interactive task where the imbalance price reflects the real-time value of energy. Meanwhile, the European legislation enforces the transition from national balancing markets to harmonized European platforms [1]. This article contributes to the discussion about the enhancement of market freedom for the purposes of designing more efficient balancing energy markets by paying special attention to an improved, market-oriented balancing approach in Germany by providing transparent imbalance pricing. Such an approach may be referred to as "self-balancing" [2] (p. 1048), "passive control" [3] (p. 102), or "passive balancing" [4] (p. 45) and is applied in The Netherlands [5] and Belgium [6]. Market participants are incentivized to deviate from their schedule to reduce the demand of balancing energy. In this article, we refer to such an approach of balancing as "smart balancing" in contrast to a balancing approach in which the market participants are left uninformed ("unaware") about the current state of imbalance of the system. Based on simulations of a smart balancing concept designed for Germany, the results in this article show which market design choices could be made to further support efficient power balancing and establish true real-time balancing energy markets. This contributes to the European harmonization, not only for Germany, but the EU in general.

Section 1 outlines power balancing strategies and smart balancing concepts. Section 2 introduces the smart balancing model, applied scenarios for Germany, and the market response potentials considered. It describes the market design parameters regarded. Section 3 presents the results from the simulation runs including a quantification of risks and benefits and identifies worst vs. best case balancing strategies. Section 4 discusses the results and evaluates the considered market design options and policy implications. Section 5 concludes the article.

Power generation and consumption are dispatched on future, day-ahead, and intraday markets, leading to schedules. The physical constraint of balancing generation and load is translated into the legal duty of having balanced portfolios. Therefore, market participants that represent one or a group of grid connected parties are called Balance Responsible Parties (BRPs). They financially account for any schedule deviation, which is settled with an imbalance price, individually for each 15 min Imbalance Settlement Period (ISP). As a result, unbalanced portfolios lead to financial risks of being accountable for balancing energy activated [7].

As described above, different power balancing strategies are applied in the Belgian, Dutch, and German control blocks. All countries measure the Area Control Error (ACE) in real time and activate Frequency Restoration Reserves (FRR) accordingly. Schedule deviations are settled with single imbalance pricing, meaning that every ISP is either settled with a positive or a negative price for energy deviations. This leads to the fundamental applicability of smart balancing in the first place, since participants of smart balancing concepts need to be sure that their balancing contribution is able to generate a benefit rather than additional costs. The Netherlands occasionally deviates from single pricing and changes to dual pricing in the case of counter-activation of balancing energy. This concept is referred to as "combined pricing" [8] (p. 82).

Smart balancing is a set of measures aiming at reducing the ACE and demand for balancing reserves. Principally, smart balancing refers to enabling a market response to transparent real-time imbalance pricing. Such an approach has been applied in The Netherlands since 2001 [9] and in Belgium since 2017 [10]. This article describes a smart balancing model applied for the German control block. Potential smart balancing of BRPs in Germany, their influence on the ACE, and central European system frequency are examined. Market design parameters that influence smart balancing risks and benefits are identified.

The research scopes are (i) the consequences of introducing smart balancing in Germany and (ii) market design for efficient power balancing. This article contributes to the question of which balancing market design best enables smart balancing.

2. Materials and Methods

The applied materials and methods are described to allow others to replicate and build on the results. It was assumed that BRPs optimize their behavior with the aim of maximizing their individual profit. Criteria for comparing different balancing system efficiencies are demand and costs for balancing power, as well as the impact on the European system frequency. A market design is found to be successful if it minimizes the demand and costs for balancing power.

Section 2.1 outlines the structure of the smart balancing model. Section 2.2 gives an overview of all simulated scenarios and introduces relevant market design parameter. The underlying materials are the demand and prices of balancing reserves in Germany. Historical vs. synthetic data for balancing demand and balancing energy prices are introduced. Section 2.3 describes the potential market response and the implemented fuzzy logic, which anticipates the behavior of BRPs in different market environments. Since not all the BRPs respond to market signals in the same way, the smart balancing model builds on a fuzzy logic approach. That way, it is able to reflect a "fuzzy" market response to real-time price incentives. Section 2.4 presents the validation of the smart balancing model. Section 2.5 reflects on recent studies about "under-cover" smart balancing and states the resulting limitations of the presented model.

2.1. *Smart Balancing Model*

The smart balancing model is implemented in Python and can be obtained by approaching the authors. Figure 1 illustrates the object-oriented model structure. On top, instances of grid elements cover calculations on system frequency (f) and activation of balancing energy according to the ENTSO-Egrid code [11]. Objects within a control block are instances of BRPs. The simulation runs carried out covered the German control block. The rest of the European synchronous zone was assumed to have a constant and balanced generation and load of 300 GW. The model can be extended by other control blocks or balancing groups.

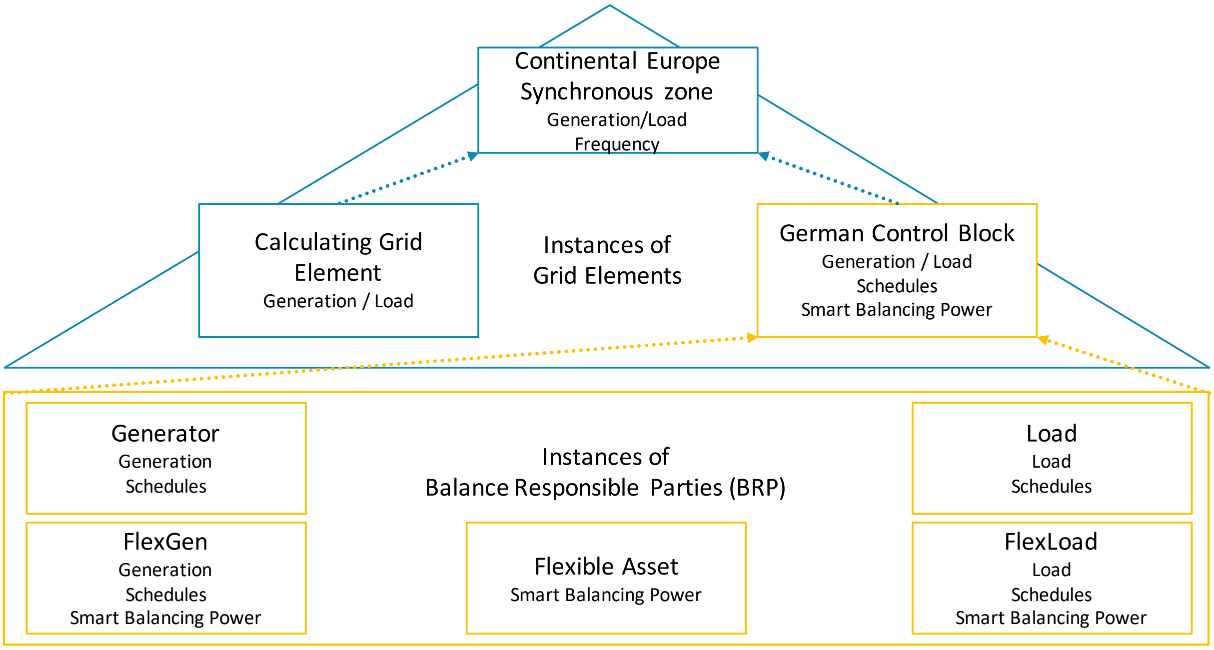

Figure 1. Smart balancing model: structure of objects and most important properties.

A previous version of the model was used to simulate the week from 18 November 2019 to 24 November 2019 in a one-second resolution with field data from four BRPs [12]. The simulated behavior of the BRPs (representing industrial consumption and generation with volatile renewable sources) would have generated profit, while the demand and costs for balancing energy are reduced. The lessons learned from this field test week were used to improve and develop the model and behavior of BRPs further.

Figure 2 shows the simulation flowchart. Relevant input data from csv files are read in the initial step. Afterwards, the simulation starts with a one-minute resolution. Generation, load, and schedules are compared to calculate the ACE. Frequency and FCR activation are calculated based on a steady-state estimation, followed by aFRR activation. In scenarios with active smart balancing, the market response is calculated in the next step. The decision for mFRR activation is not based on local load-frequency control block agreements. mFRR is an optional response to critical situations, and the decision for its activation is made by the responsible Transmission System Operator (TSO) by evaluating the individual situation. mFRR is delivered in the next ISP and is included in the ACE calculation as scheduled generation. The demand and costs of aFRR and mFRR are used to calculate the imbalance price according to the current rules, enforced in 1 July 2020 [13].

