energies

Article

Organisation of the Structure and Functioning of Self-Sufficient Distributed Power Generation

Oleksandra Hotra [1,*], Mykhailo Kulyk [2], Vitalii Babak [2], Svitlana Kovtun [3], Oleksandr Zgurovets [2], Janusz Mroczka [4] and Piotr Kisała [1]

1 Department of Electronics and Information Technology, Lublin University of Technology, Nadbystrzycka 38D, 20-618 Lublin, Poland
2 Department of Forecasting the Electric Power Complex Development, General Energy Institute of NAS of Ukraine, Antonovich St. 172, 03057 Kyiv, Ukraine
3 Department of Monitoring and Diagnostic of Energy Objects, General Energy Institute of NAS of Ukraine, Antonovich St. 172, 03057 Kyiv, Ukraine
4 Department of Electronic and Photonic Metrology, Wrocław University of Technology, ul. B. Prusa 53/55, 50-317 Wrocław, Poland
* Correspondence: o.hotra@pollub.pl

Abstract: During the operation of solar and wind power plants, it is necessary to solve issues related to the guaranteed capacity of these plants, as well as the frequency stabilisation in the power system where they operate, and maintain an operating mode of self-sufficiency conditions. One of the solutions to these problems is the use of energy storage systems. This article proposes a mathematical model for the study of frequency and power regulation processes in power systems with distributed generation, which includes renewable energy resources and energy storage systems. The novelty of the model lies in the possibility of determining energy cost indicators based on instantaneous energy power data. The model allows us to estimate the conditions under which distributed generation becomes self-sufficient. The results of the model calculations of two variants of power system operation, which includes wind generators with a capacity of 1500 MW, demonstrate the ability of the proposed model to accurately reproduce the dynamics of the frequency stabilisation process. The calculation results of the energy-economic indicators of a real power system combined with a powerful subsystem of wind generation and a battery-type energy storage system prove the competitiveness of self-sufficient renewable energy power plants.

Keywords: renewable energy resources; energy storage systems; distributed generation; principle of self-sufficiency

Citation: Hotra, O.; Kulyk, M.; Babak, V.; Kovtun, S.; Zgurovets, O.; Mroczka, J.; Kisała, P. Organisation of the Structure and Functioning of Self-Sufficient Distributed Power Generation. *Energies* **2024**, *17*, 27. https://doi.org/10.3390/en17010027

Academic Editors: Vedran Kirincic, Tomislav Plavsic, Vladimir Valentic and Marko Mimica

Received: 10 November 2023
Revised: 9 December 2023
Accepted: 13 December 2023
Published: 20 December 2023

1. Introduction

Several objective factors complicate the widespread use of renewable energy sources (RESs), such as wind power plants (WPPs) and solar power plants (SPPs). The main ones are a lack of guaranteed power and problems related to frequency stabilisation in the power system where they operate. Even 10–15 years ago, in most countries of the world, the use of these RESs was economically impossible without the state granting them certain preferences, such as exemption from requirements regarding the frequency stability of the electricity supplied by them to the power grid, or those regarding the stability of the corresponding power. In the initial stages of using RESs, tariffs for their energy were many times higher than the cost of energy from traditional sources. Such a policy in most countries was justified by the need to combat climate change, but at the same time, it was contradicted by the strategy of introducing market relations in the energy sector. As a result, in 2016, the European Union decided to cancel all preferences granted to industrial projects for the construction and operation of existing WPPs and SPPs. However, under the pressure of public environmental and other lobbying organisations, the EU passed the decision of granting preferences for RESs to each country of the Union. For certain countries (in particular, Ukraine), this decision had extremely negative consequences. At the end of 2021, the expenses of the energy market of Ukraine significantly exceeded its revenues, and therefore, the country's government was forced to implement a series of monetary measures to mitigate the threatening situation that has developed in the Ukrainian energy market because of the adoption of laws on the "green" tariff.

Countries like Ukraine, which made a strategic decision to actively use RES technologies, inevitably found themselves in a similar situation. Success in this respect can only be ensured for countries that are rich in hydroenergy (Norway, Austria, etc.), and with their powerful hydropower plants, have the opportunity to compensate for the lack of guaranteed power and frequency instability, which are characteristic of WPPs and SPPs. Nevertheless, there are very few such countries in the world.

In 2016, battery energy storage systems (BESSs) began to be used in the heavy power industry for the stabilisation of the frequency and power of energy systems. From that moment, the rapid development of a new field of energy started, namely electric energy accumulators of great power and capacity.

As a result, a wide range of scientific and technical studies have appeared, dedicated to various problems and tasks related to ensuring the efficient functioning of RESs both as part of hybrid power systems and in the form of distributed generation using electric energy storage. An important positive phenomenon in this powerful flow of current information is the process of the publication of research results on structured topics, provided with a large number of review articles [1–6], each of which is mainly devoted to a separate research problem. In particular, publication [1] analyses the development possibilities of electrical storage together with other flexible grid options. Study [2] is devoted mainly to determining the required dimensions of energy storage in renewable energy systems. The main focus is on the formalisation of the specified determination criteria, primarily of financial and technological indicators. These indicators are implemented by applying probabilistic, analytical and hybrid methods, and the latter subclass of them is a heuristic combination of the former two. Publications [3,4] contain comprehensive overviews of ways of integrating BESSs into distribution grids. Articles [5,6] provide comprehensive overviews of the formation of the BESS structure for the use of wind energy while ensuring the necessary functional indicators of the power system.

In the publications devoted to the application of mathematical methods in the field of battery systems used to ensure the necessary energy-economic indicators of RESs, the most popular are works highlighting the use of probabilistic methods. Some of them [7–9] address the necessary indicators of the storage system, and others [10–12] are used for calculating the reliability of the system as a whole. Analytical methods [13,14] currently have undeservedly limited applications, perhaps due to their increased complexity. The authors of study [15] consider the construction of models and measures for monitoring the operation of power generation facilities, which is an important aspect of evaluating their effectiveness.

According to the conducted literature review, the priority research areas in energetics include problems related to the improvement of production technologies and the structural organisation of electric energy storage systems. Such structuring of research is due to the fact that, in the case of an effective solution to the problem mentioned, the long-promised prospect of wind turbines and thermal power plants becoming sources of ecologically clean, cheap, easily available energy is becoming a reality.

Based on the priorities mentioned above, it is appropriate to single out [16–19], which focus on the problems of the effective control of BESSs, as well as [20–23], which provide important results regarding the regulation of the specified storage systems. Study [24] presents the results of improving the efficiency of hybrid wind-battery energy storage systems using nonlinear control and power control optimisation, and paper [25] considers the optimisation of the energy management system for microgrids, taking into account the optimal use of grid energy and the degradation of battery storage systems. Study [26] evaluates energy storage systems with frequency control and inertial support.

The set of technological problems related to determining the advisable size of storage batteries [6,27,28] and their impact on the structure of energy generation from renewable sources [29–31] deserve special attention.

Studies [32–35], which provide results on optimising the size and placement of the energy storage system with the aim of further increasing the economic efficiency and competitiveness of the system as a whole [26,36,37], are of great importance. Paper [38] proposes a method for determining the optimal location and size of a battery energy storage system to reduce voltage fluctuations and total active losses in the distribution system, and study [39] analyses the economic benefits of integrating energy storage systems with wind generation to maximise revenues.

