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AUTONOMOUS HYBRID SYSTEM OF COMBINED ENERGY SUPPLY WITH RENEWABLE ENERGY SOURCES

Г. Баласанян, В. Верстак, А. Остапенко. **Автономна гібридна система комбінованого енергозабезпечення з відновлювальними джерелами енергії.** Запропоновано конфігурацію ГСЕВДЕ щодо автономного забезпечення електро та теплопостачання домогосподарств з урахування енергетичного потенціалу вітрової та сонячної енергії в Одеському регіоні. Виконано узагальнення експериментальних кліматичних даних, щодо сонячної інсоляції та швидкості вітру, що отримано з метеостанції національного університету «Одеська політехніка». Отримано параметри розподілу швидкості вітру за функцією Вейбула: параметр форми, параметр масштабу та математичне очікування швидкості вітру. Отримано вирази щодо інтегральної функції повторюваності та функції щільності розподілу швидкості вітру. Розроблено методику щодо визначення конфігурації та оптимальних параметрів ГСЕВДЕ для індивідуальних домогосподарств за критерієм мінімізації вартісної складової, що включає витрати на експлуатацію, ремонт, технічне обслуговування та капітальні витрати у генеруючі потужності системи. Розв'язання задачі оптимізації здійснено в електронних таблиць Excel за опцією «Пошук рішення». Результатом розв'язання є оптимальні значення загальної площі перетину лопатей вітроустановки та загальної площі фотоелектричних панелей, що задовольняють умовам задачі. Досліджено залежність конфігурації та параметрів ГСЕВДЕ від ефективності використання встановленої потужності та економічних показників системи. При автономній роботі ГСЕВДЕ надлишковий енергетичний потенціал вітру та сонця не використовується, бо це потребує сезонного акумулювання електрики, що економічно недоцільно, та технічно малоефективне. Включення до конфігурації ГСЕВДЕ системи автономного теплопостачання зумовило значне зростання частки генеруючої потужності ВЕС в порівнянні з часткою СЕС. Підтверджено, що сезонна зміна енергетичного потенціалу вітрових та сонячних ресурсів може бути взаємокомпенсована шляхом інтеграції до єдиної системи двох різних за природою ВДЕ та оптимізації їх генеруючих потужностей.

Ключові слова: гібридна система, комбіноване енергозабезпечення, відновлювальні джерела енергії, вітроелектростанція, сонячна електростанція, математичне моделювання, оптимізація параметрів

G. Balasanian, V. Verstak, A. Ostapenko. **Autonomous hybrid system of combined energy supply with renewable energy sources.** The paper proposes a configuration of HSERES for the autonomous provision of electricity and heat supply to households, taking into account the energy potential of wind and solar energy in the Odesa region. The experimental climatic data on solar insolation and wind speed obtained from the meteorological station of the Odessa Polytechnic National University are generalised. The parameters of the wind speed distribution according to the Weibull function are obtained: the shape parameter, the scale parameter, and the mathematical expectation of the wind speed. The expressions for the integral repeatability function and the density function of the wind speed distribution are obtained. A methodology has been developed to determine the configuration and optimal parameters of a HSERES for individual households according to the criterion of minimising the cost component, which includes the costs of operation, repair, maintenance and capital expenditure in the generating capacity of the system. The optimisation problem was solved in Excel spreadsheets using the "Solution Search" option. The result of the solution is the optimal values of the total cross-sectional area of the wind turbine blades and the total area of photovoltaic panels that meet the conditions of the problem. The dependence of the configuration and parameters of the HSERES on the efficiency of the installed capacity and economic indicators of the system is investigated. During the autonomous operation of the HSERES, the excess energy potential of wind and sun is not used, as it requires seasonal accumulation of electricity, which is economically inexpedient and technically inefficient. The inclusion of an autonomous heat supply system in the configuration of the HSERES has led to a significant increase in the share of wind power generation capacity compared to the share of solar power plants. It is confirmed that the seasonal change in the energy potential of wind and solar resources can be mutually compensated by integrating two different in nature RES into a single system and optimising their generating capacities.

Keywords: hybrid system, combined energy supply, renewable energy sources, wind power plant, solar power plant, mathematical modelling, parameter optimisation

Introduction

The prevalence of hybrid energy supply systems with renewable energy sources (HSESRES) is growing significantly every year in Ukraine and in the world. This is due to the gradual increase in the cost of traditional energy resources, electricity and heat, environmental problems and requirements for the reliability of energy supply [1]. The configuration of a HSERES is quite diverse, as the system can combine several different renewable energy sources (RES) and traditional energy sources [2]. The efficiency of HSERES is correspondingly higher compared to systems containing only one type of RES. This is due to the manifestation of a synergistic effect, when the disadvantages of different RES can be mutually compensated, and the advantages, respectively, complement each other [3].

