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IMPROVING THE STRATEGY FOR USING RECHARGEABLE BATTERY ENERGY STORAGE SYSTEMS TO ENHANCE THE ECONOMIC EFFICIENCY OF PHOTOVOLTAIC POWER PLANTS IN THE ELECTRICITY MARKET

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This study investigates operational process involving rechargeable battery energy storage systems (ESSs) in a combination with photovoltaic power plants (PVPPs) in the competitive electricity market. The task addressed is to improve the functioning efficiency of electric power systems with deep PVPP penetration. This work analyzes scenarios and strategy optimization when using ESSs to increase the economic efficiency of PVPPs operating in a single complex. The research results established those factors that affect the technical and economic indicators of ESS application and helped define a combined management strategy.

Practical ESS management scenarios with different mechanisms for forming an economic effect were studied, in particular, the day-ahead market arbitrage scenario (DAM) and the PVPP balancing scenario. The latter, in addition to minimizing the costs of settling imbalances, provides for the sale of excess stored energy during hours of maximum price.

The use of an ensemble of machine learning methods (RandomForest + XGBoost + LightGBM) has made it possible to achieve high accuracy in forecasting PVPP generation. Energy indicators were optimized for each scenario of ESS control system; financial results were assessed based on the MILP and MPC methods. That made it possible to quantitatively compare the effectiveness of the arbitrage and balancing strategies and justify the choice of ESS operation mode depending on the volatility of the DAM prices, the level of forecast uncertainty of generation, and the current rules for regulating imbalances in the electricity market.

The results were verified on the example of a real 9.5 MW PVPP, supplemented by ESS with an energy capacity of 2 MWh, which made it possible to take into account the financial responsibility of the producer for imbalances and the impact of price asymmetry on the end result

Keywords: photovoltaic power plant, electricity storage system, electricity market, optimization of operation

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1. Introduction

The global energy sector is undergoing an unprecedented transformation driven by the need for decarbonization, increased energy independence, and resilience of energy systems to external influences. According to the International Renewable Energy Agency, solar energy is growing most dynamically, with an average annual growth rate of 22–25%. This dynamics is a consequence of technological progress, scaling up production, and a rapid decline in capital expenditures. At the political level, this trend is reinforced by the European Union's strategic goals of increasing the share of renewables to 42.5% by 2030 and climate neutrality by 2050. In this context, solar energy is seen not simply as a competitive generation technology but as a fundamental element of energy transformation, reducing the carbon footprint, diversifying the fuel balance, and constructing new market models based on flexibility and digitalization.

The energy system in Ukraine is evolving in line with global decarbonization trends. In addition, it is changing under the influence of challenges related to military operations.

As of 2024, the installed capacity of photovoltaic power plants (PVPPs) in Ukraine exceeded 7 GW, which was about 15% of the installed capacity of the power system, which positions Ukraine among the leaders in Central and Eastern Europe in terms of the share of solar generation [1].

The new market model with segments of the day-ahead market (DAM), intraday market (IDM), and balancing market (BM) has fundamentally changed the economics of PVPPs. Under the "green" tariff, the main focus was on maximizing production while under market conditions, forecasting accuracy, the ability to manage the hourly supply schedule, and minimize the costs of regulating imbalances became decisive.

Unlike traditional sources, the generation by photovoltaic power plants directly depends on meteorological factors, it has a pronounced daily cyclicality, seasonal unevenness, and high short-term variability. A change in cloudiness can change the generation capacity by 50–80% within 5–15 minutes [2]. In the summer months, generation can be 3–4 times higher than in winter. These properties make it difficult to form an accurate forecast and correct hourly nomination in DAM. As a result, the forecasting error turns from a technical issue into a direct economic one.

Therefore, in a multi-segment market that combines the day-ahead market with the intraday (IDM) and balancing markets (BM), the financial result of PVPP operation is determined not only by the price of electricity sales. It is affected by the costs of settling deviations between the declared (nominated) and actual electricity supply by the producer. For PVPPs, such deviations are systemic due to weather dependence and high variability in weather conditions [3].

Depending on the forecasting methods and weather conditions, the typical error in the forecast of PVPP generation for the day in advance is 10–25% [4]. Under variable cloudiness, taking into account atmospheric pollution, the error can reach 30–40% [5, 6]. Additional error is induced by the temperature effect [7], as well as the degradation of basic PVPP equipment [8], which are often not taken into account in models.

Under the conditions of the Ukrainian energy market where there is a mechanism of financial responsibility for imbalances, even a typical level of forecast error could lead to significant economic losses. In this context, rechargeable battery energy storage systems (ESS) are considered one of the key tools for increasing the controllability of PVPP generation and optimizing their operation in the electricity market. Lithium-ion storage devices dominate due to their high efficiency (85–92%) [9, 10], fast response time, scalability, as well as significant reduction in the cost of the technology [11].

The economic feasibility of ESS is determined by a set of functions within the concept of combining sources of income. For markets with pronounced intraday price volatility, the basic function of ESS is price arbitrage, that is, the accumulation and resale of electricity during periods of higher prices [12]. However, for PVPP operators under current conditions, the most profitable is the use of ESS as a tool for reducing imbalances. The accumulator can compensate for generation deficits and limit surpluses, reducing monetary losses on the balancing market, especially in the presence of imbalance price asymmetry.

Thus, the choice of optimal parameters and operating modes for ESSs is largely determined by both technical and economic factors and the chosen profit-making strategy. Therefore, it is a relevant task to determine an effective strategy for using ESS under conditions of compatible operation with photovoltaic stations, taking into account technical limitations and market mechanisms.

2. Literature review and problem statement

It is shown in [13] that the accuracy of forecasting for horizons from several hours to a day is critical for generating applications and planning flexibility. According to [14], it is precisely increasing the accuracy of the intraday forecast that is a means of reducing the risk of imbalances and the associated penalties or loss of income. Therefore, in [14], a physical approach to reproducing the generation of photovoltaic arrays based on numerical weather prediction (NWP) is investigated. It is widely used in dispatching systems since NWP provides sufficiently high-quality information about the state of the atmosphere. However, NWP errors regarding cloudiness are decisive and cause peak forecast deviations. Therefore, the authors prove the low efficiency of direct use of the method and indicate the prospects for using NWP as an exogenous input for a machine learning (ML) or deep learning (DL) model. In this way, post-correction is provided, systematic biases are reduced, and the characteristics of specific PVPPs are taken into account. In [14] it is also indicated that the quality of retrospective data on PVPP generation is decisive for the accuracy of the forecast. To achieve it, it is proposed to improve the post-processing algorithms of the tele information system. It is shown that the defuzzification process of PVPP generation is exclusively influenced by the design parameters and characteristics of PVPP, in particular, the orientation of the photovoltaic modules, their temperature coefficients and degradation, as well as the characteristics of the inverter equipment.

In study [15], the authors focused on studying the relationship between the technical accuracy and the economic value of the generation forecast. It is shown that the same value of the mean absolute error (MAE) would have different consequences depending on the time of day it occurred, what the capacity deviation is, and what the structure of imbalance prices happens to be. It is established that for markets with two-price schemes or asymmetric penalties, in order to increase the economic effect of the forecast, one should focus on adjusting the error distribution, rather than reducing MAE. However, ensuring the economic value of the forecast is impossible without the use of effective and adaptive methods for intraday forecasting of electricity production. The authors emphasize the feasibility of using different methods for day-ahead tasks and intraday forecast adjustment.

In [15] it is also shown that high forecasting accuracy cannot be achieved without high-quality sources of meteorological data and methods for detecting and validating characteristic features. In particular, for the implementation of machine learning models, correct validation of time series is important. The authors prove that for a forecast for the day before or intraday forecast, the values of meteorological parameters available at the time of forecast formation should be used. For high-quality model training, preliminary adjustment of the distribution of dataset data is necessary, and for quality assessment, constant testing of the model on data from "future" intervals (reinforcement learning).

