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RIGA TECHNICAL
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Aigars Sīlis

POWER SYSTEM MANAGEMENT UNDER MARKET CONDITIONS WITH HIGH DISPERSION OF RENEWABLE ENERGY PRODUCTION

Summary of the Doctoral Thesis

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Riga 2024

RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science, Information Technology and Energy
Institute of industrial electronics, electrical engineering and energy

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POWER SYSTEM MANAGEMENT UNDER MARKET CONDITIONS WITH HIGH DISPERSION OF RENEWABLE ENERGY PRODUCTION

Summary of the Doctoral Thesis

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Cover picture from JSC "Augstsprieguma tīkls"

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 29 August 2024 at 10.00 at the Faculty of Computer Science, Information Technology and Energy of Riga Technical University, 12/1 Āzenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby confirm that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Aigars Sīlis……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, 4 chapters, Conclusions, 18 figures, 3 tables, and 14 appendices; the total number of pages is 143. The Bibliography contains 97 titles.

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INTRODUCTION

BACKGROUND AND RELEVANCE OF THE RESEARCH

In the European Union, efforts are currently underway to develop an energy policy framework aimed at facilitating the shift towards clean energy [1] and bolstering the security and reliability of energy provision. The Clean Energy Package, comprising a comprehensive set of regulations and directives, is poised to bring about significant transformations [3]–[6]within the electricity sector across Europe and the Baltic states. By 2050, the Baltic states have set ambitious targets – to ramp up renewable energy production to 100 % [7]. Further proliferation of RES necessitates increased investments and efforts in ensuring a balance of energy generation and consumption. Intermittent generation and the poorly controllable nature of consumption elevate the problems of **energy storage and limited capacities of power plants and interconnecting power lines** [8]. On the other hand, the **demand** for electricity is also expected to experience rapid changes due to the electrification of several sectors of the economy, such as industry, transport, agriculture, buildings and waste management [9].

This new policy framework enhances legal certainty by enacting the inaugural national energy and climate plans, thereby fostering investments in this pivotal sector. Moreover, it seeks to notably elevate the role of consumers and afford them opportunities to actively engage in the energy transition process. Two fresh targets have been established for the European Union (EU) to achieve by 2030:

1) a binding renewable energy target of at least 32 %; and

2) an energy efficiency target of no less than 32.5 %, with a potential upward revision in 2023.

As for the electricity market, the new policy reaffirms the 2030 interconnection target of 15 % of installed generation capacity, thus extending the 10 % target set for the period leading up to 2020 [10].

To achieve the stated objectives, a series of technical measures must be implemented to safeguard the affordability, stability, and security of electricity systems. Among these measures are:

- Synchronization of the Baltic transmission network with the Continental European energy system by 2025. Baltic transmission system operators will need to ensure the capability to participate in frequency regulation both under normal conditions and in the event of incidents following the disconnection of a large generator or interconnection line failure. Therefore, Baltic TSOs will need to maintain frequency regulation and balancing reserves as stipulated by the Continental European synchronous operation agreement.

- Modernization of transmission and distribution power grids, including the interconnection of tie power lines to accommodate the forecasted sharp growth in electricity demand.
- Installation of energy storage units, including synchronous condensers, hydro pump power plants, and batteries. The necessity of batteries is emphasized in a study commissioned by the Baltic state grid operators Lithuania's "Litgrid," Latvia's "Augstsprieguma tīkls" (AST), and Estonia's "Elering" conducted by Japan's energy company TEPCO Power Grid Inc. The study underscores that the development of battery energy storage systems (BESS) represents the most effective strategy for Lithuania, Latvia, and Estonia to ensure the reliable and resilient operation of their electricity grids, particularly as they strive for complete reliance on renewable energy sources. Specifically, implementing a grid-forming battery system with a capacity of 240 MW would mitigate the challenges posed by the diminishing output of synchronous generators and the increasing integration of wind and solar power generation, thereby enhancing system stability [11].

The outlined measures present a significant challenge for power systems researchers, development planners, and decision-makers, including transmission system operators. There is still a need to create extremely expensive power generating and balancing resources [12], reinforce transmission and distribution grids, transform energy consumption, and develop a sophisticated management and control system based on fully-fledged energy markets, including balancing reserve markets. Promoting consumer response and aggregation is also crucial.

The implementation of the aforementioned plans for energy transformation requires concerted efforts and actions from researchers, engineers, and managers from various economic sectors, as well as multi-billion-dollar investments even in the case of relatively small regions like the Baltic countries. The industry for producing necessary equipment is rapidly developing, prices of solar and wind energy elements are falling [13], information technologies and communication are advancing rapidly, and electrification of transportation is underway. However, many problems remain unsolved or are inadequately addressed. This Thesis identifies one of them, labelling it with two keywords – **continuous balancin**g and **adequacy**. Henrik Nordstrom et al. [12] refer to the issue of **continuous balancing** in a power system as a task **to supply the demanded power at every time instant** [12]. Resource adequacy in the field of electric power is the ability of the electric grid to satisfy the end-user power demand at any time. The adequacy standard should satisfy the chosen reliability index, typically the loss of load expectation of 1 day in 10 years (so-called "1-in-10") [13].

When solving the continuous balancing problem, we will confine ourselves to extremely specific cases:

1. Long-term planning of the energy system structure, where the main challenge is ensuring the balance of accessible power generation and uncontrollable consumption [14].

2. Managing the operation mode of the energy system, where, despite the variability of generation and consumption, frequency is maintained within acceptably narrow limits.

Both mentioned problems will be considered within the conditions and peculiarities of the energy systems of the Baltic region.

HYPOTHESIS, OBJECTIVE AND TASKS OF THE THESIS

Hypothesis

By developing an appropriate power system structure and utilising energy storage technologies, it is possible to provide a cost-effective and energy-efficient energy supply. This can improve system adequacy, stability, and flexibility while also mitigating resource and electricity market price volatility caused by an increase in intermittent renewable generation in the Baltic region.

Objective

The objective of the Thesis is to develop and evaluate a methodology and algorithms to facilitate the selection of technologies, grid management, operation and development plans and control algorithms. The aim is to promote a seamless energy transition for end users, ensuring that electricity remains safe, reliable and affordable.

Tasks

1. An in-depth analysis has been conducted on the goals, tasks, resolution methods, and technologies pertinent to the transformation of the energy systems in the Baltic States, alongside the identification of the most critical research directions.
2. Reserve power estimation in alignment with the Baltic Power System 2050 Development Plan is conducted.
3. An assessment of the risks of generation capacity shortages to cover peak load and deficits in balancing capacity within the next decade has been conducted. An analysis of the implementation of balancing capacity markets and capacity remuneration mechanisms as measures capable of mitigating this risk has also been performed.
4. Considering the substantial integration of renewable energy sources (10 GW) and 2 million electric vehicles, scenarios for achieving self-sufficiency in the Baltic region's energy systems have been thoroughly investigated. The issue of the region's ability to export/import energy and reduce emissions into the atmosphere is being investigated.
5. Based on data from Nordic and Baltic markets, it is demonstrated that contracts linked to dynamic market prices of electricity provide lower prices for end-users.
6. A market-driven strategy has been devised to manage the storage state of charge for energy providers participating in primary frequency regulation. This approach showcases its

capacity to maintain sufficient resilience even in the face of worst-case scenarios, even when the device is concurrently supplying multiple reserve products.

RESEARCH METHODS AND TOOLS

Research results presented in the Doctoral Thesis were performed using adapted software modelling tools and algorithms developed at the Institute of Power Engineering of Riga Technical University.

When modelling the different future scenarios (Chapters 2, 3, and 4), MATLAB and Excel were used to organise the input data by scaling and adjusting it according to the situation assumptions. For power system transient stability simulations, ETAP 12.5 grid simulation software was used (under the license provided by the Riga Technical University).
For modelling power systems, electricity market data sets from NordPool, JSC "Augstsprieguma tīkls, JSC "Latvenergo", and Latvian Environment, Geology and Meteorology Centre were adapted and used.

SCIENTIFIC NOVELTY

An exhaustive analysis has been undertaken on the objectives, tasks, resolution methods, and technologies relevant to the transformation of the energy systems in the Baltic States, coupled with the identification of the most critical research directions. Additionally, a methodology for estimating the capacity of reserve power plants has been developed in connection with the Baltic Power System 2050 Development Plan, considering the influence of Poland, Sweden, and Finland [16].
An evaluation of the risks associated with generation capacity shortages to meet peak load demands and address deficits in balancing capacity over the next decade has been carried out. Additionally, an analysis of the implementation of balancing capacity markets and capacity remuneration mechanisms as measures to mitigate these risks has been conducted.

Furthermore, in light of the significant integration of renewable energy sources (10 GW) and 2 million electric vehicles, comprehensive scenarios for achieving self-sufficiency in the Baltic region's energy systems have been thoroughly explored. Additionally, the region's capability to facilitate energy export/import and reduce emissions into the atmosphere is under investigation.

An assessment of the impact of balancing market conditions and the applicability of battery energy storage systems (BESS) on the operation of the Baltic energy system was conducted. To simulate the operation of BESS, simulation software for the BESS control model was developed, and its operation was simulated under various specified operating modes and scenarios.

Based on data from Nordic and Baltic markets, it is demonstrated that contracts linked to dynamic market prices of electricity provide lower prices for end-users [17].

A market-driven strategy has been devised to manage the storage state of charge for energy providers participating in primary frequency regulation. This approach showcases its capacity to maintain sufficient resilience even in the face of worst-case scenarios, even when the device is concurrently supplying multiple reserve products. Two main markets were examined – Baltic balancing market and Baltic day-ahead market.

PRACTICAL SIGNIFICANCE OF THE RESEARCH

The practical significance of the research studies carried out by the author during the development of the Doctoral Thesis have contributed to several research and innovation projects. Listed below, they include not only national and international scientific projects but also contract work for a major industry stakeholder.

1. Research contract "Development of mathematical models for an economic assessment of demand-side flexibility resources and activation optimization of balancing reserves" (2017–2018), commissioned by JSC "Augstsprieguma tīkls" (the Latvian TSO).
2. Project "Innovative emergency control of RES-dominated low-inertia power systems (INNOVA)" (2024–2026), funded by the Latvian Council of Science.
3. Project "Future-proof development of the Latvian power system in an integrated Europe (FutureProof)" (2018–2021), funded by the Ministry of Economics of the Republic of Latvia within the National Research Programme "Energy".
4. H2020 INTERRFACE project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 824330.

AUTHOR'S CONTRIBUTION

During the development of the Doctoral Thesis, the author participated in several collaborative projects, implying tight cooperation with other expert members of the RTU Institute of Power Engineering. Namely, the Baltic state power system parameter search tool and EV Assess tool were adopted by the author together with researchers K. Baltputnis, Z. Broka, R. and L. Petrichenko under the supervision of Professor A. Sauhats and Professor G. Junghans. The author was involved in all stages of the work, including data extraction, model conceptualisation and definition, case studies, and result analysis.

PARTICIPATION IN SCIENTIFIC CONFERENCES AND PUBLICATIONS IN JOURNALS

The research results included in the Doctoral Thesis were presented and discussed at **5** international scientific **conferences**. Additionally, **8** papers were published in **international journals,**and conference proceedings, and **1** in **Latvian journals**. In addition, a number of publications have been published on local web sites.

1. **Sīlis**, A., Lavrinovičs, V., Junghāns, G., Sauhats, A. *Benefits of Electricity Industry Switching from Fixed to Spot-Linked End-User Prices*. In: 2018 15th International Conference on the European Energy Market (EEM 2018), Poland, Lodz, 27–29 June 2018. Piscataway: IEEE, 2018, pp. 999–1003. ISBN 978-1-5386-1489-1. e-ISBN 978-1-5386-1488-4. e-ISSN 2165-4093. Available from: doi:10.1109/EEM.2018.8469824
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13. **Sīlis, A**., Ertmanis, K. *"Neapliecinātās elektroenerģijas izcelsmes sastāvs*", Enerģija un pasaule, October 2021, pp. 30–33. ISSN 1407-5911.
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16. Baltputnis, K., Broka, Z., **Sīlis, A**., Cingels, G., Junghāns, G. *Efficient Market-Based Storage Management Strategy for FCR Provider with Limited Energy Reservoir*. In: 2023 19th International Conference on the European Energy Market (EEM 2023): Proceedings, Finland, Lappeenranta, 6–8 June 2023. Piscataway: IEEE, 2023, pp. 211-216. ISBN 979-8-3503-2452-5. e-ISBN 979-8-3503-1258-4. ISSN 2165-4077. e-ISSN 2165-4093. Available from: doi:10.1109/EEM58374.2023.10161770

VOLUME AND STRUCTURE OF THE THESIS

This Thesis is written in English. It consists of an introduction, four main chapters, conclusions and a bibliography with 97 references. The Report contains 18 figures and 3 tables. The volume of the Thesis is 143 pages. The appendices encompass the articles relevant to the Thesis research field.

