ELIT
Economic Laboratory Transition
Research Podgorica

Montenegrin Journal of Economics

For citation:

Konnikov, E., Rodionov D., Dmitriev, N., Zaytsev, A., Zengwei, Y. (2026), "Probabilistic Risk Analysis for Energy Storage Systems: Application of Gamma Distribution and Event Modeling", *Montenegrin Journal of Economics*, Vol. 22, No. 4, pp. 19-37

Probabilistic Risk Analysis for Energy Storage Systems: Application of Gamma Distribution and Event Modeling

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ARTICLE INFO

Received October 18, 2024
Revised from November 18, 2024
Accepted december 18, 2024
Available online October 15, 2026

JEL classification: O11, F62, R58

DOI: 10.14254/1800-5845/2026.22-4.2

Keywords:

Probabilistic analysis,
event modeling,
energy storage systems,
undersupply,
energy infrastructure,
economic assessment,
risk management.

ABSTRACT

The article presents a study of the probabilistic risk assessment for energy storage systems based on the analysis of data on power outages to consumers in St. Petersburg for 2022. The object of the study is power outages resulting in undersupply of electrical energy. The subject of the study is the probabilistic characteristics of risks and methods for their minimization. The aim of the work is to develop approaches to risk management through the use of energy storage systems. The research methodology includes event modeling, approximation of probability distributions using normal and gamma distributions, as well as an assessment of the quantiles of probability prices. The analysis showed a significant impact of scheduled and unscheduled outages on losses from undersupply of electricity. Based on mathematical modeling, probabilistic damage profiles were constructed, average values and quantile indicators for each type of outages were calculated. An economic assessment showed that the integration of energy storage systems can reduce losses by compensating for undersupply of electricity. The paper also substantiates the parameters of the optimal distribution of costs for the implementation of these systems, taking into account the payback period. The obtained results form a theoretical and applied basis for improving the efficiency of energy infrastructure management in large cities.

INTRODUCTION

The relevance of the study is justified by the growing need to improve the sustainability of energy supply in countries with rapidly developing economies, such as Russia, India and China, members of the BRICS group. These countries are experiencing rapid growth in urbanization, increasing energy loads and significant depreciation of energy infrastructure, giving rise to challenges in the field of energy supply management. In megacities, including St. Petersburg in Russia, Mumbai in India and Shanghai in China, power outages lead to economic and social costs, requiring the implementation of technologically sound solutions, such as energy storage systems.

The purpose of the study is to study the probabilistic characteristics of power outages, analyze their risks and assess the applicability of energy storage systems to improve the efficiency of energy supply in megacities.

Research objectives:

- Conducting an analysis of statistical data on power outages using St. Petersburg as a representative metropolis as an example.
- Studying the parameters of using energy storage systems to minimize damage from undersupply of electricity.
- Building probabilistic models for assessing the risks of outages that take into account the specifics of megacities in Russia, India and China.
- Forming approaches to improving the energy infrastructure of the BRICS countries with an emphasis on urbanized areas.
- Developing practical recommendations for the implementation of energy-saving technologies and managing energy supply risks.

The object of the study is power outages in large cities of the BRICS countries. The subject of the study is the probabilistic characteristics of the risks of outages and their impact on the implementation of energy storage systems.

Research methods include event modeling, analysis of probability distributions, economic assessment and building analytical models for quantitative assessment of damage from outages and assessment of the effectiveness of energy storage systems.

The study focuses on St. Petersburg as an example of a megacity where power outages have economic and social consequences. Analysis of statistical data showed that current energy supply management is often limited to the use of diesel generators, which have disadvantages such as noise, harmful emissions and dependence on fuel. The focus of the study is on the integration of innovative solutions into the energy sector of the BRICS countries, which requires the development of a regulatory framework, stimulation of investment in high-tech projects and the construction of analytical tools to assess their effectiveness. The proposed methods contribute to the formation of a sustainable energy infrastructure capable of minimizing the risks of outages and losses from undersupply of electricity in urbanized areas.

2. RESEARCH METHODOLOGY

Energy storage system (ESS) integration and probabilistic energy supply risk analysis are becoming the focus of research, especially in rapidly urbanizing economies such as the BRICS countries. Using probabilistic models to assess energy supply risks allows for multiple factors related to infrastructure instability and forecast uncertainty to be taken into account. Research provides evidence on the application of ESS as tools to improve energy resilience in the face of increased grid loads. These developments demonstrate the potential to minimize losses from outages and improve energy supply efficiency.

Shi et al. proposed a probabilistic planning method for power and energy balance risks based on distributed robust optimization (Shi et al., 2024). This approach addresses the instability and uncertainty issues that arise in power systems with a high share of renewable energy sources (RES). The use of probabilistic indices in this method allows for the quantitative assessment of power and energy balance risks. In the study by Pudela, Dubey, and Bose probabilistic metrics are proposed that are used to assess the operational resilience of electricity distribution systems to high-severity and low-probability events. Their model-based framework analyzes the resilience performance under different weather scenarios and provides recommendations for planning measures aimed at risk mitigation (Poudel et al., 2019).

Qi et al. proposed a unified model for universal energy storage systems (ESS) that takes into account exogenous and endogenous uncertainties. The probabilistic approach used in this study serves to assess the efficiency of ESS integration into urban power grids, ensuring energy consumption optimization (Qi et al., 2022). This approach takes into account uncertainties in forecasts and proposes solutions that contribute to improving the resilience of power systems.

The work of Zhogova et al. offers a toolkit for assessing the socio-economic situation of municipalities taking into account the impact of power outages on urban areas (Zhogova et al., 2022). In addition, the BRICS Energy Report highlights the relationship between energy infrastructure and socio-economic processes in cities (BRICS Energy Report, 2022). It also highlights the need for synergies between the energy systems of the participating countries, which play a significant role in the global energy system. The report proposes measures to stimulate direct investment, increase the transparency of licensing for exploration and development of energy resources, and enhance technology transfer between countries.

The development of positive energy balance areas, as well as connected urban areas and energy-efficient buildings, is becoming increasingly important in light of modern approaches to energy system management, as shown in the work of Anastasovski et al. (2024). Energy storage plays a special role in ensuring the balance between centralized and distributed energy generation, contributing to increased energy security and stability. Energy storage technologies provide flexible generation and transmission of energy, contributing to the development of a sustainable energy supply network. In addition, their use in modern energy networks allows avoiding peak costs and increases the efficiency of energy supply. Given the growing transition to inexhaustible energy sources, storage technologies are becoming an integral part of the energy system of the future.

