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Increasing Technical Efficiency of Renewable Energy Sources in Power Systems

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Abstract: This paper presents a method for refining the forecast schedule of renewable energy sources (RES) generation by its intraday adjustment and investigates the measures for reserving RES with unstable generation in electric power systems (EPSs). Owing to the dependence of electricity generation by solar and wind power plants (PV and WPPs, respectively) on natural conditions, problems arise with their contribution to the process of balancing the power system. Therefore, the EPS is obliged to keep a power reserve to compensate for deviations in RES from the planned generation amount. A system-wide reserve (mainly the shunting capacity of thermal and hydroelectric power plants) is used first, followed by other means of power reserve: electrochemical, hydrogen, or biogas plants. To analyze the technical and economic efficiency of certain backup means, mathematical models based on the theory of similarity and the criterion method were developed. This method is preferred because it provides the ability to compare different methods of backing up RES generation with each other, assess their proportionality, and determine the sensitivity of costs to the capacity of backup methods with minimal available initial information. Criterion models have been formed that allow us to build dependencies of the costs of backup means for unstable RES generation on the capacity of the backup means. It is shown that, according to the results of the analysis of various methods and means of RES backup, hydrogen technologies are relatively the most effective. The results of the analysis in relative units can be clarified if the current and near-term price indicators are known.

Keywords: electric power system; renewable energy sources; instability of generation; reserve means; similarity theory; criterion method

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1. Introduction

The problem with the use of renewable energy sources (RES), particularly photovoltaic and wind power plants (PV and WPPs, respectively) is that they are currently not guaranteed sources of electricity for energy power systems (EPSs). The dependence of RES electricity generation on variable weather conditions must be compensated in order to harmonize their capabilities with the technological requirements of the EPS [1–4]. However, these problems arise not only when RES operate in parallel with other EPS power plants, but also when they provide power in an autonomous power supply system. In any case, to ensure the efficient operation of RES in the power system and reliable electricity supply to consumers, it is necessary to have reserve sources of energy that could compensate for the natural instability of RES generation. Today, there may be various options that differ in their technical and economic characteristics [5–8].

If considered chronologically, from the beginning of the development of RES, to ensure their normal operation under the "green" tariff, the maneuverable capacities of the EPS were used, which were designed to balance power and electricity in the system for frequency regulation [9]. Over time, when the possible maneuverable capacities at thermal and hydroelectric power plants were exhausted, it was necessary to investigate other ways of influencing the schedules of RES generation. Owing to the insufficient amount of maneuvering power, for example, in the United Energy System of Ukraine, it is necessary to limit generation by RES in order to ensure the stability of the operation of the EPS. Obviously, this reduces their energy efficiency, restraining the investment and development of RES in the EPS. As it was not possible to get ahead of the situation with RES due to the lack of free maneuvering power, it is necessary to make up for the situation in the EPS by developing electricity storage systems [10,11].

First of all, attention was drawn to electrochemical energy accumulators, which are equally capable of being used during the balancing of the EPS mode under conditions of surplus or a shortage of RES generation (charge or discharge) [12,13]. Among other ways of accumulating sufficient energy for the needs of balancing EPS regimes, hydrogen technologies [14,15] and biogas plants [16,17] are considered, which, having accumulated reserves for the energy carrier, can convert them into electricity. The coordination of generation and consumption schedules can also be used as a reserve to reduce the impact of uneven generation of renewable energy sources on power supply systems [18]. It is impossible to unequivocally give preference to some of the listed products due to their different technical efficiencies, the possibility of providing them with the required quantity of energy, and the lack of stable and reliable price indicators. It seems expedient to make comprehensive use of possible RES reservation methods with electricity generation schedules that would satisfy the requirements of the EPS for maintaining the power and electricity balance [19–22].

The quality of RES's participation in the process of balancing the EPS modes is checked by the conformity of the forecast schedule of electricity generation and its actual value [23]. During the operation of renewable energy sources, particularly PV and WPP, the problem of balancing the consumption and generation of electricity, including all energy sources, is solved in the electric power system. The problem is formulated as the minimization of the difference between the predicted and actual values of electricity generation schedules. The error is defined as [24]

$$\delta = \frac{W_p - W_f}{W_f} 100\% \quad \rightarrow \; \min \tag{1}$$

where W_p is the value of the forecasted (predicted) hourly electricity generation of RES for the next day, and W_f is the actual ("fact") production of RES electricity during the same time.

In (1), the error δ between the predicted and actual values should be less than the permissible (for example, PV 5% and WPP 10%). Otherwise, the control body imposes fines in one form or another. For the effective integration of RES into the existing electric power systems, taking into account the peculiarities of both, it is necessary to increase the maneuverable capacity by increasing the reserve, improve the planning of the production of RES electricity to improve the quality of their participation in the optimization and balancing of the EPS mode, and agree on the schedules of electricity generation and its consumption. Figure 1 shows the structural diagram of the process of reducing the imbalance between the actually generated and forecasted RES electricity (tasks that are solved in the article are highlighted).

The goal of this article is to increase the energy efficiency of renewable energy sources by more accurately and flexibly fulfilling the conditions of reliability and stability of electric power systems put forward by them in the process of balancing power and electricity.