Chapter 1 provides an overview of the current status of the Baltic power system, alongside anticipated future developments concerning the synchronization of the Baltics with the ENTSO-E grid by 2025, and articulates the climate neutrality targets set for 2050. Background information on power system infrastructure, including power lines, primary power plants, inertia, frequency, and synchronous condensers, is examined. The benefits of the electricity industry transitioning from fixed to spot-like end-user prices are highlighted.

Chapter 2 elucidates the role and benefits of regional balancing areas within the context of addressing future challenges to system adequacy resulting from energy transmission. It delves into the significance of these areas in orchestrating balancing markets effectively.

Chapter 3 introduces a comprehensive concept and methodology for forecasting system adequacy from 2030 to 2050. It establishes a structured framework for estimating reserve power, leveraging insights from the Baltic power system's 2050 development plan. The analysis employs both historical and forecasted data, utilizing the Fourier transformation of prices to enhance accuracy and reliability. The estimation of reserve power is firmly grounded in alignment with the objectives outlined in the Baltic power system's 2050 development plan. The in-house RTU power market model is used.

Chapter 4 is devoted to the consideration of scenarios for the development of the energy systems of the Baltic countries. Significant capacities of RES (10 GW) and 2 million electric cars are expected to be commissioned by the 2050 year. The issue of the region's ability to self-sufficiency, export/import of energy, and reduce emissions into the atmosphere is being investigated. The analysis is completed on the basis of modelling the behaviour of the power system of Baltic states, taking into account the connections with Sweden, Finland and Poland. The chapter elucidates the market-based storage management strategy for FCR providers with limited energy reservoirs within the context of addressing future challenges to system adequacy.

1. TRANSFORMATION OF THE ENERGY SECTOR IN THE BALTIC STATES

1.1. BALTIC POWER SYSTEM

The objectives of the Latvian transmission system operator, in accordance with the guidelines of the European Union's common energy policy, are to ensure the stable operation of the electricity transmission system and secure electricity supply to consumers [17]. At the same time, the transmission system operator must promote the functioning of the electricity market [18] and assist the electricity production industry in gradually transitioning to more environmentally friendly electricity generation. The Latvian electricity market is relatively small – from the perspective of electricity consumption [19], Latvia's market size accounts for less than 2 % of the total Scandinavian–Baltic market or approximately 0.25 % of the total European electricity market. Ensuring self-sufficiency in electricity supply and security for Latvia would come at a very high cost. Therefore, integration into the unified European electricity market is critically important for Latvia [20]. Over the past decade, the Baltic transmission system operators have been tirelessly working towards the integration of the Baltic energy system into the European market [21]. The first interconnection between the Baltic and Scandinavian transmission systems was commissioned at the beginning of 2007, with a capacity of 350 MW (Estonia–Finland) [22]. In 2023, four interconnections between the Baltic and European transmission systems have been put into operation [23], with a total installed capacity of 2200 MW, representing approximately 50 % of the maximum Baltic electricity consumption. The construction of interconnections has significantly increased the security of electricity supply in the Baltic region and ensured the integration of the Baltic states into the European electricity market.

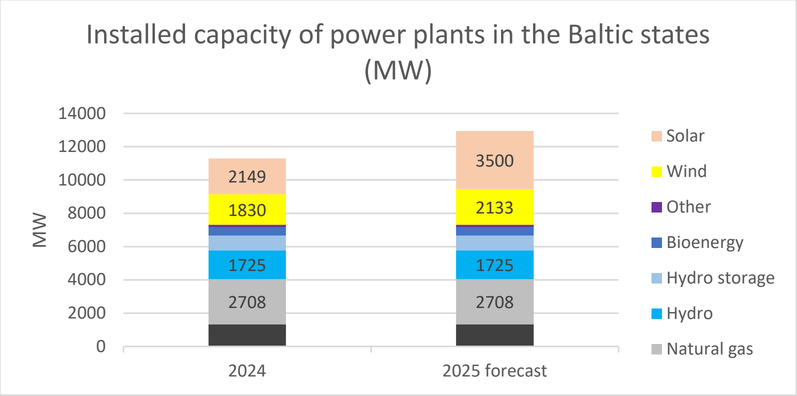

Fig. 1.1. Installed capacity of the power plants in the Baltic states (MW) [24].

In the Baltics, a reduction in production capacity is expected. Currently, the total installed capacity in Baltic power plants (Fig. 1.1) amounts to around 9000 MW [24], which is approximately twice the maximum consumption in the Baltic region.

Among these, about 5000 MW of installed capacity (Fig. 1.2) is in large thermal power plants (mainly using gas and coal as fuel). According to the capacity adequacy assessment conducted by Baltic transmission system operators for the next decade [25], a significant decrease in production capacity is foreseen after 2020, as older gas and coal-fired power plants exit the market.

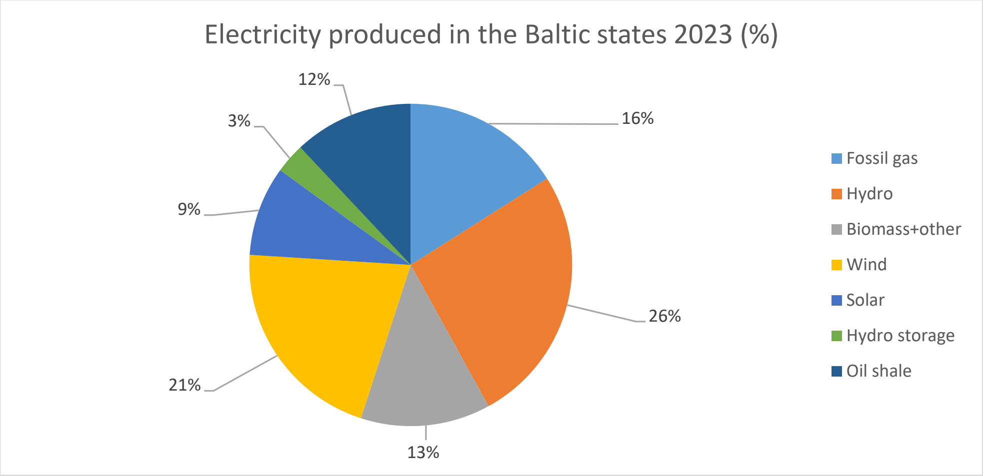

Fig. 1.2. Electricity produced in the Baltic states in 2023 [26].

By 2030, production capacities totalling around 2300 MW could be closed in the Baltics, which is roughly half of the existing capacity of large thermal power plants. As production capacities decrease in the Baltics, the importance of interconnections will increase in ensuring electricity supply. Interconnections will ensure both electricity exchange and the provision of system services (reserves) necessary for the security of supply between countries [27].

The costs of production technologies based on renewable energy sources are rapidly decreasing worldwide [28]. It is expected that in the future, decentralized generation and generation based on renewable energy sources will continue to develop in Europe and the Baltics [29]. Currently, there are already about 5500 units of decentralized generation operating in the Baltics, and further development is expected in the future. The total installed capacity of wind power plants in the Baltics currently exceeds 1871 MW, but solar 2280 MW [24], which is approximately 87 % of the Baltic peak consumption (MW) (Fig. 1.2) [30]. Considering the competitive costs of wind generation compared to other generation types, further development of this generation type is expected in the Baltics. Strengthening and integrating the Baltic transmission network with the European transmission network is a prerequisite for enabling the further connection of large volumes of renewable energy power plants to the Baltic energy system. The transmission system operators of the Nordic and Baltic countries have jointly conducted an analysis of electricity supply adequacy in the region (Fig. 1.3). According to an ENTSO-E report [31], the upcoming winter of 2022,

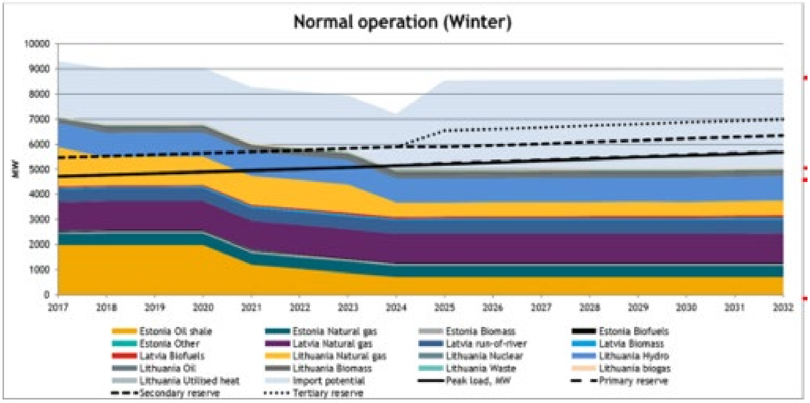

Fig. 1.3. Assessment of production and interconnection capacity adequacy. Source: AST, Elering, Litgrid.

particularly in January and February, is expected to carry a higher risk of energy unavailability and overall lower security reserves compared to previous years. In the event of low water levels in hydroelectric reservoirs, risks of electricity supply adequacy may arise in the southern parts of Sweden and Norway, as well as in the eastern regions of Denmark. If there is a reduction in production capacity at nuclear power plants, risks of energy inadequacy may increase in southern Sweden and Finland – in electricity trading areas that depend on imports.

Alongside the construction of interconnections between the Baltic and European transmission systems, Baltic transmission system operators are strengthening the Baltic transmission network.

In the development plan for Latvia's electricity transmission system, investments totalling EUR 445 million are planned for the period from 2023 to 2032 [32]. For five projects, with estimated investments of EUR 224 million over a 10-year period. Currently, financing has been allocated to three projects – the construction of the third

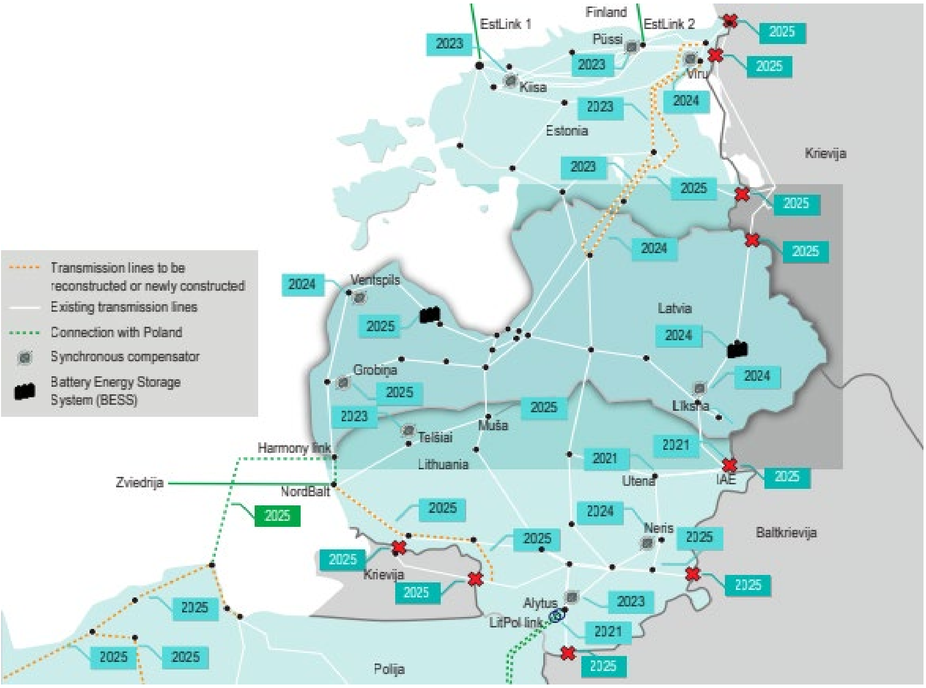

Fig. 1.4. Key development projects of the Baltic 330 kV transmission network.

phase of the "Kurzeme Loop" transmission line and substations (total investment – EUR 128 million), the construction of the third interconnection transmission line between Latvia and Estonia and the expansion of the substation (total investment – EUR 102 million), and the construction of new 330 kV transmission lines connecting Riga TEC-2 with Riga HES (total investment – EUR 20 million) (Fig. 1.4) [27].

