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Martin Håberg

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Thesis for the Degree of
Philosophiae Doctor
Faculty of Information Technology and Electrical
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Summary

At the heart of the electricity system, a System Operator (referred to as Transmission System Operator (TSO) in Europe) faces the crucial task of coordinating the continuous balance between generation and consumption. Using forecasts and measurements, the TSO counteracts an imbalance by instructing flexible generators or consumers to deliver balancing energy by increasing or decreasing their level of generation or consumption. In some European countries, the TSO minimizes the cost of balancing the system through an organized balancing energy market, where service providers compete by offering balancing energy in one direction or the other as a product, at a price.

Aiming to increase efficiency, competition and security of supply, these markets are in the process of integration. For all their differing views and operational practices, European TSOs are now jointly developing new market platforms to facilitate exchange of balancing energy, and are facing consequential design decisions. The centerpiece of each balancing platform is the Activation Optimization Function (AOF), where balancing energy bids are selected for activation to satisfy the balancing demands of all TSOs. Standard products, with certain technical characteristics agreed on by TSOs, will be used for balancing energy exchange.

This thesis addresses the design of the integrated European balancing energy market. Centering around the process of activating balancing energy, it aims to identify designs that allow efficient utilization of different balancing resources and avoids congestion in the transmission network. The research includes analyses of design elements proposed for the balancing platforms under development, as well as methodological contributions representing alternative designs of the market optimization and related processes.

A set of new model formulations are presented for activation of balancing energy, focusing especially, but not exclusively on mFRR. In contrast to traditional market clearing formulations, these models are capable of optimizing activation of *multiple* balancing products, with different characteristics. Here, activation schedules are created for each individual bid over a scheduling horizon, with a number of operational constraints ensuring feasible activation patterns for each product. This approach augments competition to incorporate not only bid prices and locations, but also their technical characteristics.

The thesis demonstrates models for proactive TSOs to coordinate the interplay between products, giving advice on what balancing volumes to defer to a later process, closer to real time. In addition to a deterministic strategy based on alternative costs, a stochastic activation model formulation provides particularly interesting results. By taking imbalance uncertainty into account, balancing resources are utilized more efficiently, shifting activation volumes toward more flexible balancing products, and reducing balancing costs under imperfect imbalance forecasts.

Balancing energy activations and exchange impacts power flows in the transmission network, and the proposed zonal market structure requires intra-zonal congestion to be handled in an external process. With inadequate time for redispatch after balancing energy bids have been selected, TSOs must resort to determine, before the fact, which balancing energy bids could lead to congestion if activated. The thesis provides a generalized method to pre-filter bids, taking into account a range of possible balancing energy exchange situations. Another methodological contribution is the new, complementary concept of exchange domains, preventing infeasible balancing exchange situations by imposing additional constraints in the balancing optimization. Regardless of its implementation, the concept of pre-filtering bids is found to be fundamentally inefficient, detrimental to market participants and incapable of preventing congestion in certain cases.

Acknowledging these shortcomings of zonal activation models in the balancing timeframe, approaches to take intra-zonal congestion into account within the market optimization are also considered. As an alternative to purely zonal and nodal markets, this thesis presents a distributed balancing model. While keeping an overarching zonal structure, the decoupling of individual zones enables dispatch autonomy, thereby allowing nodal and zonal formulations in the same market clearing. Going forward, TSOs should pursue opportunities to improve both efficiency and operational security by incorporating transmission limitations in balancing decisions.

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List of Abbreviations

ACE Area Control Error

ACER Agency for the Cooperation of Energy Regulators

aFRR Frequency Restoration Reserves with Automatic Activation

AOF Activation Optimization Function

ATC Available Transfer Capacity

BRP Balance Responsible Party

BSP Balancing Service Provider

CMOL Common Merit Order List

CNE Critical Network Element

CoBA Coordinated Balancing Area

DC OPF DC Optimal Power Flow

EBGL Guideline on Electricity Balancing

EMPS EFI's Multi-area Power-market Simulator

ENTSO-E European Network of Transmission System Operators for Electricity

EUPHEMIA EU Pan-european Hybrid Electricity Market Integration Algorithm

FAT Full Activation Time

FCR Frequency Containment Reserves

FRR Frequency Restoration Reserves

IGCC The International Grid Control Cooperation

ISP Imbalance Settlement Period

LFC Load-Frequency Control

LMP Locational Marginal Price

MARI Manually Activated Reserves Initiative

mFRR Frequency Restoration Reserves with Manual Activation

MILP Mixed Integer Linear Programming

MIP Mixed Integer Programming

MPC Model Predictive Control

NRA National Regulatory Authority

NTC Net Transfer Capacity

PICASSO The Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation

PSST Power System Simulation Tool

PTDF Power Transfer Distribution Factor

RR Replacement Reserves

T&Cs Terms and conditions

TERRE Trans European Replacement Reserves Exchange

TSO Transmission System Operator

Chapter 1

Introduction

Operating the electricity system is a coordinated act of schedules, forecasts and adjustments. Electricity consumption is largely predictable in the short run, but power generation —in particular from renewable sources— will not always follow production schedules. Imbalances, i.e. mismatch between generation and consumption, leave the electricity system vulnerable to disturbances. To safeguard the system, a system operator (referred to as Transmission System Operator (TSO) in Europe) is responsible for counteracting these imbalances through a continuous process of monitoring and adjustments, known as *balancing*. Since the possibilities of storing electricity are very limited, the TSO instructs flexible generation and consumption units, providing *reserve capacity*, to change their level of generation or consumption to meet the needs of the system, thereby delivering *balancing energy*. Growing amounts of intermittent renewable generation entails increased uncertainty and variability. This makes secure and efficient electricity balancing operations an absolute necessity, and as such, this process of adjustments plays a crucial role in decarbonizing the electricity sector.

Following the general trend of liberalization in the electricity system, some countries have developed balancing markets, with competition between suppliers of balancing services to the system operator. In addition to markets for procurement of reserve capacity, several European TSOs make adjustments to the power balance during real-time operation through a balancing energy market. In this market, a supplier offers balancing energy in the upward or downward direction (or both), at a price and maximum volume specified in a balancing energy *bid*. The TSO activates as many of these bids as necessary to cover the imbalance, starting with the least expensive ones. Under this paradigm, balancing energy is considered not only an adjustment in a physical system, but also a commercial product. With differing system characteristics and operational practices between European TSOs, balancing products are subject to diverging technical requirements (e.g. on activation time). Moreover, due to differing market rules and limited cross-border cooperation in the balancing phase, balancing energy markets in Europe are currently fragmented, and mostly national.

European TSOs are jointly developing new, common market platforms for activation and exchange of balancing energy. This integration of European balancing markets aims to increase the security of supply and facilitate competition across borders, and is subject to rules and regulations put forward in the Guideline on Electricity Balancing (EBGL) [1], developed by European Network of Transmission System Operators for Electricity (ENTSO-E). TSOs will participate on a balancing platform by submitting their demand for balancing energy, together with cross-zonal transmission capacities and a list of locally available balancing energy bids. The central element of each balancing platform is the Activation Optimization Function (AOF), responsible for selecting balancing energy bids to cover the balancing demands of all TSOs through an optimization process. To facilitate competition and exchange, only bids representing *standard products* (a list of balancing products agreed on by TSOs) can be activated through the common balancing platforms.

In designing an integrated European balancing market, TSOs face some consequential decisions. Several of these concern how to optimize balancing energy activation, considering the diverging designs of current balancing markets, the introduction of standard products, and the diversity of balancing resources. Moreover, decisions on balancing energy activation and exchange can have a significant impact on network flows, raising questions on which measures are appropriate to avoid congestion in the transmission network, particularly *within* market zones. TSOs balancing their systems using the new European platforms could also face more complex operational decisions, including considerations on which balancing energy bids could lead to congestion, how to take uncertainty in the imbalance forecast into account, and to apportion their demand for balancing energy across different balancing products and processes.

1.1 Subject Matter and Scope

With the starting point of fragmented, mostly national balancing markets and a diverse range of balancing products and philosophies, the overarching problem addressed in this doctoral work can be summarized as *identifying designs for the European balancing energy market that allow efficient utilization of different balancing resources and avoids congestion in the transmission network.*

In pursuit of this objective, the conducted work gravitates around three topical areas. The first is the topic of *balancing strategies and coordination of multiple balancing processes*. This research investigates the character of balancing energy activation strategies in different European balancing markets, and also takes on the strategic question of how a proactive TSO can coordinate activation volumes between different balancing processes.

The second topic concerns *models for activation optimization of multiple standard products*. Here, a key issue is how to decide manual control actions to balance the system when simultaneously considering activation from balancing products with different technical characteristics. Two secondary issues are also considered under this topic: taking into account uncertainty in the imbalance forecast and transmission network constraints.

The third topic delves into the issue of *managing intra-zonal congestion under different balancing exchange arrangements*, following two different paths. The first path takes the perspective of the TSO, aiming to prevent intra-zonal congestion before the clearing of the European balancing market. The second path explores opportunities for preventing for network congestion *within* the market clearing through an alternative design of the optimization process.

As reflected by the issues mentioned above, the research work takes an almost exclusively European perspective, providing discussions and methodological contributions in the context of the upcoming integrated European balancing market. Within this context, the focus is on balancing energy, rather than reserve capacity, and primarily on processes related to activation optimization and congestion management, often centering around the use of mFRR. The degree of detail and assumptions made differ between the proposed models, depending on their proposed setting and underlying assumptions. Moreover, for the methods proposed throughout the thesis and accompanying papers, attention is paid mainly to principal models and fundamental analyses rather than large-scale simulations over long horizons. As a result, implementations of the proposed methods focus mostly on systems of limited scale, rather than large data sets.

1.2 Contributions

The decision to establish an integrated European balancing market has led to the implementation of common platforms for balancing energy exchange. While discussing and reflecting on the implications of market design choices made for these platforms, the research contributions of this thesis provide alternative and complementary designs of the activation optimization and related processes. The main contributions can be summarized as follows:

Multi-product balancing optimization models. Development of new model formulations for activation of balancing energy, adequately reflecting the feasible activation patterns and limitations of products with different technical characteristics, such as full activation time and minimum duration. Such models are can also be used by TSOs to coordinate balancing energy demand across different balancing products and processes.

Methodologies for managing network congestion in zonal markets. This includes a procedure to disqualify reserves leading to congestion, and the new, complementary concept of *exchange domains*. Both elements aim to mitigate congestion by changing the input to the balancing market clearing, not its structure.

Distributed balancing energy optimization. Development of an alternative market model offering some of the advantages of nodal pricing models by taking transmission limitations into account, while keeping an overarching zonal structure, using spatial decomposition and a hybrid nodal-zonal approach.

1.3 List of Publications

Whereas this thesis encompasses a broader perspective on the subject of balancing energy exchange, seven individual publications convey its main research contributions. These are divided between the three focus areas related to Chapters 3, 4 and 5.

Publication I M. Håberg and G. Doorman, "Classification of balancing markets based on different activation philosophies: Proactive and reactive designs", in *2016 13th International Conference on the European Energy Market (EEM)*, IEEE, Jun. 2016.

Publication II M. Håberg and G. Doorman, "Proactive planning and activation of manual reserves in sequentially cleared balancing markets", in *2017 IEEE Electrical Power and Energy Conference (EPEC)*, IEEE, Oct. 2017.

Publication III M. Håberg and G. Doorman, "Optimal Activation of Standard Products for Balancing as Required by Draft ENTSO-E Network Codes", in *CIGRE International Colloquium on the Evolution of Power System planning to support connection of generation, distributed resources and alternative technologies*, Philadelphia, PA, 2016.

Publication IV M. Håberg and G. Doorman, "A Stochastic Mixed Integer Linear Programming Formulation for the Balancing Energy Activation Problem under Uncertainty", in *2017 IEEE Manchester PowerTech*, 2017.

Publication V J. Bøe, M. Håberg and G. Doorman, “Multi-Area Balancing Energy Activation Optimization Using ENTSO-E Standard Products”, in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, IEEE, Oct. 2018.

Publication VI M. Håberg, H. Bood and G. Doorman, “Preventing Internal Congestion in an Integrated European Balancing Activation Optimization”, *Energies*, vol. 12, no. 3, Feb. 2019.

Publication VII M. Håberg and G. Doorman, “Distributed balancing energy activation and exchange optimisation”, *IET Generation, Transmission & Distribution*, vol. 13, no. 18, Sep. 2019.

Three additional articles were published as a result of related research work, but these do not comprise the foundation of the thesis.

Publication VIII C. Guntermann, N. W. Gunderson, E. Lindeberg and M. Håberg, “Detecting unavailable Balancing Energy Bids due to Risk of Internal Congestions”, in *18th International Conference on Environment and Electrical Engineering (EEEIC)*, Palermo, Italy, 2018.

Publication IX M. Håberg, K. S. Hornnes and K. Dalen, “Design and Implementation of a Selective Load Curtailment Program for Managing Strained Transmission Grid Operation”, in *2017 CIGRE Dublin Symposium*, Dublin, 2017.

Publication X M. Håberg, “Fundamentals and recent developments in stochastic unit commitment”, *International Journal of Electrical Power & Energy Systems*, vol. 109, Jul. 2019.

1.4 Outline and Structure

This thesis centers around the three focus topics from Section 1.1, and is structured accordingly. Chapter 2 provides background material on electricity balancing and balancing markets, largely following a European perspective. The chapter describes recent developments in balancing market integration in detail. Being complemented by extracts from relevant scientific contributions, it establishes the paradigm in which the subsequent chapters and accompanying publications can be read and understood.

The three focus topics of the thesis are covered separately in Chapters 3-5. Each chapter contains a specific introduction of the relevant research questions, as well as a detailed context establishing the key predecessor contributions and important assumptions. For each publication, an extended summary is included inside the chapter, while publication manuscripts are located in Chapter 7. Each of the focus topic chapters ends with a discussion of findings and implications. Chapter 6 provides the main conclusions and provides indications for further work.

Chapter 2

Electricity Balancing

As society has become critically dependent on a reliable supply of electricity, modern power systems have grown to comprise large, interconnected networks of electrical infrastructure. Transmission and distribution networks are used to efficiently and securely deliver electricity from generation facilities to where it is consumed. Electric energy is transferred near the speed of light, and storing electricity in large amounts has traditionally been considered costly and impractical. The power system can therefore be considered a system of just-in-time delivery, with efforts closely monitored and coordinated by a System Operator, in Europe often referred to as a Transmission System Operator (TSO).

Among the most crucial operational tasks of a TSO is securing the net balance between generation and consumption. TSOs continuously monitor and adjust this power balance through activation of reserves, with different control processes in play to maintain scheduled net positions in different areas, and keep the system frequency close to its nominal value. At the same time TSOs must avoid violation of various operational constraints, including voltage and dynamic stability limits, thermal capacity limits on network components, and reliability considerations in the face of contingencies.

In Europe, balancing operations are undergoing a transformation together with other parts of the power system. A widespread introduction of intermittent generation resources and changing consumer behavior change the traditional patterns of consumption and generation, posing a balancing challenge. At the same time, transmission networks are extended throughout Europe[1] to support decarboniza-

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[1] These efforts are coordinated through the ENTSO-E network development plans, with an online project overview at tyndyp.entsoe.eu.

tion and secure access to electricity, offering more capacity between countries and synchronous areas. On top of this, new European market arrangements expand the opportunities for TSOs to cooperate on balancing operations by exchanging balancing energy across national borders.

This chapter provides background material on electricity balancing[2], keeping a European perspective and providing a foundation for the research presented in subsequent chapters of the thesis. The first two sections of this chapter introduce power imbalances and their origins, describing their relation to frequency deviations, and the control processes used by TSOs to maintain operational security concerning these issues. Section 2.3 describes the fundamentals of balancing markets in a European context, followed in Section 2.4 by a more detailed overview the integrated European balancing markets currently under development. The chapter concludes in Section 2.5 with a survey of literature on selected, particularly relevant electricity balancing topics.

2.1 Power Imbalances

Power imbalances denote net deviations between the electric power consumed and generated in a power system. These deviations can be caused by a number of factors and can have different dynamic characteristics.

A first reason is forecast errors, both on the side of consumption and generation. Consumption forecasts indirectly determine generation schedules through the electricity market. Such forecasts are weather dependent, and have limited accuracy, for example when temperatures turn out different than expected. Moreover, generation delivered from renewable sources like wind and solar is both variable and uncertain, with actual generation deviating from forecasted generation schedules. With growing penetration of generation from renewable energy sources, generation forecast errors is a major source of system imbalances.

A second reason is equipment failure. When generation facilities or large consumers are disconnected from the grid following an unexpected event, this leaves the system with a persistent power imbalance. Failure of transmission components can lead to partial blackouts or severe changes in cross-border flows. The synchronous grid is a dynamic system with a large number of control mechanisms involved, and large disturbances to the system frequency can also endanger

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[2] In ENTSO-E terminology, 'balancing' means all actions and processes, on all timelines, through which TSOs ensure, in a continuous way, the maintenance of system frequency within a predefined stability range as set out in Article 127 of [12], and compliance with the amount of reserves needed with respect to the required quality, as set out in Part IV Title V, Title VI and Title VII of [12].

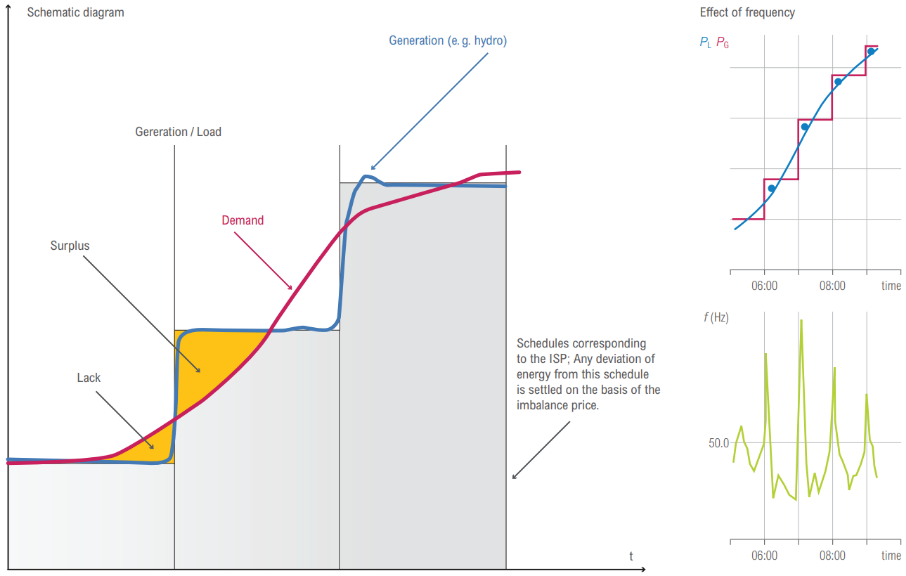

Figure 2.1: Impacts of fast changes in the output of generation/consumption on frequency (Source: University of Stuttgart) [13].

its dynamic stability if disconnections happen in an abrupt manner.

A third reason is the market structure. In current European electricity market rules, generation and consumption schedules are considered energy blocks. This causes an incoherence between generation schedules and the continuously evolving consumption profile [13] especially in markets with hourly time resolution. In addition, market rules generally incentivize market participants to stay balanced during the market period, leading to some generators adjusting their output as late as possible, resulting in an almost stepwise generation profile. These discrepancies between generation and consumption patterns are sometimes referred to *structural imbalances* [14], and may have a pronounced effect around the hour shift (cf. Fig. 2.1). Even though this effect is largely predictable, it leads to so-called deterministic frequency deviations.

In the Nordic system, the trend of increasing imbalances is a concern to the TSOs [15], entailing a clear and decisive trend of deteriorating frequency quality. The Nordic TSOs aim to counter this development not only by procuring more reserves, but also by redesigning and developing new common market-based balancing solutions, known as the Nordic Balancing Model[3]. This redesign comprises several elements. Among the most crucial ones are the transition towards 15-minute res-

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[3] http://nordicbalancingmodel.net/

olution in the balancing market, partitioning the synchronous system into a number of Load-Frequency Control (LFC) areas, extensive use of imbalance forecasts, and introducing common market platforms to coordinate activation and exchange of balancing energy.

2.2 Frequency Control and Balancing Processes

Disturbances impose operational security threats through frequency deviations. With the system consisting for a large part of synchronously rotating machinery, excessive loading of the system will consume some of its kinetic energy, causing it to decelerate and the system frequency to drop. Conversely, excessive generation will accelerate the synchronous system, leading to over-frequency. To avoid damaging components, protective relays will disconnect generating units if the frequency deviation goes beyond certain thresholds. At that point, the stability and operational security will be severely compromised, with interrupted electricity supply or even cascading blackouts.

The TSO uses different control mechanisms in the operational phase in order to safeguard the system from frequency deviations. As illustrated in Fig. 2.2, these control processes have different properties, and serve different purposes.

Following a disturbance to the system frequency, a number of local controllers distributed throughout the system will respond rapidly —within seconds— to adjust the power output of generators. This is a proportional control mechanism, using continuous frequency measurements as the control signal, with the aim of stabilizing, or *containing* the frequency within certain limits following a disturbance. In European systems, this control process is referred to as the Frequency Containment Process, with energy delivered by Frequency Containment Reserves (FCR). In other contexts, this concept is sometimes referred to as *primary control*.

To relieve frequency containment reserves and establish a buffer against future disturbances, the frequency must be *restored* to its nominal value. In ENTSO-E terminology, this is the target of the *Frequency Restoration Process*, using Frequency Restoration Reserves (FRR). This is a slower control mechanism compared to frequency containment. Frequency Restoration Reserves with Manual Activation (mFRR) should be fully deployed within 15 minutes, while Frequency Restoration Reserves with Automatic Activation (aFRR) will typically be fully activated faster, typically in 5 minutes, but also slower or faster in some European systems [17]. The latter follows a control error signal based on the principle of load-frequency control to continuously determine adjusted generation setpoints for each unit delivering balancing energy from aFRR. Whereas aFRR is recognized as a form of *secondary control*, mFRR is considered a means of *tertiary control*.

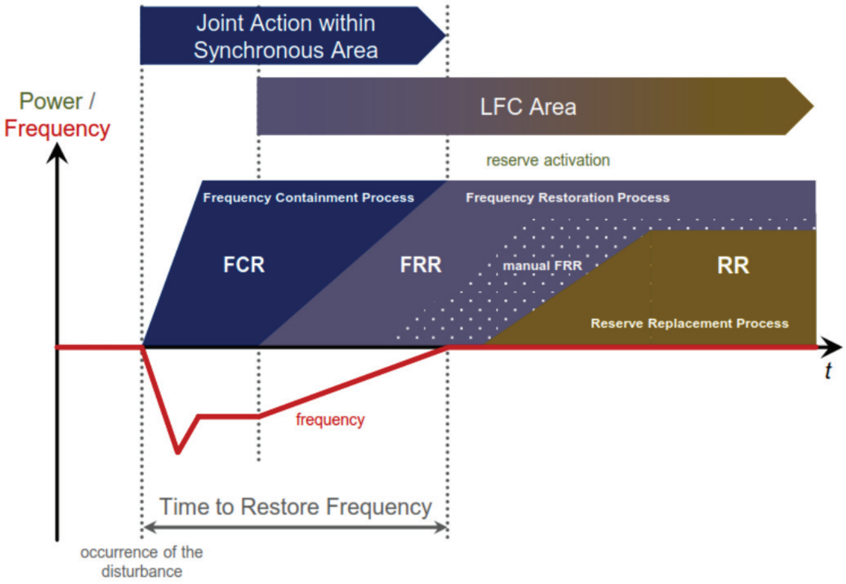

Figure 2.2: Frequency control processes and reserve activation following a disturbance [16].

FRR activation generally follows one of two patterns. In a *pro-rata* mechanism, all participating reserves are activated simultaneously, delivering balancing energy in a proportional manner based on a distribution key. In a *merit order* mechanism, reserves are selected for activation in sequential order, based on their submitted prices for delivering balancing energy. While a considerable number of European TSOs activate mFRR according to a merit order list, a large majority have so far applied pro-rata schemes for aFRR activation.

Some systems also counteract large, persisting imbalances through a *reserve replacement* process, using Replacement Reserves (RR). This control process establishes a second buffer by substituting balancing energy from activated FRR with other resources. Replacement reserves are activated manually when needed, and typically require more than 15 minutes to be fully activated.

Fundamental to both balancing cooperation and division of responsibility between TSOs is the *control hierarchy* of the power system, consisting of Load-Frequency Control (LFC) areas and LFC blocks (cf. Fig. 2.3 for an example from the Nordic system). In order to counteract imbalances in the area where they originate, the frequency deviation and tie-line control signals are combined into the so-called Area Control Error (ACE), thereby maintaining the scheduled inter-area exchange while also supporting the system frequency. Different concepts exist for balan-

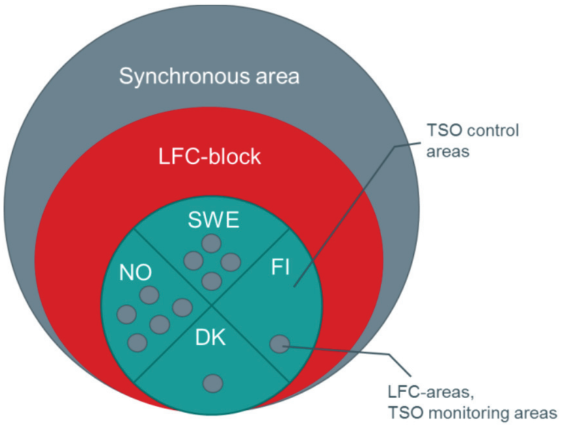

Figure 2.3: New LFC structure proposal in the Nordic synchronous area [19].

cing cooperation *between* TSOs using this hierarchy. In his thesis, de Haan [18] summarize these as *exchange* or *sharing of imbalances*, *exchange* or *sharing of reserves*, and *merged LFC blocks*.

2.3 Electricity Balancing Markets

Following the general trend of a liberalized electricity sector in Europe, market-based mechanisms have increasingly been employed also in activities related to electricity balancing. Under this paradigm, balancing markets as institutional arrangements are often described on an abstract level as consisting of three main components; balancing service provision, balance responsibility (or balance planning [20], [21]), and imbalance settlement [22], [23].

The framework in Fig. 2.4 illustrate the three components as the pillars of the market, each made up of a set of various elements, or *design variables*. On a detailed level, a variety of market designs exist, and Ocker, Braun and Will [25] conclude on the basis of reserve capacity auctions that there is no predominant balancing market design in Europe. Detailed issues related to balancing market design are revisited in Section 2.5.1, while the subsequent description only captures the general pattern of roles, responsibilities and interactions recurrent in many European countries.

Three main players interact in the balancing market. The Transmission System Operator (TSO) ensures secure system operation through procuring and employing two distinct services. Both of these services are provided by Balancing Service Providers (BSPs). Balance Responsible Parties (BRPs) are held financially

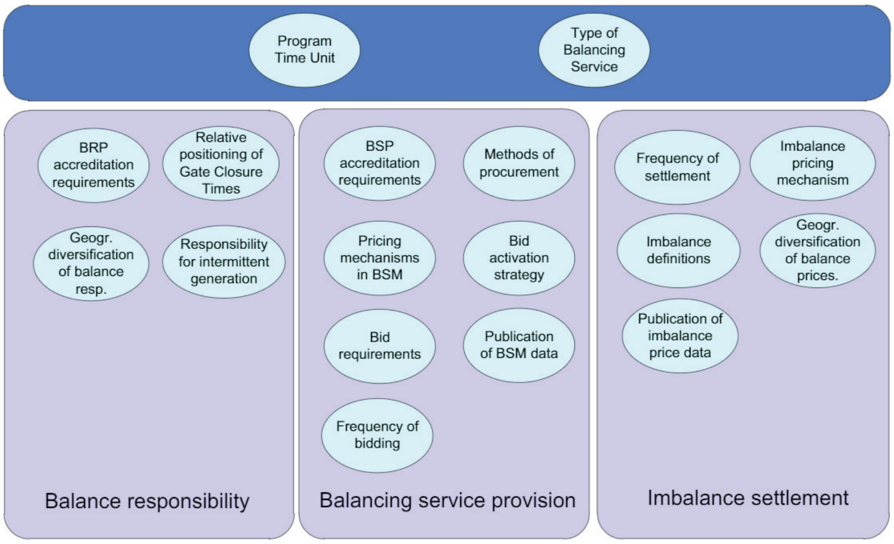

Figure 2.4: Balancing market design variables from Doorman and Van Der Veen [24]

responsible for imbalances imposed on the system due to deviations from their scheduled positions, and indirectly pay BSPs for their services, with the TSO traditionally acting as coordinator and single buyer.

The first balancing service is provision of *reserve capacity*. Flexible generation, consumption or storage units with the capability to adjust their power setpoints are allowed to offer reserve capacity, following a prequalification process demonstrating the unit's capability to meet given technical requirements. Rather than compulsory delivery, which has traditionally been the norm for FCR, reserve capacity for FRR and RR is contracted in a market-based manner in several European countries. In auctions at regular intervals, these flexibility providers offer their prices for keeping reserves available. The contracted reserves are remunerated and made available for activation.

The second balancing service is activation of *balancing energy*, i.e. adjusting the generation or consumption level of a participating unit to counteract the system imbalance and restore net positions in a given area. The balancing energy may be activated in the upward or downward direction, and can be delivered from contracted reserves or other flexible units with available capacity. In some European systems, including the Nordic countries, real-time activation of balancing energy from manual products is handled through a balancing energy market. Here, balancing resources are represented as balancing energy bids, submitted by BSPs, each with an associated activation price, maximum volume, as well as other characteristics. The system operator activates the required volume, striving to utilize the least expensive bids to cover the system imbalance.

In an imbalance settlement process, BRPs are held responsible for imposing imbalances on the system. Here, BRPs deviating from their net positions are penalized according to the imbalance price of the relevant Imbalance Settlement Period (ISP). This imbalance price may be at least partly based on a balancing energy market clearing price, determined by the balancing energy bids selected for activation. Depending on specific market rules, BRPs may also be incentivized and empowered to take an active role in balancing the system, profiting from imposing deviations opposite to the system imbalance, or they may be obliged to adhere to their schedules and leave the system-wide balancing to the TSO.

2.4 Integration of European Balancing Markets

European balancing markets are currently in a process of integration. This started with the regulations from the third Energy Package [26], [27], including requirements regarding common rules for an internal electricity market, and the establishment of ENTSO-E and ACER. In the years to follow, common rules and regulations for the balancing markets were proposed by ENTSO-E and formalized in the Guideline on Electricity Balancing (EBGL) [1]. Following the large differences between national balancing markets and arrangements, this guideline aims to facilitate cross-border exchange of balancing energy through introducing standardized products for balancing energy and reserve capacity, and common market platforms. This development is a natural extension of the ongoing integration of day-ahead and intraday electricity markets, aiming at increased social welfare through increased competition and trade. In addition, integrated balancing markets will to a larger extent enable TSOs to coordinate their balancing actions, and thus cope more efficiently with the expected increase in imbalances from renewable generation.

2.4.1 Standard Products for Balancing Energy

An important requirement in the harmonization of European balancing markets is the introduction of Standard Products for balancing energy and reserve capacity [1]. The products are defined by parameter values or ranges determining the characteristics of the balancing resource. Being jointly defined by the TSOs, they aim to facilitate sharing of reserves and exchange of balancing energy on common platforms, enabling direct competition between BSPs located in different areas.