For example, forecasting and classifying oil and gas production in the oil and gas industry are complex tasks that require significant computational resources. The reservoir modeling software used is used to predict future production and develop optimal field development plans, but the forecasting process requires tens or hundreds of model runs, making it labor-intensive. To overcome these limitations, machine learning and deep learning methods are used to significantly speed up the forecasting process. As shown in the source by Ibrahim et al., such algorithms adapted for the energy industry can be used not only to manage the performance of oil wells, but also to predict and optimize the operation of energy storage systems, increasing their efficiency and adaptability to changing energy consumption conditions (Ibrahim et al., 2022).

The scientific work by Zaytsev et al. is devoted to the analysis of the economic aspects of green energy development with an emphasis on strategic sustainability and environmental protection (Zaytsev et al., 2022). The study emphasizes the importance of integrating RES into the transition to RES. This approach contributes to the reliability of energy supply in the context of urbanization and the creation of sustainable infrastructure for megacities. The economic aspects under consideration demonstrate the need to develop strategies aimed at optimizing the use of RES and reducing dependence on traditional energy sources. The study by Zhao and analyzes the relationship between the introduction of green energy, economic growth and innovation in OECD countries (Zhao et al., 2024). The work emphasizes the importance of green energy, supported by economic growth and technological innovation, for achieving sustainable development. For the analysis, a random forest regression model was used, which processes nonlinear dependencies and assesses the importance of factors influencing the studied indicators. Statistics for the period 2013–2022 show that green energy adoption, enhanced by economic growth and innovation, has a significant impact on the human development index. This finding supports the need for a systemic approach to integrating green technologies into economic growth and sustainable development strategies.

Wei et al. investigated the impact of renewable energy transition, green growth, technology, and trade on environmental quality in sustainable development countries (Wei et al., 2023). The methodological basis of the study was the Cross-sectional-Augmented Auto Regressive Distributed Lag (CS-ARDL), Augmented Mean Group (AMG), and Common Correlated Effect Mean Group (CCEMG), which allow identifying long-term relationships between variables. The results show that renewable energy consumption and green technology adoption have a positive effect on environmental performance, while trade liberalization improves environmental quality in the short and long term. The findings support the pollution halo hypothesis and highlight the role of foreign investment in the development of green policies. Ullah et al. analyzed the impact of green investment, energy intensity, and economic complexity on the trade-off between economic growth and environmental degradation (Ullah et al., 2024). Using a panel autoregressive distributed lag model, augmented mean group, and common correlated effects group means, the authors investigated the impact of green investment, energy intensity, and trade liberalization on environmental quality in sustainable development countries. complex dynamics of interactions between economic factors and carbon emissions. The results show that in the early stages of economic growth, increases in GDP and energy intensity lead to an increase in carbon emissions, but in more advanced stages, green investments contribute to their reduction, which confirms the hypothesis of the environmental Kuznets curve. The unidirectional and bidirectional causal relationships revealed by the Dumitrescu-Hurlin method demonstrate systemic interactions between economic growth, energy intensity, and environmental complexity.

The study by Zaytsev et al. assesses the innovative potential of alternative energy in the context of the transition to a circular economy (Zaytsev et al., 2021). ASEs are considered as an element for integrating alternative energy sources and increasing the resilience of energy systems. ASEs provide a balance between the growing demand for energy and the need to reduce the negative impact of traditional energy sources on the environment, contributing to the sustainable development of megacities. Emerging economies characterized by high energy intensity face energy price volatility, which can increase macroeconomic instability and complicate sovereign debt management. The study, which implements a quantile vector autoregressive model based on 2011–2024 data, analyzes the interactions between economic uncertainty, energy risks, and sovereign risk in BRICS countries (Gnagne et al., 2024). The empirical results show that energy risks act as shock transmitters in all countries except Russia and India, where sovereign risks play a more significant role. Risk dynamics reflect the heterogeneity of country profiles, their economic structure, market conditions and energy trade status. Policy decisions should take into account energy, economic and debt factors to ensure macroeconomic stability. For BRICS countries, developing a balanced energy policy focused on the integration of renewable energy sources and financial risk management is the basis for sustainable economic growth, as confirmed in the work M. Draz (Draz et al., 2024). The combination of these approaches strengthens adaptability to crises and reduces the impact of global volatility.

The fundamentals of power system analysis and operation presented in Chapter focus on steady-state, transient and dynamic modes of operation of the power infrastructure (Nucci et al., 2021). Technical aspects related to power system analysis include load flow calculations, short-circuit analysis, frequency control, electromagnetic transient modeling, and transmission system stability. Particular importance is given to distributed generation and smart grids. In the context of a high share of renewable energy sources, which are characterized by variability and intermittency, energy storage systems (ESS) become an important element for stabilizing power systems. Overgeneration problems arising from the mismatch between renewable energy sources and loads highlight the need for standardized approaches to the economic evaluation of ESS, including the levelized cost of storage. A probabilistic approach applied to power system modeling offers an alternative to deterministic methods, which are often insufficient to manage operational uncertainty. The use of data-driven algorithms, as shown in the work of Haugen et al.,in forecasting and optimal power flow (OPF) problems improves risk management (Haugen et al., 2023). The forecasted data serve as a basis for assessing operational instability, power losses, financial costs and waste of renewable energy sources. Neural networks, surpassing traditional machine learning algorithms in accuracy, in combination with linear-quadratic controllers provide a balance between complexity and performance. Probabilistic OPF methods minimize power losses, identify load irregularities and optimize the use of energy resources.

The widespread use of conventional fossil fuels in power and electricity generation poses global environmental and climate challenges. In the context of integrated energy systems operation, taking into account the randomness of distributed generation and load, significant operational risks arise, which was developed in the paper by Y. Li and his colleagues (Y. Li et al., 2022). Probabilistic approaches such as multi-energy flow models are becoming critical to assessing the safety and cost-effectiveness of operation. Such models are based on stochastic methods including cumulant analysis, Cholesky decomposition, and Nataf transform, which allow correlations to be established between random variables. Risk indicators are developed based on these methods. The study by Mirdanies et al. (2022) analyzed the impact of MNE on reducing the risks of power outages in urban power grids with a high share of renewable generation. The use of the Monte Carlo method allowed analyzing probabilistic scenarios of power supply failures and demonstrated the ability of MNE to ensure continuity of power supply even under extreme conditions. In the work of L. Li et al., an explicit model for battery and hydrogen storage systems (HSS) is constructed, proposing optimal load shedding strategies using a sequential Monte Carlo method (Li et al., 2021). The study confirms that the implementation of HSS reduces the load on the power systems and increases their resilience, which is especially relevant for the BRICS countries, where the implementation of such technologies can minimize the impact of power outages on socio-economic stability.