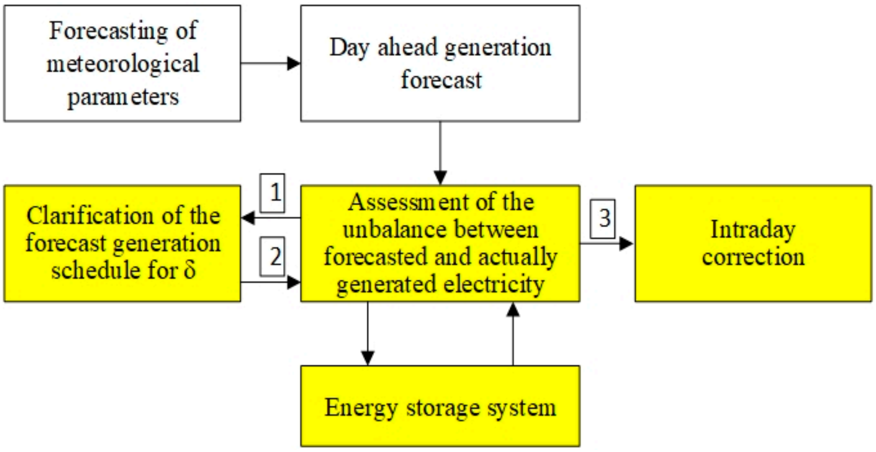

Figure 1. Structural diagram of the reduction of electricity imbalance in EPS with RES.

2. Clarification of the Forecast Schedule of RES Generation by Means of Intraday Correction

In electric power systems, in order to balance their regime and ensure the reliability and quality of electricity in accordance with the requirements, planning and constant accounting of the amounts of generated and consumed electricity are carried out. Under such conditions, both traditional and renewable energy sources should work. If there is no particular complexity for RES in the accounting of produced electricity due to modern automated systems of commercial electricity accounting (ASCEA), then everything is not as simple with planning. As the amount of produced RES electricity depends on the forecast of weather conditions, planning turns into forecasting the RES electricity produced. To date, many methods, algorithms, and programs have been developed for forecasting RES electricity generation, especially from PV and wind turbines [25–27]. Unfortunately, none of them can provide the necessary acceptable accuracy due to the impossibility of accurately forecasting weather conditions. Therefore, as a solution, the forecast of the hourly electricity generation schedule of PV and WPP can be adjusted for the next day [24]. To clarify the generation forecast and bring it closer to the fact, intraday correction is used. However, this is due to the hourly forecasting of meteorological parameters. This service is provided by only a few operators (for example, Meteoblue, Solargis, Solcast, and Weatherbit). This information is not always accurate and is expensive. Therefore, they are forced to look for other ways.

There are two ways to reduce the difference between the forecast and actual values of the power generation schedules of PV and wind turbines: influencing the forecast value of W_p or the actual value W_f. It is possible to influence the actual generation of W_f only in the direction of its reduction, which is not economically feasible. The actual power generation must be reduced only at the command of the transmission or distribution system operator when it is necessary to ensure the stability of the power system. Therefore, in normal EPS modes, it is possible to correct only the forecast values of electricity generation for a certain time Δt. The actual values of the generated electricity are approximated at the same time according to preliminary data from ASCEA.

The logical scheme for calculating the corrected value of the hourly forecast of the generation of PV for the next hour of the current day is illustrated in Figure 2. On point t_1, for example, $\delta_1 \succ 0$ and $\delta_1 \succ \delta_{per}$, the forecast must be reduced by k. Accordingly, the forecast will be $W_p = kW_p$, where $k = 1 - \delta_1$ and $\delta_1 = (W_p - W_{f1})/W_{f1}$. On point t_3, for example, $\delta_3 \prec 0$ and $\delta_3 \prec -\delta_{per}$, the forecast must be increased by k. Accordingly, the forecast will be $W_p = kW_p$, where $k = 1 - \delta_3$ and $\delta_3 = (W_{p3} - W_{f3})/W_{f3}$. If the difference between the forecasted and actual values is within the permissible range, i.e., $|\delta| \prec |\delta_{per}|$, then coefficient k = 1 and it is not necessary to correct the forecast values.

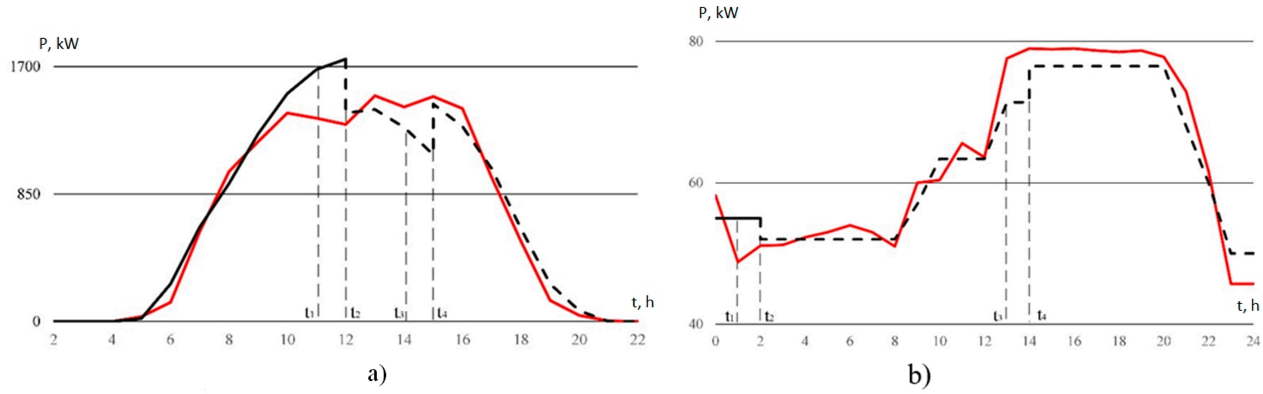

Figure 2. Correction of the forecast generation schedule of PV (**a**) and WPPs (**b**).