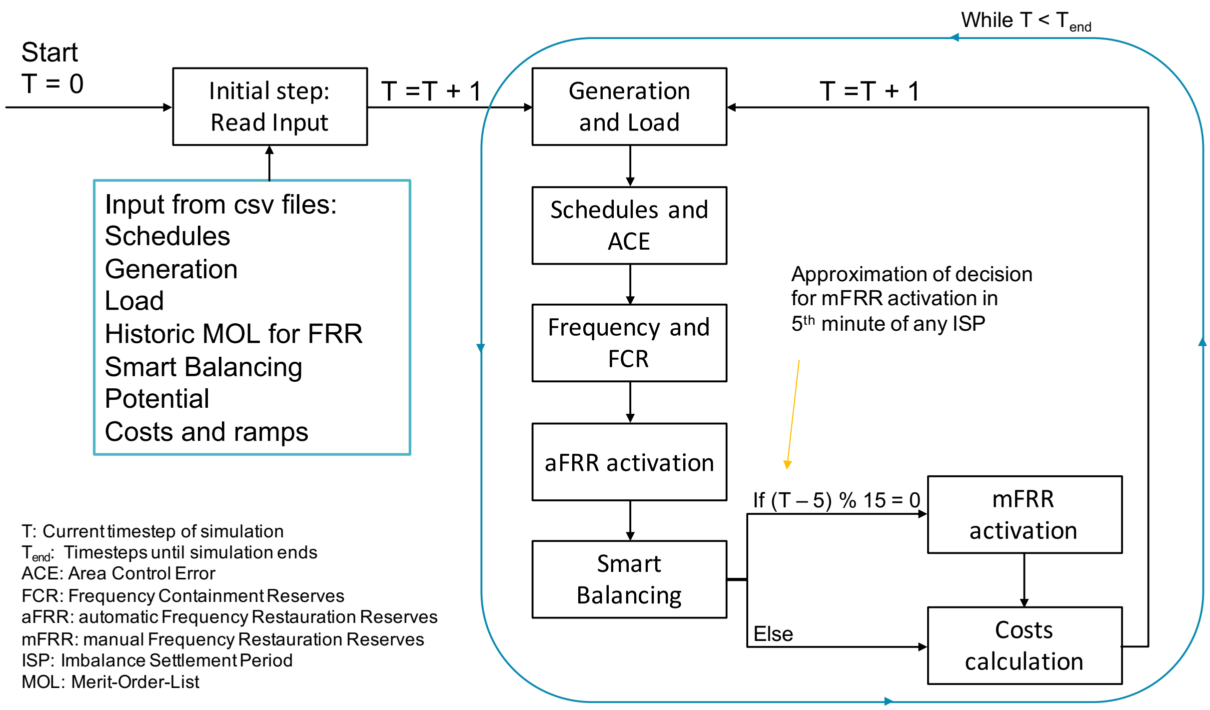

Figure 2. Flowchart of smart balancing simulation.

2.2. Market Design Scenarios

The regarded scenarios analyze "active" smart balancing and represent different combinations of market design parameters, which have been identified in previous work [14]. In contrast to "active" smart balancing, Section 2.5 describes "under-cover" smart balancing and related limitations of the analysis. Table 1 shows the market design parameters that are taken into account in the model. They are introduced in the following subsections.

Table 1. Overview of market design parameters.

Parameter	Variables
Availability of input	Frequent 1/min
	Traffic light (only in the case of high ACE)
Pricing scheme	Single pricing (DE)
	Combined pricing (NL)
Clearing scheme	Pay-as-bid
	Marginal with BEPP 15 min
	Marginal with BEPP 1 min
Input signals	Historic imbalance (ACE)
	Synthetic imbalance (ACE)
	Historic Merit-Order-Lists (MOLs)
	Synthetic Merit-Order-Lists (MOLs)

Not all parameter combinations are of interest. Table 2 shows the simulated scenarios with their related parameter variation. The first scenario with historic data and no smart balancing served for validation of the model. Ten other scenarios were simulated to answer the research question on which market design enabled efficient smart balancing.

Table 2. Overview of investigated scenarios.

Scenario	Input Signals	Market Mechanisms (Clearing, Pricing)	ACE, MOL
1 no SB	Reference without SB	Pay-as-bid, single pricing	historic 2019
2 TL2	Traffic light 2 steps	Pay-as-bid, single pricing	historic 2019
3 TL5	Traffic light 5 steps	Pay-as-bid, single pricing	historic 2019
4 DE	Imbalance, price	Pay-as-bid, single pricing	historic 2019
5 NL	Imbalance, price	Pay-as-bid, combined pricing	historic 2019
6 no SB PAB	Reference without SB	Pay-as-bid, single pricing	synthetic PAB
7 DEs	Imbalance, price	Pay-as-bid, single pricing	synthetic PAB
8 NLs	Imbalance, price	Pay-as-bid, combined pricing	synthetic PAB
9 no SB BEPP15	Reference without SB	marginal, single pricing	synthetic MC
10 BEPP: 15 min	Imbalance, price	marginal, combined pricing	synthetic MC
11 no SB BEPP1	Reference without SB	marginal, single pricing	synthetic MC
12 BEPP: 1 min	Imbalance, price	marginal, combined pricing	synthetic MC

2.2.1. Availability of Information: Full Transparency vs. Traffic Light

Besides the Belgian and Dutch approach of making the activated FRR and the current imbalance price available to the BRPs, the alternative approach to use traffic light concepts that display fixed levels of imbalance situations was investigated. Two traffic light scenarios were defined. They represented less than full transparent approaches, but were too suitable to incentivize a market response. These traffic light concepts might be used if the fully transparent approach (as used in Belgium and The Netherlands) is regarded "too risky" or is proven to trigger market responses that cause resonance oscillations in the system imbalance.

Both traffic light approaches publish signals only in cases of higher demand of balancing energy. Concept 1 makes use of a traffic light with two increments (TL2) that distinguish between situations when the balancing energy demand exceeds 80% and when the demand exceeds 100% of contracted (automatic and manual) FRR. Concept 2 is a traffic light with five increments (TL5). It adds a signal already when the demand exceeds 60% and two more increments for high demand of over 120% and 150% of contracted FRR. Table 3 shows the considered increments of both approaches and the resulting smart balancing contribution of BRPs, which represent fuzzy rules (see Section 2.3) of the traffic light scenarios.

Table 3. Traffic light concepts depending on demand of contracted automatic and manual Frequency Restoration Reserves (FRR).

FRR Demand	Concept 1: TL2	Concept 2: TL5
over 60%	-	poor smart balancing
over 80%	average smart balancing	mediocre smart balancing
over 100%	good smart balancing	average smart balancing
over 120%	-	decent smart balancing
over 150%	-	good smart balancing

2.2.2. Single vs. Combined Pricing of Balance Responsible Parties' Imbalance

Excluding the traffic light scenarios, all other simulated smart balancing concepts make the real-time ACE and resulting imbalance price available to BRPs. In the scenarios with single pricing, the imbalance price changes the sign only when the total sum of activated FRR has a sign shift. This approach gives an incentive for smart balancing, but does not limit the BRPs' contribution to the ACE and can make overreactions, especially in the end of an ISP, beneficial.

In contrast to pure single pricing, the Dutch combined pricing approach was investigated. This concepts changes from single to dual pricing in any ISP with activation of both positive and negative FRR. Dual imbalance pricing punishes all schedule deviations. Therefore, combined pricing prevents the misplaced incentive of pure single pricing at the end of an ISP.

2.2.3. Clearing of Activated Frequency Restoration Reserves

The costs for balancing result from the ACE in combination with the submitted energy bids for FRR. All bids are ordered by price and together form a Merit-Order-List (MOL). The comparison of the German balancing energy clearing scheme "pay-as-bid" vs. marginal clearing is of interest, because Germany will introduce marginal clearing in 2021 due to the European Electricity Balancing (EB) Regulation [1].

Pay-as-bid leads to an optimal bidding strategy where bids include mark-ups leading to high prices in the repeated auction setting [15]. Bidders have an incentive to include a mark-up reflecting their competitive position, but observed high prices for energy bids in Germany are also caused by the limited set of suppliers and the auctions being repeated on a regular basis [16]. Besides the energy bid, also the power bid (respectively capacity bid) and related procurement mechanisms influence the bidding strategy [17], but are not reflected by the presented model.

Marginal pricing, on the other hand, leads to underbidding of energy production costs [18].

Marginal clearing does not incentivize bidders to reveal their true costs in their bids, but to understate them for a good merit-order position. In contrast, considering the observed extreme energy bids in Germany, we assumed that substantial mark-ups were included when pay-as-bid was applied. The corresponding costs are higher than the costs of paying the uniform price to all activated BRPs at a low ACE. On the other hand, marginal pricing leads to high costs with high ACE. The resulting incentives for smart balancing should lead to less occurrences of high ACE in a marginal clearing market. Figure 3 illustrates these assumed correlations, which are subject to the discussion in Section 4.

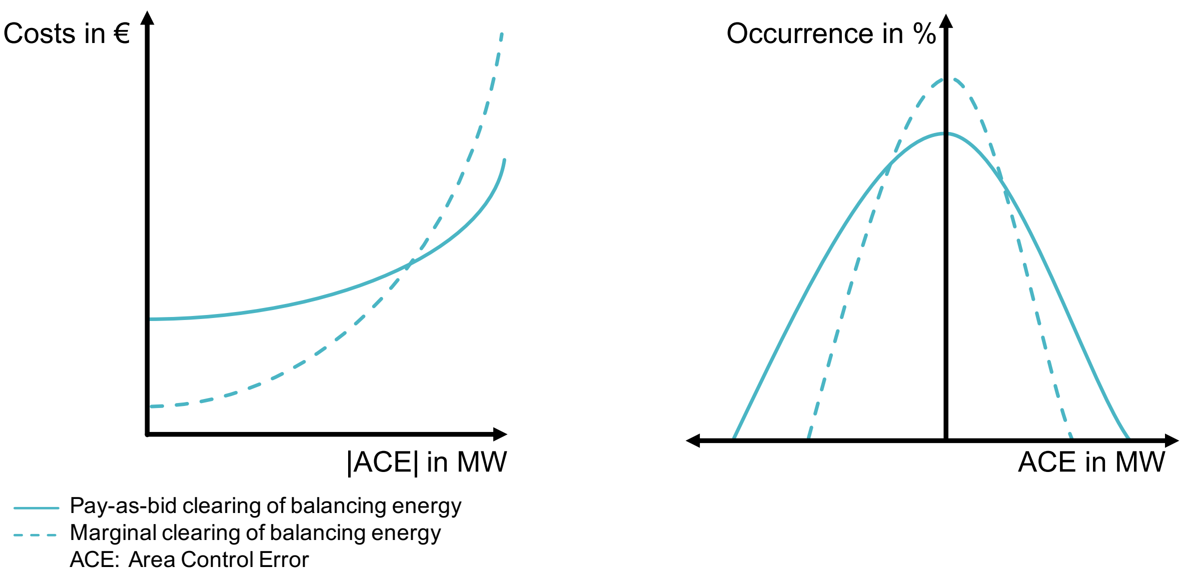

Figure 3. Correlation of costs and imbalance occurrence with pay-as-bid vs. marginal clearing of balancing energy.

