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Deterministic Step-by-Step Control of Solar Generation Imbalances in Power Systems

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Abstract

This paper examines an algorithm and evaluates the upper limits of technical parameters for step-by-step management of forecast coverage for aggregated generation from solar power plants (SPPs) in Ukraine, given the high share of renewable energy sources in the integrated power system of Ukraine. The relevance of the research is due to the growth in the installed capacity of SPPs, stricter requirements for forecasting accuracy, and the full financial responsibility of producers for imbalances in accordance with the current electricity market model. The problem is formulated as a special case of a hierarchically controlled quasi-dynamic power system, accounting for technological, energy, and economic constraints. The objective function is defined as the minimisation of the total hourly measure of discrepancy between the forecast and actual volumes of electricity supplied, whilst ensuring power balance through energy storage systems and flexible generation. The numerical implementation was carried out using the "SOPS" software and information complex. The input data used were hourly indicators of the forecasted and actual generation of Ukraine's solar power plants for 2021–2025, published by the state-owned enterprise "Guaranteed Buyer". Hourly, daily and monthly operating parameters for aggregated solar power generation in 2025 have been calculated. The calculations show that the maximum hourly mismatch between forecasted and actual solar generation in 2025 reached 3116 MW, while the maximum daily mismatch exceeded 19.8 GWh. Under the assumed operating conditions, an energy storage system with 30,000 MWh capacity and flexible generation of up to 7500 MW enabled full imbalance compensation, achieving IMB(t) = 0 for all hourly intervals in the analysed case. The required volumes of flexible generation and the operating parameters of the storage systems have been determined. The practical significance of the results lies in their potential use for operational planning of the operating modes of solar power plants, energy storage systems, and flexible generation on a daily and hourly basis, as well as for justifying technical and economic decisions aimed at reducing imbalances. The results obtained confirm the effectiveness of the proposed step-by-step control algorithm and demonstrate the potential to minimise imbalances through the rational coordination of solar power plants, energy storage systems, and flexible generation capacities.

Keywords: solar power generation; forecasting error minimisation; imbalance minimisation; power system balancing; power system flexibility; hourly optimisation; renewable energy integration; stepwise control algorithm

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Academic Editor: Cristobal Voz

Received: 25 March 2026
Revised: 4 May 2026
Accepted: 6 May 2026
Published: 8 May 2026

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1. Introduction

Against the backdrop of the rapid growth in the deployment of renewable energy sources within integrated power systems (IPS) [1–11], in particular renewable energy resources (RES) within the IPS of Ukraine, the relevance of research in this field is increasing, driven by a combination of technological, economic, environmental and geopolitical factors that determine the current state and development prospects of the IPS of Ukraine.

The main areas of focus in this field include:

1. Energy-economic optimisation of IPS operation with a high share of RES [12–14], which includes, in particular, an analysis of the impact of large-scale solar power plant deployment on power balance, electricity generation costs, cross-subsidisation, and the financial stability of the energy market and Ukraine's IPS as a whole.
2. Increased flexibility and balancing technologies [15–19], aimed at researching ways to improve system manoeuvrability: battery energy storage systems (BESS), hybrid solar power plants, demand response, power-to-heat technologies, and coordinated dispatch control of power system modes.
3. Frequency stability and automatic control through the improvement of automatic frequency and power control systems (AFPC) with a high share of solar power plants [20], the participation of inverter-based generation in primary and secondary frequency control [21], and the introduction of synthetic inertia [22].
4. Forecasting and digitalisation of control through the development of methods for short-term and ultra-short-term forecasting of RES generation [23], creation of digital twins of the power system [24], and the introduction of intelligent decision support systems for operational control [25].
5. Development of grid infrastructure and transmission capacity: assessment of the permissible share of RES at grid nodes [26], analysis of congestion, congestion management [27], and the implementation of Smart Grid technologies in Ukraine's power system [28].
6. Hybridisation and cross-sectoral integration: combining solar power plants with wind farms, energy storage systems, hydrogen production and district heating systems to reduce generation constraints and improve overall energy efficiency [29].
7. Reducing forced generation curtailments and market mechanisms, such as research into economic incentives, ancillary services markets, capacity payment mechanisms, and improvements to the RES support system (including reform of the "green" tariff) [30].
8. Reliability and resilience under emergency conditions: research into the operation of power systems with a high share of solar power plants under conditions of emergency blackouts, military impacts, and island operation; development of microgrids and black-start technologies [31,32].
9. Technologies for the direct use of solar power for heat supply: research into the application of solar power for heat generation [33] (electric boilers, heat pumps) in district heating systems to improve the energy efficiency of Ukraine's power system.

In recent years, significant attention has been devoted to the application of artificial intelligence (AI) and machine learning (ML) techniques for forecasting and operational control in power systems with a high share of renewable energy. These approaches include deep learning models for short-term generation forecasting, reinforcement learning for real-time control, and hybrid frameworks combining data-driven methods with physical system constraints [34–36].

At the same time, stochastic and robust optimisation methods have been developed to account for uncertainty in renewable generation and demand explicitly. Such approaches

https://doi.org/10.3390/solar6030024

typically rely on scenario-based modelling, probabilistic constraints, and Monte Carlo simulations to ensure system reliability under variability [37,38].