The frequency at which the forecast error δ is controlled is determined by the capabilities of the automatic control system in forecasting the generation schedule of PV and WPP, the capabilities of ASCEA, and the bandwidth of communication channels. Control is carried out evenly with cycles Δt, where Δt is no more than 1 h, and is organized as follows.

Hour i is determined, from which i_b begins and ends i_e PV power generation, where i is the current number of the hour. Further,

- i = i_b, the forecast error for the i-th hour is determined $\delta_i = \frac{w_i^p - w_i^f}{w_i^f}$;
- i = i + 1, the forecast error for the i + 1st hour is determined $\delta_{i+1} = \frac{w_{i+1}^p - w_{i+1}^f}{w_{i+1}^f}$.

If $\delta_{i+1} \succ 0$, then:

if $\delta_{i+1} \leq \delta_{per}$, then k = 1 $w_{i+1}^p = kw_{i+1}^p$ (that is, the forecast remains the same in the permissible area);

if $\delta_{i+1} \leq \delta_i$, then we go to the beginning of the cycle i = i + 1 ("forecast" is getting closer to "fact");

if $\delta_{i+1} \succ \delta_i$ ("forecast" differs from "fact") and $\delta_{i+1} \succ \delta_{per}$, then $k = 1 - \delta_i$ and $w_{i+1}^p = kw_{i+1}^p$ go to the beginning of the cycle i = i + 1.

If $\delta_{i+1} \prec 0$, then:

if $\delta_{i+1} \geq -\delta_{per}$, then k = 1 $w_{i+1}^p = kw_{i+1}^p$ (that is, the forecast remains the same in the permissible area);

if $\delta_{i+1} \succ \delta_i$, then we go to the beginning of the cycle i = i + 1 ("forecast" is getting closer to "fact");

if $\delta_{i+1} \prec \delta_i$ ("forecast" differs from "fact") and $\delta_{i+1} \prec -\delta_{per}$, then $k = 1 - \delta_i$ and $w_{i+1}^p = kw_{i+1}^p$ go to the beginning of the cycle i = i + 1.

According to the given algorithm, a program for the hourly correction of the forecasting of electric power generation by PV and WPPs has been developed, which is part of the system for reducing the electricity imbalance in the EPS with RES (see Figure 1). Figure 3 shows the algorithm of the program for the hourly correction of the forecast of RES electricity generation. The operation of the program is initiated by a signal from "Unbalance assessment" 1 (Figure 1) under the condition $|\delta| \succ \delta_{per}$. The program terminates when the condition $|\delta| \leq \delta_{per}$ is met. The results are transferred to "Unbalance assessment" 2 and further to "Intraday correction" 3 (see Figure 1).

Figure 4 shows an example of the result of an hourly forecast of generation by PV using the forecast correction program with error compensation. As can be seen, the forecasting error of PV power generation per day decreased from 15.6% to 4.7%. That is, the algorithm with the compensation of hourly errors in forecasting the generation of PV produced a satisfactory result. It can be used along with the correction of PV generation based on the hourly refinement of daily weather parameters.

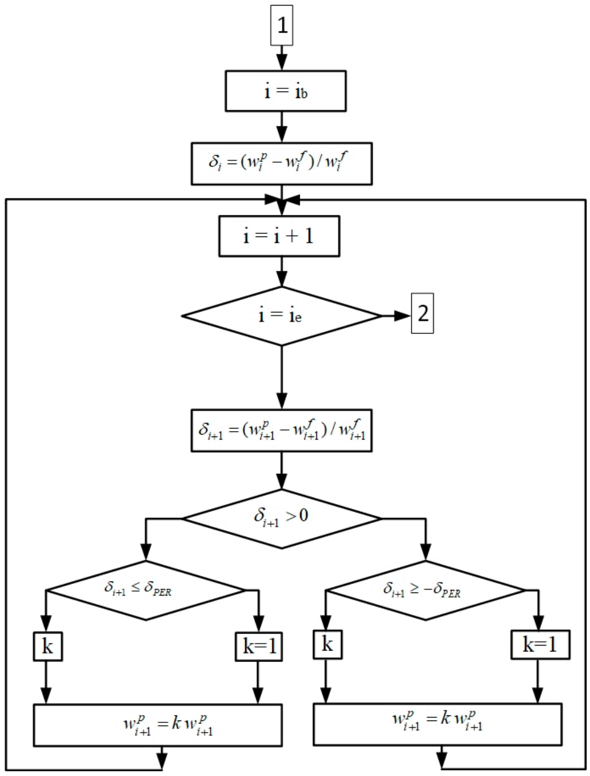

Figure 3. Algorithm of the program for the hourly correction of forecasting the power generation by PV.