At the same time, studies [14] and [15] indicate that the use of modern forecasting methods, in particular machine learning methods, does not guarantee the required forecast accuracy under variable weather conditions. Thus, the issue of the occurrence of imbalances in PVPP cannot be solved only by improving forecasting methods because the change in weather conditions is largely stochastic.

Recently, electricity storage systems (ESSs) have been used to address the issue of imbalances. They are considered to be a universal flexibility asset capable of providing energy transfer over time and responding quickly to deviations in power system parameters.

It is shown in [16] that the arbitrage value of ESS in the day-ahead market (DAM) significantly depends on the daily price spread and the duration of energy storage. The implementation and operation of ESSs is complicated by the potential limitation of receiving the full cost of services provided to the power system in the case of operation under fixed market arbitrage scenarios or balancing of PVPPs. The cost of services is usually estimated at the marginal price of electricity and does not take into account the ability to remove the power system restrictions on PVPP generation volumes. On the other hand, DAM arbitrage using ESS reduces the difference in electricity prices during the day, reducing the profitability of such a scenario. Therefore, the need for a deep analysis of ESS capabilities is noted, taking into account the current and alternative market rules, as well as the need to study the complex use of ESS, including distributed systems.

In [17], the value of ESS for DAM arbitrage is investigated. In particular, a universal algorithm is proposed that could optimize the operating modes of ESS for arbitrage, with or without reserve services, both with and without high-quality price forecasting. It is shown that the use of ESS in such a scenario is profitable even in the absence of a high-quality forecast of market prices. However, the presence of such a forecast contributes to an increase in profit by 5–25%. The participation of ESS in balancing renewable energy sources (RES) is considered as an alternative source of income. However, the need for a high-quality forecast of generation for the day in advance is indicated, as well as the need to improve control algorithms for combining ESS usage scenarios.

A classification of scenarios for the use of ESS is proposed in [18]. The choice of scenario is determined by the system level (individual household, collective use, distribution network), the operating mode and the level of integration with the market. To analyze the profitability of ESS, a generalized formula is proposed that takes into account costs and income due to the integration of renewable energy sources into the electricity system. To maximize the profit from renewable energy sources, an approach is proposed that forms a compromise solution between costs and income according to the parameters of the renewable energy source and its accessories. At the same time, it is noted that for optimal operation of renewable energy sources, further improvement of the energy management system (Energy Management System – EMS) control algorithms is required. They should take into account the forecasting errors of renewable energy sources, load schedules, and electricity market prices, ESS parameters, power system topology, as well as technical limitations.

The simplest algorithm for optimizing the charge/discharge schedules of ESS is to use a set of charge/discharge rules (rule-based strategy) by time or by price. In [19] it is shown that the process of planning the charge of ESS during hours of low prices and the discharge during the period of high prices has a low computational complexity and is often used as a baseline scenario for comparison. However, this approach does not take into account the dynamics of RES generation and can lead to lost arbitrage opportunities. Based on this, in [19] it is proposed to use linear programming (LP) and mixed-integer linear programming (MILP) methods to solve the problem. This approach makes it possible to maximize profit or minimizing costs, taking into account the forecasts of the PVPP system and the limitations on the state of charge (SOC) of ESS, its degradation, and the parameters of the power grid. However, as shown in [20], the effectiveness of these methods critically depends on the accuracy of forecasts for PVPP generation and prices on the energy market. After all, the implementation of charge/discharge schedules of ESS determined based on an incorrect forecast may be accompanied by significant deviations from the declared PVPP generation schedule and penalties for imbalance settlement.

As a solution to the problem of partial uncertainty of PVPP generation and prices for DAM, it was proposed in [20] to represent forecasts of the specified indicators in the form of stochastic and robust models. They explicitly take into account the probable deviations of input parameters from the mathematical expectation by describing the uncertainty areas of a certain form or their combinations. This approach makes it possible to set the level of acceptable risk when planning a scenario for using ESS. The estimate of the expected profit from the operation of PVPP is represented in the form of an interval taking into account the given risk of exceeding the imbalance, or the error in estimating the price spread in DAM. The disadvantage of the approach is a significant increase in the volume of calculations, which determines its application for ESS dispatching tasks.

Thus, to optimize the operating modes of ESS within a separate scenario, optimization methods are used that have a common drawback. They operate with forecast data on model parameters as input data. Thus, they provide conditions for dispatching ESSs but not for prompt adjustment of their operation schedules within a day. To solve the problem of dynamic optimization of charge/discharge modes of ESS, it was proposed in [18] to use the method of predictive control based on a dynamic process model (MPC). It involves the use of a sliding horizon of optimization with periodic updating of forecasts based on local models. This increases the adaptability of ESS operational control to changes in PVPP generation and prices for BM in real time. However, the method requires significant computing power.

When it comes to optimizing the use of aggregated ESS resources in the electricity market, the choice of an effective strategy is determined primarily by the adopted business model. Based on this, ref. [21] proved the possibility of increasing profits by coordinating the operation of several ESSs and PVPP at the level of energy communities. It is shown that such a mechanism may be accompanied by risks to the economic efficiency of the power system due to the shortcomings of the existing market structure and regulatory policy. In addition, ref. [21] formulated ways to encourage the effective development of aggregators in the electricity market, taking into account the interests of distribution system operators (DSOs).

From the above review, it follows that the choice of the scenario for using ESSs and their operating modes is largely influenced by technical and economic factors, in particular, the configuration and parameters of the ESS, the achievable quality of forecasting of influential parameters, and the operating conditions in the electricity market. To form an effective strategy for generating profits from ESSs, it is advisable to combine available usage scenarios based on current conditions. The task of determining the optimal strategy has not yet been fully solved, even at the dispatching level. Thus, it is advisable to investigate the task of improving a strategy for using ESS under conditions of compatible operation with renewable energy sources, in particular PVPPs, taking into account technical limitations, restrictions from DSOs, and existing market mechanisms.

3. The aim and objectives of the study

The purpose of our study is to improve the strategy for using ESS in combination with a photovoltaic plant by promptly adjusting scenarios and optimizing its operating modes based on the analysis of the results of forecasting influential parameters. This will make it possible to increase the technical and economic efficiency of the operation of energy complexes consisting of photovoltaic plants and electricity storage systems in the energy market.

To achieve the goal, the following tasks were set:

– to propose an algorithm to form a forecast of photovoltaic plant generation for the day in advance;

– to assess the effectiveness of using ESS to ensure maximum profitability of DAM arbitrage;

– to assess the effectiveness of using ESS to ensure profitability by reducing imbalances between the forecast and actual generation by PVPPs;

– to analyze the functioning of ESSs, identify influential factors, and develop an algorithm for choosing a relevant scenario for their use in combination with PVPPs.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the operational process involving rechargeable battery energy storage systems (ESS) in combination with photovoltaic power plants (PVPP) in a competitive electricity market.

The principal hypothesis assumes that in the competitive model of Ukraine's electricity market, as well as in other countries with a high level of RES integration, PVPP managers are financially responsible for the deviation between the hourly commercial nomination and the actual electricity supply. For PVPPs with pronounced weather dependence and high intraday variability, imbalances are one of the main factors reducing profits. To reduce the economic consequences of imbalances, it is advisable to increase the quality of forecasting by focusing on the periods of the day with maximum settlement prices. The use of ESS makes it possible to reduce PVPP imbalances and, with them, the negative economic consequences. Electricity storage units can also be used to generate profit through DAM arbitrage. Based on this, to obtain the maximum effect, their use should be considered under both scenarios simultaneously. Research into factors affecting the effectiveness of ESS in each scenario and developing an algorithm for selecting the most profitable one could allow us to improve the strategy for using ESS in combination with PVPPs.

