ENERGETICS

ЕНЕРГЕТИКА

UDC 658.264

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RESEARCH OF HYBRID ENERGY SUPPLY SYSTEM WITH RENEWABLE ENERGY SOURCES

Г. Баласанян, В. Верстак, А. Остапенко. **Дослідження гібридної системи енергозабезпечення з відновлювальними джерелами енергії.** Виконано обробку бази експериментальної даних кліматичних параметрів з метеостанції Національного університету «Одеська політехніка» щодо подальшого їх використання для оцінки енергетичного потенціалу сонячної та вітрової енергії в Одеському регіоні. Знайдено параметри розподілу Вейбула – параметр форми та параметр масштабу, що характеризує повторюваність швидкості вітру. Розраховано імовірність повторюємості швидкості вітру за знайденими параметрами розподілу Вейбула, що забезпечило більш об'єктивні результати щодо визначення потужності вітроустановки в порівнянні з застосуванням середнього значення швидкості вітру. Опрацьовано методику щодо визначення оптимальних параметрів та конфігурації автономної гібридної системи енергозабезпечення з відновлювальними джерелами енергії для індивідуального домогосподарства за критерієм мінімальних капіталовкладень у генеруючі потужності. Досліджено, що сезонні відмінності енергетичного потенціалу сонця і вітру сприяють поєднанню цих відновлювальних джерел енергії у єдину гібридну систему та створює додаткові переваги щодо їх роботи. Отримано залежність оптимальної конфігурації та параметрів гібридної системи від енергетичного потенціалі вітра в регіоні. З'ясовано, що за умови автономної роботи гібридної системи надлишковий енергетичний потенціал не завжди використовується, бо технічно складно забезпечити сезонне акумулювання електрики. Коефіцієнт використання встановленої потужності гібридної системи при цьому склав 0,58. Наведено розподіли щодо виробництва електрики між вітроустановкою та сонячними батареям за місяцями року при заданій середньорічній швидкості вітру з урахуванням зміни енергетичного потенціалу вітру за місяцями. Визначено, що змінний характер сонячних та вітрових ресурсів може бути повністю компенсовано шляхом оптимальної інтеграції двох різних джерел до єдиної енергетичної системи.

Ключові слова: гібридна система енергозабезпечення, відновлювальні джерела енергії, вітроустановка, сонячна фотоелектрична батарея, математичне моделювання, оптимізація навантаження

H. Balasanian, V. Verstak, A. Ostapenko. **Research of hybrid energy supply system with renewable energy sources.** The experimental database of climatic parameters from the meteorological station of the Odesa Polytechnic National University was processed for their further use to assess the energy potential of solar and wind energy in the Odessa region. The Weibull distribution parameters were found - the shape parameter and the scale parameter, which characterizes the repeatability of wind speed. The probability of wind speed repeatability was calculated based on the found Weibull distribution parameters, which provided more objective results for determining the power of a wind turbine compared to using the average wind speed. A methodology has been developed for determining the optimal parameters and configuration of an autonomous hybrid energy supply system with renewable energy sources for an individual household based on the criterion of minimum capital investments in generating capacity. It has been investigated that seasonal differences in the energy potential of the sun and wind contribute to the combination of these renewable energy sources into a single hybrid system and create additional advantages for their operation. The dependence of the optimal configuration and parameters of the hybrid system on the energy potential of the wind in the region has been obtained. The distributions of electricity production between wind turbines and solar panels by months of the year at a given average annual wind speed, taking into account the change in wind energy potential by months, are presented. It is determined that the variable nature of solar and wind resources can be fully compensated by optimal integration of two different sources into a single energy system. It was found that under the condition of autonomous operation of the hybrid system, the excess energy potential is not always used, because it is technically difficult to ensure seasonal accumulation of electricity. The utilization factor of the installed capacity of the hybrid system was 0.58. The distributions of electricity production between wind turbines and solar panels by months of the year at a given average annual wind speed, taking into account the change in wind energy potential by months, are presented. It is determined that the variable nature of solar and wind resources can be fully compensated by optimal integration of two different sources into a single energy system.

