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ASSESSMENT MODELS FOR THE IMPACT OF ENERGY STORAGE ON OPERATING STABILITY AND THE COMPENSATION OF GENERATION DEVIATIONS AT RENEWABLE ENERGY FACILITIES

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Keywords: energy storage systems, renewable energy, operating stability, compensation of generation deviations, hybrid energy facilities, power systems, resource adequacy.
Abstract. The article analyzes computational and applied models used to assess the impact of energy storage on operating stability and the compensation of generation deviations at renewable energy facilities. Approaches to evaluating the compensating potential of BESS (battery energy storage systems), their contribution to covering power imbalances, improving resource adequacy, and enhancing supply reliability are examined. Particular attention is paid to models linking storage parameters, storage duration, charge-discharge modes, and state-of-charge constraints with the operating conditions of hybrid wind generation and energy storage facilities. It is emphasized that energy storage should be considered not only as a means of compensating generation deviations, but also as an important instrument for increasing power system flexibility and operating stability.

МОДЕЛИ ОЦЕНКИ ВЛИЯНИЯ НАКОПИТЕЛЕЙ ЭНЕРГИИ НА УСТОЙЧИВОСТЬ РЕЖИМОВ И КОМПЕНСАЦИЮ ОТКЛОНЕНИЙ ГЕНЕРАЦИИ ОБЪЕКТОВ ВОЗОБНОВЛЯЕМОЙ ЭНЕРГЕТИКИ

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Ключевые слова: системы накопления энергии, возобновляемая энергетика, устойчивость режимов, компенсация отклонений генерации, гибридные энергетические объекты, энергосистемы, ресурсная достаточность.
Аннотация. В статье анализируются расчетные и прикладные модели, применяемые для оценки влияния накопителей энергии на устойчивость режимов и компенсацию отклонений генерации объектов возобновляемой энергетики. Рассматриваются подходы к оценке компенсационного потенциала BESS (battery energy storage systems), их вклада в покрытие дисбалансов мощности, повышение ресурсной достаточности и надежности энергоснабжения. Особое внимание уделяется моделям, связывающим параметры накопителей, длительность хранения, режимы заряда-разряда и ограничения по уровню заряда с условиями работы гибридных объектов ветровой генерации и систем накопления энергии. Подчеркивается, что накопители следует рассматривать не только как средство компенсации отклонений генерации, но и как важный инструмент повышения гибкости и режимной устойчивости энергосистемы.

Introduction

The development of renewable energy is accompanied not only by an increase in the installed capacity of wind and solar power plants, but also by the growing complexity of ensuring stable and reliable power system operation. As the share of variable generation increases, the influence of weather-dependent output, forecast errors, and uneven power delivery on operating conditions, power balance, and the need for flexible regulating resources becomes more significant. Under these conditions, energy storage systems are increasingly viewed not as an auxiliary element of local infrastructure, but as a tool for compensating generation deviations, improving system controllability, and reducing the burden on flexible generation sources.

The problem of increasing reserve requirements with the growing share of wind and solar generation was examined by Kahrl, who showed that the expansion of variable generation increases the need for reserves to cover forecast errors [1]. Issues related to the management of hybrid power plants with storage under solar forecast uncertainty were considered by Chen, who proposed an approach to market participation strategy design that accounts for available battery capacity and generation uncertainty [2]. However, the comprehensive assessment of energy storage in terms of operating stability, compensation of generation deviations, and changes in the need for flexible generation capacity remains relevant.

In this regard, the purpose of this article is to analyze computational and applied models for assessing the impact of energy storage on operating stability and the compensation of generation deviations at renewable energy facilities. Particular attention is paid to models that make it possible to evaluate the compensating potential of battery energy storage systems (BESS) under deviations between actual and forecast generation, as well as their influence on power balance, reliability of supply, and requirements for reserves and flexible generation sources. The scientific significance of the study lies in combining a power-system approach to operating stability with the applied logic of wind and BESS project development, which allows energy storage to be assessed as a tool for deviation compensation and operating adaptation of renewable energy facilities. The novelty of the article lies in the integrated systematization of BESS assessment models through the interrelated perspectives of imbalance compensation, operating stability, and practical configuration of hybrid wind and BESS facilities.

Methods

The study is based on a structured review and comparative analysis of computational and applied models used to assess the impact of battery energy storage systems on renewable generation deviation compensation, operating stability, resource adequacy, and supply reliability. The reviewed approaches were classified by functional purpose, evaluated indicators, and practical applicability in wind and BESS projects. Special attention was paid to models linking storage power, duration, state of charge constraints, and control strategy with imbalance reduction and system-level reliability effects.