Recent studies also highlight a shift toward hybrid multi-objective frameworks that integrate machine learning, evolutionary algorithms, and economic optimisation to balance and manage energy in microgrids and large-scale systems [39].

However, despite these advances, many AI/ML-based approaches face challenges related to interpretability, scalability, and integration with operational constraints of real power systems.

Based on the analysis conducted, it can be stated that existing studies have not sufficiently addressed the specific task of step-by-step hourly coverage of the forecast schedule for aggregated solar power generation whilst simultaneously accounting for energy storage systems, flexible generation, and market constraints. It is precisely this gap that makes the approach proposed in this work relevant.

The set of technological, economic, environmental, and geopolitical factors determining the current state and development prospects of Ukraine's IPS includes:

1. Structural transformation of the energy balance through a rapid increase in installed solar power capacity, leading to changes in the operating modes of the IPS, a reduction in the share of traditional flexible generation, and the complication of balancing processes. Therefore, to avoid increased system constraints and reduced stability, scientifically sound solutions to these challenges are required.
2. Energy efficiency issues, driven by the high share of solar power plants under the current energy market model, exacerbate imbalances between generation and consumption, increase the volume of forced generation curtailments and the financial burden on the market, highlighting the need for research to develop sustainable models for integrating renewable energy sources.
3. A reduction in reliability and frequency stability, as inverter-based PV generation has virtually no natural inertia, which affects the dynamic stability and operation of automatic frequency control systems. The growing share of PV requires the development of new control algorithms and digital solutions to maintain system reliability.
4. Increased demands on system flexibility due to the daily and seasonal variability of solar generation, which requires further research into the operation of energy storage systems, hybrid solutions and cross-sector integration technologies (Power-to-Heat, Power-to-Hydrogen).
5. The restoration and modernisation of energy infrastructure in the context of damage to energy facilities and grid infrastructure, making the creation of decentralised and hybrid solutions based on solar power plants capable of ensuring autonomous or island operation of individual power system nodes, is particularly relevant.
6. The integration and synchronous operation of Ukraine's power system with the European ENTSO-E grid requires compliance with strict technical standards regarding frequency, power reserves, and controllability of generation. This reinforces the need for scientific research into adapting solar power plants to the requirements of the European integrated power system.
7. The need to transition from extensive to optimised development of renewable energy sources, as the key task at the present stage is not simply to increase the capacity of solar power plants, but to integrate them rationally, taking into account energy efficiency indicators, minimising system costs, and improving the overall operational efficiency of Ukraine's power system.

In a context where research into the rapid expansion of solar power plants within integrated power systems is of strategic importance for ensuring energy security, economic stability, and the technological modernisation of Ukraine's power system, there is no doubt

regarding the relevance of addressing the task of assessing the permissible limits of the necessary technical and energy parameters for the operation of solar power plants, energy storage systems, facilities, and grid infrastructure, which is the aim of this study.

Unlike stochastic or AI-driven approaches that primarily focus on improving forecast accuracy or probabilistic optimisation under uncertainty, the proposed method addresses the operational problem of real-time imbalance compensation through a sequential control mechanism. This ensures strict compliance with balance constraints (IMB(t) = 0) at each time step, which is particularly relevant under market conditions with full financial responsibility for imbalances.

The work aims to develop and investigate an algorithm for step-by-step control of the coverage of the forecast schedule for the aggregated generation of Ukraine's solar power plants, subject to minimising the total hourly discrepancy between forecast and actual generation through the coordinated use of energy storage systems and flexible generation.

The scientific novelty of this study lies in the development of a deterministic step-by-step control framework for the coordinated operation of aggregated solar generation, energy storage systems, and flexible resources under imbalance-minimisation constraints, formulated as a system-level operational problem and validated using high-resolution real-world data. Unlike existing forecasting- or scenario-based approaches, the proposed method directly ensures hourly schedule coverage. It can be used for practical dispatch-oriented planning in power systems with high renewable penetration.

2. Input Data

The initial data for the study consist of hourly forecasts and actual aggregated capacity for Ukraine's solar power plants for 2021–2025, available on the website of the State Enterprise "Guaranteed Buyer" [40]. It is known that for failure to meet the day-ahead forecast of solar power plant capacity, the producer pays imbalance charges in accordance with Law No. 2712-VIII "On the Electricity Market" [41]. From 2021, liability was introduced in stages. The following rules apply for 2025–2026.

Hourly PV_FOR and PV_FACT values for 2025 were compiled from the official hourly operational records published by the State Enterprise "Guaranteed Buyer". The 2025 time series were not generated by extrapolation from previous years, meteorological simulation, or synthetic data generation. After extraction, the records were aligned into a continuous hourly sequence, converted to a unified system of units, and checked for missing values, duplicates, and outliers prior to their use in the model.

For solar and wind power plants, producers bear 100% responsibility for their imbalances. This means they must pay the "Guaranteed Buyer" the cost of all energy they have generated in excess of the forecast or failed to supply in relation to it. There is a small "window" of tolerance—an allowable margin of error (Quota)—which is not subject to a penalty: for solar power plants: 5%, for wind power plants: 10%. Anything exceeding these percentages is subject to payment at balancing market prices.

Thus, for the producer, the task of optimally managing the step-by-step coverage of the forecast SPP generation schedule is crucial, with the aim of minimising costs and maximising profit.

