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Forecasting Energy Storage Requirements for Energy Complex with Solar Power Plant and Battery Energy Storage System

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Abstract

Despite the many advantages of renewable energy sources, the stochastic nature of their generation creates a mismatch between the timing of electricity production and demand. Without appropriate storage solutions, surplus energy may remain unused. Therefore, the development of energy complexes based on solar power plants with the integration of battery energy storage systems, as well as the development of corresponding computational models for them, becomes critical for ensuring the stability, flexibility, reliability, and efficiency of power systems. Battery energy storage systems have become widely used due to their availability, high response speed, significant energy density, and sufficient power capacity. However, their cost remains relatively high. This paper proposes a methodology and a calculation model for determining the optimal forecasted capacity and the rational storage requirements of an energy complex consisting of a solar power plant and a battery energy storage system operating in parallel with the grid at constant power under short-term forecasting conditions (day-ahead or longer). The proposed approach makes it possible to minimise the costs of energy companies associated with the short-term lease of part of a battery energy storage system when they do not own one, or, if such a system is available, to lease out its unused capacity and obtain corresponding profits. The validation of the computational model was carried out using a dataset of hourly daily power outputs of solar power plants in the Integrated Power System of Ukraine for 2018. Statistical analysis of the obtained results showed that the probability of occurrence of maximum deviations for the optimal capacity of the energy complex (5.4%), as well as for the power and capacity of the battery energy storage system (13% and 18%, respectively), does not exceed 0.05 during the year. Although the proposed methodology was applied using solar power plant generation data for the national power system as a whole, it can also be used for individual solar power plants located in different regions and countries with different climatic conditions. Certainly, the calculated coefficients will differ, but the methodology itself and the sequence of its application will remain the same.

Keywords: solar power plant; battery energy storage system; energy storage requirements; forecasting

1. Introduction

The global energy transition, driven by climate challenges and the need to reduce CO_2 emissions, is facilitating the shift from traditional fossil-fuel-based energy sources to renewable energy sources (RES) [1]. The growing role of solar power plants (SPPs) and wind power plants (WPPs) demonstrates that renewable energy sources can form the foundation of a future low-carbon energy system [2,3]. In 2022, the total installed capacity of renewable electricity sources worldwide amounted to about

3,372 GW [4]. In 2023, their capacity increased significantly, with the total installed RES capacity reaching approximately 3,865 GW. By the end of 2023, the installed capacity of solar power plants was about 1,418 GW [5]. The year 2024 brought an unprecedented annual increase. According to the International Renewable Energy Agency (IRENA) and aggregated industry reports, approximately 585 GW of new renewable energy capacity was added in 2024, bringing the total global RES capacity to around 4,448 GW by the end of the year. The largest share of this growth (more than 75%) was attributed to SPPs, whose capacity additions exceeded approximately 452 GW in 2024, resulting in a total installed solar capacity of more than 2.2 TW by the end of 2024 [6]. Leading international agencies predict that growth rates will remain particularly high for solar power plants, which are expected to play a leading role in the expansion of renewable generation. According to estimates by the International Energy Agency (IEA), during the period 2025–2030, an additional increase of approximately 4,600 GW of renewable capacity is expected. Solar power plants are projected to account for about 80% of the total capacity growth during this period, meaning that by the end of the decade they will become the dominant source among renewable energy technologies [7].

In Ukraine, the renewable energy sector has also demonstrated significant growth, both in terms of new capacity additions and the potential for further development. As of January 2023, the total installed capacity of solar power plants amounted to 6.3 GW of utility-scale installations and 1.4 GW of residential systems [8], despite the military aggression of Russia against Ukraine. In 2024, Ukraine added more than 800–850 MW [9] of new solar capacity, both in the segment of large-scale solar power plants and among residential households. According to the Ukrainian Solar Energy Association, the share of solar generation within the renewable energy structure continues to increase, indicating strong investment and practical interest in the development of solar generation. In accordance with strategic documents such as the National Renewable Energy Action Plan [10] and the National Energy and Climate Plan until 2030 [11], Ukraine has set ambitious targets for the development of renewable energy. In particular, the country aims to reach 12.2 GW of installed solar power capacity by 2030 and to increase the share of renewable energy sources in final energy consumption to 27% [12].

