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Problematic Aspects of Energy Systems with a High Penetration of Renewable Energy Sources

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Abstract

This article considers various aspects of the functioning of electric power systems (EPSs) with a high proportion of available renewable energy sources (RES). In the absence of sufficient sources of basic generation in the EPS, new ways to eliminate possible consumer load jumps in the form of power reserves will be required. Based on the studies carried out in the Baltic States' energy systems, it follows that the best way to ensure stable and safe operation of power plants in these conditions is to use energy storage devices, namely, a battery energy storage system (BESS). The BESS battery system will be able to provide reserves in a more economical way than most power plants that use organic fuels. A model for the distribution of production capabilities of an electric power producer with specified energy characteristics in market conditions is proposed. The practical implementation of the model makes it possible to obtain the initial data for creating characteristics of price proposals in the formation of a market for power reserves. The implementation of the model is illustrated for a concrete example.

Keywords: electric power systems; renewable energy sources; electricity market; power generation price; power reserve price; balance reliability

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Academic Editor: Marek Pavlík

Received: 27 June 2025
Revised: 30 July 2025
Accepted: 6 August 2025
Published: 12 August 2025

Citation: Mahnitko, A.; Lomane, T.; Zicmane, I. Problematic Aspects of Energy Systems with a High Penetration of Renewable Energy Sources. *Energies* **2025**, *18*, 4282. https://doi.org/10.3390/en18164282

1. Introduction

The main trend in the development of modern global energy is the replacement of electricity producers operating on organic fuels (coal, gas, fuel oil, etc.) with renewable energy sources (first and foremost, solar radiation and wind). The following factors determine the need for such a replacement:

Firstly, the sources of electricity that use organic fuels, with their emissions of carbon dioxide CO_2 into the atmosphere, have adverse effects on the environment, eventually leading to climate change on the Earth, which may lead to catastrophic consequences for the inhabitants of the planet.

Secondly, many countries do not have stocks of organic fuels, the import of which requires high financial costs. At the same time, it should be borne in mind that any reserves of organic fuels may eventually be exhausted.

Thirdly, in all the countries of the world, to a greater or lesser degree, the sun is shining and the wind is blowing, which makes it possible to use solar radiation and wind energy as sources of electricity generation.

Taking into account these factors, the EU countries consider the transition to renewable energy sources (RES) to be their main priority in the development of energy in the near future. The EU's strategic plans aim at increasing the share of renewable energy sources in the total electricity source balance to 100% by 2050 [1]. Obviously, the increased share of renewable energy sources in the total electricity production should have a certain limit that does not violate the balanced reliability in the energy system. In the absence of sufficient reserves of basic power in power systems, problems may arise regarding the reliability of their operation. Redundancy is one of the main means of increasing balance reliability in the energy sector at all stages of the management of electric power systems. Despite the fact that energy professionals have been dealing with this problem for more than half a century, there is still no single generally accepted approach to its solution [2–6]. In a market environment, the power market itself can decide what level of reserve power is required to ensure compliance with reliability standards and how to distribute it among electricity producers.

2. General Characteristics of the Power Reserve Problem

As for the overall problem of reserve power, the issue of reducing it to some numerical value, in our opinion, is debatable. It makes sense to talk about the creation of a methodology recognized by the electric power community for determining the sufficiency or insufficiency of generation to meet projected consumption [7]. In other words, there should be a transparent, understandable, and universally accepted methodology for calculating the amount of reserve power.

Without reference to the specific mix of generating equipment and the consumption profile, the numerical reserve value in and of itself makes no sense. If there is an intention to meet consumption only by means of renewable energy facilities or equipment with a high accident rate, it has to be said that this is problematic at the current level of development of the global economy. As for renewable energy sources in particular, for objective reasons, due to the unpredictability of previously noted energy indicators of renewable energy resources (degree of solar radiation, wind strength, wind speed, etc.), it is not possible to guarantee electricity production at the right time and in the required amount.

The amount of installed power for solar and wind power plants, as well as hydroelectric power plants, in principle, cannot be a decisive factor for determining the value of their real reserve power [7]. In particular, the contribution of solar power plants to meeting the load of evening highs in winter is approaching zero, and the actual load of wind farms is usually lower than the established load. The actual power of hydroelectric power plants depends on the water level, the ice conditions, and other constraints in a particular year. It should be noted that the actual power of even the base power sources may be lower than the installed one. The capacity of a thermal power plant, for example, with a certain equipment mix, depends on the magnitude of the heat loads, and it is necessary to reboot the fuel at nuclear power plants. In addition to all of the above, it should be added that any type of generating source requires repairing various types of equipment, regardless of the method of electricity production. These factors indicate that the actual capacity of the energy system's generating sources, and especially renewable energy sources, is lower than the installed capacity. Thus, it is necessary to revise the modern methods for calculating power reserves.