During early phases of drafting EBGL, a working assumption was to exchange balancing energy using a *list of* standard products. The Activation Optimization Function would be given the task of selecting bids for activation, using the com-

Figure 2.5: Energy volume scheduled and settled at cross-zonal level in the TERRE project [29]

mon merit order lists for the different balancing products. With national balancing products serving as starting points, TSO discussions were initally concerned with building a portfolio of products to cover a range of provider capabilities and local market rules. In October 2015, an ENTSO-E survey featured a proposal of six manual standard products, two for RR and four for mFRR [28], Over the next years, pressure from ACER to reduce the number of standard products means most early proposals are now abandoned, aiming instead for a single standard product per balancing energy platform. This effectively establishes a unified market, where BSPs are expected to compete with each other more directly, evading misgivings about market fragmentation. On the other hand, there may be a potential backlash; if a TSO is not confident the characteristics of this standard product will serve its local system adequately, it may resort to using specific balancing products[4] with different properties. These specific products may provide the necessary performance, while at the same time eroding the potential efficiency improvements of balancing energy exchange.

Unquestionably, agreeing on *one* standard product per process allows design commonality with other market timeframes, and simplifies the design and operation of the balancing platforms considerably across a range of aspects, such as pricing, activation optimization and clarity of market results, and coordinating cross-border exchange schedules. It also simplifies the *financial settlement* between TSOs. These transactions depend on cross-border network congestion and prices in and price differences between market zones, as well as the scheduled exchange of balancing energy between them. To calculate for the manual processes (RR and mFRR) the balancing energy volume in a single 15-minute market period, an equivalent rectangular block is used, as illustrated in Fig. 2.5. This causes a discrepancy between the market schedules and the energy physically delivered, but enables balancing energy volumes to be settled according to the price in the period for which they were activated.

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[4] Balancing products used only locally, and not to be exchanged on common platforms [1].

Mode of activation	Manual
Activation type	Direct or scheduled
Full activation time (“FAT”)	12.5 minutes
Minimum quantity	1 MW
Bid granularity	1 MW
Maximum quantity	9,999 MW
Minimum duration of delivery period	5 minutes
Price resolution	0.01 €/MWh
Validity Period	A scheduled activation can take place at the point of scheduled activation only. A direct activation can take place at any time during the 15 minutes after the point of scheduled activation.

Table 2.1: Static characteristics of the proposed standard mFRR balancing energy product [30].

Price	in €/MWh
Location	At least the smallest of LFC area or bidding zone.
Divisibility	BSPs are allowed to submit divisible bids with an activation granularity of 1 MW. BSPs are allowed to submit indivisible bids pursuant to Article 7(3) of [30].
Technical linking between bids	BSPs are required to provide information on technical linking between bids submitted in consecutive quarter hours and within the same quarter hour
Economic link	Child with parent and exclusive group orders will be allowed

Table 2.2: Variable characteristics of the proposed standard mFRR balancing energy product [30].

Location	More detailed locational information, compared to what stated in Article 6(4), is defined in T&Cs for BSPs
Preparation Period	Defined in T&Cs for BSPs as long as it is compliant with the requirements set on the FAT in Article 7(1) of [30]
Ramping Period	Defined in T&Cs for BSPs as long as it is compliant with the requirements set on the FAT in Article 7(1) of [30]
Deactivation Period	Defined in T&Cs for BSPs as long as it is compliant with the requirements set on the FAT and on the minimum duration of delivery period in Article 7(1) of [30]
Maximum duration of delivery period	Defined in T&Cs for BSPs due to different requirements on preparation period, ramping period and deactivation period
Indivisible Bids	Maximum size of indivisible bids is defined according to T&Cs for BSPs
Minimum duration between the end of deactivation and the following activation	Defined in T&Cs for BSPs

Table 2.3: Characteristics of the proposed standard mFRR balancing energy product to be defined in the terms and conditions of BSPs [30].

The current proposals for standard product specifications are detailed as part of three implementation frameworks [30]–[32], and as of spring 2019, only the RR platform implementation framework has so far been approved by the relevant NRAs. In these documents, each standard product is defined through a set of characteristics that must be fulfilled by balancing energy bids for this product. Among these characteristics, some are *static* requirements to be fulfilled by all bids. As an example, Table 2.1 lists the static characteristics proposed by European TSOs for the standard mFRR product. Other characteristics are *variable*, meaning they are to be determined by the BSP providing the bid. These include *bid volume* and *direction* (upward or downward), as well as the other characteristics, cf. Table 2.2 for the mFRR product as an example. A final set of characteristics are to be defined in the terms and conditions (T&Cs) for BSPs, meaning they can be decided nationally with approval only from the local NRA. Again using the mFRR product as a reference, these characteristics are listed in Table 2.3.

2.4.2 Common Platforms for Activation and Exchange of Balancing Energy

In early drafts of EBGL, the integration strategy was built around so-called Coordinated Balancing Area (CoBA)s, comprising regional cross-border exchange arrangements and harmonization initiatives. The intention was to gradually adjust and merge these CoBAs into larger ones, with the final aim of one single, European Coordinated Balancing Area. Later, this strategy was abandoned in favor of individual multi-TSO projects for each of the different balancing processes. Today, there are four projects chosen by ENTSO-E to implement common European balancing platforms, concerning the reserve replacement, frequency restoration (automatic and manual), and imbalance netting processes[5].

The common platforms being developed for balancing energy exchange concern different control processes, yet they have commonalities revealing their common origin. As required by the EBGL, they all adhere to the use of standard products, common merit order lists, activation optimization functions, and the TSO-TSO model, meaning BSPs will only provide balancing services to other TSOs through their connecting (or local) TSOs. Congestion between market zones is managed through the use of cross-zonal capacity limits, in a similar way to day-ahead and intraday markets. To avoid network congestion inside market areas as well as other situations endangering operational security, the RR and FRR platforms allow TSOs to mark individual BSP bids as unavailable for cross-border activation.

Replacement Reserves: The TERRE Project

In 2016, the TERRE (Trans European Replacement Reserves Exchange) project obtained status as the official implementation project for a European platform for the exchange of balancing energy from replacement reserves. Only nine countries are full members of the project, reflecting the limited use of RR products among European TSOs. The project revolves around the development of an IT platform and AOF for use in a European RR market. The platform, named *LIBRA*, is expected to launch in late 2019.

The project has agreed on a standard RR product to be exchanged. Among the central characteristics are a full activation time of max 30 minutes, delivery periods between 15 to 60 minutes, and bid location specified by bidding zone. Bid activation volumes can be divisible or indivisible, and bid activations are selected in a scheduled process, i.e. through market clearing at fixed intervals. These clearings have three main sources of input: the available balancing energy bids from RR, the imbalance needs to be covered for each bidding zone, and the cross-zonal transmission capacity available for exchange of balancing energy.

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[5] Rather than activating and exchanging balancing energy from a bid, the imbalance netting process aims to avoid simultaneous FRR activation in opposite direction by through corrections of the control signals for the FRR process in two or more LFC areas

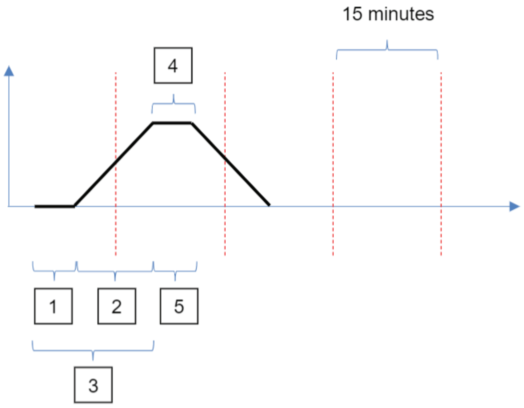

Figure 2.6: Example of a possible delivery profile of the mFRR standard product (assuming scheduled activation), according to [33].

Manually Activated Frequency Restoration Reserves: The MARI Project

The European implementation project for the mFRR platform was launched in 2017 as MARI (Manually Activated Reserves Initiative), and currently has 25 member TSOs. After drafting products, processes, and market rules in a design phase, the project is about to enter IT implementation, and the platform is expected to launch in 2022.

The standard balancing energy product to be exchanged between TSOs on the common mFRR platform has a few key characteristics, as illustrated in Figure 2.6[6] The Full Activation Time (FAT) is max 12.5 minutes, this includes a 2.5 minute preparation phase. By default, bids will be deactivated towards the end of the 15 minute ISP as soon as the 5 minute minimum delivery duration requirement is satisfied. In the current draft, BSPs are allowed to make their bid volume indivisible, as well as provide links between different bids. The location of each bid is set to at least the smallest of LFC area or bidding zone level.

Figure 2.7[7] outlines the interactions on the mFRR platform under development.

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[6] Explanations: 1. Preparation period. 2. Ramping period. 3. Full activation time. 4. Minimum duration of delivery period. 5. Maximum duration of delivery period.

[7] Explanations: 1. TSOs receive bids from BSPs in their imbalance area. 2. TSOs forward standard mFRR balancing energy product bids to the mFRR Platform. 3. TSOs communicate the available mFRR cross border capacity limits (CBCL) and any other relevant network constraints as well HVDC constraints. 4. TSOs communicate their mFRR balancing energy demands. 5. Optimization of the clearing of mFRR balancing energy demands against BSPs' bids. 6. Communication of the accepted bids, satisfied demands and prices to the local TSOs as well as the resulting CB schedules. 7. Calculation of the commercial flows between imbalance areas and settlement of the

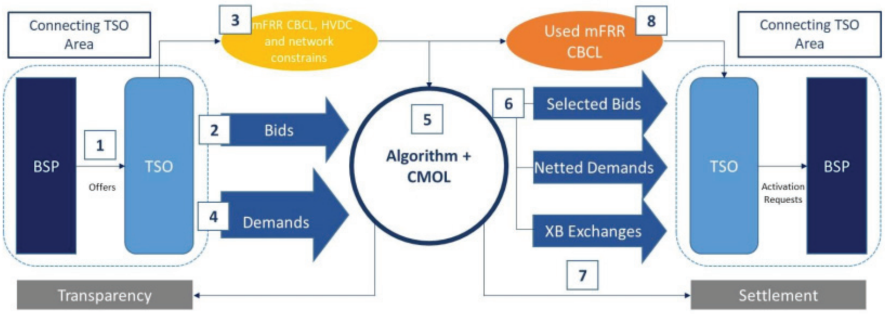

Figure 2.7: General mFRR process according to [33].

The structure is similar especially to the RR process, with only TSOs interacting directly with the balancing platform. BSPs provide TSOs with balancing energy bids, and TSOs, at certain points in time, submit their mFRR demands, available cross-zonal capacities, and available BSP bids to the platform. These mFRR demands can be inelastic, i.e. to be covered at any cost, or elastic, specified with price-volume pairs. After optimizing the balancing energy activation and exchange, the platform communicates the results to each TSO, who in turn instructs its local BSPs to activate the relevant balancing energy bids.

The platform aims to support two distinct activation processes. On a scheduled basis, the platform clears a balancing energy auction once every 15-minute interval, simultaneously taking into account the mFRR demands and available balancing energy bids, as submitted by each TSO. Considering the available cross-zonal capacity and opportunities for imbalance netting, the activation optimization function finds a feasible activation schedule that maximizes the economic welfare. The other activation process relates to direct activation. In this process, a TSO request for balancing energy will be processed almost immediately, but without the market efficiency benefits enabled by a simultaneous clearing. The optimization horizon of the mFRR platform under development does not exceed the upcoming 15-minute market period.

Automatically Activated Frequency Restoration Reserves: The PICASSO Project

The European implementation project for the aFRR platform was launched in 2017 as PICASSO (Platform for the International Coordination of the Automatic frequency restoration process and Stable System Operation). Starting as a regional project between five countries in Western Europe, it has grown to include 13 mem-

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expenditure and revenues between TSOs. 8. Remaining mFRR CBCL are sent to the TSOs.

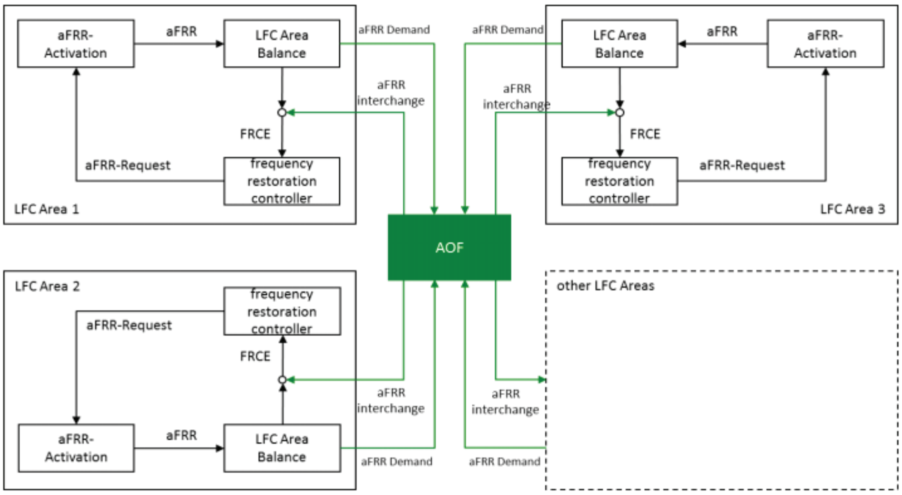

Figure 2.8: High level scheme of aFRR-Platform [34]

ber countries, plus observers.

The standard aFRR product agreed to in the PICASSO project has some distinct properties compared to the standard RR and mFRR products. Since aFRR activation is a result of continuous adaptation to a control signal, there is no minimum delivery time, and all bid volumes must be divisible. Its activation is automatic, and full activation time of the product will be harmonized to 5 minutes starting in 2025 [31]. Contrary to the platforms for exchange of manually activated balancing products, the PICASSO project aims for short and frequent optimization cycles, with a new set of activation signals and market prices every 4 seconds.

A final, and very interesting difference from the manual platforms is its control structure (cf. Fig. 2.8). Whereas the AOFs of the TERRE and MARI platforms select the individual bids to be activated by each TSO, the PICASSO platform approaches this differently, with the concept of *control demand*. In response to the balancing energy demands of each TSO, the aFRR AOF determines the aFRR *interchange*, i.e. the cross-border balancing energy flows from aFRR, rather than individual bids to be activated. Certainly, the AOF takes bid prices and volumes on the Common Merit Order List (CMOL) into account when determining these interchange volumes, along with cross-border capacities and a set of priority rules in cases of scarcity. In the end, TSOs then take the interchange volumes into account when determining (in their local controllers) which aFRR bids to activate (aFRR-request in Fig. 2.8).

Imbalance Netting: The IGCC Project

The implementation project for an imbalance netting builds on a well-established German-Austrian control cooperation, launched in 2010, and today includes 24 countries, out of which 10 are so-called operational members. As for the other platforms, the principles and functioning of this platform are described in an implementation framework [35].

While several concepts are familiar, it is also different in nature from the aforementioned RR and FRR platforms in several regards. Whereas economic optimization is absolutely central to the other platforms, the objective of the imbalance netting platform is to minimize the simultaneous activation of aFRR in opposite directions [35]. For this purpose, the *control demand* concept is used, as for the aFRR platform. Since the imbalance netting process revolves around non-activation of balancing energy, it does not directly involve any reserve products, and unlike the other platforms, no standard product is specified for this platform. The imbalance netting platform identifies opportunities for imbalance netting by simultaneously considering the aFRR demand from every participating LFC area. Since this demand (and imbalance netting potential) is also considered by the aFRR platform, their functionalities can be seen as largely overlapping. Moreover, all operational members of IGCC are also members of the PICASSO project, with the single exception of Switzerland.

2.5 Selected Studies on European Balancing Market Design and Integration

The liberalization and integration process enforced in 2009 by the European Commission [26] sparked research initiatives on aspects related to integration of European balancing markets. Part of the relevant literature has already been referred to in the preceding sections, leaving other important references and further discussion to this section. Even though balancing topics are to a large extent interrelated, a salient focus in literature concerns issues related to balancing market design in the context of European energy policy. Another main body of recent balancing literature comprises the impacts of integrated markets, including both technical and economic assessments, often based on quantitative models.

2.5.1 Balancing Market Design

A number of balancing market rules, requirements and mechanisms are subject to design decisions, impacting market performance, incentives and market behaviour. In the last decade, different, but also largely similar, frameworks (cf. Fig. 2.4) have been proposed to describe this design space in balancing markets [20],

[22], [24], [36]. Typically including both national and cross-border market design variables, these frameworks have been used to evaluate different high-level options for an integrated balancing market. A representative contribution is that of Doorman, Van der Veen and Abassy [22], presenting a set of design variables whose values define the characteristics of a balancing market, as well as a framework for evaluating market performance. The design variables are distinguished between the aforementioned three market components, balance responsibility, balancing service provision and imbalance settlement.

With balancing market design frameworks in mind, a share of academic literature on electricity balancing concerns identifying appropriate design decisions to individual market elements. The imbalance pricing mechanism provides a good example. Stressing in particular the design objective of balancing markets being cost-reflective, Vandezande [36] finds the imbalance price formation to have a crucial role. The balancing market design proposed in Vandezande's thesis makes a clear distinction between security insurance and real-time energy delivery, with the imbalance price determined only by the latter, while also reflecting capacity payments if applicable. Haring, Kirschen and Andersson [37] also refer to cost transparency, as well as other objectives, in their proposal of an incentive compatible imbalance settlement. Another example is the alternative imbalance pricing mechanism is put forward in Chaves-Ávila, Van der Veen and Hakvoort [38], aiming to mitigate adverse price signals under internal network congestions.

For cross-border balancing arrangements, Vandezandes framework [36] identified the model of TSO-TSO exchange with a common merit order as having the highest cost reduction potential. This is in accordance with the judgment of Doorman and Van Der Veen [24], years before new network codes were drafted by ENTSO-E.

A last remark is the perspective is brought forward in Rebours, Kirschen and Trotignon [39]. They provide a compilation of nine critical design issues and scoring the performance of five different procurement methods. Their assessment covers the scope of ancillary services in general, focusing in particular on frequency and voltage control. Arguing that system services are public goods and often subject to strong technical constraints, they warn against the inefficiencies of creating spot markets for procurement, but also acknowledge that no single procurement method is superior.

2.5.2 Clearing Non-convex Balancing Energy Markets

Complex bid structures, including indivisible, exclusive and conditional bids have been used in European day-ahead auctions for years, and are under consideration for use also in some of the future balancing energy markets. Such bid structures provide market participants with opportunities to represent internal constraints in the market clearing. At the same time, modeling such bid structures requires integer decision variables in the optimization. With the non-convexity of such problems, uniform prices supporting market equilibria often do not exist. The common practice in European markets is to identify prices such that no orders are *paradoxically accepted* (i.e. the order is accepted, even though being out-of-the money). *Paradoxically rejected* orders (where the order is rejected, even though being in-the-money) are tolerated. This practice eliminates the need for uplift payments [40], which are used in some markets, including in the United States. However, the search for solutions without paradoxically accepted orders requires additional effort.

For a balancing energy market design with complex bid structures (such as [41], [42]), market models from other timeframes, including day-ahead markets, can serve as starting points to clear the market and provide prices. One key concept is the approach followed by Martin, Müller and Pokutta [43]. To identify solutions and prices avoiding paradoxically accepted orders, the problem is solved iteratively. Subproblems are solved to identify supporting prices, and when a subproblem is infeasible, a cut is added to the clearing problem excluding the proposed base solution. EUPHEMIA [44], the algorithm used in used for clearing the coupled day-ahead market in most European countries, and largely based on the COSMOS algorithm [45] follows the same approach of disqualifying incumbent solutions and re-solving. A related approach is iteratively removing paradoxically accepted orders from the order book, as proposed by Biskas, Chatzigiannis and Bakirtzis [46] and other related studies.

A different set of contributions are the one-shot formulations, where the clearing of volumes and prices is solved without iterations. A starting point is reformulating the complementarity constraints using auxiliary variables, as done in Meeus, Verhaegen and Belmans [47] and also Zak, Ammari and Cheung [48], combining primal and dual constraints in a single MIP problem. Madani and Van Vyve [49] follow the same path with their primal-dual formulation, this time more efficiently, without the introduction of auxiliary variables. A final noteworthy contribution is Dourbois, Biskas and Chatzigiannis [50], offering both iterative and one-shot approaches, and comparing them in terms of solution quality and computational performance. In their own words, the analysis and comparison "can serve as a *pharos* (beacon) for future modeling activities", safe to say also for balancing energy market clearing problems.

2.5.3 Balancing Market Integration

A class of important studies on cross-border balancing have built quantitative models to assess the economic implications of market integration. In this context, interactions with other market timeframes can be significant due to variable and even seasonal generation patterns and or other long-term dynamics. For this purpose, balancing market models in such studies are usually applied as one element in a larger system of power market models, with a level of detail and aggregation suitable to allow simulation of a large number of time periods for the interconnected system.

A representative example of this approach is the real-time market model used throughout Farahmand [51], a thesis compiling studies [52]–[55]. The system balancing optimization is built on a security-constrained DC OPF, taking bid and network capacities into account, while avoiding complicating features such as integer decision variables and inter-temporal constraints. Nevertheless, an interesting modeling element in [52] is accounting for incremental network losses from activating reserves in different locations. The linear balancing model is coupled to PSST (Power System Simulation Tool) [56], a model for day-ahead market clearing and reserve procurement, using output from other models, including long-term hydropower strategies from the EMPS model [57].

For his doctoral work [58], the mathematical models developed by Stefan Jaehnert involve both reserve procurement and balancing energy activation. This model is applied together with a detailed day-ahead dispatch model (the EMPS model) using data representing the Northern European power system in 2010 and 2020, and enables comparison of the balancing market outcome from an integrated Northern European balancing market versus decoupled national markets, along with a series of analyses related to transmission capacity reservation, wind integration and reserve requirements. The increased wind power penetration in 2020 and its lack of predictability is a crucial factor for future imbalance volumes and balancing costs. Estimations based on given assumptions find balancing costs to increase by roughly 230 M€ from 2010 to 2020, while costs savings from balancing market integration are able to avoid about 70 % of this increase.

Succeeding the research of Farahmand and Jaehnert is the thesis of Gebrekiros [59], also investigating the impacts of balancing market integration. In contrast to the aforementioned rather long-term, extensive, and typically zonal balancing market models, Gebrekiros, Doorman, Jaehnert and Farahmand [60] demonstrate for a small-scale test network the cost increase of using NTCs versus a more flow-based approach (using PTDFs) for inter-area balancing. This is linked to the cost of congestion, with the two approaches committing different generating units to counteract imbalances, with different flow paths as a result.

A particular aim of Gebrekiros' thesis is, nevertheless, assessing potential benefits from reservation of transmission capacity for balancing purposes. As a result, most of his modeling work is tailored to simulate the balancing market over a long horizon (e.g. months or years). Like [51] and [58], his models build on the aforementioned EMPS and PSST models, and feature a somewhat simplified representation of the balancing energy market. The preceding stages, including FRR bidding and procurement, day-ahead market clearing, and even longer-term market dynamics (e.g. seasonal inflow variations) are taken into account more extensively in a fundamental manner. Comparing market arrangements based on NTC and flow-based market coupling, finding cost savings in both cases when reserving the optimal amount of transmission capacity in a sequential manner. However, these savings come across as very modest compared to using implicit market clearance, with reserve requirements taken into account in the day-ahead market.

The issue of whether and how to allocate transmission capacity for exchange of reserves or balancing energy has also attracted attention from researchers elsewhere in Europe, only some of which are mentioned here. A study by Bellenbaum, Weber, Doorman and Farahmand [61] concludes based on historical spot and reserve procurement data, that an interconnector between Norway and Germany would be (partially) utilized for reserve exchange 77 % of the time, and also provides indications on what shares of the transmission capacity should be exchanged. With the objective to maximize the value of transmission capacity by minimizing power system expenses, Jerom de Haan [18] presents a method that reserves part of the transmission capacity for balancing. The method follows five computational steps to identify the marginal value of transmission capacity for balancing and make an optimal capacity allocation through firm through a proposed concept of a balance flow margin. The valuation of transmission capacity for balancing builds on a probabilistic representation of balancing flows. A different approach to incorporating this uncertainty is the model of Delikaraoglou and Pinson [62]. Arguing that co-optimizing reserve procurement and day-ahead energy schedules (as in the implicit market clearance studied by [59]) are incompatible with the current market design, they formulate a stochastic bilevel program for allocating transmission capacity between energy and reserves. Here, transmission capacities and area reserve requirements are used as control variables, and solved efficiently using Benders decomposition.

Chapter 3

Balancing Strategies and Coordination of Multiple Balancing Processes

Aspirations that new balancing mechanisms can create value and enable higher levels of renewable penetration in the European power system have fueled efforts to integrate European balancing markets. The vision of an internal market has been carried not only by European authorities, but also by TSOs. At the same time, the joint development of new products and market platforms also exposes differences between existing, mostly national balancing markets. This diversity may have several roots, but is reflected both in balancing market rules and in the control room behavior of TSOs, and has been considered a barrier to fast integration [63]. Consequently, a first key issue addressed in this chapter is illuminating the character of balancing energy activation strategies in European balancing markets.

The upcoming pan-European balancing energy market platforms and products provide opportunities for balancing energy exchange and netting opposite imbalances, thereby extending market access to a new level for both BSPs and TSOs. Leaving aside implications related to product standardization and internal congestion, this balancing coordination across borders is expected to entail an overall improvement in resource efficiency, which has been singled out as one of the key objectives of successful balancing market integration [1]. Efficient utilization of resources is in principle also affected by coordination along a different dimension. Since each common platform for exchange operates as part of a distinct control process, reflected by the characteristics of each standard product, the efficiency gains from its introduction can be seen as limited to this process. However, each individual TSO has opportunities to coordinate the use of the different processes. The key issue of utilizing resources efficiently by considering balancing actions made in different balancing processes and at different points in time is addressed in this chapter, and the approach presented in Publication II follows a proactive approach using imbalance forecasts and early activations.

The major contributions of this chapter are Publications I and II (with manuscripts located in Sections 7.1 and 7.2). The subsequent sections are centered around and will elaborate on these papers. After providing a brief context and perspective in Section 3.1, the publications are summarized in Section 3.2. The chapter concludes with a short discussion on the implications and takeaways in Section 3.3.

3.1 Context and Perspective

The somewhat diverging operational philosophies developed by European TSO can be explained by a combination of factors. Even though power systems obey the same physical laws, including Kirchhoff's laws and the conservation of energy, they may have very different attributes from a control perspective. European power systems face different challenges in this regard, such as uncertainty in areas with high renewable penetration, limited flexibility depending on generation mix and consumption assets, and low inertia in smaller synchronous systems. Moreover, the systems of today are in part results of historical contexts of ownership and regulation, including different paths toward liberalization. Whereas some national markets, including the Nordics[1], have been fully coupled for decades, others have more limited records of cross-border integration.

When discussing balancing strategies, a fundamental distinction can be made between the concepts of *reactive* and *proactive* control [64], [20], differing in their control objectives, and thereby the way balancing energy activations are used to cover imbalances. Reactive control pursues *curative* objectives such as containing frequency deviation, or restore the frequency and scheduled exchange programs, whereas proactive control follows *preventive* objectives, such as reducing the future imbalance, creating margins or relieving congestion. For a set including both reactive and proactive strategies, Nilsson, Soder and Ericsson [65] provide quantitative insight to their technical performance. However, the apparent conflict of philosophies tend to center on other concerns, such as the division of responsibility between the TSO and the market [66], and how to keep balancing operations cost efficient. While a proactive strategy aims to ensure efficiency through central-

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[1] Denmark joined the Nord Pool power exchange in 2000, following Norway, Sweden and Finland.

ized planning and pooling of resources, a reactive strategy can arguably increase participation in the balancing market through the empowerment of market actors. Here, a key element is the real-time publication of price signals. In practice, most TSOs use both reactive and proactive measures in the balancing process [64].

The first publication included in this chapter was written and published in 2015-2016. At this point, the legislative framework was still unfinished, and several market design questions were very much under discussion. For the second publication, published in 2017, the European implementation projects for common balancing exchange platforms had been launched, and the largely finalized Guideline on Electricity Balancing [1] provided the contours of a future pattern of interaction between TSOs and these to-be-developed market platforms. The second paper approaches the cross-process coordination issue from the perspective of the TSO and assumes a framework consistent with key aspects obtaining European consensus around the time of publication. Especially relevant is the apparent preference for two-sided single-period auctions, the trend shift towards one single standard mFRR product, the concept of elastic balancing energy demand from TERRE [41], and the general flow of information.

3.2 Summary of Publications

3.2.1 Classification of Balancing Markets Based on Different Activation Philosophies: Proactive and Reactive Designs

M. Håberg and G. Doorman, “Classification of balancing markets based on different activation philosophies: Proactive and reactive designs”, in *2016 13th International Conference on the European Energy Market (EEM)*, IEEE, Jun. 2016.

This conference paper concerns the interrelations between balancing market design and TSOs’ activation philosophies. Finding the concepts of reactive and proactive control to have been previously introduced in various TSO reports, including [64], the paper follows an established path of distinguishing between control reactive and proactive control actions by their objectives. The objectives of reactive control can be summarized as *curative*, whereas proactive control pursues *preventive* objectives, as described in the previous section. The balancing products used by TSOs provide an indication not only on the characteristics of flexible resources in the system, but also on indirectly reveal activation philosophies of TSOs. Large RR or aFRR volumes can provide indications of preferences of proactive or reactive control, respectively. Extensive use of mFRR is more ambiguous, as this product can be used either proactively or reactively, depending on whether predictions or control error signals triggers activation actions.

From the balancing market design framework of Doorman, Van der Veen and Abassy [22], a subset of six design variables is singled out as *indicator variables*, in the sense that their values indicate one of two things: (A) preference for TSOs to follow control strategies considered as reactive vs. proactive, or (B) market incentives for BRPs to participate in system balancing.

Using publicly available information online from international TSO surveys and rules and regulations of national balancing markets, values are quantified for each of the indicator design variables for a set of European countries. The spread of these markets in terms of activation philosophy and market incentives is calculated using the relative deviations of these indicator variable values, resulting in a two-dimensional scatter classification. Here, two distinct groups stand out as largely internally harmonized: the Nordic countries (where rules and practices are already largely harmonized), and the axis BE-NL-DE-AT. However, the classification also indicates large discrepancies between neighboring countries, with BE-FR serving as an example.

3.2.2 Proactive Planning and Activation of Manual Reserves in Sequentially Cleared Balancing Markets

M. Håberg and G. Doorman, “Proactive planning and activation of manual reserves in sequentially cleared balancing markets”, in *2017 IEEE Electrical Power and Energy Conference (EPEC)*, IEEE, Oct. 2017.

In the context of new, common platforms for balancing energy exchange, this conference paper assumes the perspective of a TSO pursuing a proactive balancing strategy, where the expected future imbalance can be seen as the main control signal. To counteract an imbalance at a future point in time, a TSO can potentially use a range of products belonging to different balancing processes. Activation decisions for faster products are taken at a later point in time, and their prices depend on bids provided by BSPs.