The Balancing Energy Pricing Period (BEPP) in a marginal clearing setup is usually equal to the ISP. In the context of the new EB Regulation, a change from pay-as-bid to marginal pricing with a BEPP of 15 min vs. a BEPP of 1 min is of interest. Figure 4 illustrates and explains the BEPP with an example. A small BEPP can prevent high costs for FRR in the case of high ACE, as the marginal price is updated more frequently. A 15 min BEPP and a 1 min BEPP were compared in this study to investigate their influence on smart balancing. Since the simulations with historic data in Section 3 showed that combined pricing is a useful instrument for successful smart balancing as practiced in The Netherlands, this choice remained.

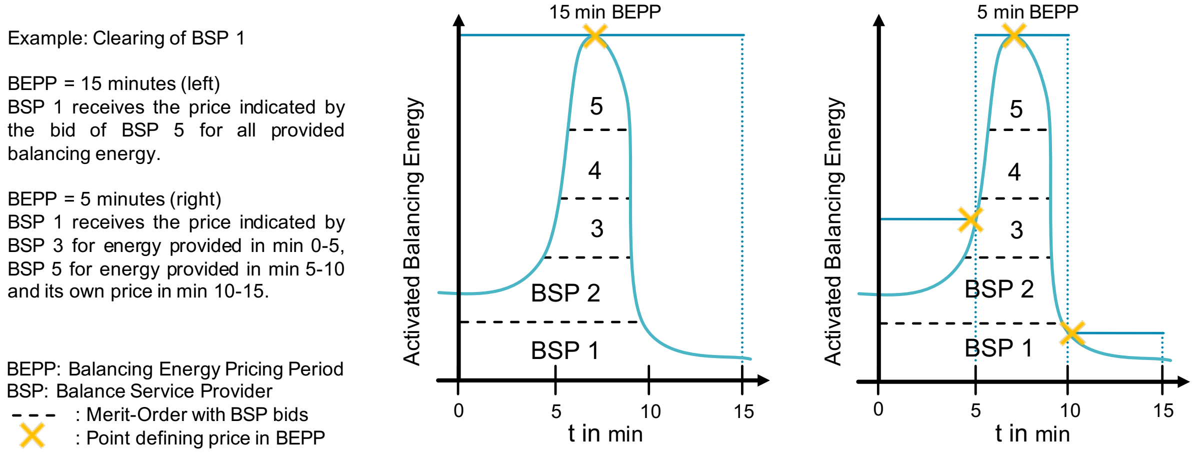

Figure 4. Example with marginal clearing of balancing energy: BEPP 15 min vs. BEPP 5 min.

2.2.4. Historic vs. Synthetic Area Control Error and Merit-Order-Lists

As shown in Table 2, five investigated scenarios used historic data from the year 2019, and six scenarios used synthetic data. In scenarios with historic data, market mechanisms and flexibility providers face the historic ACE and MOLs. This includes events with high imbalances in June 2019 and might showcase the advantage of smart balancing during these events. The considered data to (re-)build the historic ACE in a 1-min resolution were the automatic Frequency Restoration Reserves (aFFR) in a 1-s resolution and the manual Frequency Restoration Reserves (mFRR) and the emergency reserves both in a 15-min resolution [19]. The total ACE would also include the German contribution to the International Grid Control Cooperation (IGCC), but this contribution was neglected since it did not lead to an activation of FRR and even reduced the demand for balancing energy in other control blocks [20]. The historic ACE was only used for reference and for the four scenarios with the pay-as-bid clearing.

The reference scenario of 2019 served for calibration and validation in the attempt model the German energy market as it is. The current situation in Germany can be defined as a “no active smart balancing”, “single pricing”, and “pay-as-bid clearing” scenario.

Nevertheless, the historic data did include “under-cover” smart balancing (see Section 2.5), and the MOLs were determined in a pay-as-bid clearing scheme. Input data including synthetic ACE and MOLs allowed generating reasonable scenarios for market design comparison.

The ACE with pay-as-bid (PAB) clearing was defined to fluctuate between 1.1 GW and −1.1 GW with a random variation between −40 MW and 40 MW, calculated by Equation (1).

$$sACE_{PAB} = 1.1\ \text{GW} * sin(T = 12.1h) + 40\ \text{MW} * rand(-1, 1) \tag{1}$$

Marginal Clearing (MC) prevents high ACE by higher related costs, as illustrated in Figure 3. Therefore, the ACE with marginal clearing is defined to fluctuate between

1 GW and −1 GW with a random variation between −40 MW and 40 MW, calculated by Equation (2).

$$sACE_{MC} = 1\text{ GW} * sin(T = 12.1h) + 40\text{ MW} * rand(-1, 1) \quad (2)$$

Scenarios with synthetic data used two different MOLs, depending on the clearing scheme and resulting bidding behavior (see Section 2.2.3). The total average costs with pay-as-bid vs. marginal clearing of balancing energy without smart balancing were assumed to be equal, leading to the MOLs introduced in Table 4.

Table 4. Synthetic Merit-Order-Lists (MOLs) for smart balancing simulation.

Reserve Type	Pay-as-Bid Clearing Power	Price
positive aFRR	1700 MW in 100 MW steps	30 to 350 EUR/MWh in 20 EUR/MWh steps
negative aFRR	−1800 MW in 100 MW steps	−10 to 330 EUR/MWh in 20 EUR/MWh steps
positive mFRR	800 MW in 100 MW steps	110 to 250 EUR/MWh in 20 EUR/MWh steps
negative mFRR	−600 MW in 100 MW steps	80 to 220 EUR/MWh in 20 EUR/MWh steps
	Marginal clearing Power	**Price**
positive aFRR	1700 MW in 100 MW steps	30 to 190 EUR/MWh in 10 EUR/MWh steps
negative aFRR	−1800 MW in 100 MW steps	−10 to 160 EUR/MWh in 10 EUR/MWh steps
positive mFRR	800 MW in 100 MW steps	110 to 180 EUR/MWh in 10 EUR/MWh steps
negative mFRR	−600 MW in 100 MW steps	80 to 130 EUR/MWh in 10 EUR/MWh steps

2.3. Market Response with Fuzzy Logic

This section introduces the implemented flexibility providers. They respond to real-time signals, if the imbalance price covers their marginal costs. Energy exchange resulting from smart balancing contributions, as well as the resulting profit were calculated to analyze their impact. BRPs were defined within the control block, and their behavior was anticipated with fuzzy logic. They reacted to the ACE and the imbalance price of the control block.

Information relevant for financial optimization at minimized risk was identified and defined as input parameters for the fuzzy logic via fuzzy rules. Results were investigated regarding the financial benefit of BRPs and their contribution to system stability.

2.3.1. Potential Market Response

The considered technologies that have a (smart) balancing potential are shown in Table 5. Furthermore, their assumed flexibility potential and (smart) balancing logic are shown. The technologies belong to three different categories. Industrial processes represent the currently available flexibility from Demand Side Integration (DSI). Based on a recent analysis [21], it can be assumed that only the stated DSI technologies are able to contribute a market response without further investments. Renewable energy technologies have the possibility to respond to external signals and ramp down power generation. Only generation plants installed in the year 2017 and 2018 that fall under the "Markt-Prämien-Modell" were considered, because they face an incentive for smart balancing.

Table 5. Assumption for profit optimization parameters of BRP based on the German imbalance price (Ausgleichs-Energie-Preis (AEP)) and the day-ahead auction price for electrical energy (da_{price}).

Technology	Potential Up/Down (MW)	Marginal Costs Up/Down (Euro)
Aluminum electrolysis	281/-	$AEP - da_{price} > 100$/-
Cement raw mill	116/50	$AEP - da_{price} > 100/AEP < 10$
Cement mill	265/113	$AEP - da_{price} > 100/AEP < 10$
Amalgam chlorine electrolysis	114/72	$AEP - da_{price} > 100/AEP < 10$
Membrane chlorine electrolysis	359/227	$AEP - da_{price} > 100/AEP < 10$
Electric arc furnace (Steel)	753/-	$AEP - da_{price} > 250$
Polisher in paper production	207/46	$AEP - da_{price} > 100/AEP < 10$
Refiner in paper production	105/23	$AEP - da_{price} > 100/AEP < 10$
Solar and wind (Build 2017, 2018)	-/dynamic	-/$AEP < -EEGbonus - 40$
Gas fired power plants	dynamic/dynamic)	$AEP > 50/AEP < 0$

2.3.2. Profit Estimation of Smart BRPs

Smart balancing was determined by the given market design and the related opportunities to generate revenues. Figure 5 illustrates all steps around the fuzzy logic for the calculation of the respective smart balancing contribution for BRPs and assets with smart balancing potential. The net margin was derived from the imbalance price, which is the incentive for smart balancing and therefore mandatory to be considered. It quantifies the potential specific revenue and therefore the willingness to deviate from the BRP's schedule. The calculation logic differed for all simulated BRPs, as stated in Table 5. The imbalance prices and the implemented marginal costs of BRPs led to individual net margin values.