The study on the relationship between energy consumption and economic growth in the BRICS countries covers the period from 1990 to 2018 (Khobai et al., 2021). The panel data analysis revealed long-term cointegration relationships between the variables under consideration, as well as causal relationships, which were studied using the Granger causality method. The analysis shows a unidirectional relationship from economic growth to energy consumption, which confirms the possibility of implementing energy conservation policies in the BRICS countries without a significant negative impact on economic growth. The results emphasize the need to develop sustainable energy strategies aimed at reducing unnecessary energy losses, especially in the context of ongoing urbanization. The risk assessment of water supply and energy supply in urban areas was carried out in the study using the copula function to analyze the relationship between monthly water and energy consumption for the period from 2011 to 2022 (Goodarzi et al., 2024). The forecast of future needs from 2023 to 2032 is based on the seasonal autoregressive integrated moving average (SARIMA) method and cumulative distribution functions (CDF). Pearson correlation analysis showed a strong relationship between water and energy supply, indicating the importance of an integrated approach to infrastructure management. Data distributions were described by a lognormal function for water supply systems and a gamma distribution for energy supply using the Gumbel Copula function, which minimized the Akaike Information Criterion (AIC). The projected risks of water supply, energy supply and their joint dependence (WEN) show an increasing trend, which creates the need for careful assessment and planning to prevent critical situations in cities.

The issues of import substitution of processors and software in Russia are related to restrictions on external technology supplies, which significantly affects technological independence, which was considered in the study by Kurochkina et al. (2024). The development of digital solutions to overcome dependence on imported technologies is becoming a key area for ensuring the sustainability of energy systems and the implementation of energy storage systems (ESS). The use of domestic processors and specialized software allows maintaining the stability of the energy infrastructure, minimizing dependence on global supplies. This solution strengthens national energy security and creates a basis for the independent development of energy technologies.

3. METHODOLOGY

The study implemented statistical data on power outages to consumers (using the city of St. Petersburg as an example for 2022).

During 2022, 3932 consumers out of 8098 registered power outages. Outages are classified into three main categories:

- Planned outages (P) - necessary for preventive maintenance and equipment upgrades. Their schedule is agreed upon in advance, which minimizes their impact on consumers.
- Emergency outages (E) - occur as a result of equipment failures or network disruptions. These outages are difficult to predict due to many influencing factors, including the technical condition of the infrastructure and external conditions.
- Unscheduled outages (U) - carried out by operational teams or remotely, often as a result of relay protection and automation. They occur when the condition of the equipment creates a high risk of an emergency outage.

An example of reporting documentation on outages in the company Lenenergo (supplying the city of St. Petersburg) is presented in Table 1, which illustrates the main parameters: type of facility, duration of outage, consumer reliability categories and voltage levels.

Table 1. Example of a report on outages in the Lenenergo company in 2022

Data on the fact of termination of transmission of electric energy															
Electricity Transmission Termination Number / Total Line Number	Name of the structural unit of the network organization	Object type: cable power line, overhead power line, overhead cable power lines, substation, transformer substation, distribution substation	Highest voltage class of disconnected equipment of the grid organization, kV	Type of termination of electricity transmission (P, E, U)	Duration of interruption of electric power transmission, hours	Number of points of supply of consumers of the grid organization's services for which there was a power supply interruption, pcs., including:									Total volume of actual load (power) at consumer connections, kW
						TOTAL	in the division of reliability categories of consumers of electric energy			in the division of voltage levels of the consumer electronic control unit of electrical energy				Related grid organizations and producers of electric energy	
							1st category of reliability	2nd category of reliability	3rd category of reliability	HV (110 kV and above)	MV1 (35 kV)	MV2 (6-20 kV)	LV (0.22-1 kV)		
1	2	3	5	8	9	13	14	15	16	17	18	19	20	21	22
1	"Rosseti Lenenergo" Kolpinsky district of electric networks	CPL	6 (6.3)	U	0.7500	0	0	0	2	0	0	2	0	0	200.00000
2	"Rosseti Lenenergo" Resort district of electric networks	CPL	10 (10.5)	U	0.2833	0	0	1	1	0	0	0	2	0	20.00000

Source: own

An analysis of power outage data for 2022 at Lenenergo revealed that out of 8,098 consumers, 3,932 experienced power outages. The classification of outages showed that 1,374 cases were scheduled outages, and 2,558 were unscheduled. No emergency outages were recorded during the year, indicating a relatively high level of technical control. To assess the economic losses from outages, the undersupply of electricity was calculated for each type. The analysis of the data presented in Tables 2 and 3 showed that the number of technological violations (4,107 cases) significantly exceeds the number of recorded outages. This aspect is due to the fact that technological violations cover a wider range of events, including local faults and preventive maintenance.

Table 2. Power outages at Lenenergo in 2022

Type of accident	*Number of accidents per year*	*Number of enterprises*
Planned outages (P)	1 374.00	8098
Emergency outages (E)	0.00	8098
Unscheduled outages (U)	2 558.00	8098

Source: own

Table 3. Cost of outages in Lenenergo in 2022

Summary of emergency shutdowns	*Q1 2022*	*Q2 2022*	*Q3 2022*	*Q4 2022*	*Total*
Number of technological violations, pcs.	993	1042	916	1156	4107
Undersupply of electricity, thousand kWh	145.3	79.9	87.9	144.4	457.5

Source: own

To assess the undersupply of electricity for each type of outage, a calculation method was developed based on the ratio of the total volume of undersupply of electricity to the number of technological disruptions. The calculated indicator is multiplied by the number of outages by types presented in Table 2. The cost of electricity, set at 1 ruble per kWh, made it possible to estimate the economic losses from the undersupply of electricity. For unscheduled outages, an increased tariff is applied (+0.4 rubles), which is associated with a greater load on operational resources and high costs of restoration work.

The data presented in Table 4 indicate that scheduled shutdowns resulted in a shortfall of 151.14 thousand kWh and financial losses of 151,140 rubles. Unscheduled shutdowns were more costly – 281.38 thousand kWh and 383,700 rubles, respectively. This difference emphasizes the need to develop management strategies to minimize economic damage.