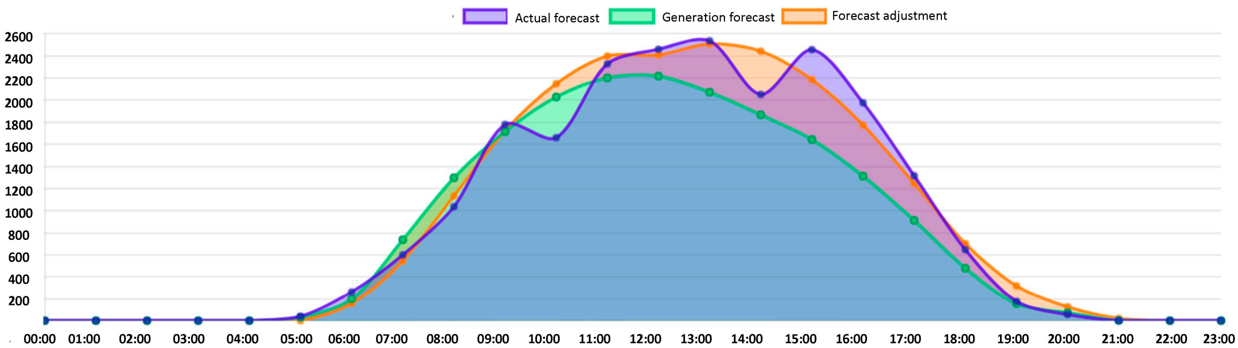

Figure 4. Correction of PV generation forecasting based on the results of error control.

3. Optimizing the Methods and Means of RES Reservation for Their Full Participation in the Control of the EPS Modes

Despite the fact that the generation of PV and WPP can be forecasted more accurately, taking into account the intraday correction, the actual value of generation remains unstable and requires redundancy in the EPS. The electricity balance in the EPS in terms of generation is formed by various power plants [28–30]:

$$P_{NPS}(t) + P_{CHPS}(t) + P_{HPP}(t) \pm P_{HAPS}(t) + P_{RES}(t) \pm P_{res}(t) - P_l(t) - \Delta P(t) = 0 \quad (2)$$

where $P_{NPS}(t)$—capacity of nuclear power plants (NPSs); $P_{CHPS}(t)$—capacity of thermal power plants (TPPs) and combined heat and power plants (CHPs); $P_{HPS}(t)$—capacity of hydroelectric power plants; $P_{HAPS}(t)$—capacity of hydro-accumulating power plants (HAPSs); P_{RES}—capacity of RES; $P_{res}(t)$—capacity of means and ways of reserving electricity during balancing; $P_l(t)$—load of transformer substations (TS); and $\Delta P(t)$—technological costs in power grid.

If the criterion of optimality is to take the total costs C_{res} for reservation $P_{res}(t)$ in (2) for unsustainable RES generation, then, taking into account currently possible reserving methods, the problem of minimization C_{res} will be written as:

$$C_{res} = C_{ch}(P_{ch}) + C_h(P_h) + C_b(P_b) + C_s(P_s) + C_{tl}(P_{tl}) + C_c(P_c) \to \min \quad (3)$$

where $C_{ch}(P_{ch})$—costs of reserving by electrochemical-type accumulators; $C_h(P_h)$—costs of hydrogen technologies; $C_b(P_b)$—costs associated with the use of biogas technologies as a reserve; $C_s(P_s)$—costs of using the system reserve, which is actually compensation for maintaining the reserve at CHPS power units operating according to price bids; $C_{tl}(P_{tl})$—costs of capacity reserves of power transmission lines, which are necessary for the transportation of electricity from/to the place of connection of the reserve capacity to the EPS; $C_c(P_c)$—costs of the implementation of the coordination of electricity generation and consumption schedules in the EPS; and P_{ch}, P_h, P_b, P_s, P_{tl}, and P_c—optimal capacity values determined from each of the reservation methods.

RES reservation methods can be classified according to several features. First of all, according to the purpose, they can be classed as only for RES reservation or complex use. Another feature is the form of implementation. These can be resources distributed directly to individual renewable energy sources or centrally located. Accordingly, it affects the mathematical model of the reservation process. Second of all, they can be classified by appointment. If RES participate in the balancing of the EPS mode, i.e., they produce electricity according to the specified hourly schedule, then the reserving means must work in the charge/discharge mode. They convert the power generated by RES into another type of energy, store it, and then feed it back into the power grid as electricity. Such reserving means include electrochemical energy storage and hydrogen technologies. The latter produce hydrogen due to electrolysis, which accumulates and can be returned to the EPS in the form of electricity in power plants according to the required schedule. The advantage of hydrogen technologies is that the so-called "green hydrogen" can be used in many other fields besides the power industry, such as in industry, in transport, in metallurgy, and in heating systems.

To moderate the instability of RES generation, the system capacity reserve in the EPS can be used. However, due to the limited amount of maneuverable power, the possibilities here are insignificant. It is intended for other purposes; therefore, the EPS tries not to use the system reserve for RES, and in critical situations, prefers to limit the generation of RES.

Characterizing the reservation methods, the following should also be noted. The cost of electrochemical-type accumulators, the production of which is sufficiently mastered in world practice, is constantly decreasing; therefore, their capacity in power systems is increasing. According to the companies Ingeteam (Italy) and Catl (China), 1 MWh of the full capacity of the electrochemical storage system costs from USD 450 to 600 thousand. Hydrogen and biogas technologies as means of reserving unsustainable RES generation are at the initial stage. Their cost does not have a clear tendency to decrease and depends on the use of hydrogen and biogas in other industries. By 2025, the cost of hydrogen produced by electrolyzers is forecast to be 1.5–3.0 EUR/kg. As for the system reserve, its value is determined by the interests of the electric power industry within the permissible limits of its use to balance unstable RES generation. If there is still interest in the development of RES in the EPS, then the cost $C_s(P_s)$ should accordingly decrease.

