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Modeling a Hybrid Power System with Intermediate Energy Storage

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Abstract: The purpose of this work is to develop a model for balancing the processes of the generation and consumption of electricity, taking into account the random nature of these processes. The subject of the study is hybrid power systems that use traditional and renewable energy sources and have the properties of a local network. Such systems are sensitive to variable generation modes, and the presence of rapid changes in power requires short time intervals. The presence of wind and solar power plants makes it difficult to ensure a balance of power, which increases the need for intermediate energy storage. The research method is a mathematical modeling of random processes of energy consumption and generation, which allows for the analysis of the current power balancing and the obtaining of the integrated characteristics of the state of energy storage and reuse. The unique goal of the study is to take into account the power gradients and the state of charge of the batteries. The results of the study allow for the comparison of the different configurations of the power system in terms of balance, storage needs, and energy loss. It has been shown that the increase in battery capacity and speed limitations are nonlinearly related to the possibilities of energy conservation and the probability of the incomplete use of the capabilities of the energy storage system.

Keywords: local power system; renewable energy sources; power balance; hybrid power systems

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Citation: Lysenko, O.; Kuznietsov, M.; Hutsol, T.; Mudryk, K.; Herbut, P.; Vieira, F.M.C.; Mykhailova, L.; Sorokin, D.; Shevtsova, A. Modeling a Hybrid Power System with Intermediate Energy Storage. *Energies* **2023**, *16*, 1461. https://doi.org/10.3390/en16031461

Academic Editor: Alan Brent

Received: 23 December 2022
Revised: 26 January 2023
Accepted: 27 January 2023
Published: 2 February 2023

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1. Introduction

The use of renewable energy sources is one of the main criteria for energy security around the world. This is due to the depletion of fossil fuel reserves, the rapid rise in energy prices, as well as uncertainty about the stability of the supply and the reliability of purchases. Moreover, the negative impact on the environment leads to severe consequences that concern society in a more obvious way. The use of renewable energy sources significantly increases the existing energy capacity, which ensures security and improves the socioeconomic situation [1].

The introduction of renewable energy sources (RES) is limited by the problems associated with the uneven mode of their generation. For wind and solar power plants integrated into a large grid, their impact is mitigated by other energy sources. The peculiarity of RES is the dispersal on the area and proximity to the final consumer. Small consumers, such as settlements and small enterprises, can benefit from the independent use of RES, possibly, its combination with traditional sources. In this case, the combination of wind and solar plants, together with the consumer, can be considered as a local combined power system. Such systems are especially interesting in remote settlements, as well as small agricultural enterprises.

Energy storage can be used to solve the problems of balancing power in combined power systems. Modes of wind generation, and especially solar power plants, are characterized by significant current power gradients, in which changes can happen within a few minutes. The same kind of changes occurs with the load. The amplitude of changes depends on the number of individual consumers included in the local power system and their modes of operation. Therefore, when choosing energy storage systems, it is necessary to take into account such factors as uneven generation and consumption, the amount of possible excess energy, the rate of capacity change, and the corresponding speed of the batteries. Actual indicators of balance variability depend on the composition of capacity and weather conditions (this applies to wind and solar energy; these sources are often combined as VRE—variable renewable energy).

2. Literature Review

The organization of limited power systems with a significant share of RES is quite widely reflected in the scientific literature. The number of works has increased, especially in the last decade, when significant cost reductions in RES-based technologies (especially photovoltaics) and traditional energy problems have aroused interest in the construction of autonomous and hybrid energy systems on the basis of renewable energy (HRES). In the work described in [2], an overview of research on the sustainability of autonomous power systems using RES is provided. Hybrid power systems, such as micro-networks using wind, solar energy, and fuel cells, are considered in the work [3]. It presents an overview of different technologies of distributed generation and the integration of different RES, as well as the possibility of regulating the output power.

The optimal combination of renewable energy sources and storage facilities aims to reduce the degree of uncertainty and make the mode of electricity generation more predictable [4–6]. The proposed optimization methods are focused mainly on minimizing the total cost [7–9]. However, there is also a growing focus on the reliability of meeting the demand for electricity. The formulation of such problems requires a proper description within the mathematical model.

An overview of publications regarding the optimal construction of such hybrid systems is contained in [10]. Some of the items included in the research are the characteristics of renewable energy systems and their influencing factors, including low wind generation in critical seasons and issues related to local people [11–16]. Another area of focus in the research is solar energy and the effect of lower power generation during the rainy and winter seasons [17–20]. The integration of renewable energy systems has various applications, especially for PV-WIND-powering ventilation devices, hydrogen production, household applications, and mobile stations [21–26].

Ref. [27] provides an overview of publications regarding optimization methods suitable for small and isolated systems. Several typical examples of hybrid systems, as well as the reliability and cost-effectiveness of HRES, are considered. An overview of possible HRES configurations, mathematical modeling methods, and control strategies is given in [28]. Among the works of recent years, ref. [29] is notable, as it examines the technical problems of hybrid systems. Possibilities for minimizing risks and energy losses are also considered. Some problems concerning the building of an autonomous system including RES and energy storage are considered in [30]. As an intermediate energy source, the use of hydrogen is proposed as a means of energy storage; optimal solutions for the electrification of a remote community are also offered.