1.2. PARTS OF THE EUROPEAN SINGLE ELECTRICITY MARKET

The harmonization of the Baltic electricity market model with the unified European market model [33] continues. Creating a unified regional electricity market requires more than just building interconnections. Different market models can significantly restrict or even block cross-border trading despite the existence of physical interconnections. Therefore, based on the European Commission's electricity network codes, transmission system operators of EU member states are implementing a unified market model in their respective countries with the aim of ensuring that the electricity market in Europe operates effectively as one cohesive market [34].

The European electricity market model consists of four parts:

- **The day-ahead market** is currently the main market where standardized supply transactions for the next day are closed by the purchased and sold volume of electricity per hour. The European Network Code establishes rules for the creation of a coordinated European day-ahead market. Therefore, transmission system operators of EU member states, in collaboration with electricity exchanges, are implementing the multi-regional coupling project, where the main principle is a unified platform and a unified algorithm for determining prices and cross-border flows. This complex project, the largest of its kind in EU practice, is being successfully implemented, and currently, 75 % of the entire European electricity market is integrated through the centralized platform, including Latvia and the rest of the Baltic states.
- **The intraday market** also serves as a physical delivery market, which opens immediately after the closure of the day-ahead market. In this market, participants can enter into delivery transactions up to 1 hour before the real-time hour. With the increasing variability and decentralization of generation, it becomes increasingly challenging for market participants to balance supply and demand in the day-ahead market. Therefore, in the intraday market, participants can make additional transactions to balance supplies. The European Network Code sets out requirements for the establishment of a coordinated European intraday market. Therefore, European transmission system operators, in collaboration with exchanges, are working on the creation of a unified European intraday market platform (the XBID project). The first phase of this extensive project was introduced in the first quarter of 2018, and the first set of EU member states, including the Baltic states, will begin organizing the intraday market through the unified European XBID platform. Over the past few years, the day-ahead and intraday markets underwent significant progress in terms of market integration. Both markets now fully couple all European bidding zones, thereby ensuring that electricity exchanges always occur in the direction that maximises social welfare. To do so, capacity is implicitly allocated to the electricity trades that create the most welfare to the coupled European bidding zones. Since all bidding zones are now part of a single coupled market in the day-ahead and intraday timeframe [21].
- **The balancing market** is a crucial tool for transmission system operators to fulfil one of their most important functions – ensuring continuous balance of electricity in the system, where rapidly increasing variable and distributed generation exists. In the balancing market, market participants sell manually activatable **frequency regulation reserves to the transmission system operators in real-tim**e (for example, increasing or decreasing power generation at power plants upon the request of the system operator). With the aim of introducing a unified European balancing market based on a unified European balancing market platform, currently, more than 20 European transmission system operators, including those from all Baltic states, are working on the unified balancing market platform project (the MARI project). The Electricity Balancing Regulation, which entered into force

in 2017, lays down detailed rules on electricity balancing. It facilitates the procurement, activation, and exchange of balancing energy. It further allows TSOs to voluntarily engage in cooperations where they harmonise the procurement and exchange of balancing capacity and the sharing of reserves, including the allocation of cross-zonal capacity. Finally, it strives to implement an integrated balancing market, where TSOs will procure, exchange, and use both balancing energy and capacity in an economically efficient and market-based manner[35]. The main achievements accomplished in 2022 in the balancing timeframe undoubtedly relate to the go-live of two European balancing platforms, the automatic frequency restoration reserve (aFRR) platform and the manual frequency restoration reserve (mFRR) platforms (respectively in the context of the projects named PICASSO and MARI) [21].

- **The capacity market** serves to guarantee that a sufficient reliable volume of energy is accessible by providing payments to encourage investment in new capacity or for the existing power plant to remain in use. In addition to the European platforms for the exchange of balancing energy, there are three cooperations which allow for the exchange of balancing capacity.
    - Nordic aFRR market: Pursuant to Article 41 of the Electricity Balancing Regulation, the Nordic TSOs submitted to the Nordic NRAs a methodology for a market-based allocation process of cross-zonal capacity for the exchange of balancing capacity or sharing of reserves. This methodology was referred to ACER, which approved it in August 2020. Following ACER's Decision, the Nordic TSOs implemented the Nordic aFRR capacity market, which began its operation on 7 December 2022. Taking stock of this successful implementation project, a common Nordic capacity market also for mFRR is expected to follow in the coming years for mFRR as well [21], [36].

1.3. STRATEGIES FOR POWER SYSTEM FREQUENCY REGULATION

Power systems are planned to operate at a specific nominal frequency, typically 50 Hz or 60 Hz, depending on the region. Variations in power demand, changes in generation capacity, and unforeseen events such as equipment failures can cause deviations in system frequency. Frequency control and regulation refer to the instruments and techniques engaged in maintaining the frequency of a power system within acceptable, strongly restricted bounds. In an interconnected power grid, the frequency of the alternating current (AC) waveform must be regulated closely to ensure the stable operation of electrical devices and equipment. Frequency control and regulation encompass a spectrum of actions that can be categorized into two primary groups: emergency control and regulation.

1. **Emergency control**: Emergency control measures are implemented to restore the grid's frequency to its nominal value during unplanned, sudden and severe frequency deviations.

These measures are crucial to prevent cascading failures and blackouts. Emergency control actions may include actions to balance energy supply with demand:

- load shedding;
- generator tripping;
- leveraging stored energy resources, such as battery energy storage systems (BESS), to either inject or withdraw additional power from the grid as needed.

2. **Frequency regulation**: FR refers to the continuous adjustment of power generation or demand to maintain system frequency within acceptable limits **under normal operating conditions.** FR systems continuously monitor grid frequency and correct generator outputs in real time to keep the frequency within a specified range. FR systems use feedback control loops to maintain the balance between generation and consumption, making rapid adjustments based on frequency deviations. Power systems frequency control and regulation become more complex in interconnected grids where multiple utility companies and generation sources are involved. Interconnected grids require precise synchronization of frequency and phase between different regions to maintain system stability.

Overall, frequency emergency control and regulation ensure grid stability, reliability, and resilience against disturbances and emergencies, and play a crucial role in performing these tasks successfully. Frequency regulation encompasses three distinct groups of measures: primary, secondary, and tertiary regulations.

1. **Primary frequency regulation:** Primary frequency regulation is the immediate response of power generation sources to changes in load demand or generation capacity. Automatic generation control (AGC) systems continuously monitor system frequency and adjust generator output accordingly to restore frequency deviations within seconds or minutes. Generators with fast response times, such as gas turbines and hydroelectric plants, often provide primary frequency regulation.
2. **Secondary frequency regulation**: Secondary frequency regulation supplements primary frequency control by providing additional fine-tuning of generation output to maintain system frequency within tighter tolerances. This is typically achieved through automatic generation control algorithms and coordinated actions among multiple generators and control devices.
3. **Tertiary frequency regulation:** Tertiary frequency regulation refers to the fine-tuning adjustments made to power generation or consumption in response to longer-term fluctuations in grid frequency. Unlike primary and secondary frequency regulation, which address immediate and short-term frequency deviations, tertiary regulation handles more gradual changes over extended periods (in the Baltic states – 1 h). Tertiary frequency regulation operates on a longer time scale compared to primary and secondary regulation. While primary and secondary regulation respond to frequency deviations within seconds

or minutes, tertiary regulation may involve adjustments over minutes to hours. Tertiary frequency regulation resources typically include slower-responding assets, such as reserve power generation capacity, demand response programs, energy storage systems (such as batteries or pumped hydro storage), and interconnection with neighboring power systems or grid regions.

In implementing the listed frequency regulation measures, two types of reserves are maintained: **containment reserves and restoration reserves**.

Frequency containment reserve (FCR):

- Frequency containment reserve denotes a reserve capacity that can be rapidly activated to neutralize deviations in system frequency.
- FCR is part of the primary frequency regulation mechanism.
- FCR is provided by generators and other resources that are capable of quickly adjusting their output in response to frequency deviations. These resources are typically equipped with automatic frequency control systems.

Frequency restoration reserve (FRR):

- FRR is a reserve capacity that is activated in the event of significant disturbances or contingencies that cause severe frequency deviations.
- FRR is part of the secondary frequency regulation mechanism.
- FRR resources are typically slower-responding compared to FCR resources, but provide larger reserves and can sustain their output for longer durations.
- FRR resources may include additional generation capacity, energy storage systems, or demand response programs that can be activated to restore system frequency.

In summary, frequency containment reserve (FCR) and frequency restoration reserve (FRR) are two types of reserve capacity within a power system that are activated to regulate system frequency and maintain stability in response to changes in power demand or supply and unexpected disturbances or contingencies. FCR provides rapid response to small frequency deviations, while FRR provides additional reserve capacity to address larger disturbances and restore system frequency to its nominal value [38]–[43].

1.4. TREND OF CHANGE

In the future, the risk of insufficient electricity supply capacity will increase. The national energy and climate plans [44] developed by the Baltic states for the period up to 2030 envisage a significant increase in the share of renewable energy resources in final consumption [47]. Therefore, in the next decade, there is expected to be a notable development of wind, solar [47], and distributed generation in the Baltic electricity system [51], leading to an increased need for balancing capacity. The planned synchronization of the Baltic energy system with the continental European power system in 2025 will also **increase the need for frequency and balancing reserves** [51]. At the same time, as non-competitive thermal power plants are phased out, centralized and controllable capacities in the Baltics will decrease. With this trend continuing, the risk of insufficient electricity supply capacity will increase in the future. Therefore, it is important to be aware of activities that help [58]–[66] mitigate this risk and to take timely action. Renewable energy resources are replacing fossil fuels.

In recent years, there have not been rapid changes in the structure of Baltic electricity production [26], but there is a clear persistent trend towards increasing production from renewable energy resources [45] and decreasing production from fossil fuels. Electricity consumption has been stable with a slight upward trend in recent years. Over the past five years, consumption in Estonia has increased by 7 %, while in Latvia, it has increased by 2 %. Data published by Lithuania [47] shows a 26 % increase in consumption over the past five years, but most of the reported consumption growth since 2017 is due to changes in consumption accounting methodology, including consumption from the Kruonis Hydroelectric Power Plant in pump mode. In recent years, around 80 % of consumed electricity in the Baltic region has been generated locally, with approximately 60 % derived from fossil fuels (mainly coal and natural gas) and 40 % from renewable energy resources (mainly hydro and wind energy). In 2017 and 2018, electricity generation from renewable energy resources reached historically high levels, exceeding 10 TWh and 8 TWh, respectively.

The largest CO_2 emitters will be phased out of the market. Estonia's coal-fired power plants have played a significant role in the Baltic energy system. In recent years, coal-fired power plants have produced around 9–10 TWh of electricity annually, accounting for approximately half of the total generation in the Baltic region. It is important to note that since coal is sourced domestically in Estonia, these power plants have ensured electricity production independent of external resource suppliers.

However, coal combustion generates a considerable amount of emissions, especially CO_2 emissions. Thus the profitability of these power plants is particularly affected by changes in the price of CO_2 emission quotas in the European market. In recent years, the stable production volumes of coal-fired power plants have been consistently supported by low and stable prices of CO_2 emission quotas (Fig. 1.5). However, as of the beginning of 2019, the price of CO_2 emission quotas exceeded 20 EUR per tonne, reaching as high as 29 EUR per tonne in July alone. As a result, electricity generation from coal-fired power plants significantly decreased.

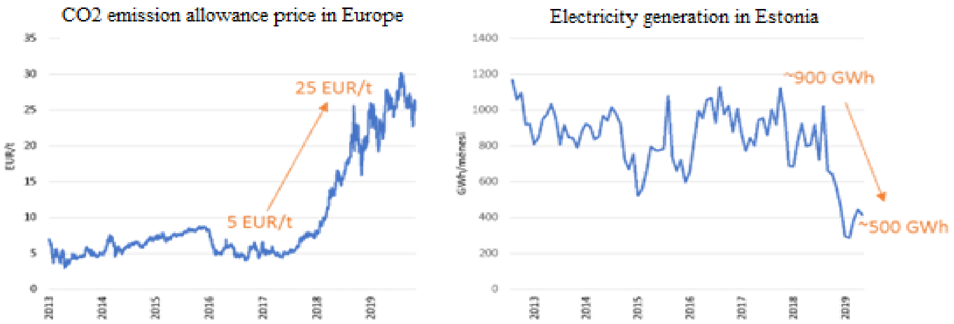

Fig. 1.5. CO_2 emission allowance price in Europe (EUR/t) and electricity generation in Estonia. Source: Nord Pool.

In July 2019, the Estonian national energy company Eesti Energia announced that, for the first time in the company's history, there was no electricity production in coal-fired power plants during an 8-hour period on June 28. In January 2019, electricity generation at Narva power plants reached 1900 MW during peak consumption hours, while in June, generation fluctuated within a range of 50–200 MW.