To ensure the accuracy of the calculations, all hourly time series were converted to a single system of units of measurement and checked for missing values, duplicates and outliers. In cases where the data source contained values that required interpretation of sign or scale, a single normalisation rule was applied in the model, which should be noted separately in the footnote to the relevant tables.

The modelling is based entirely on observed operational time series data.

3. Task

3.1. Formulation of the Task

The problem of step-by-step control of coverage of the forecast schedule for aggregated solar power generation is formulated as a special case of the model of a hierarchically controlled quasi-dynamic power system [42] with $r \in R$ levels of administrative-territorial hierarchy and sectoral (sub-sectoral) infrastructure, which is detailed according to the structure of its technological $k \in K$ content. The task of controlling such a system is formulated in [42] as follows.

At the modelling horizon T, for all $\tau = 1,2,\ldots,T$; $r = 1,2,\ldots,R$; $k = 1,2,\ldots,K$: $\Omega(\tau,r,k)$—the system state vector, $\Phi(\tau,r,k)$—the set of admissible system states, g—the economic and technological impact functional, comprising: $\omega(\tau,r,k)$—elements of the state matrix, $u(\tau,r,k)$—elements of the control action matrix, $\xi(\tau,r,k)$—random elements of the external impact matrix, for example, in our case, the generating capacity of RES, μ—the optimality criterion, $U(\tau,r,k), \Xi(\tau,r,k)$—sets of possible values for control and random external influences. When the following conditions are met: $\Omega(\tau,r,k) \in \Phi(\tau,r,k)$, $u(\tau,r,k) \in U(\tau,r,k)$, $\xi(\tau,r,k) \in \Xi(\tau,r,k)$, $\omega(\tau,r,k) \in \Omega(\tau,r,k)$, under the influence of $u(\tau,r,k)$, $\xi(\tau,r,k)$ the system transitions to the next state:

$$\Omega(\tau,r,k) \mid u(\tau,r,k), \xi(\tau,r,k) \Rightarrow \Omega(\tau+1,r,k).$$

Optimality criterion:

$$\mu_\tau = \sum_{r}^{R} \sum_{k}^{K} g(\omega(\tau,r,k), u(\tau,r,k), \xi(\tau,r,k)) \rightarrow min/max.$$

The chosen objective function reflects the operational requirement to minimise imbalances between forecasted and actual generation, which directly corresponds to cost minimisation under the current electricity market framework. It should be noted that the formulation is deterministic and does not explicitly account for stochastic uncertainty. Instead, variability and uncertainty are implicitly represented through the use of historical time series data.

The step-by-step control problem for covering the forecast schedule of aggregated SPP generation is formulated as a simplified special case of the problem described above. In this problem, the system state matrix $\Omega(k,\tau)$ reflects the structure of generation volumes, forecast and actual energy supply at step τ, $\tau = 0,1,2,\ldots,T$ of the modelling horizon. All technologies used $k = 1,\ldots,K$ contribute to ensuring the balance between forecast $E^{\Sigma}_{F\tau}$ and supplied $E^{\Sigma}_{C\tau} = \sum\limits_{k=1}^{K} E^{Consum}_{k\tau}$ energy at each time step τ. The main constraints of the model are maintaining the balance between the forecast power $P^{\Sigma}_{F,\tau}$, the manoeuvring power $P^{\Sigma}_{m,\tau}$, and the volumes of generated $E^{\Sigma}_{G\tau} = \sum\limits_{k=1}^{K} E^{k}_{G\tau}$, supplied $E^{\Sigma}_{S\tau}$ and consumed $E^{\Sigma}_{C\tau}$ energy, provided that all parameters belong to the set of possible states. A measure μ_τ of the inconsistency between the vectors of supplied and forecast energy has been introduced.

In the following exposition, the step designations τ are identical to t for the sake of convenience in implementation within the software package's formulas.

The input data for the modelling are:

- The target hourly sequence of the predicted energy supply $E^{\Sigma}_{F\tau}$, hereinafter *PV_FOR(t)*;
- The hourly sequence of delivered energy $E^{\Sigma}_{C\tau} = \sum\limits_{k=1}^{K} E^{Consum}_{k\tau}$, hereinafter referred to as *PV_CONS(t)*;

https://doi.org/10.3390/solar6030024

- The hourly sequence of actual energy generated by the PV system $E^{\Sigma}_{G\tau} = \sum_{k=1}^{K} E^{k}_{G\tau}$ hereinafter *PV_FACT(t)*;
- Hourly sequence of actual energy generated by the storage system $E^{\Sigma}_{BG\tau}$ hereinafter *BATgen(t)*;
- Hourly sequence of actual energy generated by the flexible system $E^{\Sigma}_{m\tau}$ hereinafter *P_EXT(t)*;
- Hourly sequence of energy used to charge the storage system $E^{\Sigma}_{BCh\tau}$ hereinafter *BATcharge(t)*;
- State of the charge level vector of the storage system $E^{\Sigma}_{BChLEVEL\tau}$, hereinafter referred to as *BATchargeLEVEL(t)*;
- Power efficiency coefficient of the storage system *K_BAT* = 0.9;
- Measure of the μ_τ of the discrepancy between the actual and predicted energy vectors, hereinafter referred to as *IMB(t)*;
- State of the binary vectors of the impossibility of simultaneous discharge and charge of the storage system, *B_YBG(t)* and *B_YBC(t)*.