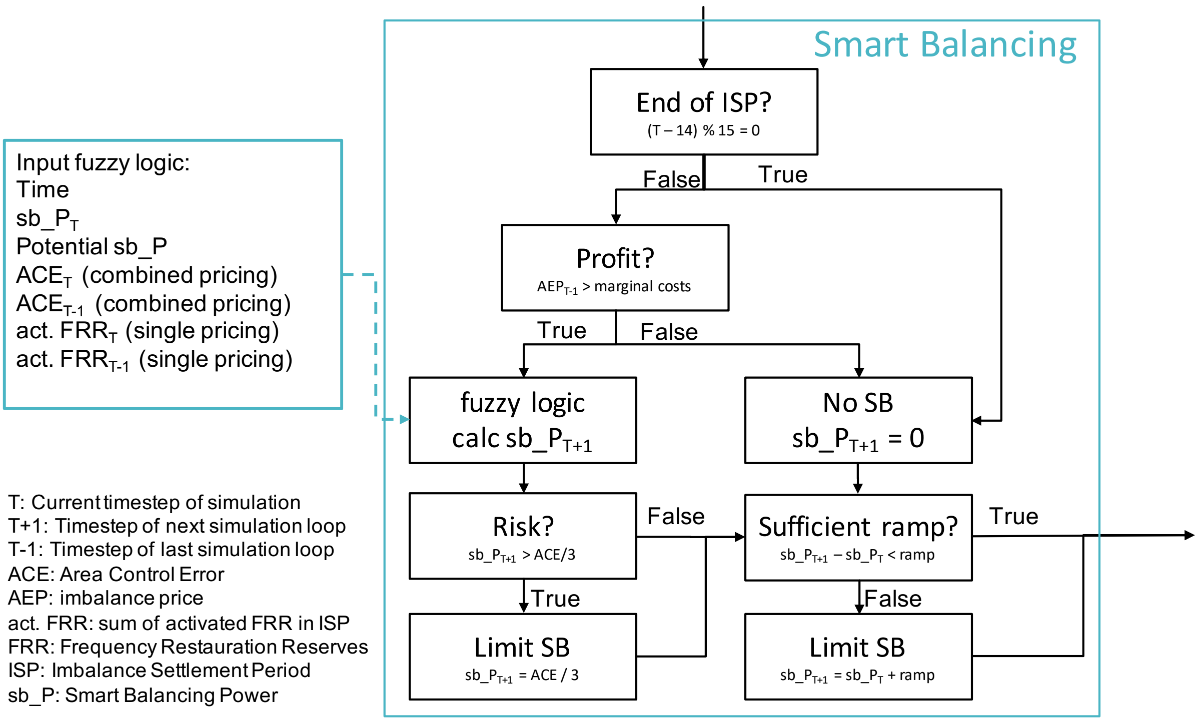

Figure 5. Details of smart balancing calculation in the simulation.

The "End of ISP" box illustrates the test, if the end of an ISP is reached, implemented by Equation (3). If T is equal to 14, the formula returns true and sets the smart balancing of the regarded BRP to zero ("No SB" box).

$$(T - 14)\ modulo\ 15 = 0 \tag{3}$$

The "Profit" box illustrates the consideration, if smart balancing would generate revenues, tested by Equation (4). If the marginal costs are higher than the imbalance price, the smart balancing of the regarded BRP was set to zero ("No SB" box).

$$AEP_{T-1} > marginalcosts \tag{4}$$

The "fuzzy logic" box represents the "fuzzy" behavior of BRPs, described in Section 2.3.3. The time step, the current smart balancing contribution, and the technical potential were used as the input. In addition, the ACE or the activated FRR quantified the absolute revenue potential. A high imbalance enabled a high smart balancing participation and set an upper limit, since a market response larger than the occurring imbalance could change the sign of the imbalance price and therefore cause monetary losses. Counter-activation of FRR immediately changed the sign of the imbalance price in the case of combined pricing, and the ACE was used as the fuzzy input. In the case of pure single pricing, the sign only changed if the counter-activation was higher than the initially activated FRR over 15 min, and the sum of activated FRR was used as input.

The "Risk" box illustrates a test, if the resulting behavior would reduce the ACE by over a third of its value, tested by Equation (5). If this was true, the "Limit SB" box reduced the smart balancing accordingly. The limit was chosen in order to avoid fast response in case of high incentives.

$$sbP_{T+1} > ACE/3 \tag{5}$$

The "Sufficient ramp" box illustrates the last test, if the resulting behavior can be realized with the underlying technology, tested by Equation (6). If this was false, the "Limit SB" box reduced the smart balancing according to the technical limit.

$$sbP_{T+1} - sbP_T < ramp \tag{6}$$

2.3.3. Fuzzy Behavior of Smart BRPs

Besides the basic consideration of profit and risks as shown in Figure 5, the further decision on how much of the smart balancing potential was activated was simulated using fuzzy logic. Fuzzy logic was first introduced in 1965 [22] for complex control of systems where behavioral aspects of multi-criteria decision making are anticipated. The applied Mamdani-type fuzzy inference was based on rules with linguistics, which was first introduced in 1975 [23]. The implementation was realized with the Python library scikit-fuzzy, which is a fuzzy logic toolkit for SciPy [24]. The centroid method was used as the defuzzification technique.

A previous version of fuzzy logic was used to anticipate the behavior of BRPs in changing market environments and a 1 GW imbalance test case [25]. The new version introduced in the following was extended to represent BRPs market response according to a situation in which all market participants would join smart balancing. It was better scaling.

Table 6 gives an overview about the considered input parameters for the fuzzy logic and implemented range.

Table 6. Overview of parameters investigated for market response modeling.

Parameter	Parameter Range	Unit	Explanation
Imbalance	−1001 to 1001	MW	Quantifies absolute revenue potential, global balancing limit
Ratio	0 to 600	%	Quantifies if Flexpotentialis higher ACE individual balancing limit
Time	0 to 15	min	Indicates probability of changing sign of imbalance price actual billing period (ISP)
Imbalance sign	0 or 1	-	Indicates that further SB contribution would increase imbalance
Smart balancing	0 to 100	%	Fuzzy output for smart balancing power calculation

These parameters were chosen since they covered the information needed to enable a reasonable balancing behavior, as simple as possible, as complex as necessary. Smart balancing is a product of activated balancing energy, time, and imbalance price.

To identify ISPs with financial opportunities, information about the imbalance price, the imbalance height, as well as the remaining time of the ISP as an indicator for the risk of loosing money in case of a changing sign of the imbalance price within the ISP needed to be regarded.

The time was used as an indicator for the risk of an changing imbalance sign. The earlier within the actual billing period we are, the greater the risk of a changing sign. For the fuzzy logic, the ISP of 15 min was therefore split into three uniform five-minute intervals "early", "middle", and "late".

Since balancing was conducted by several BRP at the same time, an additional parameter to anticipate the behavior of other participants was introduced. This was needed to scale the market response and reduce overshoots. For this purpose, the power contribution was added. The power contribution quantified the individual contribution to the system state. A high power contribution scaled the markets response to a high value, and a low contribution lowered it. This set an individual balancing limit to prevent overshooting and profit loses.

Fuzzy membership functions and fuzzy rules are listed in Appendix A.

2.4. Validation via Correlation Factor

Correlation factors were used as an indicator for the quality of the simulation. The rules for mFRR activation were tuned to optimize the correlation between the simulated and the historic mFRR activation, resulting in the following "best-fit" approach:

- Check average value of ACE over the first five minutes of any ISP
- Activation of mFRR in case the average ACE exceeds 37%/36% of procured (pos./neg.) aFRR
- Activation of mFRR, which reduces the demand to 41%/37.5% of available (pos./neg.) aFRR

The results from the validation scenario with historic ACE, no smart balancing', and 525,600 time steps at 1-min resolution was used to generate data with 35,040 time steps at 15-min resolution, representing the format of the historic data from ENTSO-E Transparency [26]. The activated balancing energy and related costs, as well as the imbalance price were compared to the historic values. Table 7 shows the correlation factors between historic values and time series resulting from the 2019 validation scenario. The comparison demonstrated that the validation scenario led to results with middle to high correlations, and only costs for downwards mFRR had a small correlation. The aFRR energy and costs values had a good quality. The mFRR energy values and costs for upwards mFRR had a middle quality. The quality of mFRR values could be traced back to the manual process in reality vs. a static decision making in the model. The resulting imbalance price had a middle correlation. On the other hand, the research scope was not to reproduce historic energy and cost values, but to apply a suitable environment to simulate different market environments and smart balancing behavior. For that reason, the model was considered to enable valid analysis.

Table 7. Correlation factors between historic values [26] and time series resulting from the validation scenario "1 no smart balancing".

Parameter	aFRR	mFRR	AEP
Energy up	0.86	0.58	-
Energy down	0.89	0.53	-
Costs up	0.69	0.57	-
Costs down	0.72	0.32	-
Price	-	-	0.52

The validation scenario was used as the benchmark "1 no smart balancing" for the four smart balancing simulations with historic data and pay-as-bid clearing. The finding error rate and accuracy of all smart balancing scenarios were not only based on the above-stated correlation factors, but were mainly driven by the accuracy of the assumed smart balancing behavior. Quantification of this accuracy made field tests necessary. The finding error rate and accuracy should be analyzed in future work.

2.5. Limitations and "Under-Cover" Smart Balancing

Smart balancing, generally said, is the market response to the ACE and the resulting imbalance price. The two input signals correlate, depending on the market design and costs for balancing energy. Germany applies single pricing, but does not allow for schedule deviations [7].

This paradox leads to "under-cover" smart balancing in Germany, which could be shown in previous studies: An equilibrium in the market of supply and demand in real-time was identified, where the system imbalance declined by 2.8 MW per 1 EUR/MWh increase in the imbalance price. According to the analysis of historic data (12.06.18 to 29.09.2019), strategic schedule deviations reduced the German ACE by about 20% [27]. This benefit was reached mainly by strategic bidding at intra-day markets where BRPs took all available information into account for an anticipation of the ACE in the next ISP. On the other hand, such a price responsiveness could lead to overreactions of the market [28]. Another evidence-based study claimed that the activation of manual Frequency Restoration Reserves (mFRR), which indicates high ACE and an expensive imbalance price, leads to "under-cover" smart balancing [29]. As no further detail on this speculative behavior is available, "under-cover" smart balancing was not included in the smart balancing model.

3. Results

This section provides the results for smart balancing simulations with different market approaches. Section 2.2 gives an overview about all considered scenarios. The target values FRR activation, FRR costs, and frequency deviations are compared. Finally, the outcome for BRPs is analyzed.

3.1. Simulation with Historic ACE and MOLs

Table 8 shows the reduction of balancing energy and related costs in relation to the simulation without smart balancing. The total costs for balancing energy were reduced with all smart balancing concepts. Furthermore, the activation of mFRR was reduced in all cases; the aFRR activation, on the other hand, was not significantly reduced in the two traffic light scenarios.