Over the past few years, Ukraine has adopted laws and regulatory acts that establish a legal framework for the development of battery energy storage systems (BESS) and for supporting renewable energy generation. In particular, the Law of Ukraine No. 2046-IX "On Amendments to Certain Laws of Ukraine Regarding the Development of Energy Storage Systems" of February 15, 2022 [13], officially recognises BESS as a new type of participant in the electricity market. The law introduced new terms ("energy storage system," "energy storage operator," and "fully integrated network elements"), provided for licensing of energy storage activities, and regulated the legal and commercial conditions for BESS operation, including in combination with renewable energy sources.

The Law of Ukraine No. 3220-IX "On Amendments to Certain Laws of Ukraine Regarding the Recovery and 'Green' Transformation of the Energy System of Ukraine" [14], which entered into force in June 2023, became a key driver for the BESS deployment in Ukraine. This law created the necessary legal framework and introduced economic mechanisms integrating BESS into the electricity market as an independent activity. It transformed BESS from unregulated technical equipment into a fully recognised and financially attractive investment object and a critically important element for the modernisation of the Ukrainian power system. In turn, the market regulator, the National Energy and Utilities Regulatory Commission (NEURC), through its resolutions, has defined and approved licensing conditions for conducting energy storage activities [15], procedures for connecting BESS to the grid, commercial metering procedures, and tariffs for transmission and distribution services during BESS operation. These measures contribute to attracting investments in flexible generation capacities and/or BESS and stimulate the development of competition in the auxiliary services market [16].

Considering the rapid growth of installed SPPs capacity, political goals related to energy independence and decarbonization, as well as the lack of sufficiently comprehensive studies in Ukraine that systematically assess the storage requirements for the forecasted capacity of energy complexes (ECs), research on forecasting and optimising the parameters of BESS is highly relevant. This task is of key importance for ensuring the reliability, economic efficiency, and stability of the country's future power system.

Despite the numerous advantages of renewable energy sources, the stochastic nature of their generation creates a mismatch between the timing of electricity production and demand. Without adequate storage solutions, surplus energy may remain unused. Therefore, the development of ECs based on solar power plants integrated with BESS and other technologies [17,18] becomes critical for ensuring the stability, flexibility, and reliability of the power system. This approach corresponds to current international trends in the development of hybrid ECs based on renewable energy sources combined with energy storage, as confirmed by studies conducted in Europe and other regions of the world [19–23].

Worldwide, active research is being conducted on ECs based on SPPs and BESS. These studies analyse the characteristics of their joint operation, the efficiency of charge–discharge cycles, the economic feasibility of using different types of BESS, and issues related to minimising the required capacity and power of storage systems within ECs.

In study [24], a comprehensive review of BESS applications in power networks was conducted, covering aspects ranging from power support and power quality improvement to market services and cycle optimisation. The study demonstrates that for the effective integration of SPP + BESS ECs, the energy management strategy and control modes are of key importance, including power limitations and depth of discharge (DoD). The economic feasibility largely depends on the electricity market structure and tariff policies.

Study [25] analyses current trends in the development of BESS, key technological directions, issues of battery degradation, control strategies, and applications in distributed power networks. The authors note that future research should focus on the coordination of solar inverters and BESS power conversion systems (PCS) operating in grid-forming and grid-support modes, as well as on cycle optimisation considering battery degradation and multi-objective optimisation problems (cost, services, and reliability).

Issues related to the optimal operation of BESS in DC microgrids, both autonomous and grid-connected, as well as charge–discharge control algorithms, are considered in the study [26]. The authors conclude that properly selected optimisation strategies (aimed at minimising costs and increasing self-sufficiency) significantly reduce storage capacity requirements while having only a minor impact on system reliability.

In paper [27], it is noted that the increasing share of solar power generation in the total energy production leads to a decrease in frequency and power stability. Therefore, the integration of BESS with solar power plants operating in a grid-forming mode (i.e., with the capability to regulate frequency and power) becomes critical for maintaining power system stability. To ensure reliable operation of SPP+BESS as a grid-forming system, coordination between power flows, generation modes, charge/discharge processes, and transitions between operating states (charging, discharging, and grid-dependent operation) is required.

In patent [28], a method for controlling linear variations in the power output of a solar power plant is proposed, based on operational forecasting and the determination of its maximum, minimum, and instantaneous power. The application of this method makes it possible to minimise the required capacity of the BESS used to compensate for maximum power fluctuations and to reduce the cyclic loading of the storage system. This contributes to extending the service life of the BESS, reducing electricity losses, lowering operational and financial costs of the solar power plant, and preventing complete discharge of the storage system.