Literature review and problem statement

Experience in the operation of HSERES shows that their implementation is most effective for individual farms, agricultural complexes, individual households, etc. For the climatic conditions of

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Ukraine, the most widespread and appropriate are HSERES that combine wind turbines and solar photovoltaic panels (SPPs) [5, 6]. Hybrid energy systems can be either fully autonomous or connected to the grid. Autonomous hybrid systems must include energy storage devices to compensate for the variability of solar and wind resources.

The most common hybrid systems are those that provide autonomous electricity supply, but for the southern regions of Ukraine, systems that also provide autonomous heat supply (heating and hot water) when integrated into the system, for example, a heat pump (HP) and an electric boiler, make sense. With this system configuration, the demand for electricity during the heating season increases accordingly, but there is no need to use fossil fuels. With a fully autonomous HSERES, the issue of optimising the capacity of each RES in the system is relevant [7].

The optimal ratio of RES elements in the system depends on the energy potential of RES in the region, its climatic conditions, energy consumption schedule, environmental conditions and economic factors [8].

Purpose and objectives of the study

The aim of the work is to optimise the configuration and study the HSERES for combined energy supply of autonomous consumers, taking into account the experimental data of the climatic conditions of the Odesa region.

To achieve the research goal, the following tasks need to be solved:

– to summarise the experimental climatic data on solar insolation and wind speed obtained from the meteorological station of the Odessa Polytechnic National University;

– to develop a methodology for optimising the configuration and parameters of an autonomous HSERES, taking into account the RES potential of the Odesa region;

– to conduct a study of the combined energy supply system in order to determine the optimal energy and economic parameters of the system.

Materials and methods of research

The structural diagram of the proposed autonomous HSERES is shown in Fig. 1. The configuration of the HSERES consists of wind and solar power plants that generate electricity, various consumers in the household, a heat pump and an electric boiler as sources of heat supply. The electricity generated by the wind turbine is converted into direct current to charge the battery. The controller protects the battery from deep discharge and overcharging. The inverter converts direct current into alternating current with a frequency of 50 Hz and a voltage of 220/380 V. The heat supply in the system is provided by the heating element, but peak heat loads, when the outside temperature is below –10 °C, are additionally covered by an electric boiler.

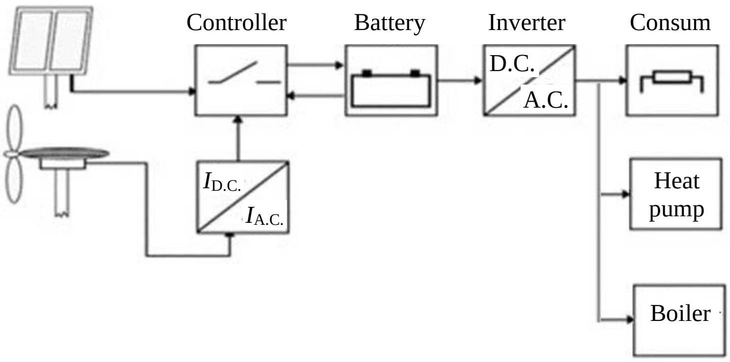

Fig. 1. Block diagram of an autonomous HSERES of combined energy supply

Methods for determining the configuration and performance of hybrid systems are based on generalised long-term data on wind speed and solar insolation for a given area. The optimisation of the structure of a HSERES can be carried out both by technical indicators that characterise the reliability and efficiency of energy supply and by economic indicators, such as the cost of energy or capital investment [8].

The objective function (OF) for optimising the configuration and parameters of the HSERES is the cost component, which is the sum of costs, including operation, repair and maintenance, capital costs, and installation costs.

The capacity of the solar (SPP) and wind (WPP) power plants that make up the hybrid system depends on climatic conditions and weather and introduces significant uncertainty into the system's operation. Electricity consumption in the system is also random.

Thus, methods for optimising a hybrid system must be stochastic. An experimental database of solar insolation, wind speed, and electricity consumption is used to evaluate the performance of the HSERES. In such a formulation, the problem of optimising the parameters of the system components is purely deterministic, and nonlinear programming methods can be used to solve it, which, provided the OF is convex, ensures the finding of the absolute optimum [9].