Pursuing the objective of minimizing activation costs across all balancing processes, the principal point at issue is determining the adequate balancing energy volume to be activated in each process, i.e. the amount of early activations versus deferring balancing actions until a later stage. An example could be the TSO of France determining how many MW of balancing energy from RR should be activated by the European RR platform to help counteract an imbalance in the French market area for the market period 12:00-12:15, taking into account predictions on the future imbalance in this area, and the possibilities of activating balancing energy later — through the mFRR or aFRR platforms, or other mechanisms. This process is illustrated in Fig. 3.1 for the interaction between the RR and mFRR

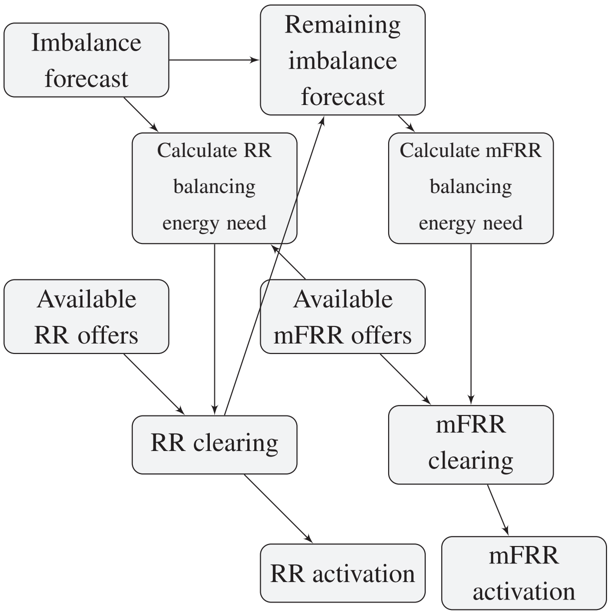

Figure 3.1: Proactive electricity balancing optimization considering RR and mFRR product [3]

processes. In principle, aFRR or local processes can also be taken into account when considering demands for balancing energy from RR.

Proactively coordinated use of a combination of balancing products requires considering a sequence of balancing markets and decision points. Early activation of reserves can allow balancing resources on the slower side to participate. However, this is only efficient from an economic perspective if faster balancing products, activated at a later point in time, are not available at a lower cost.

The proactive balancing model proposed in the paper includes a simplified representation of this decision process, paying specific attention to the stage where the TSO must submit its demand for balancing energy from a given standard product to be cleared on a balancing energy exchange platform. The decisive instrument is the opportunity for the TSO to specify balancing energy demand as *elastic*, i.e. price-dependent. Rather than deciding a firm volume to be activated from the process, the TSO can thus indicate a limited willingness to pay for balancing energy beyond prices where less expensive options are expected.

The first essential step is for the TSO to build a representation of the *expected future supply* of balancing energy from other processes for the relevant market period, i.e. the expected alternative cost of having to activate balancing energy at a later point in time. The next step is creating an elastic balancing energy demand for the upcoming balancing process by vertically subtracting this expected future supply from the imbalance forecast, creating a number of price-volume pairs indicating its marginal willingness to pay for different balancing energy demands. In the final step, just after the common balancing market for the process at hand is cleared and a given balancing energy volume accepted, the TSO adjusts its imbalance forecast accordingly.

If the TSO submitted a firm balancing energy demand volume to be activated in each process, it would have knowledge —or at least a strong expectation— of its accepted volumes, whereas when submitting elastic demands will generally result in not activating the full volume corresponding to the imbalance forecast in a single process, and the accepted volume in each process will be unknown in advance. And while firm balancing energy demands ordinarily lead to bids being accepted whatever their price, elastic balancing energy demands allow the TSO to coordinate its balancing decisions across processes through the opportunity cost.

Under this arrangement, the TSO takes a somewhat unfamiliar role. Rather than acting as a single buyer, it faces a bidding problem, and operates together with both TSOs and BSPs in an extended, international market. As a result, information about the future will always be incomplete. This is due not only to the unforeseeable nature of power imbalances, but even more so because market outcomes depend on the balancing actions of other TSOs, and because balancing bids may not be visible on local or common merit order lists until a later point in time. As a result, the future supply of alternative products will have limited accuracy.

3.3 Discussion

A substantial part of this chapter concerns the endeavor to better understand balancing activation strategies of European TSOs. This issue could be approached in a number of ways. For the contributions of Publication I and the related material in this chapter, a crucial assumption has been that balancing philosophies are visible through the lens of national balancing markets, i.e. that differences in balancing market rules can reflect strategic preferences of TSOs, no matter whether these preferences are founded historical or technical realities, or on something else. There are multiple reasons to be cautious about the assumption of market rules reflecting underlying strategic differences. Even though a national balancing market is generally operated by the TSO, it is not designed and developed in a vacuum. Such market rules require regulatory approval from the relevant NRAs, and market participants will be involved in the process and have some influence over the final outcome. A second factor is that balancing market rules may already have converged to some compromise for the sake of harmonization, without the local TSOs necessarily sharing operational philosophies. Another factor is that the indications of philosophical preferences may also be diluted as a result of TSOs performing tasks related to balancing outside the balancing market. Examples from the Norwegian TSO would be the *generation shifting* and *generation smoothing* services[2], where the end objective is reducing structural imbalances by better aligning generation schedules with the consumption profile, and both processes are external to the balancing market. And finally, balancing markets may come across as proactive or reactive depending on which type and proportions of different reserve products use. While this may be an appropriate indication of TSO preferences, it may possibly only reflect the technical capabilities of local balancing resources. An especially paradoxical case is that a low proportion of aFRR volumes relative to other products may indicate either a strong preference for manual activations (a signature indication of proactive TSOs), or an extremely successful reactive approach where volumes are low due to market participants acting effectively on price signals.

While taking into account these precautions, the perspective is meaningful in Publication I when attempting to classify market designs along a general spectrum of balancing strategies, rather than precisely classifying the strategies themselves. The classification results exhibit balancing design similarities and discrepancies between markets (in what is effectively a qualitative manner). The classification outcomes will most definitely change with time, as both operational procedures and balancing markets are subject to redesign, and new cross-border balancing markets are being introduced. Moreover, the strategic preferences of TSOs could persevere with cross-border balancing opportunities opening up. Alternatively, a TSO could see opportunities in extending its balancing operations to include new control processes or use them differently, adjusting its strategy along the way. Norwegian examples are the shift toward actively considering proactive mFRR activation [67] and Statnett joining the TERRE project [41] with observer status, even though no RR product is currently used in the local market.

This chapter spotlights one strategic opportunity in the research on coordinating balancing actions across different processes. Here, the main underlying assumption is that different balancing energy products are effective substitutes of the same commodity. This viewpoint only has merit from the viewpoint of TSOs following a proactive mindset, and even for those, it is a simplification with two major consequences. It fails to capture the value of delaying balancing decisions to a later moment in time, when forecasts are expected to be more accurate, and it down-

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[2] These are considered ancillary, or *system* services, an overview is found on https://www.statnett.no/for-aktorer-i-kraftbransjen/systemansvaret/praktisering-av-systemansvaret/systemtjenester/ (in Norwegian).

plays the quality of faster products more flexibly and capably adapting to unexpected balancing situations. Both of these consequences stem from the underlying uncertainty in the system imbalance. As noted in Publication II, they can be mitigated by accounting for this uncertainty in the model, e.g. representing the future imbalance as scenarios using stochastic programming.

Entangled with new opportunities comes additional complexity for TSOs attempting to actively coordinate and optimize their utilization of several balancing processes. Cooperatively balancing the system together with other TSOs implies partly abandoning the single-buyer role, and acknowledging that information used for planning, such as cross-border flows, will be exogenous. For some TSOs, complicated bid structures for new standard products will also be a new source of complexity. In the very same context, introducing an elastic TSO demand feature comes across as a powerful mechanism. This mechanism is instrumental to the coordination procedure described in Publication II, outlining a structured approach to attune activation volumes across balancing processes for the purpose of economic optimization.

The multi-process coordination approach does not directly overlap or compete with the multi-product optimization models described in Chapter 4. The models presented in the next chapter concern optimal activation of balancing energy bids focusing on a single process, taking the role of an AOF of a balancing energy platform. From that perspective, the multi-process coordination would be external, running in an outer loop at one or more local TSOs. For the congestion management methods presented in Chapter 5, any such efforts would also be largely independent of the cross-process coordination described in this chapter.

Chapter 4

Models for Activation Optimization of Multiple Standard Products

In European self-dispatch[1] systems, balancing product specifications have been used by TSOs to define requirements on performance and behavior of BSPs providing bids for balancing services. In the same way as for balancing market rules and operational philosophies, there are national differences between these products, providing barriers to cross-border exchange and competition. Some differences are subtle, while others are more fundamental, such as different requirements on speed of activation, minimum bid size, and locational specifications. As a result, BSPs with equal technical capabilities would typically deliver different products if located in different countries, while very different BSPs in the same area will often provide the same product.

From the early stages of designing the integrated European balancing market, standardization of balancing products has been considered a key harmonization issue. The Framework Guidelines on Electricity Balancing [68], authored by ACER in 2012 envisioned TSOs agreeing on a *list of standard products* for reserve capacity and balancing energy to satisfy their needs.

The vision of exchanging a *list of standard products* for balancing energy in the European balancing market entails both opportunities and challenges. An extens-

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[1] In a self-dispatch arrangement, generating and demand facilities determine their own generation and consumption schedules, contrary to a central dispatch arrangement, where these schedules are determined by the TSO [1].

ive portfolio of balancing products could be better adapted to the varying needs of TSOs, potentially reducing the need for aFRR, which might be more expensive. Having several products may allow market participation from a diversified fleet of BSPs, including balancing resources with distinctive capabilities or constraints, thereby obtaining some of the benefits of central-dispatch systems. However, using a range of balancing products in a single process inevitably adds layers of complexity to the decision process of balancing operations. Clearly, having TSOs primitively selecting from bids from a large number of balancing products would likely be chaotic and lead to market fragmentation. Avoiding this would require TSOs to combine bids in an intelligent manner to obtain the desired volume, speed and flexibility when activating balancing energy.

The problem of intelligently combining bid activations from products with different technical characteristics is the main issue addressed in this chapter, entailing questions on how to model the balancing activation decision process, and the balancing products themselves. Building on this activation optimization approach, two secondary issues receive attention in this chapter. The first issue is accounting for uncertainty in the imbalance forecast when making balancing decisions. The second issue relates to power flows in the transmission grid and the impact of including network constraints in the activation optimization.

The major contributions of this chapter are Publications III and IV and V (with manuscripts located in Sections 7.3, 7.4 and 7.5). The subsequent sections are centered around and will elaborate on these papers. Section 4.1 places these publications in context and provides the setting and perspective. The models developed and presented in this chapter are related, and share several similar features. After a general description of the models themselves in Section 4.2, publications are summarized in Section 4.3. The chapter concludes with a discussion in Section 4.4, focusing on the assumptions and implications of the research.

4.1 Context and Perspective

The balancing energy activation models presented throughout this chapter and in the accompanying papers have fundamental similarities. They aim to optimize manual balancing energy activation decisions while considering different balancing products simultaneously, not in a sequential manner. This allows some form of competition between different products, and there are at least two settings where such a problem could be of interest. From the perspective of an AOF, this could represent a market with more than one standard product (and more than one Common Merit Order List (CMOL)). In this case the purpose of the optimization would be selecting a set of bid activations that in the aggregate would serve the imbalance needs of all TSOs at the lowest possible cost for the time horizon that is considered in the optimization. The other relevant setting is for a TSO with alternative balancing products at hand. A relevant example would be a TSO aiming to co-optimize activation of a European mFRR standard product together with a specific mFRR product (or other local manual products), with different technical characteristics, e.g. shorter activation time.

The optimization models presented in the subsequent sections aim to minimize balancing costs to meet an imbalance forecast over a finite horizon, and re-optimize whenever an updated forecast becomes available, respecting sunk decisions (i.e. decisions that are irreversible, at least for some given period). This approach can be regarded as a variation of Model Predictive Control (MPC) (cf. [69]). Abbaspourtorbati, Scherer, Ulbig and Andersson [70] describe their MPC activation pattern for tertiary reserves as generating a sequence of control decisions by solving a constrained finite time optimal control problem, applying the first control decision, sampling system measurements and repeating the process for the next step. The concept is comparable to the perspective of power system operators in the control center of a TSO largely depending on mFRR activations; continuously monitoring and adjusting the balancing dispatch based on updated measurements and taking into account previous decisions.

Determining optimal balancing decisions for a finite horizon given an imbalance forecast can be regarded as a scheduling problem, comparable to a traditional economic dispatch. Creating such activation schedules involves not only identifying optimal activation volumes, but also the optimal timing and duration of each bid activation, thus the technical capabilities of standard products (and also complexities for individual bids) must be represented in the model. Doing so greatly increases complexity relative to the simpler, linear models traditionally used for balancing market integration studies [54], [58], [71]–[73]. Representing the specific requirements on activation time and minimum duration of these products is made possible using binary indicator variables. Leveraging the similarity to established unit commitment models, including [74], [75], the single-period balancing energy activation models in this chapter are formulated as MILP problems. As a result, the stochastic formulation in Publication IV is structurally similar to the well-studied realm of two-stage stochastic unit commitment problems (cf. Håberg [11]).

The definitions of the products have been subject to thorough discussions within ENTSO-E over the last few years. European synchronous systems differ both in terms of size, renewable penetration, the balancing products currently in use, and balancing philosophies. Discussions on product design have, understandably, reflected these diverging, and sometimes conflicting, practices between the TSOs. At the heart of the discussion are two adverse considerations: on the one hand, fostering cross-border competition and avoiding undue market fragmentation is simpler when using as few standard products as possible. On the other hand, there are concerns that a narrow portfolio of standard products may not only leave potential BSPs out of the market, but also fail to serve the needs of all TSOs, requiring extensive use of specific products [1] (i.e. balancing products not applicable for cross-border exchange).

As described in Section 2.4.1, many TSOs until recently expected the exchange platforms to optimize the activation of balancing energy using combinations of different standard products. With this starting point, a crucial feature of the AOF would be the capability to efficiently combine balancing energy activation from different products to meet the balancing needs of TSOs. The family of balancing activation models described in this chapter was developed following these early assumptions regarding the use of standard products, and Publications III and V both concern co-optimization of different mFRR products. At the same time, ACER was concerned that a large number of Standard Products would lead to lower liquidity and competition within the markets, and have urged ENTSO-E to define as few Standard Products as possible. Accordingly, the product standardization trend has since shifted to an approach pursuing a single standard product for each balancing process, and multi-product optimization is not currently expected to be a key issue for the balancing platforms in the near future. Nevertheless, the approaches presented in subsequent sections could however become useful for TSOs that will combine the use of (one or several) specific products with the European standard product in the future.

4.2 Generalized Model Description

The models presented in Publications III, IV and V all center around the same task; finding an optimal plan for the activation of balancing energy from mFRR. The activation plan specifies the balancing energy delivered by each balancing bid, for each 5-minute interval over a finite horizon. These values stem from solving an optimization problem taking into account the imbalance forecast at hand, and technical characteristics of each balancing resource. These limitations may be related to the product (such as activation time or delivery periods), or to the individual bid (e.g. divisible vs. indivisible, or upward vs. downward activation).

In such balancing activation models, energy balance constraints require that balancing energy delivery matches the forecasted imbalance. However, there are a number of situations where these cannot be satisfied. The available reserve (or transmission) capacity can be insufficient to cover the imbalance. The activation time of some manual products may make it impossible to cover the imbalance in the very short run, especially after the imbalance forecast is updated. And in the model, the flexibility of slower manual products is very limited, once activated, bids will deliver balancing energy according to a specific pattern for a period of time, regardless of how the imbalance develops.

To avoid infeasibility, the three models allow deviations in the energy balance constraint, however, this is penalized in the objective function. This penalty can be seen either as a penalty on frequency deviations, or as the alternative cost of covering the imbalance using an alternative, flexible product, e.g. aFRR. High penalties (as in Publication III) push towards a solution where the energy balance is satisfied as far as possible, whereas more moderate or calibrated penalties (as in Publications IV and V) means the solution will choose to allow a mismatch between the imbalance forecast and manual activation plans if avoiding it incurs a high cost.

The basic model in Publication III serves as a minimal starting point for this family of models, with activation plans for each bid required to satisfy the minimum duration requirement, as well as initial conditions such as activation volume and on/off state. The models presented in Publications IV and V provide improvements and extensions to this model. They both account for balancing energy delivered from mFRR during the ramping phase, and balancing activation costs are evaluated using imperfect forecasts in a rolling-horizon manner.

However, two specific features stand out as particularly relevant, independently of whether one or more standard products are exchanged. Rather than naively following the imbalance forecast, the model in Publication IV pursues a stochastic strategy based on a two-stage formulation. This reduces balancing costs in the face of uncertainty and efficiently allocates activation volumes between flexible and less flexible products. In Publication V, the balancing problem is extended to include constraints in the transmission network and applies it on a representation of the Nordic synchronous system. This approach factors the costs and impacts of transmission scarcity into the optimization and demonstrates the interrelation between balancing decisions and congestion management, between and within market zones.

4.3 Summary of Publications

4.3.1 Optimal Activation of Standard Products for Balancing as Required by Draft ENTSO-E Network Codes

M. Håberg and G. Doorman, “Optimal Activation of Standard Products for Balancing as Required by Draft ENTSO-E Network Codes”, in *CIGRE International Colloquium on the Evolution of Power System planning to support connection of* *generation, distributed resources and alternative technologies*, Philadelphia, PA, 2016.

This conference paper was written while the European balancing market was at an early stage of integration process, and a key assumption at this point was for the Activation Optimization Function to coordinate the activation of bids representing different standard products within a single process. Whereas balancing activation models existing in literature are often linear, resembling traditional economic dispatch, the differing characteristics of the standard products (such as activation time and minimum duration) introduce new layers of complexity to the problem of finding an optimal balancing dispatch.

Accordingly, the primary purpose of the paper can be seen as demonstrating an approach enabling simultaneous use of different mFRR products, formulating it as a scheduling problem with a Mixed Integer Linear Programming (MILP) structure. Specifically, the model minimizes activation costs, plus a penalty for frequency deviations (given by imbalances not covered by balancing energy activation). Requirements on activation time and duration of delivery requires keeping track of the start/stop behavior of each individual bid. This is modelled through the use of binary variables, giving a structure similar to unit commitment models, and the minimum duration constraint is based on [75].

The paper contains an example case study in four configurations; a single run of the balancing optimization model over a historical imbalance over a scheduling horizon of 90 minutes. Balancing bids are spread across three somewhat stylized standard products. These products differ in their Full Activation Times, minimum duration and deactivation times (5, 10 and 15 minutes).

Compared to the first configuration (the *reference scenario*), the three subsequent configurations constitute different restrictions to the activation process. In the second configuration, all BSPs provide the slowest 15-minute product. In the third, bids are only allowed to be activated in the merit order, and in the fourth configuration, the scheduling horizon is reduced to 15 minutes ahead, thus leaving out information on the imbalance in the medium and longer term. As can be expected, the objective function value, given as the sum of activation costs and a penalty for frequency deviations, increases when imposing additional restrictions on the model.

There are additional interesting observations. Due to constraints on minimum delivery duration, bid activation decisions are lumpy in time, and if allowed, two or more bids will often be simultaneously activated in the opposite direction parts of the time in an attempt to closely match the time-varying profile of the imbalance.

Given sufficient lead time, the activation plan is for the most part able to exactly match the imbalance forecast, even using only a 15-minute product, by starting and stopping bid activations of different sizes at different points in time. However, the use of a deterministic imbalance conceals the limited flexibility offered by such a product in coping with forecast errors. In the case when the optimization horizon is reduced, the combination of intertemporal constraints and sunk decisions leads to a somewhat cyclic start/stop behavior between different products. However, this behavior is caused not only by the short horizon, but also by constraints and assumptions regarding re-activation.

4.3.2 A Stochastic Mixed Integer Linear Programming Formulation for the Balancing Energy Activation Problem under Uncertainty

M. Håberg and G. Doorman, "A Stochastic Mixed Integer Linear Programming Formulation for the Balancing Energy Activation Problem under Uncertainty", in *2017 IEEE Manchester PowerTech*, 2017.

This conference paper presents an extended version of the model used in the Section 4.3.1, and follows a similar approach: minimizing the balancing energy activation cost by creating activation plans to meet an imbalance forecast. As in the previous paper, bid activation plans are restricted by constraints on minimum duration and full activation time. However, there are also important adjustments. Whereas the previous paper concerns activation plans for balancing bids from different mFRR products, similar techniques are used in this paper to model the feasible activation patterns and time-dependent delivery profile of the mFRR standard product, as well as a simplified representation of aFRR (represented as a flexible balancing resource with a somewhat higher activation cost), and the interplay between these. In addition, new sets of constraints (and a new binary indicator variable) has been introduced to be able to account for the balancing energy delivered by mFRR bids during their ramping phase, i.e. before the bid is fully activated. This gives a more accurate representation of the balancing energy delivered into the system.

The main focus of the paper, however, is on managing uncertainty in the imbalance forecast. The activation model is formulated as a two-stage stochastic program. To evaluate the value of taking uncertainty into account, the activation model is applied in a rolling horizon simulation. At each point in the simulation, the imbalance forecast is updated, and the activation model re-optimizes bid activation plans, taking into account new imbalance forecasts and sunk balancing decisions. Any imbalance not covered by mFRR at this point is considered to require aFRR activation. As with Model Predictive Control (MPC), the first control decision of the updated activation plan is applied before the simulation moves on to the next timestep. Compared with a deterministic strategy in a setting with inaccurate imbalance forecasts, the activation decisions made for mFRR by the stochastic strategy proved to be less naive, and are found to reduce total balancing costs over the period of simulation, as expected.

An interesting aspect observed in the resulting activation plans is the occurrence of a so-called *proactive failure*. This happens when the optimization, overconfident in the forecast, commits to early activation of mFRR to meet the expected future imbalance. When the forecast is inaccurate, in particular regarding the net balancing direction (up or down), manually activated balancing actions can be difficult to revert and expensive to counteract, especially under the assumption of mFRR products with long minimum duration. The deterministic model regards the imbalance forecast as perfect information, and as a consequence, consistently ignores the potential cost of recovering from forecast errors (often referred to as recourse decisions in stochastic programming terminology). The stochastic model, considering multiple imbalance scenarios, to a larger extent avoids gambling on long-lasting manual activations, and largely mitigates this negative impact. However, the stochastic model is also misled by forecasts in some situations, with a proactive failure clearly observed in the case study in the paper.

The complexity of the scenario tree used in the numeric example is small, with only three imbalance scenarios and the optimization horizon limited to 45 minutes ahead (9 timesteps). With a small list of 16 balancing bids, and the transmission network disregarded, the stochastic single-period problem is usually solved on a laptop in less than a minute, although proving optimality takes longer in some cases, raising questions about scalability to large problem instances. On the other hand, computation speed could be significantly increased through decomposition, parallelization, and tailored solution algorithms if needed.

4.3.3 Multi-Area Balancing Energy Activation Optimization using ENTSO-E Standard Products

J. Bøe, M. Håberg and G. Doorman, “Multi-Area Balancing Energy Activation Optimization Using ENTSO-E Standard Products”, in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, IEEE, Oct. 2018.

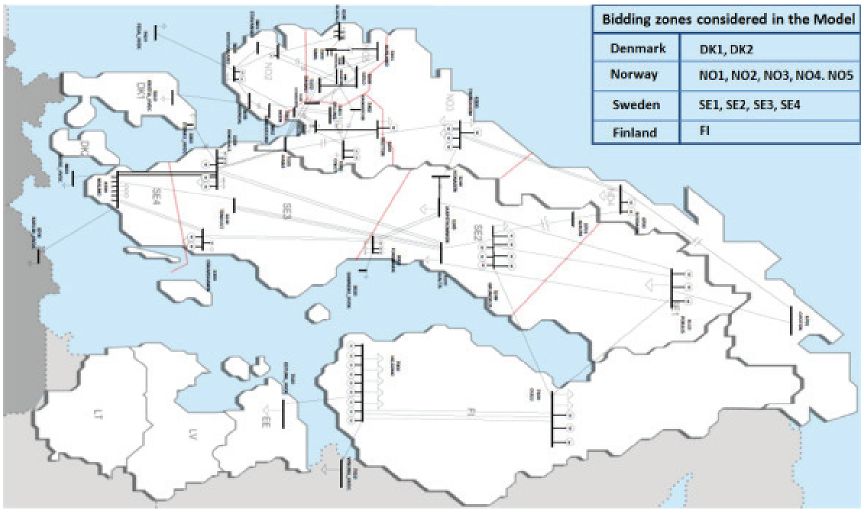
This conference paper presents and demonstrates a model related to the ones presented in Sections 4.3.1 and 4.3.2, and has both similarities and extensions. Here, as in Section 4.3.2, energy delivered from mFRR in the ramping phase is accounted for through an additional set of constraints and variables. This paper also includes a faster 5-minute mFRR product (representing a second mFRR standard product or a (local) specific product), in addition to other detailed constraints on delivery and re-activation behavior, similar to the earlier models. The objective function and energy balance constraints also contain a simplified aFRR representation (as in Section 4.3.2), and also include a penalty representing non-activation of FRR, assuming frequency deviations and corresponding activation of FCR. The penalty level was calibrated for the activation model to perform consistently with frequency quality standards in the Nordic system.

However, the most significant extension is arguably the consideration of the transmission network in the balancing optimization. A central element is the set of energy balance constraints, matching the net balancing energy flow into a bus the net volume of the local imbalance and bid activations. Following the assumptions of DC power flow, the power flow along transmission lines is represented by a linearized function of voltage angle differences. The resulting model thus has similarities to a DC Optimal Power Flow formulation, minimizing a cost function representing the supply of energy to demand at given locations. On top of this structure are the complicating variables and constraints incurred by the representation of the mFRR product across timesteps.

In the paper, the optimization model is used together with a network model in a case study. The network model consists of 44 buses [76], [77], serving as an aggregate representation of the Nordic synchronous system (cf. Fig. 4.1). The remaining available transmission capacity for balancing was found by subtracting the power flow imposed by historical commercial schedules in the day-ahead market.

The balancing activation optimization is solved for every step in a rolling horizon simulation with different configuration of balancing products. As a reference case, a single mFRR product with 15 minutes Full Activation Time and minimum duration was used to balance the system over a period of 24 hours. The imbalance forecast is based on historical imbalance data used in the simulation, but with noise added, and it is updated for each step in the simulation procedure. The limited ability of the 15 minute product in reacting to new conditions in the very near future leads to high balancing costs, compared to two other cases with more flexible configurations. The first is introducing a second mFRR product with 5 minute FAT and minimum duration, and the other is keeping a single mFRR product with 15 minute FAT, but having a minimum duration of only 5 minutes. Both of these latter configurations allow for less rigid activation plans, better suited to adapt to forecast errors, and show a clear advantage in terms of computational time and duality gaps. The same pattern was also observed when the imbalance forecast quality was significantly reduced.

As expected, including transmission constraints impacts the outcomes of the op-



Bidding zones considered in the Model	
Denmark	DK1, DK2
Norway	NO1, NO2, NO3, NO4. NO5
Sweden	SE1, SE2, SE3, SE4
Finland	FI

Figure 4.1: Nordic 44 Equivalent Model Mapped to the bidding zones of the Nordic grid used in Nord Pool for 2015 [77].

timization. The ability to cover imbalances with FRR now depends not only on available reserve capacity, but also on the locations of these bids, and the available transmission capacity. As a result, there are situations where imbalances in congested locations remain uncovered by FRR to avoid overloading the transmission network, leading to frequency deviations. Unless explicitly prohibited to do so, the balancing optimization will often simultaneously activate balancing energy in opposite directions, redispatching the system to manage grid congestion.

4.4 Discussion

As mentioned, the main issue in this chapter is modeling the activation optimization process with multiple balancing products. After first analyzing the most essential assumptions behind the models, and whether they still hold, the discussions in the subsequent paragraphs focus on the implications of the models and modeling approaches proposed in this chapter, as well as how and whether they can be relevant in the future. The secondary issues related to imbalance uncertainty and network constraints are also included in this discussion, before closing with remarks on computational performance.

In relation to the other topics addressed in this thesis, the methods and models presented in this chapter serve a different purpose from the ones discussed in Chapter 3. Whereas the proactive model in the previous chapter provides a means to integrate future balancing needs and opportunities based on considerations of the alternative cost, the models demonstrated in Publications III-V are different in nature. These models focus mainly on decisions within the FRR processes, incorporating the delivery patterns and flexibility properties of different products.

The relation to Chapter 5 is somewhat less conspicuous. The models formulations described in Sections 4.3.1 and 4.3.2 do not consider the transmission network at all, and hence only touch upon the inner workings of the balancing energy activation problem. The model in Section 4.3.3, on the other hand, represents a nodal pricing approach to congestion management, albeit on an aggregate grid representation in this case. If regarding these two approaches — *no transmission network* and *full nodal optimization* as some kind of extremes, the models and methods presented in Chapter 5 represent approaches in between, accentuating compatibility with zonal market structures.

4.4.1 Essential Assumptions

The contributions presented in this chapter and the accompanying papers rest on a set of assumptions. With European balancing exchange platforms going live within the next few years, there are especially two fundamental assumptions that could be scrutinized in retrospect. The first is the assumption that the Activation Optimization Function of European platforms for balancing energy exchange would face the issue of selecting balancing bids for activation using not one, but a *list of* standard products. The second is that TSOs would be largely indifferent to which exact bids and products are activated, as long as they serve the purpose, in combination if necessary; covering imbalances at minimum cost.

Only in the last few years have the European TSOs shifted focus towards single-product arrangements in the integrated balancing market. Within ENTSO-E's Working Group Ancillary Services, discussions on standard products for a long time reflected European TSOs' attempts to harmonize a diverse range of balancing practices. This involved meticulously reducing a lengthy list of standard products, not universally convinced that one product (or even a few) would serve the needs of all TSOs. The platform implementation projects [41], [42], [78] followed a different approach, desisting earlier discussions, and aiming from the start for using a single product in each platform.

While there are reasons for a TSO to be largely indifferent to which bids and products are used, there may also reasons not to be. From the perspective of TSOs minimizing balancing costs by utilizing the least expensive balancing resources as far as possible, having more alternatives to choose from (when appropriate) would likely decrease costs in the short run. Moreover, European TSOs typically already operate multiple control processes in parallel in the balancing stage, and some of them even optimize between different balancing products [2]. On the other hand, many European TSOs appear to operate their balancing processes somewhat independently of each other, in a sequential and procedural and manner, with distinct responsibilities and following specific rules. Moreover, European TSOs, appear to be cautious, or at least mixed, in their positions on welcoming more and alternative products in balancing operations. Even though new platforms for balancing energy exchange provide opportunities for trade and increase access to balancing resources from abroad, only France and the Czech Republic have chosen to participate in the development of *all* four platforms[2]. This could be explained not only by implementation costs, but also a possible attempt to reduce complexity in balancing operations.

4.4.2 Implications of Proposed Activation Optimization Models — and Extensions

The balancing activation models from this chapter constitute a product-agnostic approach, and center on regarding the entire available pool of bids and products when identifying a minimum cost combination of balancing actions. From a competition perspective, this product-agnostic approach provides additional dimensions compared to simplified models, where bids would compete and be selected in a purely price-based manner, possibly influenced by cross-zonal capacities in multi-area markets. When the model formulations of the papers presented in the sections above include constraints on activation time and delivery duration, the technical characteristics of each balancing bid will also have an impact. As a result, bids will compete not only on prices and locations, but also in terms of the delivery patterns and varying degrees of flexibility of their respective products in an arrangement conceptually similar to a central dispatch.

When regarding multiple products, the crucial differences between them, at least in early proposals for RR and mFRR standard products, are found along the time dimension. To assure that the selected bids will counteract the imbalance at an adequate point in time, consideration of several timesteps is required in the optimization, which again allows identifying the optimal timing and duration of bid activations. With this additional freedom comes flexibility, but also a more complex decision process. Acknowledging that balancing operations take place close to real time, some TSOs inclinations would be to maintain established procedures based on clear rules or simplified models, at the expense of multi-product considerations. This is in line with the shift towards one single standard product to be

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[2] Cf. overview of members at https://www.entsoe.eu/network_codes/eb/terre/, https://www.entsoe.eu/network_codes/eb/mari/, https://www.entsoe.eu/network_codes/eb/picasso/ and https://www.entsoe.eu/network_codes/eb/imbalance-netting/

exchanged for each platform, and the assumption of multi-product arrangements on European platforms comes across as less relevant, challenging the usefulness of the models in Publications III, IV and V. However, as outlined in Section 4.1, the modeling techniques would find purpose in the hands of a TSO optimizing activation decisions across alternative products, and conceivably also in future extensions (or consolidations) of European balancing platforms.