Keywords: hybrid energy supply system, renewable energy sources, wind power plant, solar photovoltaic battery, mathematical modelling, load optimization

Introduction

Currently, there is a growing interest in hybrid energy supply systems based on renewable energy sources all over the world and in Ukraine. This is due to the fact that at the current stage of development of the electric power industry there is a significant increase in the cost of electricity all over the world and in Ukraine [1]. Requirements for the results of the activities of energy companies, for the environmental safety of the operation of energy facilities, and the reliability of energy supply are also

DOI: 10.15276/opu.2.70.2024.04

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

increasing [2]. The operation of hybrid energy supply systems is particularly effective, since the daily, seasonal, and annual heterogeneity of renewable energy sources, which are different in nature, can be mutually compensated.

Analysis of literary data and problem statement

A hybrid energy supply system (HESS) is a combination of two or more renewable energy sources with an electricity storage system, which ensures sustainable production of electric energy and a synergistic effect from the combination of different elements of the system. A synergistic effect is the interaction of different elements of the system, the total result of which significantly exceeds the sum of the results of the individual actions of these elements. In energy, the synergistic effect of processes is manifested through additional energy advantages, i.e. the combination of different energy sources into one system creates additional advantages of their operation [3].

World experience shows that the implementation of HESS is most effective for small farms, separate agricultural complexes, separate households, etc. [4]. Hybrid energy systems most often combine several renewable energy sources: solar photovoltaic panels (SPP), wind turbines, mini-hydroelectric power plants and other devices for further energy accumulation, which are mainly intended to provide consumers with electricity and may contain equipment that performs the role of backup power.

For Ukraine, the most developed and widespread are hybrid systems using solar and wind energy. With a completely autonomous energy supply system based only on renewable sources, the question of the optimal ratio of the generating capacity of each energy source in the system is quite relevant [5].

The optimal ratio of individual elements of the HESS is determined taking into account many factors, namely: the level of provision of the region with traditional and renewable energy sources, taking into account their energy potential, climatic conditions, energy consumption schedule, environmental and economic factors [6]. The variable nature of renewable energy sources (solar and wind resources) can be fully compensated by optimal integration of two different sources into one system [7].

Purpose and objectives of the study

The purpose of the work is to develop a methodology for optimizing the configuration of a renewable energy system based on solar and wind energy, taking into account the experimental database on the climatic conditions of the Odessa region.

To achieve this goal, it is necessary to solve the following tasks:

– process the experimental database of climatic data obtained from the weather station of the educational building of the Odessa Polytechnic National University;

– develop a methodology for determining the optimal configuration of an autonomous HESS taking into account the potential of renewable energy sources in the Odessa region;

– conduct a study of HESS energy balances in order to substantiate the optimal parameters of the system.

Materials and methods of research

The structural diagram of the autonomous hybrid energy supply system, which is studied in the work, is presented in Fig. 1. The HESS consists of solar and wind power plants. The power generated by the wind power plant is an alternating current, has a variable amplitude and frequency, which is converted into direct current for charging the battery. The controller protects the battery from overcharging and deep discharge. The inverter is used to convert direct current into alternating current with a voltage of 220 V and a frequency of 50 Hz**.**

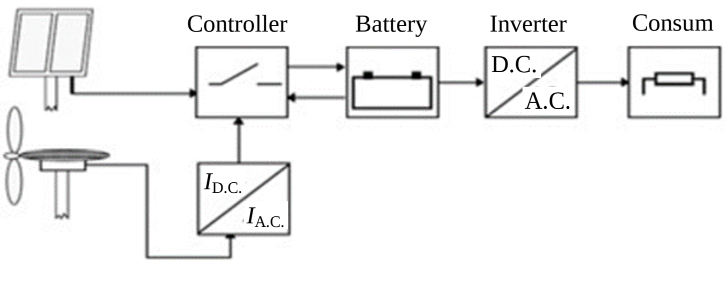

Fig. 1. Structural diagram of autonomous hybrid energy supply system

The traditional method of determining the performance of hybrid solar and wind systems is based on the use of long-term data on solar radiation and wind speed for a given area. Optimization of the structure of the HESS is carried out according to economic indicators, such as investment or cost of energy, as well as technical indicators characterizing the reliability of energy supply.

Cost component is selected as target function (TF) for optimization of hybrid power system configuration TF is the sum of all costs, including capital costs, system installation costs, operating, repair and maintenance costs.