The study used an experimental database of climate data for the Odesa region, obtained during 2022-2024 using a Vantage Pro2 weather station located on the territory of the Odessa Polytechnic National University at an altitude of 25 m [10].

The experimental wind speed data were approximated by the standard Weibull distribution function [11]. The integral function for wind speed repeatability calculates the probability that the wind speed will be equal to or lower than *V*:

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

where: *a*, *b* – respectively, the parameters of the scale and shape of the Weibull distribution; *V* is the wind speed.

Accordingly, the density function of the wind speed distribution is equal to:

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

The distribution parameters *a*, *b* were obtained after processing and summarising the experimental climate data base and subsequent double logarithmisation with the least-squares approximation of Equation (1).

Having the parameters of the integral probability function of wind speeds, respectively, it is possible to calculate the probability of wind speed repetition in the speed interval [V_1; V_2]:

$$P(V_1 < V < V_2) = F(V_2) - F(V_1) = 1 - e^{-\left(\frac{V_2}{b}\right)^a} - \left(1 - e^{-\left(\frac{V_1}{b}\right)^a}\right). \tag{3}$$

Then, taking into account the distribution of wind speed, the average annual electricity generation at a wind farm is equal to:

$$E_{\text{WPP}} = T_{\text{WPP}} \sum_{1}^{n} P_j(V) N_j(V), \text{ kWt/h}, \tag{4}$$

where: *n* is the number of wind speed ranges with a step of 1 m/s; T_{WPP} is the total number of hours of wind farm operation per year; $P_j(V)$ is the probability of repeating the wind speed in the *j*-th range; $N_j(V)$ is the electric power of a wind farm in the *j*-th wind speed range.

OF is proposed to optimise the parameters of the HSERES, which minimises investments, costs for operation, repair and maintenance of the system's generating capacities:

$$K_{\text{WPP}} + EK_{\text{WPP}} \cdot T_{lt}^{\text{WPP}} + K_{\text{SPP}} + EK_{\text{SPP}} \cdot T_{lt}^{\text{SPP}},$$

where: K_{WPP}, K_{SPP}, – respectively, capital investments in the generating capacities of WPPs and SPPs:

$$K_{\text{WPP}} = F_{\text{WPP}} \cdot K_{\text{SP}}^{\text{WPP}}; \tag{5}$$

$$K_{\text{SPP}} = F_{\text{SPP}} \cdot K_{\text{SP}}^{\text{SPP}}; \tag{6}$$

EK_{WPP}, EK_{SPP} – respectively, the costs of operation, repair and maintenance of WPPs and SPPs per year; T_{lt}^{WPP}, T_{lt}^{SPP} – respectively, the total lifetime of WPP and SPP; $K_{\text{SP}}^{\text{WPP}}$ – specific capital investment per 1 m^2 of wind-washed blade area; $K_{\text{SP}}^{\text{SPP}}$ – specific investment per 1 m^2 of PV panel area of a

SPP; F_{WPP} – total area of the wind turbine blades that is washed by the wind; F_{SPP} – total area of PV panels of the SPP.

OF is supplemented by restrictions on the generation and consumption of electricity in the system:

$$E_i \geq E_i^{\text{C}} + E_i^{\text{HP}} + E_i^{\text{B}},$$

where: E_i^{C}, E_i^{HP}, E_i^{B} – respectively, the amount of electricity consumed by a household, a heat pumpand an electric boiler in the *i*-th month of the year; $E_i = E_i^{\text{WPP}} + E_i^{\text{SPP}}$ *is* the total amount of electricity generated by WPP and SPP during the *i*-th month of the year:

$$E_i^{\text{WPP}} = N_{\text{SP}_i}^{\text{WPP}} F_{\text{WPP}} n_i; \tag{7}$$

$$E_i^{\text{SPP}} = N_{\text{SP}_i}^{\text{SPP}} F_{\text{SPP}} n_i, \tag{8}$$

where: $N_{\text{SP}_i}^{\text{SPP}}$ is the specific power of WPP per 1 m^2 of WPP blades in the *i*-th month of the year;

$$N_{\text{SP}_i}^{\text{WPP}} = 0.5\rho_a C_{\text{P}} V_i^3, \tag{9}$$

where: ρ_a is the air density; V_i is the average wind speed in the *i*-th month of the year; C_P is the efficiency coefficient for power extraction of a WPP; $N_{\text{SP}_i}^{\text{WPP}}$ *is* the specific power of a SPP in the *i*-th month of the year, determined by the average solar insolation for the corresponding month of the year; n_i – number of hours in the *i*-th month of the year.