In the first ten months of 2019, Estonia produced 517 GWh of electricity, which is 41 % less than in the same period in 2018. Overall in the Baltic region, electricity generation decreased by 22 % during the same period.

In the region, **centralized,** regulated production **capacity is decreasing**. Over the past five years, the total installed capacity of power plants in the Baltic region has been relatively stable and currently exceeds 9000 MW, which is approximately twice the peak maximum consumption in the Baltics. Over the last five years, the installed capacity of gas-fired power plants has decreased by 25 % (about 1000 MW), primarily due to the closure of older gas-fired power plant units in Lithuania. Meanwhile, the significant increase in production capacity has been facilitated by the commissioning of new wind and biomass power plants (with a total capacity of approximately 600 MW), as well as the commissioning of the new 300 MW Auvere coal-fired power plant in Estonia in 2015.

It is expected that in the coming years, the capacity of large centralized base power plants in the Baltics will continue to decrease, mainly due to the reduction in production from non-competitive older thermal power plant units in Estonia and Lithuania. At the same time, largely due to the development of wind farms, it is anticipated that the total installed production capacity in the Baltic region will increase. Considering the National Energy and Climate Plans published by the Baltic States, which outline the countries' intentions regarding the development of renewable energy production by 2030, it can be concluded that by 2030, the amount of electricity generated from renewable energy sources in the Baltics could reach at least 13 TWh per year, which is 5 TWh per year more than in 2018 and corresponds to at least 40 % of electricity consumption in the Baltics [52]–[56]. Moreover, it is expected that wind farms will provide the majority of the new production capacity.

In the coming years**, the risk of insufficient electricity supply capacity will increase**. The Baltic transmission system operators regularly assess the security of the Baltic region's electricity systems and the adequacy of capacity in the region. The TSOs prepare scenarios for the development of generation capacity, which provide an idea of how the balance between generation capacity and demand will change in the coming years, as well as the risks to energy supply security. According to the TSO's assessment, it will be technically feasible to cover maximum loads in the Baltic region with local generation capacity (without support from electricity supply via interconnections from neighboring energy systems) until 2020. After 2020, the adequacy of the Baltic States' electricity supply capacity will depend on imports via interconnections from neighboring electricity systems. The reserve capacity available for peak load coverage will significantly decrease after 2025 when the Baltic transmission system disconnects from the integrated Russian energy system and begins synchronous operation with the Continental European electricity system. However, after 2030, the generation and import capacity of the Baltic energy systems will no longer be sufficient to cover peak loads and ensure an adequate level of security in the Baltic States' electricity systems under normal conditions, with the capacity deficit reaching up to 360 MW. The generation capacity development scenarios created by the TSOs indicate the need for new electricity and balancing resource development in the Baltic region to ensure the security and quality of electricity supply.

New balancing capacities are needed. The demand for balancing capacities in the energy system is expected to increase. Approximately 12–15 years ago, when the electricity market was introduced, transmission system operators faced the first increase in volatility. Interregional electricity trading flows became more unpredictable. The direction of flows was no longer influenced by transmission system operators but rather moved from regions with lower prices to regions with higher prices, as with any commodity where price is determined based on market principles. Six to eight years ago, when the rapid development of wind and solar power plants began, transmission system operators encountered a second increase in volatility. For several years now, similar to elsewhere in Europe, wind and solar power plants have dominated the newly commissioned generation capacity in the Baltics. Currently, energy system management is rapidly changing. There is an increase in the volatility of flows and energy balances in the energy system, making it more difficult to forecast the system's condition. Therefore, there is a growing need for additional balancing capacities to be used in energy system management.

Furthermore, it should be noted that, currently, the Baltic electricity transmission system is integrated into the unified energy system BRELL, where the grid frequency is centrally regulated in Russia. Due to the planned switch of the Baltic transmission grid to synchronous operation with the continental European energy system, by 2025, Baltic transmission system operators will need to ensure the ability to participate in frequency regulation both under normal conditions and in the event of an incident following the disconnection of a large generator or interconnector line. Therefore, Baltic TSOs will need to maintain frequency regulation and balancing reserves as required by the synchronous operation agreement of continental Europe. Table 1.1 shows indicative volumes of the necessary reserves [54]. This poses a significant challenge for transmission system operators, as there is still a need to develop a fully-fledged balancing reserve market in the Baltics and create the necessary balancing resources.

Table 1.1

Indicative volumes of necessary reserves for Baltic TSOs after synchronization with the Continental European power system in 2025 (MW)

Type of reserve products	Baltic
FCR	30
aFRR up	100
aFRR down	100
mFRR up	600
mFRR down	600

FCR – frequency containment reserve (must be able to start within a few seconds after an incident and activate 100 % of reserve capacity within 30 seconds).

aFRR – automated frequency restoration reserve (managed with centralized, automatic generation control; activated to full capacity within a few minutes after a system incident).

mFRR – manual frequency restoration reserve (activated manually, brought to full capacity within a few minutes)

1.5. WHAT TO DO?

Directions to promote adequacy of power supply and development of balancing capacity:

1. Promote generation development. Various promotion instruments are available, but primarily it is necessary to start by reducing existing barriers and avoiding the creation of new ones (including bureaucratic obstacles, permit acquisition, producer fees, etc.).
2. Invest in grid development. Grid development is necessary for connecting large-scale renewable energy generation and balancing the energy system. For example, this year, JSC "Augstsprieguma tīkls" commissioned the final section of the Kurzeme 330 kV

transmission line. Now, the transmission network in the western part of Latvia is capable of accommodating up to 800 MW of wind power.

3. Promote consumer response and aggregation. Currently, the potential for consumer response in Latvia and the Baltic region is not utilized for balancing the energy system. To achieve this, the first necessary step is to establish the necessary regulations for independent aggregators to enter the market, which is a prerequisite for the development of consumer response and aggregation. This would enable aggregator competition equivalent to producers, make the energy system more flexible and secure with lower investments in power plants, and simultaneously promote the development of new market products.
4. Develop the balancing market. Especially after the planned synchronization of the Baltic energy system with the Continental European grid in 2025, Latvia's transmission system operator will require additional and new types of balancing reserves. Therefore, it is necessary to continue to undertake the necessary activities to develop a balancing reserve market in Latvia, which involves integration into the broader European balancing market, serving as a commercial environment for the development and trading of balancing resources. It is crucial to ensure that the Baltic states, including Latvia, can join the MARI energy market platform by the end of 2024, followed by the PICASSO energy market platform in early 2025. This year will be significant not only because the Baltic states will be synchronized with Continental Europe but also because the balancing market model will change significantly as market participants gain access to the Baltic Balancing Reserve Capacity Auction. Given the activities that need to be carried out, they cannot be performed in isolation from the electricity market. The electricity market also requires changes to its market design, specifically the introduction of a 15-minute trading interval from the day-ahead market to the balancing market.

2. BALTIC POWER SYSTEM'S ADEQUACY FORECASTING

2.1. METHODOLOGY OF MODELLING

A list of mathematical models is needed as a modelling platform for a comprehensive assessment of the energy balance of the Baltic power system (BPS). The flowchart in Fig. 2 reflects the structure of the required models for analysing the BPS's energy balance.

As can be seen from Fig. 2.1, two different methods are applied for the BPS's operating mode forecast:

- assessment of recorded time-series impact on the BPS operating mode (historical data);
- the scenario approach: the primary objective is to forecast the BPS's power consumption, power generation, etc.

The scenario generator block, depicted in Fig. 2.1, operates with a relatively large amount of data for BPS modelling: power generation (P GEN) and consumption (P CON) in BPS, electricity market prices (Price EL) in neighbouring countries that have interconnections through transmission lines with BPS, etc.

The final step of BPS modelling provides an opportunity with an hourly discretisation step to analyse the power disbalance of the BPS, its energy import/export and energy prices.

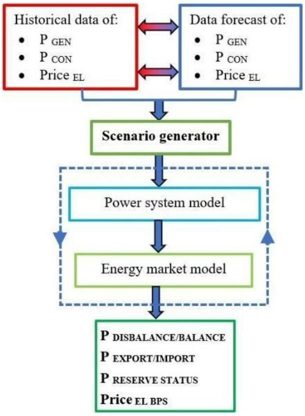

Fig. 2.1. The structure of the modelling platform.

2.2. MODEL OF THE BALTIC POWER SYSTEM

The Baltic power system's (BPS) (Fig. 2.2) model includes separate comprehensive mathematical models (submodels) correspondingly to the existing and foreseeable energy sources: pumped storage hydropower plants [60], [59]; hydropower plants (HPPs) [59], [61]; small hydropower plants (sHPPs); solar power plants (SPPs); wind power plants (WPPs); electric vehicles (EVs); power reserve (PR (cogeneration power plants and thermal power plants)) [62]–[64]; bioenergy power plants (BPPs); BPS's electricity demand and interconnections between the Baltic power system and Finland, Sweden and Poland [66].

Furthermore, each submodel considers a wide range of specific features: technic-economic limitations as well as environmental constraints. BPS's internal distribution network (330 kV) represents a simplified mathematical model excluding power losses and limitations of transmission line capacities.

The considered BPS's mathematical model encompasses the interconnection potentials of Finland (Estonia–Finland), Sweden (Lithuania–Sweden), and Poland (Lithuania–Poland). Environmental conditions have an impact on the transmission line features [66]. However, the Thesis assumes corresponding capacities of transmission lines: 1 016 MW (Estonia–Finland), 700 MW (Lithuania–Sweden), and 1 700 MW (Lithuania–Poland). In that way, the mathematical model of the BPS provides an opportunity for analysing the energy balance of the Baltic power system.

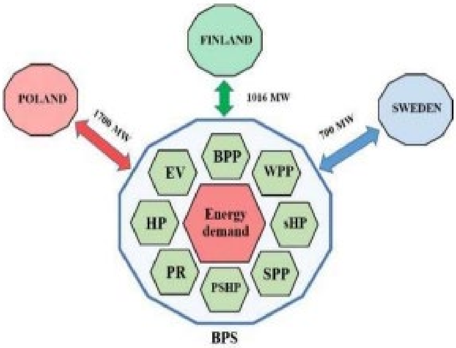

Fig. 2.2. The structure of the modelled BPS.

2.3. ENERGY MARKET MODEL

Another speculation of the Thesis is that the plants' shareholders strive to increase their profitability and are forced to follow the technical and legal constraints established by the laws of the NordPool [68] day-ahead electricity market, the government, and the networks. The final two steps of the modelling structure work together to achieve optimal power flows. The objective is to maximise the benefits of energy export while minimising expenses related to energy import and local power reserves.

Table 2.1 provides data on forecast total power consumption and power generation by source for Scenario 1 (BPS 2030), Scenario 2 (BPS 2050), and Scenario 3 (BPS 2050).

Table 2.2 presents the maximum values of the predicted power consumption and power generation by source for the BPS modelling scenarios under consideration [70]. The forecast Baltic power system consumption (BPSC) in 2030 is 37.86 TWh. The forecast BPS consumption in 2050 is 41.80 TWh [74]–[79].

Taking into account the development plans of the Baltic countries regarding the integration of EVs, the following assumptions are considered in the Thesis:

- The total number of EVs for 2030 and 2050 is EUR 1 million and 3 million, respectively.
- The average daily mileage is 15 km/day. The average energy consumption equals 0.3 kWh/km.
- The energy storage capacity of EV batteries is 90 kWh.

Also, all the cars will be charged evenly overnight, from 11 p.m. to 7 a.m. (for 8 hours) when the predicted market price will be lower than during business hours. An increasing trend in the installed capacities of renewable energy sources (RES) can be observed in the second part of

Table 2.1, in columns SPP and WPP, respectively. It has to be noted that in Scenarios 2 and 3, the RES installed capacity differs twofold. Assessment of the impact of renewable energy sources on the BPS's energy balance is a major reason for the difference in the above parameters. The capacity of the local power reserve is supported by conventional power plants that emit greenhouse gases into the atmosphere. The power reserve (PR) value summarises the capacities of thermal power plants (TPPs) located in Estonia and fuelled by oil shale. Also, the PR includes existing and planned CHPPs in Latvia and Lithuania. In the long-term perspective, the capacity of fossil energy production is planned to be limited. For example, in the long term, the Estonian National Energy Sector Development Plan implies a reduction in CO_2 emissions by reducing oil shale TPPs [67].