The uncertainty of price indicators and the incompleteness of information make it difficult to choose a method for optimizing problem (3) and to develop a corresponding mathematical model. A criterion method based on the theory of the similarity of phenomena and processes in nature is effective for solving similar problems [28,31]. The peculiarity of the criterion method is that the solution of the optimization problem is obtained in relative units. For this, (3) must be rewritten in relative units. If the basis is to take the total costs of RES reservation C_{res}, then the components (3) $C_i(P_i)/C_{res}$, $i = \overline{1, m}$ (m is the number of members of the objective function) are the "weighting" coefficients of the members of the function π_i and their sum is equal to one (normalization condition). In the theory of similarity [29], such dimensionless ‘’weighting” coefficients in the physical sense are criteria of similarity π_{i} . Hence, the criterion method.

In our case, this means that, by using the criterion method, we can provide a relative assessment for comparing individual RES reservation methods and obtain their rating according to the chosen criterion of optimality C_{res}. In optimization theory, this is commensurability [32]. In accordance with the possibility of the method, a mathematical model is formed.

Based on incomplete initial data, it should, at the first stage, provide a comparative description of RES reservation means, and at the next stage, clarify the results as the price indicators change. Taking into account the above, a mathematical model for optimizing specific costs per 1 kW of reserve power for balancing RES generation, which takes into account the peculiarities of the EPS modes, can be presented in the following form:

$$C_{res} = \frac{c_1}{P_{ch}} + \frac{c_2}{P_h} + c_3 P_b + \frac{c_4}{P_s} + c_5 \frac{P_{ch}^2 P_h^2}{P_b} \rightarrow \text{min}, \quad (4)$$

provided that $P_s \leq G_s$, $P_{ch} \leq G_{ch}$ or $g_s P_s \leq 1$, $g_{ch} P_{ch} \leq 1$, where c_1, c_2, c_3, c_4, c_5—generalized constants containing the initial data of the problem (primarily these are price indicators); G_s—the maximum capacity of the system reserve that can be used to balance RES generation ($g_s = 1/G_S$); and G_{ch}—the maximum available capacity of electrochemical-type accumulators ($g_{ch} = 1/G_{ch}$).

The first component of Equation (4) takes into account the specific costs of electrochemical storage devices. Their cost is decreasing; therefore, in the EPS, their volume is increasing and the capacity is increasing. The second component takes into account specific costs for the implementation of redundancy using a system for obtaining and using hydrogen as an energy store. Taking into account that part of the hydrogen is used in other industries, the cost of generating electricity in the balancing group will be inversely proportional to P_h. The cost of using biogas to increase reserve capacity has a linear relationship. Provided that the system reserve is available and its cost is reduced, it will be used more and Ps will increase. The last component of the costs depends on the losses of electricity in the elements of the power grid.

The objective function (4) is formed under certain assumptions. Expression (4) does not take into account some components of the reservation methods of the $\mathrm{C}_{\mathrm{rez}}$ minimization problem from (3). In particular, these are costs for increasing the capacity of power transmission lines, which is considered sufficient at the initial stage, and costs for coordinating electricity generation and consumption schedules in the EPS, which are already partially used in electric grids. The last term of the objective function (4) reflects the costs of covering electricity losses, which are associated with the implementation of redundancy measures. At the same time, it is considered that the storage devices of the electrochemical type and the system reserve are located centrally.

To analyze the RES generation reservation system, we will use the methods of the theory of similarity, particularly the criterion method [31,33]. The advantage of the chosen method is that it allows similarity criteria that connect the parameters of the same name, in our case, different reservation methods to be obtained, and conditions are created for the analysis of commensurability and sensitivity of calculation results in relative units with a limited amount of initial information [34].

Problem (4) does not meet the condition of canonicity [31], when the measure of its complexity s = $m - n - 1 = 0$, where m—number of components of the objective function; and n—number of variables P_{i}. In our case, s = $7 - 4 - 1 = 2$. According to the criterion method, we write the system of orthogonal and normalized (orthonormalized) equations for (4) relative to similarity criteria π [31]:

$$\begin{cases} -\pi_1 + 2\pi_5 + \pi_7 = 0; \\ -\pi_2 + 2\pi_5 = 0; \\ \pi_3 - \pi_5 = 0; \\ -\pi_4 + \pi_6 = 0; \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 = 1; \end{cases} \Rightarrow \begin{bmatrix} -1 & 0 & 0 & 0 & 2 & 0 & 1 \\ 0 & -1 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \\ \pi_5 \\ \pi_6 \\ \pi_7 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}. \quad (5)$$

As, in this system of equations, all parameters are valid and have certain permissible limits of existence, such equations have a valid set of solutions with respect to two (since s = 2) of the parameters. A set of solutions can be built by taking any of the reservation components in (4) as the basic ones. In our case, it is expedient to take the cost of the system reserve as the basic component for being the most stable and with which the remaining components and the cost of electrochemical storage devices, for which price indicators have been established, can be compared. If we take the costs of using the system reserve and electrochemical storage as basic variables, the system of Equation (5) is solved with respect to π_6 and π_7. Then, by means of linear transformations, the solution system of Equation (5) and the corresponding set of admissible solutions relative to π_6 and π_7 is obtained in the form:

$$\boldsymbol{\pi} = \mathbf{b}_0 + \mathbf{b}_n \begin{bmatrix} \pi_6 \\ \pi_7 \end{bmatrix} \quad (6)$$

where $\mathbf{b}_0$—normalization vector; and $\mathbf{b}_n$—vectors of discontinuity.