Table 4. Summary table of outage and cost data

Number of technological violations, pcs.	*4107*
Undersupply of electricity, thousand kWh	457.5
Undersupply of electricity per one scheduled outage, thousand kWh	0.110
Undersupply of electricity per one unscheduled outage, thousand kWh	0.150
Number of scheduled outages	1374
Number of unscheduled outages	2558
Undersupply of electricity due to scheduled outages, thousand kWh	151.14
Undersupply of electricity due to unscheduled outages, thousand kWh	281.38
Amount of lost profit due to scheduled outages, rubles	151140
Amount of lost profit due to unscheduled outages, rubles	383700

Source:own

The risk profile analysis presented in Table 5 shows that unscheduled outages require more attention, as they are the most costly. The introduction of energy storage systems (ESS) can significantly reduce the likelihood and consequences of unscheduled events. ESSs allow reducing the load on the network by providing backup power in the event of unforeseen outages. Considering that the number of emergency outages is zero, it was decided to exclude these types of outages as not affecting the analysis. Based on the above statistical data, the risk profile presented in Table 5 was compiled.

Table 5. Risk profile obtained for 2022 for outages in Lenenergo

Type of shutdown	*Number of shutdowns per year, pcs.*	*Number of substations, pcs.*	*Total amount of damage, rubles*
P-Planned shutdown	1 374.00	8098	151 140.00
U-Unscheduled shutdown	2 558.00	8098	383 700.00

Source: own

Strategic planning in the BRICS countries should include:

- Integrating outage forecasting methods using probabilistic models and machine learning technologies.
- Developing grid modernization programs taking into account local characteristics and risks.
- Optimizing tariff policies to stimulate investment in grid reliability.

The energy infrastructure of the BRICS countries faces increasing challenges associated with the intensive growth of energy consumption, urbanization, and the need to integrate renewable energy sources. Analysis of power outage data, as in the case of St. Petersburg, provides tools for assessing the vulnerability of energy systems, as well as developing strategies to improve their resilience.

For Russia, the results of the analysis allow identifying the most vulnerable links in the energy infrastructure, providing a basis for grid modernization programs and the introduction of backup energy systems. India, with its rapid growth of renewable energy, can adapt the proposed methods to reduce the impact of unscheduled outages on megacities such as Delhi and Mumbai. China, as the largest electricity producer, can use these approaches to manage loads in megacities and reduce economic losses caused by grid overloads. South Africa and Brazil can use these tools to adapt infrastructure to growing challenges, including eliminating the economic consequences of outages. The use of SES in the BRICS countries is becoming a strategic direction that can minimize losses from undersupply, increase grid stability and strengthen energy security. Risk profile analysis and development of management decisions based on statistical data ensure resource allocation and investment planning.

4. RESULTS & DISCUSSION

4.1 Probabilistic structure of the risk portfolio

To perform event modeling in Python, it is necessary to first define the probabilistic structure of the risk portfolio. Analysis of power outage events requires the use of a probabilistic approach based on modeling the frequency and severity of each event. These indicators, when multiplied by each other, form a probabilistic estimate of the cost of an outage. For the analysis, a simulation of one million events was carried out using a normal probability distribution. A variance equal to 50% of the mathematical expectation characterizes the acceptable level of price deviation.

The results of the modeling are presented in Table 6. They show probabilistic prices for scheduled and unscheduled outages, as well as the corresponding quantile values for 99% and 95% of cases.

Table 6. Probability structure of the risk portfolio

Type of shutdown	*The likely cost of shutdown*	*99 quantile probability*	*95 quantile probability*	*Probability of exceeding average severity*	*Probability of exceeding half of average damage*
P-Planned shutdown	18,67	196,19	139,87	8 %	17 %
U-Unscheduled shutdown	47,34	288,66	225,10	16 %	31 %

Source: own

The data visualization is presented in Figure 1 in the form of histograms of probable outage prices for different types of events.

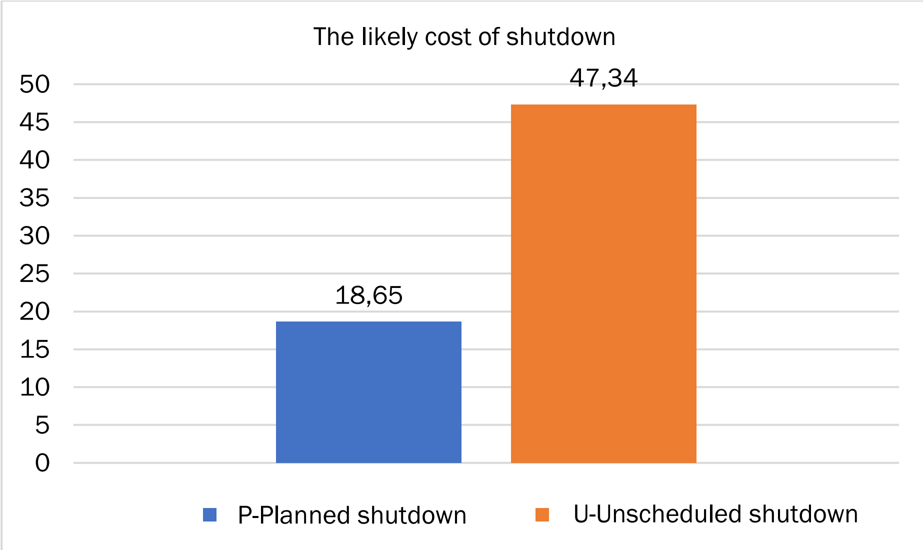

Figure 1. Probable cost of shutdown
Source: own

The graph shows that unscheduled outages are more expensive than scheduled ones, which is confirmed by the probability quantile parameters. Figure 2 shows the 99th quantile, which reflects the maximum possible price in 99% of cases.