The last column in Table 2.2, titled "PR", reflects a trend of conventional power plant capacity reduction. Thus, the hourly available PR capacity in 2030 is equal to 4 300 MWh (Scenario 1). Due to the policies of reducing CO_2 emissions into the atmosphere, it is planned to reduce the reserve power hourly capacity to 1 500 MWh (Scenarios 2 and 3). Capacity reduction of conventional power plants is a questionable development plan for the energy sector, and more in-depth consideration and argumentation are required.

Table 2.1

Power consumption and power generation data for modelling Scenarios 1, 2, and 3

	BPSC TWh	SPP TWh	WPP TWh	HP TWh	sHP TWh	BPP TWh	PSHP TWh
1	37.86	1.74	11.66	1.9	0.34	3.52	2.85
2	41.8	2.19	17.64	1.9	0.34	3.52	2.85
3	41.8	4.52	34.57	1.9	0.34	3.52	2.85

Table 2.2

Maximal power consumption and maximal power generation data for modelling Scenarios 1, 2, and 3

	BPSC MW	SPP MW	WPP MW	HP MW	sHP MW	BPP MW	PSHP MW	PR MW
1	6 026	1 489	3 907	1 562	165	522	1 625	4 300
2	7 233	1 876	5 913	1 562	165	522	1 625	1 500
3	7 233	3 872	11 586	1 562	165	522	1 625	1 500

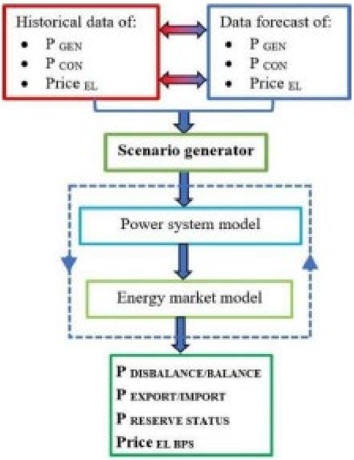

Fig. 2.3. Applied simplified structure of the energy market model.

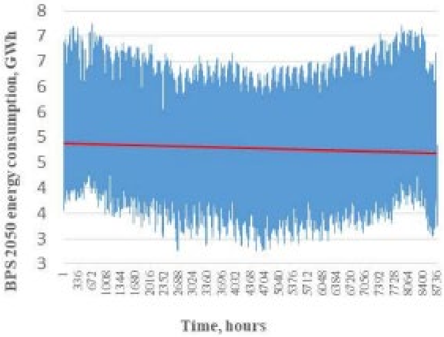

Fig. 2.4. BPS's hourly modelled energy consumption in 2050.

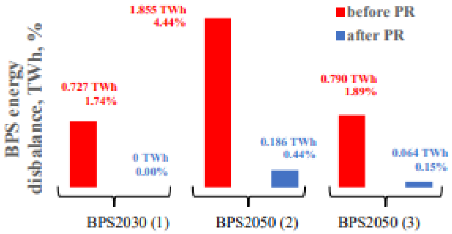

Fig. 2.5. The impact of the power reserve on the BPS's energy balance.

The capacity of the local power reserve is supported by conventional power plants that emit greenhouse gases into the atmosphere. The power reserve (PR) value summarises the capacities of thermal power plants (TPP) located in Estonia and fuelled by oil shale. Also, the PR includes existing and planned CHPPs in Latvia and Lithuania.

2.4. ESTIMATION OF MINIMUM POWER RESERVE MAINTENANCE

The value of the power reserve needed to terminate the BPS's energy deficit can vary in a sufficiently wide range. Thus, the maximum capacity of power reserve needed to compensate energy deficit in BPS 2030 equals 1 740 MWh (Fig. 2.6). At the same time, frequency analysis of required PR activation for BPS 2030 energy deficit compensation shows that the above maximum value was applied only once during a whole year. However, to ensure the BPS 2030 energy balance, it is vital to maintain the required amount of power reserve. According to the results in Table 2.1, the power reserve capacity in 2030 will be 4 300 MWh. It can be noted that the maintained PR value covers the energy deficit in BPS 2030. The histogram in Fig. 2.7 shows an opposite result. Here, the maximum capacity of energy deficit in 2050 is 2 890 MWh. As listed in Table 2.1, the planned power reserve capacity in 2050 is 1 500 MW. As a consequence of short-sighted energy sector development policies, the planned PR capacity cannot compensate the energy deficit. As a result, the maximum hourly energy deficit in BPS 2050 remains equal to 1 390 MWh. It is expected that a significant number of RES will help in energy balancing. Fig. 2.8 shows a bar diagram of required capacities to balance the BPS 2050 energy deficit in Scenario 3. In contrast to the previous case in Scenario 2, where the maximum hourly energy deficit capacity was 2 890 MWh, the result of the twofold increase in the RES installed capacity led to a maximum hourly energy deficit of 2 756 MWh. As in the previous case, the planned amount of power reserve cannot cover the energy deficit and BPS 2050 continues to be unbalanced.

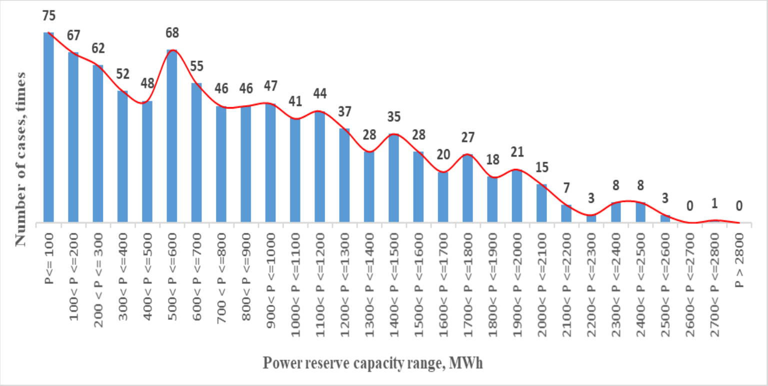

Fig. 2.6. Histogram of energy deficit in BTS 2030 (Scenario 1) after electricity import/export procedures.

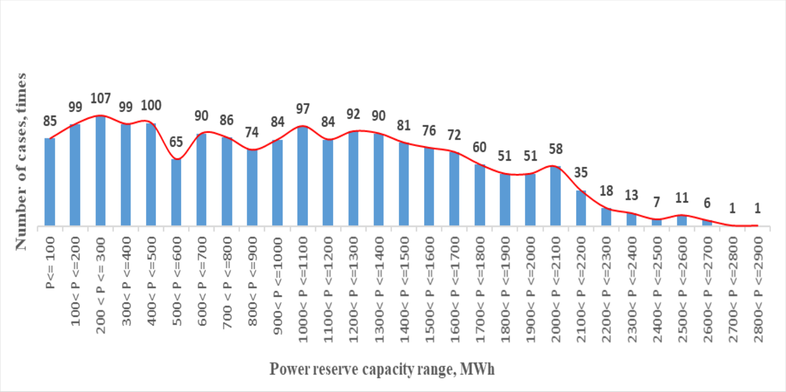

Fig. 2.7. Histogram of energy deficit in BTS 2030 (Scenario 2) after electricity import/export procedures.

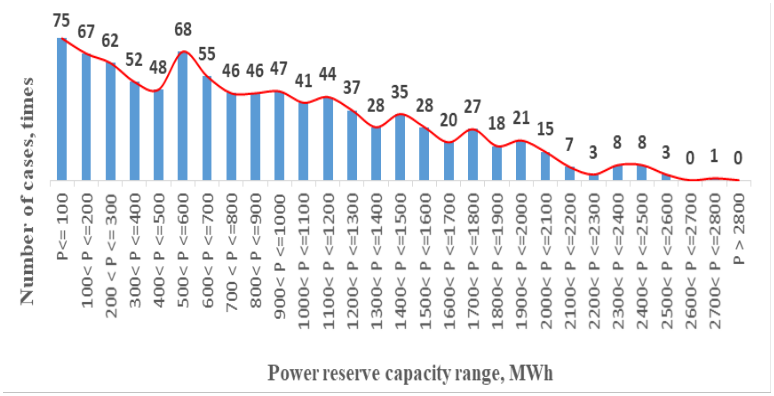

Fig. 2.8. Histogram of energy deficit in BTS 2030 (Scenario 3) after electricity import/export procedures.

2.5. MODELLING THE ENERGY DEMAND OF EVs

This subchapter is devoted to the transport electrification problem.

When modelling the consumption of EVs [70]–[72], assumptions are the following:

- The total number of EVs in the Baltic States is 2 million. We assume that by 2050, all cars in the region will be electric.
- The average daily mileage is known (we take 15 km/day). The average energy consumption is also known (0.3 kWh/km).
- The energy storage capacity of EV batteries is 90 kWh, and all cars will be loaded evenly overnight, from 11 p.m. to 7 a.m. (for 8 hours).
- At night and in 2050, the price of energy will be lower than during business hours. Fig. 2.9 reflects the Baltic energy consumption in 2050.

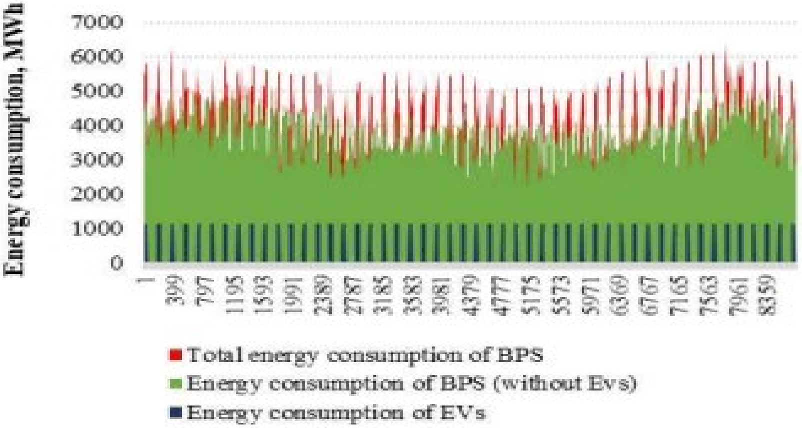

Fig. 2.9. Modelled energy consumption for BPS 2050

It can be seen from Fig. 2.9 that EVs consume about 10 % of the energy consumed in the Baltics. This is a significant quantity that affects the operation of the power system.

2.6. CASE STUDY AND RESULTS

To demonstrate the impact of the electrification of transport on the self-sufficiency of the Baltic energy system and the need to exchange energy with neighbouring countries, we will consider two main cases:

Case 1 – the power system operates without EVs.

Case 2 – to the conditions of the model according to the first point, we add the energy of the car battery charge.

Case 1.

Figure 2.10 demonstrates the imbalance of energy production/consumption of the BPS in the situation when the reserve stations using natural gas are not used.

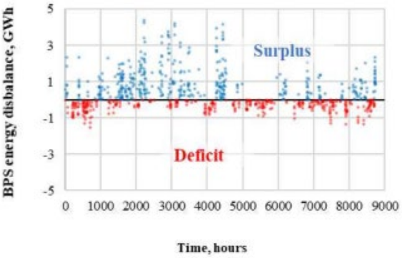

Fig. 2.10. Energy imbalance of BPS 2050 after energy import/export procedures (reserve stations are not used).

The graph shows the presence of time intervals when the energy balance is not ensured. The increase in imports is impossible due to the limited capacity of the lines. At the same time, there are periods of time when excess energy is generated. Surplus energy can be eliminated by turning off generators. However, the energy deficit is 0.13 TWh. The hourly frequency of energy deficit is 4.36 %. Consequently, we see the need to use reserve power station capacities. Figure 2.11 demonstrates the imbalance of energy production/consumption of the BPS in the event that reserve stations are used.

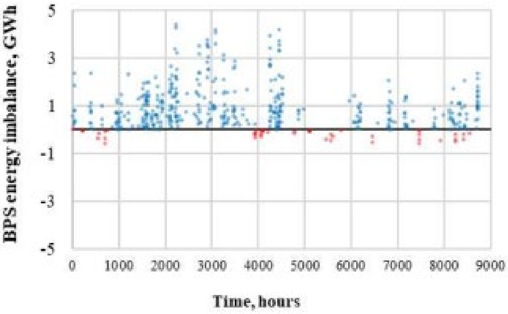

Fig. 2.11. Energy imbalance in 2050 after energy import/export procedures (reserve stations are used).

Analysing the results of Fig. 2.11, it can be concluded that the use of reserve stations reduces the energy deficit to the level of 0.009 TWh, which is 0.03 % of the energy consumption. The frequency of occurrence of the energy deficit also decreased to the level of 0.52 %. The shortage of the named insignificant volume of energy could be eliminated, for example, by organizational measures (increase in tariffs or bonuses for reducing consumption. However, as will be shown below, electrification of cars will dramatically worsen the situation.