The following assumptions were adopted in the study:

– the degradation of solar modules was not taken into account in the model for predicting the PVPP generation;

– restrictions on the modes and parameters of the complex with PVPPs and ESS from the distribution networks were not taken into account;

– the additional economic effect of the active actions of the energy complex dispatcher on RES was not taken into account.

To ensure the possibility of using linear methods to form optimal ESS charge/discharge schedules, the following simplifications were accepted:

– the ESS model did not take into account the influence of SOC on the charge/discharge rate (the processes were considered linear);

– changes in voltage levels on ESS buses during their charge/discharge were not taken into account;

– the price and energy parameters of the problem statement were considered constant within the hourly interval.

To conduct the study, based on the experience of operating PVPPs, ESSs, and their complexes, effective methods for predicting electricity production [21], as well as optimizing the charge/discharge processes of ESSs, were identified and applied.

4. 2. Rules of the Ukrainian electricity market; determining imbalance prices

According to the Rules of the Ukrainian Electricity Market, imbalance is the difference between the declared (forecasted) volume of generation and the actual production of electricity. Market participants are financially responsible for imbalances through the balancing market (BM) mechanism [1].

The model of participation of PVPP in the electricity market corresponds to the sequence of segments RDM → IDM → BM. It is believed that the main settlement of deviations occurs on the balancing market, and imbalance is defined as the difference between the actual and declared volume

$$\Delta E(t) = E_{\text{fact}}(t) - E_{\text{plan}}(t), \tag{1}$$

where $\Delta E(t)$ – imbalance at hour t, MWh; $E_{\text{fact}}(t)$ – actual electricity output of the PVPP (including ESS) during hour t, MWh; $E_{\text{plan}}(t)$ – hourly commercial nomination (plan), MWh.

Imbalance prices for Ukraine in [1] are given as min/max relative to the DAM price and the "down/up" balancing energy prices. The following formulae were used in our calculations:

$$P_{\text{imb}}^{+}(t) = \min\left(P_{\text{DAM}}(t), P_{\text{BM,down}}(t)\right), \tag{2}$$

$$P_{\text{imb}}^{-}(t) = \max\left(P_{\text{DAM}}(t), P_{\text{BM,up}}(t)\right), \tag{3}$$

where $P_{\text{imb}}^{+}(t)$ is the price of positive imbalance (surplus), EUR/MWh; $P_{\text{imb}}^{-}(t)$ – price of negative imbalance (deficit), EUR/MWh; $P_{\text{BM,up}}$ – price of DAM at hour t; $P_{\text{BM,down}}(t)$, $P_{\text{BM,up}}(t)$ – prices of electricity on the balancing market for supply and demand, respectively.

4. 3. Methods for forecasting photovoltaic power plant generation

Our review of the literature [13–16] yielded a classification of methods for forecasting photovoltaic power plant generation volumes. That made it possible to systematize approaches for different time horizons.

In practical tasks of forecasting the day ahead for PVPPs, the key is a compromise between accuracy, stability, and reproducibility, which leads to the need to form ensemble models. Therefore, within the framework of our study, an ensemble of machine learning methods Random Forest + XGBoost + LightGBM was used for forecasting PVPPs. This combination has made it possible to reduce the risk of "failures" in the quality of the forecast under variable weather conditions (clear/variable cloudiness) [22]. And this is critical for economic efficiency in DAM and in the balancing market under conditions of asymmetry of imbalance prices.

4. 4. Metrics for estimating an error in forecasting photovoltaic power plants generation

The mean absolute error (MAE) and the root mean square error (RMSE) are most often used to estimate deterministic forecasts of PVPP generation, and the mean bias error (MBE) is used to control systematic bias. To compare the results of forecasting PVPP schedules in different periods of the year or with different installed capacities, normalized values of MAE (nMAE) and RMSE (nRMSE) are used. Metric formulae:

$$\mathrm{MAE}=\frac{1}{N}\sum_{t=1}^{N}\left|P_{\mathrm{fact}}(t)-\hat{P}(t)\right|, \tag{4}$$

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(P_{\mathrm{fact}}(t)-\hat{P}(t)\right)^{2}}, \tag{5}$$

$$\mathrm{MBE}=\frac{1}{N}\sum_{t=1}^{N}\left(\hat{P}(t)-P_{\mathrm{fact}}(t)\right), \tag{6}$$

$$\mathrm{nMAE}=\frac{\mathrm{MAE}}{P_{\mathrm{inst}}}\cdot 100\%, \tag{7}$$

$$\mathrm{nRMSE}=\frac{\mathrm{RMSE}}{P_{\mathrm{inst}}}\cdot 100\%, \tag{8}$$

where N – number of time steps (hours) in the sample; $P_{\mathrm{fact}}(t)$ – actual power/generation by PVPP at hour t; $\hat{P}(t)$ – predicted power/generation at hour t; P_{inst} – installed power of PVPP.

4. 5. Methods for optimizing the modes of an electricity storage system

The potential effect from the introduction of ESS is determined by the following technical parameters:

– rated charge/discharge power $P_{\max}$;

– energy capacity $E_{\max}$;

– limit values of the state of charge of the storage device (state of charge – SoC) $\mathrm{SOC}_{\min}$, $\mathrm{SOC}_{\max}$;

– efficiency of the charge-discharge cycle η_{rt}.

For a larger reproduction of ESS operating modes, a balance model is used:

$$\begin{cases}\mathrm{SOC}(t+1)=\mathrm{SOC}(t)+\eta_{\mathrm{ch}}\cdot E_{\mathrm{ch}}(t)-\dfrac{1}{\eta_{\mathrm{dis}}}\cdot E_{\mathrm{dis}}(t);\\ E_{\mathrm{ch}}(t)=\int_{t}^{t+1}P_{\mathrm{ch}}(t)\mathrm{d}t;\ E_{\mathrm{dis}}(t)=\int_{t}^{t+1}P_{\mathrm{dis}}(t)\mathrm{d}t;\\ P_{\mathrm{ch}}(t)\le P_{\max};P_{\mathrm{dis}}(t)\le P_{\max};\\ \mathrm{SOC}_{\max}\ge \mathrm{SOC}(t)\ge \mathrm{SOC}_{\min};\\ \mathrm{SOC}_{\max}\ge \mathrm{SOC}(t+1)\ge \mathrm{SOC}_{\min},\end{cases} \tag{9}$$

where $\mathrm{SOC}(t)$ – energy in the storage device at the beginning of hour t, MWh; $P_{\mathrm{ch}}(t)$, $P_{\mathrm{dis}}(t)$ – dependence of charge and discharge power on time, MWh; $E_{\mathrm{ch}}(t)$, $E_{\mathrm{dis}}(t)$ – energy of charge and discharge during hour t, MWh; η_{ch}, η_{dis} – efficiency of charge and discharge.

As mentioned above, linear programming methods (LP/MILP), robust models, and predictive control (MPC) are used to optimize ESS modes. Therefore, to solve the task of optimizing the operation of ESS in combination with PVPP, a combination of LP/MILP and MPC methods was applied. Linear programming methods were employed to form work schedules for the day in advance, and the MPC method was used for operational adjustments when the ESS usage scenario changes. When optimizing the charge/discharge schedules, the degradation of basic ESS equipment and the operating restrictions on active power from DSOs were additionally taken into account.

4. 6. Input data and parameters of the studied object

The experimental PVPP has an installed capacity of 9.5 MW, and ESS has a rated charge/discharge capacity of 1 MW and an energy density of 2 MWh. The efficiency of the full charge-discharge cycle is $\eta_{rt}=0.88$ ($\eta_{ch}=0.938$ and $\eta_{dis}=0.938$), which corresponds to modern lithium-ion systems. The simulation was performed at hourly discretization.