$$\text{In our case } \mathbf{b}_0 = \begin{bmatrix} 1/3 \\ 1/3 \\ 1/6 \\ 0 \\ 1/6 \end{bmatrix} \text{ and } \mathbf{b}_n = \begin{bmatrix} -1 & 3/2 \\ 1/2 & -3/4 \\ 1/4 & -3/8 \\ 1 & 0 \\ -3/4 & -3/8 \end{bmatrix}. \quad (7)$$

The similarity criteria, which are expressed through criteria π_6 and π_7, are:

$$\pi_1 = \frac{1}{3} - \pi_6 + \frac{3}{2}\pi_7;\ \pi_2 = \frac{1}{3} + \frac{1}{2}\pi_6 - \frac{3}{4}\pi_7;\ \pi_3 = \frac{1}{6} + \frac{1}{4}\pi_6 - \frac{3}{8}\pi_7;\ \pi_4 = \pi_6;\ \pi_5 = \frac{1}{6} - \frac{3}{4}\pi_6 - \frac{3}{8}\pi_7. \quad (8)$$

In the criterion form, the expression of optimal costs (4) will be written as:

$$B_{res*} = \frac{\pi_{1o}}{P_{ch*}} + \frac{\pi_{2o}}{P_{h*}} + \pi_{3o}P_{b*} + \frac{\pi_{4o}}{P_{s*}} + \pi_{5o}\frac{P_{ch*}^2 P_{h*}^2}{P_{b*}} \quad (9)$$

where $C_{res*} = C_{res}/C_{res\,\min}$; $P_{ch*} = P_{ch}/P_{ch\,o}$, $P_{h*} = P_h/P_{h\,o}$, $P_{b*} = P_b/P_{b\,o}$, and $P_{s*} = P_s/P_{s\,o}$, where P_{ch}, P_h, P_b, P_s—the current and optimal power values of the reserving methods. Taking into account the values of the similarity criteria from (8), Expression (9) will be rewritten as:

$$\begin{aligned} C_{res*} = {} & \left(\tfrac{1}{3} - \pi_6 + \tfrac{3}{2}\pi_7\right)\tfrac{1}{P_{ch*}} + \left(\tfrac{1}{3} + \tfrac{1}{2}\pi_6 - \tfrac{3}{4}\pi_7\right)\tfrac{1}{P_{h*}} + \left(\tfrac{1}{6} + \tfrac{1}{4}\pi_6 - \tfrac{3}{8}\pi_7\right)P_{b*} + \\ & + \pi_6\tfrac{1}{P_{s*}} + \left(\tfrac{1}{6} - \tfrac{3}{4}\pi_6 - \tfrac{3}{8}\pi_7\right)\tfrac{P_{ch*}^2 P_{h*}^2}{P_{b*}}. \end{aligned} \quad (10)$$

The relative value of the costs for the reservation of RES generation has three components. The first component is determined by the optimal relative values of costs for reservation measures and their ratios. Others depend on system reserve power limitations G_s and electrochemical accumulators G_{ch} (in (10), it depends on π_6 and π_7). The first component C_{res*} from (10) is defined as

$$C_{res*} = \left(\frac{1}{3}\frac{1}{P_{ch*}} + \frac{1}{3}\frac{1}{P_{h*}} + \frac{1}{6}P_{b*} + \frac{1}{6}\frac{P_{ch*}^2 P_{h*}^2}{P_{b*}} \right) \tag{11}$$

It can be seen from (11) that, under such conditions, when the power values of the reserve measures are optimal, that is, in relative units, all $P_{i*} = 1$ and $C_{res*} = 1$. This means that Expression (11) allows the analysis of the RES generation reservation measures for proportionality and sensitivity C_{res*} to the power deviation P_{i*} from their optimal values in relative units [34,35].

According to the accepted model (4) of the balancing of the RES generation schedule and its modified model (11), the optimal costs for reserving means are in a certain ratio. The total costs will be economically feasible if they are distributed in the following proportions: the costs of hydrogen technology and electrochemical storage will be the same and the costs of biogas plants should be two times less for their use as an electric energy reserve. At the same time, while hydrogen and biogas technologies are developing, it Is advisable to use the system reserve.

Such results were obtained based on the fact that the values of the optimal similarity criteria do not depend on the parameters $c_1, \ldots, c_5$. As for the generalized coefficients $C_1, \ldots, C_5$, their influence on economically feasible power values P_{ch*}, P_{h*}, P_{b*}, P_{s*} and costs C_* can be estimated by determining their values from the system of equations written according to the method of integral analogs from (4), taking into account (9) [33]:

$$\begin{cases} \frac{1}{3} - \pi_6 + \frac{3}{2}\pi_7 = \frac{c_1}{C_{res}P_{ch}}; \\ \frac{1}{3} - \frac{1}{2}\pi_6 - \frac{3}{4}\pi_7 = \frac{c_2}{C_{res}P_h}; \\ \frac{1}{6} + \frac{1}{4}\pi_6 - \frac{3}{8}\pi_7 = \frac{c_3 P_b}{C_{res}}; \\ \pi_6 = \frac{c_4}{C_{res}P_s}; \\ \frac{1}{6} - \frac{3}{4}\pi_6 - \frac{3}{8}\pi_7 = \frac{c_5 P_{ch}^2 P_h^2}{C_{res}P_b}. \end{cases} \tag{12}$$