A crucial part of the results given by the models in this chapter concerns which volumes *not to activate* until a later stage. As in Publication II, the models in this chapter pursue to coordinate the relative activation volumes between different products by making early decisions on what balancing energy volumes to defer to other processes with shorter activation times. The results from the stochastic model in Publication IV are especially interesting in this regard. By accounting for uncertainty in the imbalance, the value of flexibility and reversible decisions is factored into the balancing decisions. This gives an interplay between aFRR and mFRR that is not only based on simple rules[3], or based on bid prices (as in Publication II). As a result, mFRR activation decisions will be more robust against forecast errors, making the stochastic model highly relevant for TSOs determining their demand for e.g. mFRR vs. aFRR, or for potential coordination between different balancing platforms.

A final note concerns extending the activation optimization to take transmission network constraints into account. As will be elaborated in Chapter 5, transmission congestion from balancing activations can be a source of concern for TSOs. The nodal formulation in Publication V is relevant for future development of European balancing markets, as it represents one possible approach to prevent the issue of internal congestion. Under this arrangement, the cost of transmission scarcity will be reflected in the activation decisions of individual bids, as in markets based on Locational Marginal Prices. This integration of balancing and redispatch decisions would not be directly compatible with the current market rules in some European countries, including Belgium and Germany, where clear distinctions between activation purposes (i.e. balancing or system purposes) are required. However, this approach gives feasible network flows and balances the system at minimum cost, and is comparable to the practice of TSOs in other countries, including France and Norway.

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[3] Examples of simple rules: (1) cover a certain share with mFRR, the rest with aFRR, or (2) let the imbalance forecast average decide the mFRR volume, use aFRR only to cover any residual imbalance

4.4.3 Computational Performance and Experiences

In the balancing stage, time is a limited resource, therefore computational performance is a critical factor in the balancing energy optimization. As an example, at most 60 seconds is expected to be allotted to running the optimization algorithm in the European mFRR platform under development [33]. Although most of European system will be covered by this platform, this is a market clearing problem of moderate size, considering it is solved for a single timestep with a limited number of zones. With integer decisions, this is a MILP problem, and fast solvers and heuristics are available, enabling quickly finding feasible, near-optimal solutions. At the same time, non-convexities induced by indivisible and complex bid structures, as well as specific market and pricing rules, lead to complications for these kinds of models, as described in Section 2.5.2.

For the multi-product, multi-timestep scheduling models presented in this chapter, Publications IV and V report briefly on computational experiences in their respective case studies. The deterministic model in Section 4.3.2 reaches optimality almost instantly, whereas the stochastic formulation generally needs tens of seconds to close the duality gap below 5 %. Considering the very limited size of the test problem in this case, this is not a very promising result for the stochastic formulation. From experience, the computational time appears to be driven by a considerable number of integer variables, and binary indicator variables used e.g. for the minimum duration constraints have limited potential for continuous relaxation. However, including flexible alternatives in the optimization (such as aFRR or various penalties) generally increases the computational speed. A plausible explanation could be that these continuous variables allow feasible solutions to be found almost immediately, quickly establishing upper bounds that limit the amount of branching, reducing the negative impact of using a high number of integer decision variables. This is supported by the observation that solution times decrease particularly in situations where aFRR represents a low-priced alternative, i.e. when only a portion of mFRR bids would potentially be less expensive to activate. There are also other paths to improve computational efficiency. Various matheuristics, such as tailored neigborhood searches, can be used, even in parallel, to find high-quality solutions faster than MILP approaches, as demonstrated for a similar problem by Dupin and Talbi [79]. For the stochastic model, decomposition per scenario, e.g. using Lagrangian relaxation [80] or progressive hedging, [81], [82] could also contribute to the computational improvements necessary to avoid scalability issues.

The computational experiences from the case study in Section 4.3.3 can be regarded as a mixed result. The simulated system is larger in this case, with a network containing 44 buses and 80 branches, as well as more bids compared to the previous paper. The activation model is deterministic, i.e. using a single imbalance forecast. Yet, with a cutoff time of 60 seconds per optimization run, the resulting duality gaps in the reference case are far from impressive, indicating rather weak convergence in many situations. Notably, this is the case configuration with the least flexible balancing resources, and the 15-minute minimum duration constraint is singled out as a potentially highly influential restraint.

In conclusion, applying such models as described in in this chapter to the scale of an European balancing market would not require significantly expanding the optimization horizon or network description (assuming a zonal market with tens of zones). The number of bids would, however, increase significantly, thereby introducing large numbers of integer decisions under these formulations. Although the problem would have a MILP structure, experiences from small-scale test cases put into question its scalability to very large systems with operational requirements on computational time. Pursuing such an approach would likely require parallelization or a less detailed representation of the standard products.

Chapter 5

Managing Intra-Zonal Congestion under Different Balancing Exchange Arrangements

Power flows in the transmission grid are decided by the physical network properties, as well as the locations of positive and negative power injections. A responsibility of the TSOs is to maintain reliable operation of the system. This includes, among other several other tasks, avoiding network congestion, which causes risk of overloading network elements and leaves the system vulnerable to contingencies.

The European electricity market is subdivided into zones, for the most part consistent with national borders (with notable exceptions). The integrated European markets account for limitations on transmission capacity *between* zones, but this structure does not prevent congestion *within* zones, potentially resulting in infeasible network flows. This also applies in balancing markets, where activating a balancing energy bid may or may not cause network congestion, depending on its location in the grid, and other factors. And whereas infeasible schedules from the day-ahead market clearing can be adjusted through a redispatch procedure, the available time for adjustments is very limited in the balancing stage.

In some balancing activation markets, each individual balancing energy bid is required to specify its exact location in the transmission grid. Under this arrangement, the impact on transmission flows from activating the bid can be anticipated. To avoid network congestion from balancing actions, bids are marked as unavailable and skipped on the merit order list, if identified as undeliverable due to their location in the grid. The European balancing platforms under development aim to address intra-zonal congestion in a similar manner, by having TSOs mark certain bids as unavailable (cf. Art. 29.14 of EBGL [1]), effectively disqualifying them from the market in a process sometimes referred to as *bid filtering*. In the case of the European platforms, however, TSOs are obliged to identify the undeliverable bids *before*, not *during* the bid selection process, while the outcome of the balancing market and the status of the system is still unknown.

The first main issue of this chapter concerns how to avoid intra-zonal network congestion by pre-filtering balancing energy bids, i.e. disqualifying reserves based on their location in the grid, before knowing the outcome of the European balancing market. As an alternative approach, the second main issue covered in this chapter concerns how intra-zonal network congestion can be addressed *within* the optimization, during the balancing market clearing. This requires some other mechanism to prevent bids from being selected by the AOF if their activation would lead to network congestion, while preferably preserving a zonal market structure.

The major contributions of this chapter are Publications VI and VII (with manuscripts located in Sections 7.6 and 7.7). The subsequent sections are centered around and will elaborate on these papers. Section 5.1 briefly summarizes relevant background literature on managing network congestion in balancing markets, placing Publications VI and VII in context while describing their setting and perspectives. The paper summaries in 5.2 also provide condensed methodological descriptions. The chapter concludes with a discussion on the implications of the research in Section 5.3.

5.1 Context and Perspective

For a European context, Linnemann, Echternacht, Breuer and Moser [83] summarized the three main mechanisms for congestion management: *grid expansion*, *market splitting* and *redispatch*. Also worth mentioning, *optimal transmission switching* techniques [84] have gained attention and shown signs of potential in recent years. In addition, a range of other mechanisms has been used, either traditionally or in other systems, cf. Pillay, Prabhakar Karthikeyan and Kothari [85] for an extensive overview.

Unlike redispatch, market structure cannot be adjusted in the operational timeframe, yet it can serve as a key element in preventing network congestion. When limitations on transmission capacity are included in the market clearing, solutions with unrealistic transmission flows are more likely to be discarded as infeasible. Traditional area pricing models do not adhere to Kirchoff's laws, being based only on hypthetical market flows and Net Transfer Capacities (NTCs). As an evolution, a complementary mechanism to this simple market splitting is introduced with the flow-based market coupling [86], providing a linear mapping of zonal net positions to power flows on so-called Critical Network Elements (CNEs). This concept as also been proposed for balancing optimization in Farahmand, Hosseini, Doorman and Fosso [52]. Nevertheless, aggregation steps in the method means discrepancies between physical and market outcomes cannot be fully prevented. Hence, zonal models based on the NTC and flow-based approaches are ineffective in preventing intra-zonal congestion. Nodal market structures use a detailed representation of the transmission grid in the market optimization. As a result power flows decided by market outcomes would better adhere to network capacities in a zonal model. Spatial market price differences reflect transmission scarcity, and provide locational signals for investment. Whereas price differences between zones indicate scarce cross-zonal capacity, the locational marginal prices produced by nodal markets also reflect congestion between nodes *within* zones.

Closely related problems and techniques have been studied for several US electricity markets, where traditional reserve requirements are based on deterministic reserve zones. When disregarding the grid location of reserves procured within a zone, there is a risk that the procured reserves are ineffective against intra-zonal congestion [87]. And just as in the zonal European balancing market, all reserves within a zone are assumed to have equal shift factors on critical lines, and the true deliverability of the procured reserves will be imprecise. To ensure adequate volumes and locations of operating reserves, Lyon, Zhang and Hedman [88] demonstrate a locational reserve disqualification method taking into account a range of distinct contingency scenarios.

Such concerns on reserve deliverability are mirrored in balancing markets with portfolio bidding, like the German system. Here, load flows from balancing energy activations are unforeseeable, according to Sprey, Drees, Stein and Moser [73], due to the unknown locations, not only of imbalances, but also of units providing reserves. Horsch and Mendes [89] approach this issue by splitting the reserve market into zones, with separate reserve requirements, as in some US markets. Simulating the balancing market on an aggregation of the German system, they conclude that this design has inefficiencies, leading to procuring unnecessarily high reserve amounts. Sprey, Drees, Stein and Moser [73] also simulate the German balancing market with linear models. They abstain from creating additional reserve zones, but nevertheless demonstrate how N-1 security violations can be avoided when the location of the balancing energy activation is known and deviations from the merit order are allowed.

In relation to the problem of detecting congesting balancing energy bids to withhold from European balancing platforms, Guntermann, Gunderson, Lindeberg and Håberg [9] has made a relevant contribution. This paper is referred to as Publication VIII, one of the additional articles in Section 1.3. The methodology presented in the paper aims to identify bids that should be skipped in the merit order to avoid intra-zonal congestion. It follows the approach of simulating balancing energy requests, gradually increasing in size, and from one neighboring zone at a time, activating local balancing bids in the merit order, and checking for network violations in a series of load flow calculations. Congesting bids are marked as unavailable and skipped in subsequent calculations.

The paper referred to as Publication VI was written in 2018, and at this point the concept of intra-zonal congestion management through bid filtering was rather firmly established in designs drafts of the European balancing platforms. It takes the perspective of a participating TSO, trying to predict —before the clearing of the balancing market— the necessary deviations from the merit order to avoid network congestion. Even when assuming perfect information on the locations of local imbalances and balancing bids, the TSO faces considerable uncertainty without the necessary information on transmission flows, which are affected by the activation decisions of the AOF of the platform. Facing this uncertainty, the TSO could take a conservative approach, marking individual bids as unavailable if their deliverability is not guaranteed across a range of possible flow situations, which unlike [9] include combinations of exchange requests to more than one neighboring zone. This is the approach taken in the paper, as summarized in Section 5.2.1. A more liberal approach would be to allow more bids to take part in the market, and try to make adjustments ex post, when a TSO identifies a bid activation from the market outcome as infeasible. However, the time for such adjustments would be very limited, at best.

The contribution in Publication VII, on the other hand, takes the perspective of the Activation Optimization Function of a European balancing platform. In contrast to the European balancing platforms currently under development, the distributed model proposed in the paper circumvents the bid filtering process by downplaying the importance of Common Merit Order Lists. Rather, the model acknowledges that optimal (and feasible) activation decisions depend on cross-border exchange flows. It centers around optimizing these exchange flows between zones, while bid activations and balancing costs are determined in subproblems representing individual zones. Relative to the European platform implementation projects, the distributed model presented in the paper does not try to address all aspects, and rests on simplifying assumptions, in particular regarding pricing and bid structure.

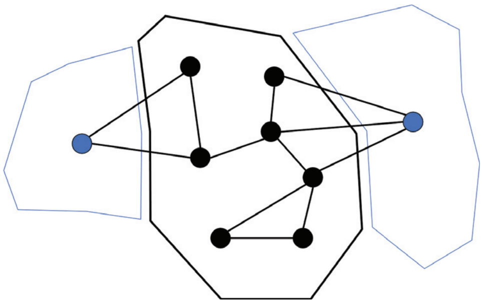

Figure 5.1: Example single-area system consisting of internal nodes and external nodes representing neighboring areas [7].

5.2 Summary of Publications

5.2.1 Preventing Internal Congestion in an Integrated European Balancing Activation Optimization

M. Håberg, H. Bood and G. Doorman, "Preventing Internal Congestion in an Integrated European Balancing Activation Optimization", *Energies*, vol. 12, no. 3, Feb. 2019.

Rather than network constraints within market zones in the balancing energy activation optimization, new European balancing platforms aim to face the issue of avoiding internal congestion by allowing each TSO to mark bids as unavailable if their activation would endanger operational security. Determining the deliverability of an individual bid is possible using power flow calculations, however this requires knowledge of the bid location in the grid and the imbalance to be covered, and also the initial flows in the network. Here, the latter two depend on the results from the Activation Optimization Function, and hence TSOs must make availability decisions with limited and imperfect information. Throughout the paper, the proposed methods hold the viewpoint of a single zone, or *focus area*, with neighboring zones represented as single nodes (cf. Fig. 5.1). Recognizing cross-zonal balancing energy exchange as the most influential source of uncertainty, the concept of *exchange scenarios* is used throughout the paper. Each scenario represents a specific situation in terms of cross-zonal balancing energy exchange (and consequently also initial flows throughout the focus area), and together all scenarios provide a discretized set of potential outcomes from the balancing market clearing.

The first main contribution by the paper is the generalized approach to detect potentially congesting bids. The method is built on evaluating the deliverability of each bid over a number of exchange scenarios to analyze whether (and in which

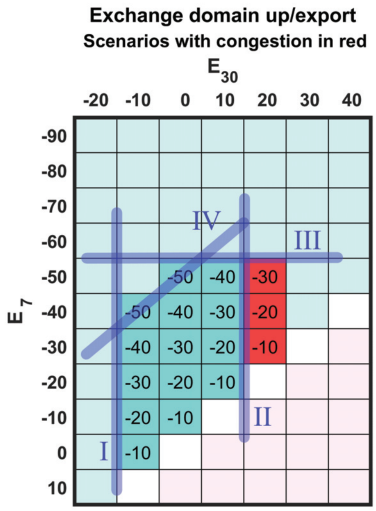

Figure 5.2: Exchange domain described by linear constraints, example from [7].

cases) deviations are required from the merit order. In each scenario, the deliverability of individual bids are determined by first running an extended DC OPF formulation with the specific exchange requirements on nodes representing neighboring zones, and a subsequent comparison of the resulting nodal prices to identify congested locations. There are three potential outcomes of this evaluation. The first is when the necessary bids may safely be activated in the merit order to satisfy the demand for balancing energy exchange (in addition to any local imbalance). In the second case, there is a feasible balancing dispatch to satisfy the exchange demand, but deviations are required from the merit order (i.e. one or more bids are at least partially skipped). The skipped bids are denoted as undeliverable for the specific scenario, and should be considered candidates to be withheld from the CMOL. In the third case, there is no feasible dispatch of the balancing bids to satisfy the exchange demand without violating network constraints.

The second contribution is the proposed introduction of *exchange domains*. This concept aims to complement bid filtering by disqualifying problematic exchange situations, i.e. combinations of cross-zonal balancing energy where skipping bids alone cannot prevent internal congestion. Exchange domains are specified as linear inequalities, and can be regarded as a generalization of so-called sum restrictions used in some markets in combination with Available Transfer Capacity (ATC). Submitting these inequalities as constraints to the optimization on the balancing platform cuts such exchange situations from the solution space and increases the likelihood of feasible activation decisions.

A third contribution is the practical example demonstrating the use of these methods on a small network. Assuming the focus area has two neighbors, exchange scenarios take the form of a two-dimensional matrix, of which some are identified as merit-order feasible with the initial bid list. There are also a few scenarios that become merit-order feasible (with the remaining list) at after one problematic bid is removed from the list. In the example, there are also scenarios where removals from the bid list can never allow the remaining bids to be feasibly activated in the merit order, as well as many infeasible scenarios. Figure 5.2 demonstrates how four linear inequalities describe the domain of situations (in a two-dimensional matrix of exchange volumes) where the bid list can feasibly be activated in the merit order, leaving out congested scenarios (cells in red) and infeasible scenarios (light blue cells without numbers).

In conclusion, the paper recognizes that network congestion within zones in the balancing stage is affected by activation of bids in congested locations, but also by the amount of balancing energy exchange to other zones. Bid filtering is ineffective against congestion in problematic exchange situations. These can, however, be prevented using the concept of exchange domains, which can be regarded as a generalization of ATCs. and can contribute to providing feasible outcomes in the balancing market. Although bid filtering is fundamentally inefficient, and not effective in all circumstances, it can improve the likelihood of feasible outcomes in zonal balancing markets, preferably in combination with exchange domains.

5.2.2 Distributed Balancing Energy Activation and Exchange Optimization

M. Håberg and G. Doorman, “Distributed balancing energy activation and exchange optimisation”, *IET Generation, Transmission & Distribution*, vol. 13, no. 18, Sep. 2019

With limited available computational time and a precedent of zonal pricing in European electricity markets, the activation optimization is based on a highly aggregated representation of the transmission system in the balancing platforms currently under development. This paper presents an alternative approach to optimize balancing energy activations and exchange decisions, preventing intra-zonal congestion without pre-filtering congesting balancing energy bids, while maintaining an overarching zonal market structure.

In the distributed model proposed in the paper, the optimization is structured as a master problem and several subproblems. The interconnected system is partitioned according to the market zones, resulting in a set of single-area systems. Each subproblem constitutes solving the detailed balancing activation problem for a single area (and single time period), given a specific balancing energy volume to be exchanged on the border nodes. The master problem aims to optimize exchange volumes between zones, using information obtained from solving the subproblems. More specifically, assuming subproblems to be convex, information on balancing costs under given exchange conditions are passed as optimality cuts from each subproblem to the master problem in a Benders-like procedure. This distributed, decomposed structure enables dispatch autonomy and parallel solution of the subproblems, each of which contains detailed (nodal) representations of the transmission network within the single area.

The paper describes an iterative procedure to solve the activation and exchange problem. After initially solving the subproblems (e.g. with *zero exchange* or some warm-start values), subgradients of these solutions are passed as optimality cuts to the master problem. The master problem decides balancing energy exchange volumes on each cross-zonal interface to minimize some artificial variable representing the estimated total balancing costs, constrained by the set of all optimality cuts generated by subproblems. Then, subproblems are solved with these new candidate exchange values, adding new cuts to the master problem. This procedure continues until the lower bound (given by the optimistic cost estimate of the master problem) converges with the upper bound (given by the sum of balancing costs in the subproblems). A small, numeric example consisting of three areas demonstrates, iteration by iteration, how the master problem identifies the optimal exchange volumes.

Whereas iteratively adding cuts to the master problem will eventually lead to optimal cross-zonal exchange values, the balancing dispatch is decided autonomously, by the subproblems. With this in mind, a feasible balancing dispatch with near-optimal cross-zonal exchange can be found without the need for iterations, reducing the amount of communication between different entities. The paper describes this as a two-step procedure, first pre-generating a set of optimality cuts from each subproblem for various combinations of cross-border exchange, before deciding cross-zonal exchange volumes using this imperfect —but perhaps sufficiently accurate— representation. Testing both the iterative and non-iterative cut generation procedures on a larger system is highlighted as a topic of interest for future work.

5.3 Discussion

Although representing very different approaches, the methods summarized in Sections 5.2.1 and 5.2.2 have several elements in common. They share the same objective of preventing intra-zonal congestion from balancing energy activations, as well as some modeling techniques and simplifications. After revisiting the essential assumptions, the subsequent paragraphs discuss the implications of each approach, their crucial differences, and their relevance for future applications.

5.3.1 Essential Assumptions

Both of the papers presented in this chapter make simplifications regarding the optimization of bid activations. Specifically, the bid activation models consider the activation of a single product for a single time period in a single area of the interconnected network, disregarding bid complexities due to indivisibility, linking etc. Under these assumptions, the activation optimization problem becomes linear and convex, allowing fast processing and the generation of optimality cuts for the master problem (in Publication VII). With a non-convex activation model, both the bid filtering process and the cut generation procedure would be precluded. These simplifications are drastic compared to the multi-product, multi-timestep models in Publications III, IV, and V. When compared to the AOFs in the balancing platforms under development, however, these simplifications should not be considered unrealistic. All of these platforms aim for the use of a single product. Apart from the RR platform, their AOFs consider only a single time period, and the aFRR product only allows simple, continuous bids. Like the RR platform, the mFRR platform has decided to include non-convex bids, a decision not universally supported among TSOs. Furthermore, the impact of misrepresenting indivisible bids as continuous would be limited considering the maximum indivisible bid size is likely to be limited by TSOs [30].

A second simplification is the partitioning of the interconnected system into smaller subsystems. Here, a neighboring area is treated as a single node, meaning its internal transmission constraints, voltage angle differences, and onward connections to other areas are disregarded. This greatly reduces the scale of the problem and allows a TSO to consider dispatch actions within its own area, given a set of exchange conditions on the border. The drawback of this approach is, of course, limited accuracy in meshed grids. Balancing energy exchange across ac interconnections will obey Kirchhoff's laws, rather than the market schedule, and be distributed throughout the entire synchronous grid. As a result, there will be discrepancies between the actual cross-border flow and the injection in the simplified neighboring-node representation. This effect will be less pronounced, however, in areas connected radially or through HVDC interconnectors.

A last, main assumption used in Publications VI and VII is that in addition to balancing activations and initial flows from earlier markets, the cross-zonal exchange is a crucial factor in estimating transmission network flows within a focus area (typically bidding zone), whereas the distribution of any internal imbalance is less important. Naturally, the imbalance would also play a role, but the assumption may hold, albeit more for some areas than for others. The assumption appears particularly applicable in areas where the scale of the system and transmission capacity within the zone is small relative to the available cross-zonal capacity to neighboring areas. In addition to scale, the variability of exchange patterns and transit flows could affect TSOs' inclinations on whether to plan for uncertainty in cross-border flows vs. other sources of uncertainty.

5.3.2 Implications of Proposed Approaches to Manage Intra-Zonal Congestion

In the short run, European balancing energy platforms aim to handle intra-zonal congestion through pre-filtering congesting balancing energy bids. This concept carries a fundamental dilemma. The TSO is forced to decide —with insufficient information— between explicitly removing participants from the market, or facing the risk of network congestion. In order to maintain operational security and minimize the impact on market participants, the filtering process should be conducted in a precise and transparent manner, making the methodology in Publication VI highly relevant for TSOs participating on European balancing platforms. However, regardless of its implementation, resource inefficiency and market distortion are unavoidable side effects of a bid filtering process. The TSO is forced to face either operational security issues or consternation from market participants about unnecessary filtering. Moreover, extensive filtering would also undermine the ability of the platform to satisfy the balancing energy demands of TSOs, calling into doubt whether a conservative approach is really an option. Observing that all of these detrimental side effects would have been avoided by accounting for network constraints in the market clearing, the concept of pre-filtering bids is clearly suboptimal, and alternative market designs should be considered to prevent intra-zonal congestion in future iterations of the European balancing market.

Introducing exchange domains could support and complement pre-filtering bids, which is ineffective against intra-zonal congestion in some cases. An intuitive example is when balancing energy exchange creates a flow situation where a most (or all) of the local balancing bids are congested. Exchange domains describe a convex set of feasible balancing exchange situations for a given zone, and prevents intra-zonal congestion by eliminating solutions in the market clearing on the balancing platform leading to challenging or infeasible exchange situations. As they do not alter the balancing dispatch, exchange domains cannot prevent all cases of intra-zonal congestion on their own. At the same time, the approach has no considerable negative impact on computational performance in the market clearing (but possibly a positive impact due to a reduced solution space), and it does not suffer from the inherent inefficiencies of bid filtering. In conclusion, exchange domains reduce operational security risks for TSOs without significant drawbacks. Hence this contribution should be considered highly relevant for improving the effectiveness of intra-zonal congestion management based on bid filtering on European balancing platforms.

Aiming to prevent intra-zonal congestion in the balancing market while also avoiding the inefficiencies of bid filtering and redispatch, two alternative market designs stand out. The first design is the pure *nodal pricing* approach, represented by Publication V in Chapter 4. Here, the activation optimization problem includes a representation of the transmission grid and its limitations, which will be satisfied by the optimal balancing dispatch. Compared to the purely zonal design pursued in current balancing platform implementation projects, the nodal pricing approach will utilize balancing resources more efficiently, implicitly avoid infeasible exchange situations and bid activations leading to intra-zonal congestion, and provide location-specific incentives for investments in flexible resources. However, employing a nodal pricing scheme in the balancing market creates distortions unless day-ahead and intraday prices are also nodal, and in the words of Chaves-Ávila, Van der Veen and Hakvoort [38], "the implementation of nodal pricing implies a significant change in the market design, which increases technical complexity and it can be political sensitive currently in Europe".

A second alternative market design is the distributed approach proposed in Publication VII. Like the nodal approach, the activation problem includes intra-zonal network constraints in the optimization, giving a feasible dispatch without prefiltering balancing bids. Compared to the full nodal approach, the partitioning into smaller subproblems distributes the computational effort of clearing the market, and allows *dispatch autonomy*, and the use of inhomogeneous system representations (e.g. different levels of detail, or coupling nodal and zonal markets). From the master problem perspective, the optimization results in a set of optimal balancing exchange volumes and cross-zonal marginal prices.

Even with a zonal master problem, it is hard to envision balancing pricing schemes fully compatible with zonal day-ahead and intraday prices. The optimal balancing dispatch obtained in a nodal subproblem will often reflect nodal price differences within a zone. These nodal prices could be aggregated to one zonal balancing energy price, but with this price signal insufficient to support the optimal balancing dispatch, extensive use of out-of-market compensation could be necessary to avoid incurring losses for BSPs. In addition, an aggregated zonal imbalance price may not be intuitive considering the direction of exchange flows, e.g. when network constraints within a zone give different cross-zonal price signals on different borders in the nodal optimization. The distributed structure is also vulnerable to the inaccuracies of partitioned networks, as discussed in the assumptions above.

Finally, allowing dispatch autonomy may have implications on transparency and discrepancies between local market rules and require new communication patterns.

Considering this set of not universally positive implications, and imperfect pricing compatibility with earlier market timeframes —even when using aggregated zonal prices—, nodal pricing is arguably a more transparent and efficient market design. However, if one or more areas would transition to use nodal pricing (as is considered in Poland), the distributed model proposed in Publication VII is especially relevant in elegantly incorporating zonal and nodal subproblems in the same market clearing.

Chapter 6

Conclusions

In Europe, the introduction of new market platforms and standardized balancing products for exchange aim to transform fragmented, mostly national markets into an integrated, European market. Focusing in particular, but not exclusively, on the exchange of Frequency Restoration Reserves with Manual Activation, the research presented in this thesis addresses some of the central design choices regarding optimization of balancing energy bid activations in the European balancing platforms under development. The main contributions of this thesis have reference to alternative designs of the activation optimization function for balancing energy and related processes, aiming especially to identify methodologies that allow efficient utilization of different balancing resources and avoid congestion in the transmission network, inter-zonal as well as intra-zonal.

As a starting point of the research, the first broad topic of the thesis relates to balancing strategies and coordination of multiple balancing processes. European TSOs pursue diverging operational philosophies, and the balancing market classification in Publication I analyzes relations between market design choices and the activation strategy of the TSO. Drawing the fundamental distinction between reactive and proactive approaches, the classification confirms that while some European countries are *natural partners for balancing*, there are also close neighbors with a significant *design gap*, indicating barriers for market integration.

In the future, European TSOs will need to determine how and when to cover their balancing demand. A proactive strategy, based on imbalance forecasts and early activations, gives the opportunity to utilize reserves with a long activation time (such as through the RR platform), or to wait for other balancing processes closer to real time. Publication II provides a methodology for TSOs to coordinate activation volumes across different balancing processes. Rather than apportioning the balancing demand according to specific rules, *elastic demand curves* can be created to reflect the (limited) willingness of the TSO to pay for different balancing energy volumes, vs. deferring activation to a later point in time. Depending on uncertain forecasts and imperfect information, the methodology cannot be expected to yield exact results. However, in conclusion, the consideration of alternative costs when determining balancing energy demands shifts volumes toward balancing processes with less expensive balancing resources, *reducing balancing costs*. In addition, this coordination approach can support TSOs in *extending their balancing operations* to include additional processes.

The second broad topic of the thesis relates to activation optimization of multiple standard products. Representing alternative designs of the European platforms under development, the family of models presented in Publications III, IV and V minimize total balancing costs by scheduling balancing energy delivery from individual bids over a number of timesteps. A set of operational constraints ensure feasible activation patterns, as determined by the minimum delivery period and full activation time of the balancing product. This provides flexibility, but computational performance is unproven for systems of large size. Most importantly, however, when including these technical characteristics, the activation optimization is *not limited to a single product*. In conclusion, these modeling techniques allow bids from different standard products to be activated *on the same platform* (and in the same process). Under this approach, the risk of market fragmentation from using multiple balancing products is neutralized by *augmenting competition* to incorporate not only on bid prices and locations, but also their technical characteristics.

Multi-product activation models can also serve a different purpose, allowing a TSO to coordinate its use of balancing products with *different flexibility*. A key contribution is the activation model in Publication IV, where uncertainty in the imbalance forecast is taken into account as scenarios in a two-stage stochastic program. In simulations of mFRR and aFRR activation with imperfect imbalance forecasts, the stochastic strategy reduces balancing costs and results in a more cautious use of mFRR compared to a deterministic strategy. This *interplay* is a key outcome, as it gives advice on *what not to activate*. The stochastic model factors the value of flexibility into balancing decisions, enabling a *more efficient allocation* of balancing energy activation volumes across products, compared to approaches based on bid prices or simple rules.

The third and last broad topic of the thesis relates to intra-zonal congestion in the transmission network. In order to avoid infeasible balancing energy flows, TSOs are allowed by the upcoming European balancing platforms to make balancing bids unavailable if their activation would lead to congestion. Since filtering is performed *before* the clearing of the balancing market, cross-zonal exchange (and thereby also intra-zonal flows) are unknown. Publication VI provides a method to identify potentially congesting bids. It mitigates the risk of congestion by considering a range of potential exchange scenarios, thereby constituting a conservative approach. However, *pre-filtering balancing bids has side effects*, and resource inefficiency and market distortions (due to artificially high or low liquidity) are *unavoidable*. The TSO will also face a *dilemma* when balancing bids are deliverable in some, but not all, scenarios. This situation forces the TSO to choose between facing the risk of congestion, or the consternation from market participants being unnecessarily removed from the market. To minimize these negative impacts, TSOs should conduct the filtering process in a *precise and transparent manner*, stressing the actuality and relevance of the proposed filtering method.