Fig. 2.12. presents the imbalance of energy production/ consumption of the BPS corresponding to the use of EVs. Fig. 2.12.BPS 2050 energy imbalance after energy export procedure (reserve stations are not used, 2 mil. EVs are used) The graph shows the situation corresponding to the power supply of two million EVs. Analysing this graph, it can be stated that the frequency of power deficit occurrence equals 65.57 % during 2050 (when in Case 1, it is equal to 61.66 %). The graph allows us to draw a conclusion about the inability of the power system of the structure under consideration to meet the demand for energy (without reserve plants).

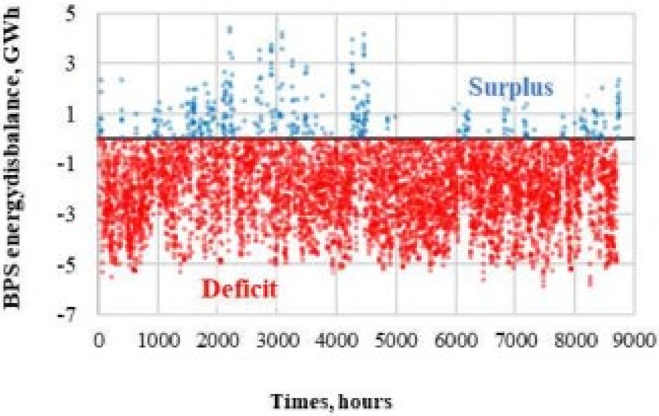

Fig. 2.12. BPS 2050 energy imbalance after energy export procedure (reserve stations are not used, 2 mil. EVs are used).

Either additional electricity generators or additional stations capable of storing energy are required, or stronger ties with neighbouring countries. Energy import in BPS 2050 practically reduces the energy deficit by up to 12.19 % (Fig. 2.13). However, this value of the deficit is not acceptable either.

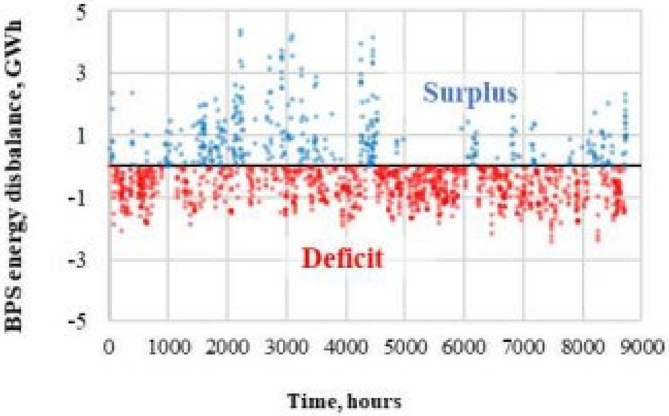

Fig. 2.13. Energy imbalance of BPS 2050 after energy import/export procedures (reserve stations are not used, 2 mil. EVs are used).

Figure 2.14 presents the electricity imbalance of BPS 2050 when the reserve energy power plants are used.

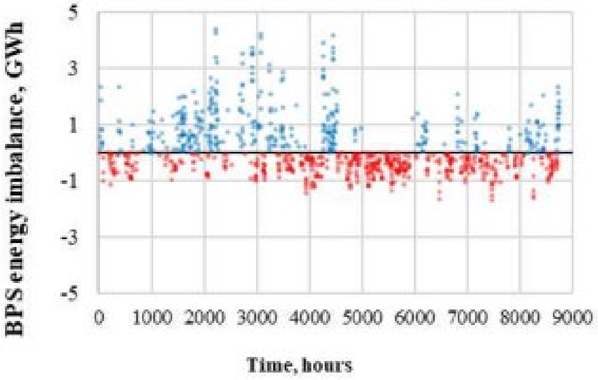

Fig. 2.14. Energy imbalance of BPS 2050 after energy import/export procedures (reserve stations are used, 2 mil. EVs are used).

The energy reserve activation led to the electricity deficit appearing frequency diminishing to 6.08 %, which is much higher than in Case 1. When comparing the energy imbalance in the BPS between Case 1 and Case 2, a significant issue of energy deficit becomes apparent.

2.7. CONCLUSIONS

To achieve the above-set goal and to stop climate change, the global and European energy development plans propose applying several strategies, at least two of which significantly affect the structure of energy systems: Strategy 1 – a precipitous increase in the capacity of power plants operating on renewable energy sources; Strategy 2 – reducing the capacity, suspending or shutting down power plants that use fossil fuels. It is a well-known fact that the production of electricity from RES is an unpredictable and volatile process. As a result, there is a problem related to manageable energy production and ensuring the power balance of any energy system. Sometimes, to entirely compensate for the power deficit by energy import from neighbouring countries is an impossible issue due to the limited capacity of transmission lines. Thus, the last opportunity to mitigate the energy deficit is to activate the local power reserve. The BPS 2030 energy development plan provides for a reserve capacity of 4 300 MW. As a result, the energy deficit of BPS 2030 is completely covered and the energy balance is maintained. The above strategies (Strategies 1 and 2) of the energy development plan are implemented in BPS 2050 (Scenario 2). Hence, the simulation results of BPS 2050 (Scenario 2) argue that attempts to ensure energy balance by power import and to compensate for the energy deficit by increasing the installed capacity of RES do not lead to success. At the same time, the reduced capacity of reserved power plants does not allow getting rid of the power deficit. A nearly twofold increase in the installed capacity of wind and solar power sources is considered in BPS 2050 (Scenario 3). However, the above-described power generation potential is not a panacea and the BPS 2050 system remains in energy deficit.

The electrification of cars will significantly worsen the Baltic power system's capacity balancing situation. To meet the demand for electricity, it will be necessary to build additional stations that can generate energy in the absence of sun and wind or create new transborder transmission lines and long-term energy storage capacities.

The results prove that the adequacy of BPS needs a more detailed assessment and analysis. The developed mathematical model allows determining the minimal value of power reserve needed to be maintained for ensuring energy balance to the BPS. Only a rational, reasonable and timely selection of the operation mode of the BPS's power plants, as well as a carefully thought-out development strategy is the only way to form a sustainable and balanced energy system of the future.

3. BENEFITS OF REGIONAL BALANCING AREAS

3.1. INTRODUCTION

This chapter provides an analysis of the operation of the common balancing area based on a case study of the Baltic common balancing energy market model, which was launched on the 1st of January 2018. The manual frequency restoration reserve (mFRR) helps to stabilize the frequency of the electricity grid**.** In most countries, the **TSO (Transmission System Operator)** is in control of its finding and activation. The mFRR (also tertiary reserve) helps to restore the required grid frequency of 50 Hz. The objectives of the development of the common Baltic balancing market were to increase balancing efficiency, to increase availability of balancing resources, and to reduce the costs of power system balancing. Establishing the common Baltic balancing market required harmonization of balancing market frameworks of the three Baltic States, including the settlement rules between market parties, the introduction of a coordinated balance control on a regional level and the introduction of a common balancing IT platform. This chapter analyses operational indicators assessing the performance of the new balancing system, including changes in area control error, changes in market liquidity and diversity, and changes in balancing costs for market participants. This chapter also analyses changes in balancing energy price dynamics in the Baltic states, including price volatility and price correlation, to understand how imbalance prices could motivate balanced steering of the balanced responsible parties. Proposals for further balancing market model development are also provided in the chapter**.** Multiple indicators are utilized to evaluate the performance of the new balancing system, encompassing alterations in area control error (indicative of balance management quality), shifts in market liquidity and diversity, and changes in balancing costs for market participants. Additionally, this chapter analyses variations in imbalance energy price dynamics within the Baltic states, including price volatility and correlation.

Utilizing data from 2017 and 2018 (see Fig. 3.1), covering a complete year of operation under the new model, facilitates a comparison between the old and new approaches. This enables the identification of trends stemming from the introduction of the common Baltic balancing market and offers insights into potential improvements for subsequent operational periods. Furthermore, the experience gained serves as valuable knowledge for other regions undertaking similar initiatives.

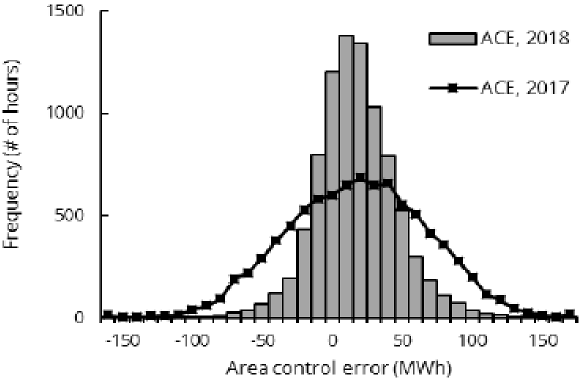

Fig. 3.1. Baltic area control error (ACE).

From 2017 to 2018, there was a visible significant impact on main balancing market performance characteristics.

3.2. CREATING COMMON BALANCING MARKET

The goal of the common Baltic balancing market is to increase transmission system operation reliability, foster the availability of balancing resources, and reduce the costs of system balancing. A common balancing market creates competition between balancing service providers which reduces the costs of balancing responsible parties.

The main objectives for the common Baltic balancing market are:

- increased reliance on local balancing resources and improved balancing market liquidity;
- levelling playing field and establishing incentivizing price signals that promote BRP’s self-balancing;
- harmonized settlement procedures to remove market entry barriers;
- improved data transparency.

The following features were introduced with Baltic CoBA:

- common balancing towards Russia;
- TSO-TSO imbalance netting;
- common centralized mFRR activation model with shared merit order list;
- Nordic-Baltic mFRR exchange;
- harmonized BRP balance management model and imbalance pricing methodology.

3.3. IMPACT ON THE BALTIC'S AREA CONTROL ERROR

Baltic's area control error (ACE) means the Baltic's not netted imbalance towards Russia.

Successful cooperation models among TSOs for balance control and imbalance netting have been in place for some time, and one successful example is the grid control cooperation (GCC) between German TSOs [95], which has grown into a pan-European imbalance netting project involving 24 countries. Introducing similar principles to a common Baltic balancing area enables optimization of balancing effort. As each country is not balanced separately, it is possible to avoid counter-activation by netting "long" and "short" positions and as a result, there is a higher availability of mFRR reserves for minimization of the Baltic's area control error (ACE).

The advantages and challenges of imbalance netting are widely discussed; [96] emphasizes the importance of TSO-TSO settlement to maintain financial neutrality; thus, all TSOs benefit from imbalance netting.

The analysis of historical data on Baltic CoBA performance revealed that the centralized balancing market approach led to a significant decrease in Baltic ACE. Average ACE decreased by 43 %, from 42 MWh to 24 MWh per imbalance settlement period (ISP) in 2018 compared to the year 2017. Similarly, improved results on maintaining ACE close to 0 MWh were observed. In 2018, ACE was within the 50 MWh range at 89 % of operational hours compared to 65 % in 2017.

The trend of monthly accumulated ACE (Fig. 3.7) indicates that ACE could continue to decrease even further as we gain experience in choosing and ordering the optimal amount of balancing energy. Improvements in ACE forecasting will also contribute to ACE reduction.

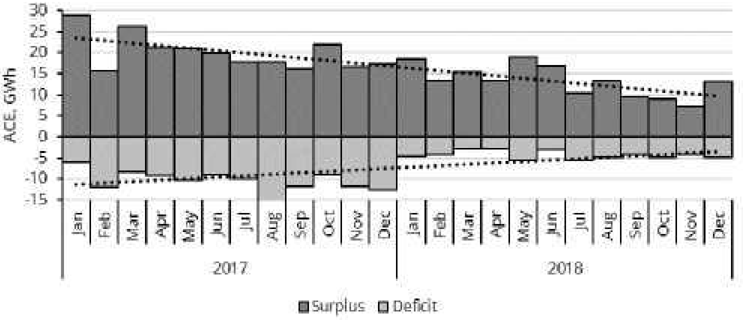

Fig. 3.6. Monthly accumulated ACE.

3.4. MARKET LIQUIDITY

More active balancing of CoBA, with the goal of minimizing the Baltic ACE, increased the frequency of use of balancing energy bids. In 2018, Baltic TSOs ordered mFRR products in 79 % of hours, which is twice as much as in 2017 (36 % of hours), as shown in Fig. 3.3.