A review of publications concerning the optimal construction of such hybrid systems is contained in the work of [31]. Several typical examples of hybrid systems are considered in this work, as well as the reliability and cost-effectiveness of HRES. The study in [32] considers various configurations of wind–solar systems, management strategies, technical and economic analyses, and social effects. A feasibility study has been performed, with the application of special calculation methods and tools (HOMER, PSO). Energy system flexibility as a strategy to integrate a higher renewable share and reduce adverse events in the power grid was studied in [33], in which a HOMER software simulation was used to simulate the economic and technical aspects. Refs. [34,35] have demonstrated the possibilities of increasing the integration of locally available renewable energy sources and ways to achieve this by using the PRISMI PLUS toolkit.

Other constructions of the calculation algorithm that meet the needs of estimating certain parameters are also possible [36–38].

It has been shown that hybrid systems can be a viable alternative to electric grids or traditional fuels for remote and rural areas around the world. The best results have been demonstrated by the systems using several energy sources (sun, wind, centralized grid), but it is important to take into account both local climatic conditions and the peculiarities of energy consumption.

In general, in HRES, we can use a variety of energy sources, but wind and solar sources are the most popular. These sources are the most attractive to researchers because such energy is readily available. This is especially important for autonomous power systems, an essential element of which is the energy storage device. Accumulation systems must comply with the mode of the power system's operation. Requirements for the amount and time of energy storage are the most common [39]. Rapid changes in the levels of generated and consumed power can cause disruption of the batteries' modes of charging or discharging, which leads to their damage [40–42]. Since financial costs of the energy storage system account for a significant share of the total cost of the power system, there is a relevant need for a preliminary study of possible modes of operation [43]. One of the promising ways to increase the efficiency of HRES is the use of combined energy storage systems with different technical characteristics [44].

Here, the optimal distribution of renewable sources and auxiliary battery storage systems (BESS) is desirable [5,6,45]. Many researchers offer optimization methods focused on total investment and reduction of operating costs [7–9,46,47]. However, as BESS and RES become more cost-effective, more attention needs to be paid to the reliability of meeting electricity demand, in addition to cost optimization.

The obtained results and conclusions relate to specific geographical, climatic, and economic conditions. Each large region has its own characteristics of wind and solar power. Conditions of consumption can also vary, as well as requirements for the quality of electricity. Therefore, the results of these studies have a local application, and the calculations of hybrid systems of this type should be performed by taking local conditions into account. Of course, in addition to climatic factors, many circumstances affect the state of the energy system. Different methods of controlling consumption are often mentioned, including dispatcher restrictions and the stimulation of a daily load balancing through a tariff policy and marketing methods. It is also important to consider the structure of consumption and its features. This paper proposes to evaluate the influence of one of these factors—the variability of renewable energy, such as solar and wind—and the possibility of mitigating it with the help of intermediate energy storage. The description of random processes of this kind can be unified with normalized variables. However, the proposed research methods including the simulation of stochastic processes are similar and can be adapted to specific tasks by the substitution of numerical parameters in the formulas.

3. Materials and Methods

A feature of the study of load modes is the pre-processing of historical data; as a result, the characteristic graph of the consumer's electrical load appears as an average hourly schedule. Figure 1 shows a typical load schedule for different seasons, listed as a percentage of the rated power or capacity of the consumer. For greater generality, we have chosen the electrical load of a number of consumers who are similar in regards to the type of economic activity in which they engage, their mode of operation, and the setup of their electrical equipment. The study considers small agricultural enterprises engaged in the processing and canning of fruits and vegetables, the production of oil and animal fats, the manufacturing of ready meals, the production of fodder for livestock farms, etc. This kind of consumer usually has some access to localized power, or power within 1 MW, and is interested in using renewable energy sources. If the characteristic power (for example, the maximum source) is considered as a combination, it will be convenient to model the energy exchange processes in normalized (relative) variables.

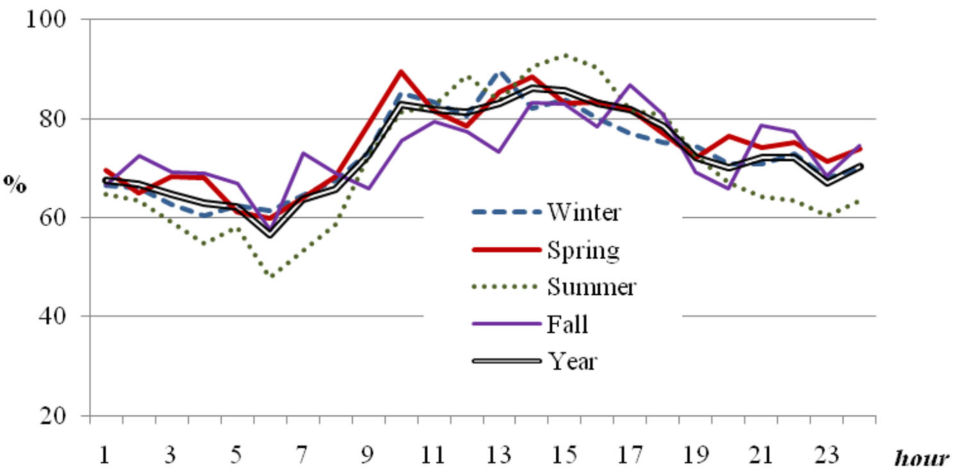

Figure 1. Typical averaged graphs of electrical loads (data from the Ministry of Energy of Ukraine).