From the system of Equation (12) for $\pi_6 = 0$ and $\pi_7 = 0$, find:

$$P_{ch} = \frac{0.77 \cdot c_1^{\frac{2}{3}}}{\left(c_2 \cdot c_3^{\frac{1}{2}} \cdot c_5^{\frac{1}{2}}\right)^{\frac{1}{3}}}; P_h = \frac{0.77 \cdot c_2^{\frac{2}{3}}}{\left(c_1 \cdot c_3^{\frac{1}{2}} \cdot c_5^{\frac{1}{2}}\right)^{\frac{1}{3}}}; P_b = \frac{0.65 \cdot \left(c_1 \cdot c_2 \cdot c_5^{\frac{1}{2}}\right)^{\frac{1}{3}}}{c_3^{\frac{5}{6}}};$$
$$C_{res} = 3.88 \cdot \left[c_1 \cdot c_2 \cdot c_4^{\frac{1}{2}} \cdot c_5^{\frac{1}{2}}\right]^{\frac{1}{3}}. \tag{13}$$

The criterion Equation (10) also allows the estimation of the impact of the source data on the cost-effective costs and power, which are determined from each of the methods of reservation; that is, to investigate the sensitivity of costs to change of power. It allows the determination of changes in specific costs when changing one or another power being optimized; that is, to investigate the economic stability of costs before changing parameters. In Figure 3, as an example, cost dependencies are given C_{res*} for changes in the power of electrochemical storage devices and for changes in the power of hydrogen technologies. From dependencies $C_{res*} = f(P_{ch*})$ and $C_{res*} = f(P_{h*})$ in Figure 5, it can be seen that the reduction in the cumulative tension of both types can be reduced to a lower C_{res*}. At the same time, up to a certain capacity, it is advisable to use electrochemical accumulators as their relative costs are lower than those of hydrogen electrolysis installations. However, when the power exceeds the specified one, it is advisable to use hydrogen technologies, because, at the same power, their relative costs are lower. In addition, in that part of the forecasted and actual schedules of RES generation, where the actual capacity exceeds the forecasted one, it is possible to reduce the imbalance by not spending the accumulated hydrogen for conversion into electricity. Instead, hydrogen can be used for other purposes in other areas, and the imbalance can be reduced by the programmatic correction of the generation forecast.

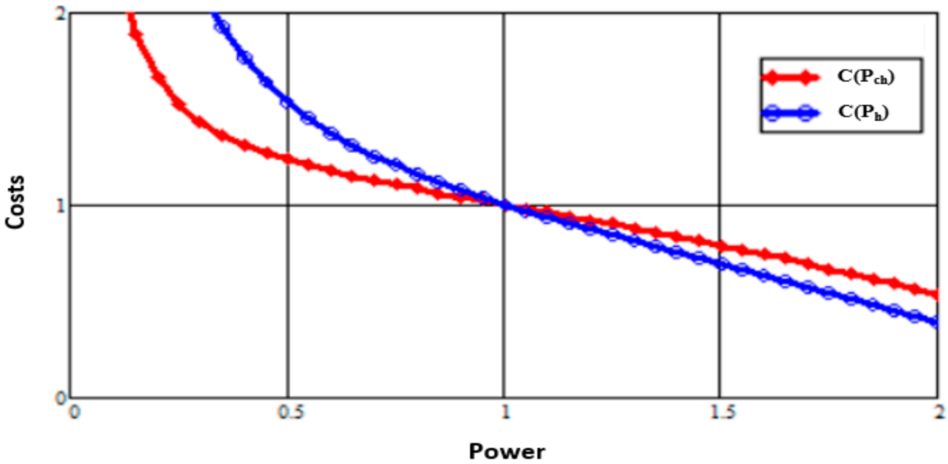

Figure 5. Sensitivity of relative costs to changes in the power generation of biogas (red curve) and to changes in the power generation of hydrogen technologies (blue curve).

From the obtained Expression (13), it is possible to estimate the impact of a change, for example, on the economically feasible values of all variables. Expression (13) shows that the economically feasible power values determined from each of the reservation methods and the costs of their implementation depend on the accepted reservation implementation scenario. Therefore, economically feasible methods of redundancy and their capacity, as well as the implementation parameters of each method, are chosen, taking into account their mutual influence in the system. For example, if c_1 relative to the basic value will increase by 20% under constant conditions c_2, c_3, c_4, c_5, the total cost C_{res} to balance the RES generation schedule through reservation will increase by 6.2%.

4. An Example of Reducing Imbalances between Forecasted and Actual Generation by a Combination of Methods

Figure 6 illustrates an example of the combined application of methods for reducing the difference between the predicted and actual electricity production by the balancing group of the PV. When, at a certain point in time, the actual value ("fact") is greater than the forecast (see Figure 6, point t_1), it is advisable to reduce this imbalance by accumulating energy, for example, in the form of hydrogen. Hydrogen can be produced directly at the PV if this possibility is provided by the appropriate installation; otherwise, it is necessary to buy the required amount of hydrogen as a service from another producer. The hydrogen option is appropriate because, when using, for example, electrochemical accumulators, we are limited by the need to convert the stored energy back into electrical energy. Meanwhile, in the case of hydrogen, there are more options, such as applications in other industries or in transport, or conversion into electricity. When the forecast at a certain time interval is greater than the "fact" (see Figure 6, point t_3), then, after running the forecast refinement program, the forecast generation of the PV is corrected to be allowable under the condition $\delta \leq \delta_{per}$.

For the case shown in Figure 6, we determined the value of the difference between the forecast and "fact" power generation of the PV, which must be compensated in the problem of balancing the EPS mode. The amount of electricity produced in excess of the required balance and that can be used for hydrogen production is defined as the area bounded by the ABC and AC curves. This is 250.5 MWh.