Thus, the problem of optimising the parameters of the proposed configuration of the is finally as follows:

$$\begin{cases} F = K_{\text{WPP}} + EK_{\text{WPP}} \cdot T_{\text{B}}^{\text{WPP}} + K_{\text{SPP}} + EK_{\text{SPP}} \cdot T_{\text{B}}^{\text{SPP}} \to \min(\text{OF}); \\ E_i \geq E_i^{\text{C}} + E_i^{\text{HP}} + E_i^{\text{B}} (\text{LIMITATION}). \end{cases}$$

The optimisation problem was solved in Excel spreadsheets using the “Solution Search” option. The result of the solution is the optimal values of the area of the wind farm blades – F_{WPP} and the area of the photovoltaic panels of the SPP – F_{SPP}, which satisfy the conditions of the problem.

Research results

A summary of experimental climatic data on solar insolation and wind speed obtained from the meteorological station of the Odessa Polytechnic National University is presented in [10].

The parameters of the wind speed distribution according to the Weibull function were obtained: shape parameter $a = 2.15$, scale parameter $b = 3.63$. The mathematical expectation of the wind speed $m_V = 3.95$ m/s.

Taking into account the experimental parameters of the distribution, we obtain an integral function for the repeatability of the wind speed:

$$F(V) = 1 - e^{-\left(\frac{V}{3.63}\right)^{2.15}},$$

and the distribution density function:

$$F(V) = 0.592 \cdot \left(\frac{V}{b}\right)^{1.15} \cdot e^{-\left(\frac{V}{3.63}\right)^{2.15}}.$$

The optimisation problem for the parameters and configuration of the HSERES was solved using the following input data:

Wind power extraction efficiency coefficient, $C_P = 0.35$;

Photovoltaic panel efficiency, $k_{PV} = 0.25$;

Density of atmospheric air $\rho_a = 1.24$ kg/m^3;

Specific investment in wind farms, $K_{\text{SP}}^{\text{WPP}} = 10400$ UAH/m^2;

Specific investment in SPPs, $K_{\text{SP}}^{\text{DPP}} = 3200$ UAH/m^2.

The average monthly value of the heat pump conversion factor during the heating period COF = 2.5.

The electricity demand of a household, for powering a HP and an electric boiler by season and generalised experimental data on solar insolation in the Odesa region are presented in Table 1.

Table 1

Household electricity demand by location of the year

Month of the year	January	February	March	April	May	June
Average monthly consumption, kWh	3976	3688	2488	1744	1000	1500
Insolation, kWh/m^2	30	49	115	160	176	210
Month of the year	July	August	September	October	November	December
Average monthly consumption, kWh	1600	1600	1300	1744	2488	2984
Insolation, kWh/m^2	198	185	130	70	31	27

The results of solving the problem of optimising the parameters of the HSERES:

$F_{WWP} = 106$ m^2 – the total cross-sectional area of the wind farm blades;

$F_{SPP} = 49$ m^2 – total area of PV panels of the WPP;

$K_{WWP} = 1094$ thousand UAH – total investment in the wind farm;

$K_{SPP} = 149$ thousand UAH – total investment in the SPP;

$K_{HSERES} = 1243$ thousand UAH – total investments in the generating capacities of the HSERES;

$N_{WWP} = 2.67$ kW is the rated capacity of a wind farm;

$N_{SPP} = 1.52$ kW – rated capacity of SPP.

The inclusion of an autonomous heat supply system in the HSERES configuration has led to a significant increase in the share of wind power generation capacity compared to the share of solar power plants. This is due to the more efficient use of wind energy potential during the heating season compared to the energy potential of solar insolation.

The graph of electricity generation by WPPs and SPPs by months of the year is shown in Fig. 2 with the mathematical expectation of wind speed $m_V = 3.95$ m/s and taking into account the distribution of wind and solar energy potential by months of the year.

The analysis of Fig. 2 shows that during the heating season (November to April), electricity is generated mainly from wind energy, and in the warm season, on the contrary, from solar energy. Such a distribution of generation by months of the year is favourable for a hybrid system of wind and solar power plants, as the energy potential of wind in the warm season decreases by 6-7 times, while solar insolation in summer increases by up to 7 times.

When operating autonomously, there is always a surplus in electricity generation, as the capacity of wind farms and solar power plants is selected to fully meet the electricity needs of consumers in any month of the year. Fig. 3 shows the ratio of electricity consumption and generation by RES by month of the year. The coincidence of generation and consumption is observed only in January, while in other months of the year, generation exceeds consumption. In the case of autonomous operation of RES, the excess energy potential of wind and solar power is not used, as it requires seasonal accumulation of electricity, which is economically inexpedient and technically inefficient. If the system is connected to the grid, excess electricity can be sold, which reduces the cost of generation.