A stimulating factor of the above studies is the positive forecasts of their authors regarding the scientific and technical progress in the sector of the accumulation of electrical energy in industrial volumes. In fact, the boldest forecasts regarding key indicators (power, energy intensity, specific capital investments) were not only easily confirmed, but even improved many times over. In 2020, specific capital investments in an industrial storage system amounted to USD 1000/kW with a capacity of 400 MW and an energy capacity of 1600 MWh [40], and in 2022, the authors of [41] implemented a design with a storage system capacity of 140 MW, energy capacity of 560 MWh and specific capital investments of USD 286/kW. The proposition in [42] of an electric storage system with a capacity of 316 MW, an energy capacity of 2528 MWh and a specific capital investment of USD 475/kW has to be completed in 2024. All these systems are implemented using lithium-ion batteries. Thus, specific capital investments in the production of lithium-ion storage systems of industrial capacity have decreased by almost four times within two years. The previous research showed that even with the achieved indicators of economic efficiency (specific capital investment) of BESSs, it is possible to consider the synthesis of the structure of distributed RES systems (primarily WPPs and SPPs), for which, due to the application of electricity storage systems of the required power, capacity and corresponding control systems will be able to guarantee predictable generation capacity and meet the regulatory requirements for frequency stability by using only their own energy. The authors of this article call such RES systems self-sufficient systems of distributed generation (SSDG).

A significant number of publications dealing with the topic of self-sufficiency in renewable energy systems focus on the integration, optimisation and utilisation potential of wind and solar systems. Thus, e.g., in [43], integrated systems of wind and solar energy are considered to enable the self-sufficiency of communities. Publication [44] focuses on solar–wind hybrid systems in urban settings and evaluates the potential of mixed wind and solar systems in different cities. In [45], the optimal combination of wind and solar sources for reducing production costs is analysed. Therefore, studies that directly focus on the organisation of the functioning of energy systems with WPPs and SPPs in self-sufficiency mode remain quite limited. They focus on the issues of the self-sufficiency of energy systems as a whole and do not solve the problem of the self-sufficiency of distributed generation.

However, BESS cost indicators, which enable WPPs/SPPs to successfully compete with traditional technologies under market rules, are not the only necessary condition. In fact, when using bidirectional converters in BESSs, at every moment of time, the energy of a self-sufficient RES is either accumulated or released into the grid. The sequence and length of these operations are unpredictable and depend on many factors. Basically, these amounts of energy determine the resulting technical and economic indicators of RESs. Thus, in order to reliably determine the technical and economic indicators and competitiveness of an SSDG, it is necessary to be able to calculate the amount of energy produced by a WPP/SPP at arbitrary time intervals, as well as the energy released from a BESS to the grid and its volumes coming from a WPP/SPP to a BESS. When creating a mathematical model capable of determining the specified indicators, it should be taken into account that the power generated by a WPP/SPP contains a wide range of frequencies. In addition, this power is strongly dependent on wind speed/the intensity of solar radiation. Therefore, under such conditions, it is unacceptable to use the equations and dependencies resulting from Heaviside's symbolic method, as they lead to unacceptable errors due to the presence of the spectrum of harmonics and the unpredictable change in time of the power of the operating body. In our opinion, probabilistic methods have no prospects for reliably determining the amounts of charge and discharge energy of BESSs, since the initial statistical data (wind speed/radiation intensity) required for this lack sufficient information. Analytical methods can be used to develop a mathematical model of the operation of a distributed RES with self-sufficiency properties. At the same time, according to Heaviside, the quantities being modelled should appear not in a complex form, but in one of instantaneous values of energy, power and other quantities.

The aim of this article is to present the developed algebraic differential mathematical model for the operation and determination of energy-economic indicators of the distributed generation of a WPP/SPP that uses BESSs and provides generation with properties of self-sufficiency and competitiveness. The novelty of this work is in the proposed tool for ensuring the organisation of energy systems with WPPs and SPPs operating in self-sufficiency mode, which allows us to build strategies for the management and development of energy systems in general, to predict the impact of various scenarios on their stability and efficiency.

This article consists of six sections. In Section 1, the problem of organising the functioning of wind and solar power plants integrated into the structure of the power system is considered. An analysis of the latest publications on methods of stabilising the frequency in the power system where they work, and maintaining a mode of operation of self-sufficiency conditions, was carried out. The aim of the work and the novelty of the results proposed in it are defined. In Section 2, the principal possibility of organising systems functioning with self-sufficient distributed generation is proven. Section 3 describes in detail the mathematical model proposed by the authors for the study of frequency and power regulation processes in power systems with distributed generation, which includes renewable energy sources and energy storage systems. Section 4 demonstrates the results of the model calculations of two variants of power system operation, which include wind generators with a capacity of 1500 MW. The calculation results of the energy-economic indicators of a real power system combined with a powerful subsystem of wind generation and a battery-type energy storage system are given in Section 5. Finally, in Section 6, conclusions regarding the results obtained by the authors and the limitations and perspectives of the present study are described.

2. The Theoretical Basis of the Organisation of Self-Sufficient RESs

All traditional power plants operate under self-sufficiency conditions, i.e., all costs incurred by the power plant during its operation (lighting, ventilation, water supply, coal mills, ensuring frequency and power stability, etc.) are covered by the power plant itself. Ukrainian WPPs and SPPs are legally exempt from the obligation to compensate for the most significant of the costs mentioned. As shown in [46], the preference for ensuring frequency and power stability led the Ukrainian electricity market to a state of hidden bankruptcy in 2021. The principle of organising self-sufficient WPPs/SPPs is obvious, namely to make their obligations regarding the compensation of costs for their own needs similar to the requirements for traditional power plants. Externally, the mechanisms for realising the self-sufficiency of RESs and traditional sources are similar, but their separate algorithms are extremely different. In the case of traditional power plants, their consumption for their own needs is a simple sum of the consumption needs for each technology, but in the case of renewable sources, the conditions for their self-sufficiency require taking into account additional dependencies and relationships, which are shown in Figure 1.

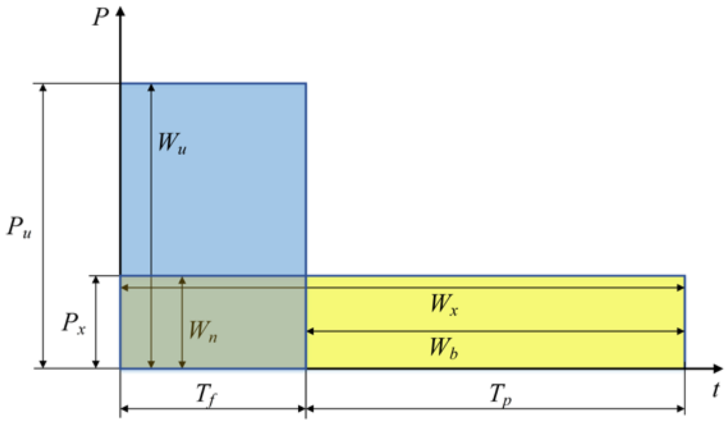

Figure 1. Functional scheme of connections and interactions of a self-sufficient WPP/SPP.