Pre-filtering balancing bids is ineffective against congestion under some circumstances, including exchange situations where few (or none) of the local balancing bids are deliverable. The concept of *exchange domains* aims to eliminate the possibility of market outcomes leading to infeasible or challenging flow situations. Exchange domains constitute a generalization of the ATC concept. They take the form of linear constraints on combinations of exchange volumes in the market clearing optimization, encapsulating the exchange situations where bid filtering can effectively prevent congestion. While not effective on their own, they complement the bid filtering process, without significant drawbacks, by conveying additional information. This could prove to be a relevant extension of European balancing platforms, improving their ability of addressing intra-zonal congestion without imposing fundamental changes to the market design.

A fundamental change to the market design would, however, allow network congestion to be prevented as an integral part of the activation optimization. Publication V demonstrates feasible transmission flows using a nodal activation model, where deviations from the merit order due to transmission congestion translate into price differences between nodes in the network. This arrangement gives efficient locational price signals and ensures feasible network flows, but leads to distortions due to incompatibilities with the zonal European day-ahead and intraday markets.

A second alternative is provided by Publication VII, presenting a *distributed* optimization model for balancing energy activation and exchange. In this model, the balancing activation model in each market zone interacts with the rest of the system on an abstract level, through cross-border exchange volumes determined by a master problem. The geographical decomposition of the problem inevitably leads to inaccuracies in transmission flows, but also allows parallel, *autonomous* balancing dispatch. This allows TSOs to include intra-zonal transmission constraints in their balancing activation models, rather than pre-filtering bids. Even though keeping an overarching zonal structure in the master problem, pricing compatibility issues earlier markets still exist, and autonomous balancing dispatch of each separate area may also have implications on transparency compared to a centralized (nodal or zonal) approach. While acknowledging that these issues exist, the distributed model is a relevant alternative, as it can *flexibly accommodate inhomogeneous system representations*. As a result, *areas using zonal and nodal activation models can be included in the same, distributed market clearing*.

European market platforms for balancing energy exchange from RR, mFRR and aFRR are currently being implemented, in addition to an additional platform for imbalance netting. Following years of discussions, TSOs have made the consequential decision of using only *one* standard balancing energy product in each of these platforms. This approach streamlines competition and simplifies several aspects of the market design. The benefits from these simplifications are partly reverted by decisions to include complex bid structures in the RR and mFRR platforms, thereby absorbing the risk of BSPs while greatly complicating the activation optimization process. The integrated European balancing market will obey a zonal structure. This allows the use of market clearing principles now well-established in Europe, and pricing compatibility with day-ahead and intraday markets, but also has a crucial deficiency in relation to intra-zonal congestion, which must be handled in an external process. With insufficient time for redispatch after the balancing market clearing, European balancing platforms are resorting to pre-filtering congesting bids *before* the clearing of the market. This has adverse consequences, not only is it suboptimal from a market efficiency perspective, it is also incapable of preventing congestion in certain situations.

In closing, through the abstraction of the balancing market, balancing activations amount to transactions of a balancing product to satisfy the balancing demands of TSOs. In a broader perspective, balancing activations should also regarded as last-minute adjustments in a physical system of just-in-time delivery. As such, balancing decisions should adhere to a set of operational security considerations. With balancing inseparably intertwined with flows in the transmission grid, network constraints are arguably the most fundamental limitations to account for. This is —albeit half-heartedly— acknowledged in markets using cross-zonal capacities. A full transition to nodal pricing in European electricity markets is costly and politically sensitive, and not a realistic alternative in Europe in the foreseeable future. TSOs should nevertheless actively pursue opportunities to incorporate transmission limitations in balancing decisions to improve the efficiency and operational security of future balancing mechanisms.

6.1 Suggestions for Future Research

For continuation of the research covered in this thesis, a number of issues are identified as especially interesting. Potential large-scale application of the activation optimization models from Chapter 4 appears to hinge on improvements in computational efficiency, especially for the stochastic model. Research work to increase scalability could encompass tightening the MILP formulation, adequate modeling simplifications, decomposition methods and parallelization, as well as tailored heuristics. For the method of pre-filtering balancing bids, an alternative way to manage risks could be with a probabilistic weighting of exchange scenarios. This could be used to accommodate a trade-off between operational security and market efficiency considerations.

Two particular issues in the distributed balancing optimization would merit further investigation. The first issue concerns incorporating integer decisions in activation optimization models, as this leads to non-convex subproblems. In addition to convexification, other techniques such as including binary cuts could be explored. The last issue concerns pricing compatibility with zonal markets. In the distributed model, nodal price differences within an area reflect deviations from merit-order activation. Moreover, price differences between nodes representing different borders of an area indicate binding constraints on transit flows. Discrepancies between nodal and zonal prices may have implications on the bidding behavior of market participants, raising questions on how (and whether) to create aggregated (zonal) prices, and how market inefficiencies can be mitigated.

Chapter 7

Publications

7.1 Publication I

Classification of Balancing Markets Based on Different Activation Philosophies: Proactive and Reactive Designs

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***Abstract*—Following the vision of an European energy union, electricity markets, including balancing markets, are being integrated. Considerable balancing market design differences between areas in some cases necessitate harmonization processes. Some aspects of balancing market design are heavily influenced by the activation philosophy of the Transmission System Operator (TSO), which again may depend on unique structural conditions.**

This paper identifies the key balancing market design variables influenced by the activation philosophy of the TSO and presents a set of indicators for proactive and reactive market designs. The indicators are used to classify various balancing markets in Northern Europe, based on their market incentives and use of proactive activations.

***Index Terms*—activation philosophy, balance responsibility, balancing market design, frequency restoration reserves, imbalance settlement**

I. INTRODUCTION

In order to maintain secure operation of the power system, it is necessary to maintain a continuous balance between generation and consumption. The TSO procures and activates reserves for this purpose. Following deregulation, TSOs typically operate a balancing market, consisting of linked submarkets for procurement of reserve capacity, activation of balancing energy, and imbalance settlement. As a part of the ongoing European-wide integration of electricity markets, ENTSO-E (the European Network of Transmission System Operators) aims to harmonize balancing market rules through the Network Code on Electricity Balancing (NC EB) [1].

For structural and historical reasons, European TSOs approach the task of balancing in different ways, and some of the market differences arise from contrasting philosophies between TSOs. One fundamental issue is whether the TSO uses forecasts and manual reserve products to prevent future imbalances, or solely let balancing activations respond to frequency or control error signals. Both approaches can be advocated, depending on the power system characteristics.

As stated in NC EB, European balancing markets shall be integrated following a stepwise process, where adjoining TSOs form Coordinated Balancing Areas (CoBAs), in which Standard Products for Frequency Restoration Reserves (FRR) will be exchanged between areas and activation of balancing energy will be jointly handled by TSOs using an Activation Optimisation Function [1]. In some cases, adjoining TSOs share similar activation philosophies. In the Nordic case, the balancing market is already jointly operated, and rules are harmonized. With the aim of a single European CoBA however, it is inevitable that markets with different activation philosophies will be integrated in the future. Harmonization may prove more difficult when design options are incompatible with the activation philosophy of one or more TSOs.

This paper investigates the influence of activation philosophies on balancing market design by identifying key design variables and their role as indicators of reactive and proactive strategies. Based on these design variables, the paper proposes a high-level relative classification of balancing markets based on activation philosophy and market incentives.

First, Section II introduces the concepts of reactive and proactive control, and explains how such means are used by TSOs in the balancing process. Section III explains the balancing market design variables influenced by activation philosophies and some of the incentives they provide to market participants. Section IV presents the classification of balancing markets based on indicators from these design variables and compares the classification of several of the balancing markets in Northern Europe. The findings are discussed in Section V.

II. REACTIVE AND PROACTIVE BALANCING STRATEGIES

Deregulation, intermittent energy sources, and the process towards integrated markets for electricity in Europe has directed scientific attention towards balancing market design over the last decade. Notable contributions include [2], [3]. [4],[5],[6],[7],[8],[9]. Even though activation philosophy can be seen as an important determinant for balancing market design choices, the notion of proactive and reactive balancing strategies has only recently become focal through ongoing discussions on balancing market harmonization and integration. Apart from [3], most of the available literature includes TSO reports on market design and cross-border balancing cooperation, focusing particularly on the Netherlands, Belgium and Germany [10], [11],[12],[13].

A. Control Processes and Concepts

In power systems, frequency control comprises distinct and sequential control processes serving different objectives. Through [14], ENTSO-E has established the control processes to be used by European TSOs. These include the Frequency Containment Process (FCP), Frequency Restoration Process (FRP), Reserve Replacement Process (RRP), Imbalance Netting process, and Time Control process.

Control processes can be classified as either reactive or proactive depending on their objectives and how they are triggered. Frequency Containment and Frequency Restoration processes observe the current imbalance situation and employ reserves in order to contain the frequency deviation or restore the frequency and scheduled programs. These are *curative* objectives [11], and hence, the FCP and FRP are in principle purely reactive processes. Time control should also be regarded as a reactive control process.

The Reserve Replacement Process is different in that its objectives are *preventive* [11]. Replacement Reserves (RR) can be employed to reduce the future system imbalance, as expected by the TSO. They can also be used to avoid future activation of FRR, create margins, optimize the system or even relieve congestion. Using RR with preventive objectives should be seen as a means of proactive control [11].

The Imbalance Netting Process can be designed as either reactive or proactive depending on whether forecasts or only real-time measurements are taken into account.

B. Proactive Activation of mFRR

The manual FRR (mFRR) product can be used by TSOs to restore frequency or Area Control Error (ACE) through the FRP. Then the product has a curative objective, and activation is determined by the actual power imbalance. Hence, mFRR can be regarded as a means of reactive control. In practice, the classification of the mFRR product is not straightforward. In some cases, TSOs may activate an mFRR product using other input than real-time control errors. In several European power systems, the same balancing energy product can be activated for different purposes [15]. In such cases the objective may very well be preventive and based on predictions, and the clear distinction between reactive and proactive control processes can not be applied to the product.

For FRR in general, "TSOs with a re-active market design only use the real-time Frequency Restoration Control Error (FRCE) or Area Control Error (ACE) as an input for the deployment of Frequency Restoration Reserves" [11]. Activation of RR and proactive use of mFRR products represents the main distinction between reactive and proactive TSOs. Moreover, "...most TSOs are neither fully pro-active nor fully re-active, but operate somewhere in between those extremes." [11]

C. Purpose of Proactive Activation of Reserves

The motivation for activating reserves for purposes other than frequency restoration may differ between TSOs. In the Nordic system, the Regulating Power product is used for purposes of frequency restoration, reserve replacement, and management of internal congestion. The Electricity Balancing System currently being introduced in the UK uses forecasting and optimization tools to schedule manual activations. The proactive activation to some extent compensates the absence of an automatic FRR (aFRR) product and the low inertia relative to the Continental system [16].

Some TSOs optimize between balancing products [12]. Manual balancing products will then not only be used based on requirements to relieve aFRR and restore frequency, but also to some extent substitute aFRR or other manual products if technically feasible through a cost minimization. Optimizing between products with different characteristics is not straightforward under uncertainty [17], and activation can not be determined by control errors alone.

III. BALANCING MARKET DESIGNS

Balancing markets design consists of three main pillars: balance responsibility, balancing service provision, and imbalance settlement [4]. Furthermore, the market consists of three main players: Balancing Service Providers (BSPs), Balance Responsible Parties (BRPs), and the TSO [18]. According to [19], "the balancing market is structured in such a way that the BRPs who cause imbalances pay indirectly to the BSPs who resolve the imbalances." As balancing markets are usually operated by their respective TSO, these markets are to a large extent designed to fit a given balancing strategy. These unique adaptions are visible in some of the design variable choices.

Both reactive and proactive designs pursue efficient use of balancing resources, but take on very different approaches. Reactive designs aim at providing strong incentives for market participants to reduce imbalances, thereby also reducing the need for balancing actions by the TSO. Proactive designs aim at efficiency through pooling of resources, early intervention, competition between products and centrally controlled price optimization through the TSO [11].

A. Design Variables

Both [6] and [5] present design variables for balancing markets. These were used to analyse options for cross-border markets in [7]. Proactive and reactive balancing market designs can to a large extent be identified based on design choices for a subset of these variables. The most central design variables are the *Program Time Unit* (PTU) and the *Type of balancing service* [6]. The types and relative volumes of balancing services procured provide an indication on the activation philosophy of the TSO. The PTU is equivalent to the Imbalance Settlement Period (ISP), the length of which determines the division of balance responsibility between BRPs and the TSO. Reactive designs require a short ISP to ensure BRP contribution in the balancing process. Short ISP reduces the risk of different regulation states and provides a stronger link between real-time price signals and settled imbalance prices. The ISP is set equal to the Time to Restore Frequency requirement of 15 minutes in several European balancing markets. Proactive designs may use longer ISPs, as market parties have weaker incentives to adjust their positions close to real time.

Relative positioning of Gate Closure Times (GCTs) is an important design variable for balance responsibility, which has strong impact on self-balancing incentives and also provides an indicator on the balancing strategy of the TSO. Programs committed by BRPs are not final until the GCT of the intraday market, hence this value determines the time available for the TSO to make final adjustments. Reactive designs enable BRPs to better balance their portfolio by setting intraday gate closure as close to real time as possible, while proactive TSOs may need programs to be fixed well in advance of real-time operation in order to determine their actions.

Reserve Requirements and *Bid requirements* are rather complex design variables concerning balancing service provision. Reserve and bid requirements are being harmonized through the ENTSO-E Network Codes [1],[14], most notably through the development of Standard Products for reserve capacity and balancing energy. Agreeing on definitions for Standard Products has proved challenging for European TSOs, in part due to differences between their current product definitions, but also the way products are procured and used. Although such differences could in principle provide balancing strategy indicators, the values of the design variable would be too complex to be useful in a quantitative comparison.

The *Bid activation strategy* includes the criteria, timing, and order of bid activation. For automatic products, this depends primarily on the technical implementation of the controller [6]. For manual balancing products, this is a *key indicator* of the activation philosophy of the TSO. As [3] points out, responsibility for generation from intermittent sources may have severe impact on the timing of activation and use of RR.

Among the design variables regarding imbalance settlement, the *Imbalance pricing mechanism* is of interest, and particularly whether single or dual pricing is used. In either case, BRPs aggravating the system imbalance will be penalized, but only in a single price mechanism may the BRP be rewarded for supporting the restoration process through passive contributions during real time, as is done in some reactive designs. This design choice is closely related to the length of the ISP and real-time publication of imbalance prices. For long ISPs, dual pricing may be necessary to avoid counter-activation [11].

The momentary *Publication of imbalance price data* and regulation state is used in some reactive markets as a crucial tool for BRPs to take a proactive balancing role in supporting the restoration process within the area through passive contributions. The price signals provide incentive and means for BRPs to change their positions in a direction beneficial for the system, and in cases of no internal congestion, programs may be allowed to change up to real-time.

B. Market Incentives

The incentive for BRPs to provide accurate energy schedules and stick to them is formed by the imbalance prices. As imbalance prices are to a large extent determined by the volume of the system imbalance through required activation of reserves, there is a main feedback loop between BRP behaviour and the performance of the balancing market [4].

TABLE I
INDICATOR DESIGN VARIABLES USED FOR CLASSIFICATION

Indicator variable	Symbol	Range
ISP length	l^{ISP}	15-60 min
aFRR energy share	r^{aFRR}	0-100%
RR product used	x^{RR}	0/1
Intraday GCT	t^{GCT}	5-120 min
Optimization between products	x^{opt}	0/1
Dual imbalance pricing	x^{dual}	0-1

Different pricing mechanism designs provide different incentives [4], but in either case, BRPs will develop strategies to minimize their imbalance costs, including over or under-contracting of energy before gate closure or self-balancing during real time. Alternative imbalance pricing schemes, such as the *incentive component* in the Netherlands give the TSO an opportunity to create stronger incentives for BRPs to be in balance in times of reduced system performance [5]. Depending on the pricing mechanism, the imbalance price may give incentives not only for the BRP to balance its portfolio, but also to support the system balance in real time. This reduces the necessary activation volumes for the TSO, but can at the same time give inadvertent incentives in terms of internal congestion [20].

Proactive designs, on the other hand, do not allow BRPs to participate in supporting the system balance during real time, and long intraday lead times and ISPs place the main responsibility for the energy balance in the hands of the TSO. Moreover, proactive activations and optimization between products may lead to lower prices in the balancing activation market, thereby also reducing the imbalance price and the incentive to provide accurate schedules.

IV. CLASSIFICATION OF BALANCING MARKET DESIGNS

A. Indicator Variables

Based on the design variables found to be influential in Section III, distinct indicator variables have been selected. These variables, presented in Table I do not encompass all aspects of balancing market design influenced by the activation philosophy of the TSO, but represent some of the logical and quantitative measures available from TSO surveys or market rules. Notably, the variable x^{dual} may not only take values 0/1, but the value 0.5 is used for markets using different mechanisms for consumption and generation, as in the Nordic countries. This value is also used for the Dutch hybrid mechanism, which in theory is a dual mechanism, but results in single pricing 90 % of the time [11].

Including more variables, e.g. timing of manual activations or the incentive strength provided by imbalance price publication or various settlement schemes would also provide good indicators, as would a relevant quantitative measure of reserve requirements. However, for these variables, data acquisition and treatment is much less straightforward.

TABLE II
INDICATOR DESIGN VARIABLE DATA FOR α CALCULATIONS

Market	r^{aFRR}	x^{RR}	x^{opt}
Austria	90 %	0	0
Belgium	90 %	0	0
Denmark	40 %	0	1
Finland	10 %	0	1
France	50 %	1	1
Germany	90 %	0	0
Netherlands	90 %	0	0
Norway	10 %	0	1
Sweden	10 %	0	1
Switzerland	70 %	1	1
United Kingdom	0 %	1	1

TABLE III
INDICATOR DESIGN VARIABLE DATA FOR β CALCULATIONS

Market	l^{ISP}	t^{GCT}	x^{dual}
Austria	15	30	0
Belgium	15	5	0
Denmark	60	60	0.5
Finland	60	60	0.5
France	30	30	1
Germany	15	30	0
Netherlands	15	5	0.5
Norway	60	60	0.5
Sweden	60	60	0.5
Switzerland	15	60	1
United Kingdom	30	60	1

B. Classification Calculations

National balancing markets can be classified along two axes based on the indicator variables in Table I. For a given balancing market m, the first coordinate α_m denotes the activation philosophy based on indicators r^{aFRR}, x^{RR}, and x^{opt}. The coordinate β_m reflects the strength of incentives for BRPs to participate actively in the balancing process.

$$\alpha_m = -\Delta r^{aFRR} + \Delta x^{RR} + \Delta x^{opt} \qquad \forall m \qquad (1)$$

$$\beta_m = \Delta l^{ISP} + \Delta t^{GCT} + \Delta x^{dual} \qquad \forall m \qquad (2)$$

The values of the indicator variables are not used directly in the calculation. Instead, their relative deviation from the sample mean is used. The relative deviation Δy for a variable y is found as the relative offset from the sample mean μ_y in terms of the sample standard deviation σ_y:

$$\Delta y = \frac{y - \mu_y}{\sigma_y} \qquad (3)$$

Being synthesized as the sum of a set of normalized deviations, the α and β variables serve no purpose apart from enabling a visual comparison of balancing market designs.

C. Comparison of Northern European Market Designs

Design parameter values (cf. Tables II and III) for several European balancing markets have been obtained from regional power exchange websites and various other sources [11],[12]. Using these values in the calculations (1)-(2) provides the coordinates for the visual illustration in Figure 1. Indicator variable data was also collected for several other European countries. Notably, alternative intraday market designs (such as consecutive auctions in Spain and Italy) exist, while other countries do not have any intraday market at all, making them incompatible for comparison through the t^{GCT} variable.

Belgium, Germany, Austria and the Netherlands clearly comprise a group in which indicator variable values are similar or equal. Similarly, the Nordic countries share most or all indicator variables as a result of harmonization.

V. DISCUSSION AND CONCLUSION

Some of the data in Tables II and III are based on surveys, and there may be uncertainty or ambiguity in the numbers. E.g. can it be argued that Nordic TSOs use a reserve replacement process even though no balancing product exists specifically for this purpose. Moreover, $x^{opt} \in \{0, 1\}$ does not reflect differences between TSOs practicing cross-product optimization.

Most TSOs are neither fully reactive nor fully proactive [11]. Although this statement can partially be justified by investigating the control processes employed by TSOs, the market classification in Figure 1 nonetheless exhibits considerable polarization. This is partially caused by the selection of, and in some cases binary requirement on, the indicator variables. However, the polarization indicates correlation between the indicator variable values, especially for the reactive markets.

The classification confirms that some areas are ”natural partners for balancing” [12], with the Nordic countries and BE-NL-DE-AT comprising two distinct groups. At the same time it also illustrates the design gap between some of the neighbouring areas, such as Belgium and France. Such incompatibilities demonstrate how differences in activation philosophies can provide barriers to market integration.

This paper presents current knowledge on proactive and reactive balancing market designs. Among the market design variables found to be heavily influenced by the activation philosophy of the TSO, some of them are used as indicators to classify different balancing market designs. This method clearly illustrates the relative design positions of various balancing markets in Northern Europe.

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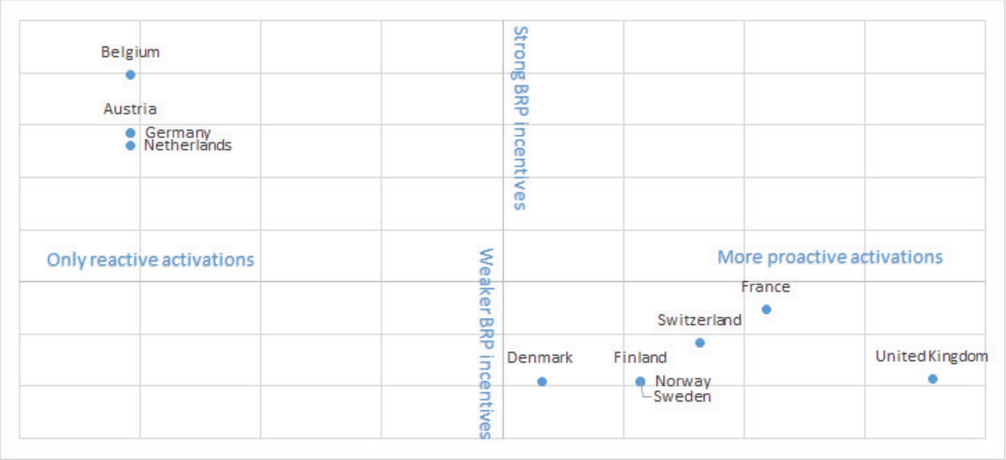

Fig. 1. Classification of Northern European balancing markets based on activation philosophy and BRP incentives

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7.2 Publication II

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7.3 Publication III

M. Håberg and G. Doorman, “Optimal Activation of Standard Products for Balancing as Required by Draft ENTSO-E Network Codes”, in *CIGRE International Colloquium on the Evolution of Power System planning to support connection of generation, distributed resources and alternative technologies*, Philadelphia, PA, 2016.

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2016 CIGRE International Colloquium

Optimal Activation of Standard Products for Balancing as Required by Draft ENTSO-E Network Codes

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SUMMARY

As a part of the new cross-border balancing arrangements in Europe, the Network Code on Electricity Balancing, developed by ENTSO-E, requires Standard Products for Operating Reserves to be defined for the exchange of balancing energy between market areas. Activation of balancing bids will be coordinated by an Activation Optimization Function. To ensure efficient use of balancing resources, the activation algorithm must select between bids with different prices and locations, but also choose between the different products, which may have different activation time and minimum duration. This algorithm is yet to be designed.

This paper investigates how Standard Products can be activated to cover an imbalance forecast at minimum cost as a scheduling problem using mixed integer-linear programming. Case studies also investigate the impact on costs of using only a single Standard Product, imposing a merit order restriction or planning only 15 minutes ahead.

The analyses show that the optimal activation not necessarily follows the merit order, but for the cases studied, imposing a merit order activation for bids of the same product was found to have low impact on costs. Using more than one Standard Product can likely reduce imbalances and the necessary amount of aFRR capacity. Disregarding information on future imbalances reduces computational complexity, but provides costly and unattractive activation schedules.

KEYWORDS

activation optimization function, balancing market integration, cross-border balancing, frequency restoration reserves, imbalance forecasts, standard products

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1 INTRODUCTION

1.1 Integration of European Balancing Markets

For many years, the European Union has pursued the vision of establishing an integrated electricity market in Europe, including balancing markets. An important motivation has been to increase efficiency in utilization of balancing resources [1], but also reducing the high concentration in many markets [2].

Balancing markets can be seen as the liberalized, market-based approach to balance management, "consisting of three main pillars: balance responsibility, balance service provision, and imbalance settlement" [3]. For the European balancing markets to be integrated, national and regional differences have to be overcome [4] in all of these pillars, i.e., harmonization is necessary. The Network Codes currently being developed by the European Network of Transmission System Operators (ENTSO-E) establish common market rules and regulations, and the Network Code on Electricity Balancing [5] aims to facilitate cross-border exchange of balancing services and integration of balancing markets.

1.2 Reserves, Standard Products and Activation Markets

ENTSO-E categorizes reserves into Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR) and Replacement Reserves (RR) [6]. Automatic (aFRR) and manual FRR (mFRR) are similar to secondary and tertiary reserves, respectively. The FRR products used differ widely between European TSOs. For cross-border exchange of these products, ENTSO-E has decided upon a Common Merit Order List (CMOL) approach [5]. In order to facilitate cross-border balancing, ENTSO-E is currently developing *Standard Products* for balancing energy. The Standard Products will define the technical requirements on bids submitted for FRR and RR. Among the characteristics are the activation time and min and max duration of the products.

An *Activation Optimization Function* will operate an activation market, performing a joint optimization of the balancing energy requests from TSOs in the CoBA using bids from the CMOLs. Neither [5], nor [7] provide details on the algorithm principles. Traditional balancing activation markets have often been single buyer auctions, with the TSO purchasing sufficient balancing energy to cover the imbalance through a marginal loading procedure. More sophisticated approaches, such as proactive balancing [8] are less intuitive, but may give lower activation costs.

1.3 Focus and Outline of Paper

The balancing energy activation problem resembles an economic dispatch, but finding the optimal activation decision is complicated when selecting between bids which not only have different prices, sizes and locations, but also are subject to temporal constraints. They also belong to distinct products with differing time constants. Under these conditions, merit order activation does not guarantee optimality.

This paper investigates how Standard Products for mFRR can be activated in a cost-optimal way using imbalance forecasts and a cost minimizing algorithm. Network congestion has been left outside the scope of the model. The optimization approach is described in Section 2, followed by results in Section 3 indicating how strict merit order activation and short-term-only scheduling increase costs. The added value of having more than one mFRR product is also investigated. This is discussed in Section 4, leading to the conclusions in Section 5.

2 METHODOLOGY

2.1 Model Formulation

The formulation proposed here is a scheduling problem, assuming credible information on the future imbalance (cf. Figure 1). The optimal activation decisions will give an activation schedule that minimizes the objective function while satisfying all constraints. The constraints, most of which are related to the technical characteristics of the system, evaluate the feasibility of a solution, while the objective function evaluate the performance of the solution in terms of costs and frequency deviations.

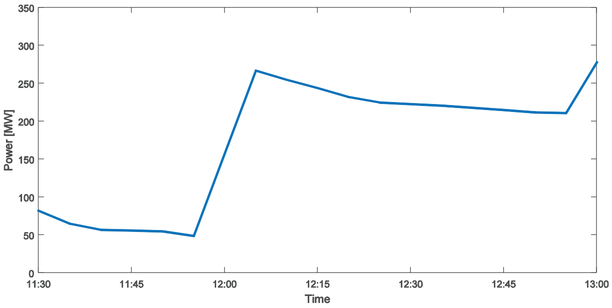

Figure 1 Imbalance forecast for afternoon, 4 Feb 2014

The model is formulated using a MILP structure with 5-minute time steps and is implemented in Xpress[1]. It minimizes the sum of the cost C^a of activated energy and a penalty cost C^p , cf. (1)-(3). The activation cost is given by bid costs c_b for each bid b in the upward and downward direction, and corresponding activation amounts y_b for each time step t. p^{DA} is the clearing price in the day-ahead market. Penalty costs used for ensuring frequency restoration and are calculated as a piecewise linear function of the estimated frequency deviation.

$$\min \boldsymbol{C} = \boldsymbol{C^a} + \boldsymbol{C^p} \tag{1}$$

$$C^a = \sum_{t \in T} \left(\sum_{b \in B_u} c_b y_{b,t} + \sum_{b \in B_d} (p^{DA} - c_b) y_{b,t} \right) \tag{2}$$

$$C^p = \sum_{t \in T} \sum_{k \in K} p_k \left(f_t^{ok} + f_t^{uk} \right) \tag{3}$$

For the discrete time steps used in the model, the frequency f_t at a given time t is estimated using the frequency bias λ together with the imbalance forecast ω_t and the activated power $y_{b,t}$ delivered from each of the bids, as shown in (4).

$$f_t = f_N + \frac{1}{\lambda} \sum_{t \in T} \left(\sum_{b \in B_u} y_{b,t} - \sum_{b \in B_d} y_{b,t} + \omega_t \right) \quad \forall\, t \tag{4}$$

Minimum and maximum capacity constraints are defined similarly to [9], using generation variables $y_{b,t}$ and a single set of commitment variables $u_{b,t}$. In addition, binary variables $v_{b,t}$ govern the ramping restrictions in (5)-(8). Note that this is a block formulation, i.e. the energy during ramping is not taken into account in the optimization.

$$y_{b,t} \le \overline{y}_b u_{b,t} \qquad \forall b, \forall t \tag{5}$$

$$y_{b,t} \ge \underline{y}_b u_{b,t} \qquad \forall b, \forall t \tag{6}$$

$$y_{b,t} \le y_{b,t-1} + \overline{y}_b x_{b,t} \quad \forall b, \forall t \tag{7}$$

$$y_{b,t} \ge y_{b,t-1} - \overline{y}_b x_{b,t} \quad \forall b, t > 1 \tag{8}$$

The Zendehdel linearization [10] is used for minimum duration constraints. Initially activated bids are forced in (9) to stay in operation for their minimum remaining duration L_b. Eq. (10) requires bids started up at s to fulfil their minimum duration. Bids activated close to the horizon $|T|$ may be forced by (11) to remain activated throughout the horizon.

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[1] FICO® Xpress optimization suite v7.8, 2015

$$\sum_{t=1}^{L_b} u_{b,t} = L_b \quad \forall b \tag{9}$$

$$\sum_{t=s}^{s+\underline{DP}_p-1} u_{b,t} \geq \underline{DP}_p\left(u_{b,s} - u_{b,s-1}\right) \quad \forall b, s \in \left\{1 + L_b + 1, \dots, |T| - \underline{DP}_p + 1\right\} \tag{10}$$

$$\sum_{t=s}^{|T|} u_{b,t} \geq \sum_{t=s}^{|T|}\left(u_{b,s} - u_{b,s-1}\right) \quad \forall b, s \in \left\{|T| - \underline{DP}_p + 2, \dots, |T|\right\} \tag{11}$$

The maximum duration constraints have not been considered in this formulation. Straightforward constraints regarding initialization and start-up behavior have been omitted here.