In conditions where there is an energy market, with a high degree of renewable energy availability in energy systems, a change in the approaches to the selection and placement of power reserves in energy systems is required. It is worth noting that the approach of using a probabilistic assessment of load loss in the power system may be useful to assess the established stock of the power reserve and stimulate investment in power generation. An approach to modeling and quantifying the stochastic properties (variability and uncertainty) of the load as a continuous random process is a fully justified solution [6,8]. Analytical expressions have been derived in [8], among other things, that can be effectively included in the assessment of the probability of load loss.

Depending on the type and structure of the power market, it is advisable to calculate the required reserve amount based on the calculation of mode balance reliability. The more reserves the power system has, the higher its reliability and the lower the probability of disconnecting consumers. The higher the reliability, the more the consumer has to pay for it in the end.

The presence of RES (primarily solar and wind power plants) in an energy system, even with a relatively large installed capacity, does not mean that it is possible to select and maintain a reserve of generating capacity sufficient to ensure the required level of reliability. This is due to the lack of constant consumption characteristics for these power plants, which determine the dependence of electricity production costs on the energy resources used. The energy indicators of these energy resources (degree of solar radiation, wind force, and speed) do not guarantee the production of electricity in the required volume and at the right time. It follows from this that it is impossible to do without the availability of basic capacities in the power systems, capable at any time, and regardless of weather conditions, to provide the necessary amount of electricity to consumers in a timely manner without reducing the reliability of their power supply. At the current level of development of energy technologies, such sources of basic power can be found in the form of hydroelectric power plants, nuclear power plants, high-power storage devices in the form of BESS (Battery Energy Storage System), etc. [1,9].

3. The Benefits of the Baltic States After Connections to the European MARI Balancing Market Platform

Participation in the MARI balancing market platform (as shown on Figure 1) will provide Latvian, Estonian, and Lithuanian electricity producers, consumers, and operators of high-capacity batteries with new opportunities to offer balancing services to transmission system operators in the region. Joining the MARI platform will provide power market participants with additional revenue opportunities, and transmission system operators will have greater access to the resources required to balance the energy system.

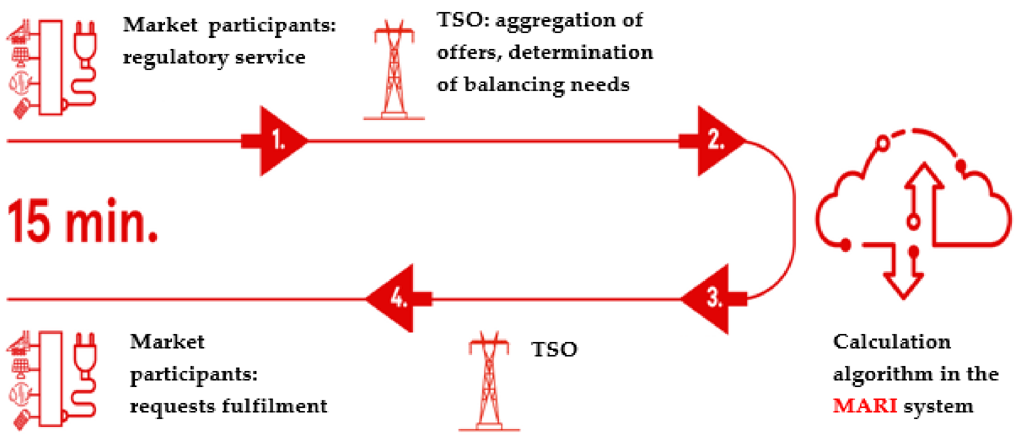


Figure 1. The structural scheme of participation in the balancing market platform MARI. 1—submission of regulatory offers; 2—sending of data; 3—sending of results; 4—sending of results.

The act of joining the European MARI balancing platform performed by the Baltic Energy System operators is a strategically sound action preceding the exit of the Baltic Energy System from the BRELL (Belarus, Russia, Estonia, Latvia, and Lithuania) in early February 2025. The disconnection of the Baltic States' electric networks from the electric networks of Russia and Belarus, which occurred on 8–9 February 2025, made it possible to create the so-called Baltic Frequency Control and Balancing Unit of the energy system. There will be new opportunities to maintain a balance of reserves of power required for the energy system to operate in a stable manner.