Figure 1 shows a diagram of the connections between a WPP/SPP and the grid, which can ensure the self-sufficiency of RESs. The following quantities are marked in Figure 1: P_x—WPP/SPP power necessary for the self-sufficiency of a WPP/SPP in the interval $T = T_f + T_p$; W_x—WPP/SPP energy necessary for the self-sufficiency of a WPP/SPP during interval T; W_n—WPP/SPP energy given to the grid during the interval [0, T_f]; P_u—WPP/SPP power required by the system operator (operator setting) during the interval [0, T_f]; $W_u = P_u T_f$—energy provided by power P_u; W_b—energy released from a BESS to the grid during the interval [0, T_p]; T_f—time during which a WPP/SPP operates; T_p—time (pause) when the WPP/SPP does not work. According to this scheme, the RES operates during the interval [0, T_f], and at the same time, produces energy W_v. Part of this energy W_n is transmitted to the grid, and the rest is transmitted into the BESS. During the time [0, T_p], the RES does not work and the BESS gives the stored energy W_b to the grid.

The given scheme can ensure the self-sufficiency of a RES only when taking into account the following general dependencies.

The energy balance at the end of the interval [0, T] is:

$$W_v - W_n - W_b = 0, \tag{1}$$

where W_v is the energy generated by the WPP/SPP during the interval [0, T_f] with the involvement of energy from other sources, W_n is the energy transmitted into the grid, and W_b is the energy accumulated in the BESS at the end of the interval [0, T_f]:

$$W_b = W_z - W_r, \tag{2}$$

where W_z is the total charge energy delivered to the BESS during the interval [0, T_f], and W_r is the total discharge energy that the BESS provided to the grid during interval [0, T_f].

Let us present dependence (1) in the form:

$$W_v = P_u T_f + P_x T_p \tag{3}$$

and introduce a new dependence:

$$W_b = P_x T_p, \tag{4}$$

where P_u is the WPP/SPP power required by the system operator (operator setting) in the interval [0, T_f]; T_f is the time during which a WPP/SPP operates; P_x is the WPP/SPP power necessary for the self-sufficiency of a WPP/SPP in the interval $T = T_f + T_p$; and T_p is the time (pause) when the WPP/SPP does not work.

W_b, W_z, and W_r are found from the algebraic differential model and are constants according to their definition. Therefore, the P_x value is immediately calculated by equation:

$$P_x = W_b / T_p. \tag{5}$$

In order to ensure the energy balance (3), it is necessary to determine P_u.

Let us assume that there is the following equality in the conditions of self-sufficiency:

$$P_u = P_x. \tag{6}$$

Then, Equation (3) will take the form $W_{vx} = P_x T$. Let us consider that W_{vx} in the model is calculated in the form:

$$W_{vx} = \int_0^{T_f} P_v(t)dt, \tag{7}$$

where $P(t)$ is the WPP/SPP power profile in the interval [0, T_f]. As [0, T_f] is measured in tens of minutes, i.e., in hours, and the integration according to Equation (7) is carried out with a constant step h = 10 ms, the W_{vx} energy—taking into account (6)—is determined with high accuracy in the form:

$$W_{vx} = P_{vs} T_f, \tag{8}$$

where P_v is the average value of $P(t)$ in the interval [0, T_f].

Then, Equation (8) takes the form:

$$P_{vs} T_f = P_x T \tag{9}$$

or

$$k P_{vs} = P_x, \tag{10}$$

where

$$k = T_f / T \tag{11}$$

is the set capacity utilisation factor of the WPP/SPP in the interval [0, T].

According to the analysis carried out, it is advisable to transform dependence (3) into the following form:

$$W_{vx} = P_x T_f + P_x T_p, \tag{12}$$

where $P_x T_f = W_n$ is part of the WPP/SPP energy transmitted to the grid during the interval [0, T_f], and $P_x T_p = W_b$ is part of the WPP/SPP energy transferred to the BESS at the end point of the interval [0, T_f]. Dependence (12) proves that assumption (6) is true, since it satisfies Equations (1) and (3) provided that limitation (6) is fulfilled at an arbitrary set capacity utilisation factor (11). Equation (6) is a necessary and sufficient condition of self-sufficiency for distributed generation.

3. Model for the Study of Frequency and Power Regulation in Power Systems with Self-Sufficient Distributed Generation

In the previous section, the principal possibility of organising systems functioning with self-sufficient distributed generation is proven. According to the literature review, it can be stated that this possibility has not been rigorously demonstrated before. However, the study of all versatile theoretical and applied aspects of these systems' functioning can be carried out only using detailed and complete models, one of which the authors propose in this article. This model is a significant development of model [47], and includes new blocks for determining the WPP/SPP energy, charge, discharge and storage energies in the BESS. It is only due to the mentioned innovations that it became possible to assess the conditions under which distributed generation becomes self-sufficient. A new important possibility provided by the proposed model is the determination of energy cost indicators based on instantaneous data of its power, which significantly improves the results of the symbolic method's application.

The proposed model is a problem-oriented set of the related equations and dependencies given below.

The overall power balance in the power system is given in the form:

$$\frac{d\omega(t)}{dt} = \frac{\sum_{i=1}^{I} P_{pi}(t) + P_{pr}(t) + P_b(t) - P_l(t) - P_g(t) + P_v(t) + P_s(t)}{T_{sys} P_{\Sigma p0} \omega(t)} {\omega_0}^2, \tag{13}$$

where T_{sys} is the power system time constant; $P_{\Sigma p0}$ is the total nominal power of generators; P_{pi} (t), P_l (t), P_{pr} (t), P_b (t), P_v (t), P_s (t) and P_g (t) are the sought variable-function power corresponding to the generators, load, generator–regulator, BESS, WPP, SPP and grid losses, respectively; and t = [t_0, t_1] represents the time interval from the beginning of the process to the current point t = t_1, at which the processes in the power system are studied.

Equation (13) is an identically modified form of the equation of the classical balance of mechanical and electrical power in the power system when transient electromechanical processes occur in it. To return Equation (13) to its classical form, it is enough to multiply both of its parts by the value $T_{sys} P_{\Sigma p0} \omega(t)/\omega_0^2$, where $\omega_0 = 2\pi f_0$ and f_0 = 50 Hz. As a result, the left side of Equation (13) gives the mechanical power of the rotating masses in the power system, which coincides with the difference between the generation and consumption of electrical power on the right side of the equation.

The equation that models the process of changing the power of traditional generators over time depending on the angular frequency $\omega(t)$ has the form [47]:

$$\frac{dP_{pi}(t)}{dt} = \frac{P_{p0i} - P_{pi}(t) + B_{pi}(\omega(t) - \omega_0)}{\tau_{pi}}, i = \overline{1, I}, \tag{14}$$

where B_{pi} is the steepness of the frequency characteristics of the generators, and I is the number of generators in the energy system.

To model the load power, the following dependence [47] is used:

$$\frac{dP_l(t)}{dt} = \frac{P_{l0} - P_l(t) + C_l(\omega(t) - \omega_0)}{\tau_l}, \tag{15}$$

where C_l is the steepness of the frequency characteristics of the load.

The equation describing wind power P_v (t) as a function of time depending on its static power P_{vw} is used in the form:

$$\frac{dP_v(t)}{dt} = \frac{B_v(\omega(t) - \omega_0) + P_{vw}(v_w(t)) - P_v(t)}{T_v}, \tag{16}$$

$$P_{vw}(v_w) = \sum_{k=0}^{N} c_k v_w^k. \tag{17}$$

which, in turn, is determined by the polynomial dependence on wind speed. Here, B_v is the steepness of the frequency characteristics of WPP, and T_v represents the WPP time constants.