The main criterion for determining the suitability of actual load schedules for further use is the continuity of measurements for at least one year. Examples of several dozens of consumers used in the study contain not only average load indicators, but also their variability over time. The authors have published some of these results in previous papers [48–51]. Based on the results of static processing for each hour of the month, the mathematical expectation and the standard deviation of the loads are calculated. The parametric description of the electrical load allows us to build a simulation model with a high level of uncertainty. This model allows significant deviations from the trend line (average daily course), which are characteristic of the monthly set of values. The traditional method of representing random processes of this kind is to represent the current value as the mean value and the random fluctuation for which an adequate mathematical model is chosen:

$$P(t) = P_c(t_i) + X(t) = 1/\Delta t \int_{t_i}^{t_i+\Delta t} P(\tau)d\tau + X(t) \quad t \in [t_i,\, t_i + \Delta t) \tag{1}$$

where $P(t)$, P_c (t_i) stand for instantaneous and average power values in the averaging interval, and $X(t)$ represents the fluctuations of the load relative to the average value. By definition, the mathematical expectation of fluctuations is zero: $M\{X(t)\} = 0$. The choice of the averaging interval Δt and the total duration of the simulated process allows for the setting of the time frame—short, medium, and long-term, depending on the task.

The nature of the RES capacity varies throughout the year and can be assessed both by retrospective weather data and by the appropriate analytical model [48]. Synchronous data on weather and consumption are not always available in the correct format, with proper time discreteness. In this case, instead of a real history of electricity consumption, the mathematical model of type (1) is used in order to simulate a random process of consumption. At the same time, the capacity of wind and solar power plants is simulated with the same time step and on the desired scale. Since the models of wind speed and insolation are based on real meteorological data, they make it possible to distinguish a typical daily course (trend) and a random component.

The representation of wind speed, typical for a certain region and a specific month, is performed as a characteristic daily course (trend line) and random deviations from the trend:

$$V(t) = w(t) + \sigma_{ad} \cdot \varepsilon + v(t) \tag{2}$$

where $w(t)$ simulates the typical behavior of the wind during the day (trend). The second component reflects the normally distributed random deviations of the daily average speed from the monthly average with the standard deviation σ_{ad}. The last component $v(t)$ signifies the random pulsations of the current speed. This representation makes it possible to take into account processes of different duration—months, days (hours), and minutes, respectively, which is important for the correct use and statistical processing of historical data. These pulsations are described by a process of the Ornstein–Uhlenbeck type:

$$v(t) = \alpha * \cdot v(t - \Delta t) + \sigma * \cdot \varphi \tag{3}$$

where the parameters of wear $\alpha^* = \alpha^*(\Delta t)$ and volatility $\sigma^* = \sigma^*(\Delta t)$ are calculated by different methods [48] using statistics on wind behavior, and the random variable φ has a Weibull distribution.

To simulate solar radiation, one can use a representation of the same type as that used for wind [52], but the trend line is typical for the specific time of year, the average daily values have a normal distribution, and the random pulsations are better described as white noise.

The transition from wind speed and solar radiation to the corresponding power of wind farms and power plants is performed for the specific energy characteristics of wind power plants and photomodules.

The traditional model of the photomodule's power is described by the formula:

$$P_{PV} = \eta \cdot A \cdot G(t) \tag{4}$$

where η is the efficiency coefficient, dependent on the temperature of the module and air; A is the area of photopanels (m^2); and $G(t)$ is solar radiation (W/m^2).

The wind turbine model is given by the power curve $P_W(V)$, while the wind speed V (m/s) is converted to the height of the rotor axis. As a rule, the following dependence is used:

$$P_W(V) = \begin{cases} p(V), & V \in (V_0, V_m) \\ 0, & V \notin (V_0, V_m) \end{cases} \tag{5}$$

Representations of forms (4) and (5) are generally accepted, and a feature of the proposed model is the representation of the arguments of power functions (parameters G, V) as the type of random processes in a formula (3).

After reducing all capacities to relative units, the equation of the current imbalance can be obtained. The model of the current balance of generation power and electricity consumption is the following:

$$p_{ij} = (a_{ij} - a_i) - [(w_{ij} - w_i) + (s_{sj} - s_i)] \tag{6}$$

where p_{ij} is the deviation from the load schedule; a_x is the level of electricity consumption; w_x and s_x indicate the capacity of the wind and solar power plants, respectively; i is the time interval (time of day); and j is the day. Indicators with one index express the average daily course; in particular, air should correspond to the planned schedule of consumption. This model takes into account the possibility of adjusting the data according to the availability of current forecasting. If the forecast is fulfilled for each day, then $p_i = a_i - w_i - s_i$ corresponds to the planned "net" load. In the absence of a forecast, the average monthly data are taken as the planned load (see Figure 1).

Accumulation of excess energy is an effective way to reduce power imbalance. When using RES, there are special requirements for energy storage systems that require consideration of both long-term and fast-changing processes. The amplitude and frequency of current power changes are of direct importance when choosing accumulating means according to the criterion of speed, and the presence or absence of a daily forecast (a daily or monthly accumulation cycle, respectively) refers to the peak power and total capacity of these systems.

Next, it is necessary to compare the natural rate of change in RES power with the available rate of energy conservation. The power gradients of wind farms and solar power plants were studied in [50]. A feature of this study is the simulation of rapid changes, with a time step of not more than 10 min.

The idealized model allows us to consider the charging power and storage capacity as independent values. This is also due to the presence of several storage units, possibly of different types, the charge level of which changes asynchronously. Thus, one can roughly consider the speed as a certain average constant.