Papers [29,30] analyse the possibilities of optimising the storage capacity of BESS in SPP–BESS ECs. The proposed approaches are based on the Pareto principle, where, as a result of statistical analysis, the inflection point of the curve representing the relationship between storage requirements and the probability of their coverage is determined. This critical point is considered optimal for selecting the storage capacity of the BESS, beyond which further capacity increase becomes impractical. In this case, the probability of covering the storage needs of the solar power plant is approximately 0.95. In study [29], multi-objective optimisation using genetic algorithms was applied to minimise investment costs of the SPP–BESS energy complex (EC). Simulation of various scenarios made it possible to obtain a Pareto frontier for determining the maximum capacity of the solar power plant and the optimal capacity of the BESS. In paper [30], based on statistical analysis of historical SPP power output data and long-term modelling combined with the application of the Pareto principle, indicators for assessing the reliability of electricity generation by an SPP–BESS EC were determined. In particular, the coefficient of installed power output factor (CPOF) represents the ratio of the constant output power of the EC delivered to the grid to the peak power of the SPP. The parameter S2P represents the normalised storage capacity of the BESS and is defined as the ratio of the required storage capacity (MWh) to the peak power of the SPP (MW). Long-term forecasting (monthly or longer) of the output power of the EC and the required storage capacity is performed by selecting combinations of constant set power levels and storage ranges around the following values: CPOF = 0.12 and S2P = 2 h; CPOF = 0.10 and S2P = 1.65 h; or CPOF = 0.06 and S2P = 0.9 h.

The publications mentioned above do not address methods for short-term forecasting of the required energy capacity and power of BESS, as well as the output power of the EC for the day-ahead period, as required by the Law of Ukraine “On the Electricity Market”, as well as by the Transmission System Code and the Distribution System Code.

This paper is a logical continuation of the studies presented in [31,32]. It incorporates both the results of previous research and the findings of further investigations in this field. The aim of the studies of WPPs and SPPs power generation profiles conducted in [31,32] was to determine the maximum feasible requirements for the energy capacity and power of an EC. As a result of these studies, it was established that to ensure constant power operation of the EC, each 1 MW of installed SPP power capacity requires approximately 1.3 MWh of storage capacity and 0.37 MW of BESS power. These results can be used in the design and construction of BESS, both for existing SPPs and for those that are currently under development.

The objective of this study is to develop a mathematical computational model for the operational forecasting of the required BESS energy capacity, BESS power, and the amount of energy requirements at the beginning of the EC operation. Such information is necessary to minimise the costs of companies associated with the short-term lease of part of an BESS when they do not own one, or, if such a system is available, to lease out its unused part of capacity and obtain corresponding financial benefits.

2. Materials and Methods

During the course of the scientific research presented in this paper, the following methods were applied: statistical analysis, factor analysis, formalisation, and modelling. The following assumptions were adopted for conducting the study:

1. Due to the lack of available data on electricity generation from individual SPPs, it was assumed that all SPPs of the Integrated Power System (IPS) of Ukraine operate as a single large power plant. This assumption made it possible to use available datasets containing hourly power output of solar power plants in the IPS of Ukraine for 2018 and 2019.
2. The EC consists of an SPP and an BESS, is connected to the grid, and operates at a constant power level to supply the base load.
3. The EC begins operation at the start of the morning increase in electrical load in the grid, for example, at 06:00 AM. However, before the start of the complex operation, during the nighttime period when electricity prices are low, the BESS is charged from the grid. The amount of accumulated energy must be sufficient to maintain the specified power level of the complex during its joint operation with the SPP until the moment when the SPP power output becomes sufficient to fully cover the connected load (point t_1, Figure 1). At this moment, the BESS must be fully discharged.

During the daylight period, when the SPP generation exceeds the specified load level, the excess electricity generated by the SPP is stored in the BESS during the time interval t_k–t_1. This stored energy is later used to maintain the specified power level during periods of low solar activity and in the evening hours, or it can be shifted to periods of maximum demand.

Let us consider the power output profile of the SPP for April 24, 2019, as shown in Figure 1.