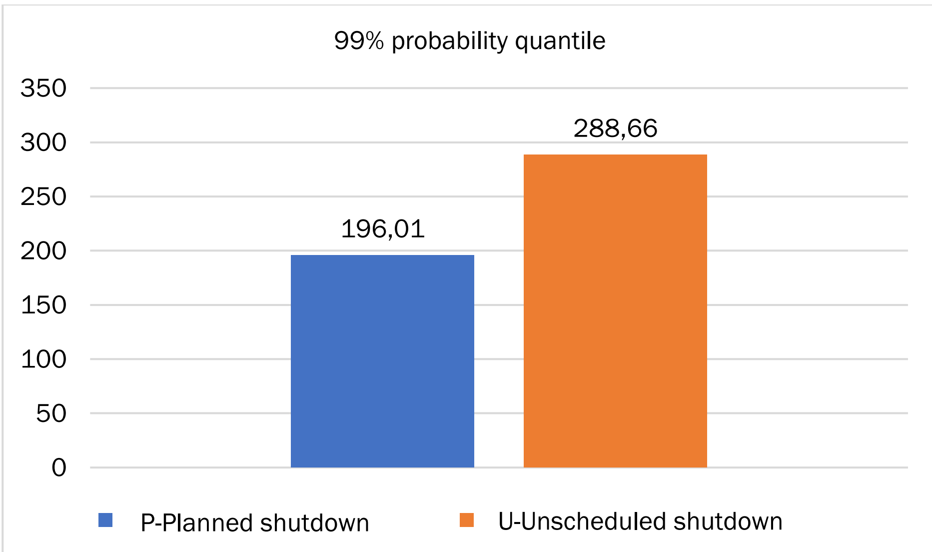

Figure 2. 99th probability quantile
Source. own

The analysis showed that the cost of unscheduled outages is significantly higher than the cost of planned outages, which is confirmed by the data presented in the probability price graphs. The analysis of the 95th probability quantile, visualized in Figure 3, shows that the maximum probable cost of unscheduled outages exceeds the cost of planned outages, reflecting the same pattern as when considering the 99th probability quantile. Such a stable trend indicates the need for special attention to the management of unscheduled events, since their financial consequences are the most significant.

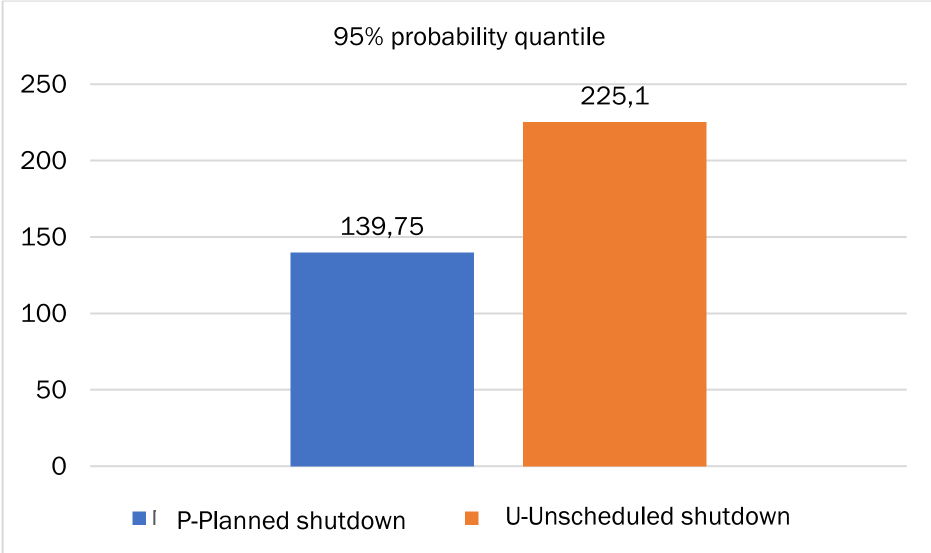

Figure 3. 95th probability quantile
Source: own

The correlation of probable costs of outages and their probability quantiles allows us to formulate several conclusions:

- All types of outages require management, since neglecting any of them can lead to significant financial and operational losses.
- Unscheduled outages are characterized by the highest probable cost and a high value of the 99th probability quantile, which requires the development and implementation of compensatory measures aimed at minimizing the consequences of such events.
- Despite the fact that the cost of planned outages is lower, their probability is also quite high, which dictates the need to plan and minimize their impact.

Figure 4 presents data on the probability of exceeding the average damage and half the average damage for different types of outages.

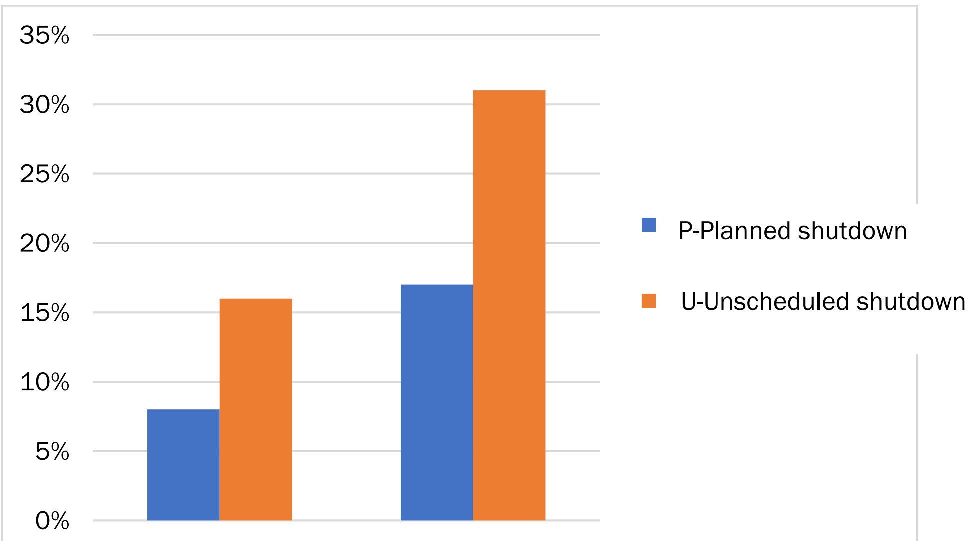

Figure 4. Probability of exceeding the average damage and half of the average damage
Source: own

The analysis of the probability of exceeding the average damage confirms that unscheduled outages demonstrate a high level of uncertainty: the probability of exceeding the average damage is 31%. This indicates a significant spread of possible prices and the need to suppress this type of event.

Event classification and strategic recommendations. Based on the analysis, two types of events were identified:

- Suppressed events: unscheduled outages that require minimization through the introduction of compensating mechanisms and increased control over operational processes.
- Controlled events: planned outages for which effective planning can significantly reduce their negative impact.

To reduce risks and minimize damage, it is recommended to:

- Develop risk management strategies based on probabilistic analysis of events and cost assessment.
- Invest in outage forecasting and prevention technologies, including energy storage systems.
- Develop adaptive network management mechanisms aimed at reducing the impact of both unscheduled and planned outages.