2.2 Data Inputs and Model Parameters

A series of imbalance forecast values for Norway, Feb 4 2014 was used (cf. Figure 1). This forecast was found as the difference between a day-ahead load forecast and scheduled values for power generation and exchange. A balancing activation market consisting of 50 bids was modelled based on information from prices and volumes in the Nordic Regulating Power Market. All bids have an associated price, capacity and product type. The Standard Products are based on an early proposal from ENTSO-E, and their most important characteristics are reproduced in Table 1. The frequency bias λ has been set to 7000 MW/Hz, similar to the Nordic system [11]. The Nordic system does not presently apply automatic reserves, and aFRR activation has been disregarded in the optimization. It could in principle be included as a flexible and expensive resource of last resort, without changing the main principles of the Standard Product optimization.

PRODUCT	FULL ACTIVATION TIME	MINIMUM DURATION	DEACTIVATION TIME
P1	15 min	15 min	15 min
P2	10 min	10 min	10 min
P3	5 min	5 min	5 min

Table 1 Standard Product Characteristics

2.3 Scenarios

The four scenarios listed in Table 2 were used to analyze alternative activation arrangements. The reference scenario uses the model formulation given by (1)-(11). For the single product scenario, all bids are assumed to have P1 characteristics. In the Merit order scenario, the model imposes an additional constraint requiring every bid to be activated to its full capacity before a more expensive bid for the same product and direction can be activated. In the short run scenario, scheduling is done in six steps, looking only 15 minutes ahead. Schedules are coupled through initialization of commitment variables and information on past events.

SCENARIO	HORIZON	PRODUCTS	SELECTION
REFERENCE	90 min	P1, P2, P3	Cost minimization
SINGLE PRODUCT	90 min	P1	Cost minimization
MERIT ORDER	90 min	P1, P2, P3	Price order
SHORT HORIZON	15 min	P1, P2, P3	Cost minimization

Table 2 Scenario configurations

3 RESULTS

Figure 2 shows the estimated frequency for all scenarios during the first 30 minutes. As expected, the Single product scenario needs 15 minutes to restore frequency. After 30 minutes have passed, all schedules follow the imbalance forecast closely, keeping estimated frequency stable at 50 Hz. This is reflected in the costs in Table 3. The Single product scenario has high penalty costs due to the first 15 minutes. This is not compensated by the lower activation cost, which is related to the scenario's inability to bring the frequency back to nominal in the first 15 minutes. The short horizon scenario has the lowest penalty costs of all scenarios, but high activation costs due to poor utilization of the least expensive resources. The Merit Order scenario is almost similar to the reference in this formulation.

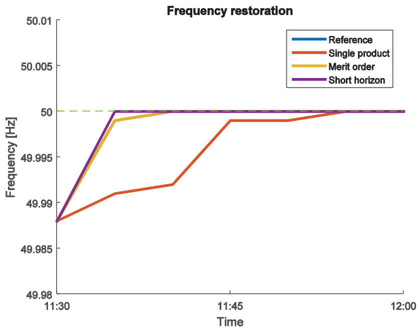
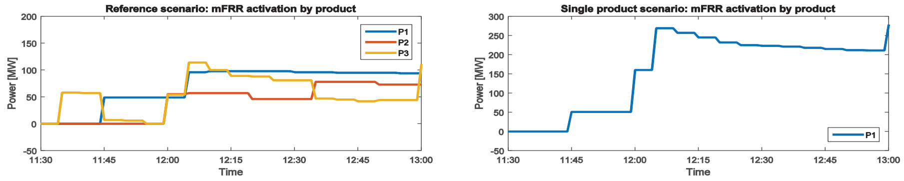


Figure 2 Estimated frequency for all scenarios

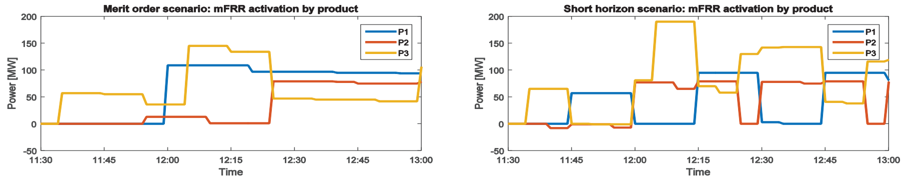
SCENARIO	ACTIVATION	PENALTY	TOTAL
REFERENCE	9 323	722	10 045
SINGLE PRODUCT	8 979	1 642	10 621
MERIT ORDER	9 324	743	10 068
SHORT HORIZON	9 552	687	10 239

Table 3 Activation costs, penalty costs and total costs



(a) Reference scenario

(b) Single product scenario

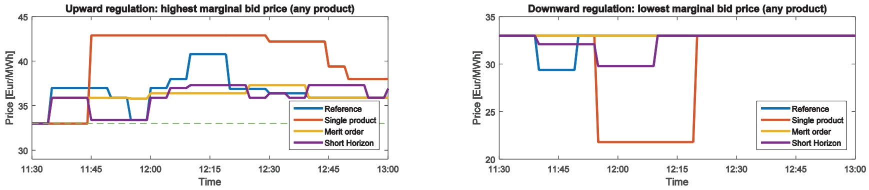


(c) Merit order scenario

(d) Short horizon scenario

Figure 3 mFRR activation by product for different scenarios

Figure 3a-d shows the delivered power from each product for each scenario. For all scenarios where available, power is delivered from P3 bids during the first part of the scheduling horizon, before being substituted and supplemented by slower products. The schedule in Figure 3b follows the 5-minute steps of the imbalance forecast closely using only a 15-minute product. This is possible by activating parallel bids at consecutive time steps. The ability to cope with unforeseen step changes is limited, and as a result, more aFRR capacity would be needed compared to the reference case.



(a) Highest upward regulation marginal price for all scenarios

(b) Lowest downward regulation marginal price for all scenarios

Figure 4 Marginal pricing maximum and minimum values

Figure 4a shows the price of the most expensive delivering bid for upward regulation among all products for each scenario, illustrating how Reference scenario makes use of more expensive bids than the Merit Order and Short Horizon scenarios large parts of the time. I.e., even though *costs* are lower, the *price* will be higher following the reference methodology. The Single Product scenario activates expensive bids to be able to follow the profile of the imbalance forecast. This is also the case for downward regulation in Figure 4b.

4 DISCUSSION

4.1 Discussion of Results

For the Reference and Merit order Scenarios (cf. Figure 3a and c) there is a tendency of cross-product equilibrium towards the end of the scheduling horizon. Here, long lead times reduce the impact of temporal constraints and their shadow costs, allowing slower products to be competitive in the product mix on the basis of lower price. Such a state of cross-product equilibrium is not evident for short horizons in Figure 3d, showing an oscillatory behavior.

Apparently, the cost increase from enforcing merit order activation is small. This is to some extent caused by the disregard of maximum duration and other temporal constraints. This allows the model to establish a base/peak load schedule, stabilizing the marginal pricing (cf. Figure 4).

4.2 Model Formulation and Implementation

The use of penalty costs in the objective function influences the search for optimal solutions. When setting the penalty levels very high, as was done in this case, the optimal solution is a minimum deviation solution. Lower penalties will create a multi-objective problem, rather than a soft constraint.

The problem formulation disregards forecast uncertainty, which may be a good approximation in the very short run. Uncertainty should be taken into account through rolling updates and re-optimizations, and in this setting, a stochastic formulation would likely perform even better in terms of costs, but at the cost of increased computational effort.

As the variables $u_{b,t}$ and $v_{b,t}$ must take integer values in a feasible solution, integer programming solution methods, such as branch-and-bound are used by the solver. The computational complexity the optimization problem is driven primarily by the amount of binary variables, and for long horizons and realistic-size CMOLs, optimality may not be proven within the desired time, but near-optimal solution can likely be found in the order of minutes. For the problem sizes used in these scenarios (1900 binary variables), the solver is usually able to close the MIP gap to less than 0.5 \% in less than a minute. Each of the 15 minute subproblems in the Short horizon scenario are solved in less than a second.

4.3 Further Work

The possibility of congestion can be taken into account by including a grid model (e.g. dc) in the optimization formulation. Current research investigates using the aFRR activation cost as an alternative to the frequency deviation penalty. This research also includes energy delivered during ramping to give more realistic activation patterns, likely reducing activation volumes and costs.

5 CONCLUSION

Balancing energy activated for frequency restoration must restore frequency at minimum cost. The characteristics of Standard Products requires using information on the future imbalance in the optimization. Using imbalance forecasts, the balancing energy scheduling approach presented in this paper finds the minimum cost schedule that also restores frequency.

Using only a single mFRR product is found to give higher estimated frequency deviations due to slower mFRR response. Short horizon scheduling is computationally efficient, but provides higher costs and increases operational complexity.

With no merit order restriction on activation within each CMOL, bid activation may deviate somewhat from the price order in the optimal solution. This is due to shadow costs arising from constraints on activation and duration time. Including the merit order restriction constrains the solution space, but for the simulated bid prices and imbalance, the impact on costs was found to be negligible in the test case, although this is not necessarily generally valid.

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7.4 Publication IV

A Stochastic Mixed Integer Linear Programming Formulation for the Balancing Energy Activation Problem under Uncertainty

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***Abstract*—In the activation market, the Transmission System Operator selects and activates balancing energy bids to cover the system imbalance. Growing use of intermittent energy sources increases uncertainty in system operation and new EU regulations, including a so-called Activation Optimization Function and new Standard Products for manual frequency restoration reserves (mFRR), will change the activation process significantly. However, commonly used price-based bid selection approaches are incapable of taking intertemporal constraints and uncertainty into account in the activation process.**

This paper presents a new optimization formulation, built on stochastic unit commitment principles, using imbalance forecast scenarios to propose bid activation schedules minimizing expected activation costs. Unlike earlier approaches, intertemporal characteristics of the proposed mFRR product are modeled in detail.

The optimization procedure is implemented in a rolling horizon simulation and demonstrated using Norwegian imbalance and market data. Compared to a corresponding deterministic approach, the stochastic strategy significantly reduces activation costs.

***Index Terms*—optimal scheduling, power generation dispatch, power system modeling, stochastic processes**

NOMENCLATURE

Indices

a	aFRR price step
b	Balancing bid
s	Imbalance scenario
t, τ	Time period

Parameters

ω_{ts}	Predicted imbalance in time period t in scenario s
$\overline{X}_b$	Capacity of mFRR bid b
$\overline{Y}_a$	Capacity of aFRR price step a
π_s	Probability of imbalance scenario s
C_a^{aFRR}	Activation cost of aFRR at price step a
C_b^{mFRR}	Activation cost for mFRR bid b

Sets

$\mathcal{A}$	Set of aFRR price steps
$\mathcal{B}$	Set of all mFRR bids
$\mathcal{S}$	Set of all imbalance scenarios
$\mathcal{T}$	Set of all time periods

Variables

u_{bts}	Commitment status of mFRR bid b in time period t and scenario s (binary)
v_{bts}	Indicates bid b starts delivery in time period t and scenario s (binary)
x_{bts}	Delivery power from bid b in time period t and scenario s
x_{bts}^R	Ramping power from bid b in time period t and scenario s
x_{bts}^S	Delivery setpoint for bid b in time period t and scenario s
y_{ats}	Activated aFRR from price step a in time period t and scenario s

Specifiers

$+$	Upward direction
$-$	Downward direction

I. INTRODUCTION

The instantaneous balance between generation and consumption in the power system must be monitored and adjusted. This is among the operational responsibilities of the Transmissoin System Operator (TSO), and adjustments are made by activating balancing energy from reserves, either provided by generating units with spinning reserve capacity or fast-start capability, or by dispatchable consumption.

Through the balancing energy activation market, the TSO aims at utilizing these reserves efficiently. Balancing Service Providers (BSPs) submit bids for balancing energy products, which will be activated by the TSO in the order of bid price until the imbalance between generation and consumption is covered. In Europe, balancing energy is activated from Frequency Restoration Reserves (FRR), which can be manually (mFRR) or automatically (aFRR) activated, or by Replacement Reserves (RR), used to relieve FRR activation for longer, persisting imbalances. While the activation of aFRR can respond to a disturbance within a few minutes, mFRR can typically need 15 minutes (and for RR, even more) before delivering the requested amount of power. And while aFRR follows a control error based on frequency and cross-border flows, manual activations are subject to operator decisions and can also be used *proactively* to cover an expected future imbalance [1].

Following significant progress in the integration of European day-ahead and intraday markets for electricity, balancing markets are currently also in the process of integration as a step towards the vision of an internal energy market. Due to differing market rules and operational practices among Transmission System Operators (TSOs), harmonization is necessary in order to create a level playing field for market participants [2]. The European Network of Transmission System Operators for Electricity (ENTSO-E) is developing new Network Codes, the rules and regulations for European power markets, including the Guideline on Electricity Balancing [3] aims to increase pan-European welfare through secure and efficient balancing operations. The Guideline requires the development of a set of *Standard Products* to be shared among TSOs and used for the exchange of balancing energy. Although several proposals have been made, the exact specifications of these products are still under discussion. The activation of balancing energy is to be governed by an *Activation Optimization Function*, the specifications of which are also still to be decided.

Several studies have been made on the integration of balancing markets, many including models of the balancing energy activation market [4]–[10]. Other notable approaches include [11] and [12]. As they are often used in long-horizon simulations, they do not model the bid selection optimization using detailed the product specifications, which requires modelling the operating states and restrictions on duration and ramping, as is done in the unit commitment problem [13].

Increasing share of power generation from intermittent renewable sources increases uncertainty on all time scales, and stochastic unit commitment [14], is a method managing uncertainty through scenario representations which has been used for day-ahead scheduling optimizations, but the technique has not seen widespread use in balancing energy operations.

This paper provides a formulation of the balancing energy activation problem, taking uncertainty into account through a stochastic optimization approach and representing the opportunities and limitations provided by mFRR Standard Products in greater detail. The optimization model is presented in Section II, together with the description of a case study based on a simplified representation of the Norwegian system, disregarding network constraints. Section III presents results and findings from the case study simulations, while their validity and implications are discussed in Section IV. Section V lists some of the most important conclusions.

II. METHODOLOGY

A. Model Formulation

The balancing energy activation model takes into account the history of previous bid activations, the current imbalance situation and expectations of the future imbalance to propose a an optimal schedule for each available mFRR bid in the market. The optimization routine is then re-run at regular intervals, e.g. every 5 minutes, using updated imbalance information and forecasts. The optimization does not provide a control signal for the aFRR, but includes a representation of the expected aFRR response to the mFRR activation and imbalance situation. The objective in (1) is to minimize the expected costs from activation of mFRR and aFRR over the scheduling horizon.

$$\min \sum_{s\in\mathcal{S}} \pi_s \sum_{t\in\mathcal{T}} \left(\sum_{a\in\mathcal{A}} C_a^{\text{aFRR}} y_{ats} + \sum_{b\in\mathcal{B}} C_b^{\text{mFRR}} x_{bts} \right) \tag{1}$$

The model formulation uses 5 minute timesteps and distinguishes between mFRR power output during the delivery period, for which the cost is reflected in the objective function, and during the ramping period, x_{bts}^R. This energy is delivered before the bid is fully activated and contributes to the power balance, but without driving activation costs. Ramping constraints are disregarded for aFRR due to its fast-ramping capability. The sum of power from mFRR and aFRR schedules must equal the imbalance forecasts ω_{ts} for each time period and scenario, as given in (2), which includes both upward and downward activations:

$$\begin{aligned} &\sum_{b\,\in\mathcal{B}^+} (x_{bts} + x_{bts}^R) - \sum_{b\,\in\mathcal{B}^-} (x_{bts} + x_{bts}^R) \\ &\quad + \sum_{a\,\in\mathcal{A}} (y_{ats}^+ - y_{ats}^-) = \omega_{ts} \qquad \forall t, s \end{aligned} \tag{2}$$

Power from aFRR is limited only by the available capacities, while delivery and ramping power from mFRR depends on the commitment status u_{bts} of the bid:

$$x_{bts} \le \overline{X}_b u_{bts} \qquad \forall b, t, s \tag{3}$$

$$x_{bts}^R \le \overline{X}_b (1 - u_{b\tau s}) \tau = t-1, t \quad \forall b, t, s \tag{4}$$

$$y_{ats}^+ \le \overline{Y}_a \qquad \forall a, t, s \tag{5}$$

$$y_{ats}^- \le \overline{Y}_a \qquad \forall a, t, s \tag{6}$$

The mFRR activation is also subject to a set of ramping, duration and other operating constraints, some of which use the binary startup indicator variable v_{bts} or the variable x_{bst}^S which defines the requested power level at the beginning of a delivery period. Then, for all b, t, s,

$$v_{bts} \geq u_{bts} - u_{b(t-1)s} \tag{7}$$

$$v_{bts} \leq 1 - v_{b(t-1)s} - v_{b(t-2)s} \tag{8}$$

$$v_{bts} \leq x_{b(t-2)s} + x^R_{b(t-2)s} \tag{9}$$

$$x^S_{bts} \leq v_{bts} \tag{10}$$

$$x^R_{bts} \leq \overline{X}_b(1 - v_{b(t+3)s}) \tag{11}$$

$$x^R_{bts} \leq \overline{X}_b\left(\frac{2}{3}x^S_{b(t+1)s} + \frac{1}{3}x^S_{b(t+2)s}\right) \tag{12}$$

$$x^R_{bts} \geq \frac{2}{3}\overline{X}_b(x^S_{b(t+1)s} - u_{bts}) \tag{13}$$

$$x^R_{bts} \geq \frac{1}{3}\overline{X}_b(x^S_{b(t+2)s} - u_{bts}) \tag{14}$$

$$x_{bts} \geq \overline{X}_b x^S_{b\tau s} \qquad \tau = t-3, ..., t \tag{15}$$

$$x_{bts} \leq \overline{X}_b \sum_{\tau=t-3}^{t} x^S_{b\tau s} \tag{16}$$

$$x_{bts} \leq x_{b(t-1)s} + \overline{X}_b(1 - v_{b(t-1)s}) \tag{17}$$

$$x_{bts} \leq x_{b(t+1)s} + \overline{X}_b(1 - v_{bts}) \tag{18}$$

$$x_{bts} \leq x_{b(t-1)s} + x^R_{b(t-1)s} - x^R_{bts} + \frac{1}{3}\overline{X}_b \tag{19}$$

$$\sum_{\tau=t}^{t+7} u_{b\tau s} \leq 7 \tag{20}$$

Eq. (10) requires a nonzero value for the binary decision variable v_{bts} for a new delivery period to start. This is ensured by (7) when the commmitment status changes, and (8) prevents prematurely starting a new delivery periods. Eq. (9) requires the delivery period to be preceded either by ramping or an earlier delivery period. Eqs. (11)-(14) govern the amount of ramping power, which is related to the capacity limit $\overline{X}_b$ and the delivery power setpoint $x^S_{b\tau s}$ in subsequent periods τ, e.g. setting ramping power to $\frac{1}{3}$ of the delivery power setpoint 5 minutes into the ramping period through (12) and (14). Eqs. (15)-(19) ensure delivery power x_{bts} mathes the setpoint, preventing change of output between periods unless a new delivery period is started (17)-(18), and (19) limits the ramp rate when such change is allowed. Eq. (20) sets a maximum duration of for the delivery period of an activated bid.

Non-anticipativity constaints require first-stage decision variables to take the same value across all scenarios before the realization of uncertain parameters. For a scenario fan, this only applies to $t = 1$.

$$u_{bts} = u_{bt\sigma} \qquad \sigma \neq s, \forall b, t, s \tag{21}$$

$$v_{bts} = v_{bt\sigma} \qquad \sigma \neq s, \forall b, t, s \tag{22}$$

$$x_{bts} = x_{bt\sigma} \qquad \sigma \neq s, \forall b, t, s \tag{23}$$

$$x^R_{bts} = x^R_{bt\sigma} \qquad \sigma \neq s, \forall b, t, s \tag{24}$$

$$x^S_{bts} = x^S_{bt\sigma} \qquad \sigma \neq s, \forall b, t, s \tag{25}$$

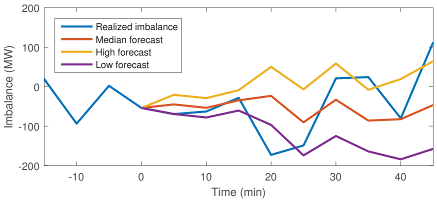

Fig. 1. Imbalance forecast scenarios and actual imbalance realization over a scheduling horizon

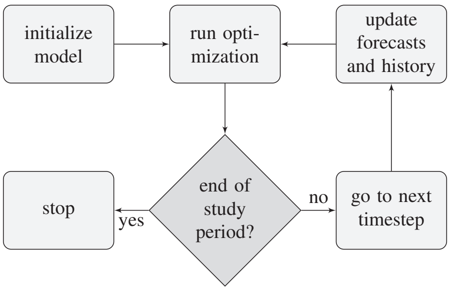

Fig. 2. Implemented rolling horizon simulation procedure

Finally, we require variables to be non-negative or binary

$$x_{bts}, x^R_{bts}, x^S_{bts} \geq 0 \qquad \forall b, t, s \tag{26}$$

$$y^+_{ats}, y^-_{ats} \geq 0 \qquad \forall a, t, s \tag{27}$$

$$u_{bts}, v_{bts} \in \{0, 1\} \qquad \forall b, t, s \tag{28}$$

Note that the formulation includes no network representation, thereby disregarding congestion and losses.

B. Model Implementation

Uncertainty in the future imbalance is represented by three scenarios in a scenario fan (cf. Fig 1), thus the model is a two-stage problem with fixed recourse, and can be solved readily using deterministic equivalents. For each re-optimization, the scheduling horizon is 45 minutes ahead, as intraday markets further ahead are not yet closed. Then, for each timestep in the study period, the actual aFRR and mFRR output can be found as the *final plan*, given at $t = 0$ in each timestep iteration. Here, the mFRR output will be a sunk decision, while the aFRR power will be chosen by the optimizer to satisfy the power balance considering actual realized imbalance.

The model has been implemented in Xpress-Mosel[1] together with a file framework for rolling horizon simulations, cf. Fig. 2. Simulations were run on an Intel Core i7-6600U laptop computer with 16 GB RAM.

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[1] FICO®Xpress Optimization Suite v7.9

C. Case Study Specifications

For the purpose of demonstrating the stochastic strategy, the activation process was simulated for 18 consecutive time periods, corresponding to 90 minutes of balancing operation, and compared against a corresponding deterministic strategy. For the imbalance realizations, Norwegian imbalance data from June 16, 2016 were used. The imbalance forecasts were generated from percentiles of probability distributions based on historical imbalance data series, with probabilities calculated from a calibration of the forecasts against the realized imbalance on a training data set. Fig. 1 shows the realized imbalance and forecasts used by the model for a specific time period in the simulation.

A list of 16 balancing activation bids for mFRR were created based on prices and volumes in the Norwegian balancing energy market, eight in each direction of power delivery. The activation market for aFRR is yet to be introduced in the Nordic system, hence activation prices are uncertain. When aFRR prices are similar to or lower than mFRR prices, automatic activations will be preferential due to shorter activation time and flexible output levels. Manual activations will only be rational when there is insufficient aFRR to cover the imbalance. In this case study, the majority of aFRR is assumed to have a higher activation price than mFRR, causing proactive activations of mFRR to minimize expected activation costs. A simple stepwise cost curve is assumed, resulting in the supply curve in Fig. 3.

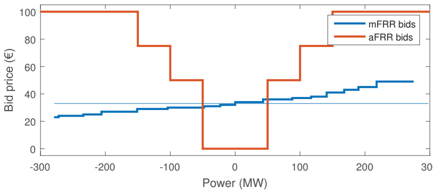

Fig. 3. Supply curve of upward and downward mFRR and aFRR capacity

III. RESULTS

A. Activation Costs

Fig. 4 shows the realized activation costs for the stochastic and deterministic optimization strategies in each 5 minute period during the simulated case study. Although activation costs are lower with the deterministic strategy during some periods, it is outperformed over the 90 minute study period, with total activation costs equalling 7 364 € in the deterministic case, 18 % higher than 6 035 € for the stochastic approach. Sensitivity analyses were run using different aFRR price curves. When almost the entire amount (290 of 300 MW in each direction) of aFRR is priced at 100 €, activation costs increase to 17 491 € (det.), 9 % higher than 16 084 € (stoch.). For low aFRR prices, the optimizer prefers to wait-and-see, rather than activate mFRR in advance. This leads to inadequate response in several cases when the imbalance turns out to deviate from the forecast.

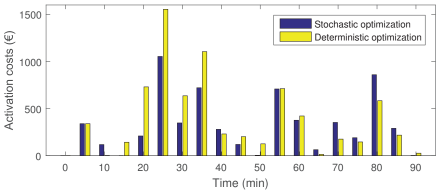

Fig. 4. Activation costs for each simulated time period with the stochastic and deterministic strategies

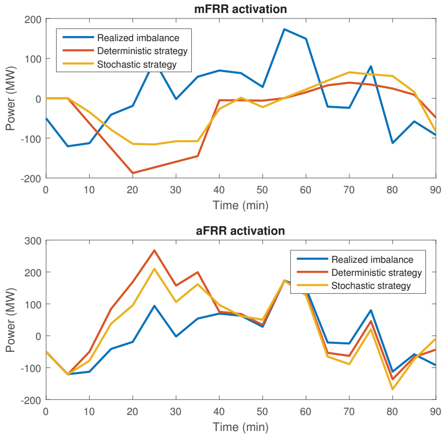

Fig. 5. Net activation volumes for mFRR and aFRR over the simulation horizon

B. Reserve Activation

Fig. 5 shows how the net activated mFRR and aFRR (i.e. upward minus downward) volumes differ under the two optimization strategies. The most prominent deviations between strategies occur in the period $t = 10 - 35$, where mFRR and aFRR are activated in opposite directions due to a significant forecast error.

The composition of upward and downward activations also differs between the strategies. Fig. 6 indicates the schedules proposed in one of the re-optimizations. Here, the deterministic strategy proposes activating both upward and downward reserves simultaneously to deal with imbalance fluctuations, while the stochastic approach proposes using more aFRR.

C. Running Times

For the optimization runs in the case study (cf. II-C), the solver is able to identify near-optimal solutions within a few

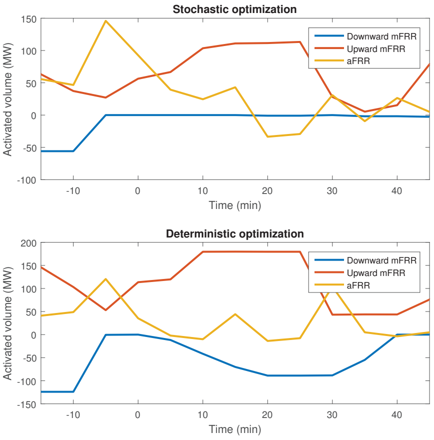

Fig. 6. Upward and downward activation volumes under different strategies

TABLE I
SIMULATION RUNNING TIMES FOR STOCHASTIC MODEL

Duality gap	**Median**	**75th pct.**	**Max**	**Max, det. model**
5 %	6 sec	10 sec	34 sec	4 sec
2 %	12 sec	44 sec	>5 min	9 sec
1 %	40 sec	160 sec	>5 min	33 sec

seconds. As Table I indicates, however, there are significant differences in running time between different time periods, and in a few cases the solver needs more than one minute to reduce the duality gap below 2 %. The deterministic model is notably quicker. It should be noted that most of the time and effort used for closing the duality gap is related to improving the lower bound, while optimal decisions are often found almost immediately using built-in heuristics in the solver. In other words, the additional running time required to converge rarely improves the quality of the solution by a significant amount.

Sensitivity analyses indicate the running time increasing with the scheduling horizon, number of bids and imbalance forecast scenarios, all of which will increase the number of binary variables. Running time was also found to decrease with increasing amounts of low-priced aFRR available.

IV. DISCUSSION

While the case study indicates potential cost savings from using a stochastic activation strategy, the added benefit depends on the relation between mFRR and aFRR bid prices. Higher aFRR prices increase activation costs, not only from forecast errors, but also from a shift towards more mFRR activations. On the other hand, a comparatively low aFRR price removes the incentive to schedule mFRR proactively.

Assuming perfect information, the deterministic strategy proposes minimum-cost schedules, sometimes including simultaneous upward and downward activations of mFRR to closely match the imbalance forecast profile. The deterministic strategy has no incentive to propose flexible schedules that easily adapt to unexpected imbalance realizations. The simulation reveals the consequence of overestimating the quality of the forecast. The stochastic optimization, on the other hand, proposes a *compromise schedule* which is not optimal for any forecast scenario, but it appears to be less vulnerable to forecast errors than the deterministic strategy.

Using the bid prices in the activation market, it is possible to cross-optimize between mFRR and aFRR using a proactive philosophy. While this can reduce activation costs, Fig. 5 gives, however, a clear illustration of a *proactive failure*, where the imbalance takes a different turn than expected, and the aFRR must cover not only the imbalance, but also the mFRR recently activated in the opposite direction.

For an optimization procedure to be applied in real-time balancing operations, computational speed is crucial. Both the Standard Product representation and imbalance forecast scenarios significantly add to the complexity of the problem. The case study simulations show that near-optimal solutions can be found quickly. However, real-life balancing energy activation markets not only include more bid providers, but there may also be network constraints or other considerations to take into account in the bid selection process, increasing the running time of the algorithm. Still, there are ways to improve the computational performance, including parallel computing and faster hardware. Other options include using tailored heuristics or a progressive hedging algorithm [15] or another dual decomposition approach [16].

V. CONCLUSIONS

An optimization model has been developed to find minimum cost solutions to the balancing energy activation problem. It uses bid data and imbalance forecasts, includes a detailed representation of an mFRR Standard Product and takes uncertainty into account through a scenario representation. Moderately-sized problem instances can be solved to near-optimality in a few seconds, and opportunities for improving the computational performance have been identified.

Case study simulations based on data from the Norwegian power system show a substantial reduction in activation costs by taking uncertainty into account in the optimization. The cost savings depend on the relative price differences between the mFRR and aFRR product, as well as the quality of the imbalance forecasts.

Simulations also demonstrate the interaction between aFRR and proactive activation of mFRR, including a *proactive failure*, where a considerable amount of balancing energy is activated in the upward and downward directions simultaneously due to forecast error.

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7.5 Publication V

7.6 Publication VI

M. Håberg, H. Bood and G. Doorman, “Preventing Internal Congestion in an Integrated European Balancing Activation Optimization”, *Energies*, vol. 12, no. 3, Feb. 2019.

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Article

Preventing Internal Congestion in an Integrated European Balancing Activation Optimization

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Abstract: New common platforms for optimization of balancing energy activation will facilitate cross-border exchange and integrate the fragmented European balancing markets. Having a zonal market structure, these platforms will optimize balancing actions as if intra-zonal transmission constraints did not exists, leaving it to each Transmission System Operator (TSO) to manage internal congestion caused by balancing energy activations. This paper describes a new method to pre-filter balancing bids likely to cause internal congestion due to their location. Furthermore, the complementary concept of exchange domains has been developed to prevent congested and infeasible balancing situations. A numerical example illustrates both the effectiveness and limitations of each method.

Keywords: balancing market design; congestion management; optimization methods; power system modeling

1. Introduction

As European balancing markets are being integrated, common methodologies and systems are being developed to optimize activation and exchange of balancing energy across borders. Under the current target model, each TSO will submit their balancing energy needs for the upcoming imbalance settlement period, as well as a list of available bids within their own area, to a common European platform. The common platform aims to identify the most efficient set of bid activations to cover the imbalances in all areas.