Table 8. Smart balancing simulation: activated FRR energy and total costs of scenarios with historic ACE and pay-as-bid clearing.

Scenario	pos.aFRR	neg. aFRR	pos. mFRR	neg. mFRR	Total Costs
1 No smart balancing	100%	100%	100%	100%	100%
2 Traffic light TL2	100%	100%	76%	95%	95%
3 Traffic light TL5	99%	99%	78%	90%	95%
4 Single pricing DE	91%	91%	53%	65%	83%
5 Combined pricing NL	85%	86%	55%	66%	70%

Figure 6 illustrates the absolute demand for positive and negative aFRR and mFRR over the simulated year 2019. All scenarios supported the hypothesis that smart balancing reduced the ACE and demand for balancing energy. The results showed that the traffic light approaches mainly reduced the mFRR demand, while aFRR could only be reduced in scenarios with full transparency.

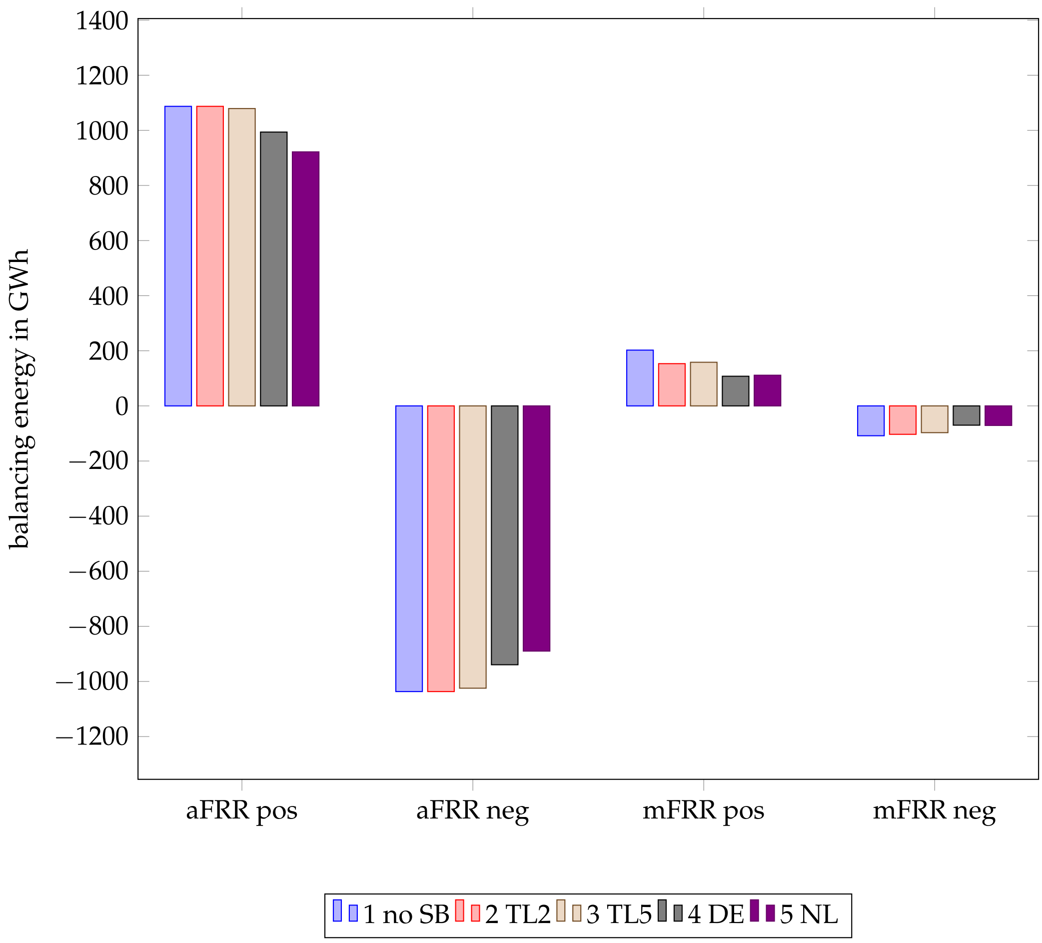

Figure 6. Smart balancing simulation: demand of balancing energy in 2019.

Figure 7 illustrates the absolute costs for positive and negative aFRR and mFRR over the simulated year 2019. Negative costs represent profit from the system perspective. The costs for positive aFRR and positive mFRR were reduced with smart balancing. The profits from activating negative aFRR were increased with smart balancing, but the profit from activating negative mFRR was reduced.

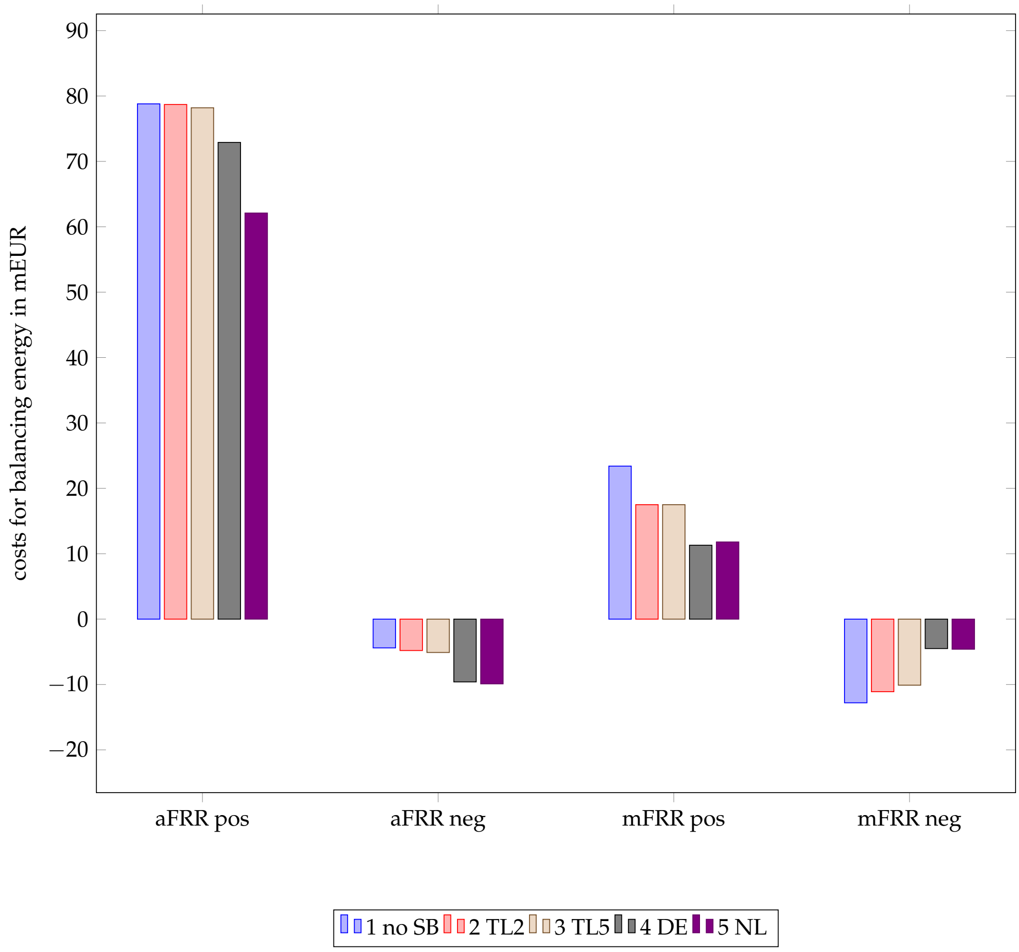

Figure 7. Smart balancing simulation: costs for balancing energy in 2019.

Table 9 shows the simulated effect of smart balancing on the frequency of the Central-West European synchronous zone. In all cases, the frequency standard deviation (std) was higher, and outliers (min,max) had a bigger distance to the set value of 50 Hz in scenarios with smart balancing. Therefore, the results indicated that smart balancing could have a negative side effect on the quality of the frequency.

Table 9. Smart balancing simulation: results of scenarios with historic ACE and pay-as-bid clearing.

Scenario	f Mean	f std	f Min	f Max
1 No smart balancing	50 Hz	0.0108 Hz	49.843 Hz	50.135 Hz
2 Traffic light TL2	50 Hz	0.0116 Hz	49.631 Hz	50.287 Hz
3 Traffic light TL3	50 Hz	0.0111 Hz	49.641 Hz	50.199 Hz
4 Single pricing DE	50 Hz	0.0123 Hz	49.759 Hz	50.179 Hz
5 Combined pricing NL	50 Hz	0.0113 Hz	49.763 Hz	50.174 Hz

The reason for the decrease in frequency quality with reduced demand for FRR is illustrated in Figure 8. The figure showcases the worst imbalance event of the year 2019 with activated reserves of over 7 GW and simulation results of the traffic light scenarios TL2 and TL5. The ACE and the demand for FRR could be reduced during each ISP, but going back to schedule at the end of each ISP led to high-frequency deviations.