The proposed measures are particularly relevant for the BRICS countries, where complex energy systems and a high degree of urbanization require the implementation of innovative solutions to ensure stable energy supply.

4.2 Approximation by normal distribution

To estimate the probability distribution of the cost of events, the obtained data was approximated by a normal distribution function described by the formula:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

μ is the mathematical expectation, which coincides with the median and mode of the distribution; σ is the standard deviation, which determines the width of the distribution.

This approach allows systematizing the array of probable prices of events (severities), adjusted for the frequency of their occurrence. Approximation is an attempt to reflect the patterns of data distribution and identify the degree of their compliance with the theoretical model. Figure 5 shows a visualization of the approximation of the array of probable prices by a normal distribution.

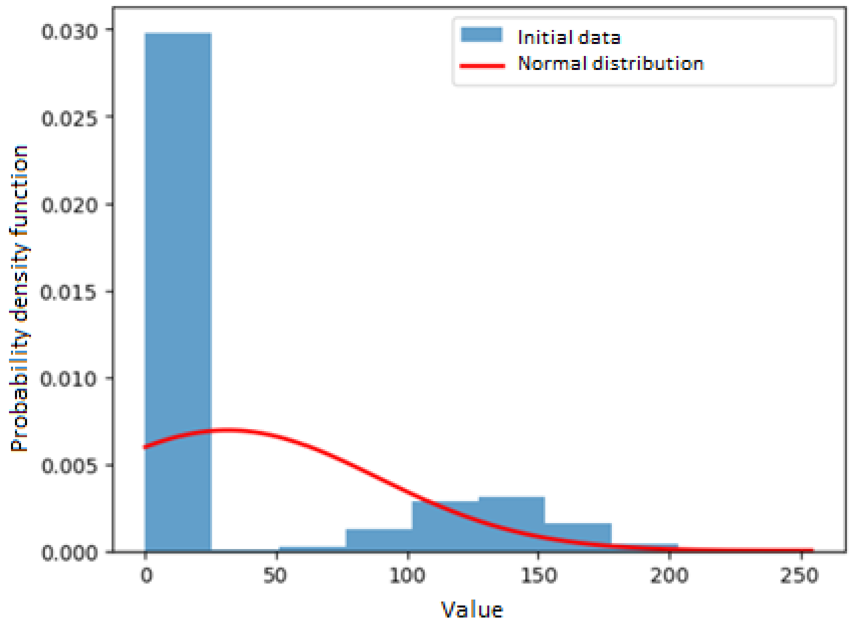

Figure 5. Approximation of the probable price by a normal distribution
Source: own

The approximation analysis is performed using the determination coefficient (R^2), which evaluates the degree of compliance of the model with the empirical data. In the case under consideration, the determination coefficient is $R^2 \approx 0{,}52$. This aspect indicates an average level of accuracy of the model and suggests that the events have a high degree of individuality. Thus, the approximated function only partially reflects the general patterns and trends in the data array.

Interpretation of results:

- The determination coefficient value within R2 ≈0,52 indicates a moderate compliance of the data with the theoretical model (explained by the significant variability of events, which makes them difficult to predict).
- Low approximation accuracy demonstrates the need to consider individual events at the individual level, especially for high-severity events, such as unscheduled outages.
- Normal distribution approximation can be used to obtain preliminary estimates, but for more accurate modeling, it is recommended to involve additional parameters that take into account asymmetry and outliers. The normal distribution is a useful tool for analyzing the structure of probable prices of events and identifying underlying patterns in the distribution of data. However, in conditions of increased uniqueness of events, such as power outages, this approximation method has limitations. The results of the analysis confirm the need to develop adaptive probability models that include stochastic and nonlinear dependencies to improve the accuracy of the forecast.

4.3 Gamma distribution approximation

To analyze the probability structure of the outage cost, an approximation using the gamma distribution was used. The probability density function of the gamma distribution is defined as follows:

$$f(x, a) = \frac{x^{a-1} e^{-x}}{G(a)}$$

for $x \geq 0, a > 0$. Here $G(a)$ refers to the gamma function. Gamma takes a as a shape parameter.

In order to effectively select the shift coefficient of the function, an iterative algorithm in Python is used. This algorithm determines at what shift value the function becomes most predictable. That is, it selects the value of a at which the gamma function describes the generated array in the best way.

As a result of the algorithm implementation, it turned out that the determination coefficient behaves non-uniformly. Moreover, at certain values of a, the dispersion increases significantly, while at others, calm sets in, i.e., there are convergence periods. Moving averages are used to correctly identify these periods. The idea of the moving average is to take the average value for a certain number of previous periods to get a "moving average" for this period. A window of 15 values was chosen to calculate the moving averages.

Figure 6 shows an approximation of the probable price of events using the gamma distribution.

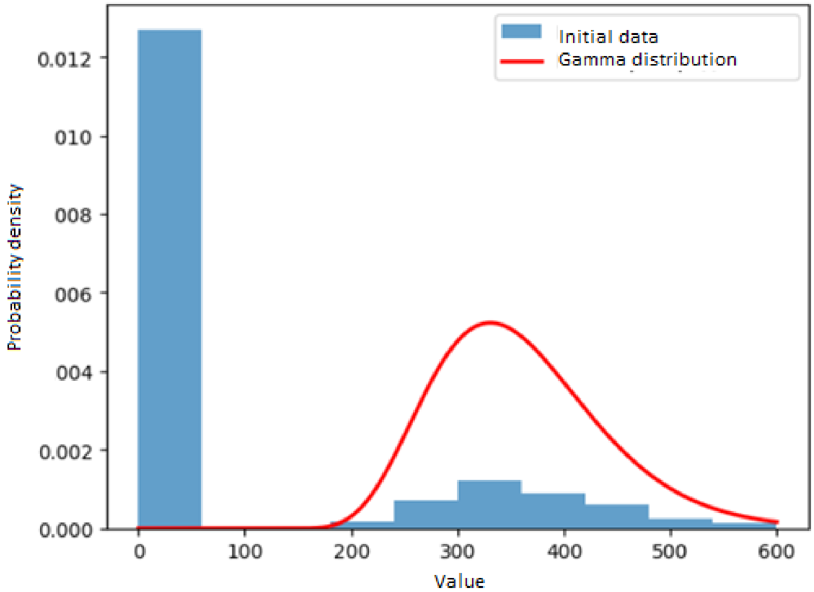

Figure 6. Approximation of the probable price by the gamma distribution
Source: own

Features of the model:

- Localization of marginal values. The gamma distribution effectively describes data areas corresponding to high-cost outages and is less suitable for analyzing periods characterized by a low event frequency, which is due to the features of the function focused on values with non-zero damage severity.
- Low event frequency. It was found that periods when there are no outages occupy a significant part of the time. However, when they occur, there is a high cost, which confirms the need to focus on compensating for marginal losses.
- Analysis of outliers. The model demonstrates that the cost of the most significant outages is subject to high variability, which is determined by the parameter a. In such conditions, the gamma approximation method shows high accuracy in describing the severity distribution of the events that occurred.