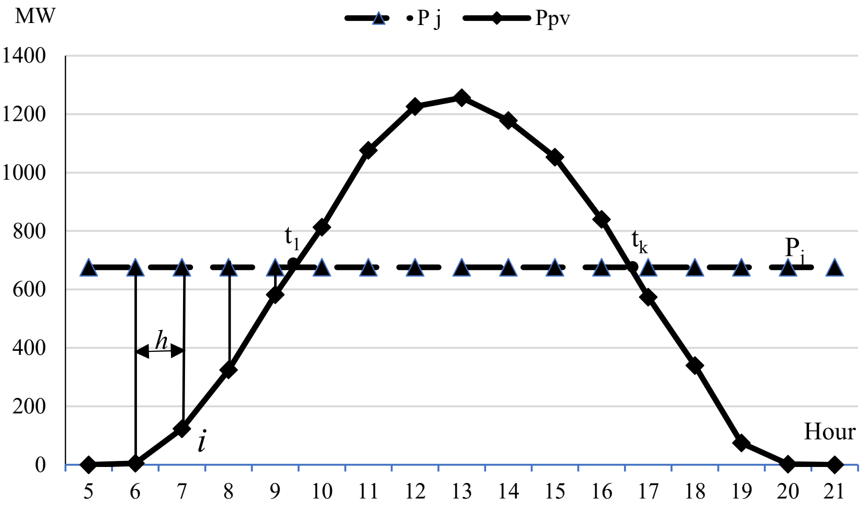

Figure 1. Power curve of the SPP for April 24, 2019.

In the first approximation, the amount of energy (and, accordingly, the required storage capacity of the BESS) that must be accumulated before the start of the EC operation and stored during the daytime period can be determined using Formulas (1) and (2), respectively,

$$E_j^{start} = \sum_{i=0}^{n}\left(P_j - P_{ij}^{pv}\right)h\,; \quad (1)$$

$$E_j^{pv} = max_{i\,\in\{t1\,\dots\,tk\}}\left\{E_{i-1j}^{pv} + \left(P_{ij}^{pv} - P_j\right)h\right\}, \quad (2)$$

where E_j^{start} – the amount of energy that must be accumulated before the start of the EC operation on the *j*-th day; P_j – the output power of the EC on the *j*-th day; *n* – the number of time intervals h, including the momentt_1, when $P_j = P_n^{pv}$; *h* – the discretization interval of the daily power profile; P_{ij}^{pv} – the power of the SPP in the *i*-th hour of the *j*-th day; E_j^{pv}– the storage requirement for excess SPP generation on the *j*-th day; E_{i-1j}^{pv} – the energy stored in the BESS during the previous hour of the *j*-th day;

From Formulas (1) and (2) as well as Figure 2, it can be observed that as the output power level of the EC increases, the need for storing excess electricity during the daytime decreases. However, at the same time, the required amount of energy that must be accumulated during the nighttime period before the start of operation increases, and vice versa. This indicates that there exists an intersection point between the functional dependency curves representing the required stored energy from the grid before the start of the complex operation and the storage requirements for excess electricity generated by the SPP during the daytime, depending on the output power level of the complex. In fact, this represents an optimisation problem that can be solved using the linear programming method. The determination of the optimal EC output power was carried out using a dataset of hourly daily power outputs of SPPs in the IPS of Ukraine for 2019. The modelling results showed that at the optimal power level, the amount of electricity that must be accumulated in the BESS from the grid during the nighttime period is equal to or close to the amount of energy that must be stored during the daytime period. Under these conditions, the minimum storage capacity requirements of the BESS are achieved. Using the Solver add-in in the Excel software environment, the optimal level of forecasted power was calculated for each day of 2019.