5. Results of investigating the operation process of an electricity storage system in a combination with a photovoltaic power plant

5. 1. Algorithm for forming a forecast of photovoltaic power plant generation for the day ahead

To form an hourly commercial nomination, a generation forecast was used, built on the basis of an ensemble of RandomForest + XGBoost + LightGBM models. Random Forest is an effective tool for forecasting PVPP generation due to its ability to model nonlinear dependences between meteorological factors and the output parameter, as well as to take into account complex relationships between variables under uncertainty. Its main advantage is the adaptability of the model to changes in weather conditions and seasonal fluctuations, which is critical for PVPP forecasting tasks [22]. Within the framework of our study, the Random Forest model was used as the basis of the forecasting block. However, to increase the stability of the forecast and reproduce realistic forecast error levels for the "day in advance" task, the model was expanded to an ensemble of several models. That has made it possible to analyze the sensitivity of economic results under different ESS control strategies to changes in forecast uncertainty. In addition, it was possible to avoid "optimistic" overestimation of accuracy during simulations.

The list of input variables included:

– meteorological parameters, in particular temperature, solar radiation, cloudiness;

– engineering characteristics of PVPP, in particular generation lags of 1–24 h, rolling statistics (rolling 3/6/12/24 h) and cyclical time components (hour/month in the form of sine and cosine functions).

For the daily horizon, an autoregressive approach was applied, that is, the forecast for hour $t+1$ was used as one of the inputs for the forecast for the interval $t+2$, etc. That has made it possible to correctly take into account the accumulation of error on the 24-hour horizon.

The following algorithm is proposed to form PVPP generation forecast [22]:

Step 1. Parallel training of three basic models. Random Forest is trained on bootstrap samples, each tree uses a random subset of features, and the final forecast is formed by averaging. XGBoost is trained sequentially: each subsequent tree minimizes the residual error of the previous ensemble taking into account regularization. LightGBM uses histogram feature partitioning and leaf-wise growth, which makes it possible to work quickly with large data sets.

Step 2. For each validation sample record, three forecast vectors are calculated (by the number of base models). These vectors are used to determine the optimal combination of models.

Step 3. The weights of base models in the ensemble w_1, w_2, w_3 are determined by minimizing the MSE on the validation sample using the SLSQP method under the conditions $w_1+w_2+w_3=1$ and $w_i>0$, $i=1\ldots3$. This condition does not allow uninterpreted negative contributions of individual models.

Step 4. Quality check on the validation sample. If the MSE exceeds the specified threshold, hyperparameter adjustment is performed and the algorithm returns to Step 1. If the quality is acceptable, the models are fixed for further forecasting.

Step 5. Formation of the final deterministic forecast. For the forecast day, the values of the three models $\hat{P}_{RF}(t)$, $\hat{P}_{XGB}(t)$, $\hat{P}_{LGB}(t)$ are combined with the optimal weights. The resulting series is the base forecast for further smoothing and quantile processing. The ensemble forecast of PVPP generation at hour t is determined using the following expression

$$\hat{P}(t)=w_1\cdot\hat{P}_{RF}(t)+w_2\cdot\hat{P}_{XGB}(t)+w_3\cdot\hat{P}_{LGB}(t). \qquad (10)$$

Step 6. Smoothing the forecast series with the Savitsky-Goley filter. Smoothing with a window of 7 samples based on a second-order polynomial is applied to the final series, which reduces high-frequency fluctuations without destroying the daily generation profile.

The forecast accuracy was assessed by metrics MAE, RMSE, and MBE offset (Table 1).

The results of forecasting the electricity production by the experimental PVPP for 9 months of 2025 yielded the following results: MAE = 577.5 kW (nMAE = 6.08%) and RMSE = = 1,139.8 kW (nRMSE = 12.0%) for the given observation period. The forecast bias is MVE = −312 kW, that is, the forecast tends to underestimate, as can be seen from Fig. 1, 2.

The economic efficiency of participation of PVPP in a competitive market is determined not only by the average forecast error but primarily by the change in the error over time and its distribution by sign. During the PVPP generation period, it changes many times and shows the greatest variability on days with variable cloudiness (Fig. 1). The same nRMSE/MAE value may have fundamentally different financial consequences depending on whether the generation deficit is formed precisely during hours with high prices of balancing energy "up" (3) and whether the error has a stable bias.

Table 1

Quality indicators of the forecast of PVPP generation from 01.01.2025 to 09.30.2025 (6552 hours)

Sample	*N*, h	MAE, kW	RMSE, kW	MBE, kW	nMAE, %	nRMSE, %
All period	6,552	577.5	1,139.8	–312	6.08	12.00
Hours with generation greater than 0.5 MW	2,806	1,269.7	1,702.4	–802	13.37	17.92
Hours with generation greater than 1.0 MW	2,401	1,393.2	1,804.8	–1012	14.66	19.00

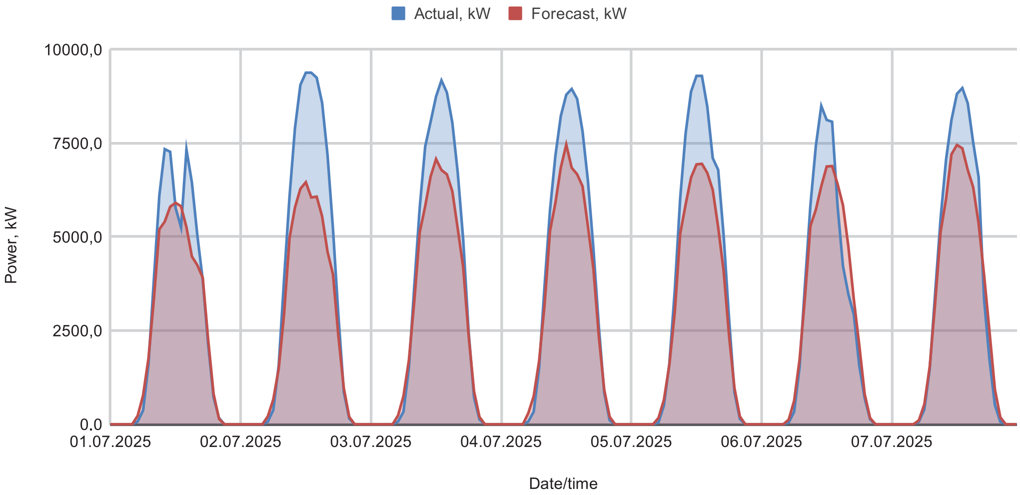

Fig. 1. Example of hourly forecast and actual generation by a pilot photovoltaic power plant during a week

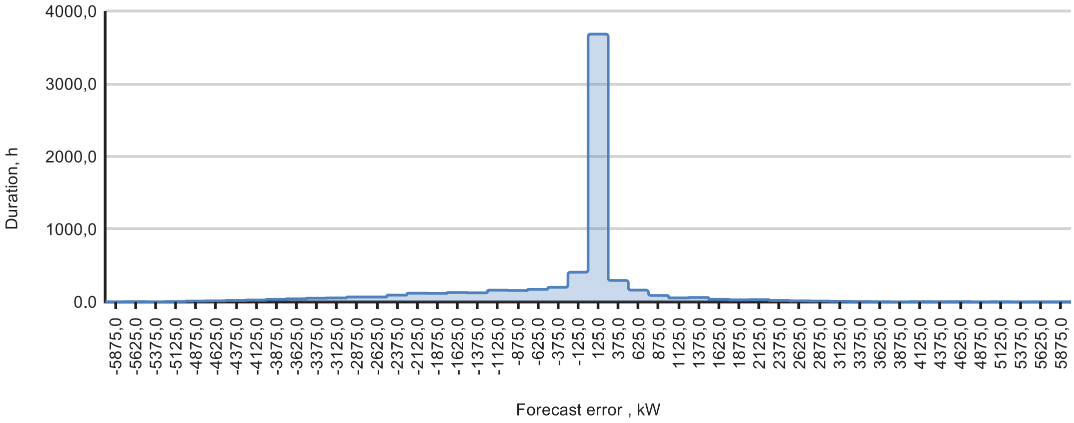

Fig. 2. Distribution of generation forecast error for the experimental photovoltaic power plant

The identified negative forecast bias (Fig. 2) for the studied process is not just a statistical characteristic of the model but a parameter of the inherent market behavior. After all, systematic underestimation of PVPP generation leads to conservative nomination in DAM, reducing the frequency and value of energy deficits that are regulated by price (3). However, at the same time, the "nominal" sales volume at the DAM price decreases, and part of the actual electricity generation is transferred to settlement as a positive imbalance at the price (2).