Congestion in the transmission grid incurs the risk of overloads, and must be managed to avoid endangering operational security. Congestion between different market areas can be prevented through cross-zonal capacity constraints in the platform optimization, but intra-zonal—or internal—congestion may occur as a result of bid locations and initial power flows in the network. The enormous size of the interconnected European system, the limited available time in the operational phase, and the preference of zonal market coupling bodes that European balancing platforms will not include the highly detailed network models necessary to represent internal bottlenecks. Rather, the common balancing platform will select the balancing actions, but the task of managing internal congestion is left to each TSO.

This paper presents two methodologies for TSOs to prevent internal congestion caused by an integrated European balancing activation optimization. Firstly, a method for *bid filtering* is described. Based on extensive power flow analyses across a variety of potential situations, the method aims to detect potentially harmful bid activations and flag the corresponding bids as unavailable. Secondly, the paper introduces a new concept of *exchange domains*, complementing the bid filtering by ensuring feasibility and enabling more bids to be made available to the common platform.

Section 2 summarizes the development of an integrated European balancing market, and highlights earlier contributions to managing internal congestion from balancing activations. The two congestion management mechanisms are described in the subsequent sections. Section 3 explains pre-filtering balancing energy bids, introducing a new, multi-dimensional approach to assess which bids to make available to a common European balancing platform. The concept of exchange domains is introduced and explained in Section 4. Following a numerical example illustrating both methods in Section 5, the paper concludes in Section 6 with a discussion on the merits and viability of each of the concepts for a future integrated European balancing market.

2. Background

Over the last few years, the European Network of Transmission System Operators for Electricity (ENTSO-E) have developed new network codes, rules and regulations for European power markets. In particular, the Guideline on Electricity Balancing [1] specifies the target model for an integrated European balancing market, including standardization of balancing energy products across countries to facilitate exchange. Aiming to increase efficiency in resource utilization, balancing energy bids located in different areas will be collected into *common merit order lists* (CMOLs), from which an Activation Optimization Function (AOF) will select bids for activation to cover the imbalances of all TSOs, taking into account possibilities for netting of imbalances and available cross-zonal transmission capacity between areas.

Several European TSOs are collaborating in balancing pilot projects to develop and implement common activation and exchange optimization platforms for the different reserve products. Notably, the *TERRE* (Trans European Replacement Reserves Exchange) project establishes a platform for cross-border exchange of balancing energy from replacement reserves (RR) [2], while the *MARI* (Manually Activated Reserves Initiative) [3] and *PICASSO* (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation) [4] projects develop European platforms for the exchange of balancing energy from frequency restoration reserves with manual activation (mFRR) and automatic activation (aFRR), respectively. The available time between optimization and activation will be limited, restricting the possibilities for redispatch. All of these projects suggest preventing balancing actions from causing internal congestion by letting each TSO mark bids as unavailable if their activation could endanger system security, in accordance with Art. 29.14 in [5].

Congestion management is a central aspect of a zonal electricity market design, and is necessary when the price structure does not reflect the impact of grid congestion, as compared to locational marginal prices (LMPs). For zonal markets, Linnemann et al. [6] identified three main mechanisms to manage congestion: grid expansion, market splitting, and redispatch. Only the latter can be applied in an operational timeframe, and it is used in several European systems to manage internal congestion.

Several factors can impact power flows, and thereby potentially also network congestion during the balancing stage. Contingencies and power imbalances from intermittent generation are inherently stochastic. Interestingly, the balancing market itself may also have a strong effect, depending on the imbalance pricing mechanism. In a study of the German balancing market, Chaves-Ávila et al. [7] argued that using a single area-wide imbalance price signal may be adverse and misleading in the presence of internal congestion, worsening the local imbalance in part of the system, with the potential result of further congesting the network. At the same time, there may be very limited time and flexibility to effectively manage congestions through redispatch during the balancing stage.

Another crucial factor is the impact of bid activations in the balancing energy market. Some systems allow portfolio-based bids, meaning the exact locations of balancing energy injections are often unknown. For the German power system, Sprey et al. [8] concluded that the effect on congestion from reserve activation is unforeseeable, and uses simulation to assess the impact. In the Norwegian system, on the other hand, the location of each balancing bid is largely known. This allows the effect on network flows from bid activation to be predicted using power flow analyses. This is used in [9] to develop an algorithm that evaluates whether balancing bids must be skipped in the merit order to satisfy requests for balancing energy exchange from different neighboring zones. This can support decisions on which bids to make available to a European balancing platform, yet the proposed algorithm is one-dimensional, only considering balancing energy requests from a single neighboring zone at a time, i.e., no combinations or transit requests.

Finally, concerns on intra-zonal network constraints are not limited to European market designs. In the US, traditional reserve requirements have partitioned the grid into deterministic reserve zones, mainly based on ad-hoc rules [10]. Disregarding the intra-zonal constraints, and thereby the grid location of reserves procured within a zone, incurs the risk of ineffective means to handle intra-zonal congestion [11]. Moreover, since all reserves within a zone are assumed to have equal shift factors on critical lines, the true deliverability of the procured reserves will be imprecise. Acknowledging that different contingencies render different reserves undeliverable, Lyon et al. [12] demonstrated a locational reserve disqualification method to ensure adequate volumes and locations of operating reserves to cope with a range of distinct scenarios.

3. Bid Filtering

A zonal market platform will optimize balancing actions as if intra-zonal transmission constraints did not exist, in some cases leading to the activation plans that are infeasible due to internal congestion. In an attempt to prevent infeasible activation plans, the *MARI* platform [3] plans to allow TSOs to mark individual bids as unavailable if their activation would lead to internal congestion. Thus, each TSO needs to assess—in advance of the platform clearing—whether activating a bid would lead to congestion or not. The impact of balancing bid activations on internal congestion depends not only on the bid location, but also on the location of the request, as well as the current (or predicted) flow in the intra-zonal network. Guntermann et al. [9] showed on a realistic dataset how bid activations can often cause congestion when requested from one or more of the neighboring zones, while causing no congestion if requested from other zones.

The bid filtering methodology proposed in this paper aims to determine the availability of balancing energy bids within a given bidding zone, with each neighboring area considered to be represented by a single external node (cf. Figure 1). It extends the work in [9] by considering combinations of balancing requests from multiple neighboring areas. While this is more realistic, it also increases complexity. Moreover, since these requests cannot be accurately predicted, the proposed method needs to consider a range of combined balancing energy requests from the immediate neighboring zones of a given zone. Each request combination is denoted as an *exchange scenario*, and the method evaluates for each of the scenarios whether avoiding internal congestion requires deviating from merit order activation.

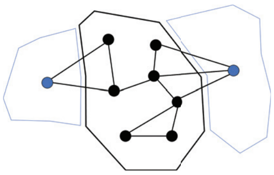


Figure 1. Example single-area system consisting of internal nodes and external nodes representing neighboring areas.

To evaluate each exchange scenario, a local balancing activation optimization problem is solved on a detailed network model. For a given zone a, the objective function in Equation (1) minimizes the activation cost given by the bid price C_b and activation volume y_b of each bid b available in the local bid list $\mathcal{B}_a$. The energy balance constraint in Equation (2) requires for each internal or external node $i \in \mathcal{I}_a$ that the net imbalance E_i is covered either by flow f_l or bid activation from bids located at node i. The adjacency parameter $A_{il} \in \{-1, 0, 1\}$ ensures adequate connections between each node i and lines $l \in \mathcal{L}_a$. Depending on the directions and volumes of imbalance volumes, upward or downward activations can be disallowed (e.g., by making sets $\mathcal{B}_i^{\uparrow}$ and $\mathcal{B}_i^{\downarrow}$ empty for all i) to prevent simultaneous counter-activations within a zone. The flow constraint in Equation (3) translates the balancing energy injection in each node to balancing energy flows f_l on each line l, through the power transfer distribution factor (PTDF) Φ_{il}, while Equation (4) limits the activation volume of each bid to its capacity $\overline{Y}_b$. Balancing energy flows are limited by the remaining available capacities $\underline{F}_l$ and $\overline{F}_l$ on each line in Equation (5).

$$\min_{f,y} \sum_{b \in \mathcal{B}_a} C_b y_b \tag{1}$$

$$\text{s.t.} \sum_{b \in \mathcal{B}_i^{\uparrow}} y_b - \sum_{b \in \mathcal{B}_i^{\downarrow}} y_b - \sum_{l \in \mathcal{L}_a} A_{il} f_l + E_i = 0, \qquad i \in \mathcal{I}_a \tag{2}$$

$$f_l - \sum_{i \in \mathcal{I}_a} \Phi_{il} \Big(\sum_{b \in \mathcal{B}_i^{\uparrow}} y_b - \sum_{b \in \mathcal{B}_i^{\downarrow}} y_b + E_i \Big) = 0, \qquad l \in \mathcal{L}_a \tag{3}$$

$$0 \leq y_b \leq \overline{Y}_b, \quad b \in \mathcal{B}_a \tag{4}$$

$$\underline{F}_l \leq f_l \leq \overline{F}_l, \quad l \in \mathcal{L}_a \tag{5}$$

The congesting bids can be identified by considering the resulting nodal balancing prices in each evaluated scenario. The Lagrangian multiplier λ_i on each energy balance constraint in Equation (2) provides a locational marginal price on balancing energy in each node i for the minimum-cost feasible balancing dispatch. If no internal transmission constraints are binding, this dispatch will follow the merit order. If, on the other hand, congestion prevents bids from being used in the merit order, this will be visible through shadow price differences between different nodes. The locational balancing energy price on the external nodes indicate the marginal costs of exporting one more unit of balancing energy to the corresponding neighboring zone. If there is unused upward capacity with a bid price lower than these marginal exchange costs, this bid is congesting the system. The same is true with opposite price differences for congested downward resources. In these cases, it is clear that the bid price does not reflect the full cost of activation, and following the merit order would have been infeasible due to transmission constraints. In short, the bids not fully utilized although priced within the marginal cross-zonal price are the ones that would cause congestion in the particular scenario if activated in the merit order.

Bids causing congestion only when activated under special circumstances provide a dilemma. Filtering such bids from the list reduces the reserve capacity and increases balancing costs in situations where they could have been used, after all. Not filtering them would lead to congestion and distorted price signals in some cases. The detection of congested bids in individual scenarios does not provide a final answer as to which bids to make available to the platform. However, it provides insight on the degree to which each bid causes congestion when it is activated, in some cases suggesting that the bid should be filtered from the list.

The computational burden of the bid filtering process depends, among other things, on the number of exchange scenarios to be evaluated. The structure of Equations (1)–(5) is linear and largely similar to a DC OPF problem, and requires minimal computational effort. Even with time requirements in the near-operational phase, this structure should allow using detailed network models and a substantial number of exchange scenarios. The scenario selection used for the numerical example in Section 5 constitutes a trivial approach, using a matrix of equidistant exchange volumes. The size of these intervals will affect both the number of scenarios and the accuracy of the results. However, with the set of merit-order feasible scenarios forming a convex region, sensitivity analysis would require only a subset of these scenarios to be evaluated for each bid list configuration. Moreover, the method does not require exhaustive enumeration of all possible bid list configurations, but iteratively removes one bid at a time and evaluates whether more scenarios become merit-order feasible.

4. Exchange Domains

Given the bid locations and initial flow in the network, there are exchange scenarios for which internal congestion cannot be avoided. Should such a scenario materialize, the congestion must be managed through an urgent redispatch to avoid disconnections. Another approach is to attempt to prevent infeasible scenarios from materializing. Rather than filtering bids, a more adequate solution to this end would be to identify and disallow unfavorable combinations of cross-border flows.

The key idea of exchange domains is to add additional constraints in the platform optimization on balancing energy exchange volumes to neighboring areas. This can be used to eliminate the possibility of exchange requests that are found to be infeasible in the exchange scenario evaluation. Furthermore, scenarios where deviation from the merit order is necessary can also be discarded in this manner, thereby enabling many bids to be made available without causing the platform to give incorrect price signals. Constraints describing exchange domains would need to be submitted to the platform together with the list of available bids.

The selection of an exchange domain for a given area can be based on the same exchange scenario analyses as for bid filtering, and needs to take into account the final list of available bids. A robust approach is to select a domain such that all scenarios are included for which merit order activation of the available bids is feasible. Since lists of upward and downward bids are used exclusively in their direction of activation, upward and downward domains must be considered separately as well. A possible step-by-step method is summarized below.

4.1. Determine List of Available Bids

The exchange domain will be tailored towards a filtered list of bids. In principle, any bid filtering method can be applied before this step.

4.2. Evaluate Exchange Scenarios

Precalculating the local balancing dispatch for different combinations of balancing energy exchange provides a discrete approximation of the feasibility region. This enables identifying the borderline of feasibility, and also where the available bids can be used in the merit order.

4.3. Convex Hull Transformation

Each evaluated exchange scenario can be represented as a point, with coordinates given by the balancing exchange volumes to neighboring zones in the particular scenario. If the set S contains all points representing exchange scenarios evaluated as merit-order feasible for the filtered bid list, then the convex hull (Convex hulls are efficiently calculated from a finite set of points using the *Quickhull* algorithm [13], even for higher dimensions.) $Conv(S)$ is the smallest convex polytope containing all these points.

4.4. Define Linear Constraints

Each facet in the convex hull corresponds to a supporting hyperplane defining a half-space, and all the points in S are enclosed by the intersection of these half-spaces. The inequalities describing each half-space directly comprises a finite set of linear constraints, efficiently describing the feasible region of exchange situations, or exchange domain.

5. Numerical Example

Based on the work in [14], this numerical example highlights the important steps in the bid filtering method and the relation to exchange domains. A test system based on the IEEE 30-bus network is used, with two of the nodes (7 and 30) assumed to represent neighboring zones (cf. Figure 2). The flow in the transmission network is already initialized by an economic dispatch, with no lines being initially congested. Six generators at different nodes serve 156 MW of local load, in addition exporting 23 MW and 11 MW on exchange nodes 7 and 30, respectively.

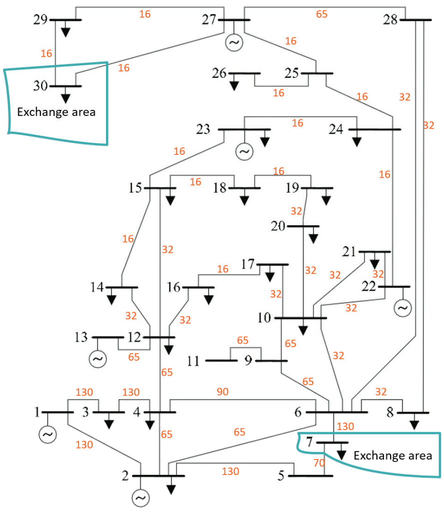


Figure 2. Single line diagram of the test system used, indicating bus numbers (black) and rated line capacities in MW (orange).

5.1. Bid Filtering

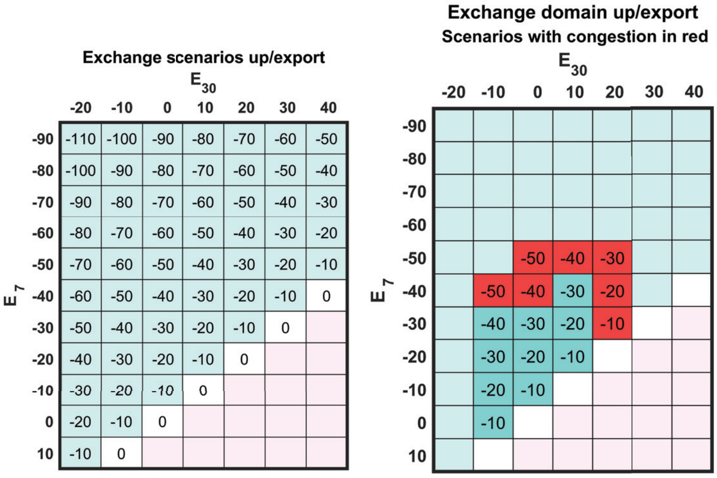
This example focuses on determining the availability of six upward bids. Downward bids could have been evaluated using broadly the same methodology [14], and have been omitted here for brevity. All bids have a capacity of 10 MW, and carry names *Bid #1–Bid #6* according to their position in the merit order, given by bid prices.

The selection of which exchange scenarios to evaluate should in principle cover all possible balancing exchange outcomes from the European balancing platform, i.e., limited by cross-zonal capacities to neighboring zones in both directions. Without sufficient bid capacity to cover many of the resulting rather extreme scenarios, this example considers a reduced set of exchange scenarios, given by the net injections $E_7 \in [-90, 10]$ and $E_{30} \in [-20, 40]$ at the exchange nodes, with 10 MW steps between scenarios (cf. Figure 3a).

Upon evaluating these scenarios using the optimization in Equations (1)–(5), only a subset of them can be balanced given the initial flow in the network and the bid list at hand. The cells with numerical values in Figure 3b represent exchange scenarios for which there exists a feasible balancing dispatch. Some of these scenarios are congested (shown in red), and require deviating from the merit order, i.e., one or more bids must be (at least partially) skipped to avoid overloading the network.

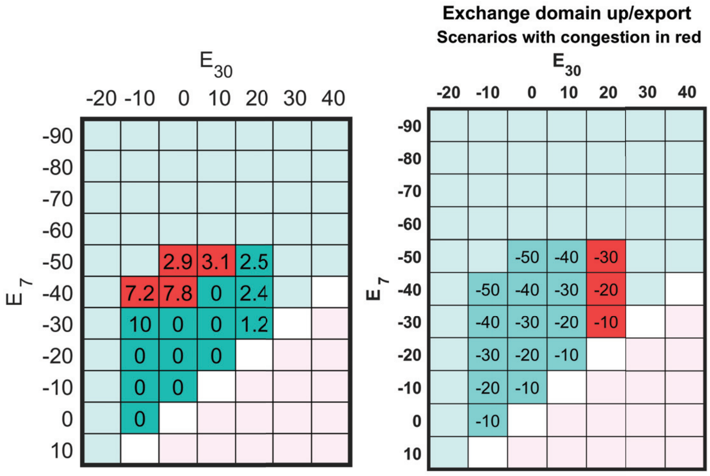
Comparing shadow prices on balancing energy exchange with bid prices in the different scenarios reveals that one of the bids, *Bid #4*, located on bus 22, causes congestion in several of the congested scenarios. These scenarios are marked as red in Figure 4a. Filtering this bid from the list and re-evaluating the exchange scenarios shows the scenarios previously congested by Bid #4 are now merit-order feasible (cf. Figure 4b).

In this example, the three red scenarios for $E_{30} = 20$ cannot be made merit-order feasible by filtering any of the bids. Moreover, there is no efficient way of filtering bids to avoid most infeasible scenarios. For example, preventing the combination $(E_7, E_{30}) = (-40, 30)$ requires making *all upward* *bids* unavailable. This scenario requires only 10 MW of activated balancing energy, so reserve capacity is not an issue here, but the transit flow is.



(**a**) (**b**)

Figure 3. Net balancing activation volumes in the considered exchange scenarios: (**a**) All exchange scenarios; (**b**) Feasible scenarios.



(**a**) (**b**)

Figure 4. (**a**) Activation volume of Bid #4, causing congestion in red scenarios; (**b**) Feasible exchange scenarios after filtering Bid #4.

5.2. Exchange Domains

Following the steps in Section 4, an exchange domain can be specified to prevent infeasible and congested exchange flow combinations. Here, exchange domains are calculated for the full upward bid list, and a list where Bid #4 is filtered.

5.2.1. All Six Upward Bids Made Available

The linear constraints corresponding to the convex hull is found using the Quickhull algorithm [13] with a list of coordinates corresponding to feasible exchange scenarios. Assuming only merit-order feasible scenarios should be included, these scenarios correspond to the green cells with numeric values in Figure 3b. The linear constraints enclosing the desired domain will be

$$\begin{aligned} E_{30} &\geq -10 \\ E_{30} &\leq 10 \\ E_7 + 0.5E_{30} &\geq -35 \end{aligned}$$

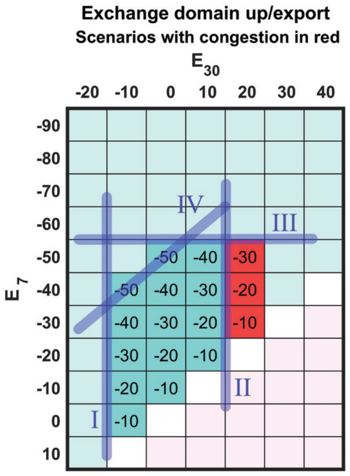
Although computed by Quickhull, these constraints can easily be manually verified in this example, since the vertices of the convex hull can be identified directly from Figure 3b as $(-10, 0)$, $(-10, -30)$, $(10, -40)$ and $(10, -20)$.

5.2.2. Bid #4 Made Unavailable

After withholding Bid #4, a larger set of exchange scenarios become merit-order feasible. (cf. Figure 4b). The scenarios in the red cells are still congested. Using Quickhull on the list of merit-order feasible scenarios eventually provides the hyperplanes constraining the feasible region (cf. Figure 5).

$$E_{30} \geq -10 \tag{I}$$
$$E_{30} \leq 10 \tag{II}$$
$$E_7 \geq -50 \tag{III}$$
$$E_7 + E_{30} \geq -50 \tag{IV}$$

Compared to the case with all bids available, the convex hull has different vertices: $(-10, 0)$, $(-10, -40)$, $(0, -50)$, $(10, -50)$ and $(10, -20)$. One more linear constraint is needed, but the resulting exchange domain is larger.



E_7 \ E_{30}	-20	-10	0	10	20	30	40
-90							
-80							
-70							
-60							
-50			-50	-40	-30		
-40		-50	-40	-30	-20		
-30		-40	-30	-20	-10		
-20		-30	-20	-10			
-10		-20	-10				
0		-10					
10							

Figure 5. Exchange domain defined by linear constraints after filtering Bid #4.

The same procedure also applies for areas with more neighboring areas, albeit with more variables due to higher dimensionality of the exchange scenarios. Including these constraints to the common platform optimization enables making the balancing bids available without the risk of activation or transit flow leading to internal congestion.

6. Discussion

The impact of balancing energy activation on internal congestion depends strongly on the location of the imbalance. With the possibility of the balancing energy recipient being several different combinations of neighboring zones, bid locations cannot be seen as singular predictors for internal congestion due to balancing actions. Cross-border balancing exchange flows, including transit flows, appear to have similar, or higher importance.

For the balancing platforms being developed, filtering congested bids is currently the preferred mechanism for avoiding internal congestion. The method for bid filtering proposed in this paper takes the uncertainty in exchange flows into account by considering a large number of discrete exchange scenarios. For each scenario, a balancing dispatch followed by a nodal price analysis detects which bids would cause congestion with the given exchange flows. While bids causing congestion are obvious candidates for being filtered from the common merit order list, the picture is rarely black and white; bids can lead to congestion under some scenarios while being perfectly safe to use in many others.

The evaluation of an exchange scenario for a given bid list distinguishes between three outcomes: infeasible, congested, or merit-order feasible. While the latter indicates that the available bids can safely be activated for the exchange flows at hand, congested scenarios require skipping bids and deviating from the merit order. Infeasible scenarios simply cannot be balanced with any combination of bids from the list, and redispatch would be critical to avoid overloading the transmission network should such a scenario materialize. Whereas making specific bids unavailable can make congested scenarios merit-order feasible, bid filtering is ineffective in preventing infeasible platform outcomes.

Exchange domains provide restrictions on cross-zonal balancing energy flow combinations. These cannot make more exchange scenarios feasible, but effectively prevent infeasible or congested situations from occurring. In this regard, the concept is complementary to bid filtering. An exchange domain must be tailored to the list of available bids, and the domains calculated for specific lists of bids can also help determine which bids to filter. More importantly, the ability to discard congested scenarios without filtering bids also enables making more bids available to the platform.

An exchange domain is described by a set of linear inequalities, and these would act as additional constraints in the platform optimization. The impact on the computational burden from these additional constraints would be negligible. The concept is newly developed and thus has not been proposed as a candidate method in the design drafts of any of the European balancing platforms being implemented. Nevertheless, the importance of cross-border balancing flows on internal congestion infers that including such a mechanism should be considered in the future.

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Abbreviations

The following abbreviations are used in this manuscript:

aFRR	Automatically activated Frequency Restoration Reserves
AOF	Activation Optimization Function
CMOL	Common Merit Order List
ENTSO-E	European Network of Transmission System Operators for Electricity
LMP	Locational Marginal Price
mFRR	Manually activated Frequency Restoration Reserves
MARI	Manually Activated Reserves Initiative
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PTDF	Power Transfer Distribution Factor
RR	Replacement Reserves
TERRE	Trans European Replacement Reserves Exchange
TSO	Transmission System Operator

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7.7 Publication VII

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Distributed balancing energy activation and exchange optimisation

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Abstract: European balancing markets are presently fragmented and mostly national. Integrating them on common platforms requires the ability to identify optimal balancing energy volumes to be activated and exchanged to cover imbalances across the interconnected system, but this leads to new challenges. To avoid balancing energy flows compromising operational security, capacity limitations in the transmission network should be taken into account in the optimisation. However, a zonal market structure and limited computational time inhibit using detailed models in the optimisation. This study describes and demonstrates a distributed formulation for optimisation of activation and exchange of balancing energy. Using Benders decomposition, the optimisation is separated into local activation problems that are smaller and less complex, distributing the computational effort. A single exchange problem identifies the optimal exchange volumes between geographical areas using optimality cuts obtained in the local subproblems. The proposed formulation is capable of optimising balancing decisions across a large, interconnected system, while still keeping a zonal market structure and taking detailed network constraints into account.

Nomenclature

Indices

a, n	balancing area
b	balancing energy bid
i, j	node
k	optimality cut
p	exchange scenario

Parameters

λ_{an}^k	shadow cost on exchange from area a to n in cut k
$\overline{X}_{an}$	available cross-zonal capacity from area a to n
$\overline{Y}_b$	capacity of bid b
Φ_{il}	PTDF from node i to line l
σ_a^k	value at zero exchange of cut k for area a
$\underline{F}_l, \overline{F}_l$	remaining transmission capacities on line l
A_{il}	adjacency of node i to line l
C_b	activation price for bid b
D_a	balancing energy demand in area a
D_i	balancing energy demand in node i
F_a^p	cost of situation p in upper bound calculation
X_{an}^p	exchange from area a to neighbour n in situation p

Sets

$\mathscr{A}$	areas
$\mathscr{B}_a$	balancing bids located in area a
$\mathscr{B}_i$	balancing bids located at node i
$\mathscr{I}_a$	nodes, including external, in area a
$\mathscr{I}_a^{\text{ext}}$	external nodes representing neighbours of area a
$\mathscr{K}_a$	optimality cuts for area a
$\mathscr{L}_a$	lines considered for area a
$\mathscr{N}_a$	neighbouring areas to a
$\mathscr{P}_a$	exchange situations evaluated for area a

Variables

α^p	weight of situation p in upper bound calculation
λ_i	marginal energy price in node i
θ_a	estimated balancing cost in area a
F_a	evaluated balancing cost in area a
f_l	power flow on line l
x_{an}	exchange from area a to area n
y_b	activated volume from bid b
z_a	activated volume in area a

Specifiers

$\downarrow$	downward direction
$\uparrow$	upward direction

1 Introduction

European power markets are in the process of integration, and significant progress has already been made in coupling the different day-ahead and intraday markets. For the balancing markets, platforms for integration of balancing services are currently being developed as part of the implementation of new Network Codes and Guidelines. The new pan-European markets for balancing energy provide opportunities to better coordinate balancing actions and exchange of balancing energy across borders. Among the objectives is increasing social welfare by enhancing competition and utilising balancing resources more efficiently [1]. The platforms being established for each of the standardised balancing products [2–4] largely share the same fundamental operational philosophy. Collecting balancing energy bids from all participating transmission system operators (TSOs) on a continuous basis, the platforms aim to identify the best decisions in terms of activation, exchange, and imbalance netting to cover the expected imbalances in each area of the system. Such an optimisation allows the least expensive balancing bids to be used as far as allowed by transmission capacities.

Since power flows due to balancing are determined by the locations of imbalances and the activated reserves, electricity balancing is inseparably intertwined with congestion management.

The European power market has a zonal structure, where existing day-ahead and intraday markets have been coupled either through net transfer capacities or using the flow-based methodology [5]. Such mechanisms address congestion between – but not within – zones, and without knowledge of the reserve location, the impacts of activations on network congestion are unforeseeable. Consequently, there is a conflict between, on the one hand facilitating a zonal approach to balancing, that allows the integration of large areas and many countries, and on the other hand the necessary consideration of intra-zonal grid constraints. The proposed solution is bid filtering [3], a concept for which methods are yet to be formalised. However, the availability of the bids depends on the final flows, which are unknown. Thus, pre-determination of which bids are available and which not will either be too restrictive, which increases costs, or too liberal, which may threaten system security.

The methodology described in this paper contrasts these earlier proposals. With the hypothesis that the inefficiencies of bid filtering can be avoided while keeping a zonal market structure, this paper aims to demonstrate a new approach to handling intra-zonal congestion in the upcoming pan-European balancing markets. The key idea is the development of a distributed market clearing structure. Decomposing the interconnected power system into smaller network areas, complexity is greatly reduced and the computational effort can be parallelised, allowing for detailed network considerations within each area. Interaction with a central master problem is handled through optimality cuts, without information on individual bids or network constraints. The mathematical techniques used to decompose and solve the distributed problem are well-established in literature, but the European balancing activation optimisation comprises a new context and application of these methods.

The distributed formulation presented in this paper is subject to a few key assumptions. Firstly, the formulation is convex with linear constraints. Some of the European balancing markets being implemented [3, 4] will likely allow indivisible and linked bids, whereas at least one [2] will not. With integer decisions, the solution algorithm would likely perform worse in terms of convergence due to weaker optimality cuts being generated from MILP subproblems. Benchmarking computational performance and convergence rate analysis of different models is outside the scope of this article, but in general, linear programs can be solved quickly, also for systems of considerable size. Still, even if computationally tractable within the limited available operational time, a centralised nodal optimisation on the full system would challenge dispatch autonomy, which is a contentious issue in Europe, and require closer harmonisation between areas, and possibly also require a system-wide transition to nodal pricing. Including integer decisions increases computational effort significantly and inhibits a full nodal approach in real time. Moreover, the decomposed formulation represents a hybrid nodal/zonal approach. Each subsystem considers a simplified representation of the transmission grid in neighbouring areas, and the transport model in the zonal master problem is unable to account for loop flows in a meshed topology. This is a notable shortcoming compared to a full nodal model, nevertheless it is the concept being implemented in the upcoming balancing platforms.

Section 2 describes established design principles for the integrated European balancing markets, as well as earlier approaches to balancing optimisation and distributed market clearing. In Section 3, the details of the optimisation and solution procedure are described, including master and subproblem formulations, and calculation of cuts and bounds. The methodology is applied on a test system in Section 4, demonstrating the steps in the method and providing a numerical example. The implications and unsolved challenges indicating areas for further work are discussed in Section 5, leading to the conclusions in Section 6.

2 Background

In the balancing market, three main parties interact to maintain the balance between generation and consumption in the power system. Balance responsible parties (BRPs) failing to counteract imbalances within their perimeter, thereby not meeting their scheduled positions, impose imbalances on the system. The necessary adjustments to mitigate the resulting system imbalance are coordinated by the TSO through activation of balancing energy. This energy is delivered through bids by balancing service providers (BSPs) holding reserve capacity. [In European Network of Transmission System Operators for Electricity (ENTSO-E) terms, balancing activation is part of the frequency restoration and reserve replacement processes. Reserves activated for balancing energy are correspondingly frequency restoration reserve or replacement reserve products, comparable to secondary and tertiary control reserves.]. To cover imbalances, the TSO activates as many bids as needed from the merit order list of balancing energy bids. In an imbalance settlement mechanism, the BRPs causing imbalances by deviating from their schedules are penalised, and thereby the BRPs indirectly pay BSPs for the activated balancing energy [6].