Discrete Fourier transform is used to determine the wind speed with an arbitrary, very short time step [44]:

$$v_w(t) = \frac{1}{2} A_{v0} + \sum_{k=1}^{N} (A_{vk} \cos k\omega_0 t + B_{vk} \sin k\omega_0 t), \tag{18}$$

$$A_{vk} = \frac{1}{N} \sum_{n=0}^{2N} \left(v_w(t_n) \cos \frac{2\pi k}{T_f} t_n \right), \ k = \overline{0, N}, \tag{19}$$

$$B_{vk} = \frac{1}{N} \sum_{n=1}^{2N} \left(v_w(t_n) \sin \frac{2\pi k}{T_f} t_n \right), \ k = \overline{0, N}. \tag{20}$$

where $A_{\nu k}$ and $B_{\nu k}$ are the coefficients of the discrete Fourier transform for the approximate function of the wind, and N is the number of natural wind speed measurements $\nu_w(t_n)$ over the entire time interval.

The model of the solar station also uses discrete Fourier transform, but at the same time, the natural power data appear [47]:

$$P_s(t) = \frac{1}{2}A_0 + \sum_{k=1}^{M}(A_k \cos k\omega_0 t + B_k \sin k\omega_0 t), \tag{21}$$

$$A_k = \frac{1}{M}\sum_{m=0}^{2M}\left(P_s(t_m)\cos\frac{2\pi k}{T_f}t_m\right),\ k = \overline{0,\ M}, \tag{22}$$

$$B_k = \frac{1}{M}\sum_{m=1}^{2M}\left(P_s(t_m)\sin\frac{2\pi k}{T_f}t_m\right),\ k = \overline{0,\ M}. \tag{23}$$

where M is the number of natural power measurements of the SPP $P_s(t_m)$ over the entire time interval, and A_k and B_k are the coefficients of discrete Fourier transform for the approximation function of the SPP power.

To calculate the regulating power of the generator–regulator $P_{pr}(t)$, the following equation was developed:

$$\frac{dP_{pr}(t)}{dt} = \frac{B_{pr}(\omega(t)-\omega_0) + F_{pr}(t) - P_{pr}(t)}{T_{pr}}, \tag{24}$$

in which the regulating function $F_{pr}(t)$ is used in the form of a proportional–integral–differential (PID) control law:

$$F_{pr}(t) = A_{pr}(\omega(t)-\omega_0) + Q_{pr}\frac{d\omega}{dt} + S_{pr}\int_{t_0}^{t_1}(\omega(\tau)-\omega_0)d\tau. \tag{25}$$

The regulating function of the BESS is the algebraic sum of the adaptive component $D_a(t)$ and the dependencies of the PID control law in the interval $[0, T_f]$:

$$P_b(t) = D_a(t) - A_b(\omega(t)-\omega_0) - Q_b\frac{d\omega}{dt} - S_b\int_{t_0}^{t_1}(\omega(\tau)-\omega_0)d\tau \tag{26}$$

where A_{pr}, A_b, Q_{pr}, Q_b, S_{pr} and S_b are the gain coefficients of the proportional, differential and integral components of the PID control law for the generator–regulator and BESS, respectively.

The equation for the adaptive component is given as the difference between the power set by operator P_u and the power of the wind/solar station:

$$D_a(t) = P_u - P_v(t) - P_s(t). \tag{27}$$

The model also calculates the energies W_v (28) and W_s (29) generated by the WPP and SPP, appropriately.

$$W_v = \int_0^{T_f} P_v(t)dt, \tag{28}$$

$$W_s = \int_0^{T_f} P_s(t)dt. \tag{29}$$

To determine the energies of charge W_z and discharge W_r, appearing in (2), the following dependence was used in the model:

$$\varphi(t) = P_u - P_v(t) - P_s(t), \tag{30}$$

from which W_z and W_r are determined:

$$W_z = \int_0^{T_f} \varphi(t)dt \; npu \; \varphi(t) < 0 \tag{31}$$

$$W_r = \int_0^{T_f} \varphi(t)dt \; npu \; \varphi(t) > 0 \tag{32}$$

Important nonlinear limitations on the following quantities are introduced into the model:

- Rate of increase/decrease in generator–regulator power:

$$L_{prlg} \le \left| \frac{dP_{pr}(t)}{dt} \right| \le L_{prug}, \; t \in [t_0, T], \; P_{pr} \in [P_{prg1}, P_{prg2}], \tag{33}$$

- Rate of increase/decrease in BESS power [47]:

$$L_{blh} \le \left| \frac{dP_b(t)}{dt} \right| \le L_{buh}, \; t \in [t_0, t_1], \; P_b \in [P_{bh1}, P_{bh2}], \tag{34}$$

- Generator–regulator power level:

$$P_{pr\min} \le P_{pr}(t) \le P_{pr\max} \tag{35}$$

- BESS power level [47]:

$$P_{b\min} \le P_b(t) \le P_{b\max}, \tag{36}$$

- Generator–regulator insensitivity zone:

$$\frac{dP_{pr}(t)}{dt} = const, \; \omega(t) - \omega_0 \in [\omega_{prs1}, \omega_{prs2}], \tag{37}$$

- BESS insensitivity zone [47]:

$$\frac{dP_b(t)}{dt} = const, \; \omega(t) - \omega_0 \in [\omega_{bs1}, \omega_{bs2}], \tag{38}$$

- Initial conditions:

$$\begin{cases} \omega(t_0) = \omega_0, \\ P_{pi}(t_0) = P_{pi0}, \\ P_l(t_0) = P_{l0}, \\ P_{pr}(t_0) = P_{pr0}, \\ P_b(t_0) = P_{b0}, \\ P_v(t_0) = P_{v0}, \end{cases} \tag{39}$$

where g and h are subscripts denoting the generator–regulator and the BESS power intervals in which the rate limitation applies; $P_{pr\,min}$, $P_{b\,min}$, $P_{pr\,max}$ and $P_{b\,max}$ represents the limits of the minimum and maximum power of the generator–regulator and the BESS; and [ω_{prs1}, ω_{prs2}] and [ω_{bs1}, ω_{bs2}] represent the zone of insensitivity of the generator–regulator and the BESS.

4. Possibilities and Prospects of Using the Model

The proposed model provides an opportunity to solve several new important problems simultaneously. The main one is the organisation of connections and interactions in the structure of distributed generation, which ensures the possibility of its self-sufficiency. Figure 2 illustrates this possibility and shows two options for the functioning of the power system, in which 1500 MW of wind generators are installed. The wind profile (see Figure 2) was changed for 1 h with a speed in the range of 3.5 to 7 m/s. Figure 2 shows identical WPP power graphs, the profiles of which practically coincide with the wind profile obtained due to the generating characteristic of the WPP $P_v = f\ (\theta)$, where θ is the wind speed. The specified data and characteristics are taken from the real operating power system. The graphs differ only in the value of the setting P_u (P_u equal to 200 MW (Figure 2a) and 63.7 MW (Figure 2b)), which is highlighted by the corresponding horizontal lines.