Thus, the Baltic energy system will become more independent, and its stability against various fluctuations in load capacity will increase. In turn, joining the European MARI balancing platform will provide the transmission system operator (TSO) with the opportunity to acquire the required balancing reserves in a regional, competitive market at the lowest possible cost. This should have a beneficial impact on the cost of electricity for consumers [10,11].

An important trait of the new balancing market model is the fact that balancing services can be rendered by using a wide range of technologies, including electric batteries, solar and wind generators, flexible consumption, etc. In a balancing energy market, participants have the possibility to propose reducing or increasing their production power or consumption in near-real time, thus ensuring a continuous balance between production and consumption of electricity, receiving compensation for this.

It should be noted that since 2018, the unified Baltic platform of the coordinated balancing area (CoBA) balancing electricity market has been operating in the Baltic States, where calculations are performed hourly [12,13]. With the accession of the Baltic States to the European MARI platform, the trading interval will be 15 min. The previous requirement for the minimum request of reserve power for regulation—1 MW—remains unchanged; however, the new range allows requesting this amount of power for shorter time intervals. Consequently, even smaller participants in the electricity market can enter the balancing reserve market with their bids. With the accession of the Baltic States to the MARI platform, as well as the introduction of the Baltic Balancing Capacity Market in early 2025, the range of balancing suppliers is expanding, and favorable conditions for new investments in balancing backup infrastructure are being created. The synchronization of the Baltic EPS with the European energy system makes it possible to the TSOs in the Baltic States to ensure the frequency control independently and enables constant, accurate balancing of consumption. This, together with the rapidly growing connection of wind and solar power plants to the grid, is going to increase the size of balancing reserves needed by the TSOs for the stable operation of the grid. Therefore, AST (Latvia's TSO), in cooperation with transmission system operators in Estonia and Lithuania, is initiating a regional market for operators to buy and sell electricity.

4. Ensuring Stable Operation of the Baltic Energy System with a High Proportion of Renewable Energy Sources

By 2050, the Baltic States are planning to augment the energy production share from RES to 100% [1,9]. To put this plan into action, the Baltic States needed to take a range of technical measures to ensure the stable operation of the energy system and reliable power supply. During the past ten years, the Latvian TSO has made transformative changes to the transmission network infrastructure and control technology [14,15]. The successful exit of the Baltic States' energy system from the BRELL electric ring on 8–9 February 2025 confirmed the practical feasibility of these changes in the infrastructure of the Baltic energy systems. The measures taken to ensure their stable operation are of particular importance in changing the infrastructure of the Baltic energy system. Significant work in this area has been carried out with the participation of the world's leading experts, in particular, TEPCO.

TEPCO Power Grid Inc. (Tokyo Electric Power Company Power Grid, Tokyo, Japan)), a Japanese energy company, commissioned by the TSOs of the Baltic countries: Lithuania (Litgrid), Latvia (AST JSC), and Estonia (Elering), conducted research to study the potential technical and economic solutions to ensure stability to the Baltic energy system at the conditions when the share of RES is high. TEPCO Power Grid, the Japanese transmission system operator, has been chosen to perform research in the Baltic States because TEPCO has extensive experience in providing electricity supply, maintenance, and development services, including operation of the system at extreme conditions. The company also has experience in the field of safe power supply to small, isolated islands and participates in the replacement of nuclear power plants with renewable energy sources.

TEPCO's experts gathered and analyzed information on the present situation and issues related to the Baltic States' capabilities in balancing generation and load and frequency regulation, assessing the needs of the Baltic States, and ensuring the development of the required technology and knowledge base. The main purpose of the research conducted was to create a technically safe and economically sound model and identify the necessary measures to ensure stable, balanced generation and consumption, and frequency regulation in the Baltic States in accordance with the target of 100% share of renewable energy by 2050.

The research has shown that the BESS (Battery Energy Storage System) battery system is the best option for Lithuania, Latvia, and Estonia to ensure the stable and safe operation of their energy systems in a situation where up to 100% of electricity generation is provided from renewable energy sources. These studies have shown that a 240 MW grid battery system can help overcome the lack of synthetic inertia associated with a considerable reduction in the power of synchronous generators in the power system, as well as a significant increase in the use of wind and solar generation. TEPCO has also studied how synthetic inertia from high-voltage DC connections, BESS, wind, and solar power plants could be used.