Generation deviations at renewable energy facilities and their impact on operating uncertainty and power balance

Generally, BESS are technical facilities designed to store electrical energy and subsequently deliver it to the grid or to a generating facility depending on operating requirements. In wind and BESS projects, storage is integrated with a wind power plant and is used to compensate generation deviations, shift energy over time, improve operating controllability, and enhance supply reliability. A key feature of BESS is that their functional role is determined by both response power and available energy capacity, since operating tasks require not only rapid deviation compensation but also sustained power delivery over a specified time interval. In this context, BESS serve as an instrument for adapting power system operation to increasing shares of variable generation. The need for such adaptation is primarily associated with the operating characteristics of renewable energy facilities themselves.

The operation of renewable energy facilities is largely determined by **meteorological conditions**, which limits the ability to maintain a prescribed power schedule with high accuracy. As the share of wind and solar generation increases, this feature acquires not only local but also system-wide significance, as it increases operating uncertainty, complicates power balancing, and raises the need for flexible regulating resources in the power system [3]. This trend is particularly evident when comparing the share of renewable electricity generation across countries with different levels of renewable energy integration (fig. 1).

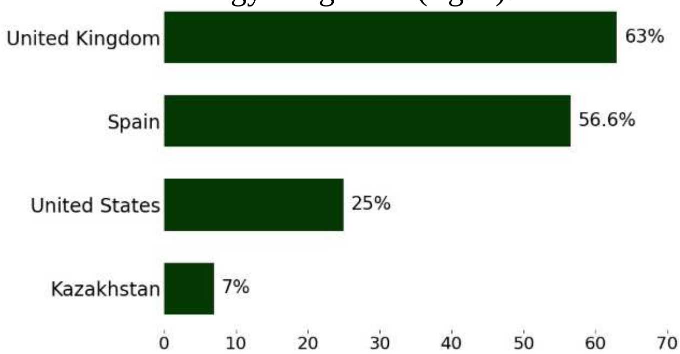

Fig. 1. Share of renewable electricity generation in selected countries in 2025, %, compiled by the author based on EIA, NESO, REE, and Ministry of Energy of the Republic of Kazakhstan data

The selected countries represent different levels of renewable energy integration, illustrating the relationship between the growing share of renewables and increasing flexibility requirements of the power system. In this context, Kazakhstan should be viewed not as lagging behind, but as following a consistent development path: in 2025, 9 new renewable energy projects with a total capacity of 503 MW were commissioned, including 5 wind power plants, 3 solar power plants, and 1 hydropower plant [4]. These data confirm that renewable generation variability and forecast errors are becoming an increasingly important factor not only at the facility level, but also at the level of system-wide operation.

The significance of such deviations depends not only on their magnitude, but also on their **timing**. NERC notes that Texas, California, and the U.S. West may face energy shortfall risks during peak demand hours and after solar output declines, while BESS charged during the day can cover part of these deficits [5]. Renewable generation deviations should therefore be viewed as a system-level risk affecting resource adequacy and operating stability.

The growing scale of the problem is confirmed by current **trends in the development of flexible resources and variable generation**. According to the IEA forecast, global renewable energy capacity will increase by nearly 4,600 GW in 2026–2030, that is, by more than 400 GW annually, with solar generation accounting for the largest share of this growth. This indicates a further increase in the importance of flexibility, reserves, and deviation-compensation resources in power systems with a rising share of renewable energy.

An additional indicator of this trend is provided by the current pace of **flexible capacity deployment and the structure of new power projects.** For example, the EIA reports that 15 GW of utility-scale battery storage was added in the United States in 2025, while a further 24.3 GW is planned for 2026. At the same time, 43.4 GW of new utility-scale solar capacity and 11.8 GW of wind capacity are also expected to come online in 2026. These figures show that the compensation of generation deviations and the provision of system flexibility are increasingly being incorporated into project design at the planning and interconnection stage, rather than being treated as an external auxiliary function of the power system.

From a theoretical perspective, this means that renewable generation deviations should be analyzed not only in terms of forecast accuracy, but also in terms of their impact on reserve requirements, the rate of imbalance variation, and the amount of flexible capacity required to maintain operating conditions within acceptable limits.

Models For Assessing The Compensating Potential Of Energy Storage Systems

Assessing the compensating potential of energy storage systems requires a formalized analysis of their ability to reduce imbalances over specific time intervals. Such models should determine what share of generation deviation can be compensated, how long the required operating mode can be maintained, and to what extent BESS reduce the need for external reserves. In practice, this task is increasingly linked with resource adequacy, renewable firming, curtailment mitigation, and the capacity credit of hybrid renewable energy facilities (tab. 1).