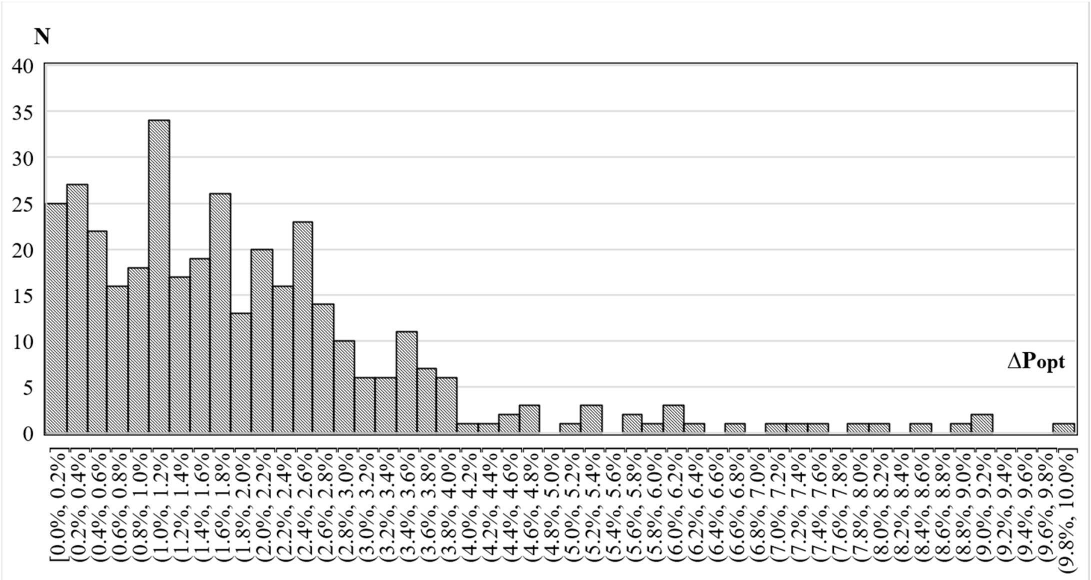

Figure 2. Distribution of the number (N) of deviations of the optimal EC power calculated by the proposed method from the actual values (ΔP_{opt}) during the year.

Based on the performed optimisation and analysis of the results of statistical studies, average monthly calculation coefficients were determined for the operational forecasting of the energy capacity and power of the BESS, as well as for the amount of energy required at the start of the EC operation:

- calculation coefficient for determining the optimal power of the EC

$$k_m^{p\_ек} = \left(\sum_{j=1}^{N_m} \frac{P_{jm}^{opt}}{P_{jm}^{avr}}\right) / N_m; \quad (3)$$

- calculation coefficient for determining the BESS capacity (and the required amount of energy at the beginning of the EC operation)

$$k_m^{es} = \left(\sum_{j=1}^{N_m} \frac{E_{jm}^{start}}{P_{jm}^{opt}}\right) / N_m; \quad (4)$$

- calculation coefficient for determining the BESS power

$$k_m^{p\_es} = \left(\sum_{j=1}^{N_m} \frac{P_{jm}^{max}}{P_{jm}^{opt}}\right) / N_m, \quad (5)$$

where P_{jm}^{opt} – optimal power of the EC on the *j*-th day of the *m*-th month; P_{jm}^{avr} – average power of the SPP on the *j*-th day of the *m*-th month; N_m – number of days in month *m*; E_{jm}^{start} – required energy (BESS capacity) at the start of EC operation on the *j*-th day of the *m*-th month; P_{jm}^{max} – maximum required BESS power on the *j*-th day of the *m*-th month for the EC.

3. Results

The average monthly values of the above coefficients and their relative standard deviations are presented in Table 1.

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Table 1. Calculation coefficients for forecasting the energy capacity and power of the BESS.

Coefficient	$k_m^{p\_es}$		k_m^{es}		$k_m^{p\_es}$	
Month	**average**	**relative SD, %**	**average**	**relative SD, %**	**average**	**relative SD, %**
January	0.892	2.50%	3.140	9.99%	1.054	9.69%
February	1.050	2.00%	2.850	10.26%	1.004	1.46%
March	1.198	2.53%	2.414	8.88%	1.004	1.46%
April	1.153	1.59%	2.836	7.80%	0.997	0.36%
May	1.235	0.67%	3.335	6.79%	0.992	1.45%
June	1.235	0.67%	3.287	3.17%	0.995	0.80%
July	1.233	0.87%	3.280	2.99%	0.997	0.31%
August	1.185	1.28%	3.517	4.30%	0.989	1.04%
September	1.252	1.51%	2.804	5.51%	0.976	2.43%
October	1.135	3.08%	3.119	8.16%	1.009	3.04%
November	1.128	1.76%	2.991	6.84%	1.025	5.75%
December	1.142	1.39%	3.143	7.13%	1.069	8.52%

The sequence for forecasting the output power of the EC and determining the day-ahead energy storage requirements is as follows:

- based on meteorological forecast data, the expected values of solar irradiance, ambient temperature, and the presence of atmospheric precipitation (rain/snow) are estimated, as well as geometric parameters, in particular the angle of incidence of solar radiation on photovoltaic panels;
- according to the forecasted weather conditions, the total predicted amount of electrical energy that can be generated by the SPP during the day is determined;
- the forecasted average power level of the SPP during its generation period is then calculated using the following formula,

$$P_{jm}^{pr\_avr} = \frac{E_{jm}}{\Delta t}, \quad (6)$$

where E_{jm} – forecasted amount of energy that will be generated by the SPP on the *j*-th day of the *m*-th month; Δt – duration of SPP generation on the *j*-th day of the *m*-th month.