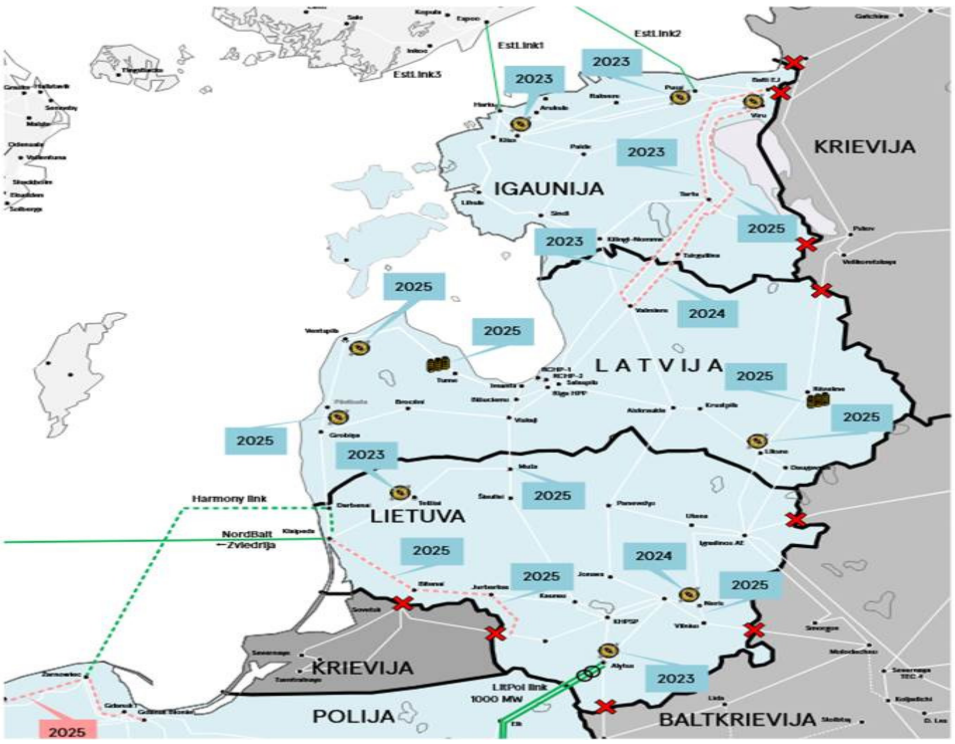
A panel of TEPCO experts has developed a BESS with a synthetic inertia function and HVDC connection simulation scenarios, which constitute a powerful tool for inertial response and frequency control. Similarly, a serious emergency scenario was developed, and by means of dynamic modeling, the necessary amount of BESS was calculated, which must be installed for stable frequency control. The study showed that the BESS power necessary for increasing the rate of frequency control (RoCoF) and the lower frequency settling point (nadir) is 240 MW for the BESS type forming the network and 400 MW for the BESS type following the network. Since the network type of BESS has a faster response and improves RoCoF more effectively, TEPCO experts recommend implementing the 240 MW BESS network type in the Baltic States [1,9].

The simulation also showed that by supplementing the HVDC connections with a frequency control function, it became possible to provide acceptable RoCoF and frequency deposition values without introducing additional BESS, although such a solution has certain drawbacks. Setting a higher response gain to the regulator can improve the effect of HVDC coupling on frequency; however, such a setting requires coordination with the TSOs of the neighboring systems, which have HVDC connections, since a high response gain has a greater effect on the neighboring system. Additionally, in this case, there is a need to limit the market capacity in advance in order to reserve sufficient HVDC power to regulate the frequency response. The study shows that if HVDC connections are equipped with a frequency control function, then the response of the HVDC connection must be in accord with the response of BESS in cases of frequency deviation. This provides a stable frequency of the power system in emergency modes, such as shutting down the generator.

In order for wind and solar power plants to have an inertial response, the experts of TEPCO recommend that the BESS capacity should be up to 2.8% of the electricity produced. At power plants with a small production capacity, BESS can be problematic to install from an economic perspective. To provide an inertial response with a certain margin, it is advised to install a BESS equivalent to about 5% of the power produced at larger power plants. In case no other measures are taken (for example, synchronous compensators), the figure can be increased to 10%. Thus, values ranging from 5% to 10% of the power generation amount must be considered as the best indicators for finding the best economic value for BESS power.