Taking into account the set of admissible states for each component of the system $\Phi(k, \tau)$, which ensures coverage of the predicted schedule of aggregated RES generation, the problem of calculating a power vector $P^{\Sigma}_{Cons,\tau}$ is solved, which minimises the measure μ^{Σ}—the total inconsistency of the vectors of the set and forecast energy, the required balance, the manoeuvring $P^{\Sigma}_{m,\tau}$, the actual hourly total power of the PV system $P^{\Sigma}_{PV,\tau}$, the hourly discharge $P_{BG,\tau}$ and charge power $P_{BCh,\tau}$ of the storage system.

3.2. Main Constraints

- Initial and final charge levels of the storage system:

$$BATchargeLEVEL(0) = BATchargeLEVEL(24) = \text{BATchargeLEVEL_INI}.$$

- Absolute value of the hourly power imbalance is defined as follows:

$$PV_DELTA(t) = PV_FOR(t) - PV_FACT(t).$$

- Hourly sequence of the actual discharge power of the storage system:

$$BATgen(t) = \begin{bmatrix} 0 & : PV_DELTA(t) < 0 \\ B_YBG(t) * PV_DELTA(t) & : PV_DELTA(t) > 0 \& PV_DELTA(t) < BATgen_MAX \\ B_YBG(t) * BATgen_MAX & : PV_DELTA(t) >= BATgen_MAX. \end{bmatrix} ; \forall t \in T;$$

- Hourly sequence of actual power, manoeuvring system:

$$P_EXT(t) = \begin{bmatrix} PV_DELTA(t) & : & PV_DELTA(t) < 0 \ ; \\ BATcharg(t) & : & PV_DELTA(t) > 0 \ ; \end{bmatrix} \quad \forall t \in T.$$

- State of the charge level vector of the storage system:

$$BATchargeLEVEL(t) = [BATchargeLEVEL(t-1) \ - \ BATgen(t-1) + BATcharge(t-1) \ ; \ \forall \ t > 1, \ t < 24 \in T;$$

- Hourly sequence of power used to charge the storage system:

$$BATcharge(t) = \begin{bmatrix} 0 & : PV_DELTA(t) < 0 \\ B_YBC(t) * PV_DELTA(t) & : PV_DELTA(t) > 0 \ \& \ PV_DELTA(t) < BATgen_MAX \\ B_YBC(t) * BATgen_MAX & : PV_DELTA(t) > 0 \ \& \ PV_DELTA(t) >= BATgen_MAX; \end{bmatrix} ; \forall t \in T;$$

4. Results

Software modules for the numerical implementation of the formulated problem have been integrated into a modification of the problem-oriented software and information complex SOPS [43] developed by the authors. The SOPS software (v. 1.0) implements a deterministic step-by-step constrained optimisation procedure for sequential hourly balancing. At each time interval, the algorithm checks the admissible ranges of storage charge/discharge power, state-of-charge limits, and the mutually exclusive charge/discharge conditions, and then updates the balance variables to minimise the hourly discrepancy between forecast and supplied power. The procedure is not based on stochastic simulation; instead, it uses a recursive feasibility check with explicit enforcement of operational constraints.

An analysis was conducted of the hourly data on the forecast and actual aggregated capacity of Ukraine's solar power plants for 2021–2025, as presented on the website of the state-owned enterprise "Guaranteed Buyer" [40]. The calculations performed made it possible to determine:

1. The main parameters of the aggregated operation of Ukraine's solar power plants for 2021–2025 (Table 1).

Table 1. Key parameters of the aggregated operation of Ukraine's solar power plants for 2021–2025.

Year	Installed Capacity, MW	Maximum Power, Pmax, MW	Date/Time of Peak Power	Maximum Imbalance, ΔP, MW	Date/Time of Peak Imbalance	Maximum Daily Generation, MWh
2021	5063	3766	9 July 2021 13:00	1984	11 April 2021 12:00	32,331
2022	5063	3587	14 February 2022 11:00	3014	22 March 2022 12:00	23,303
2023	6419	3708	1 June 2023 12:00	2973	23 April 2023 12:00	31,936
2024	6419	4027	5 May 2024 12:00	2140	10 April 2024 13:00	34,248
2025	7000–9000 *	3738	10 June 2025 15:00	3116	10 April 2025 14:00	33,638

* The installed capacity for 2025 is presented as an indicative range due to the absence of a single consolidated official value for the full year at the time of analysis. This parameter is provided for contextual reference only and is not used directly as an input to the optimisation model, which is based on hourly operational data (PV_FOR and PV_FACT).

2. Estimate the hourly values (for each of the 8760 h in 2025) of the actual PV_FACT and forecast PV_FOR power, the difference between these powers (PV_DELTA), the power generated by the BATgen storage system and used to charge the BATcharge storage system, the state of the storage system charge level vector BATchargeLEVEL, the state of the discrepancy between the supplied and forecast power IMB, the power generated by the flexible system P_EXT, and the state of the binary vectors indicating the impossibility of simultaneous discharge and charge of the storage system B_YBG and B_YBC. An example of the calculation results for the listed parameters on 20 April 2025, showing the greatest PV_DELTA power mismatch, is presented in Table 2 and Figure 1. With a total aggregated installed capacity of the storage system of 30,000 MWh, taking into account the constraints (1), the maximum permissible discharge power of the storage system of 24,300 MW and the charge power of 7500 MW, the hourly balance of forecast and supplied energy IMB(t) = 0 for all t = 1, 2,. . ., 24, the required daily volume of flexible generation is 19,823 MWh. The maximum capacity of flexible generation is 7500 MW.