Quantitative assessments show that the compensating potential of BESS is increasingly evaluated through both imbalance reduction and contribution to system reliability. The 2024 DOE report emphasizes that energy storage already plays a significant role in resource adequacy, especially during evening peak hours. Kim et al. showed for VRE-rich areas that increasing storage duration from 1 to 4 hours raises the energy value of hybrids by 29.4% for solar facilities and 26.8% for wind facilities [8]. They also found that solar hybrids reach 90% capacity credit with 4-hour storage, whereas wind hybrids require about 8 hours to achieve the same level. Thus, the assessment of BESS compensating potential should account not only for the volume of deviations that can be covered, but also for the contribution of storage duration to reliability under specific operating conditions.

Tab. 1. Main groups of models for assessing the compensating potential of energy storage systems [6, 7]

Model group	Conceptual logic of the model	Main evaluated indicators	Practical significance for wind and BESS
Balance models for deviation compensation	Comparison of forecast and actual renewable generation to determine what share of the imbalance can be covered by BESS charging/discharging within a given time interval.	Compensated deviation volume. Residual imbalance. Compensation duration. Utilization of storage power and energy capacity.	Make it possible to assess the extent to which BESS reduces deviations from the dispatch schedule and decreases the burden on external reserves.
Scenario-based and stochastic models	Analysis of multiple scenarios of forecast values, actual generation, state of charge, and operating constraints.	Probability of undercompensation. Required BESS power range. Stability of results under forecast uncertainty.	Are applicable for selecting storage parameters and operating strategies under uncertainty.
Renewable firming and curtailment mitigation models	Consideration of BESS as a means of smoothing the generation profile and shifting energy from surplus periods to deficit periods.	Reduction in generation curtailment. Increase in useful energy delivery. Improvement in the power output profile.	Are especially important for hybrid solar and wind facilities with output constraints.
Capacity credit and resource adequacy models	Assessment of the contribution of a hybrid facility with BESS to load coverage during stressed hours and to the reduction of power shortage risk.	Capacity credit. Contribution to adequacy. Net load peak coverage. Duration of reliable power delivery.	Are used in the system-level assessment of the role of BESS in supply reliability and in partially replacing flexible generation.

Models For Assessing The Impact Of Bess On Operating Stability And Supply Reliability

Assessing the impact of energy storage systems on operating stability and supply reliability requires considering BESS as a system support resource capable of compensating local generation deviations, contributing to power deficit coverage, supporting primary frequency response, mitigating transient disturbances, and improving load supply during critical hours. In this context, the applied models should account not only for storage power and energy capacity, but also for response speed, state of charge, discharge duration, conditions for participation in control loops, and the nature of system disturbances. Of greatest practical value are models that combine the assessment of adequacy effects, frequency support, and limitations associated with discharge duration and charge recovery (tab. 2).

Tab. 2. Main groups of models for assessing the impact of BESS on operating stability and supply reliability

Model group	**Conceptual logic of the model**	**Main evaluated indicators**	**Practical significance for wind and BESS**
Resource adequacy and capacity credit models	Assessment of the contribution of BESS to load coverage during hours of system stress and to the reduction of capacity shortage risk.	ELCC. Capacity credit. Contribution to peak coverage. LOLE/LOLP.	Make it possible to determine the extent to which storage improves supply reliability and can partially replace flexible generation.
Frequency stability and fast frequency response models	Analysis of the ability of BESS to respond rapidly to generation loss or frequency disturbances.	Response speed. Frequency deviation depth. Nadir. MW response volume. Droop parameters.	Are applicable for assessing the contribution of storage to frequency support and to reducing the risk of emergency deterioration of operating conditions.
Scenario-based operating stability models	Consideration of power system operation under different combinations of renewable generation deviations, load conditions, and BESS state of charge.	Probability of supply shortfall. Duration of operating support. Residual deficit. State of charge constraints.	Make it possible to test the robustness of decisions under forecast uncertainty and during stressed hours.
Supply reliability models under extreme conditions	Consideration of prolonged events, generation deficits, weather stress scenarios, and risks of storage depletion.	Load supply adequacy. Duration of autonomous support. Risk of charge depletion. Need for recharging.	Are important for assessing the limits of BESS applicability and the need to combine it with other flexible resources.

Quantitative evidence shows that BESS are already treated as a significant system-level reliability resource. In its 2025 review, NERC reports improved frequency response in areas with high BESS penetration. In the Texas Interconnection, installed battery capacity increased from 1,307 MW in January 2022 to 10,027 MW in December 2024, with expectations of approaching 19,000 MW by the end of 2025. NERC also notes that, in ERCOT, batteries provided up to 100% of total frequency regulation capacity in 2024, while during certain disturbances their contribution to total MW response exceeded 70%. At the same time, NERC points out that the reliability effect of BESS in winter stress scenarios depends on sufficient state of charge and timely recharging. Therefore, models for assessing the impact of BESS on operating stability and supply reliability should account not only for fast frequency response, but also for contribution to adequacy and discharge-duration constraints.