The research conducted has made it possible for the Baltic States to make an informed decision on installing the most powerful (currently) in Europe battery storage systems (240 MW) for storing electricity in the Baltic States (Latvia). The battery storage system is an important element of the infrastructure for ensuring the safety and stability of Latvia's energy supply. These batteries should work like modern accumulators for storing large amounts of energy. This will be important for ensuring the energy balance after the Latvian electricity supply network starts operating synchronously with the European network. Latvia's battery solutions represent a sustainable and reliable source of energy security, recognized worldwide. The Latvian transmission system operator (TSO) and the German company Rolls-Royce Solutions GmbH (Sales and Service Germany, Friedrichshafen Deutschland, Germany) have started cooperation regarding the construction of power storage systems (BESS), which are important for the security of the Latvian energy system. Rolls-Royce will install a battery system with a total capacity of 80 MW at two locations: 20 MW at Tume substation and 60 MW at Rezekne substation.

A modern battery system will ensure precisely the synchronization mode in which the electricity transmission systems of the Baltic States will operate synchronously with the power grids of continental Europe, and when high-speed, automatically activated frequency control reserves are required. This battery system will be able to provide these reserves faster and more economically than most conventional plants, which require a lot of time to start the units. Such high-speed reserves in the form of BESS will be important both for the synchronization mode and in the future, when the share of renewable energy in the energy system is going to grow more and more. Currently, in the Baltic States, the infrastructure measures are being established. Figure 2 shows these objects.



Battery Energy Storage System (BESS); Synchronous compensators;

Disconnecting from the Russian and Belarusian energy systems.

Figure 2. Implementation of measures to stabilize the Baltic energy systems.

5. The Mathematical Model for Determining the Power Reserve Price for Electricity Producers

Under market conditions, consideration of the financial interests of individual energy companies is achieved by means of ensuring a balance between the bids and demand in monetary terms. The world practice shows [7,9] that the principles of organizing wholesale energy markets in different countries and energy companies may differ significantly. The main difference in this case is the formation of electricity prices (tariffs) depending on the level of the wholesale market.

One of the strategies in the formation of wholesale prices is the following:

- Those power generation producers that have an excess of electricity generation apply for the sale of electricity through the wholesale market (price, volume);
- Those companies that have a deficit of electricity generation apply for the purchase of electricity through the wholesale market (volume);
- The choice of the wholesale price starts from the minimum price offered in the bids.

Then, all the prices in ascending order and the matching proposed amount of electricity involved in meeting the declared load are viewed. The choice ends at the price of the energy company that meets the system load. In this way, the remaining energy companies are not currently involved in the wholesale market and thus lose out on the fact that they have raised the price too much and cannot sell their surpluses. Therefore, the wholesale price is defined as the maximum price involved in meeting the load. In order to make effective decisions on the development and operation of electric power systems, a deeper techno-economic analysis of their various operating modes is required. These modes must be optimized by taking into account the criteria of quality, economy, reliability, acceptability, and technical feasibility. In doing this, it is essential to take into account the existing requirements for the minimum environmental impact of the operating modes of power plants. It can be confidently stated that, irrespective of the economic system within which the energy system is functioning, the issues related to mode optimization are of priority importance.

In a market economy, the relevance of this task has increased immeasurably. Solving it enables the producer of heat and electric energy to increase its competitiveness in the electricity and capacity market.

In the context of the functioning of energy markets, the main criterion for evaluating the effectiveness of their operation is the maximization of the so-called social welfare function of all its participants—producers (sellers) and consumers (buyers) of electricity [16,17]. Below, this function is presented in classical formulation:

$$\left(\sum_{j=1}^{m} c_j\, P_j \quad - \quad \sum_{i=1}^{n} c_i\, P_i\right) \to max \tag{1}$$

where

c_i, c_j—prices in the applications for production (sale) and consumption (purchase) of active power;

P_i, P_j—nodal volumes of production (sale) and consumption (purchase) of active power.

Depending on how the optimization problem is formulated, the objective function (1) may have different characteristics. These can be, e.g.,:

- The characteristics of relative cost increases (RCI) are based on the physical consumption characteristics of the equipment;
- The tariff price characteristics (TPC) approved by energy commissions;
- The price applications (PA) of generators and wholesale buyers, submitted to the competitive electricity market, etc.

Achieving the maximum of the welfare function of the participants in the energy market (1) is possible only with the minimum value of the second term, which shows the costs of producer *i* as a participant in the energy market.