The level of electricity consumption in the system, within certain limits, is random. The presence of wind (WPP) and solar (SPP) power plants, the capacity of which depends on the weather condition, introduce additional uncertainty into the operation of the system. Optimization of such a hybrid system should be stochastic. However, if recursive analysis methods are used to evaluate the operation of the system, using experimental data on wind speed, solar radiation and the nature of consumption, then in such a statement the problem of optimizing the power of the components of the system is completely deterministic and linear programming methods are used to solve it. Inclusion of linear equations in models guarantees finding the absolute optimum. When using nonlinear models, more complex relationships in the system are achievable, but the absolute optimum exists provided that the TF and constraints are convex [6].

To solve the problem, a round of experimental climatic data was obtained over 3 years (2020 – 2022) from the Vantage Pro2 weather station, located on the roof of educational building No. 10 of Odesa Polytechnic National University [8].

The main energy characteristic of the wind stream is the repeatability of the wind speed V, which shows how much of the time during the operation of the wind farm, the wind of a certain speed is observed.

For this purpose intervals of wind speeds with ΔV = 1 m/s are used. To predict the energy efficiency of the wind flow, experimental data on wind speed are used, which are approximated by the standard Weibul distribution function [9]:

$$F(V) = 1 - e^{-\left(\frac{V}{b}\right)^a}, \tag{1}$$

where a – scale parameter;

b – shape parameter;

$F(V)$ is an integral function of wind speed repeatability, which shows the probability that the wind speed is equal to or lower than V.

The distribution density function is:

$$F(V) = \frac{a}{b} \cdot \left(\frac{V}{b}\right)^{a-1} e^{-\left(\frac{V}{b}\right)^a}. \tag{2}$$

The distribution parameters a, b can be obtained after double logarithm of equation (1):

$$\ln 1\left[\mathrm{n}\left[\frac{1}{1-F(V)}\right]\right] = a \cdot \ln(V) - a \cdot \ln(b). \tag{3}$$

Expression (3) is a straight line equation with unknown coefficients a and b for determining which an empirical dependence ln {-ln [1-F (V)]} on ln (V) is constructed, followed by a least squares approximation.

Having obtained the probability density distribution of wind speeds, it is possible to calculate the probability of wind speed repetition in any speed interval [$V1$; $V2$]:

$$P(V1 < V < V2) = (V2) - F(V1) = 1 - e^{-\left(\frac{V2}{b}\right)^a} - \left(1 - e^{-\left(\frac{V1}{b}\right)^a}\right). \tag{4}$$

The average amount of electricity generated by the wind power plant is:

$$E_{\mathrm{WPP}} = T\sum_{1}^{m} P_j(V) N_j(\mathrm{V}), \text{ kWt/h}, \tag{5}$$

where m – number of wind velocity ranges;

T – number of WPP operation hours per year;

$P_j(V)$ – frequency (probability) of repetition of wind speeds in the j-th range;

$N_j(V)$ – wind power plant in the j-th range of wind speeds, kW (determined by the operating characteristic of the wind plant as the average value in the j-th range).

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

The mathematical expectation m_V and the standard deviation σ_V^2 velocity of the wind V using the Weibul distribution can be determined from the following expressions:

$$m_V = a\Gamma\left(1+\frac{1}{b}\right); \quad \sigma_V^2 = a^2\left[\Gamma\left(1+\frac{2}{b}\right) - \Gamma\left(1+\frac{1}{b}\right)\right], \tag{6}$$

where $\Gamma\left(1+\frac{2}{b}\right), \Gamma\left(1+\frac{1}{b}\right)$ – gamma functions of distribution parameter b.

The gamma function is defined by the expression:

$$\Gamma(x) = \int_0^\infty t^{x-1} \cdot e^{-t} dt\,. \tag{7}$$

As for optimization of parameters and configuration of HESS, TF is proposed, which minimizes the capital costs for the generating capacity of the system:

TF: $$K_{\text{WPP}} + K_{\text{SPP}} \to \min\,, \tag{8}$$

where – K_{WPP}, K_{SPP} respectively, capital investment in generating capacities of wind power plants and solar power plants, UAH:

$$K_{\text{WPP}} = F_{\text{WPP}} \cdot K_{sp}^{\text{WPP}}\,, \tag{9}$$

$$K_{\text{SPP}} = F_{\text{SPP}} \cdot K_{sp}^{\text{SPP}}\,, \tag{10}$$

where K_{sp}^{WPP} – specific investments per 1 m^2 of wind farm blade area washed by wind, UAH/m^2;