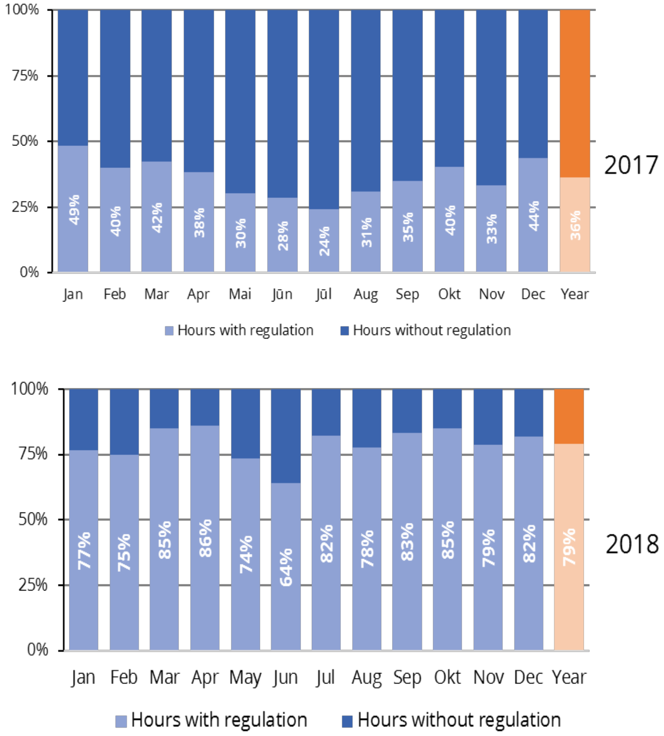

Fig. 3.3. Share of hours with regulation.

This higher demand for balancing resources increased balancing market liquidity and made it more attractive to local generation. Therefore, the amount of used balancing energy in 2018 tripled compared to 2017 (Fig. 3.4), while at the same time, the share of local balancing resources stayed at the level of 66 %.

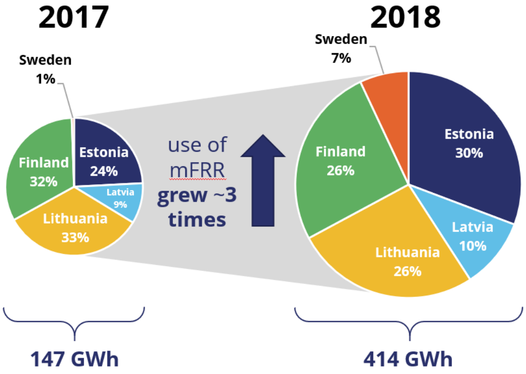

Fig. 3.4. Use of balancing energy.

3.5. IMBALANCE PRICING

The major change is seen not only by balancing service providers but also by balancing responsible parties – introduction of single pricing for BRPs regardless of their imbalance position. Until 2018, settlement procedures were country-based; imbalance prices included country-specific components. Harmonization of settlement procedure and introduction of a single imbalance price model (previously – a dual price model) led to almost full convergence of imbalance prices in the Baltic countries in 2018. Hourly imbalance prices were equal (Fig. 3.5) in Latvia, Estonia, and Lithuania in 97 % of hours in 2018.

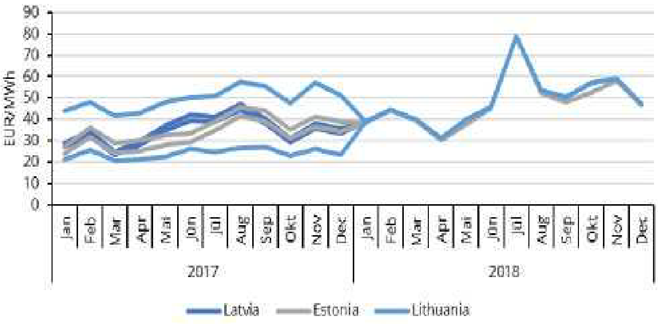

Fig. 3.5. Imbalance price.

The imbalance price in 2018, compared to the day-ahead market for Baltic countries, shows that 43 % of hours have had a higher imbalance price than the day-ahead price. In addition to that, there are continuous periods of up to 88 hours long with an imbalance price difference in one direction (smaller or larger) compared to a day-ahead price. Long periods of price difference in one direction may create motivation for BRPs to plan for intended imbalance with "long" or "short" positions. This effect should be further monitored and analysed to understand if it does not create counterproductive behaviour at the system level.

Changes in the imbalance pricing system created a more level playing field for pan-Baltic BRPs and BSPs. Total Baltic BRP balancing costs decreased from EUR 19.9 M in 2017 to EUR15.1 M in 2018. To evaluate the impact of changes in the imbalance pricing model on pan-Baltic BRP's imbalance costs, we simulated the BRP's portfolio.

Pan-Baltic BRP was created with an average hourly planned consumption of 100 MWh in each country. Hourly consumption was profiled according to the Baltic weekly average consumption profile. To create multiple scenarios with randomized imbalances towards the planned schedule, the actual position was randomly generated for each hour from the planned value. Randomization was made with normal distribution and standard deviation of 5 MW to get, on average, a 4 % imbalance (no leaning towards surplus or deficit). As a result, the cost/profit was calculated from the bought/sold imbalance volume. Average yearly cost/profit of imbalance MWh (300 scenarios) is shown in Figs. 3.6 and 3.7. It is visible that the cost of simulated BRP reduced significantly compared to 2017 to 2018 and that BRP can benefit from netting its imbalances between Baltic countries, therefore reducing the cost of balancing.

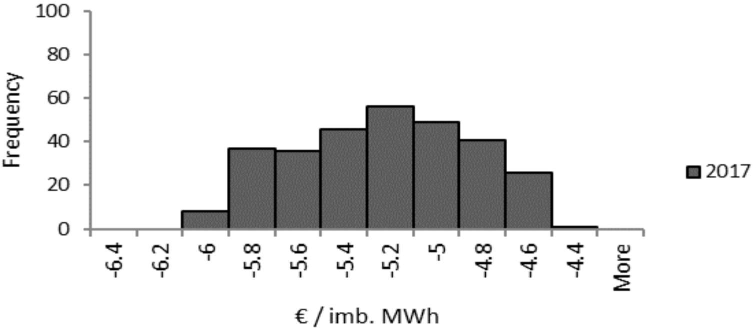

Fig. 3.6. BRP’s imbalance costs in 2017.

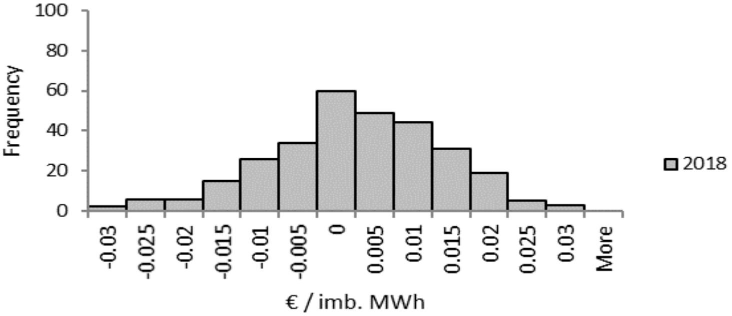

Fig. 3.7. BRP's imbalance costs in 2018.

The trend of monthly accumulated ACE (Fig. 3.8) indicates that ACE could continue to decrease even further from gaining experience in choosing and ordering the optimal amount of balancing energy. Improvements in ACE forecasting will also add to the reduction of ACE.

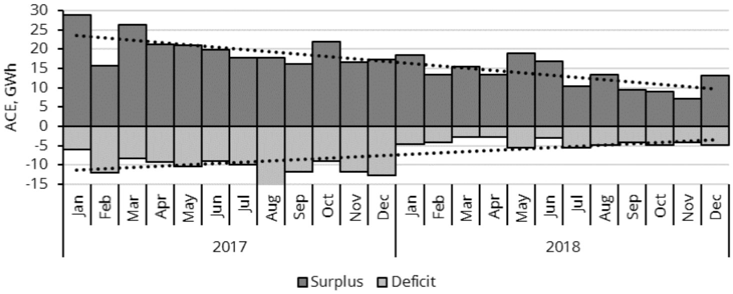

Fig. 3.7. Monthly accumulated ACE.

3.6. CONCLUSIONS

Analysis of performance indicators of the Baltic balancing system indicates clear benefits of common balancing areas and coordinated balance management. Market players, including balancing service providers and balanced responsible parties, benefited from the introduction of a single price and single portfolio model. Considering that in 2018, 97 % of hours imbalance prices were similar in all three Baltic states, the balanced responsible parties are able to exercise imbalance netting and substantially reduce balancing costs that are passed onto end-users. The analysis shows that the introduction of a common balancing area and centralized balance management at a regional level has improved the efficiency of system balancing, reduced ACE, improved the availability of balancing resources, and thus improved the security of supply.

The model presented in this chapter is not yet ready to ensure active real-time balancing from the BRP side because imbalance and balancing prices are published after real time, and that is an issue which requires further study.

4. MARKET-BASED STORAGE MANAGEMENT STRATEGY FOR FCR PROVIDER

4.1. INTRODUCTION

The focus of this chapter was publication [83], which presents a market-based storage state of charge management strategy for primary frequency control providers with limited energy reservoirs such as battery energy storage systems. The frequency containment reserve (FCR), also known as the primary control reserve*,* is the first reaction to frequency disturbances. If a deviation occurs, the automatic frequency restoration (aFRR) gets involved automatically within seconds to restore the rated frequency and the balance between supply and demand. The strategy is the result of research work motivated by relatively recent regulatory condition updates in continental Europe, which stipulate that frequency containment reserve providers cannot rely on dead-band utilization and delivery over fulfilment to manage their reservoirs. In addition, we show how the devised strategy allows an appropriately sized battery system to withstand the realization of a worst-case scenario, even if the unit is providing multiple reserve products at once and is allowed to recover its state of charge only via the intraday market.

In order to both facilitate and regulate the integration of storage systems in ancillary service markets, especially for the provision of **frequency containment reserve** (FCR), the EU System Operation Guideline [85] stipulates specific rules applicable to **limited energy reservoirs** (LERs), i.e. storage units that can be depleted within two hours of operation. Namely, the minimum activation period (Tmin LER criterion) to be ensured by FCR providers qualified as LERs is 15–30 min during the system alert state with a specific value to be proposed by all TSOs of each synchronous area. While the continental Europe (CE) TSOs lean towards a 30-min Tmin LER at least for newly installed storage power plants, the final proposal is still under development.

LERs as FCR and frequency restoration reserve (FRR) providers are of particular interest for the Baltic power system, which is scheduled to desynchronize from IPS/UPS and connect to the CE synchronous area by 2025 [86]. By this time, the Baltic TSOs ought to be able to cover their FCR and FRR needs themselves, while historically, the primary frequency control has been ensured by the neighbouring Russian power system [87], [88]. Hence, large-scale battery energy storage system (BESS) projects are under development in the Baltics to ensure FCR and FRR adequacy [89]–[91]. The outlined EU-level developments and regional challenges around the Baltic synchronization project have motivated the research question of this study: to develop an efficient market-based BESS operational management strategy subject to a set of technical and regulatory constraints related to ancillary service markets and specific reserve products as well as to electricity wholesale markets for storage recovery.

4.2. SOC MANAGEMENT STRATEGY

The main goal of the strategy is to prepare ID bids while delivering the reserves in order to assure a sufficient SOC level in line with the undertaken reserve (FCR and/or FRR) obligations. The overall philosophy of the strategy envisions a robust approach, i.e. the BESS must strive to be prepared for the realization of a worst-case scenario at any future point in time.

Assumptions and Simplifications.

We assume that the FCR provider is a single BESS with an LER which can only use market-based mechanisms for restoring the energy content of its reservoir (i.e. no alternative generation or load neither in the reserve provider's portfolio nor contracted bilaterally, which could be used to charge/discharge the BESS; intentional imbalance to manage storage disallowed). Ultimately, this means that the BESS can manage its SOC only by participating in the ID market as it has a much shorter lead time than the DA market and thus allows for more flexibility. To achieve the most effective storage management under the laid-out conditions, the optimum decision-making time on whether an ID trade offer needs to be submitted would be at the last possible moment before the GCT. However, for the sake of robustness, a certain bid preparation time should be added before each ID GCT by which the decision is made. The relationship between various time-related variables employed in the management strategy is explained in Fig. 4.1, where $t_{\mathrm{ID,\,decision}}$ – moment in time for the ID offer decision; $t_{\mathrm{ID,\,GCT,\,next}}$ – the closest ID GCT; $t_{\mathrm{ID,\,start}}$ and $t_{\mathrm{ID,\,end}}$ – the start and end time of the ID trading period with the closest GCT; $\Delta t_{\mathrm{prepare}}$ – user-selectable time period for bid preparation (expressed in minutes before GCT, e.g. 5 min); $\Delta t_{\mathrm{ID,\,GCT}}$ – ID GCT (in minutes before delivery start, e.g. 60 min in Baltics [92]); Δt_{MTU} – market time unit duration (assumed 15 min [87]).