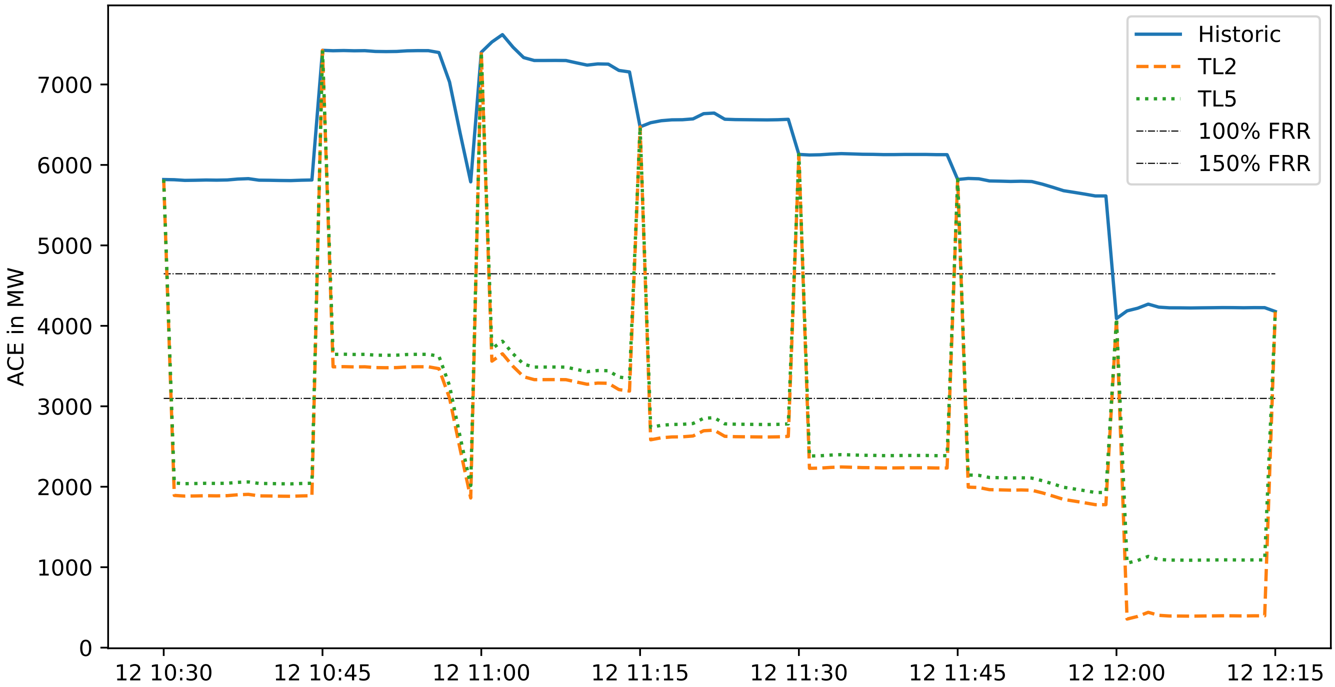

Figure 8. Historic imbalance event 12.06.2019 (Hist), traffic light scenarios (TL2 vs. TL5), and contracted automatic and manual Frequency Restoration Reserves (FRR).

Figure 8 also illustrates the difference between the two traffic light scenarios TL2 and TL5 in the case of high imbalance events. There was no further differentiation in case of an ACE that was higher than 100% of the contracted FRR. TL6, on the other hand, changed the signal at 12:00 from "over 150%" to "over 120%", and a reduced smart balancing contribution was the result. The slightly higher smart balancing contribution with the TL2 approach before 12:00 can be traced back to the fuzzy logic, where less membership functions were defined in the TL2, scenario leading to a higher output for "good smart balancing".

3.2. Simulation with Synthetic Data

As explained in Sections 2.2.3 and 2.5, the historic ACE includes "under-cover" smart balancing and MOLs resulted from a pay-as-bid clearing environment. On order to exclude these effects from the simulation, synthetic data instead of the historic data were used for the following simulations. Section 2.2.4 introduces the applied synthetic data.

Table 10 shows the reduction of balancing energy and related costs relative to the simulation without smart balancing and pay-as-bid clearing. As explained in Section 2.2.4, the MOLs for marginal clearing were chosen to result in similar costs with a 15-min BEPP, but no further differentiation of the MOLs was applied for the 1-min BEPP. As expected, this led to a decrease of the total costs compared to pay-as-bid or marginal clearing with a 15-min BEPP.

Again, the demand for FRR and the total costs for balancing energy were reduced with all smart balancing concepts. The activation of negative mFRR could even be reduced to zero by smart balancing. This could be achieved by a negative flexibility potential of DSI and renewable energies, as introduced in Section 2.3.1. Combined pricing "8 NLs" outperformed the approach with pure single pricing "7 DEs". In comparison to the simulation with historic data, this effect was less distinct. Nevertheless, the results further supported the hypothesis that combined pricing improves the smart balancing contribution.

Table 10. Smart balancing simulation-activated FRR energy and total costs of scenarios with synthetic ACE.

Scenario	pos. aFRR	neg. aFRR	pos. mFRR	neg. mFRR	Total Costs
6 no smart balancing PAB	100%	100%	100%	100%	100%
7 DEs	95%	66%	27%	0%	64%
8 NLs	91%	59%	39%	0%	62%
9 no SB BEPP15	98%	94%	74%	75%	99%
10 BEPP: 15 min	92%	55%	39%	0%	93%
11 no SB BEPP1	98%	94%	74%	75%	94%
12 BEPP: 1 min	91%	56%	39%	0%	65%

The effect of the imbalance pricing scheme outweighed the influence of the clearing scheme on efficiency of the smart balancing approach. The three scenarios “8 NLs”, “10 BEPP: 15 min”, and “12 BEPP: 1 min” were all simulated with combined pricing, but different FRR clearing schemes. Figure 9 illustrates that the differences in the activated FRR of the three scenarios were very small.

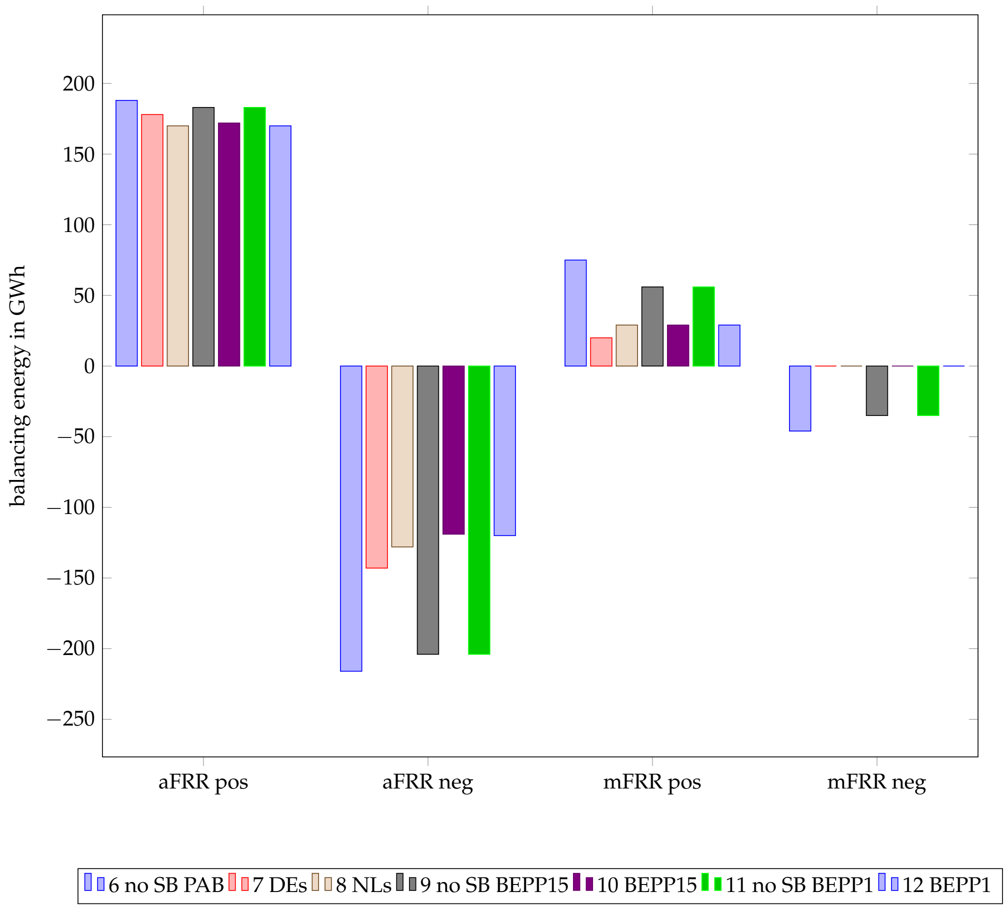

Figure 9. Smart balancing simulation: demand of balancing energy in synthetic scenarios.

In contrast to the demand of FRR, the related costs did differ, not only with the imbalance pricing, but also with the clearing scheme. Figure 10 illustrates that smart balancing could reduce the total costs only by 6% with marginal clearing and a 15-min BEPP, but the cost reduction accounted for 35% with marginal clearing and a 1-min BEPP.