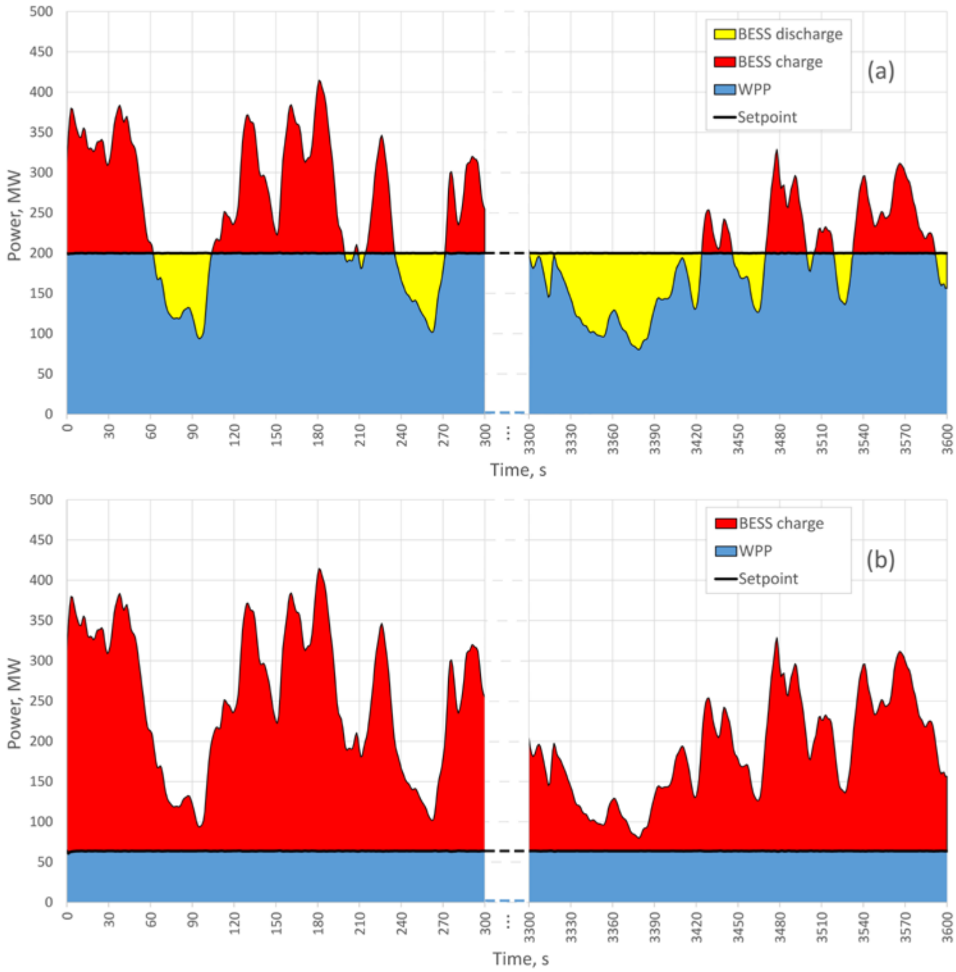

Figure 2. Formation of the self-sufficiency property in distributed generation with P_u equal to 200 MW (**a**) and 63.7 MW (**b**).

The specified values of the settings with the necessary accuracy are provided by the BESS control function (26) and negative feedback on frequency and power, which function in the developed model. In the graphs, the energy transferred from the WPP to the grid during the interval [0, T_f = 3600 s] is marked in blue, the energy transferred from the WPP to the BESS during the same time interval is marked in red and the energy transferred from the BESS to the grid during the same interval is marked in yellow. Let us emphasise that with an increase in the setting P_u, the total energy of the WPP and BESS transmitted to the grid increases and reaches a maximum at the value $P_u = P_{v\ max}$ = 430 MW. At the same time, the maximum energy is taken from the BESS, and the maximum energy is transmitted to the grid. On the contrary, when the setting P_u is reduced, the energy transferred to the grid decreases, and the energy transferred to the BESS increases. In this case, the limit includes the values $P_u = 0$, $W_b = W_{vx}$ and $W_n = 0$. That is, the function, in particular, $W_n = f(P_u)$, has the largest and smallest value, but does not have an extremum. As shown above, the best decision is reached when condition (6) is satisfied. Indeed, if $P_u > P_x$, the energy W_b decreases according to (1), that is, P_x decreases according to (5), and the system operator is forced to change the power supplied to the grid in the interval $[0, T_p]$. In the case when $P_u < P_x$, the opposite situation will be observed; energy will not be supplied to the grid, and more energy than is required for balance will be supplied to the BESS (12). We draw attention to the fact that in all three considered cases, all the energy of the WPP/SPP during the interval $[0, T]$ (28)/(29) is transferred to the grid. We also emphasise that in the proposed model, all actions to ensure the operation of the WPP/SPP are carried out exclusively by using their own energy, that is they are self-sufficient according to the above definition.

In order to confirm the possibility of using the proposed model as a self-sufficient model of distributed generation and to determine the necessary capacity of the BESS, as well as the energy-economic indicators of the WPP operating in self-sufficiency mode, calculations of the energy-economic indicators of self-sufficient distributed generation were performed for the combined energy system with operating capacity (MW): power plants (HPP—2100, TPP—9100–9910, NPP—11100, WPP—1200); systems (load—20880, BESS—650; grid losses—2320); indicators (wind speed profiles: 1. $\Theta = 3.5$–7 m/s, 2. $\Theta = 3.5$–10.5 m/s); and corresponding WPP power profiles (in Figure 2 (profile 1) and in Figure 3 (profile 2), $T_f = 3600$ s and $T_p = 6686$ s).

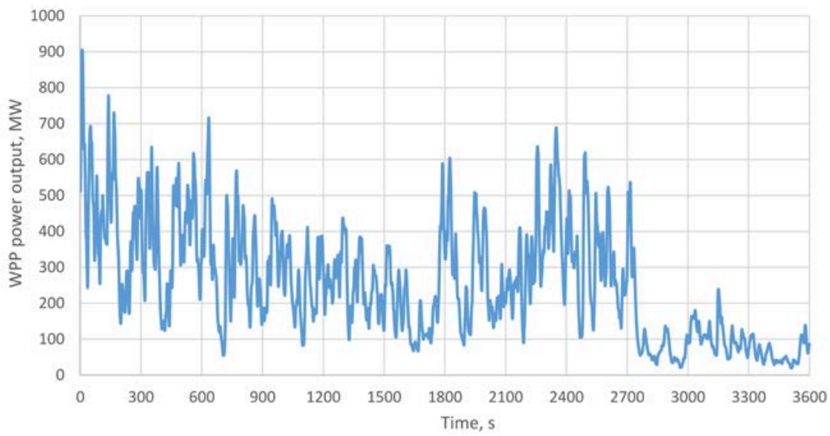

Figure 3. Change in total instantaneous power of a WPP at wind profile 2.

In this study, the mechanism for achieving a state of self-sufficiency for distributed generation is provided by modelling a series of options for the operation of a unified energy system (UPS) with one variable parameter, namely the variable of the operator setting P_u. This approach provides a change in the main indicators of the model, which, with their systematic analysis, allows us to draw a conclusion about the conditions for the self-sufficiency of WPP operation. Table 1 shows five variants of the operation modes of the UPS with its output data provided with power profile 1 (Figure 2). Variants of the operating modes of the UPS are provided in decreasing order of the operator setting P_u, the highest of which (400 MW) is close to the highest power value throughout the profile. The results of the simulation of UPS modes with wind/power profile 1 are shown in Table 1.

Table 1. Formation of the optimal setting $P_u = P_x$ with power profile 1.