A common method used to estimate a battery's performance is to represent the capacity as a function of charging time. The time required to fully discharge the battery is determined. In this case, the discharge rate is set by the battery capacity (in ampere-hours) divided by the number of hours required to charge/discharge the battery. If the available battery's capacity is denoted as C, the speed is recorded as C_x, where x is the time in hours required to discharge the battery. This can also be written as kC, where $k = 1/x$. Accordingly, the entry $6C$ means a charging/discharging time of 10 min, and $2C$ means a charging/discharging time of 30 min. Small batteries are usually designed for $1C$; lead-acid batteries are estimated as $0.2C$ (5 h) or $0.05C$ (20 h). Therefore, C/x can be considered as the available discharge rate (or charge). Then, the maximum charge capacity of the battery for a unit time interval Δt (in hours) can be defined as $\Delta t \cdot C/x$, where C is the full available capacity ($C = C_{\max} - C_{\min}$). Then $C_t = C(t) \in [0, C]$, and the restrictions on a single accumulation of energy can be represented as:

$$\delta C = \Delta t \cdot k \cdot C \tag{7}$$

For Δt = 10 min, provided that $k \geq 6$, there will be no restrictions on the amount of energy storage until the maximum capacity is reached. For slower batteries, one needs to compare the unbalanced energy with the achievable charging power at each time step.

4. Results

We believe that the average generation capacity is equal to the average consumption capacity, which corresponds to the economical formation of the energy system. Then the power balance randomly oscillates around zero, and its cumulative sum reflects the energy imbalance. Battery charge (SOC) depends on an energy imbalance, and may also randomly increase or decrease over a period of time. We accept the hypothesis of stationarity, when the average power balance and the battery charge remain constant for a long period of time. We have a zero monthly balance when the planned load schedule corresponds to the average monthly levels of consumption and generation of RES, but in some implementations, there may be significant remainders. When it is possible to forecast average levels on a daily basis, we obtain a daily cycle, while in the absence of a forecast, we achieve a monthly cycle. Random fluctuations in the balance during the day are the same in both cases, but the accumulated unbalanced energy is significantly different. To estimate imbalances, we consider standard deviations, and the probability density function corresponds to the hypothesis of normality.

An example of the simulation of two types of processes, based on the results of several thousand implementations of the daily course, are shown in Table 1. The system under study is a consumer in Figure 1, and the power of the multiple of the rated load is the generation of electricity using wind, solar, or combined stations. Energy characteristics (3) and (4) are typical for a wind turbine of medium power (up to 1 MW) and typical silicone PV modules. Standard deviations of power imbalance (p_{ij}) refer to the full dataset, and deviations of unbalanced energy (E_{Δ}) are calculated for conditions of daily and monthly cyclicity (arrays of releases of 24 or 720 h). The deviation of the load itself corresponds to the option RES = 0. Other options obtain partial generation from wind farms, solar power plants, and their combinations. The RES capacity is specified in relative units corresponding to the nominal power consumption equal to 1 (or 100% in Figure 1). RES generation is designed for winter and summer conditions.

Table 1. Standard deviations of normalized imbalance, r.u. (relative units).

Deviation		**0**	**RES Capacity**							
			Wind Farms		**Solar Power Plants**		**Wind Farms + Solar Power Plants**			
			0.5	**1**	**0.5**	**1**	**0.5 + 0.5**	**1 + 1**	**1 + 0.5**	**0.5 + 1**
p_{ij}	January	0.33	0.37	0.46	0.33	0.34	0.37	0.47	0.45	0.38
	July		0.35	0.39	0.33	0.33	0.35	0.40	0.39	0.35
E_{Δ} (day)	January	1.17	2.31	4.20	1.26	1.42	2.36	4.22	4.16	2.46
	July		1.78	3.03	1.24	1.31	1.83	3.10	3.10	1.91
E_{Δ} (month)	January	5.6	12.1	23.5	6.3	8.4	15.2	22.4	25.3	15.9
	July		8.83	15.8	6.20	6.40	10.1	16.9	18.1	10.8

Table 1 does not present absolute indicators, but rather the level of variability in the energy exchange processes, which is important for assessing the confidence intervals of the assessment and understanding the risks of guaranteed supply. Current fluctuations are typical for time intervals from a day to a month, as indicated above.

Taking into account the random nature of the simulated processes, statistical estimates are rounded up.

The consumption deviation is considered to be approximately the same throughout the year (see Figure 1), and the behavior of the RES depends on the season. Deviations in solar energy are much smaller than those in wind energy, because the energy efficiency of solar power plants is lower than that of the wind farms, relative to their rated power (0.35 for a wind turbine and 0.15 for a photomodule).

As shown in Table 1, the standard deviations with the hypotheses of normal distribution determine the probability of achieving certain values of power and energy imbalance. Therefore, by setting the desired level of confidence probability with the appropriate distribution quantile, one can determine the need for peak power and capacity for the energy storage system. Examples of possible values of quantiles of normal distribution are: $|\kappa|0.8 = \kappa 0.9 = 1.28$; $|\kappa|0.9 = \kappa 0.95 = 1.65$; $|\kappa|0.95 = \kappa 0.975 = 1.96$; and $|\kappa|0.99 = \kappa 0.995 = 2.58$.

When choosing a specific type of battery, the restrictions on the rate of charge/discharge, self-discharge, the efficiency of energy conversion, the allowable number of charge cycles, etc., should also be taken into account. However, the simulation results make it possible to assess the overall accumulation needs and compare different generation schemes. Thus, for the case $W = S = 1$ (r.u.), i.e., the nominal power of the wind farms and the solar power plants is equal to the maximum expected load, with a confidence level of 0.9, the battery power for January conditions should be 0.8 (r.u.) at a capacity of 7.0 (r.u.-hours); for July, the corresponding battery power is 0.7 (r.u.), and the capacity is 5.0 (r.u.-hours), with the availability of daily forecasting. When focusing only on long-term observations, the capacity should reach 36 and 28 (r.u.-hours) respectively, i.e., have a reserve of energy approximately equal to daily consumption. Taking into account the efficiency of wind and solar stations, their total generation will exceed half of the total consumption (approximately 70%), which is a fairly high level of integration of RES.