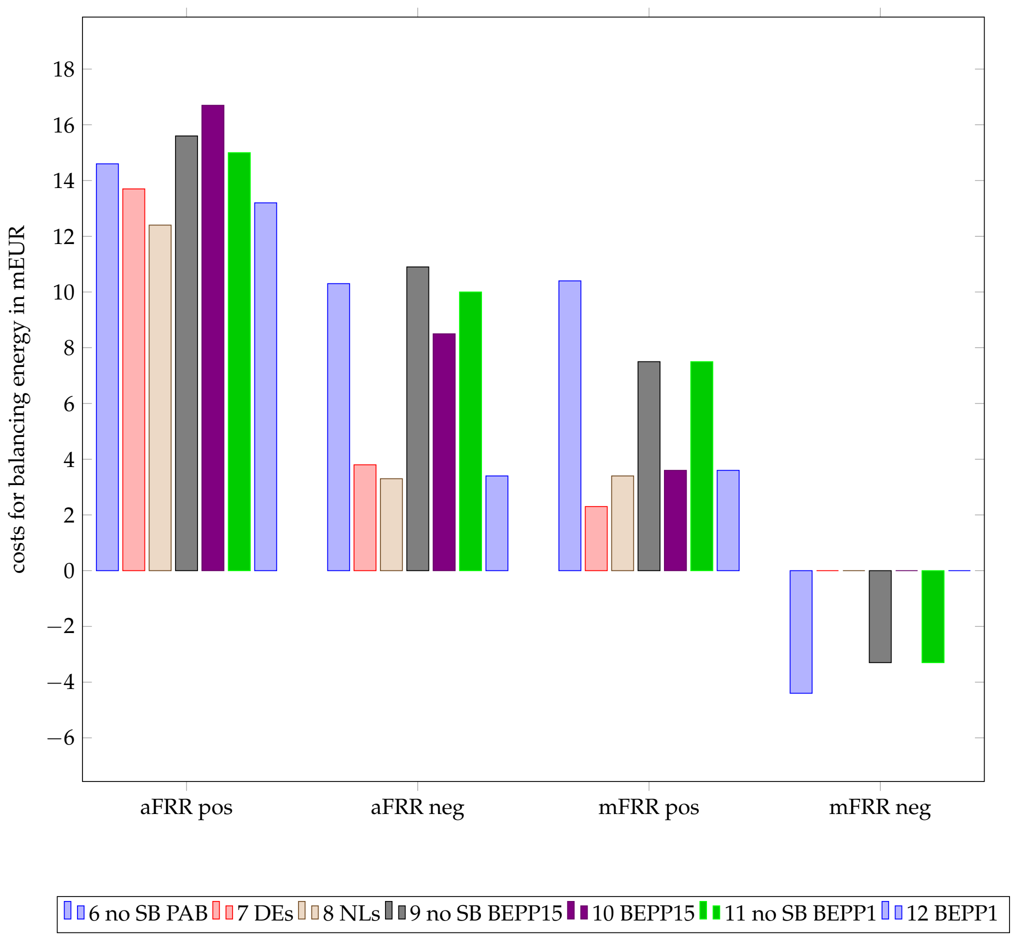

Figure 10. Smart balancing simulation: demand of balancing energy in synthetic scenarios.

Table 11 shows the effect of smart balancing on the system frequency. The difference between the scenario "6 no smart balancing pay-as-bid" with higher frequency deviation in comparison to the two scenarios "9 no smart balancing BEPP15" and "11 no smart balancing BEPP1" resulted from the different ACE, as introduced in Section 2.2.4. Similar to the simulations with historic data, the simulations with synthetic data also indicated that smart balancing could have a negative effect on the frequency quality. Again, this can be traced back to the behavior at the end of an ISP when BRPs return to their schedule (see Figure 5).

Table 11. Smart balancing simulation: results of scenarios with historic ACE and pay-as-bid clearing.

Scenario	f Mean	f std	f Min	f Max
6 no smart balancing PAB	50 Hz	0.0025 Hz	49.976 Hz	50.013 Hz
7 single pricing DE	50 Hz	0.0097 Hz	49.951 Hz	50.061 Hz
8 combined pricing NL	50 Hz	0.0085 Hz	49.931 Hz	50.063 Hz
9 no smart balancing BEPP15	50 Hz	0.0024 Hz	49.979 Hz	50.012 Hz
10 BEPP15	50 Hz	0.0116 Hz	49.901 Hz	50.071 Hz
11 no smart balancing BEPP1	50 Hz	0.0024 Hz	49.979 Hz	50.012 Hz
12 BEPP1	50 Hz	0.0093 Hz	49.932 Hz	50.073 Hz

3.3. Results from the Perspective of Participating Technologies

We compared the different scenarios from a participant technology perspective by energy, profit, specific energy purchase costs, number of balancing participation, and their average duration. Energy and profit data were used to specify the participation profile. Is more energy consumed or produced? Did a technology manage to generate profit from the participation in smart balancing, or was money lost? This information was used to assess the suitability of the different approaches for the single technologies. To give a more detailed assessment of the balancing behavior, the number of balancing actions was counted, and the average duration of the balancing action was calculated. In the case of a very short duration, it might be necessary to do further investigations on the impact of rapid load changes on the plants' operation and lifetime. The comparison of total profits and energy included the installed capacity and balancing potential of the single technologies. For a comparison of the monetary benefit for the participating technologies, therefore, the specific energy purchase costs were analyzed.

3.3.1. Technologies

In a first step, the single technologies' total energy balance and their overall profit were investigated. The energy balances are visualized in Table 12, and related profits can be read from Table 13. To enable a good overview about all technologies and scenarios, the values for energies and profits were simplified and clustered as described in Table 14.

Solar power plants achieved monetary benefits by reducing their feed-in in more than half of the scenarios. Exceptions were TL2, TL5, and the DE approach based on historic data. The same applied for wind onshore and wind offshore.

Aluminum and steel gained profits by reducing their demand. This applied for all scenarios including the exception that steel did not participate in the scenarios based on synthetic data. The revenues from demand reduction varied between 61 and 143 EUR/MWh for aluminum and from 105 and 234 EUR/MWh for steel.

Table 12. Overview of the technologies' energy balance in the investigated scenarios.

Scenario	Sol	WOn	WOf	Gas	Alu	Ste	Cem	Pap	Chl
Historic data									
2 TL2	- - -	- - -	- - -	+	++	+++	+	+	+
3 TL5	- - -	- - -	- - -	+	++	+++	+	+	+
4 DE	- -	- -	- - -	+++	+++	0	- - -	- - -	- - -
5 NL	-	- -	- - -	+++	++	0	- - -	- - -	- - -
Synthetic data									
7 DEs	-	-	-	+++	++	0	- - -	- - -	- - -
8 NLs	–	-	- -	++	+++	0	- - -	- - -	- - -
10 BEPP: 15 min	- - -	- - -	- - -	-	+++	0	- - -	- - -	- - -
12 BEPP: 1 min	- -	- -	- -	+	+++	0	- - -	- - -	- - -

In the TL2 and TL5 scenarios, cement, paper, and chlorine also reduced their demand for revenues between 108 and 127 EUR/MWh. In the other scenarios, the three technologies increased their demands and achieved profits that way. In the case of the DE approach, cement and chlorine had additional costs of 0.8 and 4.1 EUR/MWh for increasing their demand. In the other scenarios, profits from 5 to 127 EUR/MWh were made.

Gas power plants mainly increased their production. There was only the BEPP 15-min scenario where production was decreased. Profit was generated in all cases. The revenues from lowering the production varied between 81 and 1373 EUR/MWh.

In scenarios based on synthetic data, the contribution of renewables and metal industries were generally less than those of the remaining industries and the gas power plants. In the NL scenario based on historic data, average values of below two minutes were observed for renewables, which was very short. The TL2 and TL5 approaches generally led to durations above 8 min for all technologies.

Table 13. Overview of the technologies' profit in the investigated scenarios.

Scenario	Sol	WOn	WOf	Gas	Alu	Ste	Cem	Pap	Chl
Historic data									
2 TL2	- - -	- - -	- - -	+	+++	+++	+++	+++	+++
3 TL5	- - -	- - -	- - -	+	++	+++	+++	+++	+++
4 DE	- - -	- - -	- - -	+++	+++	0	-	++	–
5 NL	+++	+++	+++	+++	++	0	++	+++	++
Synthetic data									
7 DEs	+	+	+	+++	+	0	++	++	++
8 NLs	+	+	+	+++	++	0	++	++	++
10 BEPP: 15 min	+++	+++	+++	+++	+++	0	+++	+++	+++
12 BEPP: 1 min	++	++	++	+++	++	0	++	++	++

Table 14. Legend for Tables 12 and 13.

Energy	
+	increase production = decrease consumption
-	decrease production = increase consumption
Profit	
+	profits
-	losses
Ranges	
+++/- - -	x > 2/3 of technologies maximum/minimum value
++/- -	1/3 < x < 2/3 of technologies maximum/minimum value
+/-	1/20 < x < 1/3 of technologies maximum/minimum value
0	x < 1/20 of technologies maximum/minimum value

3.3.2. Overall Comparison

To be able to compare the benefit of the different scenarios for the single technologies, the specific costs or profits of the technologies smart balancing contributions were regarded. Therefore, it was distinguished whether there was an additional energy purchase or an increased production. A successful additional purchase might lead to costs lower than the average energy purchase costs. This is of importance for consumers like the industrial plants. In the case of renewable energy plants, changes in generation were successful only if profits were achieved by that, since there were no production costs to be saved. In the case of the gas power plants, both cases were possible. Table 15 gives an overview of the technologies' specific profits in the different scenarios. As a reference, always the maximum profit from the regarded technology was chosen. The values for specific profits were simplified and clustered, as described in Table 16.

Table 15. Overview of the technologies' specific profits in the investigated scenarios.

Scenario	Sol	WOn	WOf	Gas	Alu	Ste	Cem	Pap	Chl
Historic data									
2 TL2	(-)	(- -)	(-)	+	+++	++	+++	+++	+++
3 TL5	(- - -)	(- - -)	(- - -)	+	+++	++	+++	+++	+++
4 DE	(- -)	(- - -)	(- -)	+	+++	+++	-	+	-
5 NL	+	+	+	+	+++	+++	+	+	+
Synthetic data									
7 DEs	++	+++	+++	+	++	none	+	+	+
8 NLs	++	++	++	++	++	none	+	+	+
10 BEPP: 15 min	+++	+++	+++	+++	+++	none	++	++	++
12 BEPP: 1 min	++	++	++	+++	++	none	+	+	+

Table 16. Legend for the table.

Specific Profit	
+	profits
-	costs for energy purchase
(-)	costs from energy sales = losses
none	no values
Specific profits	
+++	x > 2/3 of technologies maximum profit
++	1/3 < x < 2/3 of technologies maximum profit
+	1/20 < x < 1/3 of technologies maximum/profit
Specific energy purchase costs	
-	x > 1/3 of technologies maximum profit
- -	1/3 < x < 2/3 of technologies maximum profit
- - -	2/3 < x < 1 of technologies maximum profit

From Table 15, it can be seen that the specific profits were more consistent in the synthetic data-based scenarios. The TL scenarios offered high profits for industries, but also losses for renewables. In the historic data scenarios, only the NL approach led to profits for all technologies. The highest specific profits were observed in the BEPP 15-min scenario, but also, the BEPP 1-min scenario had high specific profits. A comparison with the total profits confirmed the NL scenario and the BEPP 15-min scenario as the most profitable scenarios for all technologies.