Several studies have indicated the benefits of European balancing market integration [6–9], and key market design aspects have been set through the development and implementation of new network codes. These codes, developed by the ENTSO-E establish common rules and regulations for the European power markets. Specifically, the Guideline on Electricity Balancing [1] aims to enable and facilitate exchange of balancing energy. It requires balancing services to be harmonised into Standard Products for balancing energy, and outlines a market structure based on a common merit order list, consisting of balancing bids from all TSOs. An activation optimisation function optimises activation and imbalance netting actions to satisfy the imbalance needs of each TSO, subject to available cross-zonal transmission capacities.

The future European balancing market will have a zonal structure, largely following national borders. Three implementation projects [2–4] all currently develop common platforms for cross-border balancing in accordance with this high-level design, with cross-zonal capacities preventing congestion between market areas. The appetite for nodal approaches in Europe is limited, and in any case they would meet challenges due to problem size. Rather, in [1] handling intra-zonal constraints through *bid filtering* is proposed, i.e. TSOs may flag a bid unavailable and withhold it from the common merit order list if its activation would cause internal congestion. As the severity of intra-zonal congestion varies between different European countries, and a common standard bid filtering methodology is not expected.

Bid filtering in zonal balancing markets has not received widespread attention in scientific literature. The algorithm developed in [10] enumerates a range of different requests for balancing energy exchange from neighbouring zones. The method uses power flow analyses to detect whether a bid would need to be skipped to avoid congestion for each of the considered flow outcomes. The algorithm only considers one neighbouring zone at a time, whereas balancing market outcomes would often instruct balancing energy exchange on multiple zonal borders. Such flow combinations (including transit flows) load the network differently, and the method in [11] considers simultaneous balancing energy flow to multiple neighbours. An important finding is that bid filtering alone cannot provide any guarantee against intra-zonal congestion, and that additional measures will sometimes be necessary.

Closely related problems and techniques also been studied for US electricity markets, where traditional reserve requirements are based on deterministic reserve zones. When disregarding the grid location of reserves procured within a zone, there is a risk that the procured reserves are ineffective against intra-zonal congestion [12]. And just as in the zonal European balancing market, all reserves within a zone are assumed to have equal shift factors on critical lines, and the true deliverability of the procured reserves will be imprecise. To ensure adequate volumes and locations of operating reserves, Lyon *et al.* [13] demonstrates a locational reserve disqualification method taking into account a range of distinct contingency scenarios.

Regardless of its implementation, there are obvious drawbacks with the bid filtering approach. The impact of a bid activation on congestion depends on the exchange situation, which is unknown

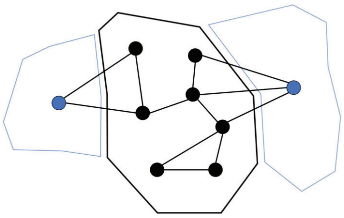

Fig. 1 *Example single-area system consisting of internal nodes and external nodes representing neighbouring areas*

before the outcome of the European activation optimisation. Under unforeseeable flow conditions, TSOs need to evaluate a range of possible exchange flow outcomes. In order to be robust against internal congestion, TSOs would need to withhold a bid even when its activation causes congestion only under specific exchange situations, potentially reducing both social welfare and security of supply. Making such a bid available, however, incurs the risk of congestion, and even when manageable through urgent redispatch, the price signals from the optimisation would still be incorrect. Without an adequate representation of the transmission grid, internal congestion can hardly be prevented efficiently.

Balancing activation optimisation models in literature often comprise linear programs covering a firm imbalance demand at minimum activation cost [8, 9]. Being a form of real-time dispatch, they are sometimes based on DC optimal power flow (DCOPF) formulations [14]. Some models extend the basic formulations into scheduling models, taking into account multiple time periods, which requires more detailed constraints regarding e.g. ramping and duration of delivery [15, 16], or even multiple balancing products or stochastic imbalances [17]. Other models [3, 4, 18] have introduced elasticity in the imbalance demand and resemble more traditional market clearing models. All such models share similar structures with either unit commitment or economic dispatch models, with network representations ranging from copper plate to nodal models.

Distributed algorithms have been developed decades ago to efficiently solve OPF (optimal power flow) problems on very large networks. The most common methodology in literature revolves around decomposing a large economic dispatch problem into smaller subproblems representing different areas in the network, creating duplicate *dummy variables* on the borders. The individual network areas are linked through coupling constraints in a central coordination problem. Often, (augmented) Lagrangian relaxation is applied to these coupling constraints, allowing for solving one smaller economic dispatch problem per area [19–22]. Rather than dualising all coupling constraints in the objective function and solving an auxiliary problem to update the Lagrangian multipliers, the authors in [23, 24] apply optimality condition decomposition on a multiarea OPF problem, a closely related but more sophisticated technique. Here, complicating constraints are kept, but in separate subproblems, resulting in automatic multiplier updates.

Benders decomposition [25] has been widely applied to solve problems with complicating variables. A master problem proposes candidate values for these variables, which are considered fixed parameters in the subproblems. Optimality (and sometimes also feasibility) cuts generated by subproblems are added as constraints to the master problem, iteratively refining the feasibility space until decision variables converge to their optimal values. In the context of power system optimisation, integer decisions such as investment or unit commitment are often considered the complicating variables, and subproblems typically comprise linear programs evaluating the minimum cost given a candidate set of decisions. Thus, the method has been widely used together in combination with OPF to solve two-stage problems, including (stochastic) unit commitment and expansion planning [23].

Even more relevant to this paper are efforts to solve large OPF problems using Benders decomposition. In [26], the total power output in each subnetwork is considered a complicating variable, and subproblems optimising smaller areas are computed in parallel. A decentralised OPF solution is found in [27] by duplicating exchange variables at the subnetwork boundaries and solving individual-area OPFs, while coordinating the values of these variables using a line search in a centralised problem. Another kind of primal decomposition is applied to a large-scale OPF in [28], abstracting neighbouring network areas into so-called marginal equivalents, solving area-dispatch subproblems, and coordinating information on binding constraints and free variables. The decomposition algorithm proposed in this paper is similar, but adopts the methodology to the context of the integrated balancing market, which shares a structure similar to the multi-area OPF problem.

3 Methodology

The objective of the balancing energy activation problem can be seen as finding the cost-minimising set of bid activations to cover the imbalances of all TSOs, while respecting the relevant constraints, including limitations on network flows. Keeping a high level of detail in the network representation, this procedure decomposes the problem into separate subproblems per balancing area. Each subproblem calculates the activation cost in its area taking into account the local imbalance and an assumed set of balancing energy exchange flows, comprising an *exchange scenario*. A master problem aims to minimise total balancing costs by finding the optimal exchange volumes between all pairs of neighbouring areas, subject to cross-zonal capacities. The master problem needs no information on bids or intra-zonal network constraints. Rather, solutions of the subproblems are used to generate optimality cuts in the master problem, providing an approximate supply function representing the true balancing activation in each area under feasible flow conditions. These cuts can be added iteratively, thereby refining the cost function representations close to the exchange volumes proposed by the master problem. They can also be pre-generated by solving the subproblems for a multitude of different exchange situations, thereby reducing the number of iterations or providing a near-optimal solution a single iteration.

Different geographical zones of the interconnected system are represented as single-area systems. For each bidding zone, the single-area system consists of a detailed model of the internal network, while disregarding the network structure inside neighbouring areas. This allows each neighbouring area to be represented by a single external node (as in [20]), and transmission lines between the areas are considered to be connected to this node, cf. Fig. 1.

3.1 Single-area subproblem

The subproblem (**SP**) (1)–(5) comprises a dispatch model, and largely follows a DCOPF structure. The set $\mathcal{I}_a$ contains all internal and external nodes associated with single-area system a. The subproblem assumes knowledge of the need for balancing energy D_i in each node $i \in \mathcal{I}_a$. For external nodes, this value denotes a specific cross-zonal balancing energy exchange program. The corresponding set of lines comprises $\mathcal{L}_a$, and an adjacency matrix contains parameters A_{il}, equalling 1 or -1 if line l is directed out of or into node i, respectively, and zero otherwise. The power transfer distribution factors (PTDFs) Φ_{il} describe the linearised relationship between a power injection in node i on the flow in line

l. Furthermore, each line $l \in \mathscr{L}_a$ has a lower and upper (bidirectional) flow capacity limit, $\underline{F}_l, \overline{F}_l$, given as the residual between the rated capacity and the initial flow on the line. All bids $b \in \mathscr{B}_a$ have an associated capacity limit $\overline{Y}_b$ and also an activation cost C_b, given by the bid prices for upward bids $\mathscr{B}^{\uparrow}$ and for downward bids $\mathscr{B}^{\downarrow}$. The set of bids located at node i is denoted by $\mathscr{B}_i^{\uparrow/\downarrow}$.

The objective in (1) is to find optimal activation volumes y_b to minimise the activation cost F_a in area a. The equality constraint in (2) ensures energy balance and flow conservation in each node of the system, while (3) sets the balancing energy flow f_l on each line based on the nodal net injections and the node-to-line PTDFs. These flow restrictions could easily be extended to include combinations of lines or other network elements. Bid capacities and available line capacities are given in (4) and (5). Note that selecting bids through cost minimisation does not inhibit compensating activated bids with a marginal (clearing) price, but it does imply that supply costs – and not only TSO payments – are minimised

$$(\mathbf{SP}) \quad \min_{f,y} F_a(\boldsymbol{D}) = \sum_{b \in \mathscr{B}_a} C_b y_b \tag{1}$$

$$\text{s.t.} \quad \sum_{b \in \mathscr{B}_i^{\uparrow}} y_b - \sum_{b \in \mathscr{B}_i^{\downarrow}} y_b - \sum_{l \in \mathscr{L}_a} A_{il} f_l = D_i, \quad i \in \mathscr{I}_a \tag{2}$$

$$f_l - \sum_{i \in \mathscr{I}_a} \Phi_{il} \left(\sum_{b \in \mathscr{B}_i^{\uparrow}} y_b - \sum_{b \in \mathscr{B}_i^{\downarrow}} y_b - D_i \right) = 0, \quad l \in \mathscr{L}_a \tag{3}$$

$$0 \le y_b \le \overline{Y}_b, \quad b \in \mathscr{B}_a \tag{4}$$

$$\underline{F}_l \le f_l \le \overline{F}_l, \quad l \in \mathscr{L}_a \tag{5}$$

3.2 Generating cuts

For the problem of identifying optimal exchange volumes, the aim is to build an approximation of balancing costs for each area with respect to exchange volumes to neighbouring areas. Denoting by y^* an optimal balancing dispatch found in (**SP**) for balancing exchange volumes D^0, and by λ_i the shadow prices of the energy balance constraints in (2), a subgradient to the cost function F_a in terms of exchange volumes D_i to neighbouring areas represented by nodes $\mathscr{I}_a^{\text{ext}}$ is given as

$$F_a \ge \sum_{b \in \mathscr{B}_a} C_b y_b^* + \sum_{i \in \mathscr{I}_a^{\text{ext}}} \lambda_i (D_i - D_i^0) \tag{6}$$

Since (**SP**) is convex, an outer approximation of F_a with respect to changes in imbalance needs D_i can be made based on the subgradient. By setting the parameter $\lambda_{an}^k = \lambda_i$ for the relevant corresponding exchange nodes, a supporting hyperplane k to the estimated balancing cost θ_a in the master problem can be expressed as a linear constraint in terms of the exchange variables x_{an}

$$\theta_a \ge \sigma_a^k + \sum_{n \in \mathscr{N}_a} \lambda_{an}^k x_{an}, \tag{7}$$

where

$$\sigma_a^k = \sum_{b \in \mathscr{B}_a} C_b y_b^* - \sum_{i \in \mathscr{I}_a^{\text{ext}}} \lambda_i D_i^0 \tag{8}$$

3.3 Multi-area master problem

The master problem (**MP**) searches for optimal exchange values x_{an} to minimise the sum of all estimated balancing activation costs θ_a in (9). To satisfy its energy balance (10), each area a can cover its demand D_a for balancing energy through import or through local activation z_a. For each area a and its neighbours n, limits on exchange are imposed in (11), and (12) couples exchange decisions in different directions. Finally, (13) applies the supporting hyperplanes (7) calculated from solutions of the subproblems, providing lower bounds on the balancing activation costs in each area

$$(\mathbf{MP}) \quad \min_{\theta, x, z} \sum_{a \in A} \theta_a \tag{9}$$

$$\text{s.t.} \quad z_a - \sum_{n \in \mathscr{N}_a} x_{an} = D_a, \quad a \in \mathscr{A} \tag{10}$$

$$x_{an} \le \overline{X}_{an}, \quad a \in \mathscr{A}, n \in \mathscr{N}_a \tag{11}$$

$$x_{an} + x_{na} = 0, \quad a \in \mathscr{A}, n \in \mathscr{N}_a \tag{12}$$

$$\sigma_a^k + \sum_{n \in \mathscr{N}_a} \lambda_{an}^k x_{an} \le \theta_a, \quad a \in \mathscr{A}, k \in \mathscr{K}_a \tag{13}$$

3.4 Iterative solution procedure

The problem can be solved by iteratively solving the master problem and each of the subproblems. The cost-minimising exchange volumes and estimated balancing costs from (**MP**) will be passed on to the subproblems as parameters, which evaluate the true balancing costs for these volumes, and if necessary add new cuts to refine the cost function representations in the master problem. Thus, the iterative solution procedure adds new balancing cost information in each iteration, until the cost estimate is proved to be valid. This is elegant and efficient, since the complexity of a sufficient balancing cost approximation will be limited.

Step 1: In the first iteration, initialise exchange volumes, $x_{an}^* = 0$, for $a \in \mathscr{A}, n \in \mathscr{N}_a$. Let $\theta_a^* = -\infty$ for $a \in \mathscr{A}$. Create empty sets K_a for $a \in \mathscr{A}$. In later iterations, solve (**MP**). Retrieve proposed exchange x_{an}^* and estimated balancing costs θ_a^*.

Step 2: For each area a: Set demand D_i in exchange nodes $i \in \mathscr{I}_a^{\text{ext}}$ equal to proposed exchange x_{an}^*. Solve (**SP**), let optimal solution be y^* with objective function value F_a^*. If $F_a^* > \theta_a^*$, add a new cut k to $\mathscr{K}_a$ as in (7).

Step 3: If $\sum_a F_a^* \le \sum_a \theta_a^* + \epsilon$, or if no cuts were added, the exchange values x_{an}^* are optimal. Else, go to step 1.

The iterative solution procedure is able to prove optimality with a finite number of cuts. At the same time, communication is required between the coordinating platform and the distributed entities providing new cuts in each iteration. Not only is the iterative method vulnerable to communication delays, also the number of iterations required to converge may be highly uncertain, as it depends on the problem instance (and the choice of tolerance gap ϵ). Finally, the time necessary to solve the single-area subproblems may differ greatly between TSOs and with different input values. An iterative procedure could be vulnerable to one or more slow-solving subproblems, although this can partly be guarded against by making the algorithm asynchronous, as in [29].

3.5 Two-step solution procedure

Another approach would be to pre-generate a set of cuts representing the balancing cost function in each area. By pre-generating cuts and submitting them all at once, the communication is simplified, and the computational workload to solve the subproblems is moved ahead of the platform optimisation. A straightforward cut pre-generation strategy could be to evaluate the F_a for a structured (regular or rectilinear) grid of different sets of values for $x_{an}, n \in \mathscr{N}_a$, and add a new cut whenever F_a exceeds all lower bounds given by previously generated cuts. Using a structured grid also enables calculating

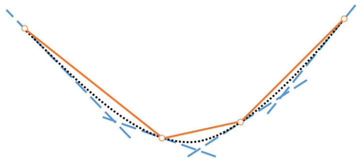

Fig. 2 *Two-dimensional example of lower bounds on F_a (blue), upper bounds on F_a (orange), and the unknown true cost function F_a (black)*

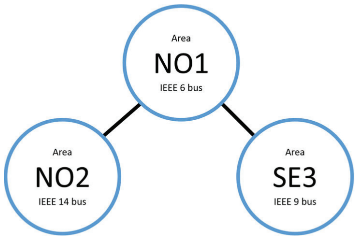

Fig. 3 *Test system topology and network models*

Table 1 Test system data per area

Area	Nodes	Gen. units	Trans. lines	Local imbalance
NO1	6	3	11	38 MW
NO2	14	5	20	120 MW
SE3	9	3	9	189 MW

Table 2 Test system data per tie-line

Tie-line	External node	Exchange cap.
NO1-NO2	Node 4	10 MW
NO2-NO1	Node 14	150 MW
NO1-SE3	Node 6	50 MW
SE3-NO1	Node 9	150 MW

upper bounds on F_a using multivariate interpolation between the evaluated points. Solving (**MP**) with a set of pre-generated cuts will yield proposed exchange values x_{an}^*. However, with incomplete outer approximations of the true cost functions, there is a possibility that the corresponding estimated balancing costs θ_a will be an underestimation. Pre-generating a large amount of cuts for each subsystem will reduce this risk, but without further iterations in the solution procedure, the cost function representation will not be refined, and a global optimum will not be guaranteed.

3.6 Upper bounds

For the system as a whole, the objective function value of (**MP**) in each iteration serves as a lower bound on the true balancing costs. Correspondingly, the sum of all *evaluated* balancing costs $\sum_a F_a$ for any given set of exchange flows $x_{an}, n \in \mathscr{N}_a$ represents the cost of a feasible solution and is thus a valid upper bound for the total balancing costs.

Fig. 2 demonstrates the calculation of upper and lower bounds for the cost function F_a of a single area. For each single-area subproblem, lower bounds on F_a are formed by the so-far generated optimality cuts. Moreover, each cut coincides with the true cost function F_a for the specific exchange flows $x_{an}, n \in \mathscr{N}_a$ for which it is calculated. If denoting by $p \in \mathscr{P}_a$ the different exchange scenarios for which (**SP**) has been evaluated with costs F_a^p and exchange volumes X_{an}^p, upper bounds on F_a can be observed as the facets of the lower convex hull containing points $\mathscr{P}_a$. The bound value $F_a^{\mathrm{UB}}(\boldsymbol{x})$ along the facets can be found as the minimum cost convex combination (14)–(17) of the evaluated scenarios p. For a specific scenario with exchange volumes $x_{an}, n \in \mathscr{N}_a$

$$(\mathbf{UB}) \quad \min_{\alpha} F_a^{\mathrm{UB}} = \sum_{p \in \mathscr{P}_a} \alpha^p F_a^p \tag{14}$$

$$\sum_{p \in \mathscr{P}_a} \alpha^p x_{an}^p = x_{an}, \quad n \in \mathscr{N}_a \tag{15}$$

$$\sum_{p \in \mathscr{P}_a} \alpha^p = 1 \tag{16}$$

$$0 \le \alpha^p \le 1, \quad p \in \mathscr{P}_a \tag{17}$$

4 Numerical example

4.1 System description

To improve understanding of the proposed methodology, this section demonstrates the distributed optimisation on a very simplified scale. Three different power system models represent subsystems (corresponding to balancing areas) in a larger, interconnected test system, as shown in Fig. 3. The test system areas carry names NO1, NO2, and SE3, and are indexed as areas 1, 2, and 3.

Area NO1 is represented by a 6-bus system from [30], NO2 by the IEEE 14-bus system, and SE3 by the IEEE 9-bus system. Key information on the subsystem models is summarised in Tables 1 and 2. The models are inhomogeneous, yet this poses no issues under the simplifying assumptions of network decomposition and flow in neighbouring areas. This inhomogeneity also illustrates a flexibility advantage in that TSOs are not required to align the level of detail in the models used for evaluating balancing costs.

Exchange between areas is limited by remaining cross-zonal capacities, which are directional and asymmetric due to utilisation in other markets. Moreover, each area needs to cover a local imbalance, either through exchange or local activation.

4.2 Implementation

The iterative solution procedure has been implemented as a Python library, in particular leveraging modelling functionality from the Pyomo framework [31]. Subproblems are managed and solved with functionality from PyPower, which is based on the Matpower toolbox [32].

4.3 Solution

The iterative solution procedure is used in this example. In each iteration, the exchange volumes proposed by the master problem are added as additional demand at the nodes in each subsystem corresponding to the exchange corridor. The one-area system optimises its balancing actions (using a modified DCOPF calculation in this example) according to the exchange situation, taking into account intra-zonal grid constraints, and passes balancing cost information back to the master problem in the form of a cut.

Iteration 1

Step 1: Initialise all exchange volumes x_{an}^* to 0, and all cost estimates θ_a^* to $-\infty$.

Step 2:

Area 1: Set $D_4 = x_{1,2} = 0$ and $D_6 = x_{1,3} = 0$. Solving (**SP**) gives $F_1^* = 7246$, and since $F_1^* > \theta_1^*$, a cut is added

$$\theta_1 \ge 7246 + 31.90 x_{1,2} + 31.90 x_{1,3}$$

In this case, both marginal exchange costs $\lambda_{1,2}$ and $\lambda_{1,3}$ from area 1 take the value 31.90.

Area 2: Set $D_{14} = x_{2,1} = 0$. Solving (**SP**) gives $F_2^* = 7643$, and since $F_2^* > \theta_2^*$, a cut is added

$$\theta_2 \ge 7643 + 39.01 x_{2,1}$$

Area 3: Set $D_9 = x_{3,1} = 0$. Solving (**SP**) gives $F_3^* = 5216$, and since $F_3^* > \theta_3^*$, a cut is added

$$\theta_3 \geq 5216 + 24.04x_{3,1}$$

The evaluated balancing costs $\sum_{a \in \mathscr{A}} F_a^* = 20105$ provide an upper bound on the total balancing cost.

Step 3: We have $\sum_a F_a^* > \sum_a \theta_a^* + \epsilon$, and at least one new cut was added, hence the exchange values x_{an}^* were not optimal.

Iteration 2

Step 1: Solving (**MP**) with the updated list of cuts yields $\theta^* = (2780, 7252, 8823)$ for $x_{1,2}^* = 10$ and $x_{3,1}^* = 150$. New lower bound: $\sum_{a \in \mathscr{A}} \theta_a^* = 18856$.

Step 2: Subproblem evaluation yields $F_1^* = 4802$, $F_2^* = 7256$, $F_3^* = 9598$. New cuts

$$\theta_1 \geq 4802 + 0.0x_{1,2} + 0.0x_{1,3}$$

$$\theta_2 \geq 7639 + 38.28x_{2,1}$$

$$\theta_3 \geq 4441 + 34.38x_{3,1}$$

New upper bound: $\sum_{a \in \mathscr{A}} F_a^* = 21656$.

Step 3: We have $\sum_a F_a^* > \sum_a \theta_a^* + \epsilon$, and at least one new cut was added, hence the exchange values x_{an}^* were not optimal.

Iteration 3

Step 1: Solving (**MP**) with the updated list of cuts yields $\theta^* = (5173, 7256, 7019)$ for $x_{1,2}^* = 10$ and $x_{3,1}^* = 75$. New lower bound: $\sum_{a \in \mathscr{A}} \theta_a^* = 19448$.

Step 2: Subproblem evaluation yields $F_1^* = 5191$, $F_2^* = 7256$, $F_3^* = 7213$. New cuts

$$\theta_1 \geq 7220 + 31.22x_{1,2} + 31.22x_{1,3}$$

$$\theta_3 \geq 5022 + 29.21x_{3,1}$$

New upper bound: $\sum_{a \in \mathscr{A}} F_a^* = 19660$.

Step 3: We have $\sum_a F_a^* > \sum_a \theta_a^* + \epsilon$, and at least one new cut was added, hence the exchange values x_{an}^* were not optimal.

Iteration 4

Step 1: Solving (**MP**) with the updated list of cuts yields $\theta^* = (4802, 7256, 7577)$ for $x_{1,2}^* = 10$ and $x_{3,1}^* = 87.5$. New lower bound: $\sum_{a \in \mathscr{A}} \theta_a^* = 19\,635$.

Step 2: Subproblem evaluation yields $F_1^* = 4804$, $F_2^* = 7256$, $F_3^* = 7582$. New cuts

$$\theta_1 \geq 7204 + 31.00x_{1,2} + 31.00x_{1,3}$$

$$\theta_3 \geq 4952 + 30.07x_{3,1}$$

New upper bound: $\sum_{a \in \mathscr{A}} F_a^* = 19642$.

Step 3: We have $\sum_a F_a^* > \sum_a \theta_a^* + \epsilon$, and at least one new cut was added, hence the exchange values x_{an}^* were not optimal.

Iteration 5

Step 1: Solving (**MP**) with the updated list of cuts yields $\theta^* = (4802, 7256, 7584)$ for $x_{1,2}^* = 10$ and $x_{3,1}^* = 87.5$. New lower bound: $\sum_{a \in \mathscr{A}} \theta_a^* = 19\,642$. No new cuts are added in this iteration, and the solution is optimal.

Solution summary: In this example, the first iteration is calculated with zero exchange, thereby providing the balancing costs and marginal prices from using only local balancing. For the global optimum, the procedure needs four full iterations (cf. Figs. 4 and 5) to find optimal exchange values. With a higher tolerance ϵ, three iterations would suffice. Marginal balancing costs on each side of the non-congested link between NO1 and SE3 have almost converged to around 30–31 €/MWh, whereas marginal costs are around 38 €/MWh on the NO2 side of the NO1–NO2 link, thus it is used at full capacity. Also, for illustration, the cuts generated for area SE3 are included in Fig. 6. Cuts generated for area NO1 are shown in Fig. 7, requiring a 3D projection as the area has two exchange dimensions.

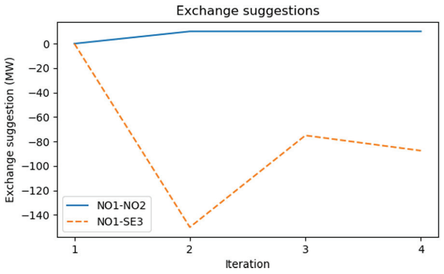

Fig. 4 *Exchange volumes x_{an}^* suggested by (**MP**) in each iteration*

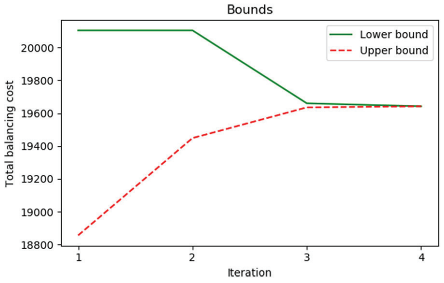

Fig. 5 *Upper and lower bounds on total balancing activation cost*

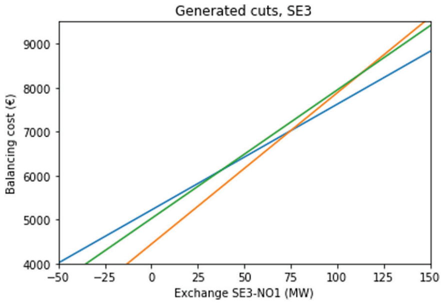

Fig. 6 *Cuts representing balancing costs in SE3 for different exchange volumes*

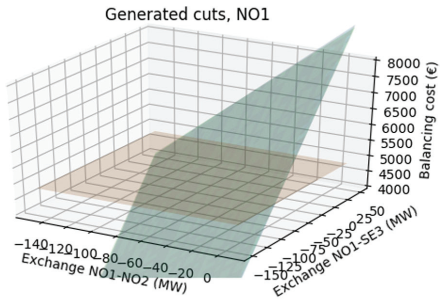

Fig. 7 *Cuts representing balancing costs in NO1 for different exchange volumes*

5 Discussion

The proposed distributed approach serves as an alternative method to a zonal optimisation with bid filtering, with its main advantage being the efficient handling of intra-zonal constraints. Regardless of implementation, pre-filtering balancing bids reduces social welfare. TSOs will in some cases detect balancing energy bids that can be used safely only under specific flow conditions. As exchange flows are unknown, the TSO can decide to make such bids unavailable to avoid internal congestion. When the safe flow conditions occur, these bids are underutilised. If such bids are made available and the safe flow conditions do not occur, the solution to the optimisation problem will be infeasible, and the exchange flows will generally be suboptimal. By distinguishing between an exchange problem and multiple dispatch problems, all resources can be considered available without taking the risk of infeasible dispatch solutions.

The distributed method carries fundamental implications. A distinction between exchange and dispatch gives each TSO an active role in the optimisation. In the distributed balancing optimisation algorithm, the platform's ability to identify optimal exchange volumes depends not on available balancing bids, but rather on TSOs' evaluations of their total and marginal balancing costs under different exchange scenarios. This shifts computational workload and also responsibility to the TSOs.

A distributed, iterative solution procedure is elegant, but also poses potential challenges. The balancing cost cuts provide an approximate representation of the true balancing costs in each area given different exchange volumes. The iterative procedure gradually refines these representations by adding more cuts, until the balancing cost estimation is representative. Moreover, the procedure will produce a feasible solution (as well as a lower bound) in each iteration, since the TSOs' response to a given exchange scenario is evaluated. Although the number of iterations required to reach a global optimum is limited, it is nevertheless unknown. Even if subproblems are evaluated promptly and efficiently, the exchange optimisation algorithm would still be vulnerable to communication delays or numeric instabilities causing slow convergence.

Pre-generating cuts provides a head start, but generally not an optimal solution. By solving the single-area subproblem for a set of different exchange scenarios and submitting the resulting cuts to the exchange optimisation, the balancing cost representation can be pre-refined. Solving the exchange problem using pre-refined cost representations can lead directly to a solution close to the true optimum. The direct solution will generally be an underestimation of the true balancing costs, and unless more cuts can be added, the exchange volumes will not be guaranteed to be optimal. The underestimation is bounded, however. An upper bound on the true balancing costs for a given exchange situation can be found as the minimum cost convex combination of already evaluated exchange scenarios.

Analysing computational performance is not the focus of the case study, however such insight could be obtained by running the algorithm on networks of realistic size. This would also allow direct comparison between the iterative solution and the cut pregeneration procedures, and possibly also against other methods, including bid filtering. Moreover, some markets allow complex bid structures, such as linked or indivisible bids, which introduce integer variables in the subproblems. Investigating methods for efficiently incorporating non-convex subproblems in the distributed balancing optimisation is of therefore also of interest in future work.

6 Conclusions

An integrated European balancing market needs to efficiently identify the optimal balancing actions in terms of activation and cross-border exchange of balancing energy. The European legislation strongly favours a zonal network representation, and there is political opposition against moving to a nodal system. Yet the aggregated network representation fails to effectively manage congestion within market areas, leading to inefficiencies and infeasible network flows. The methodology presented in this article allows for more detailed network representations to be used efficiently in the balancing energy optimisation without abandoning the overarching zonal market structure. Decomposing the system into smaller network areas, the computational effort to identify the optimal bid activation volumes can be parallelised by distributing it across several local subproblems. A master problem searches for optimal cross-zonal balancing exchange flows to minimise total balancing costs, doing so without information on bids or intra-zonal network constraints, but rather using information from the subproblem solutions using a cutting-plane method. The decomposition also allows flexibly integrating areas with network models of different scales and detail levels. The numeric example with a small number of cuts and iterations demonstrates the elegant iterative procedure, although near-optimal solutions can also be identified directly by pre-generating cuts. Open questions remain regarding convergence properties and approximation accuracy of the cutting-plane approach proposed in this paper, but the distributed solution structure gives TSOs a more active role, and handles intra-zonal network constraints more efficiently than alternative methods.

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