K_{sp}^{SPP} – specific investments per 1 m^2 of the area of photovoltaic panels of SES, UAH/m^2;

F_{WPP} – wind farm blade area washed by wind, m^2:

F_{SPP} – area of photovoltaic panels of SPP, m^2,

and constraints that establish a balance between electricity generation and consumption:

LIMITATION: $$E_i \geq E_i^{con}\,, \tag{11}$$

where E_i^{con} – the amount of electricity consumed for the *i*-th month of the year, kWh;

$E_i = E_i^{\text{WPP}} + E_i^{\text{SPP}}$ – the amount of electricity generated together by WPP and SPP for the *i-th* month of the year, kWh:

$$E_i^{\text{WPP}} = N_{sp\,i}^{\text{WPP}} F_{\text{WPP}} n_i\,, \tag{12}$$

$$E_i^{\text{SPP}} = N_{sp\,i}^{\text{SPP}} F_{\text{SPP}} n_i\,, \tag{13}$$

where $N_{sp\,i}^{WPP}$ – the specific capacity of the wind farm in the first month of the year, determined by the average wind speed per month, W/m^2:

$$N_{sp\,i}^{\text{WPP}} = 0.5\rho_n C_P V_i^3\,, \tag{14}$$

where ρ_n – air density, the value is taken within 1.2...1.3 kg/m^3;

V_i – average wind speed for the i-th month, m/s;

C_P – efficiency factor of wind farm power takeoff, depending on the design features of the wind generator, the value is taken within 0.35...0.45;

$N_{sp_i}^{\text{SPP}}$ – specific capacity of SPP in the first month of the year, determined by the average insolation per month, W/m^2;

n_i – number of hours in the corresponding month of the year.

The optimization problem was solved using the "Solution Search" option of Excel spreadsheets. According to the results of solving the problem, the optimal values of the title F_{WPP} and the title F_{SPP} satisfying the given conditions are determined.

Research results

Results of processing and averaging of experimental climate data on wind speed and insolation during 2020 – 2022 is presented in Table 1.

Table 1

Experimental data on wind speed and insolation

Month of the year	January	February	March	April	May	June	
Average monthly wind speed, m\s	4.8	5	4.8	4.8	3.7	2.9	
Insolation, kW g/m^2	28	47	116	162	175	208	
month of the year	July	August	September	October	November	December	Average annual
Average monthly wind speed, m/s	2.9	2.7	2.9	3.2	4.4	4.7	3.9
Insolation, kW g/m^2	195	180	131	71	30	28	114

The data from Table 1 indicate a significant difference in terms of insolation in the summer and winter months (almost 7.5 times), and the opposite picture in terms of wind speed (almost 2 times, but taking into account the cubic dependence of power on wind speed - the energy potential of the wind decreases in summer 6...7 times).

Such seasonal differences in the energy potential of the sun and wind contribute to the combination of these renewable energy sources into a hybrid system and create additional advantages for their work.

Figure 2 shows the distribution by experimental data of the average daily wind speed by months of the year with the range of wind speed variation with $\Delta V = 1$ m/s. Average daily data for 365 days of the year were used. The given distribution is characteristic of the distribution by the Weibull function.

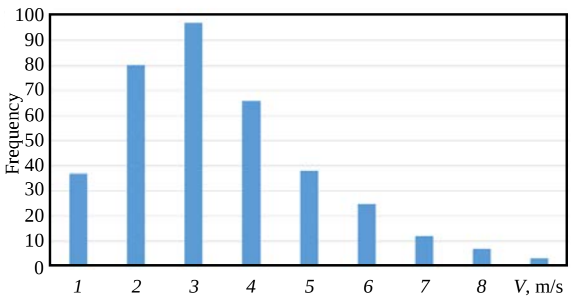

Fig. 2. Distribution of the frequency of repetition of the average daily wind speed per year according to experimental data