To participate in the power reserve market, the electricity producer in node i solves the following problem for himself:

What part of its production capabilities should be declared in the form of generation P_{gi} and sold on the power market at the power generation price c_{gi}, and what part of its production should be sold on the power reserve market in the form of power reserve of P_{Ri} at the power reserve price c_{Ri} [18]. To solve this problem, we will introduce all the above parameters of the electricity producer into the welfare function (1). We assume that there are the following relationships between these parameters. The power reserve in node *i* can be determined from the following expression:

$$P_{gi} + P_{Ri} = P_{gi,max} \tag{2}$$

If the power reserve P_{Ri} is not sold, then the producer's profit B_i in node *i* per unit of time, can be defined by the following equation:

$$B_i = c_{gi} P_{gi} + c_{Ri} P_{Ri} - C_{gi}(P_{gi}) \tag{3}$$

Equation (3) does not take into account the costs of starting and stopping the units.

In (3), the value of $C_{gi}(P_{gi})$ represents the cost of producing power at node *i* per unit of time. These costs are determined by an expenditure characteristic of the following form:

$$C_{gi}(P_{gi}) = \alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 \tag{4}$$

where

α_i, β_i, γ_i are coefficients that are known.

The power generated in node *i* must meet the following technological limitation:

$$P_{gi,min} < P_{gi} < P_{gimax} \tag{5}$$

The optimum amount of electricity offered for sale by the producers in node *i* at price c_{gi}, from the profit maximization point of view, can be determined as the result of solving the problem of unconditional optimization of function (3) with respect to the P_{gi} variable. From the condition that the first derivative of function (3) with respect to P_{gi} equals zero, considering (2), we have

$$\frac{\partial B_i}{\partial P_{gi}} = c_{gi} - c_{Ri} - \frac{\partial C_{gi}\ (P_{gi})}{\partial P_{gi}} = 0, \tag{6}$$

where the relative increase in producer costs is determined by the following expression:

$$\frac{\partial C_{gi}(P_{gi})}{\partial P_{gi}} = \beta_i + 2\gamma P_{gi} \tag{7}$$

The resulting relationship may be the starting point for the participation of producer *i* in power generation and power reserve markets. It should be noted beforehand that the optimum volume of electricity offered for sale by producer P_{gi} in node *i* at price c_{gi}, in terms of its maximum profit, can be determined as the result of solving the problem of conditional optimization of the welfare function (1) using variable P_{gi}. This problem of finding the maximum can be replaced by the problem of finding the minimum of a function of the form

$$F_1 = \sum_{i=0}^{n} c_{gi}P_{gi} + \sum_{i=0}^{n} c_{Ri}\, P_{Ri} \tag{8}$$

in which the total costs of producer i are divided, respectively, as the cost of power sold on the market P_{gi} at the price of c_{gi} and the cost of reserved power P_{Ri}, with a previously unknown reserved power price c_{Ri}. Taking into account relationships (2), (4), and restrictions (5), the minimization of function (8) can be reduced to the minimization of function

$$F_1 = \sum_{i=0}^{n} c_{gi}P_{gi} + \sum_{i=0}^{n} c_{Ri}\, \left(P_{i,max} - P_{gi}\right) \tag{9}$$

Minimization (9) makes it possible to determine generation power P_{gi}, on the basis of which, using expression (7) and relationship (6) sequentially, it is possible to determine the price of power reserve C_{Ri} in the volume P_{Ri}, satisfying condition (2), which the manufacturer of node i can offer to the market of reserves of power. As a result, the power reserve price is determined using the expression

$$c_{Ri} = c_{gi} - 2\gamma_i\, P_{gi} - \beta_i \tag{10}$$

The system operator, which is the buyer of the service of power reserve provision, determines the purchase volume P_{gi} for each market participant based on applications for the active capacity market $P_{gi}\left(c_{gi}\right)$ and the marginal price c^* at which this capacity will be purchased. After that, a market for power reserves is formed: each seller announces their proposed reserve from (2) at the power reserve price c_{Ri}, determined from (10). If the equilibrium price c^* in the power market is greater than the relative increase $\partial C_{gi}\left(P_{gi}\right)/\partial P_{gi}$, then this means that node i producer is excluded from the number of generation sources involved in meeting the load, and completely switches to the market of power reserves by providing a power reserve value

$$P_{Ri} = P_{i,max} - P_{i,min}.$$

at the power reserve price

$$c_{Ri} = \left(C_i\left(P_{gi,min}\right) - c^*\, P_{gi,min}\right)/P_{Ri}. \tag{11}$$

Expression (11) can be considered a characteristic of the bid of the power reserve price $c_{Ri}(P_{Ri})$ requested from the power reserve market. It depends on the equilibrium price c^* determined by the power market.