3.3.3. Summary/Conclusions Technologies

From the evaluation of the single technologies' data, it can be seen that the consistency between the data of different technologies was higher in scenarios based on synthetic data than in the scenarios based on historic data. Based on synthetic data, the highest revenues could be achieved in the BEPP 15-min scenario.

4. Discussion

Based on the model presented in Section 2, the simulation outcomes showed the effects different smart balancing schemes could have if applied in Germany. The impacts of the imbalance pricing (single vs. combined) and the method of balancing energy clearing (pay-as-bid vs. marginal pricing with 15-min BEPP vs. marginal pricing with 1-min BEPP) were quantified. The results supported the initial hypothesis that smart balancing can reduce the ACE closed loop and the demand for balancing energy activated via FRR products. In all considered scenarios, the demand for balancing energy and related costs were reduced by active smart balancing.

As expected, especially the reduction of manual FRR balancing energy was a direct consequence of smart balancing, since large system imbalances sustained for several ISPs were especially suitable for BRPs to support the system without taking high risks that the direction of the system imbalance changes and the imbalance price results in costs rather than revenues.

Regarding the FRR settlement, results were surprisingly similar when comparing pay-as-bid and marginal pricing in all the settings with each other. The potential of smart balancing was apparently not mainly driven by marginal pricing with a BEPP of 15 min. Nonetheless, a disclaimer has to be made for the applied pay-as-bid and marginal bidding curves with the synthetic data in our simulations. In cases where prices of balancing energy bids are more volatile and extreme, smart balancing would probably lead to better results in a marginal pricing scheme rather than in a pay-as-bid scheme.

The results were more driven by the technology chosen to contribute to smart balancing, especially since the demand-side integration technologies mainly provided downward energy in the simulations. For an application of smart balancing in Germany, the obtained real effects will obviously deviate from the presented effects.

For a gradual implementation of smart balancing in Germany, the traffic light concept might be a concept to be considered. Independent of the chosen layout of the German imbalance price calculation based on a PICASSO cycle-based BEPP, such a concept could support Germany during system scarcity and persistent imbalances exposed to the system.

Secondly, it is recommended to apply a combined pricing for imbalance in case the German system is exposed to zero-crossings.

Future research may focus on how active smart balancing could work best within the emerging European platforms IGCC and PICASSO. The damping effect of changing the BEPP in a future marginal clearing environment, including effects on the MOL, should be analyzed with higher accuracy. Regarding the applied fuzzy logic, further investigations on the effects of tuning fuzzy sets, fuzzy rules, type of inference, defuzzification technique, and type-1 vs. type-2 fuzzy logic can improve the understanding of market response. Other smart balancing algorithms could also lead to similar results, and future work could investigate the effect of replacing the fuzzy logic by conventional decision trees or applying machine learning. On the other hand, simulation-based research cannot predict the real market behavior without big uncertainties, as described in Section 2.4. This limitation leads to the need for field tests to generate more profound knowledge about active smart balancing and its value.

5. Conclusions

The simulation with synthetic ACE and MOL confirmed the findings from the pay-as-bid simulations with historic data. Combined pricing is more beneficial than single pricing. The scenarios with combined pricing and marginal clearing could benefit from smart balancing and reduce the demand for balancing reserves in a similar range, but related costs substantially decreased only in the case of a 1-min BEPP. This could be traced back to the limited reflection of bidding behavior, as no difference between the two marginal pricing scenarios (BEPP15 vs. BEPP1) was assumed. Nevertheless, the result that smart balancing saved a higher share of the total costs with pay-as-bid pricing confirmed the correlation between cost and imbalance occurrence, illustrated in Figure 3. The results were considered to be plausible, because BRPs would have generated profit with their behavior.

Other findings could be made from defining the smart balancing decision making process of BRPs in the first place. Implementing a fuzzy logic which leads to profit for BRPs is required to limit the reaction in order to prevent overreaction and financial losses, as described in Section 2 and Appendix A. Nevertheless, the introduction of active smart balancing could lead to overreaction and financial losses on the first day. An optimization of smart balancing, similar to the tuning of fuzzy rules, might be seen in real operations. This hypothesis is supported by the observations made in The Netherlands in 2001, when the smart balancing was introduced and improved over time [9].

As a consequence, to reduce the risks from potential overreactions, a damping of smart balancing with the traffic light approach or a limitation of financial incentives could be chosen for a first introduction period. Pay-as-bid clearing and marginal clearing with a short BEPP would limit the incentive in comparison to marginal pricing with 15-min BEPP. On the other hand, the optimization of BRPs could make damping unnecessary.

In contrast to the reduction of demand and costs for balancing energy, the simulation indicates that smart balancing might have a negative effect on the overall frequency stability at the transition form one ISP to the next. The higher deviation and lower minimum and higher maximum of the frequency result from the fast reaction, especially at the end of each ISP, when all BRPs return to their schedule. Such an extreme behavior is not seen in real operations in The Netherlands and Belgium, but the smart balancing logic in the simulation led to this fast behavior in response to the uncertain source of the ACE, which also reflected scheduled energy exchanges with other control blocks and can, therefore, change in the beginning of an ISP.

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Abbreviations

The following abbreviations are used in this manuscript:

AEP	imbalance price (Ausgleichs-Energie-Preis)
ACE	Area Control Error
aFRR	automatic activated Frequency Restoration Reserves
BEPP	Balancing Energy Pricing Period
BRP	Balance Responsible Party
DE	Germany (Deutschland)
EB GL	Electricity Balancing Guideline
FRR	Frequency Restoration Reserves
IGCC	International Grid Control Cooperation
ISP	Imbalance Settlement Period
mFRR	manually activated Frequency Restoration Reserves
MOL	Merit-Order-List
MC	Marginal Clearing of balancing energy
NL	Netherlands
PAB	Pay-As-Bid clearing of balancing energy
PICASSO	The Platform for the International Coordination of aFRR and Stable System Operation

SB	Smart Balancing
TL2	traffic Light with two increments
TL5	traffic Light with five increments
TSO	Transmission System Operator

Appendix A. Fuzzy Logic Input Parameters, Membership Functions, and Rules

Section 2.3.3 introduces the applied fuzzy logic, representing the decision of BRPs with smart balancing potential in the model. The input parameters represent all relevant information for smart balancing. The fuzzy rules were developed in order to analyze different imbalance clearing schemes (single and combined clearing). In a last step, the fuzzy membership functions were optimized until the decisions of BRPs led to profit rather than overshoots and financial losses.

Input parameters were distributed into fuzzy logic membership functions to apply the fuzzy rules. Table A1 gives an overview about the used parameters, the used number of fuzzy membership functions, and the style of definition. A uniform distribution in a given number of membership functions is referred to as "auto". Other distributions are defined individual.

Table A1. Overview of assumed profit optimization parameters of BRP.

Parameter	Membership Functions	Section Style
Imbalance	5	5 individual
Power contribution	5	5 individual
Time	3	3 individual
Change of imbalance sign	2	2 individual
Output: smart balancing	5	5 auto

Table A2 shows the wording of the membership functions. After the definition of fuzzy logic membership functions, fuzzy logic rules can be applied.

Table A2. Overview of profit optimization parameters of BRP.

Parameter	Section Wording	Section Shifts at
Imbalance	neg high, neg average, close to zero, pos average, pos high	−1150, −900, −350, 350, 900, 1150
FRRsum	neg high, neg average, close to zero, pos average, pos high	−1150, −900, −350, 350, 900, 1150
Time	early, middle, late	3.5, 10.5
Change of imbalance sign	no change, change	0.5
Output: smart balancing	poor, mediocre, average, decent, good	auto (0 to 100)

The applied fuzzy logic rules depend on the chosen market design. Different rules apply with changing market design, as summarized in the following Tables. Time-related rules are similar, because the risk assessment of changing incentives is improving over time within each ISP.

Table A3 shows fuzzy logic rules with the German approach of single pricing. "FRRsum" means all activated FRR energy in the current ISP, which was set to zero in the beginning of each ISP. This value represents the risk of a changing sign of the single imbalance price.

Table A3. Overview of fuzzy logic rule set for single pricing (DE).

Rule	Input: If ...	Output: SB Is ...
SP 1	Time is early	mediocre
SP 2	Time is middle	mediocre
SP 3	(Time is late) AND (FRRsum is (neg average OR pos average))	mediocre
SP 4	(Time is late) AND (FRRsum is (neg high OR pos high))	average
SP 5	(Time is late) AND (FRRsum is close to zero)	poor
SP 6	(Imba sign is no change) AND (FRRsum is (neg OR pos high))	good
SP 7	(Imba sign is no change) AND (FRRsum is (neg OR pos average))	decent
SP 8	FRRsum is close to zero	poor

Table A4 shows fuzzy logic rules with the Dutch approach of combined pricing. Imbalance means the ACE in the current time step. This value represents the risk of changing to dual pricing in the combined pricing approach.

Table A4. Overview of fuzzy logic rule set for combined pricing (NL).

Rule	Input: If ...	Output: SB Is ...
CP 1	Time is early	mediocre
CP 2	Time is middle	mediocre
CP 3	(Time is late) AND (Imbalance is (neg average OR pos average))	mediocre
CP 4	(Time is late) AND (Imbalance is (neg high OR pos high))	average
CP 5	(Time is late) AND (Imbalance is close to zero)	poor
CP 6	(Imbasign is not changed) AND (Imbalance is (neg OR pos high))	good
CP 7	(Imba sign is not changed) AND (Imbalance is (neg OR pos average))	decent
CP 8	Imbalance is close to zero	poor
CP 9	Imba sign is changed	poor
CP 10	Imba sign is not changed	average

The presented scenarios are based on these parameters and rules.

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