The rate of synchronicity regarding the direction of changes in the generated RES and power consumption can be seen in the actual example [49]. Several consecutive days for the settlement are considered; at equal capacities of wind and solar stations, the values of the capacity changes for the unit of time (1 h) are specified; the results are shown in Figure 2.

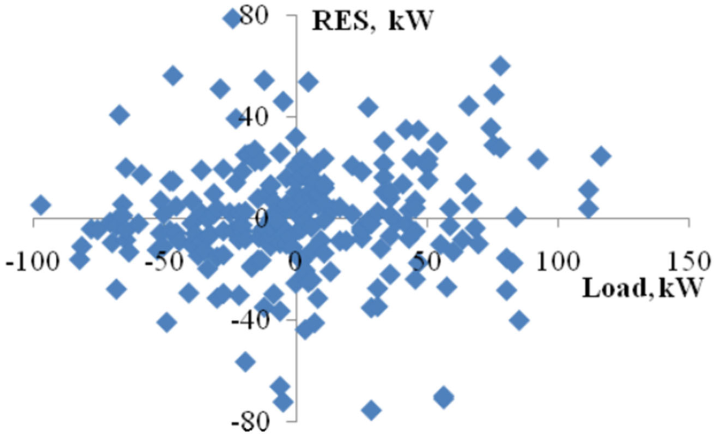

Figure 2. Examples of synchronous fluctuations of RES power and consumption.

It can be seen that favorable cases (simultaneous increase in generation and load) have the same probability as unfavorable examples (changes in antiphase). In general, the distribution of random deviations from the mean value is well described by normal law, except for some extreme values (emissions).

In particular, the obvious conclusion from the obtained results is the unequal influence of wind farms and solar power plants. If the increase in the share of RES increases the spread of imbalance values, then at low solar power plants capacities, there is an equalization of the balance of consumption and generation, which is partly explained by the simultaneous increase in energy needs and insolation during the day. In general, the impact of wind farms is more noticeable than the same impact on solar stations with nominal power, which is explained by both the longer duration of action (photomodules are active only during the day) and differences in energy efficiency. In addition, when using wind farms, the simultaneous presence of solar generation slightly increases the variability of balancing, as expected, but a larger share of solar stations causes fewer changes. This phenomenon is observed in both the winter and summer months (Table 1, indicator E_{Δ}), especially for the monthly cycle. An example of the approximation of the RES generation mode to the traditional consumption by the settlement when combining wind farms and solar power plants is shown in Figure 3. This example reflects the balance of capacities for a consumer (Figure 3) or a small settlement, and wind and solar conditions are typical for the southern regions of Ukraine in the spring season.

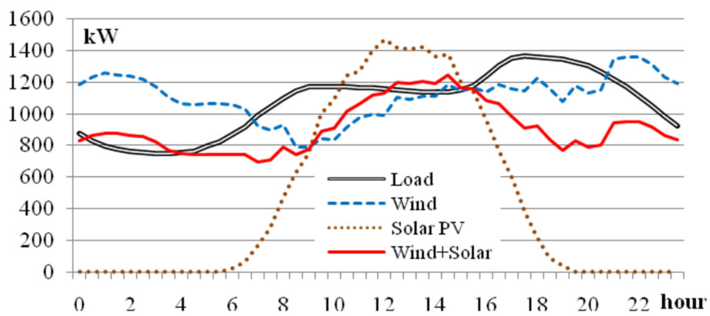

Figure 3. Examples of combining wind farms and solar power plants (averaged data).

The results obtained indicate a high need for battery capacity. However, this applies to a rather conditional situation, when the power imbalance is determined only by the deviations in wind–solar generation from a constant load, determined by the average monthly level of consumption. However, the real situation will be determined by the variable level of consumption, which also has a random component. In addition, the daily forecasting determines, in advance, both the level of load and the averaged generation of RES. This significantly reduces uncertainty and the corresponding need for energy storage.

When the charging rate is limited, the battery discharge also slows down; as a result, the average charge level is maintained. However, the possibility of excess energy accumulation is reduced. Since it is not possible to make an accurate analytical description of the random accumulation process, it is more appropriate to determine such losses by simulation. Let us consider the effect of restrictions on the rate (k) and capacity (C) of batteries on the possible amount of stored energy, taking into account only positive imbalances. The load is considered constant. The RES generation mode corresponds to the average annual values, and the nominal capacities of wind farms and solar power plants are the same and equal to 1 (see Table 1). Table 2 shows the energy loss, i.e., the part of the imbalance that cannot be accumulated due to the limitations of the storage system. The maximum energy imbalance in this example is 16 relative units (monthly cycle).

Table 2. Indicators of energy loss due to constraints (r.u.).