6. Study Results

Let us consider the problem of determining the price of the power reserves for four concentrated power plants operating for a total load. The input data consist of the cost characteristics of the power plants (EUR/MW):

$$C_1\left(P_{g1}\right) \;=\; 500 \;+\; 5.3\; P_{g1} + 0.004P_{g1}^2$$

$$C_2\left(P_{g2}\right) = 400 + 5.5\; P_{g2} + 0.006P_{g2}^2$$

$$C_3\left(P_{g3}\right) = 200 + 5.8\; P_{g3} + 0.009P_{g3}^2$$

$$C_4\left(P_{g4}\right) = 300 + 6\; P_{g4} + 0.0085P_{g4}^2$$

It is necessary to take into account the technological limitations on generation (MW) when solving the problem. The technological limitations on power generation:

$$200 \leq P_{g1} \leq 450$$

$$150 \leq P_{g2} \leq 350$$

$$100 \leq P_{g3} \leq 225$$

$$110 \leq P_{g4} \leq 300$$

To calculate the optimal values of the generating and reserve capacities of these manufacturers, we use the expression of the objective function of the form (9). The calculation was performed using the MATLAB R2022b program and Visual Basic 6.0 within the Microsoft Excel application. The c_{gi} prices for the sale of power generation of EPS power plants were set in an arbitrary manner. EPS modes for a total load of 800 MW were calculated. Table 1 shows the calculation results for the two variants of the proposed price bids for the power sold by market participants. Figure 3 shows the generalization block diagram of the calculation process for optimization.

Input Data:

P_{load} —the total load of consumers for the purchase of active power;

$C_i(P_{gi})$—cost characteristics of market suppliers for power generation;

c_{gi}—the active power generation price of market suppliers;

P_{gi_max}, P_{gi_min} —production limitations of active power generation for each producer.

↓

Optimization process by using MATLAB built-in functions:

The minimization of the total cost for active power generation by all producers by using the function of ***fmincon***(F1):

$$\left[F_1 = \sum_{i=0}^{n} c_{gi} P_{gi} + \sum_{i=0}^{n} \left(c_{gi} - 2\gamma_i P_{gi} - \beta_i\right) * (P_{i,max} - P_{gi})\right] \rightarrow min$$

↓

Output Data after Optimization Process:

P_{gi}—optimum volumes of active power generation to the electricity market for each supplier;

P_{Ri}—optimum volumes of active power to the active power reserve market for each supplier;

c_{Ri} —optimum selling price for active power reserves for each supplier.

Figure 3. The generalization block diagram of the calculation process for optimization.

Table 1. The results of determining a generation and reserve power for energy markets.

Consumption Characteristics	$P_{g,case1,2}$, MW	$P_{R,case1,2}$, MW	Case 1		Case 2	
			c_{gi}, EUR/MW	c_{Ri}, EUR/MW	c_{gi}, EUR/MW	c_{Ri}, EUR/MW
C1 (P_{g1})	224.65	225.354	10	2.9	13	5.9
C2 (P_{g2})	262.95	87.05066	12	7.09	15	11.83
C3 (P_{g3})	202.03	22.97275	15	5.54	12	7.45
C4 (P_{g4})	110.38	189.6225	13	5.12	10	2.12

The analysis of the optimization results shown in Table 1 confirms the analytical relationship (6), which implies the obvious fact that, regardless of the declared selling price of generation power, the reserve power price is always lower. The amount of power reserves of each power supplier determined in this case (without economic damage to themselves) to balance the power market can be used. In this case, the welfare function of all participants in the power market will have the maximum value at which the economic interests of all participants in the power market, both sellers and buyers of power, must be satisfied.

7. Discussion

The results of this study underscore the critical role of battery energy storage systems (BESSs) in enhancing the stability and reliability of electric power systems (EPSs) that use a high share of renewable energy sources (RES). As conventional base generation capacities decline, BESSs provide an effective solution for smoothing load fluctuations and maintaining the balance between generation and consumption.

The authors' findings align well with previous studies that emphasize the rapid response and operational flexibility of BESSs compared to traditional reserves relying on fossil fuels [9–11]. Unlike costly and time-consuming grid infrastructure upgrades, BESS can reduce operational expenses while also mitigating environmental impacts through decreased greenhouse gas emissions.

The proposed production capability distribution model complements existing approaches to reserve market optimization by incorporating realistic market conditions and energy source characteristics. Practical implementation demonstrated the model's applicability; however, further research is needed to validate its performance in large-scale, dynamic power systems.