The optimal value of the forecasted power $P_{jm}^{pr\_opt}$, the required storage capacity (energy required at the start of EC operation) E_{jm}^{start} and the BESS power P_{jm}^{max} on the *j*-th day of the *m*-th month are determined using the formulas presented below:

$$P_{jm}^{pr\_opt} = k_m^{p\_es} P_{jm}^{pr\_avr}; \quad (7)$$

$$E_{jm}^{start} = k_m^{es} P_{jm}^{pr\_opt}; \quad (8)$$

$$P_{jm}^{max} = k_m^{p\_es} P_{jm}^{pr\_opt}. \quad (9)$$

Formulas (7)–(9) represent the computational model, the validation of which was carried out using a dataset of hourly daily power outputs of SPPs in the IPS of Ukraine for 2018. Next, for each day of 2018, the proposed method was used to determine the indicators of the optimal EC power, as well as the required BESS capacity and power, and their relative deviations from the actual calculated values (hereinafter referred to as the actual) values ΔPopt, ΔEss, ΔPss, respectively. Based on the results of the statistical analysis, histograms of the distribution of the number (N) of these deviations from their actual values (%) during the year were constructed. These histograms are presented in Figures 2–4.

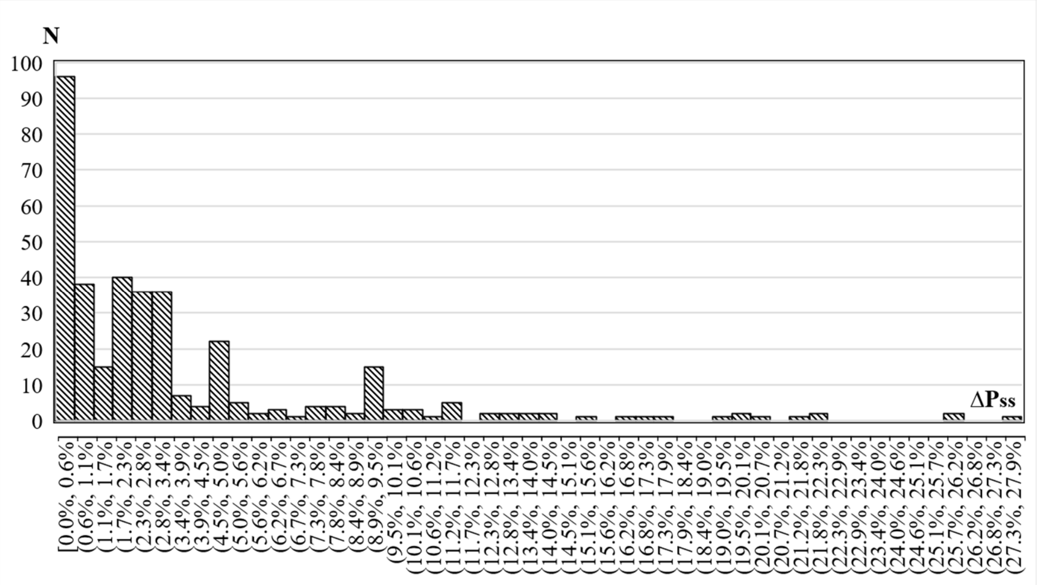

Figure 3. Distribution of the number (N) of deviations of the BESS power calculated by the proposed method from the actual values (ΔP_{ss}) during the year.