Practical Application Of Models In Substantiating The Parameters And Operating Modes Of Wind And Bess

The practical application of models in wind and BESS projects involves their use in addressing specific tasks related to substantiating storage parameters and operating modes. Of particular importance are the selection of storage power and duration, the definition of target modes for compensating generation deviations, and the coordination of the operational and system-level functions of BESS. The main practical tasks of such substantiation are presented in table 3.

Tab. 3. Practical areas of model application in selecting the parameters and operating modes of wind and BESS [9, 10]

Engineering task	Parameters to be substantiated	What needs to be determined	Practical significance for the project
Compensation of deviations between actual and forecast generation.	BESS power. Operating state of charge range. Charging and discharging strategy.	What share of the imbalance the storage system can cover without external reserves and what the residual imbalance is.	Makes it possible to reduce deviations from the schedule and decrease the burden on balancing resources.
Coverage of critical load hours and adequacy effect.	Storage duration. Available power during peak hours. Reserve margin.	To what extent BESS increases contribution to peak coverage and the capacity value of the hybrid facility.	Helps justify the choice of a 2-, 4-, or 8-hour configuration depending on the system profile.
Reduction of curtailment and alignment of the output profile.	Storage capacity. Activation thresholds. Rules for shifting energy over time.	What volume of surplus generation can be stored and shifted to higher-value hours.	Increases useful energy delivery and improves facility controllability.
Operation in the system support mode.	Response speed. Droop settings. Power reserve. Charging requirements.	Whether the storage system can participate in frequency response and operating support without losing its primary function.	Makes it possible to coordinate the commercial and system-level roles of BESS.
Selection of the operating strategy.	Functional priorities. Depth of cycling. Degradation constraints.	How the compensation effect, adequacy value, and storage wear change under different control algorithms.	Provides a basis for long-term O&M and asset management decisions.

The practical significance of the models considered is particularly evident in large hybrid projects, where storage parameters directly determine the ability to compensate generation deviations, contribute to stressed-hour coverage, and improve the reliability of power delivery. In such projects, storage acts not only as a means of shifting energy over time, but also as an instrument for reducing operating uncertainty, improving the controllability of power output, and adapting wind generation to power system requirements.

This applied logic is also confirmed by broader market data. According to Berkeley Lab, by the end of 2023 the United States had 469 operating hybrid plants with nearly 49 GW of generating capacity and 3.6 GW / 11.1 GWh of storage. Among operating hybrids, PV+battery configurations were dominant, and the typical storage duration in many such projects was close to 4 hours [11]. The trend toward hybridization is even more pronounced in interconnection queues. At the end of 2023, they included 2,532 solar hybrids totaling 602 GW of generation capacity and 1,336 GWh of storage, as well as 2,243 storage hybrids with 1,763 GWh of storage capacity. These data suggest that project design is increasingly focused not on whether storage is needed, but on which storage parameters are required to perform a specific system and commercial function.

Storage duration is a key parameter in BESS design. The 2024 DOE report shows that storage approaching 4 hours gains substantial capacity value because it can cover a large share of evening peak stress periods. Berkeley Lab likewise reports that solar hybrids can reach 90% capacity credit with about 4 hours of storage, whereas wind hybrids require about 8 hours to achieve a comparable level. This means that, in wind and BESS projects, configuration should be selected according to the target system function rather than a universal storage standard.

Operating strategy is also critical. NREL emphasizes that the value of storage in hybrid plants depends not only on battery size, but also on dispatch rules, since the same system may be used for energy shifting, smoothing, reserve provision, or resilience support. Therefore, practical model application should lead not only to the selection of storage power and capacity, but also to an operating regime that balances deviation compensation, reliability enhancement, and battery degradation control.

Conclusion

The analysis shows that energy storage systems in wind and BESS projects perform a broader function than generation smoothing, contributing to operating stability, compensation of deviations between actual and forecast generation, and reduction of the burden on flexible generation sources. The approaches considered confirm that the practical effectiveness of BESS is determined by a combination of parameters, including power, storage duration, response speed, state of charge range, and control algorithm. At the same time, recent studies show that, as the share of renewable energy increases, the role of storage is increasingly shifting toward resource adequacy, frequency response, renewable firming, and curtailment mitigation. This means that BESS assessment models should be integrated and account simultaneously for power balance, supply reliability, and operational constraints. Further research potential lies in the development of comprehensive models combining renewable generation forecasting, probabilistic imbalance assessment, operating disturbance scenarios, and optimization of BESS operating modes within a single analytical framework.

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