Table 2. Results of calculations of hourly parameters for the day of greatest power imbalance PV_DELTA on 20 April 2025.

T, h	PV_FACT, MW	PV_FOR, MW	PV_DELTA, MW	BATgen, MW	BATcharge, MW	BATchargeLEVEL, MWh	IMB	P_EXT, MW	B_YBG	B_YBC
1	−10	−9	0	0	0	27,000	0	0	0	1
2	−10	−9	1	0	0	27,000	0	0	0	1
3	−10	−9	1	0	0	27,000	0	0	0	1

Table 2. *Cont.*

T, h	PV_FACT, MW	PV_FOR, MW	PV_DELTA, MW	BATgen, MW	BATcharge, MW	BATchargeLEVEL, MWh	IMB	P_EXT, MW	B_YBG	B_YBC
4	−10	−9	0	0	0	27,000	0	0	0	1
5	−10	−9	1	0	0	27,000	0	0	0	1
6	−7	−6	1	0	0	27,000	0	0	0	1
7	106	104	−2	0	0	27,000	0	−2	1	0
8	688	670	−18	0	0	27,000	0	−20	1	0
9	1694	1701	7	7	0	27,000	0	7	1	0
10	2075	2732	657	657	0	26,993	0	0	1	0
11	1678	3506	1828	1828	0	26,337	0	0	1	0
12	1329	3920	2591	2591	0	24,509	0	0	1	0
13	1085	4045	2960	2960	0	21,918	0	0	1	0
14	906	4022	3116	3116	0	18,958	0	0	1	0
15	788	3754	2966	2966	0	15,842	0	0	1	0
16	631	3226	2595	2595	0	12,876	0	0	1	0
17	625	2474	1849	1849	0	10,281	0	0	1	0
18	790	1530	739	739	0	8433	0	0	1	0
19	549	596	47	47	0	7693	0	0	1	0
20	94	91	−3	0	0	7646	0	0	1	0
21	−7	−6	0	0	7500	7646	0	7500	0	1
22	−9	−9	0	0	7500	15,146	0	7500	0	1
23	−10	−9	1	0	4838	22,646	0	4838	0	1
24	−9	−9	0	0	0	27,484	0	0	0	1
SUM	12,946	32,283	19,337	19,354	19,838	27,484	0	19,823		
MIN	−10	−9	−18	0	0	7646	0	−20		
MAX	2075	4045	3116	3116	7500	27,484	0	7500		

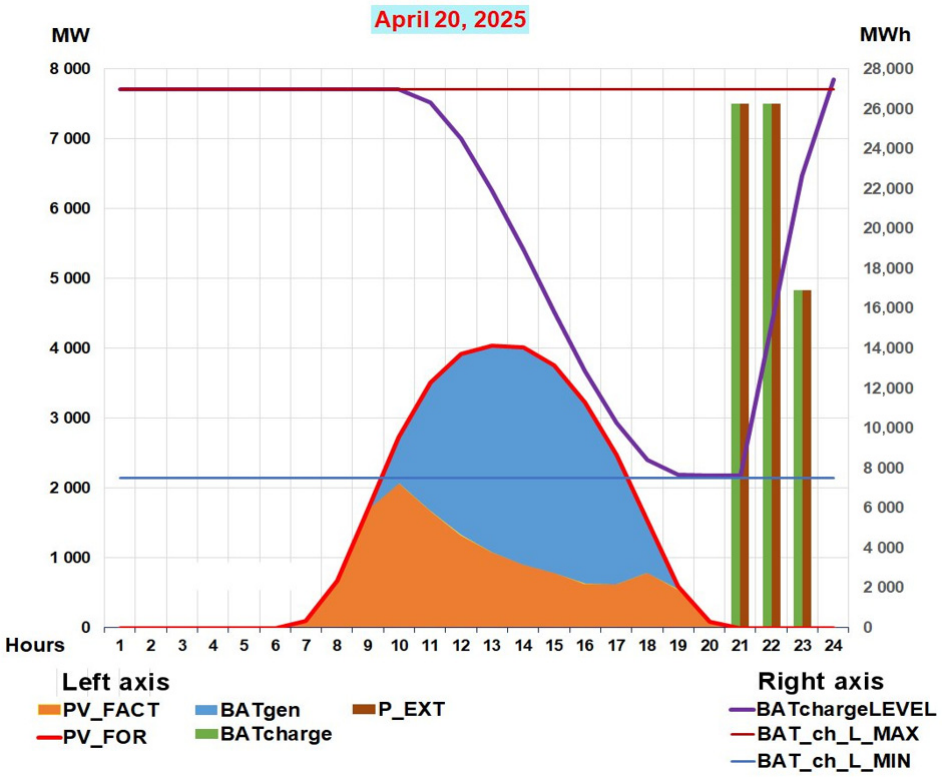


Figure 1. Graph of hourly parameters for the day of greatest power imbalance PV_DELTA on 20 April 2025.