The gamma distribution is an effective tool for analyzing the cost of outages, especially in the case of high-cost events. The main focus should be on managing marginal losses and minimizing their consequences. At the same time, for events with zero damage severity, which are not taken into account in the model, it is advisable to develop additional approaches. The use of the gamma function confirms the possibility of accurately assessing risks in the energy infrastructure and allows adapting management methods to improve the reliability of energy supply.

4.4 Applying the gamma distribution to each group of violations

For an in-depth analysis of the characteristics of various types of outages, including scheduled and unscheduled ones, we calculated data arrays generated based on the gamma distribution. The approximation process included selecting the parameter a (shape parameter) so that the gamma function best described the distribution of probable event prices. Based on the calculations, we obtained the alpha parameter values and constructed the corresponding approximation graphs for each group of violations.

Figure 7 illustrates changes in the alpha parameter, where a pattern is observed: as the parameter a increases, the distribution shifts to the right, indicating an increase in the average cost of events.

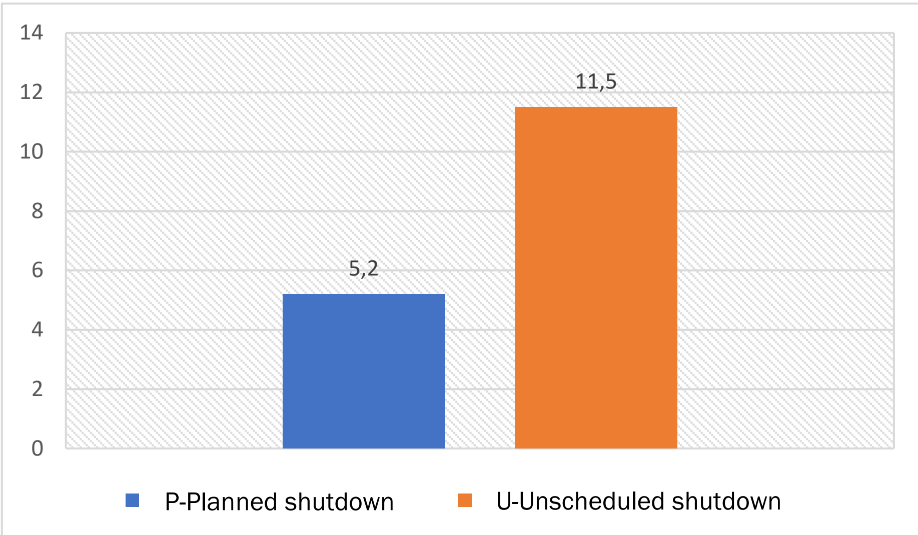

Figure 7. Alpha parameter

Figure 8 presents a gamma distribution fit for planned outages. The data demonstrates relatively low variance and high predictability, indicating a systematic nature of these events. The low variance confirms the presence of careful planning and risk minimization associated with this type of outage.

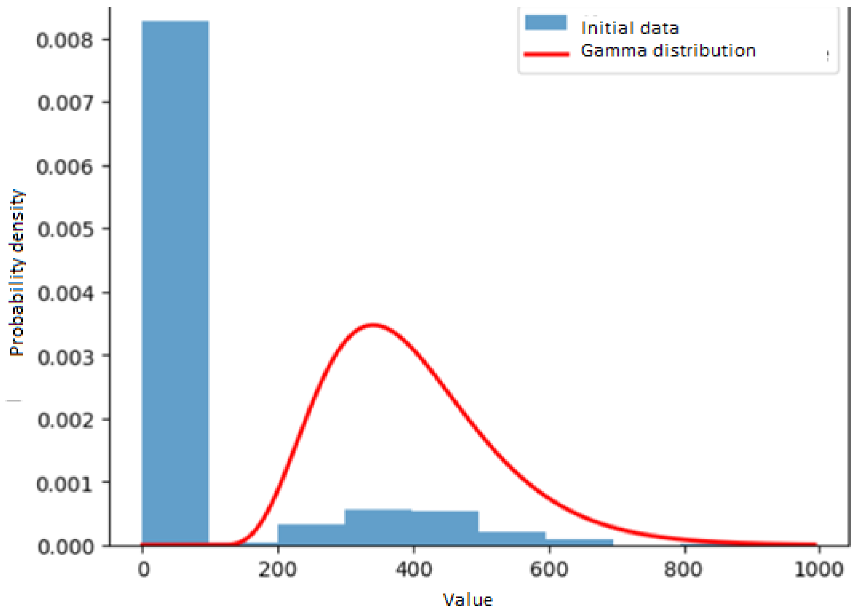

Figure 8. Gamma distribution fit for planned outages

Figure 9 shows the approximation for unscheduled outages, where a significant shift in the distribution is observed. The high values of dispersion confirm the instability of this type of outages and the need for additional control measures. The analysis shows that the average price and the maximum damage values for unscheduled outages are significantly higher than for planned ones.