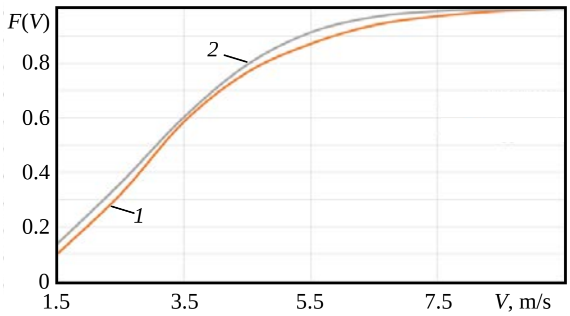

Fig. 3. Integral function of wind speed repeatability: *1* – experiment; *2* – model

The Weibull function distribution parameters (a, b) were determined according to procedure (1) to (4). A form parameter a = 2.15 and a scale parameter b = 3.63 were obtained with a coefficient of determination R^2 = 0.989. The mathematical expectation of wind speed m_V = 3.95 m/s.

Figure 3 graphs of the integral function of wind velocity repeatability are given, which is constructed from experimental data and from the calculation model (1). We can note a significant approximation of the experimental data to the model of the integral function of wind repeatability.

Taking into account the repeatability of wind speed according to the found parameters of the Weibul distribution provides more objective results in calculating the power of the wind installation in comparison with the application of the average wind speed. This consideration provided an increase in the estimated capacity of the wind farm in the above study by 1.7 times.

Input data on the solution of the problem of optimization of parameters of HESS:

Efficiency factor of WPP power takeoff, C_P = 0.4;

Efficiency factor of solar panels, K_{SPP} = 0.2;

Air density ρ_n = 1.25 kg/m^3;

Average monthly electricity consumption by the household, E_i^{con} = 1000 kWh;

Specific investment in the wind installation, K_{sp}^{WPP} = 10500 UAH/m^2;

Specific investments in SPP, K_{sp}^{SPP} = 3150 UAH/m^2.

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

According to the results of solving the problem of optimizing the HESS parameters, the following is obtained:

$F_{\text{WPP}} = 28$ – wind-driven wind farm blade area, m^2:

$F_{\text{SPP}} = 51$ – area of photovoltaic panels of SPP, m^2;

$K_{\text{WPP}} = 290.3$ – capital investment in generating capacity of wind farm, thousand UAH;

$K_{\text{SPP}} = 161.8$ – capital investment in SPP generating capacity, thousand UAH;

$K_{\text{HESS}} = 452.1$ – capital investment in HESS generating capacity, thousand UAH;

$N_{\text{WPP}} = 0.692$ – design capacity of wind farm, kW;

$N_{\text{SPP}} = 1.606$ – design capacity of SPP, kW.

Figure 4 shows the distribution of electricity production between WPP and SPP by months of the year with an average annual wind speed $V_{av} = 3.9$ m/s, but taking into account changes in the wind energy potential by months.

Analysis of Fig. 4 shows that the balance between electricity production and consumption at the level of 1000 kWh per month is performed only in October and November. In the remaining months of the year, there is excessive power of the HESS. Under the conditions of connection to the network, excess electricity could be sold to the power system, which, accordingly, would reduce the cost of generating HESS. But under the condition of autonomous operation of the HESS, the excess energy potential is not used, because it is technically very difficult to ensure seasonal accumulation of electricity. The utilization factor of the installed power of the HESS at the same time amounted to $K_{ut} = 0.579$.

The research on the influence of the energy potential (speed) of wind on the distribution of electricity production between WPP and SPP in the system, and investment in generating capacity, was carried out. Wind energy potential may be higher for other regions of Ukraine, and also increases with height above the surface [10].

The average annual wind speed in the study gradually increased to 10 m/s in increments of 2 m/s.

With an increase in the average annual wind speed to 6 m/s inclusive, the optimal distribution of electricity production between WPP and SPP by months of the year did not change, but investment in WPP decreased due to an increase in the specific capacity of the WPP.

When the average annual wind speed increased to 8 and 10 m/s, the distribution of electricity production between the WPP and SPP changed in favor of the WPP (Fig. 5, Fig. 6), and, accordingly, the installed capacity of the SPP decreased.