Quantity	**Variant**				
	1	**2**	**3**	**4**	**5**
	Value				
Setting, P_u (MW)	400	300	200	100	63.7
Charge energy BESS (MWh)	0.2	3.1	24.5	86.0	118.6
Discharge energy BESS (MWh)	217.9	120.9	42.3	3.7	0.3
BESS energy at the end of the interval [0, T_f] (MWh)	−217.7	−117.8	−17.8	82.3	118.3
WPP energy (MWh)	182.3	182.3	182.3	182.3	182.0

When analysing Table 1, it should be taken into account that in self-sufficient systems, the energy must satisfy Equation (12), where W_v (energy of the WPP) is its only source. The energy of the WPP does not depend on the setting P_u, so its value in Table 1 is constant. It is also necessary to take into account that the value of energy W_u (Figure 1) numerically coincides with the value of the setting P_u, since T_f = 1 h. In each column of Table 1, the value of the fifth line is algebraically equal to the sum of the values of the first and fourth lines. As the W_u energy in 1–3 variants exceeds the W_v energy, these variants cannot ensure the self-sufficiency of the system. Variant 4 independently ensures frequency stability in the system, but is unable to ensure power stability. The energy available in the BESS at the end of the interval [0, T_f] is sufficient only to provide power of P_u = 44.3 MW. Variant 5 provides the system with a value of P_x = 63.7 MW according to (5), when P_u has the same value. Thus, variant 5 is the only one considered, which ensures the self-sufficiency of the system.

In order to check the stability of the model in response to the change in its parameters and to determine the generation of WPPs at their maximum capacity, for the calculation of the energy-economic indicators of self-sufficient distributed generation, the system with power profile 2 shown in Figure 3 was investigated. The results of the research are given in Table 2, which is similar to Table 1.

Table 2. Formation of the optimal setting $P_u = P_x$ with power profile 2.

Quantity	**Variant**				
	1	**2**	**3**	**4**	**5**
	Value				
Setting, P_u (MW)	900	500	400	300	200
Charge energy BESS (MWh)	0.0	7.3	20.6	47.6	94.5
Discharge energy BESS (MWh)	645.0	252.3	165.6	92.7	39.5
BESS energy at the end of the interval [0, T_f] (MWh)	−645.0	−245.0	−145.0	−45.1	55.0
WPP energy (MWh)	255.0	255.0	255.0	255.0	255.0

The analysis of Table 2 shows that, as in the previous case (Table 1), the energy of the WPP is not enough to ensure normative values of frequency and power in the system at the operator settings according to variants 1–4. Therefore, the model in such situations involves additional (external) energy that is previously externally introduced into the BESS. In variants 5–6, the model provides frequency stability with WPP energy, but cannot achieve the required power. In variant 5, according to (5), the power P_x equals 29.6 MW instead of the required 200 MW, and in variant 6, the power P_x equals 83.4 MW instead of 100 MW. The optimal value of P_u is reached according to (6), when P_x is determined from dependence (5) with a given power profile of the WPP (Figure 3).

The optimal value, according to the calculation results, is $P_u = P_x = 89.25$ MW (variant 7). For the same variant, the frequency deviation during the studied time interval was calculated, the graph of which is shown in Figure 4.

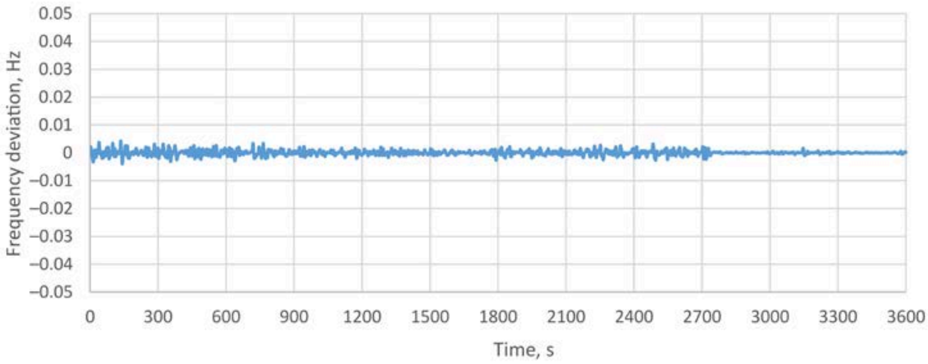

Figure 4. Frequency deviation in the grid at the optimal setpoint value $P_u = P_x$= 89.25 MW.

This graph demonstrates that the frequency remains within the permissible range of deviations, which supports the model's ability to accurately reproduce the dynamics of the frequency stabilisation process. It also illustrates the effectiveness of a BESS-based regulator in mitigating disturbances introduced by a WPP into the grid (Figure 3).

It is appropriate to emphasise that the mentioned studies and results were obtained only because new variables were first introduced into the general model of UPS operation with significant capacities of the WPP/SPP, namely the total energy of the BESS charge in the interval [0, T_f], the total energy of the BESS discharge in the same interval and the total energy of the charge retained in the BESS at the end of this interval.

It is worth noting that the study of the possibilities of organising self-sufficient operation modes of an SPP and an SPP together with a WPP can be carried out without additional methodological and model changes in comparison with the given example. In addition, the proposed method and model can be applied with equal success not only in the operation of the WPPs/SPPs as part of a UPS, but also in their autonomous functioning.

5. Energy-Economic Indicators of WPP Operation in Self-Sufficient Generation Mode

Determining the competitiveness of self-sufficient renewable energy power plants (see Table 3) was carried out by calculating the energy-economic indicators of operation using the example of a WPP according to the following characteristics: the installed capacity of the WPP (year 2021) is 1529 MW; the installed capacity utilisation coefficient is 0.35; the period of WPP operation is 25 years; specific capital investment in the WPP is USD 1200/kW; the electricity price (Italy, 2022) is EUR 294/MWh; the operating capacity of the WPP, taking into account self-sufficiency, is 89.25 MW; electricity production in the WPP in 1 h is 255 MWh; the BESS power is 650 MW; specific capital investment in the BESS is USD 286/kW; and the period of the BESS operation is 16 years.

The results of the calculations show that the transfer of the powerful WPP subsystem operating in the UPS to the principle of self-sufficiency using the BESS provides a project payback period of less than one year, which indicates the high competitiveness of WPPs and SPPs in self-sufficient mode.

Table 3. Main energy-economic indicators of WPP operation in self-sufficient mode.

Quantity	Unit	Value
Electricity production by the WPP in 1 year	kWh	781.8×10^6 *
Capital investment in the WPP for 1 year	USD	73.39×10^6
Capital investment in the BESS for 1 year	USD	11.62×10^6
Total capital investment for 1 year	USD	85.0×10^6
Construction costs (11.2% of item 4)	USD	9.52×10^6
Staff salary with accruals	USD	3.34×10^6
Other expenses (2% of item 4)	USD	1.47×10^6
Gross expenses for 1 year (items 4 + 5 + 6 + 7)	USD	99.33×10^6
Cost of electricity production	USD	0.127
Gross revenue of WPP	USD	252.83×10^6
Gross profit of WPP	USD	153.5×10^6
Net profit of WPP	USD	122.8×10^6
The project payback period	Year	0.81

* Electricity production (symbolic method) for 1 year (kWh). $P_{inst.}$—1529 MW; $P_{op.}$ = 1223 MW; installed capacity utilisation coefficient = 0.35; $W_v = 1.223 \times 10^6 \times 8.76 \times 10^3 \times 0.35 = 3.75 \times 10^9$ (kWh).