5. 2. Application of electricity storage systems to increase the profitability of photovoltaic power plants through arbitrage (Scenario 1)

Within Scenario 1 "DAM Arbitrage", optimization of ESS functioning ensures the maximum hourly increase in the selling price of PVPP electricity. To determine the optimal schedule of the installation during each day of the observation period, a set of methods described in chapter 4. 3 was used. As a result, part of the forecasted PVPP production volume from hours of lower prices was transferred to hours with a higher price, which is illustrated in Fig. 3. The key feature of assessing the economic effect is to apply the same ESS charge/discharge schedule to both the forecasted and actual PVPP generation. Thus, the forecast error and, accordingly, the volumes of imbalances for PVPP for this scenario of using PVPP practically do not change.

The economic effect (Table 2) is achieved mainly due to the increase in the average selling price of electricity from PVPP in DAM, as well as the difference in additional income from the sale of positive imbalance (Table 3).

Formally, the modified nomination can be written as:

$$\begin{cases} E_{\text{plan}}^{A}(t)=\widehat{E}_{\text{PV}}(t)-E_{\text{ch}}^{A}(t)+E_{\text{dis}}^{A}(t); \\ E_{ch}^{A}(t)=\int\limits_{t-1}^{t} P_{\text{ch}}(t)\text{d}t;\ E_{dis}^{A}(t)=\int\limits_{t-1}^{t} P_{\text{dis}}(t)\text{d}t; \\ P_{\text{ch}}(t)\le P_{\max};P_{\text{dis}}(t)\le P_{\max}; \\ \text{SOC}_{\max}\ge \text{SOC}(t)\ge \text{SOC}_{\min}, \end{cases} \quad (11)$$

where $E_{\text{plan}}^{A}(t)$ – PVPP generation nomination for the DAM arbitrage strategy, MWh; $\widehat{E}_{\text{PV}}(t)$ – predicted PVPP generation without an energy storage system, MWh; $E_{\text{ch}}^{A}(t)$ – ESS charge energy per hour t, MWh; $E_{\text{dis}}^{A}(t)$ – ESS discharge energy per hour t, MWh.

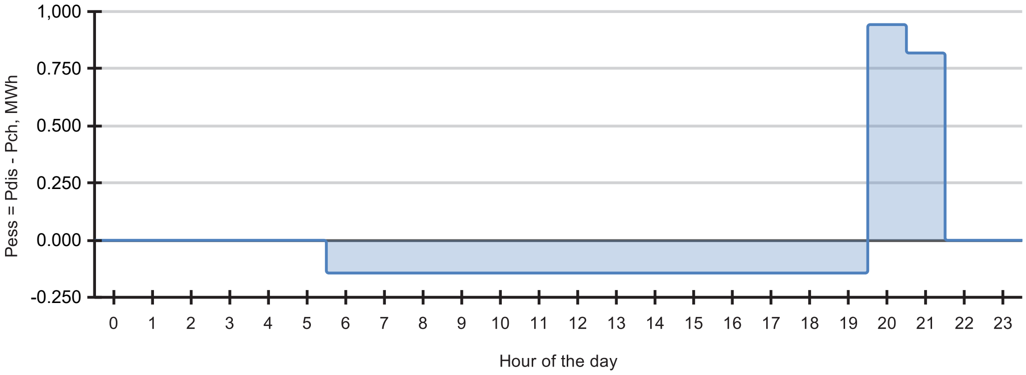

Fig. 3. An example of changing the modes of energy storage system in 24 hours (07/01/2025) according to the market arbitrage strategy for a day in advance: P_{ESS} is determined by the difference between the hourly volume of discharge and charge

Table 2

Key results of ESS functioning under Scenario 1 (DAM Arbitrage) during the observation period

Indicator	Value
Nominated volume of electricity sales in DAM, MWh	9,921.908
Weighted average price of DAM (by denomination), EUR/MWh	67.75
ESS charge per period, MWh	540.976
ESS discharge per period, MWh	475.677
Energy losses in ESS, MWh	65.299
Equivalent number of cycles ($E_{\text{dis}}/E_{\text{ESS}}$, MWh), cycle	237.84
Average price of charging hours, EUR/MWh	82.46
Average price of discharging hours, EUR/MWh	199.04
Additional income from Arbitrage in DAM (relative to the baseline scenario – in the absence of ESS), EUR	50,068.51

Table 3

Energy-weighted average prices of imbalances for the period (calculated based on actual volumes of imbalances during the observation period)

Indicator	Scenario 1 (DAM Arbitrage)	Scenario 2 (PVPP Balancing)
$\overline{P}_{\text{imb}}^{+}$, EUR/MWh	38.47	42.60
$\overline{P}_{\text{imb}}^{-}$, EUR/MWh	83.71	76.36
Ratio $\overline{P}_{\text{imb}}^{-} / \overline{P}_{\text{imb}}^{+}$, times	2.18	1.79

Note: conversion of economic indicators from UAH to EUR was performed at the average official exchange rate of the National Bank of Ukraine for the period 01.01.2025–30.09.2025: 1 EUR = 46.49 UAH.

Our research results showed that increasing the weighted average electricity sales price in DAM from an average of 57.6 to 62.6 EUR/MWh provided additional income of EUR 46,308.22 for 9 months of 2025. Energy losses due to cycle efficiency amounted to 65.3 MWh. At the same time, the high intraday price spread in selected hours (on average over 100 EUR/MWh between charge and discharge hours) fully compensated for energy losses and provided a positive margin effect.

5. 3. Application of energy storage systems to increase the profitability of photovoltaic power plants by reducing imbalance (Scenario 2)

Within Scenario 2 "PVPP Balancing", the optimization of ESS functioning focuses on reducing negative imbalances, the settlement of which in BM is the costliest due to the max() formula and market asymmetry [1]. Unlike Scenario 1 "DAM Arbitrage", in this case the energy storage system affects the volumes of actual electricity supply from PVPP and covers the deficit. The commercial nomination is determined by the PVPP system forecast for the day in advance and remains unchanged. Thus, under this strategy, ESS works as a risk management tool for reducing the quality of PVPP forecast.