3. Estimate the daily (for each of the 355 days of 2025) values of the total actual *PV_FACT_D* and forecast *PV_FOR_D* generation, the energy generated by the *BATgen_D* storage system and used to charge the *BATcharge_D* storage system, and the volume of energy generated by the *P_EXT_D* flexible system. An example of actual values and calculation results for daily generation volumes for January 2025 is presented in Table 3 and Figure 2.

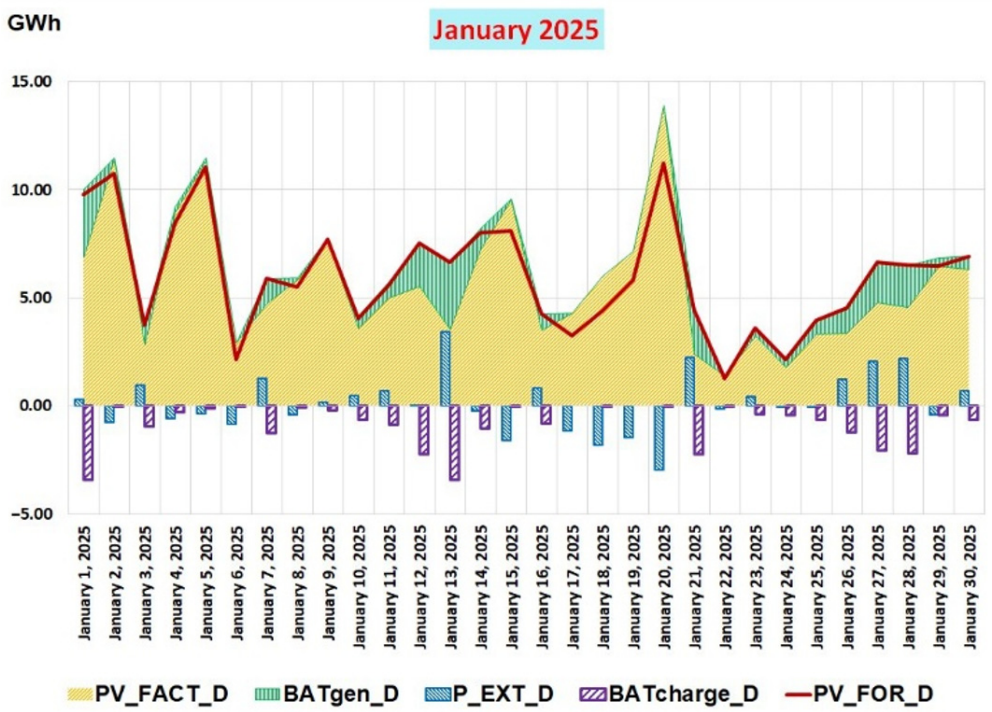


Figure 2. Actual values and calculated results for daily generation volumes for January 2025.

Table 3. Actual values and results of calculations of daily generation volumes for January 2025.

Date	PV_FACT_D, GWh	PV_FOR_D GWh	P_EXT_D GWh	BATgen_D GWh	BATcharge_D GWh
1 January 2025	6.90	9.79	0.29	3.10	−3.44
2 January 2025	11.44	10.76	−0.76	0.02	−0.02
3 January 2025	2.84	3.74	0.97	0.88	−0.97
4 January 2025	8.96	8.46	−0.58	0.28	−0.31
5 January 2025	11.36	11.05	−0.37	0.12	−0.13
6 January 2025	2.91	2.15	−0.87	0.00	0.00
7 January 2025	4.73	5.88	1.26	1.13	−1.26
8 January 2025	5.83	5.49	−0.40	0.07	−0.08
9 January 2025	7.57	7.69	0.18	0.19	−0.21
10 January 2025	3.58	4.04	0.49	0.57	−0.63
11 January 2025	4.97	5.61	0.68	0.78	−0.86
12 January 2025	5.53	7.54	0.00	2.02	−2.25
13 January 2025	3.54	6.63	3.43	3.08	−3.43
14 January 2025	7.25	8.00	−0.25	0.95	−1.05
15 January 2025	9.54	8.12	−1.60	0.01	−0.02
16 January 2025	3.48	4.26	0.84	0.76	−0.84
17 January 2025	4.29	3.24	−1.18	0.00	0.00

Table 3. *Cont.*

Date	PV_FACT_D, GWh	PV_FOR_D GWh	P_EXT_D GWh	BATgen_D GWh	BATcharge_D GWh
18 January 2025	6.00	4.39	−1.81	0.00	0.00
19 January 2025	7.14	5.82	−1.48	0.00	0.00
20 January 2025	13.90	11.25	−2.97	0.01	−0.01
21 January 2025	2.40	4.46	2.25	2.03	−2.25
22 January 2025	1.36	1.25	−0.15	0.01	−0.01
23 January 2025	3.21	3.59	0.42	0.36	−0.40
24 January 2025	1.79	2.17	−0.02	0.38	−0.43
25 January 2025	3.32	3.95	0.00	0.60	−0.67
26 January 2025	3.36	4.51	1.24	1.12	−1.24
27 January 2025	4.76	6.64	2.06	1.85	−2.06
28 January 2025	4.54	6.53	2.19	1.97	−2.19
29 January 2025	6.46	6.48	−0.42	0.38	−0.43
30 January 2025	6.33	6.92	0.68	0.60	−0.67
31 January 2025	2.76	3.52	0.00	0.73	−0.82
SUM_GWh	172.08	183.92	4.13	24.01	−26.68
MIN	1.36	1.25	−2.97	0.00	−3.44
MAX	13.90	11.25	3.43	3.10	0.00

4. Estimate the monthly (for each of the 12 months of 2025) values of the total actual *PV*_FACT_*M* and forecast *PV_FOR_M* generation, the energy generated by the *BATgen_M* storage system and used to charge the *BATcharge_M* storage system, and the volume of energy generated by the *P_EXT_M* flexible system. Examples of actual values and calculation results for monthly generation volumes in 2025 are presented in Table 4 and Figure 3.