6. Conclusions

The new principle of WPP/SPP operation proposed in this article, namely one of self-sufficiency, gives a strong position in the competitive environment of electric energy markets to renewable energy sources. Such a perspective is based on the fact that each of the mentioned power plants can operate under self-sufficiency mode during its operation, as proven by the authors. That is, all operations necessary for the operation of the plant, including stabilisation of the frequency and power of energy, are carried out exclusively due to the use of its own energy. Currently, most WPPs/SPPs ensure the stability of the frequency and power of their energy by involving in their operation external fast-acting sources, the energy of which is expensive. On the contrary, the energy of WPPs/SPPs in its original and natural form is very cheap. The methodology, mathematical models and necessary IT tools presented in this article ensure a fairly simple transfer of WPPs/SPPs from a mode of importing expensive, fast-acting energy to a mode of self-sufficiency. For this purpose, the complex of mathematical and software and information tools [47] previously developed by the authors was improved and supplemented with units for determining the energy of WPPs and SPPs using instantaneous values of their power, charge volumes, BESS discharge, required capacity, etc. In contrast to the model in [47], the proposed model allows us to solve the problem of the self-sufficiency of distributed generation. Currently, there are no technologies in the world (except for the authors' one) that ensure the stability of the frequency and power of WPPs/SPPs as part of the UPS exclusively with their own energy. The model is adapted for application to a generalised power system scheme. At the same time, it remains flexible and can be supplemented with a detailed description of each component of the power system, from individual generators to specific consumers. The model can be used to simulate and analyse power systems with both conventional and renewable generation with a BESS, and serve as a useful tool for developing management and planning strategies, modifying power systems, and studying the impacts of various scenarios on the stability and efficiency of the power system.

The study of the energy-economic indicators of a large real UPS with a powerful WPP subsystem showed that the transfer of this subsystem to the principle of self-sufficiency with a new BESS provides a project payback period of less than one year, which indicates the high competitiveness of self-sufficient WPPs and SPPs.

We can be sure that the rapid development of electric energy storage technologies, which is currently observed, will continue for a considerable period in the future with a corresponding decrease in cost indicators. Slower but still tangible progress is being made in the field of WPP and SPP generation technologies. Therefore, it can be predicted that in the near future, taking into account environmental factors, these sources could become the basis for providing humanity with energy.

Author Contributions: Conceptualisation, M.K., V.B. and O.H.; methodology, M.K. and S.K.; software, O.Z.; validation, S.K. and O.Z.; formal analysis, V.B., O.H., J.M. and P.K.; investigation, M.K.; data curation, O.Z.; writing—original draft preparation, M.K.; writing—review and editing, O.H., S.K. and J.M.; visualisation, O.Z. and P.K.; supervision, O.H. and S.K.; project administration, V.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

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

References

1. Numan, A.M.; Baig, M.F.; Yousif, M. Reliability evaluation of energy storage systems combined with other grid flexibility options: A review. *J. Energy Storage* **2023**, *63*, 107022. [CrossRef]
2. Yang, Y.; Bremner, S.; Menictas, C.; Kay, M. Battery energy storage system size determination in renewable energy systems: A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 109–125. [CrossRef]
3. Stecca, M.; Elizondo, L.R.; Soeiro, T.B.; Bauer, P.; Palensky, P. A comprehensive review of the integration of battery energy storage systems into distribution networks. *IEEE Open J. Ind. Electron. Soc.* **2020**, *1*, 46–65. [CrossRef]
4. Hannan, M.A.; Wali, S.B.; Ker, P.J.; Abd Rahman, M.S.; Mansor, M.; Ramachandaramurthy, V.K.; Muttaqi, K.M.; Mahlia, T.M.I.; Dong, Z.Y. Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues. *J. Energy Storage* **2021**, *42*, 103023. [CrossRef]
5. Sterjova, M.; Minovski, D.; Sarac, V. Battery energy storage systems and technologies: A review. *ETIMA* **2021**, *1*, 95–104.
6. Mohamad, F.; Teh, J. Impacts of energy storage system on power system reliability: A systematic review. *Energies* **2018**, *11*, 1749. [CrossRef]
7. Al Ahmad, A.; Sirjani, R.; Daneshvar, S. New hybrid probabilistic optimisation algorithm for optimal allocation of energy storage systems considering correlated wind farms. *J. Energy Storage* **2020**, *29*, 101335. [CrossRef]
8. Lan, T.; Zhou, Z.; Huang, G.M. An approximation for parallelism in ACOPF based stochastic optimal transmission switching with battery energy storage systems. In Proceedings of the 2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018), Doha, Qatar, 10–12 April 2018; pp. 1–7. [CrossRef]
9. Metwaly, M.K.; Teh, J. Probabilistic peak demand matching by battery energy storage alongside dynamic thermal ratings and demand response for enhanced network reliability. *IEEE Access* **2020**, *8*, 181547–181559. [CrossRef]
10. Chen, F.; Li, F.; Feng, W.; Wei, Z.; Cui, H.; Liu, H. Reliability assessment method of composite power system with wind farms and its application in capacity credit evaluation of wind farms. *Electr. Power Syst. Res.* **2019**, *166*, 73–82. [CrossRef]
11. Oh, U.; Lee, Y.; Choi, J.; Karki, R. Reliability evaluation of power system considering wind generators coordinated with multi-energy storage systems. *IET Gener. Transm. Distrib.* **2020**, *14*, 786–796. [CrossRef]
12. Metwaly, M.K.; Teh, J. Optimum network ageing and battery sizing for improved wind penetration and reliability. *IEEE Access* **2020**, *8*, 118603–118611. [CrossRef]
13. Mohamad, F.; Teh, J.; Lai, C.M. Optimum allocation of battery energy storage systems for power grid enhanced with solar energy. *Energy* **2021**, *223*, 120105. [CrossRef]
14. Javadi, M.S.; Gough, M.; Mansouri, S.A.; Ahmarinejad, A.; Nematbakhsh, E.; Santos, S.F.; Catalão, J.P. A two-stage joint operation and planning model for sizing and siting of electrical energy storage devices considering demand response programs. *Int. J. Electr. Power Energy Syst.* **2022**, *138*, 107912. [CrossRef]
15. Babak, V.P.; Babak, S.V.; Eremenko, V.S.; Scherbak, L.M.; Zaporozhets, A.O. Models and Measures for the Diagnosis of Electric Power Equipment. In *Studies in Systems, Decision and Control*; Springer: Cham, Switzerland, 2021; pp. 99–126. [CrossRef]
16. de Siqueira, L.M.S.; Peng, W. Control strategy to smooth wind power output using battery energy storage system: A review. *J. Energy Storage* **2021**, *35*, 1022052. [CrossRef]
17. Honarmand, H.A.; Rashid, S.M. A sustainable framework for long-term planning of the smart energy hub in the presence of renewable energy sources, energy storage systems and demand response program. *J. Energy Storage* **2022**, *52*, 105009. [CrossRef]
18. Datta, U.; Kalam, A.; Shi, J. A review of key functionalities of battery energy storage system in renewable energy integrated power systems. *Energy Storage* **2021**, *3*, e224. [CrossRef]
19. Su, H.; Zhou, Y.; Feng, D.; Li, H.; Numan, M. Optimal energy management of residential battery storage under uncertainty. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12713. [CrossRef]