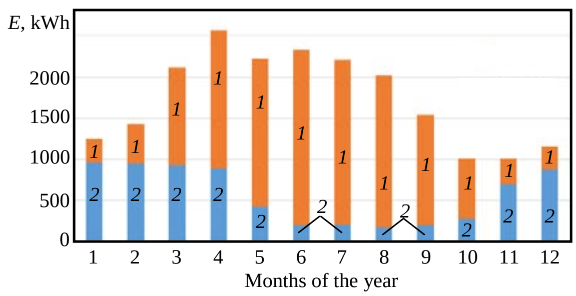

Fig. 4. Distribution of electricity production between WPP and SPP by months of the year at $V_{av} = 3.9$ m/s: *1* – sun; *2* – wind

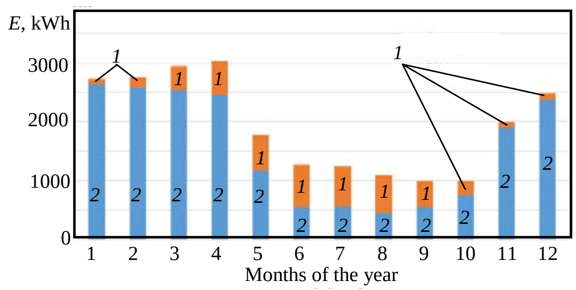

Fig. 5. Distribution of electricity production between WPP and SPP by months of the year at $V_{av} = 8$ m/s: *1* – sun; *2* – wind

With $V_{av} = 10$ m/s, the installed capacity of the wind farm increased 3.5 times, and the installed capacity of the SPP decreased 4.5 times accordingly.

Figure 7 shows the dependence of investments in RES generating capacities on wind speed during separate generation at a wind farm or SPP and when they are combined into a hybrid system. Investments in a separate SPP do not depend on wind speed and are higher than HSPP, because with the autonomous operation of the SPP, its power is calculated from the minimum insolation in winter, as a result of which it has a very low utilization factor of the installed power in summer. The investment in a separate wind farm is also higher than the HSPP, because with the autonomous operation of the wind farm, its power is calculated from the minimum wind speed in the summer, as a result of which, with a relatively high wind speed in the winter, no excess power is used.

So, the most favorable option for investment is a hybrid system that combines the advantages of wind farms and SPPs, and with a significant average annual wind speed (10 m/s) it is close in efficiency to a separate wind farm, although such a speed is an exception for Ukraine.

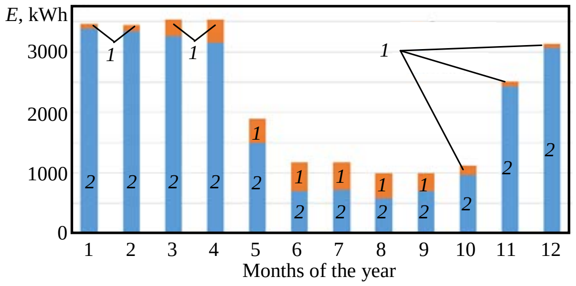

Fig. 6. Distribution of electricity production between WPP and SPP by months of the year at V_{av} = 10 m/s: *1* – sun; *2* – wind

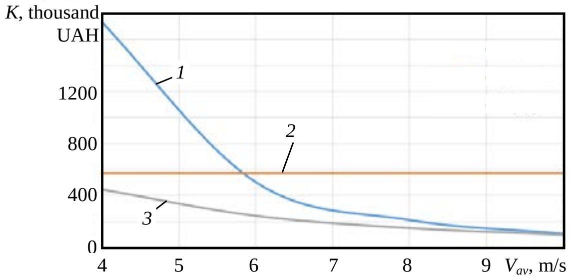

Fig. 7. Dependence of investments in generating capacities of renewable energy sources on wind speed: *1* – WPP; *2* – SPP; – Hybrid

Conclusions

The processing of the database of the experimental database of climatic parameters from the weather station of Odesa Polytechnic National University for further use in assessing the energy potential of solar and wind energy in the Odessa region was carried out.

The methodology for determining the optimal parameters and configuration of an autonomous hybrid energy supply system with renewable energy sources for an individual household has been worked out according to the criterion of minimum investment in generating capacities.

The dependence of the optimal configuration and parameters of the hybrid system on the wind energy potential in the region is investigated.

It is determined that the variable nature of solar and wind resources can be fully compensated by optimal integration of two different sources into a single energy system.

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ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

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Received September 30, 2024

Accepted November 15, 2024