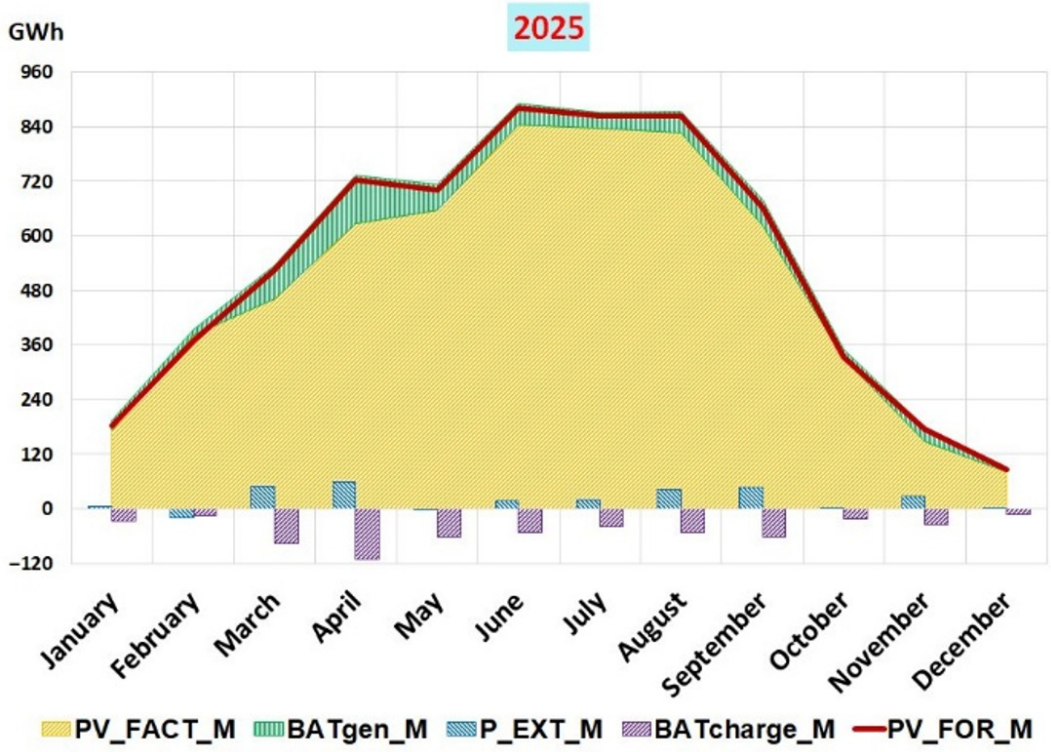


Figure 3. Actual values and calculated results for monthly generation volumes in 2025.

Table 4. Actual values and results of calculations for monthly generation volumes in 2025.

Month	PV_FACT_M, GWh	PV_FOR_M GWh	P_EXT_M GWh	BATgen_M GWh	BATcharge_M GWh
January	172.08	183.92	4.13	24 Jan	−26.68
February	382.85	369.42	−18.95	12.99	−14.44
March	461.00	527.26	49.56	74.72	−76.86
April	628.19	723.11	60.55	104.21	−110.79
May	658.10	700.63	−0.63	55.60	−61.78
June	844.12	882.24	16.39	46.89	−51.27
July	837.62	864.81	20.40	34.54	−38.38
August	827.79	863.23	41.98	45.77	−50.86
September	621.26	662.94	48.14	56.95	−61.26
October	330.58	332.36	0.01	19.68	−21.87
November	149.30	174.24	27.08	32.02	−35.57
December	81.02	85.53	3.76	11.38	−12.64
SUM_GWh	5993.92	6369.69	252.41	518.78	−562.40
MIN	81.02	85.53	−18.95	11.38	−110.79
MAX	844.12	882.24	60.55	104.21	−12.64

5. Discussion

The study has identified the characteristic features of Ukraine's aggregated solar power generation in the period 2021–2025. There is a steady increase in installed capacity and a rise in maximum hourly generation values, accompanied by significant discrepancies between forecast and actual generation volumes. Sometimes, the imbalance reaches 3000 MW or more, creating significant financial risks for producers under 100% liability for imbalances. An analysis of the day with the highest imbalance (20 April 2025) showed that, in the absence of adjustment mechanisms, the imbalance exceeds 19 GWh per day. The application of a developed step-by-step control algorithm, in the presence of an energy storage system with a capacity of 30 GWh, makes it possible to completely eliminate imbalance (IMB = 0) through the coordinated redistribution of energy between the charging and discharging phases and the engagement of flexible generation. It should be emphasised that the presented 30,000 MWh storage capacity reflects a model-based technical threshold under aggregated assumptions. The paper does not assess capital costs, operating costs, battery degradation, financing, or market-price dynamics; therefore, the economic feasibility of such a configuration remains outside the scope of the present study.