To calculate the potential volume of green hydrogen production using electrolysis, we calculated that 4.5 kWh of electricity is provided for 1 m^3 of hydrogen or 50.56 kWh for 1 kg of hydrogen [36]. An amount of 250.5 MWh can be used to produce hydrogen, that is, M = 250.5/50.56 = 4954 kg of hydrogen per day. This hydrogen, if the power system is deficient in electricity generation, can be used to generate electricity and improve the balance of the EPS mode. If the energy system is in surplus, it is advisable to use hydrogen in other industries and in transport. The difference between the forecasted and actual generation of PV in the balancing group can be reduced with software by correcting the forecast, as shown in Figure 6.

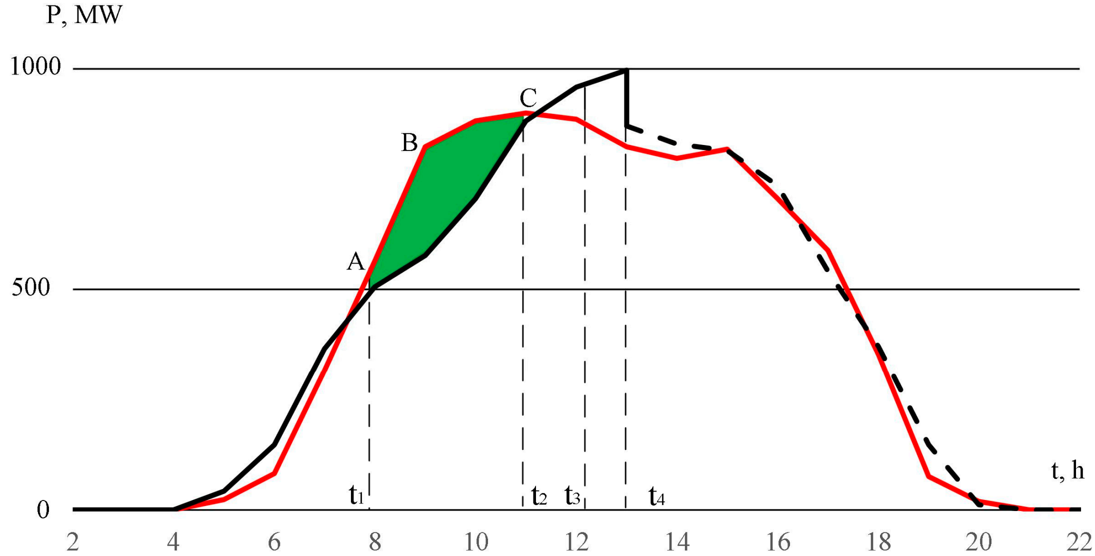

Figure 6. Combination of various methods of reducing the imbalance.

5. Conclusions

With the construction of power plants using renewable energy, there is not enough maneuverable power in the EPS to compensate for their unstable generation. Therefore, based on the specifics of electricity generation by PV and WPPs, the EPS has to develop special methods and means for balancing modes with the participation of PV and WPPs. There are two conditions for PV and WPPs to successfully participate in managing the current balance of power and electricity in the EPS. The first is the hourly forecasting of generation by PV and WPPs with a given accuracy. The second condition is the use of methods and means of electricity storage. When there is a surplus of electricity in the EPS, the electricity of PV and WPPs must be accumulated. Conversely, when there is a shortage of electricity in the EPS, the accumulated electricity of PV and WPPs must be fed into the system.

As the hourly forecast of the generation of PV and WPP by the developed methods does not meet the accuracy required for EPS, an algorithm and a program for refining the forecast schedule of their generation by means of intraday adjustment are proposed. The criterion for adjustment is the condition that the relative value of the difference between the forecasted and actual values should be less than the permissible error. The intraday correction program is implemented as an addendum to the program for forecasting the daily generation schedule for the next day.

Electrochemical accumulators, hydrogen technologies, and biogas plants are considered among the methods of accumulating energy in sufficient quantities for the needs of balancing the EPS modes, which, having accumulated reserves of the energy carrier, can convert it into electricity. A system reserve can be used as a reserve to reduce the impact of the uneven generation by PV and WPPs on power supply systems, as well as coordination of generation and consumption schedules.

It is impossible to unequivocally give preference to some of the listed methods and means due to their different technical efficiency, the possibility of providing them energy in the required quantity, and due to the lack of stable and reliable price indicators. Therefore, a method for optimizing the power reserve of the EPS is proposed to compensate for the unevenness of the generation by PV and WPPs in relative units, compared with each other. For this, a criterion method based on the theory of similarity is used, which allows the best option to be chosen with a limited amount of information. The results of the optimization are obtained in such a form that allows the analysis of the proportionality and sensitivity of costs for methods of compensating for the unevenness of the generation of PV and WPP.

The commensurability results allow the ways of compensating for generation unevenness to be ranked according to costs and sensitivity in order to rationally and most efficiently use the powers of various methods during operation. According to the results of the analysis of various methods and means, the relative efficiency of hydrogen technologies is shown as an example. For the future, in the presence of accurate price indicators, the optimization results are specified and shown already in named units.

Thus, the novelty of this article lies in the clarification of the RES generation forecast by correcting the intraday forecast with software tools, rather than by specifying meteorological parameters, as well as the optimization and comparison of methods and means of reservation of RES generation with incomplete information in relative units using the methods of similarity theory.

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Abbreviations

The following abbreviations are used in this manuscript:

ASCEA	Automated systems of commercial electricity accounting
EPS	Energy power system
PV	Photovoltaic power plant
RES	Renewable energy sources
WPP	Wind power plant

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