C	**k**		
	0.03	**0.05**	**≥0.08**
≥16	0		
13	0.22	0.02	0.003
10	0.37	0.1	0.03
8	0.55	0.24	0.1
6	0.75	0.45	0.26
4	0.95	0.72	0.52
2	1.10	0.95	0.80
1	1.25	1.16	1.07

In contrast to the total energy imbalance E_{Δ} (in this example ± 16), the actually accumulated energy is limited by the limit values [0, C] and the allowable increase in δC, i.e., determined by the dependence:

$$C_i = C_{i-1} + p_{ij}\Delta t,\ p_{ij}\Delta t \leq \delta_C,\ 0 \leq C_i \leq C. \tag{8}$$

Energy losses due to speed limitations become noticeable at $\delta_C < 0.1$ (r.u.); at $\delta_C = 0.03$, they make up half of the possible accumulation, and in the extreme case (at $\delta_C = 0$), all unbalanced energy is lost. The dependence of the lost energy on the battery capacity is shown in Figure 4, in which the regression scale regarding capacity is chosen.

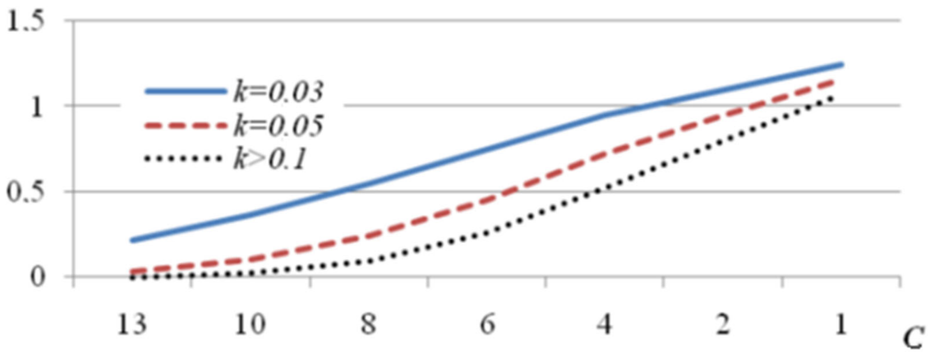

Figure 4. Energy loss due to limited battery capacity (r.u.).

5. Discussion

The effect of battery capacity on the amount of stored energy is noticeable, even at values equal to the hour of RES operation with nominal power. Thus, the increase in battery capacity is nonlinearly related to the possibility of energy conservation, and these effects are specific to the conditions of repeated changes in the direction of energy flow to and from the battery.

Another consequence of this mode of operation is the excess of the total stored energy compared to a single full charge of the battery. Thus, when working nearly without restrictions (C = 3 r.u., k = 1), the average battery charge would be 0.55, and the mathematical expectation of stored energy is 1.76. Obviously, the capabilities of the battery are not fully utilized here. We note that the deviation in the amount of stored energy is quite high, as the coefficient of variation is 0.2–0.3. This means a high probability of overflow of the available battery capacity with increasing restrictions. In this case, the stored energy may exceed the full capacity of the battery, with the probability that can be determined by the quantile of normal distribution.

6. Conclusions

The proposed mathematical model makes it possible to estimate the random component in the generation of energy by the wind and solar power plants and to determine the possibility of compensation for this variability through the use of batteries. The computational algorithm allows for obtaining a set of implementations of a random process that describes the balancing of electrical energy with random changes in generating and consumed power, as well as the intermediate accumulation of energy by the storage system. The practical use of the proposed model is the possibility of pre-selecting the battery parameters to ensure a given level of uncertainty or risk. A specific option for the construction of the power system includes the installed capacity of RES, the energy characteristics of wind or solar installations, typical weather conditions (average values and possible deviations), storage parameters, and accepted restrictions. In this study, each calculation option is represented by several thousand implementations. The result is dataset that describes the possible states of the power system and is suitable for statistical evaluation and calculation of the required values. It is established that the amount of stored energy increases with increasing capacity of the energy storage system. This takes into account the speed, which depends on the type of battery used. The variation of these parameters will allow for choosing the composition of the power system that will best meet the needs of consumption. The next step should be to take into account the cost of equipment (batteries, wind turbines, photovoltaic modules) and electricity tariffs. The use of technical and economic criteria will ensure the optimal choice of parameters that take into account the economic benefits and technical reliability of the energy supply.

Author Contributions: Conceptualization, M.K. and T.H.; methodology, O.L. and K.M.; database creation, O.L. and P.H.; validation, F.M.C.V. and L.M.; formal analysis, D.S. and A.S.; supervision, T.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financed by the subsidy of the Ministry of Education and Science for the Hugo Kołłątaj Agricultural University in Kraków, 2023.

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

References

1. Kucher, O.; Hutsol, T.; Glowacki, S.; Andreitseva, I.; Dibrova, A.; Muzychenko, A.; Szeląg-Sikora, A.; Szparaga, A.; Kocira, S. Energy Potential of Biogas Production in Ukraine. *Energies* **2022**, *15*, 1710. [CrossRef]
2. Negi, S.; Mathew, L. Hybrid Renewable Energy System: A Review. *Int. J. Electron. Electr. Eng.* **2014**, *7*, 535–542.
3. Krishna, S.; Kumar, S. A review on hybrid renewable energy systems. *Renew. Sustain. Energy Rev.* **2015**, *52*, 907–916. [CrossRef]
4. Obukhov, S.; Ibrahim, A.; Tolba, M.; El-Rifaie, A. Power balance management of an autonomous hybrid energy system based on the dual-energy storage. *Energies* **2019**, *12*, 4690. [CrossRef]