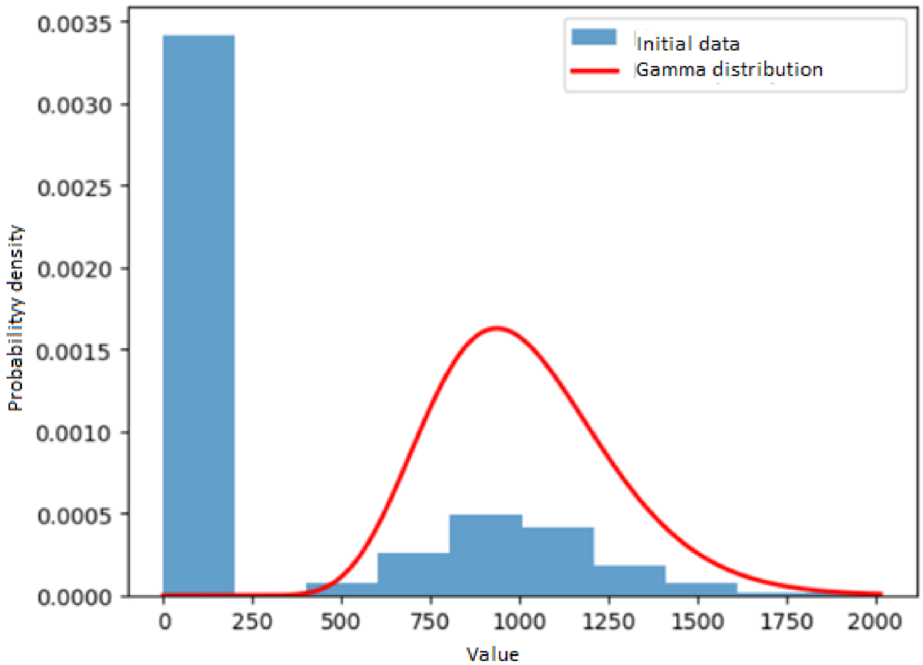

Figure 9. Gamma distribution approximation for unscheduled outages

Comparative analysis:

- Shape parameter (α). Scheduled outages have a higher α value, indicating their stability and predictability. For unscheduled outages, a low α value reflects a high degree of uncertainty and randomness.
- Probability quantiles. The values of the probable price, the 99th and 95th probability quantiles calculated for both types of outages coincide with the simulated values, confirming the reliability of the selected model.
- The shift in distributions for unscheduled outages is significantly greater, indicating higher risks associated with these events. In turn, the distribution of scheduled outages is characterized by smaller fluctuations.

Applying the gamma distribution to the cost analysis of different types of outages confirms that scheduled outages are systemic in nature, while unscheduled outages require close attention due to their high cost and uncertainty. Taking into account the parameter α and building accurate approximation models is an important step in developing effective power system management strategies, especially in the context of complex infrastructure and limited resources. The results presented in the graphs indicate the need for differentiated approaches to managing outage risks.

CONCLUSION

Conclusions from the Python Analysis

The analysis performed using Python methods demonstrated that both types of outages under study - scheduled and unscheduled - are high cost and require a strategic approach to management. Consideration of the probabilistic structure of the outage costs, as well as analysis of the 99th and 95th probability quantiles, allowed us to identify key patterns in the risks associated with these events.

Key findings:

- Analysis of the probable cost of events. The graph of the probable cost of events (Figure 1) showed that both types of outages are costly. Scheduled outages have a more predictable cost, while unscheduled ones are characterized by a higher price spread.

- The ratio of the probable cost to the 99th quantile (Figure 2). Unscheduled outages have the highest values of both the probable cost and the 99th quantile, which indicates the need to develop compensation and management measures aimed at reducing the frequency and consequences of such outages. Planned outages, despite their lower cost compared to unscheduled ones, still require systematic management. Their high 99th quantile indicates that they can only be eliminated with careful planning and modernization of the network infrastructure.
- Event typification. Containable events - unscheduled outages are included in this category, since their high cost and uncertainty require special attention. Controllable events – planned outages can be classified in this category, as they are characterized by high predictability and can be systematically minimized by improving the efficiency of planning and preventive maintenance processes.
- Necessity of control and compensation measures. Unscheduled outages require the implementation of measures aimed at reducing their frequency, which may include the installation of monitoring systems, the introduction of energy storage systems and the use of predictive models to minimize the likelihood of these events. For planned outages, it is necessary to strengthen the processes of optimizing the schedules of preventive maintenance and equipment modernization.

The conducted analysis emphasizes the need for a differentiated approach to managing different types of outages. Unscheduled outages, due to their high cost and uncertainty, require special attention. At the same time, planned outages, although less expensive, should be included in strategic plans for the modernization of energy infrastructure. The presented results form the basis for the development of management decisions aimed at reducing economic losses and increasing the reliability of energy systems.

Interpretation of Results for Energy Storage Systems

An analysis of the probabilistic characteristics of outages showed that it is impossible to completely eliminate the probability of power outages, as this requires significant investments in upgrading the infrastructure and increasing the reliability of equipment. This approach is not economically feasible due to the high cost of implementing modern solutions with minimal payback. Instead, it is advisable to focus on the ESS as an alternative for managing the consequences of outages and reducing damage from undersupplied electricity.

A. The problem of equipment reliability:

- In the process of designing electrical equipment, a certain level of reliability is established, which assumes the possibility of failures in a limited percentage of cases. For example, overhead power lines are designed to withstand the effects of medium-intensity lightning, but can be disconnected when directly hit by high-intensity lightning.
- The economic logic of this approach is that the losses from undersupplied electricity are less than the costs of building more reliable systems.

B. The role of energy storage systems:

- The SES provide an alternative solution to the problem, ensuring the possibility of temporary backup power supply during a main grid outage, which helps minimize losses without requiring capital investments in global modernization of power systems.
- For unscheduled outages, the SES can be used to completely eliminate their consequences. In this case, investments in such systems should be justified by calculations demonstrating that the costs of their installation and operation will be lower than the economic damage from outages during the payback period.

C. Approach to planned outages:

- For planned outages that are known in advance, the SES allow for temporary power supply, minimizing economic damage.
- Since the outage schedule is known, the company can optimize the logistics and use of the SES, determining their capacity and placement depending on the needs of specific consumers.
- Planning the installation of the SES for such outages helps achieve a balance between the costs of purchasing and installing equipment and losses from lost electricity supply.

D. Economic feasibility of implementing SES:

- Investment costs for the purchase and operation of SES should be calculated in such a way that their payback is achievable within a reasonable time frame.
- Particular attention should be paid to optimizing the capacity of storage devices and their number. For unscheduled outages, it is advisable to implement backup systems in the most vulnerable areas, and for planned outages, to use mobile energy storage devices that can be distributed according to a schedule.

SES are an effective tool for managing the consequences of outages, minimizing losses and increasing the flexibility of energy systems. Their integration is especially relevant for countries with a high load on energy networks, such as the BRICS countries, where urbanization and economic growth increase the risks of infrastructure overload. The use of SES helps to reduce damage from outages and create a sustainable energy system adapted to local characteristics and needs.

ACKNOWLEDGEMENTS

The article is based on the results of a study conducted with the financial support of the Russian Federation represented by the Ministry of Science and Higher Education of Russia in the process of implementing the project “Management of Sustainable Development of Industrial Structures within the Concept of Water-Energy-Food” (application No. 075-15-2024-673).

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