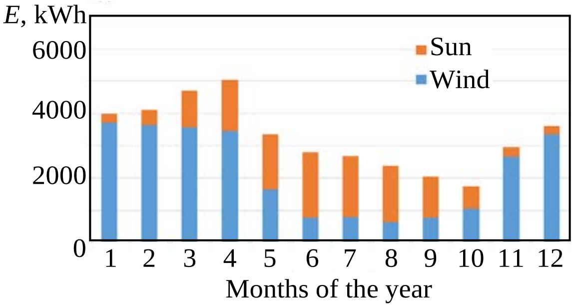

Fig. 2. Electricity generation by WPPs and SPPs by months of the year, $V_{av} = 3.95$ m/s

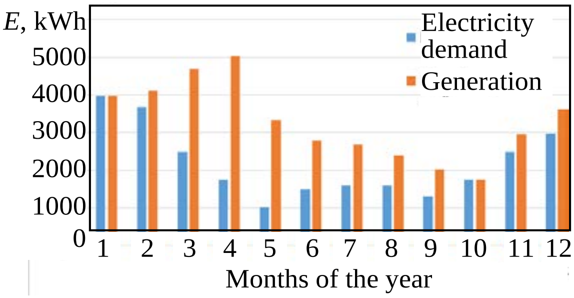

Fig. 3. Ratio of electricity demand and generation by HSERES by months of the year

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In the autonomous operation of a HSERES, the issue of the efficiency of using generating capacities depending on the system configuration is relevant [12]. In this study, we investigated the effect of the system configuration on the installed capacity factor (ICF).

Fig. 4 shows the impact of the HSERES configuration on the installed capacity utilisation factor under the condition of equal energy effect for each system configuration.

The highest value (ICF = 0.664) was obtained for the hybrid system of the proposed configuration, and the lowest – 0.134 for the autonomous system with generation only from SPPs. For the system with wind farms only, the efficiency factor was 0.608, respectively. Such a ratio of the efficiency for different configurations indicates the feasibility of using hybrid systems that meet the consumer's needs not only in electricity but also in heat supply.

The proposed configuration of the HSERES also has economic advantages compared to systems with separate use of SPPs or WPPs. Fig. 5 shows the dependence of the amount of investment in systems of different configurations under the condition of equal energy effect.

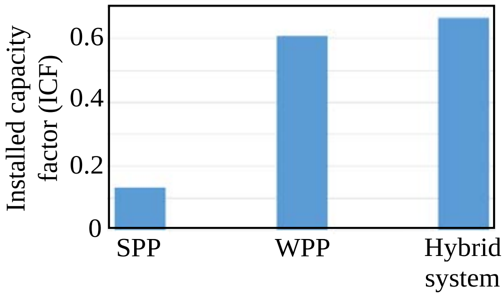

Fig. 4. Influence of the HSERES configuration on the installed capacity factor

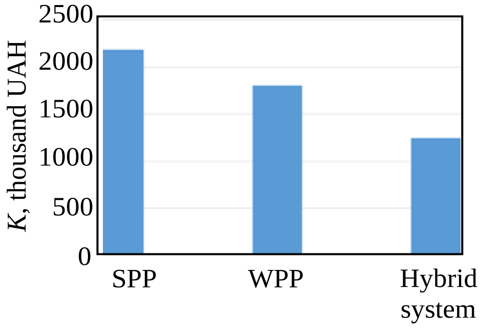

Fig. 5. Capital investment in systems of different configurations

The proposed configuration of the HSERES requires 1.75 times less investment compared to a single SPP and, accordingly, 1.45 times less compared to a single WPP.

Conclusions

1. The configuration of the HSERES for the autonomous provision of electricity and heat supply to households, taking into account the energy potential of wind and solar energy in the Odesa region, has been proposed.

2. A methodology has been developed to determine the configuration and optimal parameters of HSERES for individual households based on the criterion of minimising the cost component, including the costs of operation, repair, maintenance and capital expenditure on the generating capacity of the system.

3. The dependence of the configuration and parameters of the HSERES on the efficiency of the installed capacity and economic indicators of the system is investigated.

4. It is confirmed that the seasonal change in the energy potential of wind and solar resources can be mutually compensated by integrating two different in nature RES into a single system and optimising their generating capacities.

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