After ESS application, the actual volume of electricity supply to the market is described as follows:

$$\begin{cases} E^{B}_{\text{fact}}(t) = E_{\text{fact.PVPP}}(t) + E^{B}_{\text{dis.cov}}(t) + \\ + E^{B}_{\text{dis.grid}}(t) - E^{B}_{ch}(t); \\ E^{B}_{ch}(t) = \int\limits_{t-1}^{t} P_{\text{ch}}(t)\text{d}t;\ E^{B}_{dis.\text{cov}}(t) = \int\limits_{t-1}^{t} P_{\text{cov}}(t)\text{d}t; \\ E^{B}_{dis.grid}(t) = \int\limits_{t-1}^{t} P_{\text{grid}}(t)\text{d}t; \\ P_{\text{ch}}(t) \le P_{\text{max}};\ P_{\text{cov}}(t) + P_{\text{grid}}(t) \le P_{\text{max}}; \\ \text{SOC}_{\text{max}} \ge \text{SOC}(t) \ge \text{SOC}_{\text{min}}, \end{cases} \qquad (12)$$

where $E^{B}_{\text{fact}}(t)$ – actual electricity release for Scenario 2 (PVPP balancing), MWh; $E_{\text{fact,PVPP}}$ – actual PVPP generation without ESS, MWh; $E^{B}_{\text{dis.cov}}(t)$ – ESS discharge energy to cover the PVPP deficit (compensation of negative imbalance), MWh; $E^{B}_{\text{dis.grid}}(t)$ – ESS charge energy in the power grid in excess of PVPP balancing needs, MWh; $E^{B}_{ch}(t)$ – ESS charge energy per hour t, MWh; $P_{\text{cov}}(t)$, $P_{\text{grid}}(t)$ – ESS power consumed to cover the PVPP deficit and fed into the power grid during hours of maximum BM price, MWh.

To determine the optimal schedule of the installation during each day of the observation period, a set of methods described in chapter 4.3 was used. An example of the schedule of ESS operation according to Scenario 2 is shown in Fig. 4. It corresponds to the following sequence of actions:

– charging occurs from the power grid at night (2 h × 1 MW) at the lowest prices;

– covering negative imbalances of PVPP in the energy market during the daytime (from 6:00 to 16:00) within the available volume of electricity (SOC);

– issuing surplus electricity in the evening (from 17:00 to 22:00).

The cost of charging is determined by the price and volume of electricity purchased in DAM. The effect of using ESS electricity to compensate for imbalances is estimated through the increase in actual generation by the complex of ESS and PVPP, which is reflected in the calculation of imbalances (Tables 4, 5).

During the observation period, negative imbalances were reduced by 333.9 MWh (–14.2%), which provided savings in imbalance costs of EUR 39,552.23. Additionally, income from positive imbalances increased by EUR 16,967.65; however, this effect is largely absorbed by the costs of charging ESS (EUR 39,538.62). The total increase in income from the operation of ESS according to Scenario 2 (PVPP Balancing) amounted to EUR 16,981.25 over 9 months of 2025.

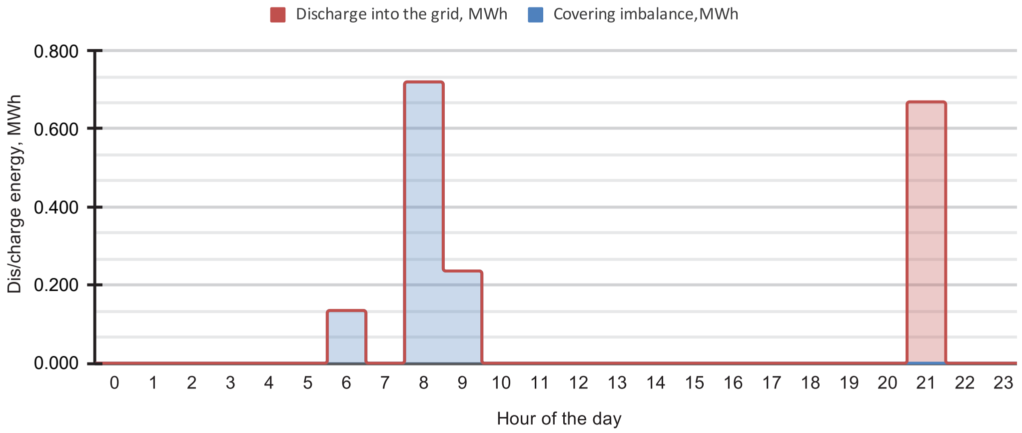

Fig. 4. Example of changing the modes of energy storage system in 24 hours (01.07.2025) according to Scenario 2 "PVPP Balancing"

Table 4

Energy and economic effect of using ESS according to Scenario 2 "Balancing of PVPPs" during the observation period

Indicator	Baseline scenario (without ESS)	Scenario 2 "PVPP Balancing"	Change
Positive imbalances, MWh	62.94	66.09	146.581 (+5.01%)
Negative imbalances, MWh	50.63	43.45	–333.899 (–14.18%)
Income from positive imbalances, EUR	112548.89	130,894.33	18,345.44
Costs for settling negative imbalances, EUR	197017.25	154,253.32	–42,763.92
Costs for ESS charging (purchase in DAM), EUR	0.00	42,749.20	–42,749.20
Economic effect (income increase), EUR			18,360.16

Table 5

Technical indicators of ESS functioning according to Scenario 2 (PVPP Balancing)

Indicator	Value
ESS charge from the network, MWh	546.000
ESS discharge to cover the imbalance, MWh	331.178
Excess discharge of ESS to the network, MWh	149.302
Share of ESS discharge to cover the deficit, %	68.9
Equivalent number of cycles (E_{dis}/E_{ESS}, MWh), cycle	240.24
Average discharge per day, MWh/day	1.754

5. 4. Comparative analysis of the functioning of energy storage systems under different scenarios

By comparing the results of our feasibility analysis of ESS operation in combination with a photovoltaic power plant under different scenarios (Table 6), the following conclusions can be drawn.

During the observation period, Scenario 1 "DAM Arbitrage" provided a higher economic effect. The reason is a significant increase in DAM income due to the transfer of energy to hours of maximum prices. At the same time, Scenario 2 "PVPP Balancing" demonstrated a smaller volume of negative imbalances and a lower share of costs for their settlement. Thus, this scenario is more protected from the risks of electricity shortages in the power system.

Fig. 5 demonstrates that the advantage of usage scenarios can change during the year. It is situational and depends on the structure of the daily price profile and the nature of the forecast error.

To illustrate this effect, Fig. 6 shows the results of optimizing the functioning of ESS for three representative days. Fig. 6, *a* depicts a day with the dominance of the arbitrage scenario, which occurs at a high price spread in DAM and a low error in the hourly forecast of PVPP. Fig. 6, *b* corresponds to a day with the dominance of the PVPP balancing scenario, which is associated with a high price of capacity deficit on RES and significant underproduction of electricity by PVPP. Fig. 6, *c* corresponds to a day when the effects of the studied scenarios of ESS use are close.

From a practical point of view, this means the feasibility of using an improved combined ESS control strategy. Part of the capacity should be reserved for balancing PVPP. The other part is allocated for arbitrage actions in DAM. The control algorithms should be changed based on specified events, for example, exceeding the maximum predicted generation variability, or exceeding the specified predicted volatility in the DAM prices.

However, a universal approach to choosing an ESS control scenario is an analysis of the economic consequences of both scenarios with the choice of the best one. Given the time frame for solving the ESS dispatching task, this approach is quite acceptable.