The results demonstrate the significant role of energy storage systems in ensuring forecasting discipline and enhancing the economic stability of the power system. At the same time, the maximum required capacity of flexible generation (up to 7500 MW) indicates the need to maintain a sufficient volume of regulating capacity within the power system structure.

A monthly analysis of 2025 demonstrates pronounced seasonality: the spring–summer period is characterised by increases in both absolute generation volumes and the magnitude of deviations, due to the high variability of weather conditions and the complexity of short-term forecasting. In the autumn–winter period, total generation volumes are lower, though relative variability persists.

Thus, the effective integration of solar power plants into Ukraine's power system requires a comprehensive combination of:

- The development of energy storage systems;

- Improvement of ultra-short-term forecasting algorithms;
- Maintaining sufficient reserve capacity;
- The implementation of intelligent decision-support systems.

The results obtained are consistent with current trends in the optimisation of power systems with a high share of RES [8,44] and confirm the advisability of transitioning from extensive PV capacity expansion to its optimised integration.

It should be noted that the proposed model adopts an aggregated ("copper plate") representation of the power system, assuming unlimited transmission capacity between all nodes. This simplification allows focusing on system-level balancing mechanisms; however, it neglects the spatial heterogeneity of generation and potential grid constraints [45–47].

In real power systems, transmission bottlenecks, regional imbalances, and congestion may limit the ability to redistribute energy across the network. As a result, the actual required volumes of flexible generation and storage capacity may be higher at specific locations than those obtained in this study. Therefore, the results presented can be interpreted as a lower-bound estimate under idealised network conditions [48].

Compared to AI/ML-based and stochastic optimisation approaches, the proposed method provides a deterministic, operationally interpretable framework that may be advantageous for real-time dispatch and regulatory applications.

Results are obtained for a fixed set of model parameters, including storage efficiency and capacity limits. Sensitivity analysis with respect to these parameters has not been performed in the present study.

6. Conclusions

1. A mathematical model of step-by-step control of the coverage of the forecast schedule of aggregated PV power generation has been developed as a special case of a hierarchically controlled quasi-dynamic power system.
2. A criterion has been proposed for minimising the total measure of inconsistency between forecast and actual generation, taking into account constraints regarding power balance, storage capacity and the system's manoeuvrability.
3. An analysis of hourly data for 2021–2025 revealed a significant level of imbalances in the aggregated generation of Ukraine's solar power plants, exceeding 3000 MW in capacity and 19 GWh per day in energy during certain periods.
4. It has been established that, under the adopted model assumptions and with an energy storage system of 30,000 MWh, coordinated operation with flexible generation can ensure full coverage of the forecast schedule (IMB = 0). This result characterises the technical upper bound of imbalance compensation rather than an economically optimised investment decision.
5. The required volumes of aggregated flexible generation and the operating parameters of storage systems that ensure the cost-effective operation of generators under conditions of full responsibility for imbalances have been determined.
6. The results obtained confirm that the key direction for the development of the IPS of Ukraine is the optimised integration of solar power plants with energy storage systems and intelligent control algorithms, which contributes to improving the reliability, stability and cost-effectiveness of the Ukrainian energy market.
7. The results are obtained under the assumption of an aggregated system without network constraints. Future research should extend the proposed approach to multi-node models that account for transmission limitations and the regional distribution of renewable generation.
8. Future work will involve investigating the potential for developing the proposed approach to minimise imbalances between aggregated forecast and actual generation

from wind power plants within Ukraine's IPS, and assessing the necessary limits of the economic and energy parameters of energy storage systems and flexible generation, relative to the installed capacity of individual solar and wind power plants in Ukraine.

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

Funding: This research received no external funding.

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.

Acknowledgments: This work was supported by projects "Integrated modeling for robust management of food-energy-water-social-environmental (FEWSE) nexus security and sustainable development" (IIASA-NASU, 22-501 (R-45-T)), "Comprehensive analysis of robust preventive and adaptive measures of food, energy, water and social management in the context of systemic risks and consequences of COVID-19" (0122U000552, 2022–2026), "Development of the structure and ensuring the functioning of self-sufficient distributed generation" (0125U001572, 2025–2026), and "Development of models and means of control of integrated power systems with powerful wind and solar power plants in normal and emergency modes" (0122U000343, 2022–2026) funded by the National Academy of Sciences of Ukraine.

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

Abbreviations

The following abbreviations are used in this manuscript:

AFPC	Automatic frequency and power control
BESS	Battery energy storage systems
ENTSO-E	European Network of Transmission System Operators for Electricity
IMB	Imbalance (measure of discrepancy between forecast and actual energy)
IPS	Integrated power system
PV	Photovoltaic
PV_FACT	Actual photovoltaic generation
PV_FOR	Forecast photovoltaic generation
PV_CONS	Supplied (consumed) photovoltaic energy
PV_DELTA	Difference between forecast and actual PV generation
P_EXT	Power of flexible (external) generation
RES	Renewable energy sources
SPP	Solar power plant
BATgen	Energy generated (discharged) by storage system
BATcharge	Energy used to charge storage system
BATchargeLEVEL	State of charge of storage system
B_YBG	Binary variable prohibiting simultaneous discharge
B_YBC	Binary variable prohibiting simultaneous charge

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