5. Faccio, M.; Gamberi, M.; Bortolini, M.; Nedaei, M. State-of-art review of the optimization methods to design the configuration of hybrid renewable energy systems (HRESS). *Front. Energy* **2018**, *12*, 591–622. [CrossRef]
6. Olatomiwa, L.; Mekhilef, S.; Ismail, M.S.; Moghavvemi, M. Energy management strategies in hybrid renewable energy systems: A review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 821–835. [CrossRef]
7. Zhang, Y.; Dong, Z.Y.; Luo, F.; Zheng, Y.; Meng, K.; Wong, K.P. Optimal allocation of battery energy storage systems in distribution networks with high wind power penetration. *IET Renew. Power Gener.* **2016**, *10*, 1105–1113. [CrossRef]
8. Geem, Z.W. Size optimization for a hybrid photovoltaic–wind energy system. *Int. J. Electr. Power Energy Syst.* **2012**, *42*, 448–451. [CrossRef]
9. Ghaffari, R.; Venkatesh, B. Energy reserve trade optimization for wind generators using black and scholes options in small-size power systems. *Can. J. Electr. Comput. Eng.* **2015**, *38*, 66–76. [CrossRef]
10. Naveen, R.; Revankar, P.P.; Rajanna, S. Integration of Renewable Energy Systems for Optimal Energy Needs—A review. *Int. J. Renew. Energy Res.* **2020**, *10*, 2. [CrossRef]
11. Shafiullah, G.; Oo, A.M.; Ali, A.S.; Wolfs, P. Potential challenges of integrating large-scale wind energy into the power grid–A review. *Renew. Sustain. Energy Rev.* **2013**, *20*, 306–321. [CrossRef]
12. Kuvlesky, W.; Brennan, L.; Morrison, M.; Boydston, K.; Ballard, B.; Bryant, F. Wind energy development and wildlife conservation: Challenges and opportunities. *J. Wildl. Manag.* **2007**, *71*, 2487–2498. [CrossRef]
13. Ajayi, O.O. Assessment of utilization of wind energy resources in Nigeria. *Energy Policy* **2009**, *37*, 750–753. [CrossRef]
14. Ibrahim, H.; Ghandour, M.; Dimitrova, M.; Ilinca, A.; Perron, J. Integration of wind energy into electricity systems: Technical challenges and actual solutions. *Energy Procedia* **2011**, *6*, 815–824. [CrossRef]
15. Garry, P.; Spurlin, C.; Nelsen, D.A. Wind Energy in Indian Country: A Study of the Challenges and Opportunities Facing South Dakota Tribes. *SDL Rev.* **2009**, *54*, 448.
16. Ellabban, O.; Abu-Rub, H.; Blaabjerg, F. Renewable energy resources: Current status, future prospects and their enabling technology. *Renew. Sustain. Energy Rev.* **2014**, *39*, 748–764. [CrossRef]
17. Shanmugapriya, S.; Premalatha, M.; Anantharaman, N. Solar Photocatalytic Treatment of Phenolic Wastewater Potential, Challenges and Opportunites. *J. Eng. Appl. Sci.* **2008**, *3*, 36–41.
18. Sharma, N.K.; Tiwari, P.K.; Sood, Y.R. Solar energy in India: Strategies, policies, perspectives and future potential. *Renew. Sustain. Energy Rev.* **2012**, *16*, 933–941. [CrossRef]
19. Kapoor, K.; Pandey, K.K.; Jain, A.; Nandan, A. Evolution of solar energy in India: A review. *Renew. Sustain. Energy Rev.* **2014**, *40*, 475–487. [CrossRef]
20. Posadillo, R.; Luque, R.L. A sizing method for stand-alone PV installations with variable demand. *Renew. Energy* **2008**, *33*, 1049–1055. [CrossRef]
21. Shun, S.; Ahmed, N.A. Utilizing wind and solar energy as power sources for a hybrid building ventilation device. *Renew. Energy* **2008**, *33*, 1392–1397. [CrossRef]
22. Setiawan, A.; Zhao, Y.; Nayar, C.V. Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse osmosis desalination plant for remote areas. *Renew. Energy* **2009**, *34*, 374–383. [CrossRef]
23. Sopian, K.; Ibrahim, M.Z.; Daud, W.R.W.; Othman, M.Y.; Yatim, B.; Amin, N. Performance of a PV–wind hybrid system for hydrogen production. *Renew. Energy* **2009**, *34*, 1973–1978. [CrossRef]
24. Panayiotou, G.; Kalogirou, S.; Tassou, S. Design and simulation of a PV and a PV–Wind standalone energy system to power a household application. *Renew. Energy* **2012**, *37*, 355–363. [CrossRef]
25. Kusakana, K.; Vermaak, H.J. Hybrid renewable power systems for mobile telephony base stations in developing countries. *Renew. Energy* **2013**, *51*, 419–425. [CrossRef]
26. Higier, A.; Arbide, A.; Awaad, A.; Eiroa, J.; Miller, J.; Munroe, N.; Ravinet, A.; Redding, B. Design, development and deployment of a hybrid renewable energy powered mobile medical clinic with automated modular control system. *Renew. Energy* **2013**, *50*, 847–857. [CrossRef]
27. Bhandari, B.; Lee, K.-T.; Lee, G.-Y.; Cho, Y.-M.; Ahn, S.-H. Optimization of Hybrid Renewable Energy Power Systems: A Review. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2015**, *2*, 99–112. [CrossRef]
28. Kyari, I.B.; Muhammad, J.Y. Hybrid Renewable Energy Systems for Electrification: A Review. *Sci. J. Circuits Syst. Signal Process.* **2019**, *8*, 32–39. [CrossRef]
29. Muhammad Lawan, S.; Wan Zainal Abidin, W.A. A Review of Hybrid Renewable Energy Systems Based on Wind and Solar Energy: Modeling, Design and Optimization. In *Wind Solar Hybrid Renewable Energy System*; IntechOpen Limited: London, UK, 2020; Volume 23. [CrossRef]
30. Dawood, F.; Shafiullah, G.; Anda, M. Stand-Alone Microgrid with 100% Renewable Energy: A Case Study with Hybrid Solar PV-Battery-Hydrogen. *Sustainability* **2020**, *12*, 2047. [CrossRef]
31. Wu, Y.-K.; Chang, S.-M. Review of the Optimal Design on a Hybrid Renewable Energy System. *MATEC Web Conf.* **2016**, *55*, 06001. [CrossRef]
32. Sawle, Y.; Gupta, S.C.; Kumar Bohre, A. Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2217–2235. [CrossRef]
33. Siamak, H.; Garcia, D.A. Techno-economic assessment of hybrid energy flexibility systems for islands' decarbonization: A case study in Italy. *Sustain. Energy Technol. Assess.* **2022**, *51*, 101929.