Table 6

Comparison of economic results of ESS operation according to the proposed usage scenarios over the observation period

Indicator	Scenario 1 (DAM Arbitrage)	Scenario 2 (PVPP Balancing)
Positive imbalances, MWh	62.94	66.09
Negative imbalances, MWh	50.63	43.45
Income in DAM, EUR	672,064.15	621,995.64
Income from positive imbalances, EUR	112,548.89	130,894.33
Costs for settling negative imbalances, EUR	197,017.25	154,253.32
Costs for ESS charging, EUR	0.00	42,749.20
Economic effect (income increase), EUR	598,116.65	582,291.79
Share of expenses for imbalance settlement, %	0.51	0.49

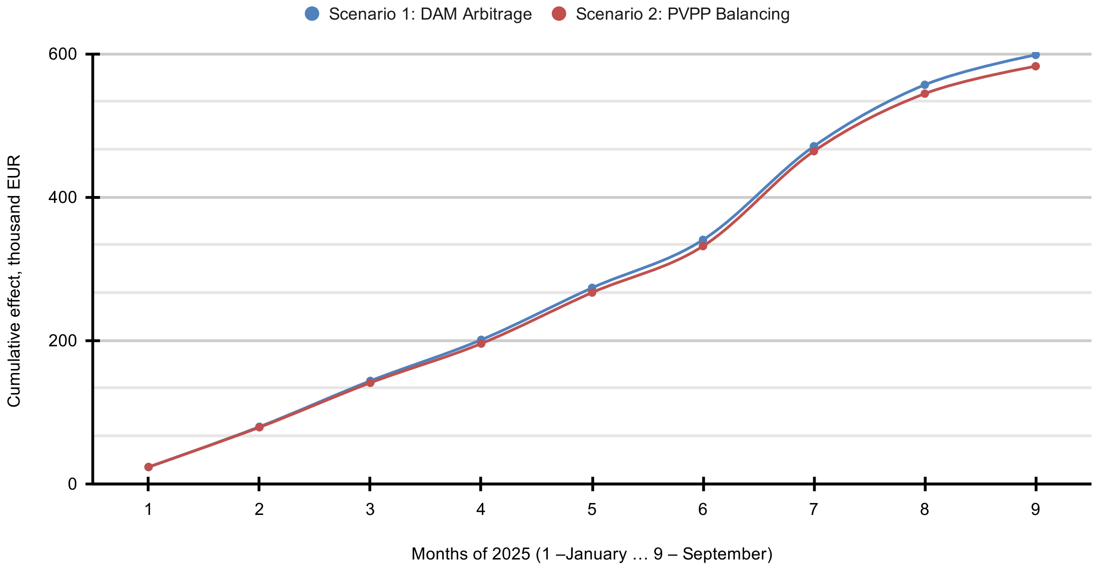

Fig. 5. Economic effect of using energy storage systems at a photovoltaic plant during the observation period

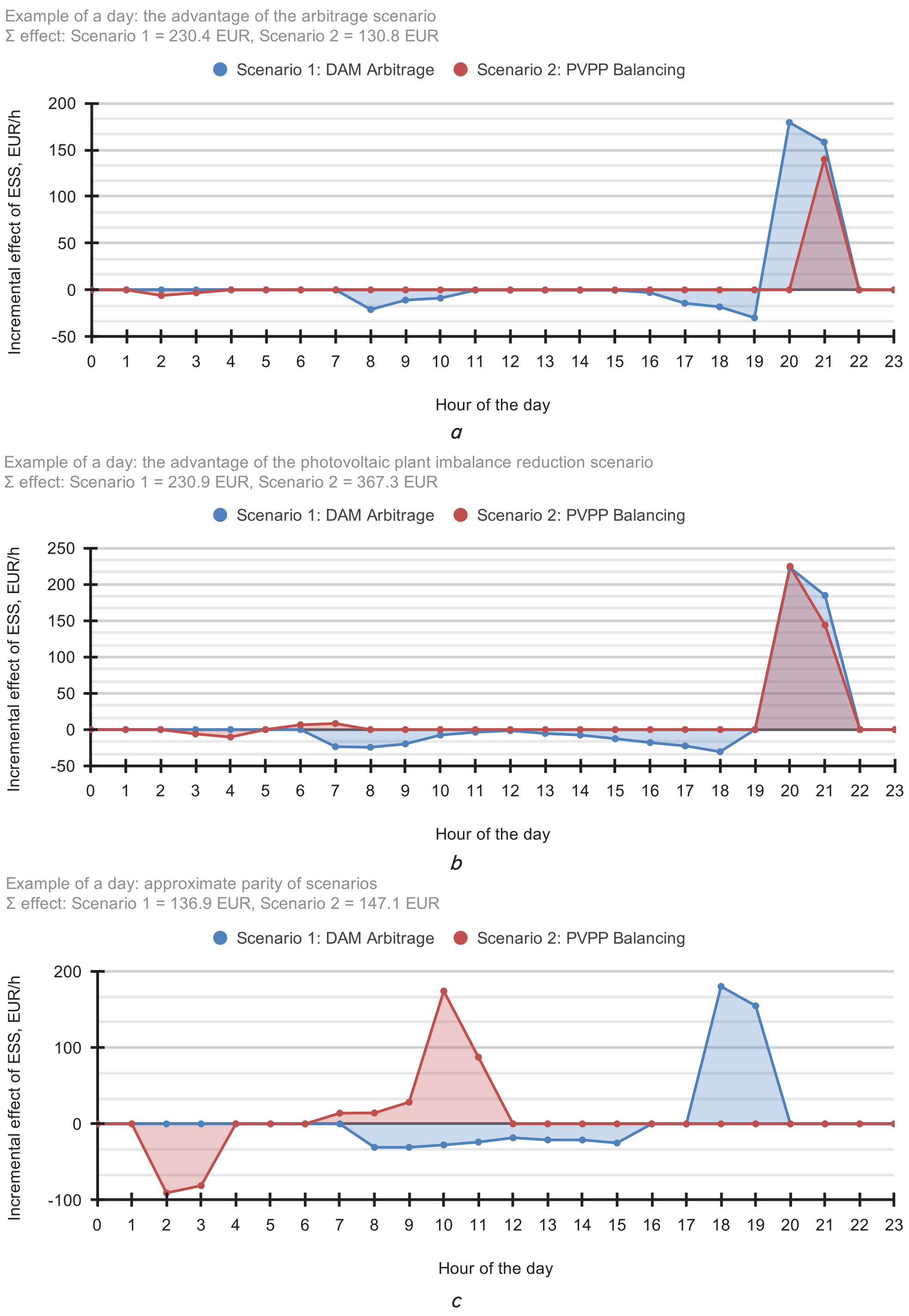

Fig. 6. Hourly effect of using energy storage systems:
a – 24 hours with the advantage of the arbitrage scenario; *b* – 24 hours with the advantage of the photovoltaic plant imbalance reduction scenario; *c* – 24 hours with parity of scenarios for using energy storage systems

Therefore, the following algorithm is proposed to select an ESS use scenario in accordance with the estimated conditions:

Step 1. Calculate the potential of an arbitrage scenario. Based on the optimized ESS operation schedule to ensure DAM arbitrage, the expected income R_{arb} from energy transfer between hours of the day is determined.

Step 2. Calculate the potential of a balancing scenario. Based on the forecasted deficit of PVPP generation $\hat{P}_{def}(t) = \hat{P}(t) - P_{fact}(t) > 0$ and the prices of negative imbalance $\hat{\lambda}^{-}_{imb}(t)$, the expected savings R_bal from using ESS to cover deficits is estimated

$$R_{bal} = \sum_{t\in\mathcal{T}^-} \hat{\lambda}^-_{imb}(t)\cdot\hat{P}_{def}(t). \tag{8}$$

Step 3. Marginal condition for strategy selection. If $R_{bal} < R_{arb}$, then the arbitrage strategy is activated. If $R_{bal} \geq R_{arb}$, priority is given to balancing the PVPP because reducing imbalances has a higher expected economic value.

Step 4. Checking the adequacy of SoC. If the current charge level of ESS is lower than the minimum required, the algorithm, regardless of the selected strategy, activates night charging to ensure the technical readiness of the storage system.