From the perspective of the working hypotheses, the study confirms that integrating BESS is a key factor for ensuring the secure and efficient operation of energy systems with significant RES penetration. Nevertheless, challenges remain, including high capital costs and the need for advanced control strategies capable of managing the variable nature of renewable generation and rapidly changing market conditions.

In a broader context, these results highlight the importance of transitioning towards hybrid energy systems that combine diverse storage and generation technologies. This approach aligns with global trends towards decarbonization and digitalization of energy, supporting the development of control systems that are intelligent and adaptive.

Future research directions include:

1. Developing and integrating advanced forecasting and control algorithms for BESS under renewable generation uncertainties.
2. Investigating hybrid storage solutions, such as combinations of batteries and pumped hydro storage.
3. Analyzing the impact of regulatory frameworks and market mechanisms on the adoption of energy storage technologies.

4. Assessing the scalability and robustness of the proposed models in large, interconnected power systems.

In conclusion, this study demonstrates that backward modeling techniques coupled with the integration of BESS offer promising avenues for improving the resilience and economic performance of future power systems.

8. Conclusions

1. Formation of the reserve capacity market is an important condition for ensuring a reliable power supply to consumers and sustainable operation of electric power systems. The availability of sufficient reserve capacity contributes to the expansion of the range of system services provided under market conditions.
2. The developed model for calculating the capacity reserve for an individual producer can be used as a basis for determining the required reserve volumes from basic generation sources with predictable characteristics. Such sources include nuclear and hydroelectric power plants.
3. For power systems with a high share of renewables (solar and wind plants) that do not have stable generation, the reserve volumes should be determined based on a reliability analysis of the balance in the EPS. High-capacity energy storage systems, including battery energy storage systems (BESSs), can be used as baseload capacity under these conditions.
4. The proposed mathematical model makes it possible to determine the optimum ratio between generation and reserve capacity volumes for producers based on their individual economic characteristics and constraints. This creates conditions for fair participation in capacity and reserve markets.
5. The analytical expression for the reserve capacity price obtained within the model allows producers to form reasonable price bids. The calculation demonstrates that the reserve price is always lower than the price of active capacity, which corresponds to the logic of rational market behavior.
6. The model was successfully applied to an example with four power plants, showing practical feasibility and compliance with analytical relationships. The results obtained confirm the applicability of the method under different scenarios of market bids.
7. The developed approach can be used as a decision support tool for energy market participants, system operators, and regulators, especially in the context of the growing role of renewable generation and the need for flexible capacity management.
8. The scientific novelty of the proposed approach consists of the integration of technical characteristics of generation, market price mechanisms, and public welfare functions into a single mathematical model of optimal capacity allocation.

Unlike existing methods, the model allows the following:

- Simultaneously considering active generation and reserve;
- Deriving an analytical formula for the price of reserve capacity;
- Optimizing producer participation in two markets (capacity and reserve) without sacrificing economic efficiency.

The proposed approach expands the modeling tools in the electric power industry and can be used to build more flexible and sustainable energy markets, especially in the context of the growing share of RES.

9. The main economic criterion for the efficiency of the energy market is the maximization of the welfare function of all market participants (sellers and buyers of electricity). The originality of the study lies in the fact that by introducing the corresponding expression of the electricity producer's income into the target function when distribut-

ing its production capacities for sale and reservation, the problem of forming price bids for the capacity reserve market is solved.

10. The participation of the Baltic countries' TSOs in the European MARI balancing reserve trading platform provides additional opportunities to generate income thanks to the absolute reliability of power delivery from the BESS device. Reducing the trading interval on the MARI platform to 15 min, with absolute reliability of power delivery and BESS device speed, creates a corresponding economic model.

Author Contributions: Conceptualization, A.M.; methodology, A.M.; software, A.M. and T.L.; validation, A.M., T.L. and I.Z.; formal analysis, T.L. and I.Z.; investigation, A.M., T.L. and I.Z.; resources, A.M., T.L. and I.Z.; data curation, A.M., T.L. and I.Z.; writing—original draft preparation, A.M., T.L. and I.Z.; visualization, A.M., T.L. and I.Z.; supervision, A.M., T.L. and I.Z.; project administration, A.M.; funding acquisition, I.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research has not received external funding.

Data Availability Statement: Information can be found by linking to publicly available sources listed in References.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EPS	Electric Power System
RES	Renewable Energy Sources
BESS	Battery Energy Storage System
MARI	Manually Activated Reserves Initiative
BRELL	Belarus, Russia, Estonia, Latvia, Lithuania
TSO	Transmission System Operator
HVDC	High-Voltage Direct Current
Fsw()	Social Welfare Function

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