34. Hoseinzadeh, S.; Groppi, D.; Sferra, A.S.; Di Matteo, U.; Astiaso Garcia, D. The PRISMI Plus Toolkit Application to a Grid-Connected Mediterranean Island. *Energies* **2022**, *15*, 8652. [CrossRef]
35. Hoseinzadeh, S.; Nastasi, B.; Groppi, D.; Garcia, D.A. Exploring the penetration of renewable energy at increasing the boundaries of the urban energy system–The PRISMI plus toolkit application to Monachil, Spain. *Sustain. Energy Technol. Assess.* **2022**, *54*, 102908. [CrossRef]
36. Karemore, S.V.; Kamdi, S.Y. Optimal sizing of Autonomous Wind-PV hybrid system by genetic algorithm with LPSP technology. *Int. Refereed J. Eng. Sci. (IRJES)* **2013**, 29–35. Available online: http://www.irjes.com/Conference/Raee/F3035.pdf (accessed on 5 January 2023).
37. Li, J.; Wei, W.; Xiang, J. A Simple Sizing Algorithm for Stand-Alone PV/Wind/Battery Hybrid Microgrids. *Energies* **2012**, *5*, 5307–5323. [CrossRef]
38. Jahnavi, A.; Krishna Kishore, J. Computer Aided Optimal Sizing of Hybrid Photovoltaic Wind System for Rural Electrification in India. *Int. J. Eng. Res. Dev.* **2012**, *2*, 19–29.
39. IRENA. *Battery Storage for Renewables: Market Status and Technology Outlook*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2015; p. 32.
40. Hu, X.; Martinez, C.; Yang, Y. Charging, power management and battery degradation mitigation in plug-in hybrid electric vehicles: A unified cost-optimal approach. *Mech. Syst. Signal Process.* **2017**, *87*, 4–16. [CrossRef]
41. Lahyani, A.; Sari, A.; Lahbib, I.; Venet, P. Optimal hybridization and amortized cost study of battery/supercapacitors system under pulsed loads. *J. Energy Storage* **2016**, *6*, 222–231. [CrossRef]
42. Jossen, A.; Garche, J.; Sauer, D.U. Operation conditions of batteries in PV applications. *Sol. Energy* **2004**, *76*, 759–769. [CrossRef]
43. Ataei, A.; Nedaei, M.; Rashidi, R.; Yoo, C. Optimum design of an off-grid hybrid renewable energy system for an office building. *J. Renew. Sustain. Energy* **2015**, *7*, 053123. [CrossRef]
44. Bocklisch, T. Hybrid energy storage systems for renewable energy applications. *Energy Procedia* **2015**, *73*, 103–111. [CrossRef]
45. Birnie, D.P., III. Optimal battery sizing for storm-resilient photovoltaic power island systems. *Solar Energy* **2014**, *109*, 165–173. [CrossRef]
46. Maleki, A.; Khajeh, M.G.; Ameri, M. Optimal sizing of a grid independent hybrid renewable energy system incorporating resource uncertainty, and load uncertainty. *Int. J. Electr. Power Energy Syst.* **2016**, *83*, 514–524. [CrossRef]
47. Hedman, K.W.; Sheblé, G.B. Comparing hedging methods for wind power: Using pumped storage hydro units vs. options purchasing. In Proceedings of the International Conference on Probabilistic Methods Applied to Power Systems, Stockholm, Sweden, 11–15 June 2006; pp. 1–6. [CrossRef]
48. Kuznietsov, M.; Vyshnevska, Y.; Brazhnyk, I.; Melnyk, O. Modeling of the Generation-Consumption Imbalance in the Heterogeneous Energy Systems with Renewable Energy Sources. In Proceedings of the 6th International Conference on Energy Smart Systems (ESS), Kyiv, Ukraine, 17–19 April 2019; pp. 196–200. [CrossRef]
49. Kuznietsov, M. Modeling of Joint Work of Wind and Solar Power Plants. *Renew. Energy* **2016**, *1*, 12–16.
50. Kuznietsov, M.; Lysenko, O. Statistical analysis of energy indices of solar radiation (Based on the data of Tokmak Solar Power Station). *Probl. Energeticii Reg.* **2017**, *2*, 139–147. [CrossRef]
51. Kuznietsov, M.; Lysenko, O. Estimation of Power Balance of combined Power Systems. *Renew. Energy* **2018**, *4*, 6–14. [CrossRef]
52. Olsson, M.; Perninge, M.; Soder, L. Modeling real-time balancing power demands in wind power systems using stochastic differential equations. *Electr. Power Syst. Res.* **2010**, *80*, 966–974. [CrossRef]

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