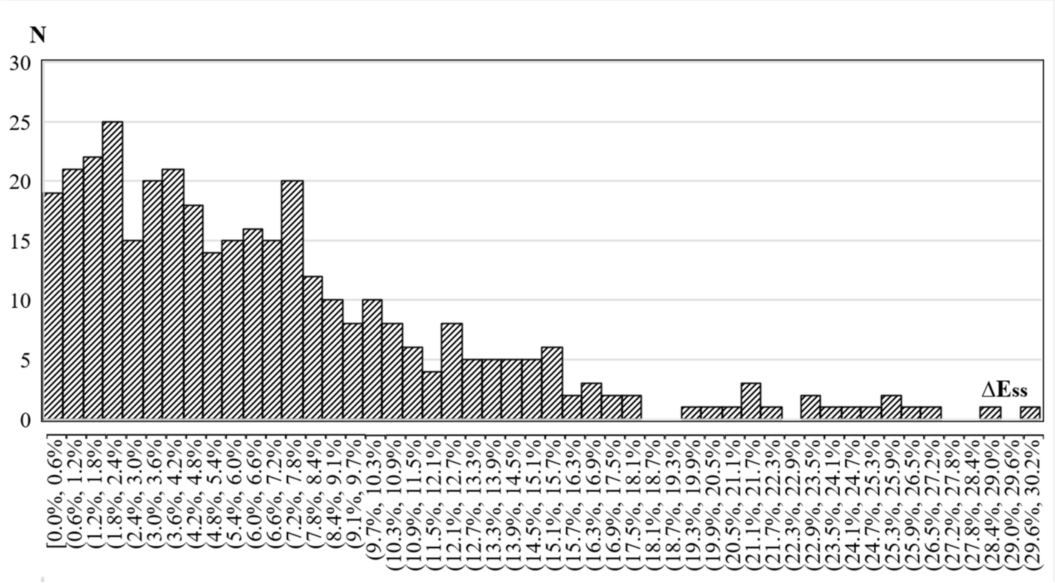

Figure 4. Distribution of the number (N) of deviations of the BESS capacity requirements calculated by the proposed method from the actual values during the year.

4. Discussion

From Table 1, it can be seen that the standard deviations of the coefficients do not exceed 10%, which is relatively high for BESS. However, considering that such deviations are typical only for winter months with low solar irradiance, this error does not significantly affect the ability of the EC to maintain the scheduled output power.

As shown in Figures 2–4, significant deviations of the optimal power, as well as the required BESS capacity and power, from their actual values when calculated using the proposed method occur very rarely—only once or several times per year. Statistical analysis of the obtained results showed that the probability of occurrence of significant deviations between the calculated parameters and the actual values does not exceed 0.05. At the same time, the magnitude of these deviations does not exceed 5.4% for the optimal power of the EC, and 13% and 18% for the power and capacity of the BESS, respectively.

It should be noted that the largest standard deviations of the calculated coefficients (and, consequently, of the calculated indicators) are observed in December, January, and February, when the generation power of SPPs is minimal. Accordingly, the data used during these periods may not be entirely accurate. In addition, the maximum deviations of the calculated optimal EC power and its BESS capacity and power requirements from the actual values could have been significantly smaller if the available datasets of hourly solar power output of the IPS of Ukraine for 2018 and 2019 had included information on forced curtailment of SPP generation.

The constant power operation mode of the EC was selected solely to minimise its storage requirements. After the completion of the energy storage process during the daytime period, the EC can operate in other modes as well, for example, in an energy shifting mode for operation during peak demand periods.

5. Conclusions

The proposed methodology and calculation model make it possible to determine the optimal power and energy storage requirements of an EC consisting of a solar power plant and BESS operating in parallel with the grid under short-term forecasting conditions (day-ahead or longer). This approach enables energy companies to minimise the costs associated with short-term lease of part of BESS when they do not own one, or, if such a system is available, to lease out its unused capacity and obtain additional profit.

Statistical analysis of the obtained results showed that the probability of occurrence of maximum deviations from the actual values does not exceed 0.05 during the year. At the same time, the deviations do not exceed 5.4% for the optimal power of the EC, and 13% and 18% for the power and capacity of the BESS, respectively.

Although the proposed methodology was applied to the power system of the country as a whole, it can also be used for individual solar power plants located in different regions and countries with different climatic conditions. Naturally, the calculation coefficients will differ, but the methodology itself and the sequence of its application will remain the same.

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

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Data Availability Statement: The data presented in this study are available on request from the corresponding author due to special restrictions on access to data regarding the functioning of critical infrastructure.

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

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Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery Energy Storage System
CPOF	Coefficient of Power Output Factor
DC	Direct Current
DoD	Depth of Discharge
EC	Energy Complex
IEA	International Energy Agency
IPS	Integrated Power System
IRENA	International Renewable Energy Agency
NEURC	National Energy and Utilities Regulatory Commission
PCS	Power Conversion System
RES	Renewable Energy Sources
S2P	Storage-to-Power Ratio
SPP	Solar Power Plant
WPP	Wind Power Plant

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