6. Discussion of results based on investigating the operation of energy storage systems in combination with photovoltaic power plants

Paper [20] shows that the economic efficiency of PVPP participation in a competitive market, as well as the effect of using ESSs, depends on the accuracy of the forecast of generation schedules. However, the results of our study demonstrate that the efficiency of ESS control is determined primarily by the change in error over time and its distribution by sign. The same value of nRMSE/MAE may have fundamentally different financial consequences, which depend on the formation of a generation deficit during hours with high prices for imbalance settlement (3) and a stable error bias.

It has been shown that to reduce the costs of settling deficits at price (3), a negative forecast bias can be used. This approach, due to the conservativeness of nominations in DAM, reduces the frequency and value of deficits in PVPP production. However, it is not universal, as it leads to a decrease in the "nominal" volume of PVPP electricity sales at DAM prices. In addition, part of the actual generation is transferred to the settlement as a positive imbalance according to expression (2), which may reduce the average income per unit of generated energy. Thus, our results confirm the need to transition from deterministic forecasting to forecast correction for the formation of a nomination based on maximizing the expected profit taking into account the asymmetry of imbalance prices. The solution to such a problem is significantly simplified if there is a PVPP within an ESS.

Comparison of the two proposed scenarios for controlling ESS demonstrates a fundamental difference in the nature of the economic effect and sensitivity to market signals. Scenario 1 "DAM Arbitrage" in the adopted statement forms an effect through the temporal transfer of energy and a change in the weighted average sales price. If there is a sufficient price spread and acceptable efficiency of the charge/discharge cycle, such a strategy can provide a stable economic result (Table 2). The peculiarity of the proposed implementation is that the charge/discharge schedules of ESS are formed symmetrically to the forecast and actual generation profiles of PVPP. Thus, the sensitivity of the arbitrage is determined primarily by the characteristics of DAM, in particular the intraday price spread, the frequency of days with a clear night minimum and evening maximum, as well as the correctness of the choice of time windows.

Scenario 2 "PVPP Balancing" involves the use of ESS as a buffer to compensate for generation deficits, which directly reduces the volume of expensive negative imbalances (Fig. 4). In this case, the key effect is formed on the difference between the costs of regulating the deficit without ESS and with ESS (Table 4). In [17] it is shown that such a scenario of using ESS is the most acceptable for industrial PVPPs. However, our studies have shown that balancing is accompanied by additional operating costs, in particular, charging ESS from the power grid and losses in the storage system. Therefore, the attractiveness of this scenario is uneven in time and depends on the nominations of the electricity market. It has been established that it is relevant at high prices for regulating the deficit and forecast uncertainty of generation. However, at high night-time prices in DAM or a low difference between the prices in DAM and balancing energy "down" (3), the price of stored energy increases and the scenario loses its effectiveness.

Unlike [18], which indicates that the optimal strategy for using ESS is determined by the type of power plant, our results show that for the complex of PVPP and ESS, the optimal policy is not fixed throughout the year (Fig. 5, 6). It depends on the season, weather variability, and market conditions. This means the validity of a comprehensive ESS control strategy that combines the above scenarios of their use. Therefore, it is advisable to reserve part of ESS capacity for balancing PVPP, and part for arbitrage. The current ESS control scenario should change in accordance with the expected variability of generation, or the increase in DAM prices. To select the appropriate scenario within the framework of the improved ESS control strategy, an algorithm based on the comparison of economic results is proposed. Thus, the prerequisites for obtaining higher profits are formed, compared to the use of static control scenarios, considered in [17].

Therefore, unlike [17, 18], the improved control strategy will allow us to move from the use of fixed scenarios to the construction of an adaptive control system, which could ensure a stable economic result under changing weather conditions and electricity market conditions. For the implementation of the system, the use of linear programming methods, as proposed in [19], may not be effective. Therefore, according to the results of our study, these methods were combined with predictive control over ESS modes within current 24 hours.

Our study has a number of limitations. In particular, it does not take into account the degradation of solar modules, restrictions on the voltage at the connection nodes of PVPP and ESS, and most importantly, the possibility of influencing a PVPP profit by active actions in DAM. The latter is a key tool for reducing imbalances by clarifying PVPP nominations closer to the time of electricity delivery. Therefore, further research should be aimed at taking into account this mechanism for clarifying nominations on a horizon of 1–6 hours when planning ESS management measures in the day-ahead market.

7. Conclusions

1. We have proposed an algorithm for forecasting hourly volumes of power generation by PVPP, characterized by the use of an ensemble of Random Forest + XGBoost + LightGBM machine learning models. The process of parallel training of models is built in such a way that dynamic determination of the most important time intervals and weather factors is ensured. Their analysis makes it possible to determine the weighting factors for the adaptive combination of forecasting results according to three models. In this way, the stability of the forecast is increased under conditions of sudden changes in cloud cover and other adverse weather conditions. According to the results of forecasting the electricity generation by an experimental PVPP during the observation period, a root mean square error within 12% was obtained, which indicates the high efficiency of the algorithm. In addition, it makes it possible to set the forecast bias indicator (MBI) as a parameter of underlying market behavior.

2. Using an example of the energy complex of PVPP and ESS, the effectiveness of application of the DAM arbitrage scenario has been investigated. The peculiarity of experiment design was that the optimal charge/discharge schedules of ESS were formed separately for the forecast and actual generation profiles of PVPP. That has made it possible to separate the effect of DAM arbitrage from the total revenue from the sale of electricity by PVPP. A set of linear programming

methods was used to optimize the charge/discharge modes of ESS, which showed a reasonably high efficiency. Thus, the weighted average selling price of electricity from PVPP increased by an average of 8% due to the dispatching of ESS, which provided additional income of EUR 46,308.22 over 9 months of 2025.

3. Scenario 2 "PVPP Balancing" was studied as a risk-oriented mechanism aimed at reducing negative imbalances, which under conditions of market asymmetry form the main part of operating costs. Within this scenario, ESS is considered as an additional means of compensating for forecast uncertainty. It has been shown that the priority of this scenario increases during periods of high prices for settling negative imbalances, increased uncertainty in the PVPP generation forecast, and low night-time prices in DAM. Due to the optimization of ESS schedules, negative imbalances were reduced by 14.2% during the observation period, which provided savings in costs for their settlement of about EUR 40,000. In addition, income from the sale of surplus electricity increased by more than EUR 15,000.

4. Over the observation period, the use of the arbitrage scenario provided a higher economic effect (about EUR 600,000) compared to the PVPP balancing scenario (about EUR 580,000), which is due to high daily price volatility. At the same time, periods were recorded when the effect of PVPP balancing exceeded the DAM arbitrage indicators by more than twice. Therefore, the results of investigating the functioning of ESS in a combination with PVPP show that the optimal scenario for using ESS is not stable. Depending on the season, weather conditions, and market signals, it is advisable to change the priority of scenarios. We have proposed an algorithm for selecting the best ESS control scenario for current conditions, based on assessing the economic effect of implementing optimal charge/discharge schedules. The procedure for determining the current scenario for a certain time period consists of a preliminary assessment and operational adjustment, each of which uses available data to forecast the PVPP generation and prices in the energy market. That has made it possible to improve the strategy of using ESS in a combination with PVPP. During the observation period, the economic effect of its implementation amounted to about EUR 15,000.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The ChatGPT 4.5 artificial intelligence model was used to generate a review of publications on the topic of the study. All references to sources were checked for correctness and correspond to reality. Artificial intelligence models were not used to compile research results and draw conclusions.

Authors' contributions

Volodymyr Kulyk: Conceptualization, Writing-review and editing, Supervision; **Maksym Zatkhei**: Methodology, Software, Visualization; **Vira Teptia**: Writing-original draft, Formal analysis; **Yurii Hrytsiuk**: Investigation, Resources; **Sviatoslav Vishnevskyi**: Validation, Data curation; **Iryna Hrytsiuk**: Writing-review & editing.

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