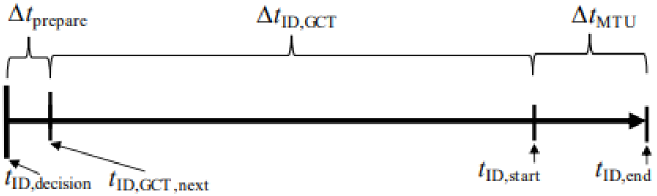

Fig. 4.1. Relationship between the time-related variables.

Relationship between the time-related variables, to minimize over-correction risks, prepares ID trades only for the shortest possible delivery periods, i.e. at each decision time, only one potential MTU is considered for delivery. On the other hand, this means that the need for corrective trade has to be evaluated before each ID GCT; with a 15-minute MTU, this equals 96 decisions a day.

Based on an analysis of the EU regulatory framework, we derive the following main requirements for the SOC management strategy of a BESS to provide FCR with an LER qualification:

- Capability to provide a prolonged full FCR activation at least until the Tmin LER criterion is satisfied during the system alert state.

- Capability to provide uninterrupted prolonged FCR up to 25 % of the total committed reserve power in one direction during the system's normal state.

- Recovery of sufficient storage level to fulfill the Tmin LER criterion no later than 2 hours after the end of a prior system's alert state.

- The previous three requirements need to be met also when the BESS provides FRR alongside FCR. However, the committed FRR must be fully activated at any given time for any duration regardless of the Tmin LER criterion and post-alert state's recovery status. This is because there are no special properties defined or exemptions allowed for an FRR provider with a LER.

4.3. ALGORITHM

The main steps of the devised algorithm are generalized in Fig. 4.2, and explained in detail in Appendix [83],

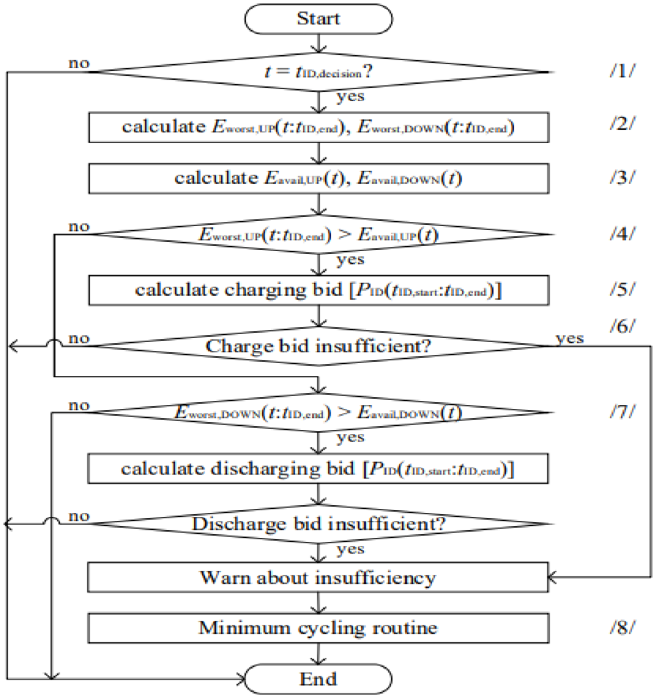

Fig. 4.2. The main steps of the energy recovery algorithm [83].

The mathematical model developed to simulate and validate the outlined strategy, could be used in future work to study the impact of BESS technical parameters on their reserve provision capabilities as well as the impact of market regulations on BESS performance.

4.4. VALIDATION

A model for algorithm validation was created in publication [83], a BESS with 80 MW charge/discharge capacity, 160 MWh rated storage, 0.95 charge and discharge efficiencies, and reservoir limits of 10 % and 90 %. The BESS has to provide 8 MW of FCR and 32 MW of FRR in each direction. The selected parameters have been derived from the estimated reserve needs in the Latvian power system after desynchronization from the IPS/UPS in 2025 and from the specification of BESS that is being discussed for installation in Latvia [84]. In terms of reserve activations, for FCR, we assume a six-hour frequency deviation profile, as depicted by the brown line/right axis in Fig. 4.9 (NB: FCR providers observe a ±10 mHz dead-band followed by a proportional response reaching a full activation at ±200 mHz deviation). This profile is entirely artificial as its only purpose is to demonstrate that the devised BESS management strategy can ensure the reserves as expected. The FRR activations are likewise simulated to enforce a worst-case scenario realization (i.e. full activation for the entire six hours).

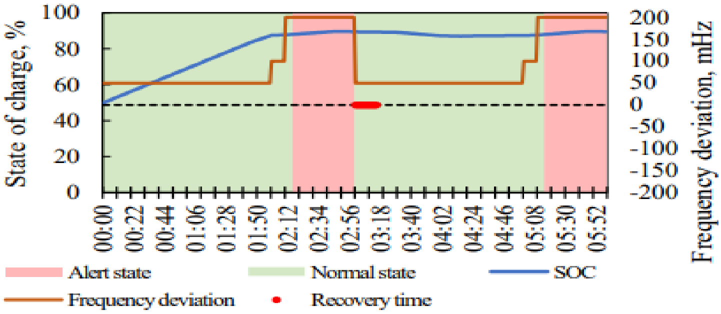

Fig. 4.8. Simulated frequency deviation and LER SOC evolution.

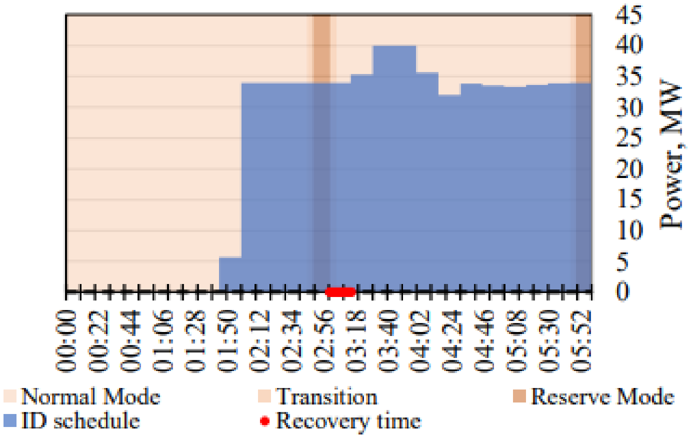

Fig. 4.4. The schedule of corrective ID trades and FCR provision mode

In the simulated scenario, the BESS is able to continuously provide a 25 % FCR activation during the normal state of the power system together with a full FRR activation without any issues. At 2:15, an alert state is declared due to frequency deviation exceeding 50 mHz for 15 minutes and 100 mHz for 5 minutes. The LER starts the transition to reserve mode only at 2:44, when the 30-minute Tmin LER criterion has been fulfilled. At 3:00, the alert state ends due to the frequency deviation dropping slightly below 50 mHz, at which point the 2-hour countdown for LER recovery starts. However, the LER already completed the recovery at 3:16, which means that it only required 16 min to be completed. This is due to the robust nature of the storage management algorithm. It is also partly because of the fact that scheduled future ID deliveries are taken into account when evaluating the recovery conditions, provided that there is no risk of violating the SOC constraints at any point in the considered future time horizon. At 5:15, another alert state is declared, and again, the LER only starts transition to the reserve mode once 30 min of full activation have been endured. In Fig. 4.9, it can be seen how the SOC trajectory approaches the upper constraint of 90 % but does not violate it, instead remaining near it. Moreover, thanks to the scheduled ID deliveries (Fig. 4.4), the LER can even guarantee the continued capability to provide the required FCR and FRR despite the SOC presently being close to the constraint.

4.5. CONCLUSIONS

The validated market-based BESS SOC management strategy enables robust and reliable LER participation in FCR provision, meeting all the additional properties and regulatory provisions that FCR providers with LERs are subjected to in continental Europe. It is also suitable for LERs providing both FCR and FRR. The devised strategy can be applied to prospective BESS installations in the Baltic power system after synchronization with CE and also elsewhere in the EU as it follows the most recent regulations to be adopted by the Member States. Moreover, the tool allows testing the impact of important technical parameters and market settings to aid in decision-making. The crux of the offered approach is anticipating and preparing for the emergence of a worst-case scenario. Due to the limitations of chapter size, only a part of the overall BESS operational management strategy has been presented, which, among other aspects, also manages the LER's transition between normal/reserve mode and estimates the voluntary FRR energy bids. Hence, the elaboration of the additional model components and features remains a topic for future work. Furthermore, the mathematical model developed to simulate and validate the outlined strategy could be used in future research to study the impact of BESS technical parameters on their reserve provision capabilities as well as the impact of market regulations on BESS performance. The potential topics of future studies include BESS and reserve sizing, pros and cons of qualification as an LER, duration of the Tmin LER criterion, recovery duration, market lead time, etc. Moreover, the model can be extended to also consider diverse economic criteria to ultimately provide a comprehensive cost-benefit assessment of a LER-qualified BESS with varied control strategies.

CONCLUSIONS OF SECTIONS AND FUTURE WORK

The main preconditions for the Baltic States mentioned in **Chapter 1** on the transformation of the energy sector in the Baltic States to promote adequacy of power supply and development of balancing capacity are:

1. Promote generation development.
2. Invest in grid development.
3. Promote consumer response and aggregation.
4. Develop the balancing market, especially after the planned synchronization of the Baltic energy system with the continental European grid in 2025.

Chapter 2 highlights that the global and European energy development plans propose applying several strategies, at least two of which significantly affect the structure of energy systems.

Strategy 1: A precipitous increase in the capacity of power plants operating on renewable energy sources.

Strategy 2: Reducing the capacity, suspending or shutting down power plants that use fossil fuels.

It is a well-known fact that electricity production from RES is an unpredictable and volatile process. As a result, there is a problem related to manageable energy production and ensuring the power balance of any energy system. Sometimes, to entirely compensate power deficit by energy import from neighbouring countries is an impossible issue due to the limited capacity of transmission lines.

The simulation results of all BPS 2050 scenarios show that attempts to ensure energy balance through power import and to compensate for the energy deficit by increasing the installed capacity of RES do not lead to success.

Additionally, car electrification will significantly worsen the Baltic power systems' capacity balancing situation. To meet the demand for electricity, it will be necessary to build additional stations that can generate energy in the absence of sun and wind or create new interconnection transmission lines and long-term energy storage capacities.

Conclusions of **Chapter 3** based on analysis of performance indicators of the Baltic balancing system indicate clear benefits of common balancing areas and coordinated balance management. Market players, including balancing service providers and balanced responsible parties, benefited from the introduction of a single price and single portfolio model. Considering that in 2018, 97 % of hours imbalance prices were similar in all three Baltic states, balanced responsible parties are able to exercise imbalance netting and substantially reduce balancing costs that are passed onto end-users.

Analysis shows that the introduction of a common balancing area and centralized balance management at a regional level has improved the efficiency of system balancing, reduced ACE, improved availability of balancing resources and thus improved security of supply.

The model presented in this chapter is not yet ready to ensure active real-time balancing from the BRP side because imbalance and balancing prices are published in real time, and that is an issue that requires further study.

Conclusions of **Chapter 4** based on the validated market-based BESS SOC management strategy enable robust and reliable LER participation in FCR provision, meeting all the additional properties and regulatory provisions that FCR providers with LERs are subjected to in continental Europe. It is also suitable for LERs providing both FCR and FRR. The devised strategy can be applied to prospective BESS installations in the Baltic power system after synchronization with CE and also elsewhere in the EU as it follows the most recent regulations to be adopted by the Member States. Moreover, the tool allows testing the impact of important technical parameters and market settings to aid in decision-making. The crux of the offered approach is anticipating and preparing for the emergence of a worst-case scenario. Due to the limitations of chapter size, only a part of the overall BESS operational management strategy has been presented, which, among other aspects, also manages the LER's transition between normal/reserve mode and estimates the voluntary FRR energy bids. Hence, the elaboration of the additional model components and features remains a topic for future work. The mathematical model developed to simulate and validate the outlined strategy, could be used in future work to study the impact of BESS technical parameters on their reserve provision capabilities as well as the impact of market regulations on BESS performance. The potential topics of future studies include BESS and reserve sizing, pros and cons of qualification as an LER, duration of the Tmin LER criterion, recovery duration, market lead time, etc. Moreover, the model can be extended to also consider diverse economic criteria to ultimately provide a comprehensive cost-benefit assessment of an LER-qualified BESS with varied control strategies.

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