20. Sang, Y.; Ardakani, S. Enhancing wind energy integration by co-optimizing energy storage systems and transmission switching. In Proceedings of the 2019 IEEE Power & Energy Society General Meeting (PESGM), Atlanta, GA, USA, 4–8 August 2019; pp. 1–5. [CrossRef]
21. Peker, M.; Kocaman, A.S.; Kara, B.Y. Benefits of transmission switching and energy storage in power systems with high renewable energy penetration. *Appl. Energy* **2018**, *228*, 1182–1197. [CrossRef]
22. Erdinç, F.G.; Çiçek, A.; Erdinç, O.; Yumurtacı, R.; Oskouei, M.Z.; Mohammadi-Ivatloo, B. Decision-making framework for power system with RES including responsive demand, ESSs, EV aggregator and dynamic line rating as multiple flexibility resources. *Electr. Power Syst. Res.* **2022**, *204*, 107702. [CrossRef]
23. Reihani, E.; Sepasi, S.; Roose, L.R.; Matsuura, M. Energy management at the distribution grid using a Battery Energy Storage System (BESS). *Int. J. Electr. Power Energy Syst.* **2016**, *77*, 337–344. [CrossRef]
24. El Mezdi, K.; El Magri, A.; El Myasse, I.; Watil, A.; Bahatti, L.; Elaadouli, N.; Ouabi, H. Performance improvement through nonlinear control design and power management of a grid-connected wind-battery hybrid energy storage system. *Results Eng.* **2023**, *20*, 101491. [CrossRef]
25. Babu, V.V.; Preetha Roselyn, J.; Sundaravadivel, P. Multi-objective genetic algorithm based energy management system considering optimal utilization of grid and degradation of battery storage in microgrid. *Energy Rep.* **2023**, *9*, 5992–6005. [CrossRef]
26. Niu, D.; Fang, J.; Yau, W.; Goetz, S.M. Comprehensive evaluation of energy storage systems for inertia emulation and frequency regulation improvement. *Energy Rep.* **2023**, *9*, 2566–2576. [CrossRef]
27. Sun, Y.; Pei, W.; Jia, D.; Zhang, G.; Wang, H.; Zhao, L. Application of integrated energy storage system in wind power fluctuation mitigation. *J. Energy Storage* **2020**, *32*, 101835. [CrossRef]
28. Ahmad, T.; Zhu, H.; Zhang, D.; Tariq, R.; Bassam, A.; Ullah, F.; AlGhamdi, A.S.; Alshamrani, S.S. Energetics systems and artificial intelligence: Applications of industry 4.0. *Energy Rep.* **2022**, *8*, 334–361. [CrossRef]
29. Heylen, E.; Deconinck, G.; van Hertem, D. Review and classification of reliability indicators for power systems with a high share of renewable energy sources. *Renew. Sustain. Energy Rev.* **2018**, *97*, 554–568. [CrossRef]
30. Shen, Z.; Chiang, H.D.; Tang, Y.; Zhou, N. An online line switching methodology with look-ahead capability to alleviate power system overloads based on a threestage strategy. *Int. J. Electr. Power Energy Syst.* **2020**, *115*, 105500. [CrossRef]
31. Little, E.; Bortolotti, S.; Bourmaud, J.-Y.; Karangelos, E.; Perez, Y. Optimal transmission topology for facilitating the growth of renewable power generation. In Proceedings of the IEEE Madrid Power Tech, Madrid, Spain, 28 June–2 July 2021; pp. 1–6. [CrossRef]
32. Kang, H.; Jung, S.; Lee, M.; Hong, T. How to better share energy towards a carbon-neutral city? A review on application strategies of battery energy storage system in city. *Renew. Sustain. Energy Rev.* **2022**, *157*, 112113. [CrossRef]
33. Kim, D.K.; Yoneoka, S.; Banatwala, A.Z. *Handbook on Battery Energy Storage System*; Asian Development Bank: Manila, Philippines, 2018. [CrossRef]
34. Yang, B.; Wang, J.; Chen, Y.; Li, D.; Zeng, C.; Chen, Y.; Guo, Z.; Shu, H.; Zhang, X.; Sun, L.; et al. Optimal sizing and placement of energy storage system in power grids: A state-of-the-art one-stop handbook. *J. Energy Storage* **2020**, *32*, 101814. [CrossRef]
35. Zhou, P.; Jin, R.Y.; Fan, L.W. Reliability and economic evaluation of power system with renewables: A review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 537–547. [CrossRef]
36. Numan, M.; Khan, A.Z.; Asif, M.; Malik, S.M.; Imran, K. Exploiting the inherent flexibility in transmission network for optimal scheduling, wind power utilization, and network congestion management. *IEEE Access* **2021**, *9*, 88746–88758. [CrossRef]
37. Khoo, W.C.; The, J.; Lai, C.M. Integration of wind and demand response for optimum generation reliability, cost and carbon emission. *IEEE Access* **2020**, *8*, 183606–183618. [CrossRef]
38. Damian, S.E.; Wong, L.A. Optimal Energy Storage Placement and Sizing in Distribution System. In Proceedings of the 2022 IEEE International Conference in Power Engineering Application (ICPEA), Shah Alam, Malaysia, 7–8 March 2022. [CrossRef]
39. Zhang, X.; Feng, L.; Li, X.; Xu, Y.; Wang, L.; Chen, H. Economic evaluation of energy storage integrated with wind power. *Carbon Neutrality* **2023**, *2*, 16. [CrossRef]
40. Energy Storage in Moss Landing: A Smoky Challenge to a New Chapter. The Monterey Herald. 2022. Available online: https://www.montereyherald.com/2022/06/12/energy-storage-in-moss-landing-a-smoky-challenge-to-a-new-chapter (accessed on 27 July 2023).
41. Valley Center Battery Storage Project 2022. Valley Center (VC) Battery Storage Project Fully Online. Available online: https://www.valleycenter.com/articles/vc-battery-storage-project-fully-online/ (accessed on 27 July 2023).
42. New York Approves 316 MW Battery Plant for Peak Power, First of Its Kind in Region. Available online: https://www.smartenergyportal.ch/new-york-approves-316mw-battery-plant-for-peak-power-first-of-its-kind-in-region/ (accessed on 27 July 2023).
43. Temiz, M.; Dincer, I. Cleaner production of energy and fuels from a renewable energy-based self-sufficient system with energy storage options. *J. Energy Storage* **2023**, *72*, 108415. [CrossRef]
44. Ge, J.; Shen, C.; Zhao, K.; Lv, G. Energy production features of rooftop hybrid photovoltaic-wind system and matching analysis with building energy use. *Energy Convers. Manag.* **2022**, *258*, 115485. [CrossRef]

45. Superchi, F.; Schepers, S.; Moustakis, A.; Pechivanoglou, G.; Bianchini, A. Towards the Introduction of Green Hydrogen in the Energy Mix of Mediterranean Islands Through the Integration of Wind and Solar Power: A Techno-Economic Case Study. In Proceedings of the 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023), Las Palmas, Spain, 25–30 June 2023. [CrossRef]
46. Kulyk, M.; Nechaieva, T.; Zgurovets, O.; Shulzhenko, S.; Maystrenko, N. Comparative Analysis of Energy-Economic Indicators of Renewable Technologies in Market Conditions and Fixed Pricing on the Example of the Power System of Ukraine. *Stud. Syst. Decis. Control.* **2023**, *454*, 433–449. [CrossRef]
47. Kulyk, M.; Zgurovets, O. Modeling of power systems with wind, solar power plants and energy storage. *Stud. Syst. Decis. Control.* **2020**, *298*, 231–245. [CrossRef]